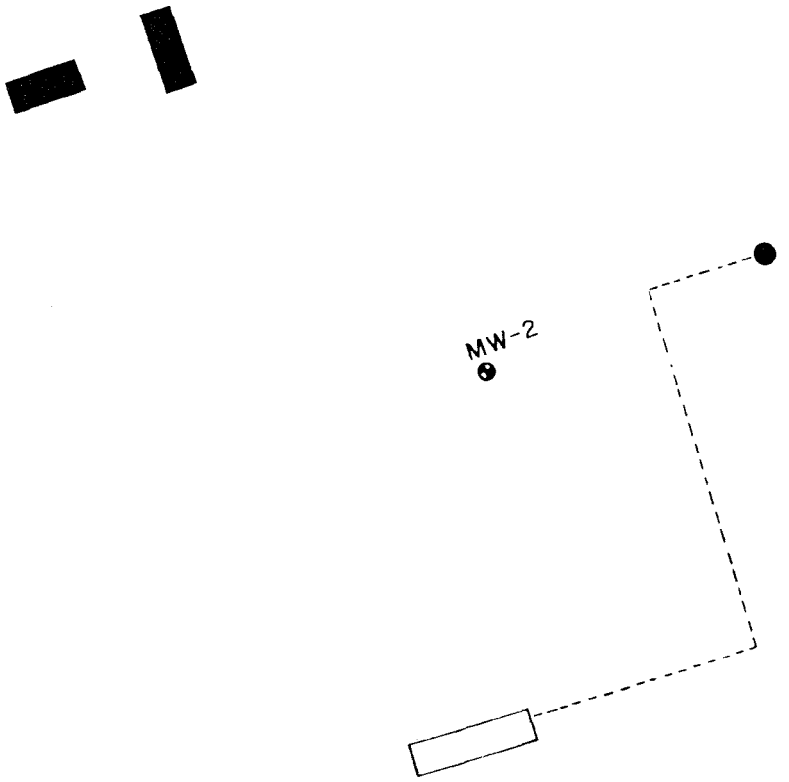

BIOTREATABILITY INVESTIGATION REPORT

for

Chicago & North Western
Transportation Company
Southeast Minneapolis Yards

REPORT #VEMN896-001
February 25, 1992

DAHL
& ASSOCIATES, INC.

UMR-66

ENVIRONMENTAL CONSULTANTS, CONTRACTORS & ENGINEERS

DAHL & ASSOCIATES, INC.
Environmental Consultants, Contractors & Engineers

4390 McMENEMY ROAD
SAINT PAUL, MINNESOTA 55127

BIOTREATABILITY INVESTIGATION REPORT

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February 25, 1992

Copies Submitted To:

Mr. Tom Greenland, Chicago & North Western Transportation Company
Mr. Don York, Chicago & North Western Transportation Company
Ms. Sarah Halvorson, Lindquist & Vennum
Mr. Gerald Stahnke, Minnesota Pollution Control Agency
Mr. Jim Bratina, Reilly Industries, Inc.
Ms. Fay Thompson, University of Minnesota

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APPENDICES

1.0 INTRODUCTION

1.1 Purpose

Dahl & Associates, Inc. (DAHL) was retained by Chicago and North Western Transportation Company (C&NW) to conduct a biotreatability investigation for their property located between 17th and 25th Avenues SE and 4th Street SE and Burlington Northern Railroad property, Minneapolis, Minnesota, known as the C&NW Southeast Minneapolis Yards (Appendix A). The biotreatability investigation was requested after polynuclear aromatic hydrocarbons (PAHs) were detected in the soil beneath the site during an environmental site assessment conducted as part of a proposed sale of the property.

This report presents the results of the biotreatability investigation and outlines anticipated activities for remediation of the soil surrounding the former creosote plant, previously located at the site.

2.0 BACKGROUND

2.1 Previous Investigations

DAHL performed a Phase I and Phase II environmental evaluation on the C&NW Southeast Minneapolis Yards property. The results of the Phase I and Phase II investigations are contained in two reports entitled *Phase I and Phase II Property Evaluation, Southeast Minneapolis Yards,* Report #MN778-002, Dahl & Associates, Inc., June 18, 1990, and *Phase II Property Evaluation, Southeast Minneapolis Yards,* Report #MN778-003, Dahl & Associates, Inc., August 1, 1990.

Results of the Phase I investigation revealed the possible presence of creosote contaminated soils on the site in the vicinity of the former Republic Creosoting Company plant. The plant was known to have been in operation on the site from 1903 through 1916. As part of the Phase II investigation, test borings were drilled at various locations throughout the yard, and specifically in the area of the former creosoting plant. Soil samples, collected from an area where storage tanks and settling basins for creosote sludge were formerly located, were impacted. The contaminants identified in the soil consisted of semi-volatile organic compounds, commonly referred to as polynuclear aromatic hydrocarbons (PAHs). Soil contamination appeared to be three to six feet below ground surface, with a total volume, including overburden, of approximately 1500 to 2000 cubic yards.

2.2 Remedial Alternative Selection

Several options including high temperature incineration, landfilling, encapsulation by vitrification, and bioremediation were initially evaluated for the remediation of the creosote contaminated soil. Due to the shallow depth of the contamination, the availability of space at the site, and the ultimate fate of the contaminants, bioremediation was considered the most efficient and cost effective remedial alternative.

To ascertain the feasibility of bioremediation as a treatment method, proposals for a feasibility study were obtained from bioremediation companies. The criteria used for the selection of the bioremediation company to conduct the study included direct experience with the remediation of creosote contaminated soil. Remediation Technologies, Inc. (ReTeC) was chosen primarily because of their involvement in the successful bioremediation of creosote contaminated soil at the Burlington Northern, Brainerd, Minnesota, site on file with the Minnesota Pollution Control Agency (MPCA).

3.0 BIOTREATABILITY INVESTIGATION

ReTeC conducted the biotreatability investigation using a two-phase approach. The first phase consisted of a slurry reactor study to determine the feasibility of bioremediation as a viable treatment option. In the second phase of the investigation, soil treatment alternatives were examined using bench-scale pan and compost reactors to determine the most effective full-scale treatment option. Detailed results of the biotreatability investigation are contained in the ReTeC report entitled *Laboratory Treatability Testing of Bioremediation Processes for Treatment of Creosote-Contaminated Soils* (Appendix B).

A composite soil sample collected by DAHL and transported to ReTec was used as the representative site soil in the biotreatability investigation. The sample was considered a "worst case" sample since it was collected in an area identified in the Phase I and Phase II investigations as having the highest concentrations of PAH compounds found at the site. It is anticipated that the overall level of PAH compounds involved in the full-scale remediation will be lower than the level used in the biotreatability investigation.

3.1 Biofeasibility Study

A slurry reactor study was conducted to assess the susceptibility of the site soils to

bioremediation, and to determine the capability of the indigenous microorganisms to degrade the PAH compounds in the soil. A slurry reactor was selected as the method of screening since the operating conditions (agitation, nutrient additions, and aeration) were considered a suitable bioremediation environment for the breakdown of contaminants in the soil. Under these conditions, the feasibility of bioremediation as a viable treatment option would become evident within a relatively short period of time.

Results of the slurry reactor study demonstrate that bioremediation is a viable treatment option for the remediation of the creosote contaminated soil at the site. The soil characteristics were defined and determined to be compatible for solid phase bioremediation. Concentrations of PAH compounds, oil and grease, and phenols in the site soil were found to be typical when compared with other similar sites impacted by creosote contaminants. Levels of PAH compounds were reduced approximately 65% within 20 days [from approximately 5700 parts-per-millon (ppm) to 2000 ppm], indicating the presence of an indigenous consortium of microorganisms in the site soil capable of degrading PAH compounds.

3.2 Full-Scale Treatment Evaluation

Two solid phase bioremediation systems, prepared bed land treatment and composting, were evaluated as treatment options for full-scale soil remediation at the site. These alternatives were examined using pan and compost reactors, which simulated the two full-scale treatment systems on a bench-scale level.

In the pan reactor study, the soil was spread in an open air pan and hand mixed periodically. Nutrients were added to the soil, and the soil pH and moisture were adjusted as necessary to maintain proper microbial conditions. The compost reactor study was conducted in a similar manner, with the exception of the addition of wood chips and the application of circulated air to the soil in a closed reactor. The rate and extent of PAH degradation, as determined by laboratory analysis of PAH compounds from soil samples collected during the operation of the reactors, were the primary criteria used in the evaluation of the two solid phase treatment alternatives.

Results of the full-scale treatment evaluation indicate that both prepared bed land treatment and composting, as simulated by the pan and compost reactors, are technically feasible solid phase remediation options for the site. The biodegradation of PAH compounds began to plateau at approximately the same concentration at approximately the same rate in both reactors. At the termination of the operation of the pan reactor, concentrations of PAH compounds were degraded to a level of approximately 2170 ppm, achieving a reduction of 62%. Concentrations of PAH compounds were degraded to

a level of 1770 ppm, a reduction of approximately 69% reduction, over the period of the operation of the compost reactor. At the conclusion of the biotreatability investigation, a continuing downward trend of PAH degradation was observed in both reactors, indicating that with additional treatment time, further reduction of PAH compounds would occur. Since the full-scale treatment system will be designed to operate longer than 120 days (the treatment time of the biotreatability investigation), an increased percent of PAH biodegradation is expected.

The PAH removal efficiencies of both the pan and compost reactors were similar to the degradation reduction achieved in the slurry reactor study (approximately 65%) and demonstrate the effectiveness of either the prepared bed land treatment or composting treatment for the full-scale remediation of the site soil. Based on an expected initial lower PAH concentration in the soil in a full-scale operation, as discussed earlier, and the removal efficiencies achieved in the pan and compost reactor studies, a greater overall reduction of PAH compounds would be expected to be attained in a full-scale bioremediation treatment system.

4.0 ANTICIPATED ACTIVITIES

The full-scale remediation of the creosote contaminated soil at the site is anticipated to be completed in a four phase approach as follows:

Phase 1 - The first phase will consist of the completion of a full-scale engineering design. Information obtained from the operation of both the pan reactor and compost reactor will be utilized to design a solid phase bioremediation system specific for the site. Also taken into account in the design will be various site constraints and weather conditions that would typically be encountered in a northern climate.

Phase 2 - The second phase of the remediation will be the implementation of the full-scale design. This will include construction and start-up of the treatment system.

Phase 3 - The third phase will be the operation, maintenance and monitoring of the system. Periodic progress reports will be submitted as required during this phase.

Phase 4 - The fourth and final phase of the remediation will consist of site closure. Included as part of the site closure activities will be the final disposition of the

treated soil at the site. All equipment will be dismantled and properly disposed. The MPCA will be approached for site closure at the conclusion of this phase.

The recommendations and methodologies contained in this report represent our professional opinions and are based on accepted analytical practices and documented industry standards. Services performed on this project have been conducted in a manner consistent with standards of care practiced by members of this profession in this area, under similar time and budget restraints. Beyond this, no warranty is expressed or implied.

This report was prepared by:

Laure L. Schaefer 2/26/92

Laure L. Schaefer DATE
Project Manager
Dahl & Associates, Inc.

Approved and submitted by:

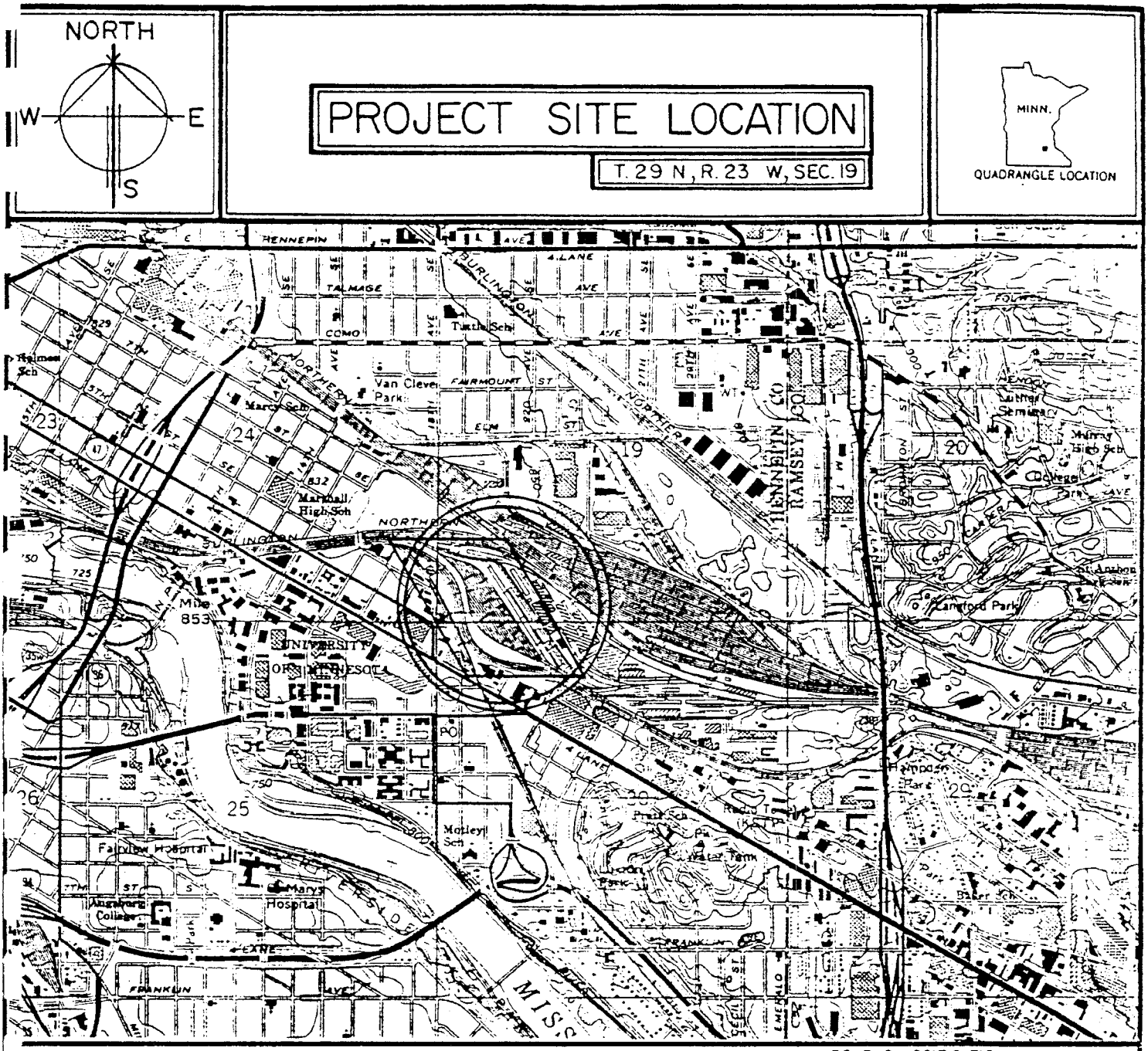
Rodney M. Jasmer 2/26/92

Rodney M. Jasmer DATE
Project Director
Dahl & Associates, Inc.

