Green Remediation of Perchlorate-Contaminated Soil by On-Site Bioremediation at an Active Manufacturing Facility - 11320

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ABSTRACT

As available landfill space decreases, green remediation approaches and sustainable waste minimization practices allowing for the on-site reuse of excavated soil are gaining in popularity. In addition, landfill operators have shown a reluctance to accept perchlorate contaminated soils due to the lack of clear waste acceptance criteria and the high mobility of perchlorate and related potential for migration to groundwater. Further, the effectiveness of in-situ treatment of perchlorate contaminated soils through the introduction of liquids to promote in-situ biodegradation results in a potential threat to underlying groundwater due to the potential for mobilization of perchlorate given its significant solubility and mobility. While research and development of other technologies for in-situ treatment of perchlorate, such as the introduction of gaseous electron donors, is ongoing, these technologies are still in the developmental stage and have not been demonstrated at field scale. At a manufacturing facility in southern California, an on-site ex-situ bioremediation treatment process provided a fast-track sustainable remediation approach whereby landfilling of the contaminated soil was avoided by amending and biotreating soils on-site, thus allowing for the reuse of the treated soil as backfill for the foundation of a building expansion. Other benefits included 1) conservation of significant landfill space, 2) avoidance of fuel consumption for transportation of the excavated material to the landfill, and 3) avoidance of import of backfill and subbase material for the building expansion. Despite an aggressive schedule due to expansion plans for the manufacturing facility (approximately four months from the start of field work), approximately $1.5 million was saved over traditional excavation, disposal, and backfilling with imported materials. This green remediation approach resulted in a cost-effective, reliable solution for the remediation of perchlorate-contaminated soil.

During planning activities, a soil cleanup level (remedial action objective) of 500 µg/kg was demonstrated to be protective of human health and underlying groundwater. Following approval of work plans by State of California regulatory agencies, implementation of the remedial action involved excavation of approximately 10,000 m^3 (13,000 cy) of soil with perchlorate concentrations up to 5 mg/kg, approximately 15% of which was boulders and cobbles as large as two feet in diameter or more. All excavated material was processed by crushing to 50-mm minus, followed by mixing with water, glycerin, and phosphorus in a pug mill, to produce a homogeneous material with approximately 10% moisture content, 1,200 mg/kg glycerin and 37 mg/kg of disodium phosphate. All processed material was placed in biotreatment cells and sealed in 10-mil polyethylene sheeting to prevent the intrusion of oxygen into the soil and to maintain soil moisture content. After approximately a month of treatment in the biotreatment cells, perchlorate concentrations were reduced to non-detectable levels in more than 70% of the post-treatment confirmation soil samples with more than 95% below the remedial action objective of 500 µg/kg. This allowed for the reuse of treated soil as backfill material immediately following regulatory agency approval. The timely completion of the remedial action allowed the property owner to proceed with the planned expansion of their manufacturing facility.

INTRODUCTION

The Project Site is located in the City of Azusa, California within the north-central portion of the San Gabriel Valley, Los Angeles County, California. Properties in the vicinity of the Project Site include office, light industrial, and research and development buildings, with concrete and/or asphalt roadways and parking areas. Remediation of a portion of the Project Site was required to allow the property owner to expand their manufacturing facility. The Project Site encompasses portions of two properties, one the property with the manufacturing facility and the second an adjacent property to the south consisting of a partially paved parking lot owned by a separate entity. The entire Project Site comprises approximately 4.3 hectares (10.7 acres) and is primarily covered with asphalt parking areas and a single concrete building covering approximately 1,950 m^2 (21,000 ft^2). Small areas of decorative landscaping adjacent to the building or within the parking areas have exposed earth surfaces containing trees, shrubs, or lawn turf. The area of perchlorate-contaminated soils excavated during the implementation of the remedial action project described in this paper covers approximately 0.9 hectare (2.2 acres).

The Project Site is underlain by unconsolidated alluvial sediments composed of poorly sorted sand and gravel with the gravel fraction containing cobbles and boulders as large as two feet in diameter or more. These unsaturated sediments are collectively referred to as soil in this paper. The distribution of perchlorate in soil in and around the Project Site has been characterized by the drilling of approximately 100 soil borings and the analysis of more than 900 soil samples since perchlorate-related subsurface investigations commenced in 2000. The distribution of elevated concentrations of perchlorate in soil (greater than 500 micrograms per kilogram [µg/kg]) at the Project Site and surrounding area prior to the completion of this remedial action was summarized as follows:

- A broad area of elevated perchlorate concentrations (greater than 500 µg/kg) exists beneath the existing building on the site and extends to the north and south of the building (Figure 1). The majority of the elevated perchlorate concentrations occur in the upper 6 m (20 feet) of soil, though detectable perchlorate concentrations extend to a depth of 75 m (250 feet) in the area immediately south of the building.

