

*“Oil Lakes”  
Monitoring and Assessment Report  
Marine and Coastal  
Monitoring and Assessment Report*

***Oil Lakes Volume 2, Appendix E:***

***Marine and Coastal Appendix M:***

***Results of Laboratory Scale, Field  
Demonstration, and Comparative Studies  
of Effective Technologies***

*Monitoring and Assessment of the Environmental  
Damages and Rehabilitation in the Terrestrial  
Environment (Cluster 3) and in the Coastal and  
Marine Resources (Cluster 2)*

*UNCC Claims 5000432 and 5000398*

*27 August 2003*

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# 1 Overview and Objectives

As part of the State of Kuwait's Monitoring and Assessment Program, the Consortium of International Consultants reviewed technologies that are potentially applicable to the remediation program for the oil contamination caused by Iraq. This contamination includes tarcrete included in the State of Kuwait's Third Instalment Claim, terrestrial oil contamination related to the State of Kuwait's Fourth Instalment Claim 500454 and coastal oil contamination included in the State of Kuwait's Fourth Instalment Claim 5000259. Technologies to address tarcrete were previously evaluated and presented in a series of technical papers listed in Section 2.1. The focus of the work described in the present document is the assessment of remedial technologies and methods to address oil contamination related to the State of Kuwait's Fourth Instalment claims.

The technology assessment work consists of four components:

- Data gathering and technology identification;
- Technology-specific sample collection and testing;
- Bench-scale testing; and
- Field demonstrations.

The Consortium of International Consultants believes that sufficient information is available to support technology selection of high-temperature thermal desorption for remediation of terrestrial areas of oil contamination, including wet and dry oil contamination, oil-contaminated piles, oil trenches, Iraqi pipelines and associated spills; and for remediation of visible coastal contamination. This is a final report with respect to that technology selection.

No report has yet been generated with respect to the field demonstration of materials handling for terrestrial "wet oil" contamination. A report on that demonstration together with the resulting of the remaining laboratory analysis of samples collected for technology analysis is expected to be available in October.

This is only an interim report with respect to residual contamination along Kuwait's coast.

## 2 Types of Oil Contamination Addressed in This Report

Past studies conducted to determine the nature and extent of oil contamination in Kuwait have used varying terminology to describe the various forms in which terrestrial oil contamination occurs (see Volume 1, Summary Report of the “Oil Lakes” M&A Report). The following subsections describe the various types of oil contamination that are considered in the remedial program.

### 2.1 Terrestrial Oil Contamination

Visible oil contamination in the terrestrial environment included in the Fourth Instalment Claim has been identified in the following forms:

1. Wet oil contamination;
2. Dry oil contamination;
3. Oil-contaminated piles; and
4. Oil trenches, pipelines, and spills.

These categories are described in the following paragraphs.

**Wet Oil Contamination.** Consists of black liquid or semi-solid oil over or interspersed within oil-contaminated soil. The wet oil contamination occurs in areas where liquid oil accumulated because of microrelief and local topography. Such places include shallow depressions and drainage channels. The liquid oil surfaces may have a thin hardened layer on the surface, but this surface is not strong enough to support a person walking on it.

The presence of free liquid has precluded completion of ordnance clearance in the areas where this type of contamination occurs, and the presence of free liquid also presents distinct materials handling issues for remediation.

**Dry Oil Contamination.** Comprises a thin, black, moderately hard, tar-like dry surface layer (that may contain some contaminated soil material) – sometimes with a layer of oil sludge – overlying dark brown oil-contaminated soil that in turn overlies soil with no visible oil contamination. The dry oil contamination occurs in shallow depressions and flat areas, often fringing areas of wet oil contamination.

Several extensive studies have been completed which, although directed only to tarcrete, contribute to assessing remedial technologies that may be effective in addressing dry oil contamination. The results of these studies were presented in a series of technical papers submitted to the Commission in October 2002:

- *Review of New and Existing Technologies;*
- *Bioremediation of Tarcrete;*
- *High-Temperature Thermal Desorption System for Remediation of Tarcrete Contamination;* and

- *Landfill Conceptual Design for Tarcrete*

**Oil-Contaminated Piles.** The piles occur where earthmoving equipment has been used to consolidate oil-contaminated soil and/or liquid oil into mounds. These piles were made in efforts to stop the spread of oil flows caused by the destruction of the State of Kuwait's oil wells, or to clear areas of heavy oil contamination as necessary to facilitate fire-fighting or subsequent Kuwait Oil Company field operations.

**Oil Trenches, Pipelines, and Spills.** This material consists of oil-contaminated soil from in-filled trenches. During Iraq's invasion and occupation of Kuwait, Iraqi troops excavated oil trenches, mainly along the southern border zone of Kuwait parallel to the northern Saudi Arabian border. The oil trenches were filled with oil that was piped from the oil fields through a network of Iraqi-constructed pipelines. After the liberation of Kuwait, some of the liquid oil was recovered from the trenches; the trenches were then backfilled during the period from 1993 to 1994. Included in this category are contaminated soils associated with oil flows from the Iraqi pipeline and the *Wadi Al Batin* spill.

## 2.2 Types of Coastal Contamination

Oil contamination in coastal areas exists in several forms. This assessment addresses technologies for treatment of the following types of oil contamination:

1. Oil deposits;
2. Oil trenches;
3. Weathered oil layers; and
4. Residual contamination.

These categories are described in the following paragraphs.

### Oil Deposits

This material is characterized by the presence of visibly oiled or stained sediment not located in oil trenches. Coastal oil deposits may contain some or all of the following:

- Hardened oil sludge
- Asphalt-like material
- Oil-contaminated sediments

The coastal oil deposit is similar in consistency to the terrestrial dry oil contamination category materials.

### Oil Trenches

This material contains visibly oiled or stained sediment, associated with Iraqi-built trenches, which may contain some or all of the following:

- Liquid oil or oil-water emulsion
- Contaminated sediments
- Asphalt-like material at the surface

### **Weathered Oil Layers**

This material is generally a layer of accreted sediment and visibly oily material, asphalt-like in appearance, and occurring in discrete bands or patches. Ongoing Monitoring and Assessment studies continue to map the extent of this type of contamination.

The coastal weathered oil layers are similar in consistency to the terrestrial dry oil contamination.

### **Residual Contamination**

Ongoing Monitoring and Assessment studies continue to map the extent of coastal residual contamination. Residual contamination generally takes the form of **non-visible petroleum contamination**. This contamination occurs at levels that are not discernable with the naked eye. Because this contamination may not be readily visible, laboratory testing results are necessary to determine the extent of this contamination. Monitoring and Assessment studies to fully delineate the extent of coastal residual contamination are ongoing.

### 3 Remedial Technology Investigation Methods

The Consortium of International Consultants assessed the capabilities of a wide range of remedial technologies. Information gathering and technology evaluation and selection were initiated in the summer of 2002. This work involved a review of technology databases and literature pertaining to remedial technologies.

With respect to terrestrial contamination, technologies were assessed based on the following three screening criteria:

**Criterion 1. Technical capability:** The technology must have the ability to permanently destroy contaminants, so that the treated soil exhibits no visible contamination with a minimal likelihood of other environmental impacts.

**Criterion 2. Proven large-scale performance:** The technology must have been successfully demonstrated in actual, full-scale field or commercial applications, and should be scalable to the very large volumes of contaminated materials to be remediated.

**Criterion 3. Competitive cost:** Treatment costs using the technology are expected to be cost-effective relative to any other technologies that satisfy the first two criteria.

Based on the initial data gathering and technology assessment for technologies to address terrestrial contamination, three *ex situ* technologies were selected for further testing at the bench-scale level:

- Thermal treatment (high-temperature thermal desorption);
- Biological treatment; and
- Soil washing using the Clean Sand Process.

In addition to collecting a small number of samples for bench testing, supplemental technology assessment sample collection and testing was performed as part of the technology assessment (See Annex 5 to this Appendix). These additional data were required to assess the variability in technology-sensitive parameters and to better support extrapolation of results from bench testing to full-scale remediation in Kuwait. For instance, bench testing of thermal treatment was performed on a small number (20) of samples. However, through acquisition of British thermal unit and moisture content data for a larger number (more than 125) of samples collected as part of the supplemental technology assessment sampling program, these results can be extrapolated to more accurately estimate thermal treatment unit operational parameters.

Following consideration of the same three screening criteria, this bench testing was also applied to the visible coastal contamination (not the residual oil contamination).

For that residual contamination, field testing of *in situ* technology (biological treatment) is being performed for a contaminated coastal area (*Khiran*). This field testing includes a bench testing component.

A field demonstration is also being performed to investigate materials handling methods needed to support application of *ex situ* technologies in the field. This field

demonstration is designed to assess materials handling aspects associated with excavation of wet and pooled areas of liquid oil that have not been cleared of unexploded ordnance.

## 4 Study Results

### 4.1 Objectives

The objectives of the studies conducted to evaluate the effectiveness of high-temperature thermal desorption, bioremediation, and soil washing treatment technologies were to:

- Acquire more specific data pertaining to the performance of high-temperature thermal desorption to facilitate the development of an accurate cost estimate;
- Assess whether *ex situ* biological treatment meets the three selection criteria for use on terrestrial oil contamination in Kuwait;
- Assess whether the Clean Sand Process meets the three selection criteria for use on terrestrial oil contamination in Kuwait;
- Assess methodologies and costs associated with materials handling; and
- Assess a method for *in situ* biological treatment of residual coastal oil contamination.

