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THERMAL TREATMENT OF EXPLOSIVES AND PERCHLORATE IN SOIL MEDIA.

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ABSTRACT

Explosives contaminated soils, scheduled for remediation using a thermal treatment unit, was also found to contain low levels of perchlorate. It was decided that the treatment process could be altered to address this compound as well as the explosives. A bench scale study verified treatability of perchlorate via thermal destruction and helped establish baseline treatment conditions. Subsequently, pilot scale studies were conducted with soils spiked with perchlorate. These tests allowed field proofing of the laboratory results and defined the process parameters. During full scale operations, process parameters were further modified to increase the efficiency of remediation. Analytical results from approximately 60,000 tons of treated soils indicate that thermal treatment is successful in the removal of explosives and perchlorate from soil.

INTRODUCTION

A 7-acre site was formerly used for demolition training and open burn/open detonation of explosives, munitions, and fireworks. The result of these activities was surface and sub-surface contamination, buried disposal pits, and widely scattered unexploded ordnance. It was determined through test pits and borings that about 2.5 meters of fill had been placed in the bottom of a topographic bowl during site activities. Much of the fill and surrounding surface soils were determined to be contaminated with perchlorate and explosive compounds Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrocine(HMX), detected in a wide range of concentrations across the site. Perchlorate was detected at a maximum of 26.9 part per billion (ppb) with an average of 0.96 ppb. The maximum RDX concentration detected in the soil was 14,000 parts per million (ppm) with an average of 30 ppm.

Remediation of this site was deemed necessary because the groundwater beneath the site is a sole source drinking water aquifer. It was decided that surface soil across the entire site and the filled material in the bottom of the bowl would be removed in order to prevent further impact to the groundwater. The volume of soil excavated from this site was approximately 16,800 cubic meters (m^3) (22,000 cubic yards [yds^3]).

Once excavated, several alternatives were available for managing the contaminated soil. These included landfill disposal, soil washing and thermal desorption. The relative costs of these options were estimated to be similar for the expected quantity, but given that additional areas would likely be excavated, thermal desorption became the economically attractive alternative. Soil washing was also expected to be ineffective for the chunks of explosive materials found in some of the source areas. Furthermore, on-site treatment eliminated the potential liabilities typically associated with landfill disposal.

Several additional source areas were treated including training ranges, disposal sites, target areas, and firing positions. The total volume of soil excavated and treated from these areas was approximately 13,000 m^3 (17,000 yds^3) bringing the project total to 29,800 m^3. Contaminants at all the sites were primarily perchlorate and explosives. It was determined that all of the soil would be placed in the 7-acre site after treatment to minimize restoration costs. Therefore, the contaminated soils from all the sites had to be treated to the remediation goal of the 7-acre site. In agreement with the regulatory community, the remediation goal was set based on the reporting limits of the available laboratory analyses – 4 ppb for perchlorate and 120 ppb for RDX and HMX. Since that time, soil standards for perchlorate and RDX that are orders of magnitude higher than these goals have been proposed by the state regulatory agency.

Environmental Chemical Corporation (ECC) was contracted by the United States Army Corps of Engineers (USACE) to mobilize and operate a Thermal Treatment Unit (TTU) at the site. This paper describes the system, the studies conducted to determine feasibility of the system, the TTU operation and outcome of the project. This project was the first known full-scale demonstration of thermal decomposition of perchlorate in contaminated soil using a TTU.

TREATMENT PROCESS

The TTU consists of a solids treatment system and an air pollution control (APC) system. The solids treatment system contains a soil feed system, direct-fired rotary drum (Dryer), and product discharge system. The air pollution control system contains a cyclone, thermal oxidizer, evaporative cooling chamber, bag house, induced draft blower, and a stack. The fuel source for the burners is vaporized liquid propane. The process flow diagram is shown in Figure 1.

Soil is prepared for treatment by screening out items greater than 1 inch in diameter. Contaminants are removed from the soil in the parallel flow, direct-fired rotary drum. By virtue of the parallel flow design, all soil, soil particulates and fines travel the entire length of the drum where they are heated to the target temperature.