- A second area of elevated perchlorate concentration occurs near the southern boundary of the property. This area extends south on to the adjacent property to the south. The majority of the elevated perchlorate concentrations in this area occur in the upper 6 m (20 feet) of soil as well.

- Three additional areas of elevated perchlorate concentration occur along the western boundary of the property and extend west on to the adjacent property to the west. The majority of the elevated perchlorate concentrations in this area also occur in the upper 6 m (20 feet) of soil. These three areas were not included in the remedial action described in this paper due to logistical constraints related to the presence of subsurface utilities and property access. These areas are currently being evaluated for potential future remedial actions.

The proposed remedial action alternative for the Project Site was soil excavation and on-site bioremediation combined with institutional controls targeting soils shallower than 6 m (20 feet) in depth above a remedial action objective of 500 µg/kg, which considered both the protection of human health and groundwater. Remediation of perchlorate contaminated soils to a depth of 20 feet would remove the majority of the perchlorate mass at the Project Site. Further, excavation of perchlorate impacted soils below 20 feet in depth was considered impractical due to logistical and cost considerations including worker safety, excavation shoring, potential undermining of building foundations, and the practical limitations of earthmoving equipment. In addition, perchlorate concentrations below a depth of 20 feet were considerably lower and were therefore considered to pose a much lower threat to groundwater quality. The remedial action objectives for the Project Site were to excavate soils containing perchlorate shallower than 6 m (20 feet) at concentrations equal to or greater than 500 µg/kg and to treat the excavated soils using ex-situ bioremediation to achieve a treatment goal of 500 µg/kg prior to utilizing the soil as backfill in the soil excavations.

PERCHLORATE

Ammonium perchlorate and potassium perchlorate are inorganic salts that combine the perchlorate anion (ClO_4^-) with cations, typically either ammonium (NH_4^+) or potassium (K^+) cations. These perchlorate compounds are strong oxidizers and are commonly used as oxidizers in solid rocket propellants. When either of these salts is dissolved in water the cations and anions are released and become hydrolyzed. Perchlorate salts, including ammonium and potassium perchlorate, are very soluble. For example, ammonium perchlorate has a water solubility of 106 grams/liter (g/l) and potassium perchlorate 7.5 g/l at 0°C, and the solubility increases rapidly with temperature. At high concentrations, perchlorate impacts human health by interfering with iodide uptake into the thyroid gland. Dissolved perchlorate is very stable under ambient conditions in the environment, which translates into a long half-life in aerobic, aqueous environments. However, perchlorate is readily degraded under anaerobic and anoxic conditions as indicated by its high reduction potential, which generally falls between denitrification and manganese reduction.