The detailed assessments consisted of:

1. Collecting samples from oil-contaminated areas for bench testing of remedial technologies, and collecting and analyzing supplemental samples to acquire technology-specific analytical data.
2. Conducting laboratory-scale bench tests to assess the performance of the three selected technologies. In the case of high-temperature thermal desorption, bench testing was performed in order to acquire data that is helpful in defining treatment system parameters (Annex 2).
3. Conducting field tests of materials handling methods tasks (unexploded ordnance clearance and excavation) for oil-contaminated areas.
4. Conducting bench-scale and field tests of *in situ* biological treatment for residual contamination in a coastal area.

This section summarizes the results of the bench testing programs, including the supplemental technology assessment sample collection and testing program. Detailed reports for the bench testing programs are provided in the annexes. The field testing programs are ongoing, and will be reported at a later date. For the coast, only preliminary observations are available on the field and bench-scale testing of *in situ* biological treatment. These observations are included in Appendix L to the 27 August 2003 Marine and Coastal M&A Report.

## 4.2 Supplemental Technology Assessment Sample Collection and Testing – Terrestrial Contamination and Coastal Contamination

### 4.2.1 Program Scope and Rationale

The supplemental technology assessment samples were intended to provide additional data regarding the physical and chemical properties of the oil contamination to assist in the technology evaluation. These data and information were used to supplement data gathered as part of the determination of quantities under the Monitoring and Assessment Program (as described in Volume 1 of the “Oil Lakes” M&A Report). The data also were used to assess the variability in technology-sensitive parameters and to better support extrapolation of results from bench testing to full-scale remediation in Kuwait, as noted in Section 3.

The program provides for sample analyses to be grouped into three suites—a baseline suite, a general chemical characterization suite, and a biological testing suite.

#### Baseline Technology Suite

The baseline technology suite of analytical parameters is as follows:

- Asphaltene content;
- Chloride content (as an indicator of salinity);
- Grain size distribution;
- Heat value (gross calorific value in British thermal units);
- In-place density;
- Moisture content;
- Soil pH;
- Total organic carbon; and
- Total petroleum hydrocarbons.

The baseline technology suite of parameters provides basic information to assess the viability and costs of the three technologies being studied. For example, data regarding the physical properties of soil, such as in-place density, grain size, and total organic carbon, helps in the assessment of requirements for technology application. Grain size data are also used to better define bag house requirements (for thermal treatment), water retention capacity, and permeability for bioremediation and soil washing process needs. Total organic carbon data help define amendment needs for biological treatment. Salinity, soil pH, and asphaltene content help assess the ability of bioremediation to reduce total petroleum hydrocarbon concentrations. Energy content and moisture content enable the prediction of factors such as retention time (for contaminant desorption) and

fuel costs associated with thermal treatment. In-place density data are used to estimate the weight of material to be treated, based on its in-place volume.

## Chemical Characterization

The chemical characterization suite of analytical parameters and the significance of the data are:

- Metals: arsenic, barium, cadmium, copper, iron, zinc, mercury, nickel, lead, chromium, manganese, molybdenum, selenium, and silver. Metals data are needed to determine residual metals concentrations in the soil after treatment, because each of the technologies identified for further study addresses organic rather than metallic contaminants. Moreover, the metals content in the soils may influence the applicability of a particular technology. For example, high levels of certain metals may inhibit biological treatment.
- Semivolatile organic compounds (United States Environmental Protection Agency 8270 list of parameters), and volatile organic compounds (United States Environmental Protection Agency 8260 list of parameters). Data regarding volatile and semivolatile organic compounds are necessary to identify possible special precautions needed to minimize worker exposure during remediation, to ascertain the treatability of soil contaminants, and to estimate residual contaminant concentrations that may remain after treatment. These data may also be used to support calculation of the quantity of off-gases released during high-temperature thermal desorption.

## Biological Suite

Bacteriological data are used to assess the suitability of soil to support growth of petroleum-degrading microbes and to identify any such microbes already present. This supports the assessment of the viability of biological treatment. The biological suite of analytical parameters is as follows:

- Anions (nitrate and nitrite nitrogen, ammonia nitrogen, and phosphorous-dissolved orthophosphate). Analysis of anion concentrations in the soil helps determine microbial ecology, and enables estimates of the quantities of co-metabolites required for hydrocarbon degradation to be made.
- Bacterial identification of Heterotrophic bacteria population, and hydrocarbon utilizing bacteria.
- Sulfides. Assessment of sulfide levels supports a determination of the viability of bioremediation, because high sulfide levels may be toxic to petroleum-degrading microbes.

Table 4-1 indicates the number of terrestrial samples collected for each of the suites of testing, by location. At wet oil contamination locations, samples of the sludge/liquid as well as the underlying contaminated soils were collected.

**Table 4-1 Number of Supplemental Technology Assessment Samples by Location**

Location	Contamination Type	Contaminated Soil				Sludge/Liquid	
		Baseline, excluding density	Density	Chemical	Biological	Base-line	Chemical
<b>Terrestrial Samples</b>							
<i>Bahra</i>	Dry Oil Contamination	2	2	Not Analyzed	1	Not Analyzed	Not Analyzed
<i>Burgan</i>	Dry Oil Contamination	39	12	Not Analyzed	2	Not Analyzed	Not Analyzed
	Wet Oil Contamination	18	7	1	2	18	3
	Oil-Contaminated Piles	6	7	1	2	Not Analyzed	Not Analyzed
<i>Minagish</i>	Dry Oil Contamination	2	0	1	1	Not Analyzed	Not Analyzed
<i>Raudhatain</i>	Dry Oil Contamination	25	6	Not Analyzed	1	Not Analyzed	Not Analyzed
	Wet Oil Contamination	5	3	1	1	5	1
	Oil-Contaminated Piles	2	1	Not Analyzed	1	Not Analyzed	Not Analyzed
<i>Sabriyah</i>	Dry Oil Contamination	10	5	Not Analyzed	1	Not Analyzed	Not Analyzed
	Wet Oil Contamination	3	2	1	1	3	1
	Oil-Contaminated Piles	2	2	Not Analyzed	1	Not Analyzed	Not Analyzed
<i>Umm Gudair</i>	Dry Oil Contamination	1	3	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed
	Wet Oil Contamination	1	0	1	1	1	1
<i>Wafra</i>	Dry Oil Contamination	8	4	1	1	Not Analyzed	Not Analyzed
Oil Trench	Oil Trench Soils	3	3	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed

Note: A program for performing supplemental technology assessment sampling for coastal areas is currently under development. It will be submitted at a later date.

Supplemental technology assessment samples were generally collected at locations where sampling to map and quantify contamination for the terrestrial Monitoring and Assessment Program occurred. With the exception of in-place density, supplemental technology assessment samples were collected as composites to provide a representation of the material to be treated.

**4.2.2 Testing Results - Terrestrial**

Available results of supplemental technology assessment sample testing for these suites are summarized below. Currently completed sample testing results are provided in full in Annex 5.

**Baseline Technology Suite Testing Results**

Table 4-2 presents results for baseline technology suite analyses, except for *in situ* density results, which are presented in Table 4-3. Units are milligrams per kilogram based on dry weight, except as noted. Results are summarized separately for contaminated soils and sludge/liquid.



**Table 4-2 Baseline Technology Testing Results - Terrestrial**

Analyte	Contaminated Soil			Sludge/Liquid		
	Average	Range	Standard Deviation	Average	Range	Standard Deviation
Asphaltenes	6,486	567 to 50,800	6,552	283,326	11,100 to 770,000	234,198
Chlorides	2,187	12 to 19,200	4,758	Not Analyzed	Not Analyzed	Not Analyzed
Heat Value (British Thermal Units per pound)	644	<43 to 17,400	1,619	7,541	<43 to 18,100	7,092
Moisture Content (percent)	2.43	0.1 to 44.8	4.46	28.61	0.60 to 77.20	26.95
Soil pH (pH units)	7.7	4.8 to 8.9	0.7	6.7	5.0 to 7.7	0.6
Total Organic Carbon (percent)	4.8	0.7 to 29.0	4.2	45.8	6.2 to 91.0	27.4
Total Petroleum Hydrocarbons	34,013	8,330 to 155,000	22,575	329,296	57,000 to 802,000	176,904

Table 4-3 presents results of in-place density testing for contaminated soils by location. Sludge/liquid samples for in-place density analysis have not yet been collected and therefore results are not available at this time.

**Table 4-3 In-Place Density Test Results - Terrestrial (grams per cubic centimeter)**

Location	Contaminated Soil		
	Average	Range	Standard Deviation
<i>Bahra</i>	1.746	1.703 to 1.804	0.045
<i>Burgan</i>	1.700	1.329 to 2.022	0.141
<i>Minagish</i>	Not Analyzed	Not Analyzed	Not Analyzed
<i>Raudhatain</i>	1.737	1.440 to 2.019	0.170
<i>Sabriyah</i>	1.682	1.435 to 2.061	0.183
<i>Umm Gudair</i>	1.703	1.584 to 1.823	0.078
<i>Wafra</i>	1.796	1.667 to 1.907	0.074
Oil Trench	1.621	1.383 to 1.928	0.187

### Chemical Characterization Suite Testing Results

Table 4-4 summarizes results of chemical characterization suite testing. Units are micrograms per kilogram for semi-volatile organic compounds and milligrams per kilogram for metals, both based on dry weight. Results are summarized separately for contaminated soils and sludge/liquid.