A

APPENDIX A

Location Map



BASED ON U.S.G.S 7.5 MINUTE SERIES (TOPOGRAPHIC) MAP

4390 McMenemy Road
Saint Paul, MN. 55127
Telephone (612) 490-2905

DAHL & ASSOCIATES, INC.

Environmental Operations
Consultants, Contractors & Engineers.

LOCATION MAP

CHICAGO & NORTHWESTERN RAILROAD
SOUTHEAST MINNEAPOLIS YARDS
MINNEAPOLIS, MINNESOTA

U.S.G.S STANDARD NAME:
ST. PAUL WEST , MINN.

Date Drawn	5-18-90	Drawn By	RON D.	Approved By	
Project Number	MN-778	Drawing Number	A-01-A	Figure Number	UMR-78

B

APPENDIX B

Laboratory Treatability Testing of Bioremediation Processes
for
Treatment of Creosote-Contaminated Soils

LABORATORY TREATABILITY TESTING OF BIOREMEDIATION PROCESSES FOR TREATMENT OF CREOSOTE-CONTAMINATED SOILS

Prepared For:

DAHL & ASSOCIATES, INC.
4390 McMenemy Road
St. Paul, Minnesota 55127

Prepared By:

REMEDIATION TECHNOLOGIES, INC.
23 Old Town Square, Suite 250
Fort Collins, Colorado 80524

ReTeC Project No. E30-609-400

JANUARY 1992

EXECUTIVE SUMMARY

Remediation Technologies, Inc. (ReTeC) was contracted by Dahl & Associates, Inc. to evaluate the technical feasibility of bioremediation of creosote contaminated soil at a former wood treating site. Bioremediation, as the name indicates, is a treatment approach that uses microorganisms, and the assimilative capacity of the soil matrix, to biodegrade and immobilize site chemicals-of-interest to environmentally safe endpoints. The performance of bioremediation requires bench-scale engineering testing to determine treatment levels which can be attained and biodegradation rates.

To evaluate the feasibility of bioremediating the site soils, laboratory treatability testing was carried out at ReTeC's Engineering Evaluation Testing Facility in Pittsburgh, PA. The primary objective of the laboratory work was to simulate two bioremediation processes on a bench-scale basis, prepared bed land treatment, and composting. Before composting and land treatment studies were initiated, slurry reactor treatment was conducted to assess the feasibility of bioremediation as a treatment option. After bioremediation was confirmed to be viable remediation option by a slurry reactor study, soil pan reactors and compost reactors were operated to determine the rate and extent of contaminant reductions achievable in these two solid phase bioremediation systems.

Significant findings and observations of the laboratory testing are summarized below:

1. The site soil was determined to be defined as a "coarse-grained soil with clayey fines." This is based on the fact that the soil was measured to contain 8.6 percent coarse sand, 37.1 percent medium sand, 21.3 percent fine sand, 14 percent silt and 19 percent clay.

2. The site soil "as received" contained approximately 5,680 mg/Kg total PAH consisting of 7 percent 2-ring PAHs, 33 percent 3-ring PAHs, 40 percent 4-ring PAHs, 13 percent 5-ring PAHs and 7 percent 6-ring PAHs. The initial concentration of oil and grease was measured at 7,400 mg/Kg and the initial concentration of phenols (4-AAP) was measured at 1.6 mg/Kg. These values are typical of other sites which have been impacted by creosote wood treating operations.

3. Soil PAH concentrations in the slurry, compost, and pan reactors were reduced from 5700 ppm to a plateau of approximately 2000 mg/kg. At the termination of the studies, continued downward trends of the PAH concentrations were observed in all of the reactors, although at much slower rates. This represents a PAH concentration whereby PAHs can no longer be desorbed from the soil and are unavailable to soil microorganisms for biodegradation. In essence, the treated soil can be viewed as being biostabilized.

4. Based on the above results, both solid phase bioremediation approaches (land treatment and composting) appear technically feasible for full-scale remediation of the site. Selection of a final alternative should be based on the space and schedule constraints placed on the full scale bioremediation system.

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1.0 INTRODUCTION

Dahl & Associates, Inc. contracted Remediation Technologies, Inc. to conduct laboratory studies to evaluate the technical feasibility of bioremediation of creosote-contaminated soil at a former wood treating site near Minneapolis, Minnesota. Bioremediation, as the name indicates, is a treatment approach that uses microorganisms, and the assimilative capacity of the soil matrix, to biodegrade and immobilize site chemicals-of-interest to environmentally safe endpoints. Specific solid phase bioremediation processes evaluated included: i) prepared bed land treatment, and (ii) composting. Further discussions of these two processes are given in Section 2.0.

The primary objective of the laboratory work was to simulate two solid phase bioremediation processes on a bench-scale basis, prepared bed land treatment and composting. This was first accomplished by determining susceptibility of site soils to biodegradation in slurry reactors. Second, soil pan reactors and compost reactors were operated to determine the rate and extent of contaminant reductions achievable in these two solid phase bioremediation systems. Results from these studies will be used for full-scale engineering design and implementation.

This report presents the procedures and results of the work performed, as well as discusses the effect of specific fate mechanisms on treatment levels attainable and their environmental significance. Specifically, Section 2.0 presents background information related to the feasibility evaluation process and to the two full-scale soil bioremediation processes simulated. Section 3.0 provides a study overview with Sections 4.0 and 5.0 detailing the experiment procedures and study results. A discussion of results is provided in Section 6.0. Conclusions and recommendations are provided in Section 7.0.

2.0 DESCRIPTION OF BIOLOGICAL TREATMENT PROCESSES

Full-scale bioremediation is a technically viable and cost-effective approach for the reduction and immobilization of PAHs present in contaminated soil. The potential solid phase biological treatment processes for the soil include: (i) prepared bed land treatment, and (ii) composting. Process descriptions of each treatment approach follow with more details provided elsewhere[1,2,3,4,5]. Prior to the selection of a full-scale treatment process, a feasibility study is conducted to evaluate the susceptibility of site soils to bioremediation as described below.

2.1 BIOREMEDIATION FEASIBILITY EVALUATION

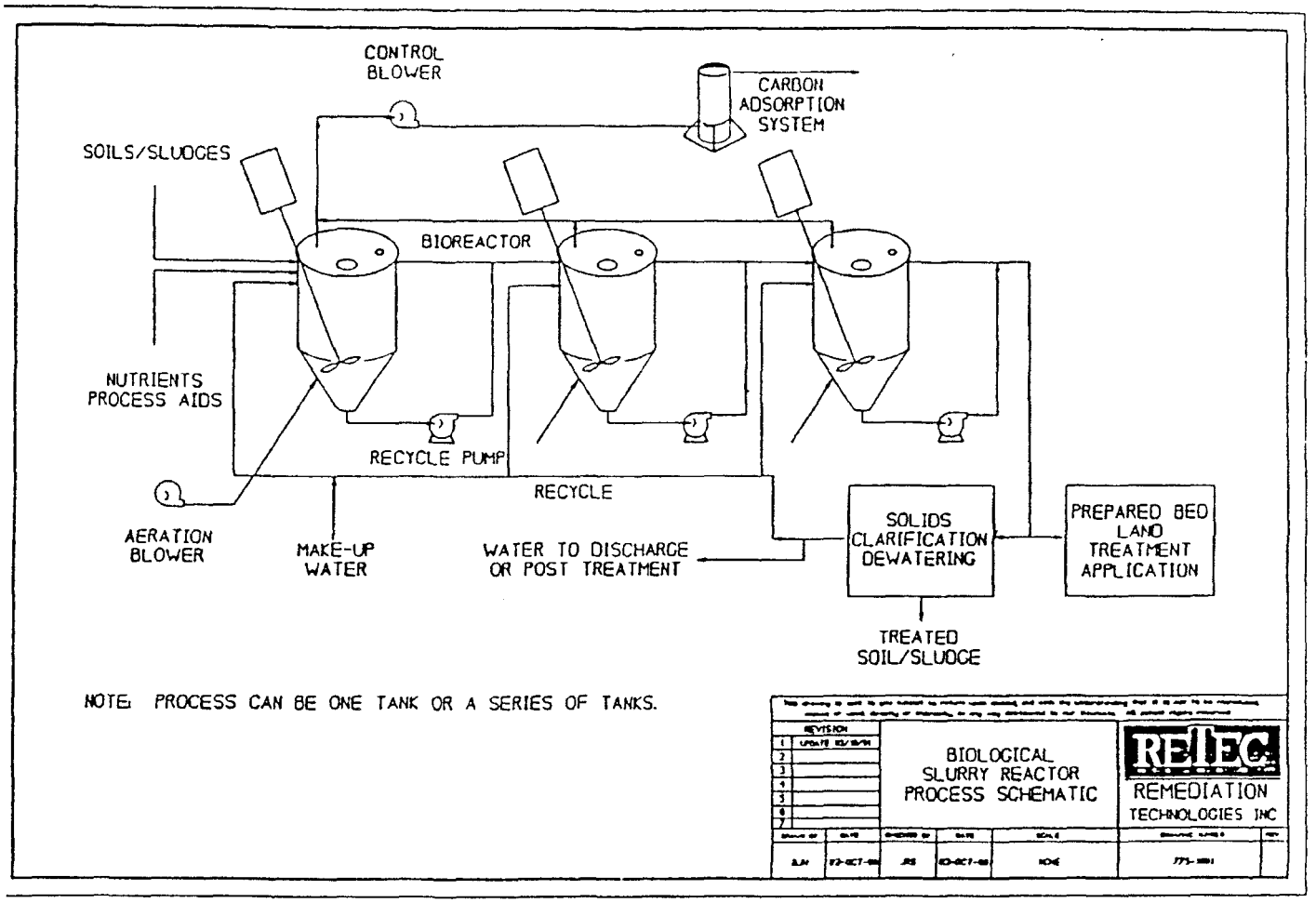
2.1.1 Biological Slurry Reactor Study

The biological slurry reactor is a modified version of the activated sludge process used for the treatment of soils and sludges. Figure 2-1 provides a simplified process flow schematic for this system.

The treatment process can be used to evaluate the feasibility of bioremediation as treatment option for contaminated soils. An aqueous slurry, created by combining contaminated soil or sludge with water, is fed to a biological slurry reactor and aerated. The principal objective of aeration is to supply sufficient oxygen throughout the slurry to promote aerobic microbial activity to degrade organics within the soil matrix. Like other biological systems, slurry reactors are operated to maximize mass transfer rates and contact between contaminants and microorganisms. Due to this factor, a biological slurry reactor is a good screening technique for evaluating the potential of bioremediation with site-specific soils. The three generic elements common to most biological slurry reactor studies are: 1) pretreatment (if necessary); 2) creation of an aqueous slurry with mechanical agitation; and 3) aeration, and addition of nutrients and indigenous microorganisms (if necessary). Biodegradation is achieved in a biological slurry reactor when the hydrocarbons are degraded (mineralized) to carbon dioxide and water.

FIGURE 2-1

BIOLOGICAL SLURRY REACTOR PROCESS SCHEMATIC



2.2 FULL-SCALE SOLID PHASE TREATMENT PROCESSES

2.2.1 Prepared Bed Land Treatment

Land treatment is an engineered unit process that involves the controlled application of a residual material (i.e.,contaminated soil or sludge) onto a prepared soil surface and the incorporation of the residual into the upper soil zone. The technology can also be used directly as an *in situ* method for decontamination of soils in-place or as an on-site method in which the contaminated soils and residual are mixed in an above-ground process and then applied on a designated area. This process is one of the older and most widely used treatment technologies for hazardous waste treatment. In particular, the technology has been used successfully throughout the United States, especially at petroleum refinery sites treated under RCRA, and also with creosote contaminated soils and sludges.

The applied material can be liquid, semi-solid, or solid. In either case, the design and operation of a land treatment facility is based on sound scientific and engineering principles as well as on extensive practical field experience. A land treatment site is designed and operated to: (i) maximize residue degradation and immobilization, (ii) minimize release of dust and volatile compounds, as well as percolation of water soluble compounds, and (iii) control surface water run-on and run-off. A set of important site factors which influence the design of full-scale land treatment facilities is provided in Table 2-1.

Figure 2-2 schematically illustrates that land treatment is generally an aerobic soil mixture, approximately 0.5 to 1.0 feet deep, that is managed to promote the growth of indigenous microorganisms to biodegrade contaminants and to promote immobilization of contaminants. Figure 2-2 also indicates the numerous factors which must be accounted for in the design and operation of a land treatment process. The contaminated soil can be handled in a variety of manners to minimize odors and provide good distribution by plowing, disc harrowing, or other similar methods. Mixing also provides aeration of the soils to enhance biological activity. In some cases, nutrients or fertilizer may be required to maintain the proper microbial environment and lime may be needed periodically for pH control.