Treated soil is discharged from the rotary drum into the pugmill, which mixes the hot soil with cooling water. The re-humidification process controls dust emissions and prepares the soil for future handling. A draft is induced on the headspace of the pugmill and any steam generated within the pugmill is vented to the bag house.

Exhaust gases leaving the rotary drum pass through a cyclone, which is the primary control for entrained particulates. Particulates removed in the cyclone are gravity fed to the pugmill where they are blended into the treated soil before exiting the system.

The exhaust gas leaving the cyclone continues to a thermal oxidizer. Before entering the baghouse, the hot gases exiting the thermal oxidizer are cooled with air-atomized water spray nozzles in the evaporative cooling chamber to a temperature below 450°F (232^{o}C).

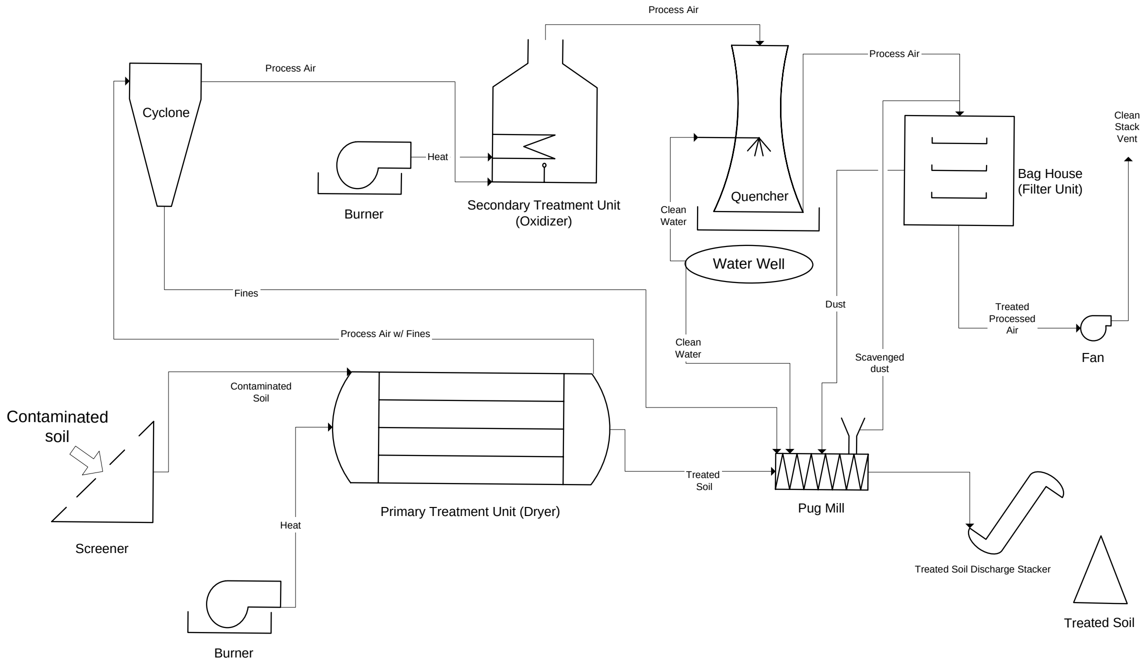

Figure 1
Thermal Treatment Unit - Process Flow Schematic

The bag house is designed to remove fine particulates entrained in the exhaust gases. The fines form a cake on the bag surface, which is periodically cleaned by a pulse of air. A screw auger transfers these fines to the soil discharge pugmill and blends the fines back into the treated soil. An induced draft (ID) blower located after the bag house is used to maintain a negative pressure on the treatment system. Clean exhaust gases are emitted to the atmosphere through a vertical stack.

TREATABILITY STUDY

It had been established in previous full-scale operations that an operating temperature of approximately 650^{o}F (343^{o}C) was sufficient to remove explosive contaminants [predominantly RDX and HMX]. However, ammonium perchlorate had previously never been treated on site in a thermal desorption process. A literature search revealed that ammonium perchlorate sublimes and undergoes thermal destruction at about 725^{o}F (380^{o}C).