**Table 4-4 Chemical Characterization Testing Results - Terrestrial**

Analyte	Contaminated Soil			Sludge/Liquid		
	Average	Range	Standard Deviation	Average	Range	Standard Deviation
<b>Volatile Organic Compounds:</b>						
2-Butanone	12.4	<9.97 to 23.2	5.3	100.4	<17.3 to 356.0	126.8
2-Hexanone	11.4	<9.55 to 15.3	2.4	36.5	12.2 to 117.0	40.2
4-Methyl-2-pentanone	<9.9	<9.55 to <10.1	--	18.5	<9.93 to 28.9	10.9
Acetone	19.1	<9.99 to 40.1	11.3	219.8	65.8 to 780.0	276.4
Benzene	<5.0	<4.78 to <5.05	--	15.86	<4.96 to 48.4	16.84
Carbon disulfide	4.95	<4.78 to <5.05	0.12	9.27	<4.96 to <17.5	5.42

**Table 4-4 Chemical Characterization Testing Results - Terrestrial**

Analyte	Contaminated Soil			Sludge/Liquid		
	Average	Range	Standard Deviation	Average	Range	Standard Deviation
Cyclohexane	<4.95	<4.78 to <5.05	--	86.05	<4.96 to 296.0	126.5
Ethylbenzene	7.13	<4.78 to 18.1	5.37	65.38	<4.96 to 211.0	91.93
Isopropylbenzene	5.30	<4.78 to 7.12	0.90	23.50	<4.96 to 64.5	25.90
Methylcyclohexane	<4.95	<4.78 to <5.05	--	140.5	<4.96 to 486.0	212.4
Toluene	<4.95	<4.78 to <5.05	--	71.88	<4.96 to 266.0	108.2
Xylene, Total	15.50	<4.78 to 68.3	25.87	298.7	<4.96 to 998.0	457.4
<b>Semivolatile Organic Compounds:</b>	Not detected			Not detected		
<b>Metals:</b>						
Arsenic	2.60	1.78 to 5.04	1.23	1.33	<0.86 to <2.41	0.62
Barium	60.2	14.6 to 238.0	87.6	17.4	<1.92 to 48.0	20.3
Chromium	13.5	10.2 to 16.0	2.2	4.3	<0.86 to 14.0	5.4
Copper	3.26	1.92 to 5.38	1.37	2.73	<1.71 to 6.01	1.69
Iron	4,132	3,280 to 5,130	765	1,270	73 to 4,520	1,774
Lead	1.83	0.94 to 3.35	0.88	0.67	<0.43 to <1.2	0.28
Manganese	97.65	66.6 to 120.0	19.23	30.75	2.45 to 89.0	33.58
Nickel	18.48	14.8 to 22.10	3.13	14.43	6.69 to 28.60	9.08
Selenium	1.115	<0.89 to 1.71	0.342	1.630	<0.86 to 3.36	0.997
Zinc	6.36	4.49 to 8.12	1.35	3.81	<0.86 to 11.30	4.14

Note: Analytes not shown above are not detected in the analysis.

### Biological Suite Testing Results

Table 4-5 presents anions results of biological suite testing. Results are reported as milligrams per kilogram dry weight. Bacteria results are summarized and discussed separately in Annex 4 to this Appendix.

**Table 4-5 Biological Testing Results – Terrestrial**

Analyte	Contaminated Soil			Sludge/Liquid		
	Average	Range	Standard Deviation	Average	Range	Standard Deviation
Ammonia, Nitrogen	3.57	<3.01 to 8.61	1.49	Not Analyzed	Not Analyzed	Not Analyzed
Nitrogen, Nitrate (As N)	3.70	<2.0 to 28.50	6.61	Not Analyzed	Not Analyzed	Not Analyzed
Nitrogen, Nitrite (As N)	<5.61	<2.0 to <40.5	--	Not Analyzed	Not Analyzed	Not Analyzed
Phosphorus, Dissolved Orthophosphate (As PO <sub>4</sub> )	3.80	<2.01 to 25.20	5.82	Not Analyzed	Not Analyzed	Not Analyzed
Sulfide	84.5	27.7 to 137.0	34.4	Not Analyzed	Not Analyzed	Not Analyzed

As part of CIC's supplemental technology assessment sampling and analysis program, sixteen representative samples were collected from *Burgan*, *Raudhatain*, *Bahra*, *Minagish*, *Umm-Gudair* and *Wafra*. These samples were analyzed for total bacteria populations and the population able to utilize Kuwait crude oil for growth. The bacteria present were then identified by species. These results are included in Annex 4 to this Appendix.

Microbiological results of analysis of these samples indicate considerable variation between samples. Two of 16 samples (12.5%) yielded no organisms after a 48-hour

incubation period. Populations of heterotrophic bacteria present in samples containing bacteria ranged from approximately 1,000 colony-forming units per gram of soil to approximately 40,000 colony-forming units per gram of soil. Zero to six types of bacteria were isolated per sample, based on colony morphology, indicating considerable diversity. Bacterial identification analysis performed on 11 of the samples yielded 39 morphologically unique strains of bacteria. Several genera of bacteria commonly associated with hydrocarbon-contaminated soil such as *Acinetobacter*, *Pseudomonas* and several species of *Bacillus* were identified and quantified. These results are consistent with previous microbiological studies. Analysis performed to isolate the bacteria types capable of utilizing crude oil from Kuwait as a sole carbon source yielded a relatively low population. This population ranged from one to several orders of magnitude less than the total heterotrophic population.

#### 4.2.3 Testing Results - Coastal

As noted above, a plan for performing supplemental technology assessment sampling for coastal areas (including the baseline suite, the chemical characterization suite, and the biological suite) is being refined and will be submitted at a later date. The corresponding analytical results will therefore be provided at a later date.

### 4.3 Bench-Scale Testing Program

Although treatment results can be inferred from the available literature, it is important to assess the effectiveness of a potentially applicable technology through bench-scale testing of the actual contaminated media to be treated. Accordingly, bench-scale testing was performed for the three retained treatment technologies. The complete bench-scale results are provided in the following Annexes and summarized in the following subsections:

- Annex 2: High Temperature Thermal Desorption Bench Test Results
- Annex 3: Soil Washing Bench Test Results
- Annex 4: Ex Situ Biological Bench Testing Results

A fourth bench test is being performed as part of the *in situ* bioremediation field demonstration, intended for possible application to residual oil contamination in coastal areas and to provide information useful in estimating costs for full scale application. This ongoing work is discussed in Section 4.3.4.

#### 4.3.1 Bench-Scale Testing of Thermal Treatment

The overall objective of the bench-scale treatability study was to establish design parameters for a full-scale high-temperature thermal treatment system. In the design of a full-scale high-temperature thermal treatment system for treating petroleum-contaminated soil, soil temperature and soil retention time are critical parameters. These parameters directly influence the size and performance characteristics of the system. In the treatment of oil-contaminated soil, the soil temperature and soil retention time required for desorption are influenced by the following parameters:

- Soil moisture content (percent);
- Soil energy content (kilocalories per kilogram or British thermal units per pound);

- Soil contamination level (total petroleum hydrocarbons);
- Required maximum allowable soil residual contamination level after treatment (total petroleum hydrocarbons); and
- General soil characteristics (such as grain size).

Thermal bench testing total petroleum hydrocarbon results are summarized below. A complete report of the thermal bench testing program, including temperature, retention time, moisture content, and weight loss data, is provided in Annex 2.

**4.3.1.1 Samples Utilized for Bench Testing**

Thirteen samples were collected from areas of terrestrial contamination and submitted for bench testing to assess thermal treatment. See Table 4-6. Samples were selected to be representative of the types of contamination found. Six samples were collected from areas of dry oil contamination from the *Burgan* and *Raudhatain* oil fields. Sample sites were selected based on visual observation of the degree of contamination. Samples ranged from a lightly stained sand to a mixture of tar and sand. Four samples were collected from oil-contaminated piles. Three of the four consisted of a sand and tar mix, the fourth sample was a stained sand. Two samples of wet oil contamination were collected. One sample was soft and nearly liquid, the other firm. One sample, a mixture of tar and sand, was collected from a terrestrial oil trench.

**Table 4-6 Terrestrial Samples for High-Temperature Thermal Desorption Bench Testing**

Contamination Type	Oil Field or Location	Sample Identification
Wet Oil Contamination	<i>Burgan</i>	T251-12
Wet Oil Contamination	<i>Burgan</i>	T251-13
Dry Oil Contamination	Northern ( <i>Raudhatain/Sabriyah</i> )	T-251-03
Dry Oil Contamination	<i>Burgan</i>	T251-08
Dry Oil Contamination	Northern	T251-05
Dry Oil Contamination	<i>Burgan</i>	T251-07
Dry Oil Contamination	<i>Burgan</i>	T251-09
Dry Oil Contamination	<i>Burgan</i>	T251-14
Oil-Contaminated Piles	Northern	T251-02
Oil-Contaminated Piles	Northern	T251-04
Oil-Contaminated Piles	<i>Burgan</i>	T251-11
Oil-Contaminated Piles	<i>Burgan</i>	T251-15
Oil Trenches	South	T251-01

Seven samples were collected from coastal areas, as shown in Table 4-7. Two were collected from the oil deposit on the north coast of Kuwait Bay, representing high and medium levels of contamination (based on visual observations). Two samples were also collected from the coastal oil trench, one containing liquid oil and sand, the other containing more of a silt matrix based on field classification. Two samples were collected from weathered coastal layers. The first included a relatively thick layer of tar from the mid-tidal range, the other a thin layer of tar from the upper tidal range. The seventh sample was collected as a composite of the upper 15 centimeters of sediment from an area with a thin layer of visible contamination at a depth of approximately 10 centimeters.