The foundation of a land treatment unit can be either an impermeable liner (plastic or clay) or a prepared packed ground surface. Both are designed to insure minimal downward migration of contaminants. For the case of a prepared ground surface, the soil

TABLE 2-1

PREPARED BED LAND TREATMENT DESIGN AND OPERATING CONDITIONS

PERTINENT WASTE FACTORS

- Physical Composition
- Organics
- Metals
- Salts
- Nutrients
- pH

PERTINENT SITE FACTORS

Soil Characteristics
- Topography
- Soil Texture
- Soil Moisture
- Cation Exchange Capacity
- Soil pH
- Soil Microorganisms
- Nutrients

Climate
- Temperature
- Precipitation
- Evaporation

Hydrogeology
- Depth to Seasonally High Water Table
- Depth to Useable Aquifer
- Proximity to Surface Water

OPERATION FACTORS

Waste Application
- Oil Loading
- Hydraulic Loading
- Frequency of Application
- Method of Application

Storm Water Management
- Runon/Runoff Control

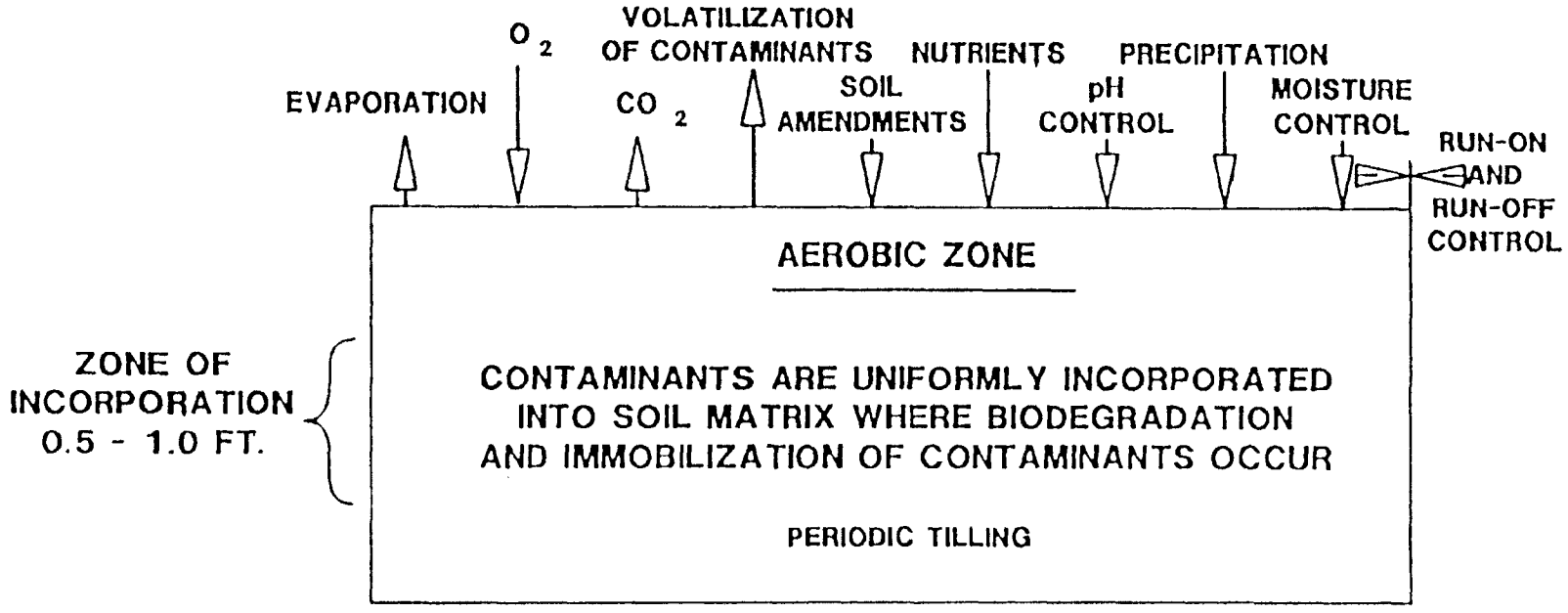
Monitoring
- Moisture
- pH
- Microbial
- Leaching
- Chemicals-of-Interest

Waste Incorporation
- Depth of Incorporation
- Frequency of Cultivation

Soil Amendments
- Nutrients
- Moisture
- pH Control
- Material for Disaggregation

FIGURE 2-2

ENGINEERED LAND TREATMENT UNIT
PROCESS SCHEMATIC



bed is designed to reduce or eliminate downward percolation of excess water to the underlying groundwater by enhancing run-off which is collected and recycled as irrigation water. The unit is designed to prevent precipitation run-on so that water moving through and around it can be controlled. The size of a unit can range from a quarter of an acre to ten acres or more. The system is engineered in a manner appropriate for the specific site situation taking into account available land area, the amount of material to be treated, the desired treatment level, and the time frame of treatment.

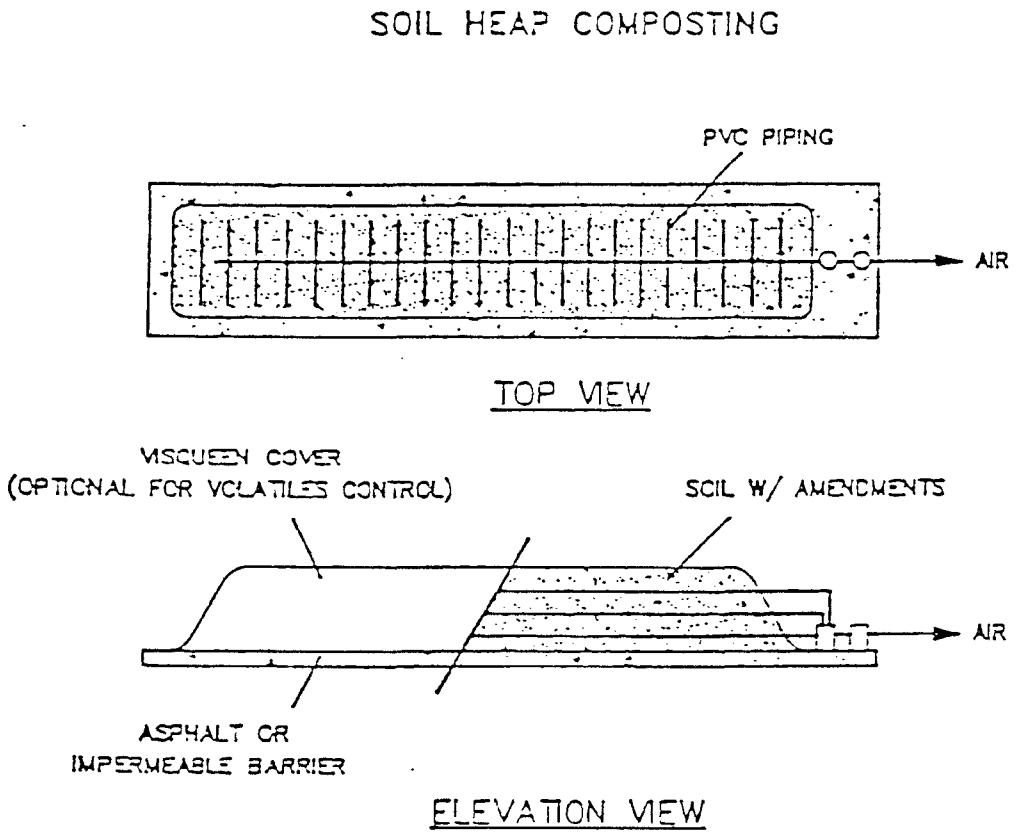
2.2.2 Composting

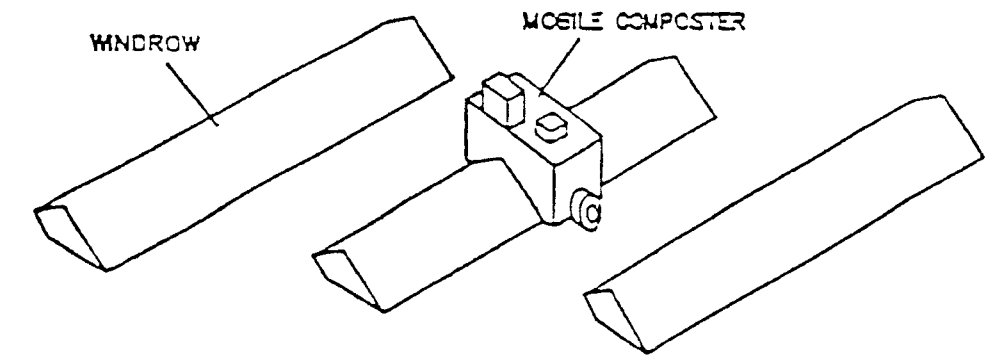
Composting is a solid phase biological process used to treat organically contaminated soils and sludges. This type of treatment consists of piling the contaminated material, sometimes mixing with a bulking agent, at heights of three to six feet. Aeration is provided by either forcing air through a contained system, such as in "Soil Heap Composting," or by mechanically turning over the soil which also serves to mix the material, such as in "Windrow Composting." Both of these systems are illustrated in Figure 2-3.

These systems are amenable to moisture, pH, and nutrient control by simple irrigation techniques, and to volatile emission control when the system is covered. The foundation of the compost area can be either an impermeable liner or a prepared packed ground surface. When temperature is critical to increasing removal rates, the compost pile can be amended with other sources of organic matter to increase biological activity and the temperature of the system, or it can be covered or enclosed for better process and temperature control. The addition of bulking agents serves to increase the total volume of the material to be treated, and facilitates mixing requirements and oxygen transfer.

FIGURE 2-3

TYPICAL COMPOSTING PROCESSES SCHEMATIC





3.0 STUDY OVERVIEW

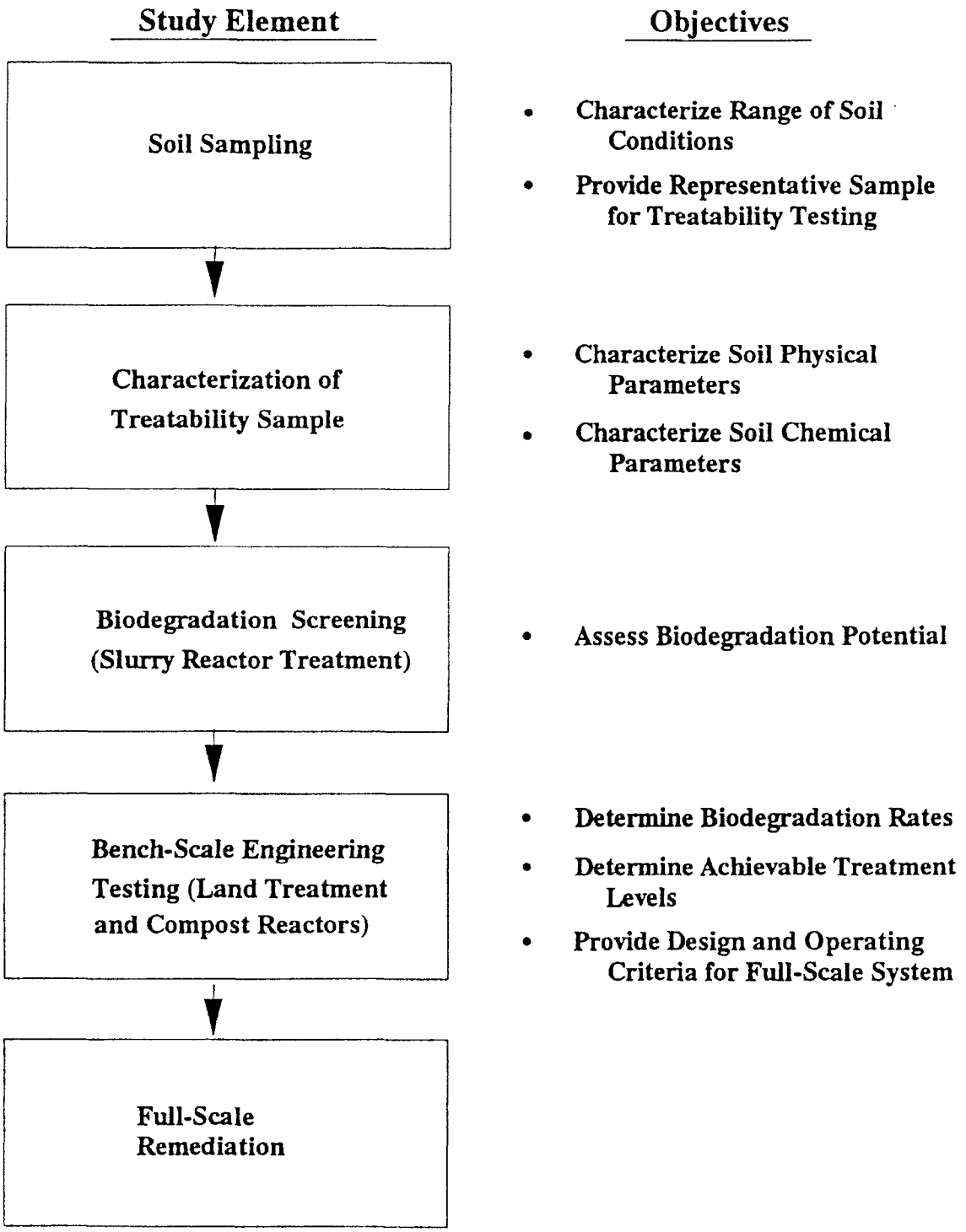
As discussed in Section 2.0, the reduction of PAHs from contaminated soils can be achieved by various biological treatment processes. The two most common solid phase biological processes refer to the technologies of prepared bed land treatment and composting. With these treatment processes in mind, laboratory biodegradation studies were designed and performed by ReTeC's engineering personnel at ReTeC's Engineering Evaluation Testing Facility located in Pittsburgh, Pennsylvania. Figure 3-1 summarizes the approach developed for the biodegration study.

First, a site assessment was conducted by Dahl & Associates, Inc., to characterize the range of contaminant levels present at the site. Results of the site assessment are described in the Phase II Property Evaluation Report [6], dated August 1, 1990. Based on the results of the site assessment, Dahl and Associates collected a "worst case" soil sample for treatability testing. This worst case sample was then sent to ReTeC's Pittsburgh Facility for characterization and engineering testing.

Initial soil characterization involved both physical and chemical analyses. The physical analysis focused on determining grain-size distribution of the soil and the chemical analyses measured the PAH concentration of the "as received" soil. The results were used to characterize baseline conditions for the biodegradation evaluation. After soil characterization activities were completed, the site soil was placed in a slurry reactor to screen the soil as to its biodegradability. After the slurry reactor testing was completed, soil pan reactors and composting reactor studies were conducted to determine biodegradation rates and achievable treatment levels in solid phase bioremediation systems. This information along with site information is used to define design and operating criteria for full-scale remediation.

All treatability studies were performed in accordance with ReTeC's Standard Operating Procedures. Wadsworth/Alert Laboratories, Inc., also located in Pittsburgh, carried out all analytical testings following procedures given in Table 3-1. Microbial enumerations were performed at ReTeC's laboratory in Seattle, Washington. Routine monitoring and operating parameters were analyzed by ReTeC personnel in Pittsburgh.

