COMPLIANCE / ENGINEERING / REMEDIATION

LT Environmental Inc.
4600 West 60th Avenue
Arvada, Colorado 80003
T 303.433.9788 / F 303.433.1432

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Mr. Paul Weaverling
Lowry Assumption, LLC
7991 Shaffer Parkway, Suite 300
Littleton, CO 80127

RE: Carbon Tetrachloride Source Area Remediation
BOS 100® Injection Program
Former Lowry Air Force Base
Denver, Colorado

Dear Mr. Weaverling:

LT Environmental, Inc. (LTE) was retained by Lowry Assumption, LLC (LAC) to implement a Carbon Tetrachloride (CT) source area groundwater remediation project as described in the *Work Plan/Phase II Corrective Action Plan Addendum for Treatability Study, Remediation of Carbon Tetrachloride in Alluvial and Water Bearing Zones Using BOS 100® in the Vicinity of Well ETMW03, Operable Unit 5, Former Lowry Air Force Base,* (Work Plan) dated May 21, 2008. LAC and the Lowry Redevelopment Authority (LRA) are conducting groundwater remediation at this site under a Consent Agreement with the Colorado Department of Public Health and Environment (CDPHE). The remediation program was designed to address CT in groundwater that is coincidental with a portion of the larger, Main Trichloroethene (TCE) Plume in Operable Unit 5 (OU5). The remediation area (Site) is located on vacant land (known as Wetlands Park) to the east of the intersection of Uinta Way and 8th Avenue, between East 11th Avenue (to the North) and East 6th Avenue (to the South), as shown on Figure 1. This work was implemented in the area considered to be the CT source release, based on the historically highest CT concentrations in groundwater observed in monitoring well ETMW-03. Based on previous work by others, the CT Plume exists solely within the shallow claystones of the Denver Formation.

The selected remedy for this location was to treat chlorinated hydrocarbons using *in-situ* injection methods. The BOS 100® injectate consists of activated carbon impregnated with nano-scale iron. Once injected, contaminants such as CT and TCE are adsorbed by the carbon, thereby co-locating CT and TCE with the reactive iron. Because the solutes are trapped on the carbon in concentrated form, the reductive dechlorination process facilitated by the nano-scale iron is efficient and complete.

The remediation program injection events associated with the project were accomplished between May 27, 2008 and July 2, 2008. The injection program was conducted in two phases. The first phase was completed to evaluate injection equipment with regard to feasibility and field performance to determine which delivery system setup would be used for full-scale implementation (Phase II). The second phase included installing the treatment slurry for the remaining injection locations. A total of 83 injection points were completed and one groundwater monitoring well was installed. LTE subsequently completed post-injection performance groundwater monitoring at the CT source area to assess the effectiveness of the remediation project. The results indicate the program was extremely successful in reducing the CT concentrations in the source area. The injection activities, well installation, and groundwater monitoring results are summarized in the following report.

**UIC Rule Authorization Request, Right of Way Permits, and Utility Clearance**

Prior to engaging in invasive field activities, LTE prepared and submitted a Rule Authorization request to the U.S. Environmental Protection Agency (EPA) Region 8 Underground Injection Control (UIC) Section to allow for injection of BOS 100® into the subsurface. The request was consistent with Title 40 Code of Federal Regulations Parts 144.12, 144.24 and 144.27. Additionally, LTE completed appropriate utility location notifications prior to beginning field activities. An electronic format (PDF) copy of the UIC Rule Authorization letter from EPA authorizing the BOS 100® injections is included in Attachment 1.

**Injection Program Phase I**

The first phase of the remediation program was conducted to evaluate injection equipment with regard to feasibility and field performance in order to determine the best apparatus for injecting the treatment slurry at the Site. A heavy duty direct-push drill rig, provided by Site Services, Inc., was used to attain the desired injection depths at each location. During the Phase I period, 13 locations in the test grid were injected (Injection Points A2, A4, B2, B5, B6, C4, C5, C6, D3, D4, D5, E4, and E5) at the locations shown on Figure 2.