**Table 4-7 Coastal Samples for High-Temperature Thermal Desorption Bench Testing**

Contamination Type	Oil Field or Location	Sample Identification
Oil Deposit	Northern Kuwait Bay	T1342
Oil Deposit	Northern Kuwait Bay	T1343
Oil Trench	<i>Ras As Subiyah</i>	T1219
Oil Trench	<i>Ras As Subiyah</i>	T1220
Weathered Oil	Pipeline Beach	C41-03
Weathered Oil 1	<i>Khiran Beach</i>	C41-01
Residual	<i>Khiran (subsurface)</i>	C41-02

#### 4.3.1.2 Testing Results

High-temperature thermal desorption bench-scale testing was performed for the types of oil contamination described in Section 2. For each sample, tests at three temperatures: (750° Fahrenheit, 850° Fahrenheit, and 950° Fahrenheit) and three residence times (10 minutes, 20 minutes, and 30 minutes) were performed. Thus, there were 9 test conditions for each sample. Three sets of sample runs at identical conditions of temperature and residence time were run, in order to obtain information regarding variability of the results. Thus, 27 tests were performed on each sample, except for sample T251-13, for which only two tests were performed because of excessive heat created in the exhaust system of the test apparatus. This sample contained more than 90 percent combustible materials, and would in any case not be representative of the blended feedstocks that would actually be utilized for remediation in the field.

#### Terrestrial Results

Thermal bench testing results for terrestrial samples are summarized in Table 4-8. A complete report of the thermal bench testing program results is provided in Annex 2.

#### Coastal Results

Thermal bench testing results for coastal samples are summarized in Table 4-9.

#### Relevance of Supplemental Technology Assessment Samples

Although bench testing can be done only on a limited number of samples, the data from a larger number of locations (from the supplemental technology assessment sampling) can be used to complement bench testing results in developing design parameters. As an example, one design parameter important for thermal treatment is soil moisture, which influences fuel consumption. A weighted average soil moisture value taken from the supplemental technology assessment sampling will provide a more accurate benchmark for estimating process fuel requirements than the pretreatment moisture data from the limited number of samples that were subjected to high-temperature thermal desorption bench testing. See Table 2 of Appendix F of Volume 2 to the “Oil Lakes” M&A Report.

Table 4-10 shows a comparison between bench-scale data and baseline suite data for four parameters that were used in the high-temperature thermal desorption design. This comparison shows that the average values of total petroleum hydrocarbons, asphaltenes, moisture, and British thermal units from the bench study are in close agreement with

those measured in the much larger number of samples from the baseline suite data. Therefore, it can be seen that the data from the bench-scale study represent the much larger population of samples from the baseline suite study, and consequently, a design based on the bench-scale data is compatible with the overall soil population.

**Table 4-10 Comparison of Bench-Scale and Baseline Analytical Data**

	Total Petroleum hydrocarbons (milligrams per kilogram)		Asphaltenes (milligrams per kilogram)		Moisture <sup>1</sup> (percent)		British Thermal Units (per pound)	
	Bench-Scale Samples	Baseline Suite	Bench-Scale Samples	Baseline Suite	Bench-Scale Samples	Baseline Suite	Bench-Scale Samples	Baseline Suite
Average	87,022	88,268	38,299	54,224	8.76	7.39	2,109	1,847
Minimum	677	8,330	926	567	0.823	0.10	43	22
Maximum	431,500	802,000	400,000	770,000	41.8	77.2	18,100	18,100

Note: 1. Moisture based on laboratory values and field moisture contents may be lower.

#### 4.3.1.3 Bench Testing Conclusion

Based on the high-temperature thermal desorption bench-scale testing results, it has been concluded that for temperatures of 850° Fahrenheit (454° Celsius), and retention times of 20 minutes, all coastal and terrestrial soils can be treated generally to levels of nondetect for total petroleum hydrocarbons, and to non-detectable or low (less than 400 milligrams per kilograms) levels of asphaltenes. The resulting treated soils and sediments closely resemble similar, uncontaminated soils, except that hydrocarbons (including organisms) have been removed.

The only exception to the above results was sample T251-13 Wet Oil Contamination (*Burgan* Thick). As noted above, this sample contained more than 90 percent combustible materials, and would in any case not be representative of the blended feedstocks that would actually be utilized for actual remediation in the field. Because the bench-scale study demonstrated that a full-scale high-temperature thermal desorption system operating at temperatures of 850° Fahrenheit (454° Celsius), and soil retention times of 20 minutes or greater, can successfully treat the hydrocarbon-contaminated soils to levels of nondetect for total petroleum hydrocarbons and asphaltenes for all soil combinations except T251-13, the use of blended combinations of soils will provide adequate assurance of achieving these treatability levels during full-scale high-temperature thermal desorption operations.

The bench testing results also provide process control data (regarding process residence time and operating temperatures) that are useful for design of the actual high-temperature thermal desorption process for application to Kuwait and for developing an accurate estimate of costs.

#### 4.3.2 Bench-Scale Testing Physical/Chemical (Soil Washing) Technology

The Consortium of International Consultants directed bench testing for a physical/chemical (soil washing) technology known as the Clean Sand Process. This process uses heated water, agitation, and particle separation based on size and density to remove petroleum contamination from sand. The objectives of bench testing this technology were to:

- Assess its effectiveness with respect to the various oil-contaminated materials described in Section 2;
- Identify its byproducts;
- Identify its material and logistical needs; and
- Develop information to support a unit cost.

A detailed report on this bench testing program, including information pertinent to the objectives listed above, is provided in Annex 3. The main findings are summarized below.

#### 4.3.2.1 Samples Utilized for Bench Testing

Testing was performed on a more limited number of samples than for the thermal bench testing, because the major goal of the soil washing tests was to check if this technology meets the selection criteria listed in Section 3, rather than to obtain additional data that might be needed to optimize process control requirements. Five samples were submitted for bench-scale testing: one sample of dark-stained sand; one sample from the oil trench consisting of a mix of tar and sand; one sample of oil sludge; one composite sample of oil-contaminated pile material consisting of a mix of tar and sand (i.e., all four of the types of terrestrial oil contamination described in Section 2); and one of the four types of coastal contamination (coastal oil deposit).

#### 4.3.2.2 Testing Results

Testing results for this technology are presented in separate sections for terrestrial samples and for the coastal sample, as shown below. A complete report of Clean Sand Process bench testing program, including answers to the microbiological questions listed above, is provided in Annex 3.

#### Terrestrial Results

The bench testing results for terrestrial samples are summarized in Table 4-11.

**Table 4-11 Results of Soil Washing (Clean Sand Process) Bench Testing for Terrestrial Samples**

Sample Identification	Type of Soil	Description	Analytical Results (milligrams per kilogram)			
			Total Petroleum Hydrocarbons		Asphaltenes	
			Pre	Post	Pre	Post
T251-07	Dry Oil Contamination	<i>Burgan</i> Dark	30,750	1,780	6,015	589
T251-12 Note 1	Wet Oil Contamination	<i>Burgan</i> Thin	259,000	Not Applicable Note 1	130,450	Not Applicable Note 1
T251-04/11/15 Note 2	Oil-Contaminated Soil Piles	North Pile 2/ <i>Burgan</i> Pile 1/ <i>Burgan</i> Pile 2	77,400	1,360	13,600	689

**Table 4-11 Results of Soil Washing (Clean Sand Process) Bench Testing for Terrestrial Samples**

Sample Identification	Type of Soil	Description	Analytical Results (milligrams per kilogram)			
			Total Petroleum Hydrocarbons		Asphaltenes	
			Pre	Post	Pre	Post
T251-01 Note 3	Oil Trenches	Oil Trench	136,500	2,440	16,050	664

Notes:

1. Sample T251-12 was mainly sludge, water, fines, water-soluble solids, and coke or coke-like material. There was very little recoverable sand in this sample.
2. Samples T251-04, T251-11, and T251-15 were composited for Clean Sand Process testing.
3. Sample T251-01 required an additional bench-scale gravity separation step to remove low-density coarse materials (probably coke). These materials would be automatically removed by a full-scale Clean Sand Process system. This is because a full-scale system uses a spiral separator to achieve simultaneous separation of fines and of low-density coarse material. Rather than using a spiral separator, the bench test procedure used a sieve to separate fine materials from the sand. It did not separate low-density materials gravimetrically (with the exception of sample T251-01, for which a gravimetric separation was performed, as described in Annex 3).

**Coastal Results**

Bench testing results for the coastal sample are summarized in Table 4-12.

**Table 4-12 Results of Soil Washing (Clean Sand Process) Bench Testing for Coastal Samples**

Sample Identification	Type of Soil	Description	Analytical Results (milligrams per kilogram)			
			Total Petroleum Hydrocarbons		Asphaltenes	
			Pre	Post	Pre	Post
T1220	Oil Trench	Sand/Oil— Trench	69,550	1,810	30,600	Not Detected

**Relevance of Supplemental Technology Assessment Samples**

The data from the supplemental technology assessment sample suites that are relevant to soil washing (the baseline technology suite and the chemical characterization suite), as presented in the tables provided in Section 5.2, indicate that the bench testing samples exhibited properties that fall within the range of values that are representative of full-scale implementation of soil washing.

**4.3.2.3 Bench Testing Conclusion**

The Clean Sand Process produced sand that was not visibly stained, when applied to samples from dry oil contamination, from oil-contaminated soil piles, and from oil trenches. However, the treated sand contains much higher levels of hydrocarbons (between 1,300 and 2,500 milligrams per kilogram) than sand treated by HTTD. Moreover, the Clean Sand Process generates significant treatment residues. In particular, the Clean Sand Process generates “oily float” material and oily fines. In the bench test results, those treatment residues amounted to between 13.5 and 33 percent of the total amount of material treated (on a dry weight basis), and this material contained the bulk of the hydrocarbon contaminants originally present in the contaminated soil. Management of these treatment residues would be a significant issue and would impose significant

additional cost. Further study would be required to estimate the cost to manage the oily floats and fines. At a minimum, based on professional judgment and past experience, treatment and disposal of these materials should be expected to add 13.5 percent to 33 percent to the overall cost of this technology.