A treatability study was designed to target operating parameters that simulate the full scale conditions. The test program was carried out at Hazen Research, Inc., Golden, CO. The apparatus used consisted of a cylindrical quartz rotary kiln in a muffle furnace, with all off-gases collected in a 2-stage condensing system that separated the condensed water vapor and particulates from the non-condensable gases. The test soils were carefully weighed and spiked with a known quantity of perchlorate and homogenized before adding to the reactor. The reactor was rotated during the test to simulate full scale operation, and heated up at a controlled rate to the desired operating temperature. When the reactor and soils reached the desired temperature, a timed run was initiated. An outline of the tests is shown in Table I. All products (soils, particulates, water vapor and non-condensable gases) were analyzed for residual perchlorate. Analysis of the soils prior to thermal testing had shown little to no perchlorate present. Thus, two sets of tests were carried out with the soils spiked to 100 ppb (low level) and 100,000 ppb (high level). The low-level spike was introduced with the perchlorate dissolved in water. The high-level spike was accomplished by adding a prescribed weight of perchlorate and hand kneading the resulting mix

Table I. Operating Conditions, Treatability Study

Operating Condition Number	Concentration of Perchlorate in Feed Soil (ppb)	Treated Soil Temperature (OF)	Residence Time at Temperature	Oxygen Content
1	100,000	650	10 minutes	> 7%
2	100,000	900	10 minutes	> 7%
3	100,000	1150	10 minutes	> 7%
4	100,000	650	30 minutes	> 7%
5	100,000	1150	30 minutes	> 7%
6	100,000	900	10 minutes	<1%
7	100	650	10 minutes	> 7%
8	100	900	10 minutes	> 7%
9	100	1150	10 minutes	> 7%
10	100,000	725	10 minutes	> 7%
11	100,000	775	10 minutes	> 7%

^{o}F = degrees Fahrenheit ppb = parts per billion

Table II. Soil Analytical Results, Treatability Study

Description	Pre-spike and Pre-Test	Run 1 100 mg/kg, 650 ºF, 10 min., >7% O_2	Run 2 100 mg/kg, 900 ºF, 10 min., >7% O_2	Run 3 100 mg/kg, 1150 ºF, 10 min., >7 % O_2	Run 4 100 mg/kg, 650 ºF, 30 min., >7% O_2	Run 5 100 mg/kg, 1150 ºF, 30 min., >7% O_2	Run 6 100 mg/kg, 900 ºF, 10 min., <1% O_2	Run 7 0.1 mg/kg, 650 ºF, 10 min., >7% O_2	Run 8 0.1 mg/kg, 900 ºF, 10 min., >7% O_2	Run 9 0.1 mg/kg, 1150 ºF, 10 min., >7% O_2	Run 10 100 mg/kg, 725 ºF, 10 min., >7% O_2	Run 11 100 mg/kg, 775 ºF, 10 min., >7% O_2
Units	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg /kg
Perchlorate	3.5 J	**51**	1.3 U	1.3 U	**25**	1.3 U	1.3 U	**41**	1.3 U	1.3 U	**74**	1.3 U
HMX	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U
RDX	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U	120 U

J = estimated result U = non-detect result
^{o}F=degrees Fahrenheit mg/kg = milligrams per kilogram

Table II shows the results obtained from analysis of the soil constituents and Table III shows the analytical results from the condensates collected during each run. The analytical data indicate that explosive compounds were destroyed under all conditions tested. Perchlorate was removed in six of the initial nine conditions evaluated. The tests which failed were at the lowest temperature, 650°F (343°C). Since perchlorate was removed successfully at the two higher operating temperatures, two extra tests were run at intermediate temperatures of 725°F (385°C) and 775°F (412°C). Traces of perchlorate were present in the 725°F treated soils but none at 775°F.