FIGURE 3-1
BIODEGRADATION STUDY PROGRAM



4.0 INITIAL SOIL CHARACTERIZATION

Contaminated site soil was received in a five-gallon bucket at ReTeC's Engineering Evaluation Testing Facility in Pittsburgh. The soil sample was stored in a cooler room at 4°C. This type of storage was done to keep biological activity in the soil sample at a minimum when not being used. The soil sample was taken out of cold storage when required for testing and put back in the cooler room when not required.

As previously cited, the purpose of the initial soil characterization was to conduct appropriate analyses on the soils "as received" and use the results to define the start-up condition of the slurry, pan, and composting reactors. The initial characterization work consisted of:

- physical characterization, and
- chemical characterization.

Procedures and results of these two phases of work follow.

4.1 PHYSICAL CHARACTERIZATION

4.1.1 Parameters of General Interest

Procedures

The soil sample arrived at ReTeC's facility on February 18, 1991. Visual observation showed the soil to be dark black in color and it had a typical creosote odor. The soil was moist but with no free water present. The workability of the soil was good in the sense that any large clumps broke up easily.

Results

The results of the physical parameters of general interest are presented in Table 4-1. As given, the soil contained approximately 14 percent moisture and approximately 86 percent dry solids (i.e.,at 103°C) of which 10.3 percent was volatile (i.e.,burned off at 550°C and indicating organic matter).

TABLE 4-1

PHYSICAL PARAMETERS OF GENERAL INTEREST

PARAMETER	MEASURED/OBSERVED VALUES
Percent Moisture[1]	14.09
Percent Solids[1]	85.91
Percent Volatiles[1]	10.32
Percent Fixed Solids[1]	89.68
Color[2]	Dark Black
Odor[3]	Creosote

[1]Measured Values

[2]Visual Observation

[3]Physical Observation

4.1.2 Grain Size Analysis

Procedures

Grain size analysis is a measurement of the size distribution of individual particles in a soil sample. It provides the information needed to classify a soil based on its particle size distribution.

The distribution of particle sizes larger than 75μm (i.e., retained on a No. 200 sieve) was determined by dry sieving while the distribution of particle sizes smaller than 75μm was determined by a sedimentation process using a hydrometer.

For the grain-size distribution by dry sieve analysis, the soil as received was first thoroughly mixed to make it as homogeneous as possible. From the well mixed soil, two samples, each weighing about 500 grams, were taken and air dried on aluminum foil, under a fume hood, for approximately 24 hours. The following special materials and equipment were used:

- a set of seven U.S. standard sieves, Nos. 10, 20, 40, 60, 80, 100, and 200;
- a mechanical horizontal sieve shaker; and
- a tare balance.

The air dried soil was weighed lightly crushed with a rolling pin to break up large clumps, and placed on the top of a previously weighed nest of sieves. All the sieves were then put on a mechanical horizontal shaker which was run for 30 minutes. At the end of this run, all the sieves were reweighed and their weights recorded. The weight of soil on each sieve was calculated from the difference between the initial and final readings of each sieve. This test was repeated one more time on the other air dried sample for QA/QC purposes.

When a soil sample contains more than 10-15 percent fines, as determined by dry sieve analysis, the ASTM wet method[7] can be used to determine the soil fractions in the fines. The results of the dry sieve analysis showed that the site soil had about 5 percent fines. However, visual observation of the soil suggested that the ASTM wet method[7] would be more appropriate for the soil. This method is briefly described below.

For the hydrometer analysis, a sample weighing approximately 100 grams was taken from the well mixed "as received" soil and it was air dried. This air dried sample was then sieved through a No. 10 sieve. The portion passed through the No. 10 sieve was first soaked in a dispersing agent and then a sodium metaphosphate solution for 16 hours. The soaked soil was then dispersed in distilled water. Using a 152H hydrometer, readings were taken at frequent intervals until two consecutive readings did not give appreciable change in particle diameters of the suspended soil; this was done for QA/QC purposes.

Results

The results of the dry sieve and the hydrometer analyses are presented in Tables 4-2 and 4-3, respectively. The results are also depicted graphically in Figure 4-1.

From Figure 4-1, it can be seen that the results of the dry sieve analysis pertaining to the soil fines do not correspond with the results of the hydrometer analysis. Conflicting results, such as shown in Figure 4-1, are obtained when a soil sample contains more than 15 percent fines. It must be remembered that dry sieve analysis gives faulty results when a soil contains a sizable fraction of clay or silts which are not adequately broken up by light crushing. In such cases, the fines may adhere to the larger sand particles when wet and may not come off during the dry sieve analysis. As a result of this type of physical adherence, the dry sieve analysis gives lower values for sizes less than 75μm and higher values for sizes larger than 75μm (i.e., No. 200 sieve).

The chemical used, sodium metaphosphate, in the ASTM method[28], enhances dispersion of fines in the solution. Therefore, this analysis gives more reliable results for soil sizes less than 75 μm. As such, Figure 4-2 is drawn to show a realistic particle distribution of the soil. In this graph, for particles less than 0.085 mm, the values are chosen from the hydrometer analysis and for particles larger than 0.42 mm, the values are taken from the dry sieve analysis. The gap, 0.085 to 0.42 mm is then joined smoothly.

From Figure 4-2, it can be seen that more than 50 percent of the soil is retained on the No. 200 sieve. Moreover, it has more than 12 percent fines. Therefore, according to ASTM, the soil is classified as coarse-grained sands with fines. It can be either silty sand or clayey sand. Because no test was done to determine the liquid limit and plasticity index of the soil, it is not possible to make any definite conclusion as to whether the soil belongs to the silt or clay category. However, the soil passing a No. 200 sieve exhibited plasticity when wet and Figure 4-2 shows the soil contained 33% fines consisting of 14% silt (-0.74 to +0.005

TABLE 4-2

DRY SIEVE ANALYSIS RESULTS

U.S STANDARD SIEVE NO.	MESH OPENING mm	PERCENT FINER		
		RUN 1	RUN 2	AVERAGE
4	4.76	100.00	100.00	100.00
10	2.00	91.81	90.97	91.39
20	0.84	73.66	73.14	73.40
40	0.42	53.82	54.68	54.25
60	0.25	25.12	23.35	24.24
80	0.18	13.86	11.98	12.92
100	0.149	9.16	8.56	8.86
200	0.075	5.00	4.74	4.87
PAN	---	---	---	---

NOTE: Raw data given in Appendix A-1.

TABLE 4-3

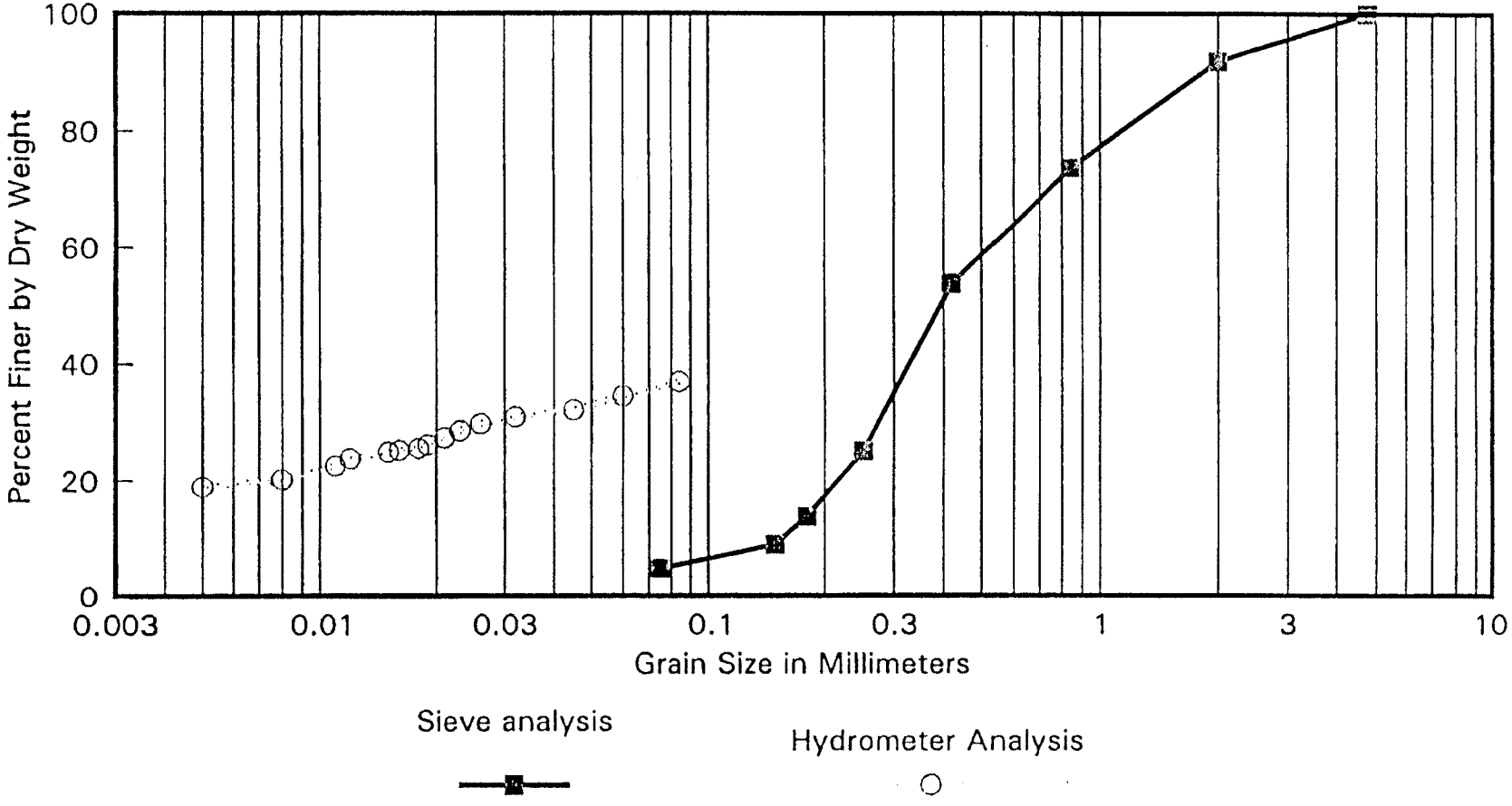
HYDROMETER ANALYSIS RESULTS

PARTICLE DIAMETER (mm)	PERCENT FINER
0.084	37.0
0.060	34.6
0.045	32.2
0.032	31.0
0.026	29.8
0.023	28.6
0.021	27.4
0.019	26.20
0.018	25.60
0.016	25.30
0.015	25.00
0.012	23.80
0.011	22.60
0.008	20.2
0.005	19.0

NOTE: Raw data given in Appendix A-2.

FIGURE 4-1

MEASURED GRAIN SIZE DISTRIBUTION



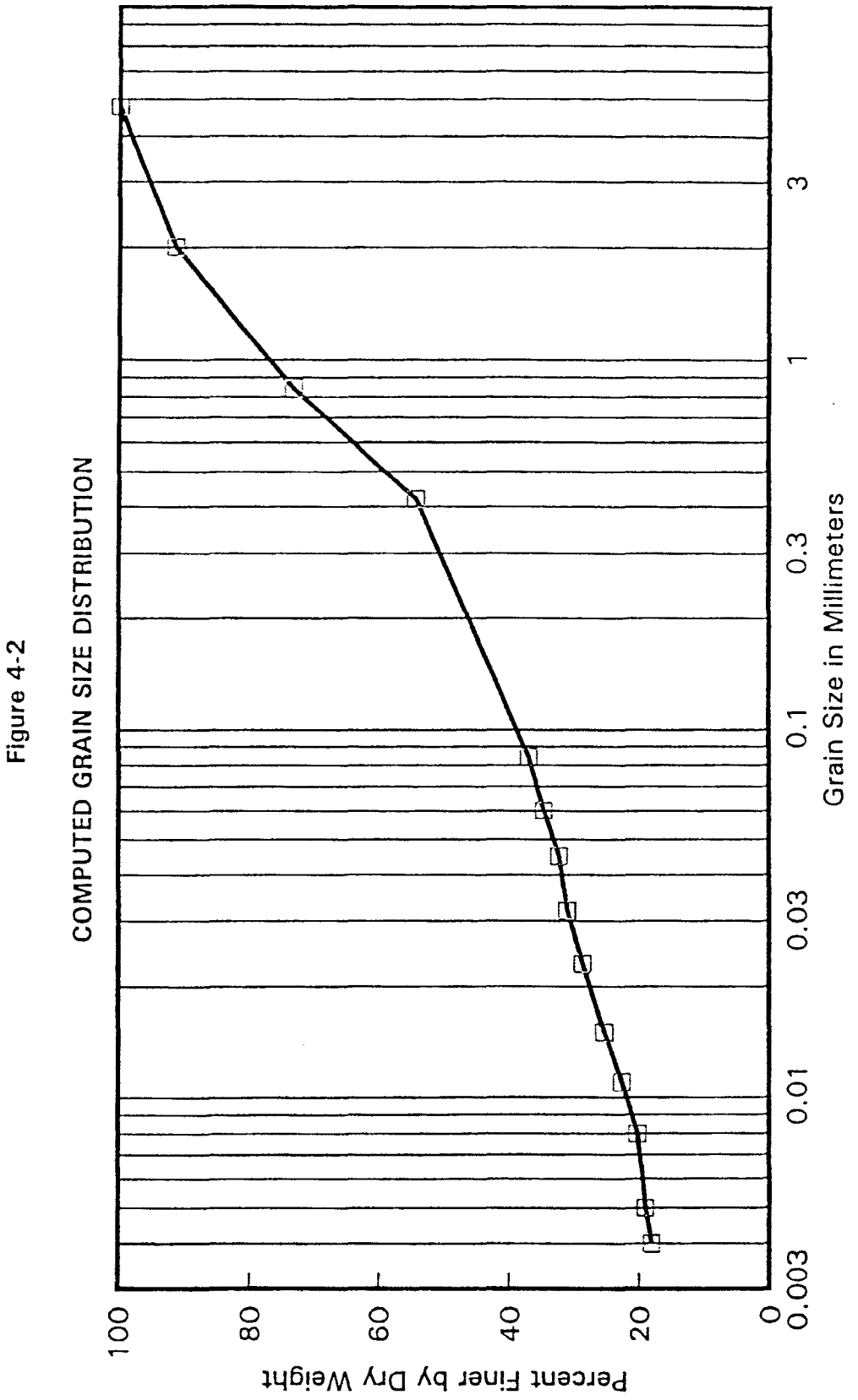

COMPUTED GRAIN SIZE DISTRIBUTION
Percent Finer by Dry Weight
100
80
60
40
20
0
0.003
0.01
0.03
0.1
0.3
1
3
Grain Size in Millimeters

Figure 4-2

mm) and 19% clay (-0.005 mm). Therefore, it can be inferred that the soil sample tested is defined as a "coarse-grained sand with clayey fines."