In addition, the Clean Sand Process is not applicable to materials that contain a small amount of sand, such as areas of wet oil contamination that contain mainly liquids and sludges, because it merely separates the contamination from the sand, but does not destroy the contamination. For materials that contain little sand, little is achieved by the application of this process.

### **4.3.3 Bench-Scale Testing of Biological Treatment – Ex Situ Application**

The Kuwait Institute for Scientific Research (2000) has done considerable research regarding bioremediation to rehabilitate contaminated soil. The Kuwait Institute for Scientific Research has demonstrated that while bioremediation has limited capability for reducing contamination levels, the principal constituents of the contamination are recalcitrant to biodegradation. This recalcitrant contamination limits the effectiveness of bioremediation as compared to other technologies that have greater removal efficiencies. The rationale of the biological bench-scale testing program described herein was to build upon the information collected by the Kuwait Institute for Scientific Research, and to see if a version of this technology could be effective. The biological bench-scale testing study was designed to answer the following basic questions:

Is the technology of biodegradation feasible for the types of oil contamination and the concentrations of the contaminants that exist?

- Are there indigenous bacteria present in the soil, and, if so, what types are they and at what level are they present?
- What portion of the total heterotrophic bacterial population has the ability to utilize hydrocarbons contained in Kuwait crude oil?
- What will be the resultant abiotic effects on contaminant concentrations if the soil is only excavated and physically mixed (only indigenous nutrients and bacteria)?
- How effective are indigenous, naturally occurring microorganisms in degrading total petroleum hydrocarbons and/or polycyclic aromatic hydrocarbons?
- How effective are commercially available, naturally occurring microorganisms in degrading total petroleum hydrocarbons and/or polycyclic aromatic hydrocarbons?

The Consortium of International Consultants chose the landfarming methodology for bench testing as representative of the multiple variations of bioremediation technology. Landfarming of contaminated soil has also been applied more often, on a wider range of contaminated sites, and has generated more data on which to evaluate its efficacy than has the windrow method (which is also referred to by the terms pile-turner or windrow composting).

Use of landfarming for the testing was also based on the Consortium of International Consultants' analysis that, while windrow-style and static pile bioventing bioremediation have potential advantages such as requiring less space, less operation and maintenance,

and better moisture retention, they also have practical limitations that may render them less effective than landfarming. These include insufficient oxygen transport, localized zones of degradation or “channelization” along channels formed by water, and/or nutrient applications resulting in incomplete mineralization of the contaminants. Although oxygenation is accomplished by mechanical mixing of the soil by turning the windrow, or by air injection into static piles periodically, physical distribution of moisture and nutrients is less efficient than using the landfarming technique. Heat production during contaminant degradation may be counterproductive, given the hot ambient environmental conditions generally prevalent in Kuwait. Also, for another similar method (composting), organic material must be mixed with the contaminated soil (in a ratio of 1:5 or 20 percent) to improve soil moisture retention and aeration, but this creates additional material to be disposed of and adds to the cost of the method.

#### **4.3.3.1 Samples Utilized for Bench Testing**

Composite samples of terrestrial oil contamination were collected from areas of dry oil contamination (eight locations composited into one sample), from areas of wet oil contamination (eight locations composited into one sample), and from oil trench locations (three locations composited into one sample). Similarly, a composite sample was collected from coastal oil deposit areas (eight locations composited into one sample).

The Consortium of International Consultants utilized solid-phase bioremediation techniques in this study. Concentrations of contaminants, nutrients, and bacterial populations and types were measured over time in one control and two treatment “bioreactors.” The composite samples were split into three subsamples each: a “control” subsample, a “biostimulated” subsample, and a “bioaugmented” subsample.

Control subsamples received no additional nutrients or inoculants, but were maintained at conditions intended to resemble natural conditions. Control subsamples can therefore be regarded as a baseline against which the biological treatment can be measured.

The biostimulated subsamples received a prescribed nutrient solution as described in Annex 4. This treatment encouraged the growth and promulgation of indigenous bacteria.

The bioenhanced (augmented) treatments were enhanced using the commercially selected, isolated, and cultured WST Bioblend M-B4W strain with a specially prescribed nutrient amendment obtained from Waste Stream Technology, Inc., as described in Annex 4. The nutrients and exogenous bacteria were selected for their purported ability to degrade oil contamination.

Each soil subsample receiving biotreatment was provided water daily and thoroughly mixed to distribute water/nutrient applications and maintain optimum soil moisture and oxygen concentrations for biodegradation. Control subsamples underwent a similar procedure (but without nutrient and/or bacteria addition), reducing the variables between the control treatments and the biostimulated and bioenhanced treatments.

#### **4.3.3.2 Testing Results**

Testing results for this technology are presented in separate sections for terrestrial samples and for the coastal sample, as shown below. A complete report of the *ex situ* biological bench testing program is provided in Annex 4.

## Terrestrial Results

Biological treatment was performed for four months for dry oil contaminated soils, and for seven months for the wet oil contamination and oil trenches samples. Results of testing indicate that although bacteria are present in the soil, there was no statistically significant biological degradation of hydrocarbon contaminants in any of the treatments performed.

## Coastal Results

Biological treatment was performed for four months for the coastal oil deposit sample. Results of testing indicate that although bacteria are present in the soil, there was no statistically significant biological degradation of hydrocarbon contaminants in any of the treatments performed.

## Relevance of Supplemental Technology Assessment Samples

The data from the supplemental technology assessment sample suites as presented in the tables provided in Section 4.2 indicate that the *ex situ* biological bench testing samples exhibited properties that fall within the range of values that are representative of full-scale implementation for this technology. The biological parameters measured in the supplemental technology assessment samples were consistent with those in treatability samples. There was a high concentration of contamination in supplemental samples, relative to the composite samples collected for treatability studies. The nature of the contamination, however, was similar in both sets of samples, therefore rendering the results of treatability testing relevant to full-scale implementation.

### 4.3.3.3 Bench Testing Conclusion

Based on the bench testing results, this technology did not result in any significant level of total petroleum hydrocarbon reduction for the materials tested.

Weathering and natural degradation of the contamination have likely continued in the years since the *ex situ* biological treatment study performed by the Kuwait Institute for Scientific Research (2000), which recorded reductions in total petroleum hydrocarbons by biological means during 1998 and early 1999. Although the Kuwait Institute for Scientific Research study was able to achieve reductions in total petroleum hydrocarbon levels in soils using bioremediation, the soils so treated still retained total petroleum hydrocarbon contamination in the range of 3,000 milligrams per kilogram to over 10,000 milligrams per kilogram. The remaining contaminants are now significantly more weathered than was the case for the Kuwait Institute for Scientific Research study, which means they have an even greater proportion of asphaltene constituents that are resistant to biodegradation. The results of the bench scale study indicate that the majority of the total petroleum hydrocarbon constituents that are amenable to biodegradation have already degraded (biologically and chemically) over time, leaving recalcitrant, weathered, less biologically treatable residues.

#### 4.3.4 Bench-Scale Testing to Assess In Situ Application of Biological Treatment

The Consortium of International Consultants is performing a series of bench-scale tests designed to emulate *in situ* biological treatment for contamination in coastal areas, to determine the effectiveness of this technology and/or to optimize the treatment approach for different sediment types. Bench-scale tests will enable the evaluation of the potential effectiveness of *in situ* treatment, primarily as a method of addressing residual contamination in an effort to achieve reductions in contaminant levels while stimulating the biota in these areas. Based on *ex situ* bench testing results, there is little expectation that bioremediation will be effective as a remedial technology to address high level, visible oil contamination. However, for completeness, *in situ* biological treatment is also being tested at the bench scale level on samples of sediments with higher levels of total petroleum hydrocarbons. In particular, bench-scale tests are being carried out on sediments collected from:

- An upper tidal flat area with extensive tar (5 to 10 hectares) overlying oily sand along the north shore of Kuwait Bay. Sediments from this site are generally sandy; contain a wide range of total petroleum hydrocarbon concentrations; and are currently being tested to assess how quickly the oil will bioremediate, whether nutrients or oxidants are the limiting factor, and whether toxins are present that may restrict bioremediation. Total petroleum hydrocarbon levels in the samples undergoing bench-scale testing are on the order of 15,000 to 50,000 milligrams per kilogram;
- The south shore of Kuwait Bay (*Sulaibikhat* Bay). Sediments from this area are muddy and expected to contain variable levels of total petroleum hydrocarbons, from very low to high, and contain high sulfide levels, and might also contain high levels of other contaminants from industrial and municipal sources;
- The *Khiran* site. Residual contamination at this site consists of a thin layer, typically less than 1 centimeter in thickness, of highly weathered oil at depths of 0 to 15 centimeters. Total petroleum hydrocarbon levels at this site are variable, ranging from negligible to 50,000 milligrams per kilogram within the thin layer of contamination. Sulfide levels are low; and
- *Bubyan* Island. Sediments near *Bubyan* are typically muddy and expected to have low levels of total petroleum hydrocarbon and variable sulfides. A sediment sample for bench-scale testing was collected from the mid-tide zone of the south portion of *Khor as Sabiya* adjacent to *Bubyan* Island. Total petroleum hydrocarbon levels in that sample are in the order of 100 to 150 milligrams per kilogram.

This broad range of samples will enable assessment of treatment effectiveness for very different sediment types and comparison of results from the bench-scale test directly to the pilot-scale test.

The well-weathered oil on the beaches of Kuwait may need synthetic agents to facilitate the bioremediation processes, in addition to just nutrients and bio-oxidants.