It is known that perchlorate decomposes in two primary ways, by sublimation into the carrier gas phase (as noted in the referenced literature) and by thermal destruction both in the gas phase and soil phase. The condensed streams from the reactor were analyzed and showed that less than 0.05 percent of the perchlorate anions in the feed soils were present in the condensate. In the full-scale system, it was expected that any un-decomposed perchlorate in the gaseous phase would be destroyed in the secondary oxidizer.

Table III. Condensate Analytical Results, Treatability Study

Description	Detection Limit	Run 1 100 mg/kg, 650 °F, 10 min, >7 % O_2	Run 2 100 mg/kg, 900 °F, 10 min, >7 % O_2	Run 3 100 mg/kg, 1150 °F, 10 min, >7 % O_2	Run 4 100 mg/kg, 650 °F, 30 min, >7 % O_2	Run 5 100 mg/kg, 1150 °F, 30 min, >7 % O_2	Run 6 100 mg/kg, 900 °F, 10 min, <1 % O_2
Units	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
Perchlorate	0.35	160	110	140	140	150	220

µg/L = micrograms per liter °F = degrees Fahrenheit

The treatability study successfully demonstrated that perchlorate contaminated soils can be thermally treated and that > 99.9% of perchlorate was decomposed in the kiln operated at 775°F (412°C) or higher. The balance would be decomposed at full scale in the secondary treatment unit operated at 1400°F (760°C).

SHAKEDOWN AND TESTING

During shakedown operations, the TTU was prepared for the full scale operations. The initial set point for the soil discharge temperature was 775°F (412°C), based on the treatability study results for perchlorate. TTU performance is often system specific and each unit must be optimized to ensure adequate performance. Furthermore, the site soils were generally wet (10- 18% moisture) and would have to be dried before being heated up to the required treatment temperature. Drying the soil requires approximately half of the residence time, leaving the remaining half for thermal destruction of the contaminants.

Twenty spike tests were conducted to determine the minimum required temperature and other operating parameters which would ensure the treatment of all contaminants. The feed rates for the testing period varied between 20 to 40 tons per hour. Measured amounts of the spiking agents were added based on feed rate. Spike tests also involved addition of anthracene and HMX. Results from the tests are included in Table IV.

Table IV. Spike Test Results For Perchlorate

Test #	Feed Perchlorate Concentration (part per billion)	Treated Soil Perchlorate Concentration (part per billion)	Minimum Temp Goal (F)	Average Temp (F)	Average Feed Rate (tons per hour)	Treatment Efficiency
1	100,000	45	775	807	25	99.955%
2	82,000	4500	725	756	30	94.543%
3	121,000	3500	675	705	21	97.102%
4	76,000	280	825	832	35	99.633%
5	83,000	20	875	886	33	99.976%
6	77,000	88	825	833	35	99.885%
7	82,000	13	875	886	33	99.984%
11	1,000	<0.8	925	958	30	100.000%
12	1,100	<0.9	900	911	26	100.000%
13	900	<1.0	875	877	25	100.000%
14	1,200	<1.1	850	853	26	100.000%
15	1,100	3.5	800	804	27	99.683%
16	110,100	3.3	925	936	29	99.997%
17	109,000	13	900	912	33	99.988%
18	102,700	65	875	884	35	99.937%
19	111,300	140	850	857	35	99.874%
20	105,500	340	800	807	37	99.678%

The first ten tests involved spiking feed soil with high concentrations of reagents (approximately 100 parts per million). Only HMX was tested in test numbers 8 through 10 (not listed in the table) and was successfully treated in all tests at temperatures ranging from 600^{o}F (315^{o}C) to 700^{o}F (370^{o}C). Seven tests (1 though 7) were conducted with soils spiked with perchlorate and anthracene. Anthracene was used to serve as a surrogate for polychlorinated naphthalene and was successfully removed at all temperatures. The first three tests were run with a minimum operating condition of 775^{o}F (412^{o}C), 725^{o}F (385^{o}C) and 675^{o}F (357^{o}C), respectively. Analytical results of treated soil indicated that perchlorate was not removed in accordance with the project remediation goals (Table IV). Subsequently, the remaining four tests were run at minimum operating temperatures of 825^{o}F (440^{o}C) and 875^{o}F (468^{o}C) on feed comprising of native soil and with feed of imported clean sand. Analytical results showed that the treated soils still contained perchlorate at levels above the project remediation goal. Results did not show any significant difference in removal efficiency of perchlorate in the different soil matrices. It should be noted that the control of treatment temperature during this early stage of shakedown testing was inconsistent. The control was improved in subsequent operations after the burner control components were further tuned.