The computed values from Figure 4-2 cited previously are presented in Table 4-4. It can be inferred from this data that the soil has the following size fractions as graphically illustrated in Figure 4-3:

- coarse sand (-4.76 to 2.0 mm) 8.61%,
- medium sand (-2.00 to 0.42 mm) 37.14%,
- fine sand (-0.42 to 0.075 mm) 21.25%, and
- fines (-0.074 mm)
  - silt (-0.074 to +0.005 mm) 14.00%
  - clay (-0.005 mm) 19.00%.

Raw laboratory data for these results are given in Appendix A.

4.2 CHEMICAL CHARACTERIZATION

4.2.1 Site Chemicals-of-Interest

Procedures

For this study, PAHs were the major site chemicals-of-interest. PAHs are neutral, non-polar organic compounds consisting of two or more fused benzene rings in linear, angular, or cluster arrangements. Previously cited Table 3-1 gives the analytical methods used for PAH analyses and their detectable limits. This table also provides methods and detection limits for oil and grease and total phenols analyses. These compounds are of interest initially since high levels may present adverse affects on the bioremediation process.

Results

Table 4-5 provides a summary of the concentration of individual PAH compounds measured in the soil. To provide enough data for statistical analysis, four duplicate samples of the soil were analyzed for PAHs. Only one sample was analyzed for oil and grease and total phenols. The average values of the four PAH analyses, as well as their 95% confidence

TABLE 4-4

COMBINED DRY SIEVE ANALYSIS AND
HYDROMETER ANALYSIS RESULTS

PARTICLE DIAMETER (mm)	PERCENT FINER[a]
4.76	100
2.00	91.4
0.84	73.3
0.42	54.3
0.084	37.0
0.060	34.6
0.045	32.2
0.032	31.0
0.023	28.6
0.015	25.3
0.011	22.6
0.008	20.2
0.005	19.0

NOTE: [a]Based on values in Tables 4-2 and 4-3.

FIGURE 4-3

ASTM PARTICLE SIZE CLASSIFICATION

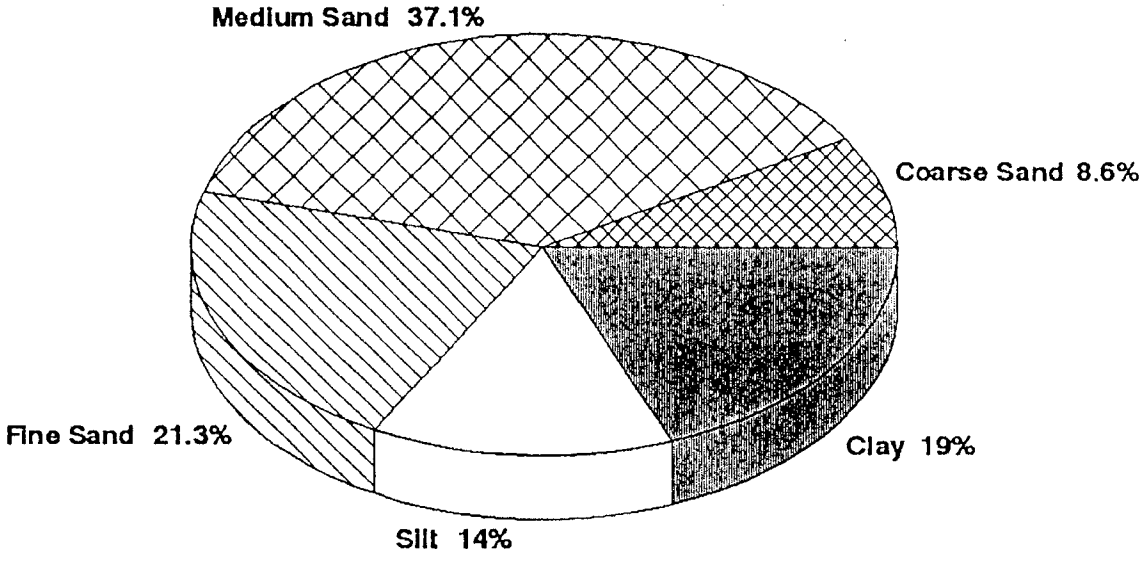


TABLE 4-5

INITIAL SOIL CHARACTERIZATION FOR CHEMICALS-OF-INTEREST

PARAMETER	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	AVERAGES	COMPOSITION OF TOTAL PAHs
Naphthalene	410.0	420.0	370.0	410.0	402.5 ± 35.3	
TOTAL 2-RINGS	**410.0**	**420.0**	**370.0**	**410.0**	**402.5 ± 35.3**	**7.1%**
Acenaphthylene	12.0	12.0	12.0	13.0	12.3 ± 0.8	
Acenaphthene	590.0	590.0	520.0	530.0	557.5 ± 60.1	
Fluorene	330.0	310.0	220.0	240.0	275.0 ± 84.7	
Phenanthrene	710.0	640.0	550.0	600.0	625.0 ± 107.5	
Anthracene	390.0	400.0	350.0	370.0	377.5 ± 35.3	
TOTAL 3-RINGS	**2,032.0**	**1,952.0**	**1,652.0**	**1,753.0**	**1,847.3 ± 278.8**	**32.5%**
Fluoranthene	740.0	750.0	680.0	710.0	720.0 ± 50.3	
Pyrene	800.0	730.0	710.0	820.0	765.0 ± 84.7	
Benzo(a)anthracene	300.0	330.0	330.0	320.0	320.0 ± 22.5	
Chrysene	510.0	510.0	480.0	480.0	495.0 ± 27.6	
TOTAL 4-RINGS	**2,350.0**	**2,320.0**	**2,200.0**	**2,330.0**	**2,300.0 ± 107.9**	**40.4%**
Benzo(b)fluoranthene	230.0	230.0	220.0	210.0	222.5 ± 15.2	
Benzo(k)fluoranthene	110.0	120.0	110.0	100.0	110.0 ± 13.0	
Benzo(a)pyrene	280.0	270.0	260.0	270.0	270.0 ± 13.0	
Dibenzo(a,h)anthracene	130.0	130.0	120.0	110.0	122.5 ± 15.2	

TABLE 4-5
(Continued)

INITIAL SOIL CHARACTERIZATION FOR CHEMICALS-OF-INTEREST

PARAMETER	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	AVERAGES	COMPOSITION OF TOTAL PAHs
TOTAL 5-RINGS	**750.0**	**750.0**	**710.0**	**690.0**	**725.0 ± 47.7**	**12.8%**
Benzo(g,h,i)perylene	210.0	200.0	200.0	200.0	202.5 ± 7.6	
Indeno(1,2,3-cd)pyrene	210.0	220.0	200.0	190.0	205.0 ± 7.6	
TOTAL 6-RINGS	**420.0**	**420.0**	**400.0**	**390.0**	**407.5 ± 23.9**	**7.2%**
TOTAL PAHs	**5,962.0**	**5,862.0**	**5,332.0**	**5,573.0**	**5,682.2 ± 191.2**	**100.0%**
Oil & Grease (mg/kg)	7,400					
Total Phenols (4-AAP)	1.6					

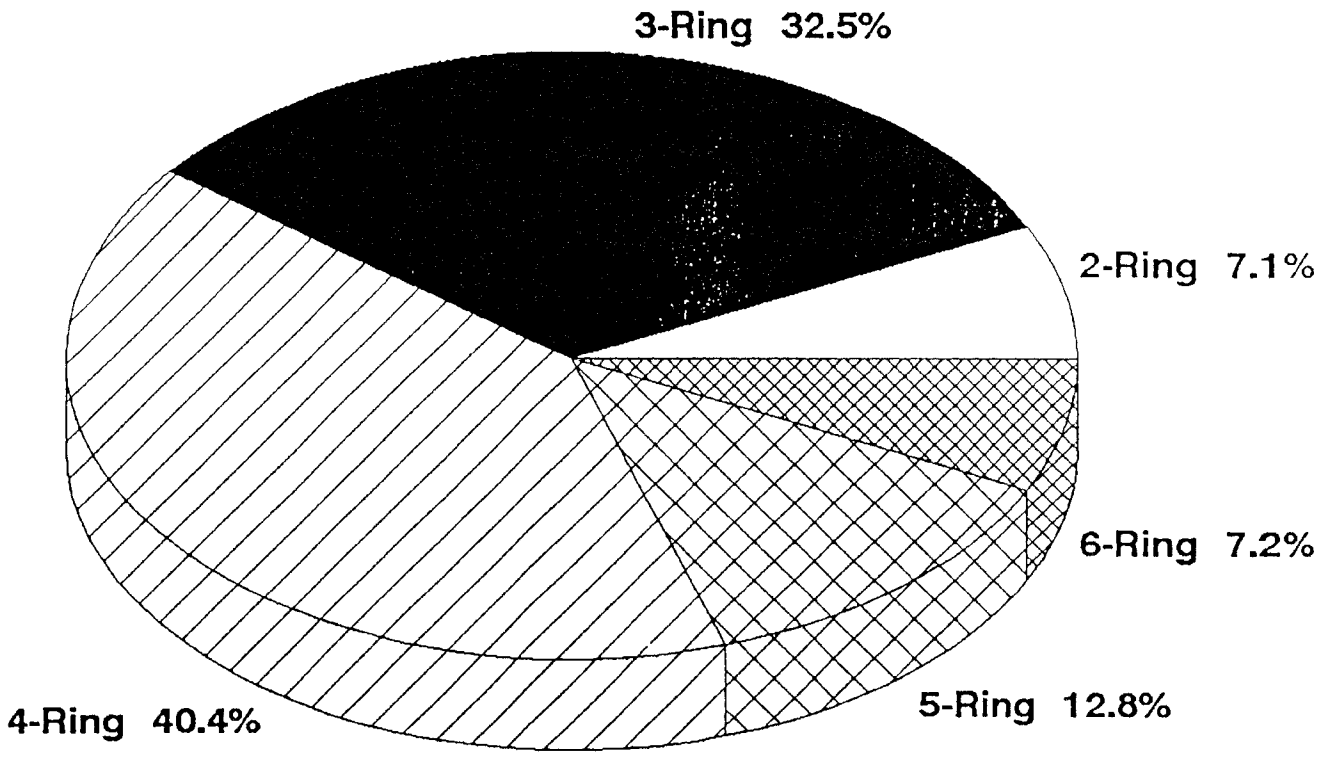
NOTE: Raw analytical data given in Appendix B-1.
All concentration values in mg/Kg dry weight.
PAH averages are based on 4 analysis with 95% confidence intervals.

intervals, are also summarized in Table 4-5. Laboratory analytical reports are provided in Appendix B1.

The results of chemical analysis show the total PAH concentration of the soil averages approximately 5,680 mg per kg of dry soil. The analysis also indicates that this total PAH value consists of 7.1, 32.5, 40.4, 12.8 and 7.2 percent of 2-, 3-, 4-, 5- and 6-ring PAHs, respectively. This is represented in Figure 4-4 and is consistent with creosote-contaminated soil. The concentration of oil and grease was measured at 7,400 mg/Kg, and the soil also had a measured total phenols value of 1.6 mg/Kg. These levels indicate there should be no detrimental affect on the bioremediation process.

FIGURE 4-4

INITIAL SOIL PAH RING DISTRIBUTION



5.0 BIOREMEDIATION EVALUATIONS

5.1 BIODEGRADATION SCREENING STUDY - PHASE I SLURRY REACTOR TREATMENT

As discussed previously, a biological slurry reactor is a good screening technique for evaluating biotreatment of many types of contaminated soils because treatment endpoints can be evaluated in a slurry reactor in a relatively short time frame. The slurry reactor provides a suitable environment for breakdown of contaminants in soil because the contents are agitated, enhancing transfer of chemicals from soil to aqueous phase, and the reactor is highly aerated. The reactor is also provided with sufficient nutrients. If bioremediation is possible for a particular soil, it should become evident during slurry reactor testing.

5.1.1 Procedure

Figure 5-1 illustrates the laboratory-scale slurry reactor used for this study. The primary reactor consisted of a three-gallon stainless steel vessel with side ports from which samples of the slurry could be obtained. Mixing of the slurry was achieved with a variable speed mixer. Oxygen was provided with the introduction of air through a submerged diffuser. For the addition of acid or base, to maintain the pH between 7.0 to 7.5, an additional port was provided on the top of the reactor.

The slurry reactor was initially loaded with the contents detailed in Table 5-1. As cited, no supplemental bacteria were added and the slurry contained approximately a 20 percent soil concentration by weight. Table 5-2 details the operational monitoring schedule followed to maintain the reactor within the proper conditions needed for biological activity (i.e., sufficient nutrients, dissolved oxygen greater than 3.0 mg/L, a pH between 7.0 to 7.5, and sufficient mixing). From such monitoring, adjustments were made as needed.