Reagents selected for the experiments include nitrate, humic acid, and a proprietary organic amendment. Nitrate is a powerful oxidant that facilitates oxic conditions

necessary for aerobic bioremediation. The organic amendment is used in an attempt to assist the bioremediation process. Experiments include a control, nitrate, and amended sample, as well as various doses of humic acid and organic amendment.

This testing is ongoing. Preliminary results for some of the tests are discussed in Appendix L to the 27 August 2003 Marine and Coastal M&A Report.

#### 4.4 Field Testing

In order to gain further information relevant to technology selection, the Consortium of International Consultants is performing field demonstration testing of:

- Materials handling methods for dry oil contamination and for wet oil contamination in terrestrial areas; and
- An *in situ* biological treatment process for contamination in a coastal area at the *Khiran* site in southern Kuwait.

No reports have been generated from these studies to date; however, information regarding material handling methods is being actively examined as it is generated, in support of the cost estimate for terrestrial remediation (Appendix G).

##### 4.4.1 Field Testing – Materials Handling Methods for Terrestrial Areas

Although areas of dry oil contamination and areas of wet oil contamination may be similar from a chemical constituent point of view, their materials handling requirements are expected to be different. For example, although areas of dry oil contamination may contain undetected unexploded ordnance, they generally have been examined at least once for such ordnance, whereas the areas of wet oil contamination generally have not yet been subject to any significant clearance efforts. Thus, the possible presence of unexploded ordnance in areas of wet oil contamination must be taken into account. Moreover, it is anticipated that there will be difficulties in gaining access in the wet oil contamination areas due to the soft or liquid nature of the surface in these areas. The Consortium of International Consultants is accordingly performing a materials handling pilot study with the following objectives:

- Ascertain relevant Kuwait Oil Company procedural requirements through field implementation of excavation in areas of wet oil contamination;
- Develop a methodology for oversight of unexploded ordnance clearance to be implemented before excavation;
- Assess methods for excavating and handling excavated materials to support development of a cost estimate; and
- Assess the variability in the depth of penetration of the oil contamination into the soil.

This field test has two components:

1. A test trenching program to assess the depth of penetration and the variability in the depth of penetration of oil into the subsurface.

2. An excavation program to more fully assess materials handling requirements by attempting various excavation methods.

Fieldwork is currently under way, and is expected to be completed in September 2003. Test trenches are being excavated in four locations to gather information pertaining to the variability in the depth of penetration of oil contamination. This information will be used to verify assumptions regarding the volume of contaminated material and the amount of excavation necessary. Two test trenches are located in the *Burgan* oil field, and two are located in the *Sabriyah* oil field. Test trenches are made by constructing causeways into the areas of oil contamination. The trenching will proceed down the center of the causeway, leaving the sides of the causeway to hold back sludge materials. Excavation will occur in one area of the *Burgan* oilfield to gather information regarding handling of sludge material. The excavation methodology involves pre-filling the areas of wet oil contamination with dry contaminated soils and uses unexploded ordnance specialists to clear areas ahead of the advancing work. A report detailing the results of these efforts is planned for late October 2003.

#### **4.4.2 Field Testing – In Situ Biological Testing for a Coastal Area**

The technology of *in situ* bioremediation has been applied around the world to address shoreline oil contamination. To assess the effectiveness of this technology with respect to the highly weathered oil contamination in one of the harshest marine environments in the world, the Consortium of International Consultants is performing a field demonstration. The field demonstration test is being carried out in conjunction with multiple bench scale tests of petroleum contaminated sediments with varying levels of overall hydrocarbon contamination and weathering of identified petroleum deposits. The combination will provide useful data which will enable the State of Kuwait to evaluate the overall viability of this technology in this environment and within the required time frame.

Reagents selected for the experiment include nitrate, humic acid, and an organic amendment. The organic amendment is being used in an attempt to assist the bioremediation process. Experiments include control, nitrate, and amended samples as well as various doses of humic acid and organic amendment.

The *in situ* bioremediation field demonstration is being conducted in the *Khiran* area of southern Kuwait, on a designated section of shoreline in the intertidal zone. Initial test amendments were selected based on preliminary observations made and on the experience of researchers at the National Water Resource Institute Canada, Centre for Inland Waters. Amendments have been applied to the sediment surface, then tilled-in using an agricultural disc. The test involves seven test plots (cells) with treatments as summarized in Table 4-13. Monitoring of these test plots is ongoing. Preliminary results are discussed in Appendix L to the 27 August 2003 Marine and Coastal M&A Report.

The specifications for the amendments used in the field demonstration are shown in Table 4-14.

**Table 4-14 Specifications for In Situ Bioremediation Amendments**

Chemicals	Specifications	Package	Product Origin
Calcium Nitrate	water soluble calcium: 19.0 percent nitrate (N): 14.4 percent ammonium (N): 1.1 percent	50 kilograms / bag	Belgium
Ammonium Nitrate	total nitrate: 34.5 percent ammonium (N): 17.3 percent nitrate (N): 17.0 percent	50 kilograms / bag	Belgium
Nitrogen, Phosphorus, Potassium	total nitrate: 13.0 percent ammonium (N): 9.3 percent nitrate (N): 3.7 percent soluble phosphate: 40 percent soluble potassium: 13.0 percent	25 kilograms / bag	Belgium
Peat Moss	organic matter: 90-95 percent water-absorbing capacity 20 times/volume pH 3 to 4	liters / bag	Germany
Humic Acid	Black Earth	25-kilogram drum	Canada
Compost	organic matter: 50 percent pH: 6 – 7 moisture: maximum 50 percent	30 liters / bag	Canada
Yeast	crude protein: >34 percent crude fiber: <5 percent crude fat: >1 percent moisture: <4 percent	25-kilogram bag	Canada

This work to assess *in situ* bioremediation continues in both the laboratory and the field. Results of this testing are expected in November of 2003.

## 5 Comparison of Technologies

This section compares the technologies that have been subjected to bench-scale testing for this report, in the context of the types of contamination in Kuwait other than residual coastal contamination.

### 5.1 Technology Capability

A comparison of total petroleum hydrocarbon results for the three technologies tested is shown in Table 5-1 for terrestrial contamination.

#### 5.1.1 Terrestrial Contamination

##### High-Temperature Thermal Desorption

The results of the bench testing indicate that high-temperature thermal desorption can successfully and practically treat the contaminated soils, producing “clean” soil with a total petroleum hydrocarbon concentration on the order of 500 milligrams per kilogram or less.

##### Clean Sand Process

Soil washing using the Clean Sand Process produces a visibly clean sand product, but this product has a substantial residual total petroleum hydrocarbon level (on the order of 1,000 to 2,500 milligrams per kilogram, much higher than the total petroleum hydrocarbon residual achieved by high-temperature thermal desorption). Soil washing also concentrates the contaminants in treatment residues (oily float and oily fines) that would require further management at additional cost.

##### Ex Situ Biological Treatment

As illustrated on Table 5-1, *ex situ* biological treatment was shown to be generally ineffective in treating the heavily weathered oil deposits that characterize the terrestrial oil contamination in Kuwait. These deposits contain a high proportion of heavy hydrocarbons that are resistant to biodegradation.

**Table 5-1 Comparison of Bench Test Results for Terrestrial Contamination**

Type of Soil	Untreated	Post-Treatment Total Petroleum Hydrocarbons, milligrams per kilogram		
	Total Petroleum Hydrocarbon Contamination Level, milligrams per kilogram	High-Temperature Thermal Desorption <sup>1</sup>	Soil Washing	Ex Situ Biological (Augmented)
Dry Oil Contamination	19,150 to 120,500 (high-temperature thermal desorption); 30,750 (soil washing); 16,267 (biological)	153	1,780	18,800
Wet Oil Contamination	259,000 to 431,500 (high-temperature thermal desorption); 259,000 (soil washing); 31,900 (biological)	Testing suspended for initial 431,500 samples <sup>2</sup>	Not applicable; no sand for recovery	40,867

**Table 5-1 Comparison of Bench Test Results for Terrestrial Contamination**

Type of Soil	Untreated	Post-Treatment Total Petroleum Hydrocarbons, milligrams per kilogram		
	Total Petroleum Hydrocarbon Contamination Level, milligrams per kilogram	High-Temperature Thermal Desorption <sup>1</sup>	Soil Washing	Ex Situ Biological (Augmented)
Oil-Contaminated Soil Piles	35,150 to 106,200 (high-temperature thermal desorption); 77,400 (soil washing)	230	1,360	No test
Oil Trenches	136,500 (high-temperature thermal desorption and soil washing); 24,400 (biological)	215	2,440	13,700

Notes:

1. High-temperature thermal results shown are average values for tests with a temperature of 454 degrees Celsius, and a retention time of 20 minutes, based on the data summarized in Table 4-5.
2. Two samples of wet sludge from the wet oil contamination areas were tested by high-temperature thermal desorption. Testing was suspended for sample T251-13, which consisted primarily of combustible material. Values for sample T251-12, which contained a similarly high level of combustible material, are shown in Table 4-5. Both samples contain much higher levels of total petroleum hydrocarbons than would be the case for the blended feed that a high-temperature thermal desorption system would receive.

**5.1.2 Coastal Contamination**

A comparison of the results of the bench testing performed for coastal soil samples is shown in Table 5-2.