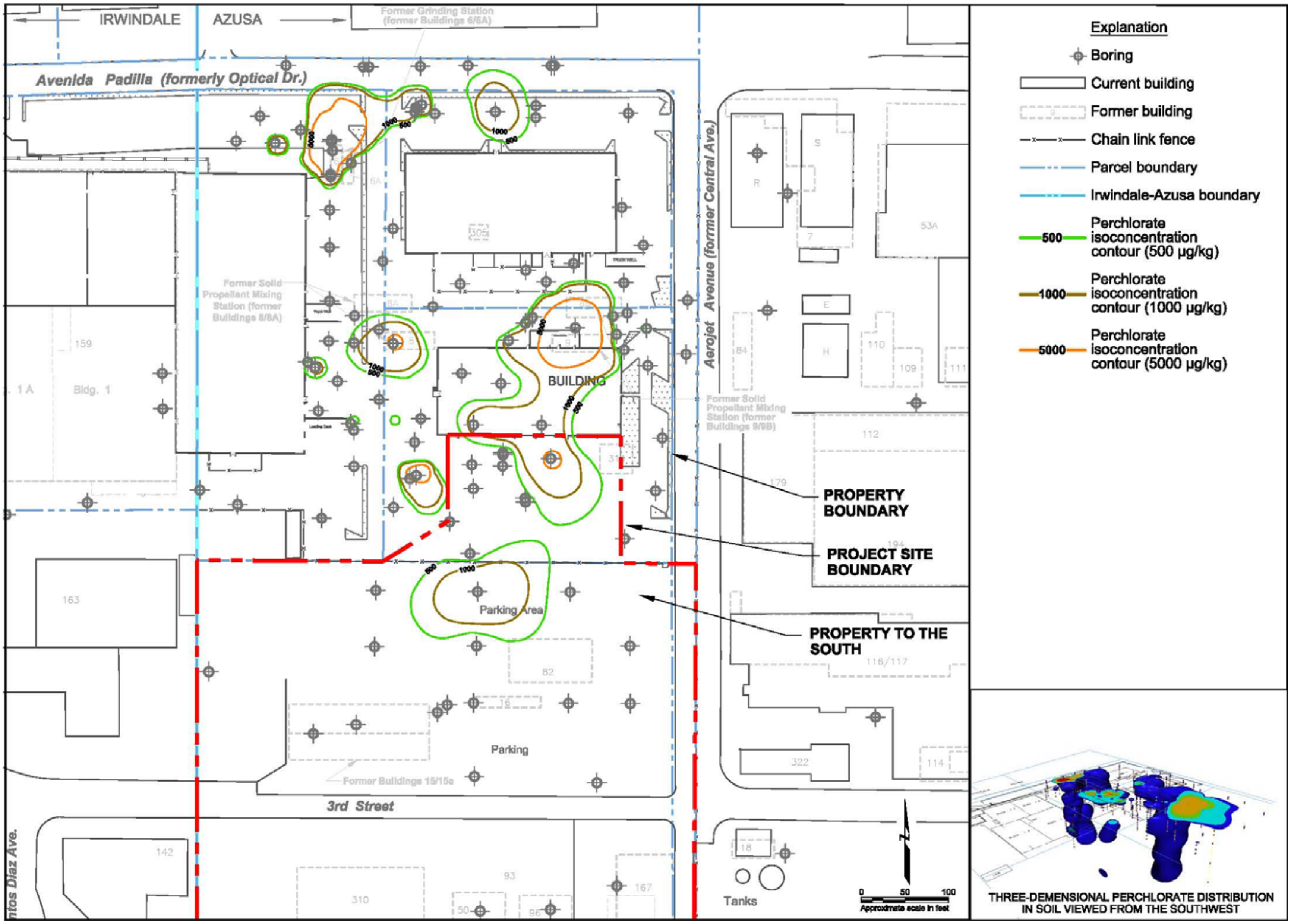

Figure 1. Plan View of Extent of Perchlorate Concentrations above Remedial Action Objective of 500 µg/kg in upper 20 feet of Soil

The biotreatment method discussed herein removes perchlorate from the soil by a microbial transformation of the chemical. Perchlorate-degrading microorganisms have been found to be widespread in the subsurface environment and have been found at many perchlorate-contaminated sites (Coates et al., 1999: Waller et al., 2004). Microbial activity is stimulated by the addition of an organic carbon food source (electron donor), moisture and nutrients, primarily nitrogen and phosphorous, if not already present in the contaminated soils. Under anoxic conditions perchlorate degrading microbes naturally present in the soil consume organic carbon and utilize perchlorate as a terminal electron acceptor (perchlorate reduction), resulting in the conversion of perchlorate to chlorate, then immediately from chlorate to chloride, water and carbon dioxide. The process is highly temperature and moisture dependent, and at times soils are nutrient limited. Because the order of degradation is based on ORP, perchlorate in the soil cannot be degraded until all the oxygen and nitrate is first degraded, therefore the treatment process must be provide an anoxic environment, and the treatment time required is dependent on the amount of nitrate present in the soil.