Spiking events eleven through twenty were designed to determine both the treatment temperature for perchlorate and the effect that feed concentrations had on the treatment of perchlorate. These tests were run with minimum temperatures of 800, 850, 875, 900 and 925^{o}F (426, 454, 468, 482 and 496^{o}C) respectively. Five of these events were run with native soils spiked with a high concentration (approximately 100 ppm) of perchlorate and the other five were run with native soils spiked with a low concentration (approximately 1 ppm of perchlorate). Results (Table IV) showed that the high concentration spiked soil was treated to below the project remediation goal only at the highest temperature (Test 16). The low concentration spiked soils were successfully treated to below the project remediation goal in all the tests.

Figures 2 and 3 illustrate the variation of removal efficiency of perchlorate with respect to average operating temperatures. Removal efficiency of the soils containing low concentrations of perchlorate rose sharply between 800 and 850°F; beyond 850°F, perchlorate was not detected in any of the treated soils samples. Removal efficiency of the soils containing a higher level of perchlorate rose sharply in the beginning, and continued to rise gradually after 800°F.

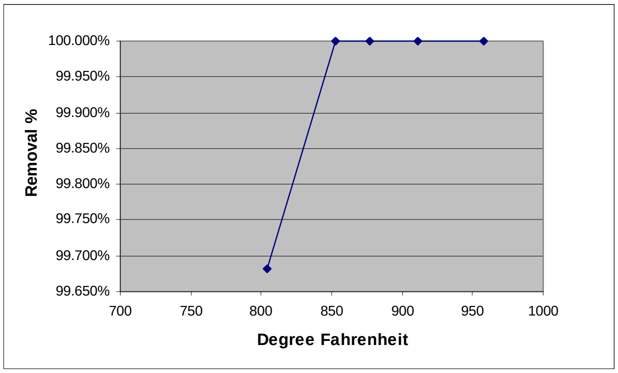

Figure 2. Removal Efficiency vs Temperature
(Low Spike Concentration)

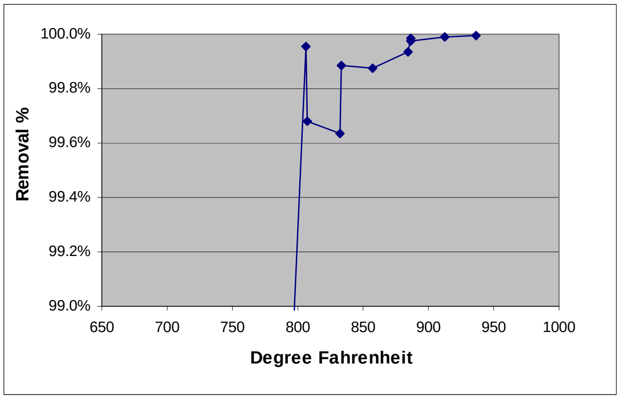

Figure 3. Removal Efficiency vs Temperature
(High Spike Concentration)

Once operating conditions were sufficiently field tested during this period, the treatment unit underwent a Proof of Performance (POP) test.

POP TEST

The primary objectives of the POP test, conducted over three days, were to demonstrate that:

- the air emissions would meet the criteria established by the state Air Permit,
- ECC’s TTU system would meet the project specified treatment criteria for soil and
- the equipment could be safely operated in a controlled manner.