Table 5-3 summarizes the analytical sampling schedule performed for the biological slurry reactor. As given, the two water phase samples (i.e., 15 minute and final) were obtained by first centrifuging the slurry at 12,500 rpm for 30 minutes and then filtering the centrate through a 1.5 μm filter. This was done to insure, as much as possible, that the PAHs detected were indeed soluble and not associated with any suspended material. Soil samples were also analyzed after centrifugation, with the centrate used for nutrient analysis. Microbial enumeration analysis was also conducted on centrifuged soil samples. Lastly, the

FIGURE 5-1

SCHEMATIC DIAGRAM OF AEROBIC SLURRY REACTOR

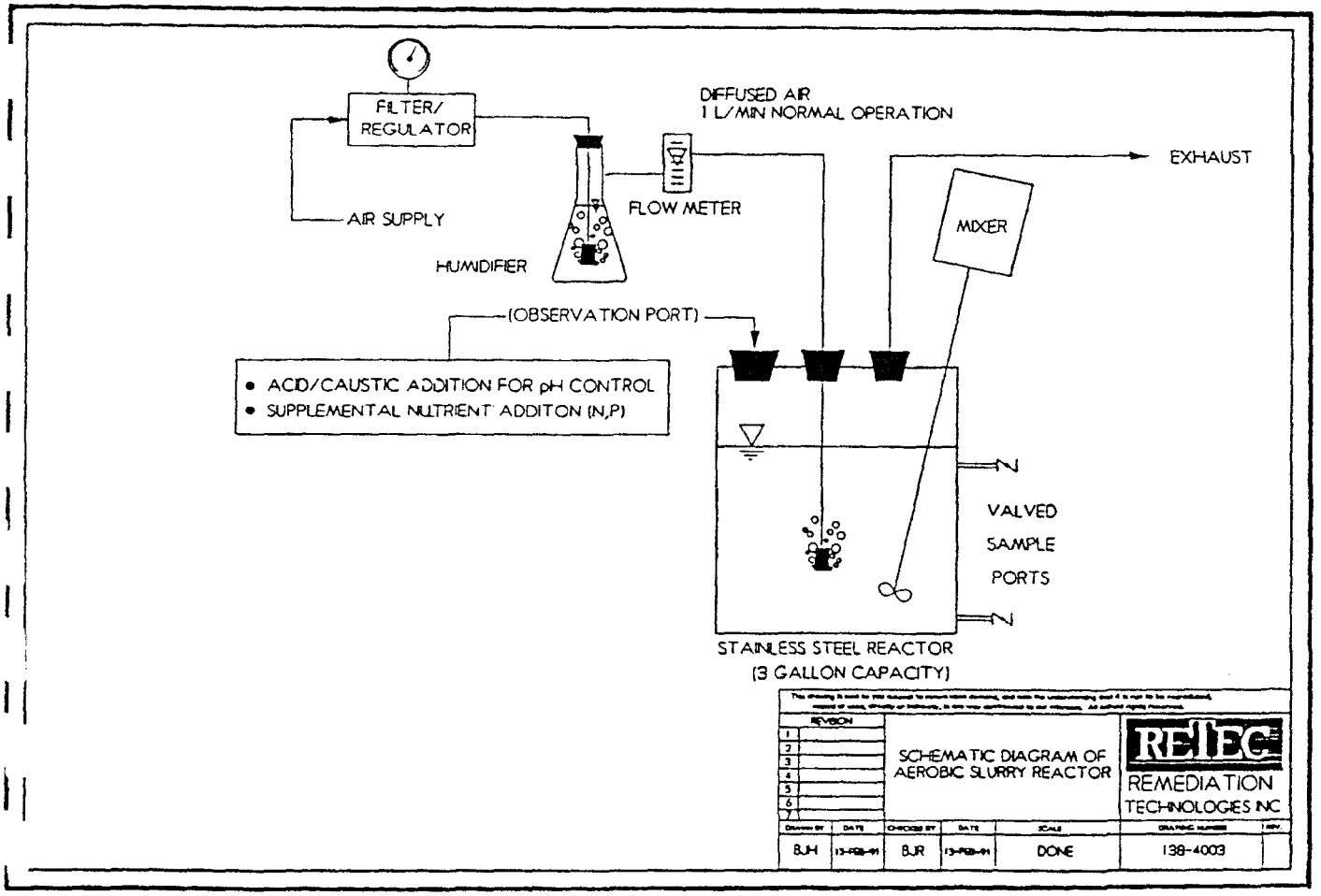


TABLE 5-1

SLURRY REACTOR INITIAL CONTENTS

Weight of Wet Soil	=	2.47 kg
Estimated Dry Weight of Soil	=	2.12 kg
Volume of Buffered Water Added	=	8.14 L
Percent Slurry (weight)	=	19.98
$NH_4 NO_3$ Added	=	17.00 g
85% H_3PO_4 Added	=	6.6 mg/L (11.1 g)
Initial Slurry Volume	=	9.0 L
Initial pH	=	5.59
10% NaOH Added	=	55 ml
Adjusted pH	=	7.63
Nutrients		
NO_3-N	=	200 mg/L
NH_4-N	=	80 mg/L
H_3PO_4-P	=	42 mg/L

TABLE 5-2

SLURRY REACTOR OPERATIONAL MONITORING SCHEDULE

Air Flow	=	Daily
Mixing Speed	=	Daily
Mixing Watts	=	Daily
Mixing Flow	=	Daily
pH	=	Daily
Dissolved Oxygen	=	Daily 1st week and 2 times a week thereafter
Nutrients	=	Initially, twice weekly, and final.
• NO_3-N		Initial (once), 2 times (weekly), and Final (once)
• NH_4-N		Initial (once), 2 times (weekly), and Final (once)
• PO_4-P		Initial (once), 2 times (weekly), and Final (once)

TABLE 5-3

SLURRY REACTOR SAMPLING SCHEDULE

TESTING	Initial Soil[a]	15 Min.		12 H Soil	1 D Soil	3 D Soil	5 D Soil	W 1 Soil	W 2 Soil	W 3 Soil	W 4 Soil	W 5 Soil	W 8 Final	
		Soil	Water										Soil	Water
ANALYTICAL														
% Solids	4	1	--	1	1	1	1	1	1	1	1	1	4	--
PAHs	4	1	1	1	1	1	1	1	1	1	1	1	4	1
Phenols (4-AAP)	1	--	1	--	--	--	--	--	--	--	--	--	--	1
IR Fingerprint	1	--	--	--	--	--	--	--	--	--	--	--	1	--
MICROBIAL														
Total	2	--	--	1	1	1	1	1	1	1	1	1	1	--

[a]The PAH and phenols (4-AAP) initial values correspond to those measured as part of the initial soil characterization (see Section 4.2). These initial soil values also serve as initial conditions for the pan and compost reactors.

H = Hour
D = Day
W = Week

infrared (IR) fingerprint analysis was conducted of the initial and treated soil to identify the particular creosote components biodegraded in terms of providing a qualitative assessment of specific organic components removed during the biodegradation process.

The mixer set at 1700 rpm and air flow set at 2 L/min kept the dissolved oxygen level in the reactor more than 6.0 mg/L at all times. Sufficient nutrients were added at the beginning of the experiment and the concentrations of nitrogen and phosphorus were checked periodically, using test kits. During the last stages of the slurry reactor treatment, it became difficult to measure the concentration of nitrogen in the water because of color interference. Ammonium nitrate was added weekly to avoid nutrient deficiency in the reactor.

5.1.2 Results

Operational Monitoring

The data summarized in Table 5-4 shows that the reactor was operated under proper environmental conditions. Specifically, the data shows that the pH in the slurry reactor was maintained between 7 and 7.5, phosphorus was greater than 30 mg/L, nitrate nitrogen was greater than 174 mg/L, ammonia nitrogen was greater than 64 mg/L, and dissolved oxygen was greater than 6 mg/L. This indicates that the environmental conditions in the slurry reactor were favorable for microbial growth.

Analytical Monitoring

The analytical results of the eight-week slurry reactor study are summarized in Tables 5-5 and 5-6 for the soil and water phases, respectively. All analytical results related to slurry reactor testing are given in Appendix B2.

As can be seen from Table 5-5, the initial PAH concentration of 5,682 mg/Kg dry weight of soil was slightly lower than the 15-minute value of 6,693 mg/Kg. Without an external source of addition, an initial increase in PAH concentration has been observed by ReTeC in other slurry reactor experiments and often represents the fact that the soil collected is well agglomerated and that the increase at 15 minutes is believed to be due to soil disagglomeration in the slurry reactor, thus making a more efficient analytical extraction than initially measured in the "as received" site soil.

TABLE 5-4

MEASURED SLURRY REACTOR MONITORING OPERATING PARAMETERS

DAY	pH		Test Kit PO_4-P (mg/L)	Test Kit NO_3-N (mg/L)	Test Kit NH_3-N (mg/L)	D.O. (mg/L)	TEMP. °C
	Initial	Adjusted					
0	5.6	7.6	42	200	80	7.5	22.1
3	7.8	7.5	30	174	64	7.6	22.6
6	7.4	---	60	190	128	7.7	24.2
10	7.3	---	50	200	80	7.8	24.4
14	7.6	---	60	450	112	7.5	25.6
22	6.7	7.6	73	430	160	6.8	33.5
27	7.0	7.7	84	312	140	6.7	29.0
35	6.7	7.4	58	450	80	6.2	22.6
42	7.4	---	75	NR	NR	6.5	29.4
46	7.4	---	75	NR	NR	6.2	29.4
55	7.0	---	60	NR	NR	6.9	29.0

NOTE: NR—Not Recorded because of color interference in the test.

TABLE 5-5

SLURRY REACTOR BIODEGRADATION SOIL RESULTS

PARAMETERS	INITIAL[a]	15 MIN.	12 HOUR	DAY 1	DAY 3	DAY 5	DAY 7	DAY 20	DAY 27	DAY 34	DAY 55[b]
Naphthalene	402.5 ± 35.3	540.0	390.0	410.0	200.0	87.0	39.0	31.0	27.0	15.0	11.7 ± 5.4
TOTAL 2-RINGS	**402.5 ± 35.3**	**540.0**	**390.0**	**410.0**	**200.0**	**87.0**	**39.0**	**31.0**	**27.0**	**15.0**	**11.7 ± 5.4**
Acenaphthylene	12.3 ± 0.8	16.0	17.0	16.0	16.0	17.0	17.0	10.0	130.0	99.0	98.8 ± 53.2
Acenaphthene	557.5 ± 60.1	800.0	550.0	580.0	270.0	640.0	400.0	58.0	110.0	76.0	76.3 ± 29.2
Fluorene	275.0 ± 84.7	340.0	230.0	250.0	140.0	140.0	34.0	4.4	8.8	9.3	6.4 ± 2.9
Phenanthrene	625.0 ± 107.5	880.0	610.0	660.0	280.0	54.0	38.0	11.0	13.0	11.0	9.7 ± 4.0
Anthracene	377.5 ± 35.3	450.0	310.0	360.0	180.0	380.0	61.0	7.0	10.0	9.2	5.8 ± 2.3
TOTAL 3-RINGS	**1,847.3 ± 278.8**	**2,486.0**	**1,717.0**	**1,866.0**	**886.0**	**1,231.0**	**550.0**	**90.4**	**271.8**	**204.5**	**196.9 ± 85.9**
Fluoranthene	720.0 ± 50.3	850.0	620.0	630.0	350.0	900.0	870.0	150.0	140.0	150.0	109.8 ± 45.8
Pyrene	765.0 ± 84.7	940.0	700.0	490.0	380.0	1,000.0	1,100.0	420.0	480.0	430.0	350.0 ± 157.5
Benzo(a)anthracene	320.0 ± 22.5	310.0	240.0	220.0	140.0	340.0	350.0	82.0	85.0	86.0	86.8 ± 44.2
Chrysene	495.0 ± 27.6	540.0	390.0	430.0	220.0	570.0	580.0	220.0	190.0	210.0	175.0 ± 58.8
TOTAL 4-RINGS	**2,300.0 ± 107.9**	**2,640.0**	**1,950.0**	**1,770.0**	**1,090.0**	**2,810.0**	**2,900.0**	**872.0**	**895.0**	**876.0**	**721.5 ± 296.8**
Benzo(b)fluoranthene	222.5 ± 15.2	220.0	170.0	170.0	87.0	250.0	230.0	230.0	200.0	210.0	250.0 ± 79.0
Benzo(k)fluoranthene	110.0 ± 13.0	110.0	85.0	88.0	50.0	120.0	140.0	100.0	100.0	100.0	98.5 ± 38.8
Benzo(a)pyrene	270.0 ± 13.0	270.0	210.0	200.0	120.0	300.0	320.0	280.0	240.0	270.0	277.5 ± 106.6
Dibenzo(a,h)anthracene	122.5 ± 15.2	87.0	100.0	99.0	43.0	130.0	140.0	98.0	78.0	85.0	101.0 ± 40.0
TOTAL 5-RINGS	**725.0 ± 47.7**	**687.0**	**565.0**	**557.0**	**300.0**	**800.0**	**830.0**	**708.0**	**618.0**	**665.0**	**727.0 ± 246.1**

TABLE 5-5
(Continued)

SLURRY REACTOR BIODEGRADATION SOIL RESULTS

PARAMETERS	INITIAL[a]	15 MIN.	12 HOUR	DAY 1	DAY 3	DAY 5	DAY 7	DAY 20	DAY 27	DAY 34	DAY 55[b]
Benzo(g,h,i)perylene	202.5 ± 7.6	180.0	170.0	150.0	82.0	220.0	230.0	200.0	200.0	150.0	195.0 ± 74.1
Indeno(1,2,3-cd)pyrene	205.0 ± 12.7	160.0	170.0	170.0	79.0	220.0	230.0	180.0	190.0	140.0	200.0 ± 76.9
TOTAL 6-RINGS	407.5 ± 23.9	340.0	340.0	320.0	161.0	440.0	460.0	380.0	390.0	290.0	395.0 ± 150.7
TOTAL PAHs	5,682.3 ± 191.2	6,693.0	4,962.0	4,923.0	2,637.0	5,368.0	4,779.0	2,081.4	2,204.8	2,050.0	2,052.1 ± 769.6

NOTE: Raw Analytical Data Given in Appendix B2.
All soil concentration values in mg/Kg dry weight.
[a] Average values based on four analyses with 95% confidence intervals (see Table 4-5).
[b] Average values based on four analyses with 95% confidence intervals.

TABLE 5-6

COMPARISON OF SLURRY REACTOR
AQUEOUS PHASE PAH

PAH COMPOUND	MAX. AQUEOUS SOLUBILITY (µg/L)	INITIAL AQUEOUS PHASE CONC. (µg/L)	FINAL AQUEOUS PHASE CONC. (µg/L)	% REDUCTION
Napththalene (2)[b]	31,700	630	21.0	96.7
Acenaphthylene (3)	3,930	22	<2.3	>89.5
Acenaphthene (3)	3,420	370	<2.3	>99.4
Fluorene (3)	1,690	140	<0.2	>99.9
Phenanthrene (3)	1,000	140	1.4	99.0
Anthracene (3)	450	22	0.9	95.9
Fluoranthene (4)	206	33	7.3	77.9
Pyrene (4)	132	39	28.0	28.2
Benzo(a)pyrene (4)	1.2	4.2	2.6	38.1
Chrysene (4)	1.8	8.9	5.6	37.1
Benzo(b)fluoranthene (5)	1.4	3.4	6.9	(+)[C]
Benzo(k)fluoranthene (5)	4.3	1.8	2.7	(+)
Benzo(a)pyrene (5)	1.2	4.2	7.8	(+)
Dibenz(a,h)anthracene (5)	0.5	0.7	2.4	(+)
Benzo(g,h,i)perylene (6)	0.7	2.9	5.7	(+)
Indeno(1,2,3-cd)pyrene (6)	0.5	2.4	6.3	(+)

NOTE: < Indicates less than detectable concentration.
[a]Maximum aqueous solubilities taken from Table 2-2.
[b]Number in ( ) indicates respective PAH ring number.
[c](+) indicates an increase in the measured aqueous phase concentration.