Test injections were performed in two steps: 1) using a high-pressure/high flow rate hydraulic fracturing method provided by the Well Improvement Company, Inc. from May 27 through May 29, 2008, and 2) using conventional injection equipment and methods supplied by Alpine Field Services (Alpine) from June 4 through June 6, 2008. Based on the comparative testing, the conventional injection equipment supplied by Alpine was faster and as productive as the high pressure/high flow technology provided by the Well Improvement Company, Inc. In the 2-day time span using the high-pressure/high flow hydraulic fracturing method, a total of five injections were completed. Multiple plugs were encountered within the injection tooling during this initial event. The conventional injection equipment allowed for completion of seven injection points over 2.5 days. Fewer plugging problems and maintenance issues were experienced with the conventional injection pump. Although some influence extending beyond the estimated 5-foot radius of influence was observed with the high-pressure/high flow pump, preliminary laboratory results from interim groundwater sampling indicated the contact was not sufficient at the greater distance. These results indicated groundwater concentrations in monitoring well MWCT08 decreased initially from 3,735 micrograms per liter (µg/L) to 530 µg/L, and then rebounded to

1,266 µg/L during the initial injection phase. Based on these results, LTE completed Phase II of the project with the latter conventional injection pump technology and a 10-foot grid spacing.

The Phase I injection events were also used to evaluate the optimal direct push method to reach the target zones and to accomplish the injection program. During the test period, it was determined that drill rods larger than 1.5-inch diameter could not be used to reach the targeted injection depths in the bedrock intervals. Setting temporary wells for groundwater sampling require using the larger (2.5–inch diameter) rods; therefore, setting a well by direct push methods could not be accomplished. An additional groundwater sample could not be obtained from the bedrock interval using direct push methods in this phase, as planned. The 2.5-inch diameter rods were successfully used to inject into the shallow alluvial interval. Additionally, it was determined that the best success was accomplished using 2.5-inch diameter direct push rods to create a pilot hole into the top 6-inches of the bedrock and then pushing smaller 1.5-inch diameter rods into the bedrock to complete the injection program.

**Injection Program Phase II**

The injection program was accomplished according to the CDPHE-approved Work Plan with several exceptions that resulted from field adjustments required because of injectate surfacing or excessive pressure requirements at individual injection locations. The Work Plan called for a total of 12,800 pounds (lbs) by weight of BOS 100® to be injected into 80 locations in the apparent CT source area. Including the work accomplished during Phase I, a total of 15,000 lbs of BOS 100® were injected into the bedrock and alluvial intervals. The Phase II work was accomplished between June 17, 2008 and July 2, 2008.

The Phase II injection program was accomplished using injection locations spaced on 10-foot centers and 2-foot vertical spacing between injection horizons. A total of 81 injection points were implemented in the bedrock interval and 83 points were implemented in the alluvial interval. A summary of the injection progress, quantities injected, and the injection intervals for each completed point are provided in Table 1. Injection locations are shown on Figure 2. Copies of all Injection Data Sheets are included in electronic format (PDF) on the enclosed CD as Attachment 2. The injection program described below was followed except for changes required by the subsurface conditions encountered.

The injection volumes and depths were designed to distribute the injectate evenly throughout the saturated interval at each injection point. Injections to the prescribed depths were accomplished using a track-mounted direct push rig and 1.5-inch to 2.5-inch diameter direct push rods. The BOS 100® injectate for each injection point was prepared by mixing 210 lbs of granular BOS 100® with approximately 365 gallons of water. The desired quantity of BOS 100® was then pumped into the bedrock interval with a top to bottom sequence. An additional 24 lbs of BOS 100® were then pumped into the alluvial intervals using either a top to bottom sequence or bottom to top sequence. The pumping system was connected to the direct push rods and the mixture injected into the subsurface. In instances when flow could not be established at an injection pressure of 100 to 200 pounds per square inch (psi), the injection point was extracted to flush out any plugs that may have developed inside the injection rods. The mixing and injection process was repeated until the planned volume was attained at the injection location. The total amount of BOS 100® was modified at several locations due either to injectate surfacing or refusal of the push rods.