BIOTREATABILITY STUDIES

Bench-scale and pilot-scale biotreatability studies were performed contemporaneously using the soil retained from geotechnical test pits performed near the building in order to confirm the presence of indigenous perchlorate-reducing microorganisms, as well as any microbial inhibitors, and to determine their potential for perchlorate reduction. In addition, the treatability studies were performed to help determine the optimum target concentration levels for the carbon food source, glycerin, nutrients and moisture content and to help determine the anticipated time required to achieve treatment goals. The design of the treatability studies was based on previous work performed with perchlorate impacted soil. Four soil samples were taken from the geotechnical test pits and analyzed by an independent CA-ELAP laboratory using modified EPA Method 314.0 with a reporting limit of 20 µg/kg to understand initial perchlorate concentrations for soils to be used in the biotreatability studies. The results of these sample analyses yielded perchlorate concentrations ranging from non-detect (< 20 µg/kg) to 93.8 µg/kg. These concentrations were much lower than expected and were not considered representative of perchlorate concentrations from planned remedial action excavations. As a result, soils used for the biotreatability studies were spiked with sodium perchlorate to concentrations of approximately 5,000 µg/kg (5 mg/kg) to ensure that perchorate concentrations used in the biotreatability studies were representative of site conditions. A summary of the setup, testing, and results, for both the bench-scale and pilot-scale biotreatabilities studies are presented below.

BENCH SCALE TESTING

A bench-scale soil treatability study was initiated in June 2008 to support the pilot-scale treatability study and the full-scale remedial action at the Project Site. Soil from the geotechnical test pits performed in May 2008 was analyzed for naturally occurring soil moisture, nitrogen and phosphorous as a baseline. The remaining soil was spiked with 5 milligrams per kilogram (mg/kg) perchlorate to provide a representative initial perchlorate concentration for the bench-scale testing. Twenty-seven different combinations of initial glycerin concentrations (0, 500, and 1,000 mg/kg), diammonium phosphate (DAP) concentrations (0, 50, and 100 mg-N/kg), and moisture contents (10%, 13%, and 15%) were established. Each of the twenty-seven different combinations was mixed in the laboratory and the soil was placed into five separate 4-oz airtight jars, for a total of 135 jars. The jars were then allowed to incubate for predetermined amounts of time prior to sampling.

Samples were then collected for laboratory analysis from each of the twenty-seven combinations at 0, 1, 2 and 4 weeks. The sample jar being sampled was discarded after each sampling event to prevent the intrusion of air into the container during sampling from biasing the results. Samples were sent to an independent analytical laboratory for analysis. Initial (Week 0) samples were analyzed for pH, perchlorate, total Kjeldahl nitrogen (TKN), chemical oxygen demand (COD), percent moisture, nitrate, and nitrite. Samples from subsequent sampling events were only analyzed for pH, perchlorate, nitrate and nitrite.

PILOT-SCALE TESTING

A pilot-scale testing program was also initiated in June 2008. Soil from the geotechnical test pits was spiked with 5 mg/kg sodium perchlorate in order to observe the reduction of perchlorate over time. Twelve 30-gallon drums were used for the pilot testing setup. Two control drums were set up with no glycerin or DAP added. The remaining ten drums were loaded with soil amended with approximately 1,000 mg/kg of glycerin and 100 mg-N/kg of DAP.

Drums were also amended with different water contents (approximately 11%, 12%, 13%, and 14%). Mixing of the soil and amendments was accomplished with a motorized cement mixer.

Samples were taken from each of the twelve drums at roughly 0, 1, 2, 3, 4 and 6 weeks of incubation. Samples were sent to an independent analytical laboratory for analysis. Samples from the first five sampling events were analyzed for perchlorate, COD, Total Organic Carbon (TOC), TKN, nitrate, nitrite, pH and moisture content. Samples from the final sampling event were only analyzed for perchlorate.

BIOTREATABILITY STUDY FINDINGS

Results from the bench-scale study indicated that soil moisture and glycerin addition are the two main factors that facilitate perchlorate degradation. DAP addition, though, showed a potential negative effect. Glycerin in concentrations of 500 milligrams (mg/kg) and 1,000 mg/kg, reduced perchlorate concentrations in the soil to below the detection limits within four weeks, provided that sufficient moisture (above 10%) was present. The reason for the apparent inhibition of perchlorate reduction by DAP appears to be attributable to biological nitrification of ammonia to nitrite and nitrate. Nitrite and nitrate are more readily utilized by bacteria than perchlorate; therefore, high nitrite or nitrate concentrations inhibit perchlorate degradation. While some nitrogen is required by the bacteria to promote activity, it appears that sufficient nitrogen was initially present in the soil to support the bacteria and additional nitrogen was not required.

Pilot-scale results also indicated a glycerin concentration of 1,000 mg/kg could produce significant perchlorate reduction in approximately four weeks. Nitrification was not observed in pilot study, where DAP was added in all tests. The pilot-scale results also indicated that higher moisture contents produced improved results.