**Table 5-2 Comparison of Bench Test Results for Coastal Contamination**

Type of Soil	Untreated	Post-Treatment Total Petroleum Hydrocarbons, milligrams per kilogram		
	Total Petroleum Hydrocarbon Contamination Level, milligrams per kilogram	High-Temperature Thermal Desorption <sup>1</sup>	Soil Washing	Ex Situ Biological (Augmented)
Coastal Oil Deposits	42,150 to 153,000 (high-temperature thermal desorption); 11,790 (biological)	458	No test	16,900
Oil Trench	12,630 (high-temperature thermal desorption); 69,550 (soil washing)	216	1,810	No test
Coastal Weathered Oil Layers	677 to 51,200 (high-temperature thermal desorption)	280	No test	No test
Coastal Residual Contamination	2,037 (high-temperature thermal desorption)	155	No test	No test

Notes:

1. High-temperature thermal results shown are average values for tests with a temperature of 454 degrees Celsius, and a retention time of 20 minutes, based on the data summarized in Table 4-5.
2. Only one coastal sample was tested using soil washing, and only one coastal sample was tested using *ex situ* biological means.

## 5.2 Implementation

Each of the technologies evaluated in this report has been demonstrated in full-scale application; thus, each is considered to be implementable on a field scale. However, the scope of the remediation program in Kuwait is unprecedented, presenting several implications that must be evaluated when considering the implementability of each technology. The following discussion presents the potential impacts of implementation of these technologies on such a vast scale.

### Project Staffing and Risks to Workers

**Materials Handling:** There are inherent risks to site workers associated with any construction work; in Kuwait, there is added risk associated with the potential presence of unexploded ordnance. This risk may be mitigated using trained professionals to perform ordnance clearance and disposal as the work proceeds. Each of the technologies involves excavation and hauling of contaminated material; thus, none of the technologies pose a greater risk to workers than the others in this respect. A large pool of qualified earthwork contractors exists in Kuwait, and therefore staffing this work should not be problematic, although slightly higher labor and equipment rates may be expected because of the scale of the project contemplated.

**Treatment:** Similarly, there are inherent risks associated with work at any industrial process. This level of risk may be expected at operating thermal or soil washing plants. Of these two, thermal treatment has been more commonly implemented and, therefore, there are well-established industry safety protocols and a large pool of experienced operators available for staffing. Soil washing has been applied at relatively fewer sites, and the pool of experienced staff is relatively limited. In addition, this technology is proprietary. Training and license agreements would be required in order to staff a full-scale application of this technology.

Risks to workers involved with biological treatment would be similar to those experienced by agricultural workers. Workers involved with operating tilling or pile turning equipment might require respiratory protection because of potential dust generation during this work.

### Area of Disturbance

Each of the *ex situ* treatment technologies assessed would involve the construction of treatment centers. At the completion of the project, the area occupied by the treatment center would require restoration. A typical soil washing or thermal treatment plant is expected to encompass about 2 hectares, including room for the treatment plant staff, drying and stockpiling beds, and staff parking. Application of bioremediation would result in a much larger area of disturbance. For instance, a 100-U.S. ton-per-hour (about 91 tonnes/hour) thermal treatment plant, occupying approximately 2 hectares, would treat approximately 385,000 cubic meters per year of contaminated soil. An *ex situ* biological treatment using pile turner technology would have to be on the order of 1.3 square kilometers in size (more than 60 times the size of the thermal treatment plant) in order to have a similar annual production. Use of landfarming technology to treat that volume per year would require on the order of 2 square kilometers (about 100 times the size of the thermal treatment plant).

## Impacts to Infrastructure

Transportation: Each of the technologies is *ex situ* and would require haulage of contaminated material to treatment centers. Thus, each would have similar impacts on traffic.

## Water Usage

**High-Temperature Thermal Treatment.** A 100-ton-per-hour (about 2,180 tonnes per day) thermal treatment plant would require approximately 213 to 275 liters of fresh water per tonne of soil to condition treated soil, for boiler makeup, and for general plant use. The higher figure includes water addition to permit plant operation at full capacity even if total petroleum hydrocarbon levels are well above the blended average anticipated level.

**Soil Washing.** The amount of fresh water required by the Clean Sand Process is estimated by the vendor to be about 0.5 million to 1.2 million liters per day for a soil washing plant of a capacity on the order of 1,500 tonnes per day, for net water consumption about 330 to 800 liters per tonne of soil.

**Ex Situ Biological Treatment.** A biological treatment facility would require an estimated 1,716 liters of water per tonne of soil over the duration of the treatment period.

## Electric Power and Fuel Costs

There is an ample supply of electrical power in Kuwait. The thermal treatment process would require the greatest amount of power; however, depending on the British thermal unit content of the soil being treated, this need may be minimal, as the plant preliminary design includes a turbine generation facility that is capable of supplying the plant's electricity needs. Fuel consumption costs associated with both soil washing and biological treatment are also expected to be minimal, given that these are not particularly energy-intensive treatment methods, and given Kuwait's ability to produce economical fuel.

## Air Emissions

**General.** Testing results from the soil washing bench tests indicate that the majority of the oil contamination exists in the small particles (less than 0.075 millimeter in diameter). This particle size may be susceptible to becoming entrained in the wind during material handling activities such as excavation, and during material transfer activities that would be required by any of the *ex situ* technologies. Due to the weathered nature of the contaminants, volatilization of organic compounds is not expected to be significant. The current material handling field demonstration work will provide observations regarding dust generated during excavation operations. It is anticipated that excavation operations would cease during strong dust storms, for operational reasons and to minimize the generation of airborne dust.

**High-Temperature Thermal Desorption.** A thermal treatment plant would be equipped with appropriate air control equipment. This type of equipment is well established and is in common use with known and proven effectiveness. Thermal treatment systems come equipped with a high-efficiency cyclone, followed by a baghouse/dry scrubber and a high-temperature thermal oxidizer. This type of system, as described in Appendix F to the "Oil Lakes" M&A Report, has been defined by the United States Environmental

Protection Agency as the maximum achievable control technology for rotary dryers and incinerators. This air pollution control system has been used extensively in the United States for hazardous waste incinerators, medical waste incinerators, and soil decontamination units. The high-efficiency cyclone removes large dust particles and cools the exhaust gases. The cyclone has a greater-than-80-percent removal efficiency for particles larger than 10 microns. The baghouse/dry scrubber removes very small dust particles, metal fumes, and inorganic gases when combined with chemical injection. Particulate removal efficiency is greater than 99 percent for particles greater than 1 micron. The thermal oxidizer raises the gas stream temperature to between 1,600° Fahrenheit (871° Celsius) and 2,000° Fahrenheit (1,093° Celsius), resulting in the destruction of organics (hydrocarbons) at a destruction efficiency typically greater than 99 percent. Annex 1 to this Appendix E is a case study for the high-temperature thermal desorption unit Case Study at the C.A. Meyer Soil Remediation Facility, Clermont, Florida. Table 1 in Annex 1 shows the results of testing a thermal oxidizer for a 100 ton per hour high temperature thermal desorption facility. These results show that at 100 tons per hour at a thermal oxidizer temperature of 1,531° Fahrenheit, 99.44 percent of the hydrocarbons were destroyed. This facility has operated for more than ten years under these conditions.

**Soil Washing.** Soil washing using the Clean Sand Process would require handling of dry material in order to physically transfer it into the process stream, where it would be mixed with water to form a slurry. The water slurry should have the effect of minimizing particulate emissions. At least some volatilization of hydrocarbons could be expected from the Clean Sand Process, due to its use of elevated temperatures (on the order of 90 degrees Celsius) in the treatment process. According to the vendor, volatiles are withdrawn and treated in a conventional gas treatment system, to prevent air emissions. The Clean Sand Process does not use chemicals, so emissions from chemical additives are not an issue for this technology.

**Ex Situ Biological Treatment.** Volatilization of organic compounds would not be expected to be significant. Particulate emissions might therefore be expected to be the main contributor to air emissions associated with *ex situ* biological treatment. For example, activities associated with the construction of land treatment facilities would likely cause considerable fugitive dust emissions. Fugitive emissions from vast biological treatment cells pose a potential concern. Aggressive and frequent mixing of soils dried in the hot Kuwaiti environment could result in significant particulate emissions.

## Wastes and Byproducts Produced

**High-Temperature Thermal Desorption.** High-temperature thermal desorption would not produce significant volumes of wastes as such, although debris that is screened from the soil (before treatment) would require proper disposal. The planned high-temperature thermal desorption plants include a provision for treating and using plant process wastewater in the process itself, so that no net wastewater results.

**Soil Washing.** The soil washing process produces significant waste byproducts, including oily fines and oily float that require additional treatment for disposal. Based on bench testing results, these byproducts may equal 13.5 to 33 percent of the total mass treated, increasing costs at least in proportion to their volume (see Section 5.3).

**Ex-Situ Biological Treatment.** Biological treatment would generally not create waste products, although a composting approach, if taken, could add up to 20 percent to the

resulting volume of material, depending on the degree to which the compost breaks down and intermixes with the soil.

### 5.3 Costs

Based on treatment unit cost information as provided in the bench-scale test reports, Table 5-3 shows the relative costs of the technologies tested. As shown on this table, high-temperature thermal desorption is the least costly technology.

**Table 5-3 Summary of Treatment Costs**

Technology	Approximate Cost <sup>1</sup> (per tonne)	Comment <sup>2</sup>
Thermal (high-temperature thermal desorption)	US\$25	Including fixed and operating costs.
Soil washing (Clean Sand Process)	US\$32 to US\$37+	Including fixed and operating costs and licensing fees, the Clean Sand Process would cost approximately US\$28 per tonne. In addition, this technology would produce oily fines and oily float (estimated at 13.5 percent to 33 percent of the total weight of material to be treated). This could add a comparable percentage range to the total cost (or more). Thus, the total cost for the this process may be in the range of US\$32 to US\$37 (or more) per tonne, plus costs for disposal of wastewater.
Ex situ biological treatment	US\$41 (landfarming)	Biological treatment does not effectively treat the contaminated materials. Therefore, the cost per tonne indicated reflects a cycle of treatment, rather than the achievement of an acceptable result.