Feed material for the test included approximately 2,500 tons (1270 m^3) of soil from the contaminated sites and treated soil from spiking events that had failed the treatment criteria. Composite samples of the targeted feed material (prior to spiking) were collected and analyzed at a rate consistent with treated soil verification testing, to verify the levels of the contaminants of concern before treatment and to establish a baseline for air permit emissions calculations. Samples were also collected from the cyclone discharge and from the baghouse dust stream prior to being mixed with the treated soil.

In order to demonstrate the efficacy of the thermal treatment system’s air pollution control system, soils in the POP test were spiked with perchlorate and anthracene on day two and HMX on day three. Particulates, metals, carbon monoxide, sulfur dioxide, oxides of nitrogen and carbon dioxide emissions were tested on Day 1. These emissions are independent of perchlorate and explosive contaminant loadings and therefore no spiking agents were used.

Feed soil, treated soil and baghouse and cyclone dust analytical results are presented in Table V, VI and VII, respectively. The analytical results indicated that the pre-spiked feed soil for the POP had varying concentrations of perchlorate ranging from 46 to 100 ppb and that RDX and HMX feed soil concentrations ranged from non detectable to 330 ppb. The major contributing source of perchlorate in the feed soil was from recycled stockpiles that had previously failed to meet the targeted cleanup standard for perchlorate during the spike tests.

A total of 20 post treatment samples were collected during the POP test. The results from the treated soil samples show that RDX, HMX and all other explosive compounds were treated to below detection levels at the treatment temperatures. Similarly, anthracene, considered as a surrogate SVOC, was also treated to below the treatment goal at the treatment temperatures.

Nineteen of the twenty treated sample results indicate that perchlorate was treated to below the detection level. This level of success (95%) demonstrates that the treatment system and operational parameters are effective in meeting the soil remediation goal.

The baghouse and cyclone samples were below the treatment goals for explosives on all three days of the POP. The results were mixed for the soil samples from the cyclone and baghouse streams with regard to perchlorate. Soils removed in the baghouse were above the treatment goal for perchlorate on days 1 and 2 and for the cyclone on day 1. The cyclone sample on day 2 met the treatment goal for perchlorate and both the baghouse and cyclone samples met the treatment goal for perchlorate on day 3.

Table V. POP Test Feed Soil Summary Data

Sample ID	RDX (ppb)	HMX (ppb)	Perchlorate (ppb)	Moisture %
Day 1				
FS033104-019	120U	120U	100	14
FS033104-020	120U	120U	91	14
Day 2				
FS040104-024	120U	120U	66	18
FS040104-027	120U	120U	57	16
FS0401044-030	120U	120U	46	17
Day 3				
FS040204-033	120U	140	50	14
FS040204-036	330	120U	63	14

Table VI. POP Test Treated Soil Summary Data

Sample ID	RDX (ppb)	HMX (ppb)	Perchlorate (ppb)	Moisture %
Day 1				
TS033104-019	120U	120U	4.3J	12
TS033104-020	120U	120U	5.8U	14
Day 2				
TS040104-024	120U	120U	3J	15
TS040104-025	120U	120U	3.5J	13
TS040104-026	120U	120U	3.3J	14
TS040104-027	120U	120U	1.9J	12
TS040104-028	120U	120U	4.3J	11
TS040104-029	120U	120U	10	14
TS040104-030	120U	120U	2.8	18
TS040104-031	120U	120U	2.8J	14
TS040104-032	120U	120U	5.9U	15
Day 3				
TS040204-033	120U	120U	5.6U	11
TS040204-034	120U	120U	5.6U	11
TS040204-035	120U	120U	5.7U	13
TS040204-036	120U	120U	5.7U	12
TS040204-037	120U	120U	5.6U	10
TS040204-038	120U	120U	5.7U	12
TS040204-039	120U	120U	5.6U	11
TS040204-040	120U	120U	5.7U	12
TS040204-041	120U	120U	5.7U	12

Table VII. POP Test Baghouse/Cyclone Summary Data

Sample ID	RDX (ppb)	HMX (ppb)	Perchlorate (ppb)	Moisture %
Day 1				
BD033104	120U	120U	22	2
CD033104	120U	120U	46	0
Day 2				
BD040104	120U	120U	9.5J	1
CD040104	120U	120U	5U	0
Day 3				
BD04020	120U	120U	5U	0
CD040204	120U	120U	5U	0