The data in Table 5-5 is also graphically illustrated in Figure 5-2. Referring to Figure 5-2, total PAHs were reduced from an initial concentration of approximately 5,700 mg/Kg to a concentration of approximately 2,000 mg/Kg after 20 days. No further reduction was observed after this, indicating that the PAHs remaining were no longer desorbable from the soil and were no longer in the liquid phase and available to bacteria. Therefore, the 2,000 mg/Kg total PAHs concentration represents a biostabilized endpoint. As compiled in Table 5-7 and illustrated in Figure 5-3, slurry reactor treatment achieved a total PAH reduction of approximately 64 percent, with the majority of the reduction associated with the more soluble and more desorbable 2-, 3- and 4-ring PAHs.

Results of the bacterial enumeration are presented in Table 5-8. The total bacterial counts are high and typical of those measured in other bioremediation studies. The total bacterial counts increased by a factor of 30 after nutrients were added to the slurry reactor. Since PAHs were removed in the slurry system and total bacterial counts increased by a factor of 30, this indicates that there was a substantial population of PAH degraders in the slurry reactor.

The results of the infrared analyses can be found in Appendix B2. These results show that the ratio of creosote/petroleum oil was about 90/10 in the initial soil sample and the final treated soil sample contained only heavy ends of the creosote fraction, i.e., those less desorbable and less biodegradable compounds.

5.2 PHASE II - SOIL PAN AND COMPOST REACTOR STUDIES

5.2.1 Soil Pan Reactor Study

Traditionally, soil treatability studies have been accomplished with pan studies. Soil pan biodegradation studies are an accepted method for simulating prepared bed land treatment in the laboratory to evaluate the rate and extent of degradation achievable during full-scale biological prepared bed land treatment.

The pan study was designed to estimate the approximate treatment time and degree of remediation that could be achieved using the naturally occurring bacteria from the site under conditions which would mimic a full-scale bioremediation process. As a result, no bacterial inoculum were used in this study.

FIGURE 5-2

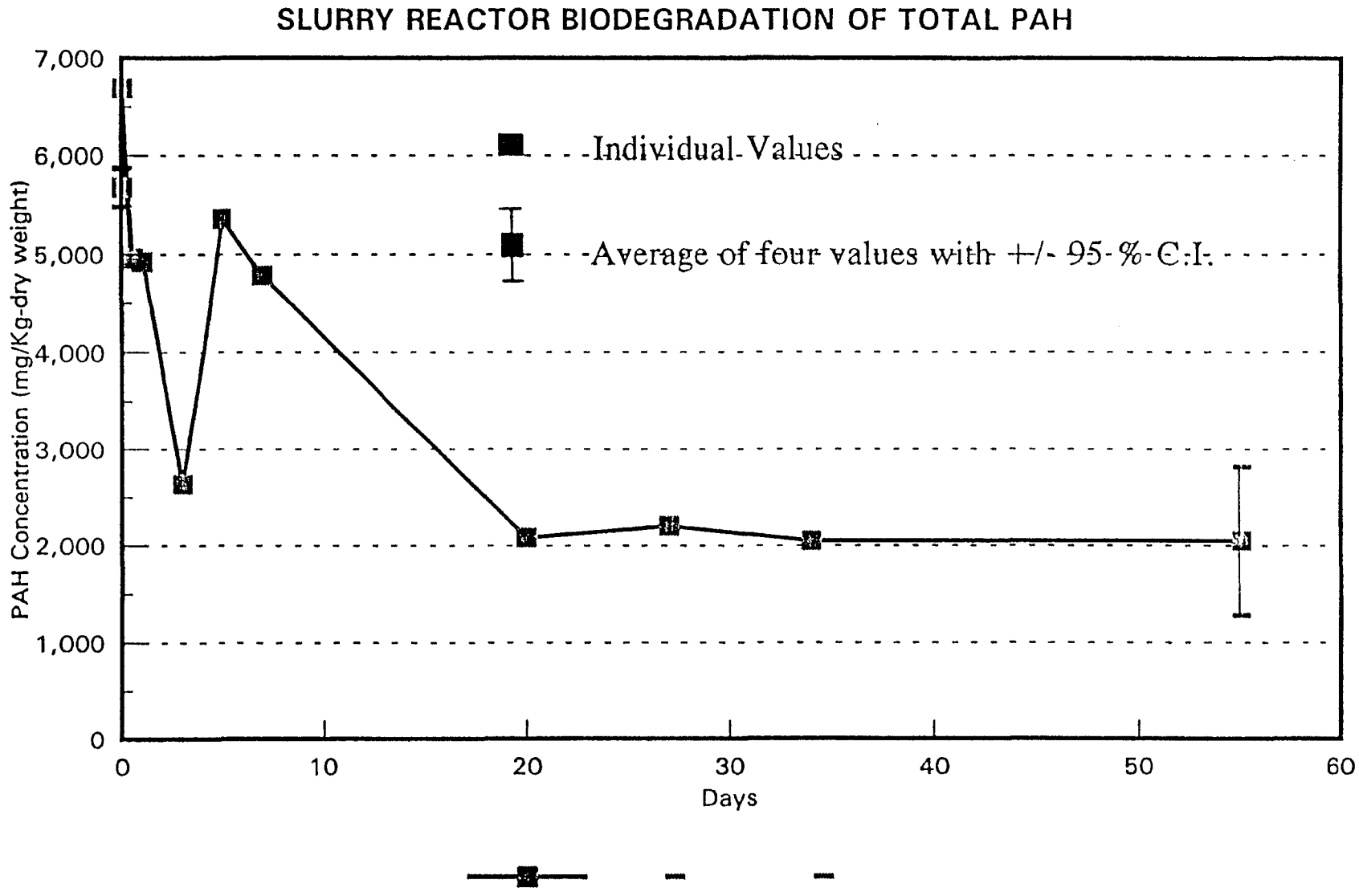

SLURRY REACTOR BIODEGRADATION OF TOTAL PAH
Individual Values
Average of four values with +/- 95 % C.I.
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0
10
20
30
40
50
60
Days

TABLE 5-7

SLURRY REACTOR PERCENT REMOVALS
BY PAH RING GROUPINGS

PAH RING GROUPING	INITIAL SOIL (mg/Kg)	FINAL SOIL (mg/Kg)	REMOVAL (%)
2-Ring	402	12	97.1
3-Ring	1847	197	89.3
4-Ring	2300	722	68.6
5-Ring	725	728	$\simeq 0$
6-Ring	407	395	3.1
TOTAL	**5682**	**2052**	**64**

NOTE: Based on data given in Table 5-5.

FIGURE 5-3

SLURRY REACTOR INITIAL AND FINAL
SOIL PAHs BY RING GROUPINGS

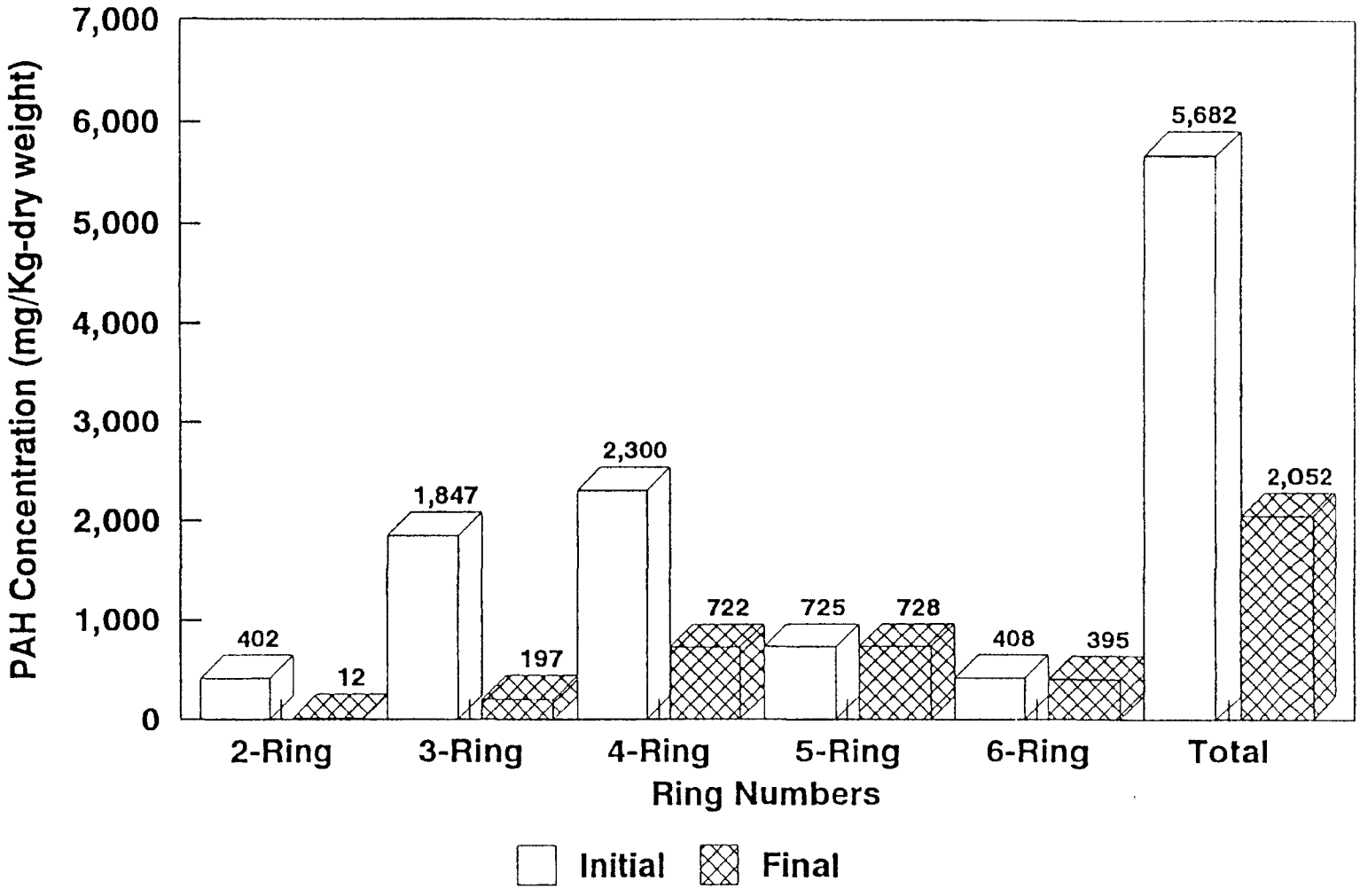


TABLE 5-8

SLURRY REACTOR BACTERIAL ENUMERATION RESULTS

TIME	TOTAL NUMBERS CELLS/g OF SOIL[a]
Initial Soil	2.3×10^6
Initial Soil	1.9×10^6
12 Hour Slurry Soil	35.3×10^6
24 Hour Slurry Soil	41.8×10^6
Day 3 Slurry Soil	45×10^6
Day 5 Slurry Soil	72×10^6
Week 1 Slurry Soil	52×10^6
Week 3 Slurry Soil	61.4×10^6
Week 4 Slurry Soil	0.08×10^6
Week 5 Slurry Soil	0.03×10^6
Week 8 Slurry Soil	0.16×10^6

NOTE: Results are on dry weight basis.
[a]Total all count determined by Agar Plate Method[29].

Procedures

Figure 5-4 schematically illustrates the configuration of the pan reactor used for the study. The pan reactor was 13 inches long, 10 inches wide and 5 inches deep and was constructed of durable rubber. Contaminated soil was placed into the pan at a depth of approximately 4 inches. Nutrients (nitrogen and phosphorus) were added to enhance growth of indigenous bacteria. Details of the contents of the reactor are provided in Table 5-9. The maintenance and sampling schedules for the soil pan reactor study are provided in Tables 5-10 and 5-11, respectively.

Before the commencement of the pan reactor, the field capacity of the soil was determined. Field capacity is related to the maximum percent moisture content in a soil sample under gravity conditions. The test consists of pouring distilled water slowly on top of a known weight of soil until the soil becomes saturated and water begins to drain from the soil sample. The water is then allowed to drain for approximately 6 hours. From the final weight of the wetted soil, the percent moisture in the soil is then calculated. The calculated value is the field capacity of the soil.