LTE field geologists managed the injection program and collected field data during the injection activities. LTE documented activities at each injection location on an Injection Data Sheet. Documented activities include detailed site activities, general observations, injection pressures and volumes, injection interval, injection depth, flow rates, and injection locations. Additional information recorded in the field logbook included location, time on site, personnel and equipment present, down time, material usage, BOS 100® surfacing, injection pressures and volumes, injection intervals, other injection measurements taken, and other observations that would be necessary to reconstruct field activities at a later date. Alpine was contracted to complete the mixing and injection applications for the injection event, and Site Services Inc. was contracted to complete the direct push and drilling services.

**Bedrock Zone Injection Summary**

A total of 81 injection points were advanced into the bedrock. The bedrock injections were conducted at a depth of approximately 4 feet below the top of bedrock and continued down at depths ranging from 24 feet below ground surface (bgs) to 39 feet bgs in 2-foot intervals. The 40 injection points located closest to monitoring well ETMW03 received 25 lbs of BOS 100® at each injection interval and 41 injection points located downgradient from monitoring well ETMW03 received approximately 15 lbs of BOS 100® per injection interval. Eight vertical injection intervals were completed for each injection point with three exceptions. The amount of BOS 100® injected was reduced or modified at locations B5, F8 and I6 due to complications encountered in the subsurface injection intervals. At B5, short-circuiting of water and BOS 100® to the surface occurred at multiple locations around the injection point. At F8, refusal was encountered at 21 feet bgs and again at 27 feet bgs. To compensate for the reduced volumes injected at B5 and F8, the remaining volumes were distributed into an added injection point (E9) which is in the general proximity of E8 and D8. Additionally, refusal was encountered at injection point I6 at 35 feet bgs. To compensate for the loss of two injection depths at point I6 (37 and 39 feet bgs), three injection shots were completed at 35 feet bgs.

Groundwater wells throughout the injection area were monitored for the presence of injectate and for groundwater elevation changes during the injection event. The groundwater elevation increased during injection to the top of the monitoring well casings in monitoring wells ETMW03, CT08, CT09 and CT01A. In some instances, a few of the groundwater monitoring well caps popped off due to increased groundwater pressure.

**Alluvial Zone Injection Summary**

Of the 80 planned alluvial interval injection points, 30 injections started at the top of the saturated interval (approximately 12 feet bgs) and continued downward. The remaining alluvial injection points were completed bottom up, starting at a depth of 16 feet bgs. The change from top/down to bottom/up injection was made to minimize surfacing and to improve the efficiency of the process. A total of three vertically discrete injections were accomplished for each injection point at 2-foot intervals unless injection results were hampered by subsurface conditions.

The injection program was modified at several locations and three additional alluvial injection points (O1, O2, and O3) were completed at the end of the injection event. Of the planned 80 injection points, 11 injection points (A2, D3, E6, E7, E8, F5, G6, I5, L3, M1, and N1) only received one injection, and four injection points (D5, E4, H1, and K4) only received two injections as a result of surfacing observed during the injection process. To make up for the loss of some of the injectate due to surfacing, seven injection points (F3, F6, F7, G7, H5, H7, and J5) received one supplementary injection shot during the injection event, and four injection points (E1, E2, F8, and H2) received two extra injection shots. Two of the three added injection points (O1 and O2) received five injection shots at 2-foot intervals between 12 feet and 16 feet bgs. The other point (O3) received three injection shots between 12 and 16 feet bgs.

**Monitoring Well Installation**

A temporary bedrock monitoring well (MWCT09) was installed at the location indicated on Figure 3, in the northwestern portion of the Site to evaluate injection results. This bedrock monitoring point was installed with a screened interval from 29 feet bgs to 39 feet bgs; the top of bedrock was encountered at 19 ft bgs. The temporary well was installed using a solid-stem auger drilling rig and equipment on June 3, 2008. The temporary well was installed as a stick-up without a protective casing and surrounded with orange fencing supported by steel fence posts. Monitoring well installation activities were recorded in a bound field notebook and included, but were not limited to, site activities, general observations, and installation progress. Monitoring well completion form and lithology log are included as Attachment 4.