Note:

1. Costs do not include contingency allowance or engineering and program support management costs.
2. As noted above, each technology utilizes water. The high-temperature thermal desorption process would not generate net wastewater for disposal. This would also be the case for biological treatment. The Clean Sand Process, however, would generate significant quantities of wastewater. Detailed analysis of wastewater treatment costs has not been performed for the Clean Sand Process, as this process is significantly more expensive than treatment by high-temperature thermal desorption, even without taking into account wastewater costs.

### 5.4 Technology Assessment Conclusions

#### 5.4.1 Terrestrial Oil Contamination

High-temperature thermal desorption can successfully treat the range of contaminated materials that form the subject of this report. HTTD provides the greatest reduction of hydrocarbons and has the lowest costs of the candidate technologies that were identified and bench tested as reported above. Of the technologies typically used to treat oil-contaminated materials, the alternative thermal treatment methods are more expensive. Biological treatment would be more expensive and would not be capable of reducing hydrocarbon levels below percent levels at which visible contamination would remain,

thus leaving compromised the ability of the soil to support growth of native vegetation. Soil washing could apparently produce visibly clean sand, but with higher levels of residual contamination than high temperature thermal desorption and at significantly higher cost.

Given the selection of high temperature thermal desorption to treat the contaminated materials, the State of Kuwait established 500 milligrams per kilogram total petroleum hydrocarbons as a reasonable treatment target based on the performance of high-temperature thermal desorption technology and the levels of hydrocarbon contamination that will be left in the ground after visible contamination has been removed. The 500 milligrams per kilogram standard is low enough to remove visible oil contamination, leaving the treated soil with total petroleum hydrocarbon levels that are similar to the contaminated soil that will remain after visible contamination is removed. At the same time, the 500 milligrams per kilogram standard is an easy standard for high temperature thermal desorption treatment to achieve at a reasonable cost.

Although the 500 milligrams per kilogram standard is to some extent a technology-driven standard, it is important to recognize that it is not as demanding a standard as technology-driven treatment standards typically are. For example, the United States Environmental Protection Agency – which typically establishes treatment standards based on the capabilities of treatment technologies – sets such standards at aggressive levels that reflect the lowest levels a given technology can reliably achieve. By contrast, the standard proposed by the State of Kuwait reflects a level of performance that can be achieved economically, without the costs associated with efforts to push this selected treatment technology to levels that approach the limits at which the technology can consistently perform.

#### **5.4.2 Coastal Oil Contamination**

The extent of contamination in the coastal areas and the appropriate remediation technology are still being evaluated. Data collected to date indicate that contamination in coastal areas differs from terrestrial oil contamination in that it occurs as widespread residual contamination surrounding limited pockets of high-level contamination. *In situ* biological technology would not be capable of achieving the degree of contaminant reduction necessary for visible, higher level contamination, but may nevertheless reduce residual contamination and provide ancillary benefits by stimulating microbial activity, thus enhancing overall ecosystem recovery.

## 6 References

Kuwait Institute for Scientific Research, Report Number 5996, Remediation and Rehabilitation of Kuwait's Oil Lake Beds, Volumes 1 to 5, N. Al-Awadhi and R. Al-Daher in cooperation with Petroleum Energy Center, Japan, December 2000, Kuwait.

**Table 4.8 Average Total Petroleum Hydrocarbon Results from Thermal Bench Testing of Terrestrial Samples**  
**Milligrams per kilogram**

	Pre-burn TPH =136,500			Pre-burn TPH =75,350			Pre-burn TPH =24,550		
	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)
10 minutes	1,246	425	226	522	317	254	335	340	267
20 minutes	463	279	220	1,113	378	389	500	208	ND
30 minutes	410	327	227	477	236	455	230	507	206

	Pre-burn TPH =106,200			Pre-burn TPH =27,350			Pre-burn TPH =30,750		
	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)
10 minutes	189	233	221	205	ND	ND	202	195	202
20 minutes	446	174	273	ND	ND	ND	196	426	ND
30 minutes	327	328	385	ND	ND	ND	505	224	ND

	Pre-burn TPH =19,150			Pre-burn TPH =120,500			Pre-burn TPH =80,550		
	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)
10 minutes	560	ND	ND	3,202	ND	1,684	334	188	172
20 minutes	ND	206	ND	2,395	ND	2,354	318	203	198
30 minutes	ND	ND	ND	1,109	203	ND	1,106	3,003	208

	Pre-burn TPH =259,000			Pre-burn TPH =431,500			Pre-burn TPH =62,650		
	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)	750°F (399°C)	850°F (454°C)	950°F (510°C)
10 minutes	37,067	823	482	NA	NA	NA	166	180	ND
20 minutes	6,783	6,800	2,559	NA	NA	NA	206	202	440
30 minutes	5,180	1,157	966	51,800	NA	129,000	2,347	213	187

	Pre-burn TPH =35,150		
	750°F (399°C)	850°F (454°C)	950°F (510°C)
10 minutes	500	281	248
20 minutes	295	326	244
30 minutes	382	463	ND

Note: When non-detected (ND) results occur in two or fewer data points in a given time/temperature combination, the average presented includes the PQL value. ND signifies that the analyte was not detected above the practical quantitation limit for all data points. Generally, the practical quantitation limit was approximately 200 milligrams per kilogram.

**Table 4.9 Average Total Petroleum Hydrocarbon Results from Thermal Bench Testing of Coastal Samples  
Milligrams per kilogram**

<b>T1219</b>	Pre-burn TPH =12,630			<b>T1220</b>	Pre-burn TPH =69,550			<b>T1342</b>	Pre-burn TPH =153,000			
	750°F	850°F	950°F		750°F	850°F	950°F		750°F	850°F	950°F	
	(399°C)	(454°C)	(510°C)		(399°C)	(454°C)	(510°C)		(399°C)	(454°C)	(510°C)	
10 minutes	ND	ND	ND	10 minutes	1,016	530	191	10 minutes	24,667	6,340	537	
20 minutes	ND	ND	373	20 minutes	634	365	703	20 minutes	13,133	782	1,986	
30 minutes	ND	334	490	30 minutes	268	415	286	30 minutes	3,786	683	624	
<b>T1343</b>	Pre-burn TPH =42,150			<b>C41-01</b>	Pre-burn TPH =677			<b>C41-02</b>	Pre-burn TPH =2,038			
	750°F	850°F	950°F		750°F	850°F	950°F		750°F	850°F	950°F	
	(399°C)	(454°C)	(510°C)		(399°C)	(454°C)	(510°C)		(399°C)	(454°C)	(510°C)	
10 minutes	333	241	ND	10 minutes	397	215	303	10 minutes	ND	ND	ND	
20 minutes	198	230	176	20 minutes	ND	285	551	20 minutes	ND	ND	ND	
30 minutes	269	263	651	30 minutes	330	472	341	30 minutes	ND	ND	ND	
<b>C41-03</b>	Pre-burn TPH =51,200											
	750°F	850°F	950°F									
	(399°C)	(454°C)	(510°C)									
10 minutes	735	227	239									
20 minutes	309	280	262									
30 minutes	282	204	211									

Note: When non-detected (ND) results occur in two or fewer data points in a given time/temperature combination, the average presented includes the PQL value. ND signifies that the analyte was not detected above the practical quantitation limit for all data points. Generally, the practical quantitation limit was approximately 200 milligrams per kilogram.

**Table 4-13 Field Demonstration Applications**

Cell Number	1	2	3	4	5	6	7
Configuration	calcium nitrate: peat moss (nitrogen, phosphorus, potassium)	plow only	ammonium nitrate (nitrogen, phosphorus, potassium)	ammonium nitrate peat moss compost (nitrogen, phosphorus, potassium)	ammonium nitrate peat moss humics (nitrogen, phosphorus, potassium)	ammonium nitrate peat moss yeast (nitrogen, phosphorus, potassium)	control
Processing Date	May 18 (1 plow) May 21 (2 plows)	May 17 (1 plow) May 21 (2 plows)	May 21 (2 plows)	May 21 (2 plows)	May 19 (1 plow) May 21 (2 plows)	May 20 (2 plows) May 21 (2 plows)	May 21 (no plow)
Low-Tide Time/Height	19:49 hour / 0.17 meter 22:13 hour / 0.09 meter	22:13 hour / 0.09 meter 22:13 hour / 0.09 meter	22:13 hour / 0.09 meter 22:13 hour / 0.09 meter	22:13 hour / 0.09 meter 22:13 hour / 0.09 meter	22:13 hour / 0.09 meter 22:13 hour / 0.09 meter	22:13 hour / 0.09 meter 22:13 hour / 0.09 meter	22:13 hour / 0.09 meter
Ammonium Nitrate Dosage	0	0	50 kilograms × 9 bags = 450 kilograms	50 kilograms × 9 bags = 450 kilograms	50 kilograms × 9 bags = 450 kilograms	50 kilograms × 9 bags = 450 kilograms	0
Nitrogen, Phosphorus, Potassium Dosage	6 kilograms	0	6 kilograms	6 kilograms	6 kilograms	6 kilograms	0
Peat Moss Dosage	340 liters × 20 bags = 6,800 liters	0	0	340 liters × 20 bags = 6,800 liters	340 liters × 20 bags = 6,800 liters	340 liters × 20 bags = 6,800 liters	0
Humics Dosage		0	0	0	25 kilograms × 18 bags = 450 kilograms	0	0
Yeast Dosage	0	0	0	0	0	25 kilograms × 18 bags = 450 kilograms	0
Compost Dosage	0	0	0	30 liters × 128 = 3,840 liters	0	0	0