The bench- and pilot-scale biotreatability studies concluded that perchlorate could best be degraded by maintaining a moisture-content of 10-13% or above, and optimally around 13%, while amending soils with greater than 1,000 mg/kg of glycerin. Addition of greater than 1,000 mg/kg of glycerin, rather than the 1,000 mg/kg tested in the bench- and pilot-scale biotreatability studies, was recommended in order to provide sufficient carbon source for perchlorate degradation in the event nitrification occurred in the treatment process and utilized some of the glycerin. A disodium phosphate (DSP) additive was recommended to be substituted for DAP to ensure adequate phosphorus concentrations were present to promote microbial degradation of perchlorate while eliminating the potential negative effects of nitrogen addition. The final amendment recommendations for full-scale implementation, based on the results of the biotreatability studies, were as follows:

- ≥10-13% moisture content,
- 1,200 mg/kg glycerin
- 35 mg/kg DSP

In addition, the biotreatability studies suggested approximately 3-4 weeks would provide sufficient time for the incubation of microorganisms and the degradation of perchlorate to achieve treatment goals.

SETUP AND EXCAVATION

Prior to initiation of excavation activities, the contractor prepared a soil staging area, a soil processing area, a biotreatment area, as well as an equipment decontamination and refueling area. Due to the solubility and mobility of perchlorate and the concerns of the regulatory agencies involved, best management practices (BMPs) for stormwater control at the site were significantly increased above those typically seen at similar construction sites; all areas where soil was to be stockpiled or staged were underlain by 30-mil PVC plastic providing separation between perchlorate impacted soils and non-impacted surfaces, minimizing the potential for spreading perchlorate to non-impacted areas of the site. The biotreatment, decontamination and refueling areas were constructed by laying down 30-mil PVC plastic liner and creating berms on all sides to prevent the release of water containing perchlorate, grease or fuel during decontamination, refueling and other maintenance activities. Figure 2 shows the approximate location of the various work zones and areas described above.

In the biotreatment area, fifteen biotreatment cells with an approximate capacity of 10,000 m^3 (13,000 cubic yards [cy]) of soil were constructed on top of the continuously sealed 30-mil PVC liner in the southern portion of the