**Performance Monitoring Program**

Periodic sampling of key monitoring wells and temporary groundwater sampling points was performed in order to monitor treatment performance. Sampling locations included two wells screened in the alluvial zone (MWCT01A and SBCT01A) and five wells screened in bedrock (MWCT01, MWCT03, MWCT08, MWCT09, and ETMW03) at the locations shown on Figure 3. Groundwater samples were collected while the injection events were in progress and analyzed for volatile organic compounds (VOCs) using EPA method 8260B, by Remediation Products, Inc., the BOS 100® injectate supplier. These samples were collected between May 30 and June 30, 2008.

Post-treatment groundwater samples were collected from the seven monitoring locations at 2 weeks, 1 month, and 4 months after injection completion in accordance with the work plan. To further evaluate the success of the injection program, and examine possible rebound, an additional groundwater sampling event was conducted 2 months after completion of the injections. During sampling, each well was purged using low flow methods with a peristaltic pump while recording pH, temperature, and conductivity. After the readings stabilized, the sample was collected. A listing of the monitoring wells sampled, total depth measurements, fluid level measurements, field parameters, and other observations were recorded in a bound log book. Purge forms detailing field parameters are included as Attachment 3. The July 16, 2008 (2 weeks) and August 5, 2008 (1 month) samples were submitted under standard chain-of-custody procedures to ChemSolutions laboratory in Larkspur, Colorado. The September 2 (2 months) and November 6, 2008 (4 months) samples were submitted under standard chain-of-custody procedures to Accutest Laboratories in Houston, Texas. All samples were analyzed for VOCs using EPA Method 8260B. Analyses for potential CT degradation daughter products (chloroform, methylene chloride, and chloromethane) were also included. Groundwater fluid level measurements and field parameters from the four post-treatment sampling events are provided in Table 2. Historical and current groundwater analytical data with the vertical well screen interval are provided in Table 3.

The target post-treatment equilibrium concentration of CT is 5 μg/L, the drinking water standard. (Note: The Colorado Basic Standards for Ground Water [5CCR 1002-41] show a CT standard with a range of 0.27 to 5 μg/L. Per Regulation No. 41, "where ground water quality exceeds the first number in the range due to a release of contaminants that occurred prior to September 14, 2004, (regardless of the date of discovery or subsequent migration of such contaminants) clean-up levels for the entire contaminant plume shall be no more restrictive than the second number in the range or the ground water quality resulting from such release, whichever is more protective.")

**Performance Monitoring Results**

Post-injection monitoring event results indicated a substantial decline in CT concentrations in the source area bedrock monitoring wells. Monitoring well ETMW03, screened from 29 feet bgs to 39 feet bgs in the CT source area, revealed an initial reduction from 5,856 μg/L to less than 5 μg/L 2 weeks after the injection work was completed. Subsequent samples from ETMW03 indicated CT concentrations ranging from 5 μg/L to 6 μg/L, then less than 2 μg/L in the November 2008 sample. TCE concentrations were also reduced in this monitoring well, from a pre-injection concentration of 175 μg/L to less than 2 μg/L in the November 2008 sample. Decline in concentrations in bedrock monitoring well MWCT08 also indicated significant improvement with a pre-injection CT concentration of 3,735 μg/L reduced to a concentration ranging from 8.6 μg/L to 25 μg/L following injection. The CT concentration in monitoring well MWCT08 appears to have stabilized at 21 μg/L based on the November 2008 monitoring event. TCE concentrations were also reduced in well MWCT08, decreasing from 61 μg/L to less than 2 μg/L. Sampling results for bedrock monitoring well MWCT09, installed after the completion of the injection events in the northwestern portion of the injection grid, revealed CT and TCE concentrations less than 2 µg/L.

CT degradation products were observed concurrent with CT at higher concentrations prior to, and during the injection events and at much lower concentrations in the post injection events. The pre-injection concentration (535 µg/L) of chloroform in bedrock monitoring well MWCT08 decreased to 120 µg/L initially during the pilot testing, and then increased to 349 µg/L. The chloroform concentrations then decreased from 240 µg/L to 18 µg/L during post-injection monitoring. Results for monitoring well ETMW03 reveal a similar trend where the chloroform concentration was 197 µg/L prior to injection and was reduced to less than 2 µg/L (Table 3).