HMX= octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine RDX = hexahydro-1,3,5-trinitro-1,3,5-triazine
U = non-detect result J = estimated result

Perchlorate detected in the cyclone and baghouse samples was most likely an artifact of previous testing. It takes upwards of 24 hours to reach steady state conditions in the baghouse. Cycling the plant on and off (caused by intermittent operations) makes discharging from the baghouse at a steady state condition difficult to achieve during the short term. Contaminated material detected in the baghouse samples on days 1 and 2 of the POP test is believed to be a remnant of material that remained in the baghouse from the failed spike tests.

Air Emissions

Air emissions were measured to demonstrate that there is no degradation of ambient air quality. Standard stack testing methods, as per 40 CFR 60 Appendix A, were used for the performance test. Stack test sampling included the following United States Environmental Protection Agency (EPA) approved methods:

- Methods 1 through 4 for stack gas composition and flow determination;
- Method 6C for sulfur dioxide by CEM;
- Method 5 for particulate matter;
- Method 7E for oxides of nitrogen;
- Method 10 for carbon monoxide by CEM;
- Method SW846-0010 with GC/MS analysis, method 8270 for SVOCs, and HPLC analysis, method 8330, for nitro aromatics including TNT, RDX and HMX; and Method 29 with multiple metals analyses for inorganic metals including Hg;
- Method 9 visible emissions test; and
- Perchlorate by Modified EPA 5/ 314.1.

Results from the stack test, as well as the modeling runs performed using a SCREEN3 model indicate that the operating conditions for the Secondary Treatment Unit (STU) effectively met the air quality requirements established by the air permit.

Laboratory Methods

Major interferences were evident in the analysis of all feed and treated soil samples that were analyzed for perchlorate by Method 314.0. Pre-treating the soils with quicklime is believed to be the cause of the interferences present in the sample extracts. Three false positive results were reported in the first set of samples using this method. Positive results are confirmed in the laboratory by spiking the suspect sample extract with perchlorate at a concentration that would double the response of the perchlorate peak if perchlorate were actually present in the original sample extract. Reanalysis of spiked sample extracts was necessary for all of the feed and treated soil samples. The positive results that were initially reported could not be confirmed by the reanalysis. Therefore, the results were revised to non-detect.

Based on the fact that interferences were persistent during the analysis of the feed and treated soils by Method 314.0, the project testing changed to the more definitive LC/MS/MS method (EPA Method SW846/8321) for the analysis of all soil samples collected for evaluation of thermal treatment. This change also caused the reporting limit of the analytical method to shift from 4 ppb to 3 ppb, although the treatment standard remained the same at 4 ppb.

FULL SCALE OPERATIONS

Based on the results from the performance test, the following treatment parameters were established as suitable for meeting project and permit performance goals:

- Soil treatment temperature: 839°F (448°C), minimum
- Soil feed rate: 40.4 tph, maximum
- STU discharge temperature: 1489°F (809°C), minimum.

The system was operated 24-hours per day, seven days per week. Maintenance activities for the plant were planned and conducted as necessary, typically once a week for approximately a 24-hr outage. Additional unplanned outages resulted in short-term downtime which varied on a daily basis. The process online availability (operational hours divided by available hours represented as a percentage) was 75 % overall for the project (including shakedown) and 80 % during full scale operations.

Of the initial twenty 382 m^3 piles during full scale operations, fourteen met the treatment standards (30% failure rate). The treatment failures were all for residual perchlorate contamination with failed concentrations ranging between 7 to 22 ppb. Reviews of the TTU process, sampling and laboratory analysis were conducted to determine the cause and to reduce the frequency of treatment failures. No apparent causes for the treatment failures were identified.

Increases in the treatment temperature were made twice in an effort to reduce treated soil residual perchlorate concentrations. The final treatment temperature established in full scale operations was 925°F (496°C). The dryer cylinder rotation was also slowed down to increase the soil residence time (an increase in residence time of approximately 5%).