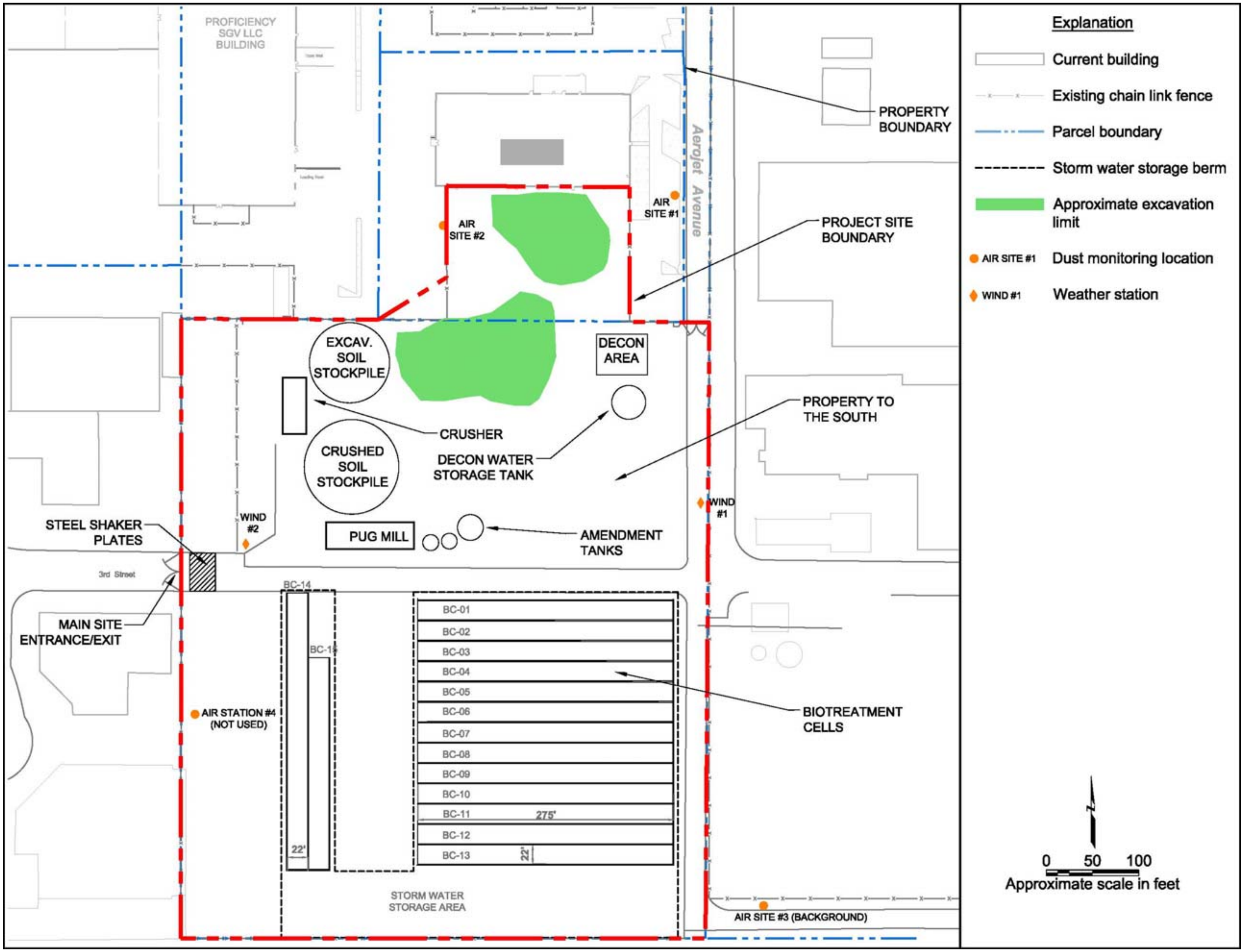

Figure 2. Project Site Layout

Project Site. Biotreatment cells were constructed using concrete traffic barriers as walls to provide the structural support on three sides for each cell. In general, biotreatment cells measured approximately 6.7 m (22ft) wide by 83.8 m (275 ft) long. Stormwater controls and storm water retention areas were constructed around these cells in accordance with the Storm Water Pollution Prevention Plan (SWPPP).

Excavation activities were initiated on August 19, 2008, after all storm water controls and perimeter air monitoring stations were in place, and were completed on October 06, 2008 resulting in the removal of approximately 10,000 m^3 (13,000 cy) (in-place volume) of perchlorate impacted soil. Areas for proposed soil excavation areas were selected based on the interpreted extent of perchlorate concentrations exceeding 500 µg/kg, as detailed in an RD/RA Work Plan previously prepared. Based on these areas designated for excavation and confirmation sampling results, approximately 10,000 m^3 (13,000 cy) of soil were excavated and treated during the project, with approximately 5,350 m^3 (7,000 cy) removed from the property and 4,550 m^3 (6,000 cy) removed from the property to the south. The total excavation area was approximately 2,300 m^2 (25,000 square feet [sf]), with approximately 1,068 m^2 (11,500 sf) excavated on the property and 1,250 m^2 (13,500 sf) excavated on the property to the south. Figure 3 shows a photograph of the completed excavation, as well as the soil processing and biotreatment cells in the background.

Figure 3. Completed Excavation with Soil Processing and Biotreatment Cells in Background.

Excavation confirmation samples were taken on a 25-foot by 25-foot grid, from the excavation sidewalls and bottom. Sidewall samples were collected at depth of 2.5 feet, 10 feet and 20 feet or the excavation bottom if less than 20 feet. A total of 143 excavation confirmation samples were collected. Confirmation samples were analyzed for perchlorate by modified EPA Method 314.0 for soils with a reporting limit of 40 µg/kg. If confirmation samples indicatefd perchlorate concentrations above 500 µg/kg, excavation continued unless excavation encroached on a building foundation or property boundary, or if excavation would have proceeded below a depth of 20 feet. Of the 143 confirmation samples, only 4 indicated soil with perchlorate concentrations in excess of 500 µg/kg were left in place.

SOIL HANDLING AND PROCESSING

In order to easily amend the material and improve the biotreatment process, it was necessary to produce a uniform sized material 2 inches and diameter and smaller. As soil was being excavated, it was stockpiled approximately 10 feet outside of the excavation limits. Front end loaders and track mounted excavators moved the soil to a soil stockpile area near the soil processing area. Crushing of the excavated material was initiated on August 22, 2008. A track mounted excavator was used to place material from this stockpile into a track-mounted combination screener/crusher plant (crusher). The crusher had a capacity of approximately 63 m^3/hr (85 cy/hr) for handling the excavated material. The crusher processed all material placed into the loading hopper creating a uniform sized material 2 inches in diameter or smaller. An integral conveyor moved the crushed material to a second crushed soil stockpile for loading into the pug mill as described below. Large diameter material, which could not be loaded into the loading hopper, was temporarily set aside in a stockpile. This material was later broken into smaller fragments using a hydraulic ram and crusher attached to a track-mounted excavator and subsequently loaded into the crusher for processing.