Analytical results for the downgradient bedrock groundwater monitoring well revealed substantial CT and TCE reductions while the upgradient bedrock groundwater monitoring well did not indicate a considerable change in TCE concentrations. Monitoring well MWCT01 is located at the northern end of the injection area, and is outside and downgradient of the direct influence of the injectate. Injection in the immediate vicinity of this well was not practical, as it is located in a gully adjacent to a concrete storm drain line approaching the area from the west. MWCT01 was sampled three times during the post injection monitoring events and the CT concentration in groundwater decreased from 220 µg/L prior to injection to 15.5 µg/L in November 2008. The TCE concentration decreased from 240 µg/L to 25.7 µg/L during this time period. Bedrock monitoring well MWCT03 is an upgradient well, located outside the injection area and upgradient of the bedrock CT source area. During the post-injection groundwater monitoring events this well did not exhibit a detectable CT concentration but the TCE concentrations observed ranged from 250 µg/L to 630 µg/L. These data are consistent with the historical range of TCE concentrations at this location.

Alluvial zone monitoring was accomplished in monitoring well SBCT01A located near the center of the CT plume and in downgradient well MWCT01A. The monitoring results indicate TCE concentrations in SBCT01A reduced from 20 µg/L, initially, to 13 µg/L and then to 9.2 µg/L in November 2008. MWCT01A located at the downgradient extent of the injection program was sampled twice during the post-injection monitoring events. Both TCE and CT concentration were non-detect (<5 µg/L) in MWCT01A. Recent semiannual monitoring data for alluvial zone monitoring well IRAMW01 located upgradient of the CT plume area is included in Table 3. These data indicate CT and TCE concentrations remained less than the reporting limit (5 µg/L) after completion of the injection event.

The final performance groundwater monitoring data from the November 2008 sampling event indicate the CT source has been substantially mitigated, and stable and/or decreasing CT and TCE concentrations continue to be observed in the injection area. Groundwater analytical results for the November 6, 2008 sampling event are shown on Figure 3. Laboratory analytical results are included as Attachment 5 on the enclosed CD.

**Summary**

The CT source area treatability study injection activities were completed from May 27 to July 2, 2008 in accordance with the CDPHE-approved Work Plan. Variations to the approved Work Plan were necessitated by subsurface field conditions. Treatment was accomplished in both the bedrock CT source area and the overlying alluvium. A total of 15,000 lbs of BOS 100® was injected into the CT source area at 81 injection points in the bedrock and 83 injection points in the alluvium.

Post-injection performance groundwater monitoring was conducted during four sampling events to assess the efficacy of the injection activities. Both bedrock and alluvial wells were sampled to document the effectiveness of the selected remedy in reducing or eliminating CT in the source area at well ETMW03 and in reducing TCE concentrations in the saturated alluvium and upper bedrock intervals at the Site. Analytical results indicate that remediation of the CT source area has been highly successful, the CT plume is diminishing, and CT and other daughter products have completely degraded into other byproducts. It is apparent the downgradient bedrock groundwater (MWCT01) has been positively influenced by the injection program while the upgradient bedrock groundwater has not (MWCT03).

Based on the four post-injection monitoring events, contaminant rebound has not been observed and the degradation of CT in the source area has been very successful. Continued natural degradation processes combined with continued remediation of impacted groundwater due to the presence of BOS 100® in the subsurface is expected to adequately complete remediation. Further efforts are not believed necessary to address the bedrock CT plume in this area. LTE recommends performing one additional groundwater monitoring event at monitoring wells MWCT01, ETMW03 and MWCT08 in April 2009 to demonstrate that the CT concentrations have adequately decreased and to support a request for closure of the CT plume.

Please contact our office at 303-433-9788, if you have any questions about the data provided or need further information regarding the work described.

Sincerely,

LT ENVIRONMENTAL, INC.

Chris Purcell
Staff Geologist

Chris Shephard, P.E.
Project Manager