The treated soil stockpile area was initially configured to manage soils in batches of 380 m^3 piles, which corresponded to the sampling frequency for explosives. The sampling frequency of treated soils for perchlorate was increased through regulatory concerns to one every 76 m^3. If any of the five samples representing the treated soil stockpile was above the treatment standard, the entire 380 m^3 pile was retreated through the TTU. The treated soil stockpile area was reconfigured early within full-scale operations so that the treated soil could be managed in 76 m^3 stockpiles. Reconfiguring the stockpile area mitigated the consequence of a treated soil failure by reducing the quantity of soil requiring re-treatment.

Full Scale Treatment Results

Samples were collected from the TTU throughout the project to determine the effectiveness of the plant in treating the contaminants of concern. The four types of solids sampling performed during soil treatment operations were: 1) feed stockpile sampling, 2) treated soil sampling, 3) baghouse dust sampling, and 4) cyclone dust sampling.

A total of 60,036 tons were processed and 55,123 tons were successfully treated during full-scale operations. The failure rate (for perchlorate) during full-scale operations was 8.9%. Of the initial twenty 500 cubic yard (380 m^3) piles during full-scale operations, fourteen met the treatment standards (30% failure rate). After the treated storage area was reconfigured to accommodate the separation of 76 m^3 piles and the process was optimized, the failure rate dropped to 1.33%. The majority of soil on the project was processed at this lower failure rate.

The TTU successfully treated 100% of explosives throughout the project, never failing a treated soil sample.

During full-scale operation, two daily composite samples were collected from the material transferred from the baghouse to the pugmill and from the cyclone dust effluent, respectively. These samples were analyzed for perchlorate. Based on past sampling and analyses, explosives contamination was not a concern in these locations. Only one out of 85 bag house samples was above the remediation goal of 4.0 ppb and 12 out of 85 cyclone samples were above 4.0 ppb.

Operating data imply that low levels of perchlorate in the baghouse and cyclone streams are likely due to short-circuiting within the process so that small portions of contaminated soil are not exposed to the treatment temperature for the necessary amount of time. Recycling these fines back through the process was discussed but determined to be impractical under the existing systems configuration.

CONCLUSIONS

The following conclusions can be incorporated as lessons learned from this project:

1. A direct-fired Thermal Treatment Unit (TTU) was effectively used for the removal of the inorganic salt perchlorate as well as explosive compounds and polychlorinated naphthalene in soils from several source areas. This was the first reported full scale application involving remediation of perchlorate in soil.
2. A laboratory scale treatability study determined that an operating temperature of 775^{o}F (412^{o}C) for dry soils was sufficient to reach the treatment goal of 4 ppb. However, a temperature of 925^{o}F (496^{o}C) was required for wet soil during full scale operations.
3. On-site pilot studies demonstrated that soils containing approximately 2 ppm of perchlorate and up to 18 % moisture levels could be treated with a high percentage of success at feed rates of 40 tons per hour.
4. High efficiency operations were routinely achieved for all contaminants; however occasionally treatment batches failed the perchlorate remediation goal of 4 ppb. In order to minimize cost impact due to off-specification soils, the batch size was reduced to coincide with the sampling frequency required by the regulatory agencies.
5. Some difficulties were encountered with small portions of perchlorate-contaminated soils bypassing the primary treatment process and entering the air pollution control equipment. This resulted in occasional low level detections of perchlorate in the treated soil. This would not be a problem with less stringent treatment goals derived from risk-based levels instead of laboratory reporting limits. However, future designs intended for perchlorate treatment could try to

account for this by recycling dust to the beginning of the treatment train instead of the treated soil discharge.

6. Cost evaluations at the end of the project indicated that the TTU process was cost effective compared to other options. Future projects would likely be spared of some of the learning costs incurred in this project. Less stringent regulatory criteria would greatly reduce sampling and other operational costs, making thermal treatment even more cost effective.