In order to promote biological activity and perchlorate degradation in the biotreatment cells, it was necessary to mix the crushed soil with the amendments in the concentrations recommended as a result of the biotreatability studies. Recommended amendments were glycerin (1,200 mg/kg), DSP (35 mg/kg) and water (≥10% moisture content). Amendment of crushed soils and placement in the biotreatment cells began on September 03, 2008 and was completed on October 06, 2008. Crushed excavated material was loaded into a pug mill by a track mounted excavator for mixing with the recommended amendments to produce a homogeneous mixture prior to loading the material into the biotreatment cells. Amendments were added in the pug mill using an automatic metering system to provide even distribution and to maintain the recommended concentrations. The pug mill had a capacity of approximately 96 m^3/hr (125 cy/hr).

Because it was unknown how much water the crushed material could hold without the presence of free-draining liquids, a portion of the first week of soil processing was spent optimizing the moisture content of the amended soils. As a result, the processing of soils placed in the first few biotreatment cells were later found to be somewhat below the optimum moisture content. Visual observation of soil moisture content during the processing of soil for the first part of the first cell seemed to indicate that the soil was at or near saturation and could not retain additional water. Based on this observation, the amount of water added to the processed soil was reduced slightly for the remainder of the first two cells and the first portion of the third treatment cell. Moisture content analyses taken from the first cell indicated moisture contents from 6 to 9 percent rather than the desired moisture content of 10 to 13 percent based on biotreatability testing results. As a result, the amount of water added to the amended soils was further optimized using visual observations including slump tests. Once the optimal moisture the soil could hold was determined, the resulting water addition was approximately 13.5 gallons of water per ton of soil processed through the pug mill.

BIOTREATMENT CELL LOADING

After mixing in the pug mill, amended soil was delivered directly into end-dump trucks by a conveyor and driven immediately to the biotreatment area for loading into the biotreatment cells. 10-mil polyethylene sheeting was placed over 30-mil PVC liner in the bottom of the cells and over the k-rail cell walls to allow the loading of soil. End-dump trucks were backed into the biotreatment cells to unload the amended soil and a small track-mounted excavator was used to place and shape the soil in the cells. Cells were loaded from the back of the cell to the front and were largely filled to a level height of approximately 4 feet. As the biotreatment cells were filled, the 10-mil polyethylene sheeting was manually overlapped from both sides completely encapsulating the soil. The polyethylene sheeting was secured with glue and/or tape to retain moisture and prevent oxygen diffusion into the soil matrix. As previously discussed, fifteen biotreatment cells were constructed, filled and sealed. Biotreatment cells were designated by number in the order they were filled (e.g. BC-01 for the first cell filled). Cells BC-01 through BC-13 were filled with soil from east to west within the biotreatment cells, and the cells were filled from northernmost cell (BC-01) to southernmost cell (BC-13). Cells BC-14 and BC-15, which were located to the west of the other thirteen cells, as shown on Figure 2, were filled with soil from south to north. Figure 4 shows a photograph of a biotreatment cell being loaded.

Figure 4. Loading of a Biotreatment Cell

POST-TREATMENT CONFIRMATION SAMPLING

To document that the biotreatment process had reduced the perchlorate concentrations in the soils below the treatment goal of 500 µg/kg, discrete post-treatment confirmation samples were required by the regulatory agency to be collected from the biotreatment cells at a frequency of one sample per every 37 cubic yards of soil. Post-treatment confirmation samples were sent to an independent CA-ELAP laboratory for analysis for perchlorate by modified EPA Method 314.0 with a reporting limit of 40 µg/kg. Results from the post-treatment confirmation samples were evaluated relative to the treatment goal of 500 µg/kg; soil with less than 500 µg/kg of perchlorate was suitable to be used as backfill in the excavation upon written approval from the regulatory agency. Post-treatment confirmation sampling was initiated in the first five cells the week of October 6, 2008 after 27-33 days of incubation in the cells. Subsequent post-treatment confirmation sampling on the other cells was largely performed approximately four weeks after loading and sealing each biotreatment cell.

Post-treatment confirmation sampling was accomplished in the biotreatment cells using a small powered auger with a 6-inch and/or 8-inch diameter auger. Samples were collected at a depth of approximately 61 cm (2 feet), a depth that is approximately in the middle of each biotreatment cell. For biotreatment cells with soil depth greater than 122 cm (4 feet), the depth was adjusted accordingly to collect the sample at a depth that is approximately in the middle of the biotreatment cell. Due to the width of the cells and to provide unbiased sample coverage and representative data, post-treatment confirmation samples were collected on alternating sides of the treatment cell along the cell length. Excavated material was replaced into the resulting void after sampling and the biotreatment cell liner was repaired by placing a polyethylene patch over the hole, sealing with glue and placing a sand bag over the patch in order to minimize oxygen intrusion into the soil mass.

Once sample results were received, soil with sample results indicating perchlorate concentrations were less than the treatment goal of 500 µg/kg was removed from the treatment cell and reused as backfill. Where results indicated perchlorate concentrations remained above the treatment goals, the liner was resealed and the soil was left in place in order to allow more treatment time. Eleven post-treatment confirmation samples indicated perchlorate concentrations were above the treatment goal, four of which did not meet the treatment goal after additional incubation time. A total of 250 cubic yards of soil did not meet the treatment goal after 6 weeks and was shipped off-site for disposal at a properly permitted disposal facility. A majority of the soil met the treatment goal within 4 to 5 weeks.

A front-end loader was used to remove approved soil from the biotreatment cells and place the soil into end-dump trucks where possible; a track-mounted excavator was used where necessary. The soil was delivered to the excavation areas where a front-end loader spread the soil. Soil was placed and compacted in lifts of approximately 8 inches. Soil was compacted to 95% relative compaction; testing was performed at a frequency of 1 test per 380 m^3 (500 cy) of backfilled soil. Moisture content was controlled to meet the optimum moisture content, plus or minus 3%. Since soil removed from the biotreatment cells was above the optimum moisture content, no water was required to be added during backfill and compaction. Approximately 907 metric tons (1,000 tons) of imported soil was required to bring the excavation back to grade for final compaction and paving. Paving was performed to prevent the possibility of stormwater entering the subsurface between the time the remedial efforts had ceased and construction of the planned building expansion commenced.

SUMMARY OF REMEDIAL ACTION ACHIEVEMENTS

The implementation of the remedial action described in this Completion Report achieved the following:

- The remedial action successfully removed approximately 10,000 m^3 (13,000 cy) of soil (in-place volume) containing perchlorate at concentrations greater than 500 µg/kg to a maximum depth of 6 m (20 feet). This reduced the threat of mobilization of perchlorate to groundwater, and reduced any future human health risk associated with future construction.

- The remedial action successfully processed and treated approximately 9,750 m^3 (12,750 cy) of soil to concentrations below the treatment goal of 500 µg/kg. The remaining 250 cy of partially treated soil was transported offsite for management at a permitted disposal facility. Only 907 metric tons (1,000 tons) of imported soil was required for completion of the project, as opposed to over 18,000 metric tons (20,000 tons) of imported soil that would be required if the material had been landfilled instead of on-site treatment.

- Only approximately 20 truckloads of soil were required for off-site disposal of soil to a properly permitted waste disposal facility. Due to the liability associated with perchlorate, the disposal facility of choice was approximately 306 km (190 miles) away, resulting in a round trip of over 612 km (380 miles) for disposal of one truck load of soil. Were all the impacted soil disposed of at this facility, over 1,000 truck loads would have been required. In total, approximately 643,750 km (400,000 miles) of trucking were not required, as well as the 9,750 m^3 (12,750 cy) of landfill space.

- Treated soils were backfilled and appropriately compacted in the remedial action excavation after obtaining necessary approvals from regulatory agencies, providing a suitable base for the construction of the property owner's planned building expansion. No imported material was required for subgrade preparation during the building expansion activities.

- The total time in the field from pilot testing through demobilization was 16 weeks. The timely completion of the remedial action allowed the property owner to proceed with their planned expansion of their manufacturing facilities.

- Despite an aggressive schedule due to expansion plans for the manufacturing facility (approximately four months from the start of field work), approximately $1.5 million was saved over traditional excavation, disposal, and backfilling with imported materials.

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