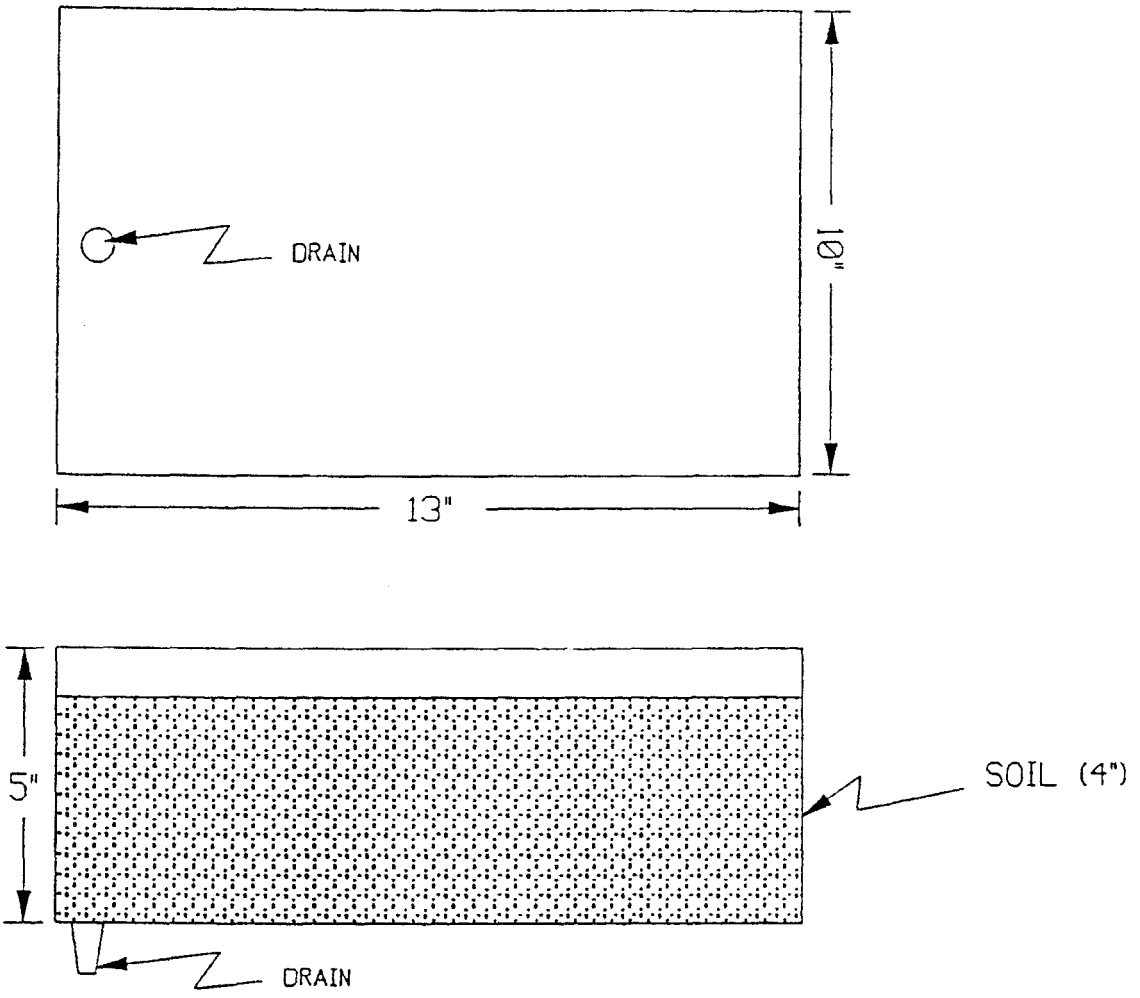
Soil moisture was maintained at 60 to 70 percent of the soil field capacity, which was measured at approximately 27 percent moisture. The pan soil was mixed periodically, as detailed in Table 5-10, and the levels of the nutrients, pH and moisture were measured and adjusted as necessary. With the exception of month three, soil samples were collected monthly for PAH analysis.

Operational Monitoring

The data summarized in Table 5-12 show that the pan reactor was operated under the proper environmental conditions. Specifically, the data shows that the soil pH maintained a level consistently between 7-8 without any supplemental chemical addition. The soil moisture content of the soil varied between 17 percent to 22 percent representing a range from 60 to 82 percent of the field capacity of the soil. Lastly, there was always sufficient N and P in the soil matrix. Thus, the operational monitoring results show that the pan reactor was maintained under environmental conditions favorable to microbial growth.

FIGURE 5-4

SOIL PAN REACTOR SCHEMATIC



REVISION		STANDARD SOIL PAN SOP 710		REMEDIATION TECHNOLOGIES INC
1				
2				
3				
4				
5				
DRAWN BY	CHECKED BY	DATE	SCALE	DWG. NO.
RPC		13-OCT-1989	NONE	SOP-710

TABLE 5-9

DETAILS OF PAN REACTOR CONTENTS

Weight of Soil Used (wet)	=	6117 g
Moisture Content of "Soil As Is"	=	14 %
Computed Weight of Dry Soil	=	5261 g
Weight of Manure Added	=	526 g
Ammonium Nitrate Added	=	27.7 g
Trisodium Phosphate Added	=	37.1 g
Field Capacity	=	27.3 %
Initial pH	=	7.8
Adjusted Moisture Content of Soil	=	20.1 %
Nutrients (Test Kits)		
Phosphate as P	=	500 mg/Kg
Nitrate as N	=	700 mg/Kg
Ammonia as N	=	160 mg/Kg

TABLE 5-10

PAN REACTOR MAINTENANCE SCHEDULE

Water Addition	Visual examination of soil daily and add water as necessary.
Moisture Content	Three times a week during first month and weekly once thereafter.
Nutrients	Once a week during first month and bi-weekly thereafter.
pH	Once a week during first month and bi-weekly thereafter.

NOTE: All parameters were adjusted as needed.

TABLE 5-11

PAN REACTOR SAMPLING SCHEDULE

DESCRIPTION OF TEST	INITIAL[a]	MONTH			
		1	2	3	4
ANALYTICAL					
% Moisture	4X	1X	1X	—	2X
PAH	4X	1X	1X	—	2X

[a]The PAHs and % moisture initial values correspond to those measured as part of the initial soil characterization (see Section 4.2). These initial soil values also serve as the initial conditions for the slurry and compost reactors.

TABLE 5-12

PAN REACTOR MONITORED PARAMETERS

DAY	NUTRIENTS (mg/kg, D.W.)			MOISTURE		Operating pH (Initial)
	NO_3 as N (Test Kit)	NH_4 as N (Test Kit)	PO_4 as P (Test Kit)	% Moisture	% Field Capacity	
0	700	160	500	22.4	82	7.8
4	722	145	745	18.7	68	7.8
7	--	--	--	19.7	72	
8	800	64	400	--	--	7.7
14	200	22	300	17.9	66	7.8
18	--	--	--	17.0	62	7.8
21	1,200	600	400	16.6	61	7.6
31	1,250	250	417	17.6	64	7.1
36	1,200	160	333	16.9	62	7.2
42	1,200	160	333	18.0	66	7.3
54	1,500	240	266	--	--	7.2
60	1,500	240	400	16.5	60	7.2
67	1,400	320	267	17.0	62	7.3
77	1,200	480	300	17.0	62	7.3
83	1,000	400	267	17.2	63	7.2
120	1200	24	333	18.7	68	7.2

NOTE: Field Capacity was measured at approximately 27% moisture.

Analytical Monitoring

The analytical results of the four month pan reactor study are summarized in Tables 5-13 and 5-14. All analytical results related to soil pan testing are given in Appendix B3. As the data shows, PAH soil concentrations were reduced, but not at the same rate as in the slurry reactor. The total PAH concentrations were reduced from an initial concentration of approximately 5,600 mg/Kg to a final concentration of approximately 2,200 mg/Kg after 120 days of treatment. The rate of reduction in PAH soil concentrations appeared to decrease after Day 60 compared to Days 0 to 60. These results are graphically illustrated in Figure 5-5 for total PAH and in Figure 5-6 for different PAH ring classes. The results are further illustrated in Figure 5-7.

5.2.2 Compost Reactor Study

Like the soil pan reactor study, a compost reactor study was performed to measure the rate and extent of PAH reduction during the bioremediation of creosote contaminated soil. The experiment was performed under suitable conditions for biological activity. The compost reactor study was conducted to determine whether soil amendment with wood chips and forced air circulation would achieve greater PAH biodegradation compared to a pan reactor.

Procedure

Figure 5-8 shows the schematic details of the compost reactor. The 4" diameter and 24" high reactor is constructed of PVC pipe with an air inlet at the bottom and an air outlet at the top. The air inlet also serves as a water drain. The air outlet is connected to a suction pump through a water condenser. A second port at the top is provided for watering. The bottom 2" of the reactor was filled with pea gravel. This gravel media supported the soil sample and enhanced uniform distribution of air in the soil column.

Soil for the compost reactor was initially mixed with nutrients such as ammonium nitrate and trisodium phosphate. The soil was amended with wood chips passing through 1/4" screen mesh. The weight ratio of dry soil to dry wood chips was about 9:1. The amended soil was mixed with water to make the soil wet at 60-80 percent of its field capacity. The nutrient-rich wetted soil was placed over the pea gravel to a height of

TABLE 5-13

PAN REACTOR BIODEGRADATION RESULTS

PAHs (mg/kg)[a]	INITIAL SOIL[b]	MONTH 1	MONTH 2	MONTH 4[c]
Naphthalene	402.5 ± 35.3	160.0	64.0	58.5
TOTAL 2-RINGS	**402.5 ± 35.3**	**160.0**	**64.0**	**58.5**
Acenaphthylene	12.3 ± 0.8	220.0	190.0	151.5
Acenaphthene	557.5 ± 60.1	380.0	220.0	270.0
Fluorene	275.0 ± 84.7	130.0	49.0	36.0
Phenanthrene	625.0 ± 107.5	350.0	110.0	70.0
Anthracene	377.5 ± 35.3	230.0	120.0	108.0
TOTAL 3-RINGS	**1,847.3 ± 278.6**	**1,310.0**	**689.0**	**635.5**
Fluoranthene	720.0 ± 50.3	530.0	360.0	235.0
Pyrene	765.0 ± 84.7	520.0	680.0	475.0
Benzo(a)anthracene	320.0 ± 22.5	230.0	170.0	117.5
Chrysene	495.0 ± 27.6	330.0	230.0	180.0
TOTAL 4-RINGS	**2,300.0 ± 107.9**	**1,610.0**	**1,440.0**	**1,007.5**
Benzo(b)fluoranthene	222.5 ± 15.2	140.0	120.0	78.5
Benzo(k)fluoranthene	110.0 ± 13.0	78.0	62.0	46.0
Benzo(a)pyrene	270.0 ± 13.0	180.0	150.0	101.0
Dibenzo(a,h)anthracene	122.5 ± 15.2	56.0	55.0	37.5
TOTAL 5-RINGS	**725.0 ± 47.7**	**454.0**	**387.0**	**263.0**
Benzo(g,h,i)perylene	202.5 ± 7.6	100.0	110.0	58.5
Indeno(1,2,3-cd)pyrene	205.0 ± 12.7	81.0	130.0	146.0
TOTAL 6-RINGS	**407.5 ± 23.9**	**181.0**	**240.0**	**204.5**
TOTAL PAHs	**5,682.3 ± 191.2**	**3,715.0**	**2,820.0**	**2,169.0**

NOTE: See Appendix B3 for Raw Analytical Results.
[a]On dry weight basis.
[b]Averages with ± 95% confidence intervals on 4 results (See Table 4-5).
[c]Average values of 2 data points.

TABLE 5-14

PAN REACTOR PERCENT REMOVALS
BY PAH RING GROUPINGS

PAH RING GROUPING	INITIAL SOIL (mg/Kg) Dry Weight	FINAL SOIL (mg/Kg) Dry Weight	REMOVAL (%)
2-Ring	402	59	85
3-Ring	1847	636	66
4-Ring	2300	1008	56
5-Ring	725	263	64
6-Ring	407	204	50
TOTAL	**5682**	**2170**	**62**

NOTE: Based on data given in Table 5-13.

FIGURE 5-5

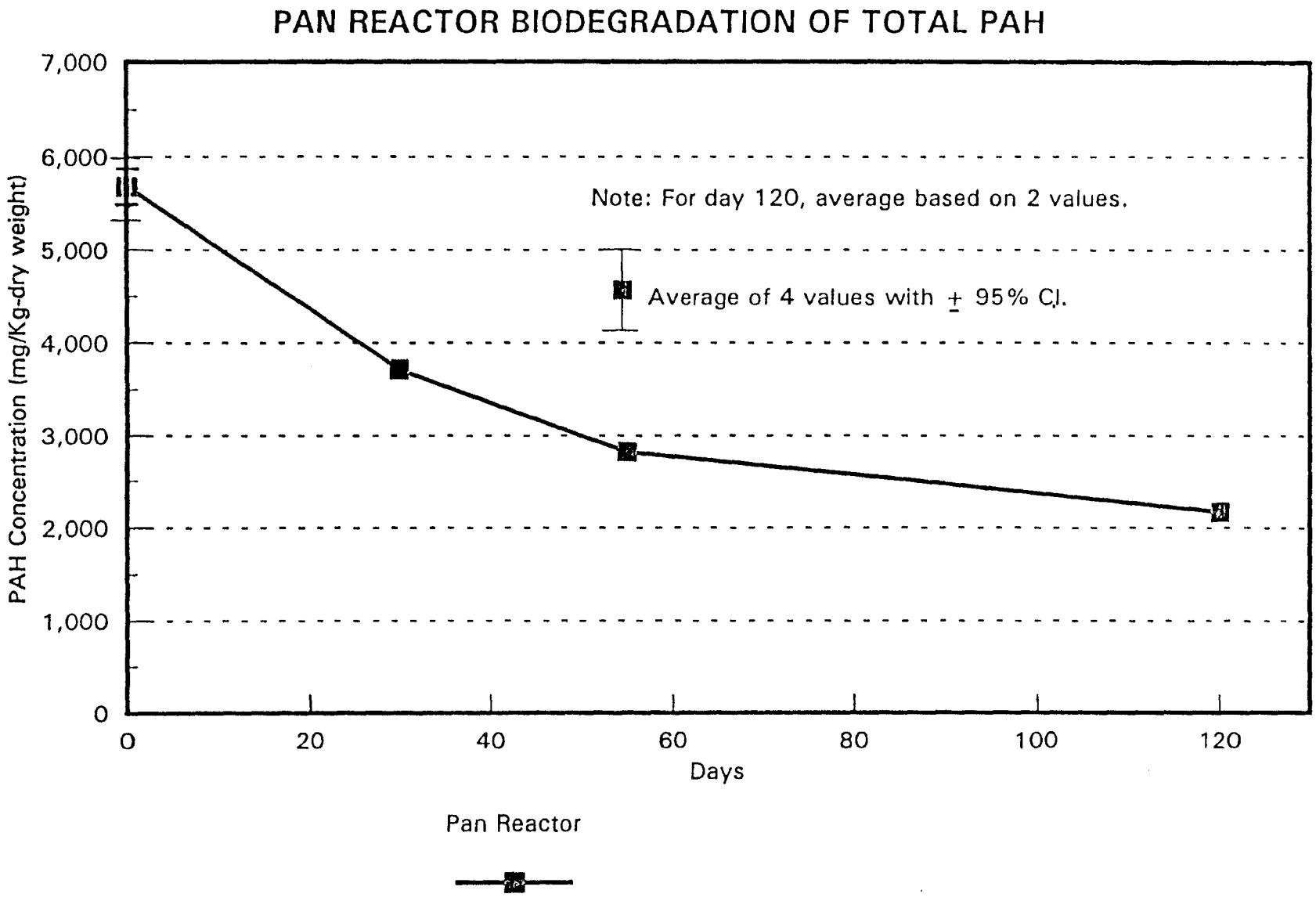

PAN REACTOR BIODEGRADATION OF TOTAL PAH
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Note: For day 120, average based on 2 values.
Average of 4 values with ± 95% C.I.
0
20
40
60
80
100
120
Days
Pan Reactor

FIGURE 5-6

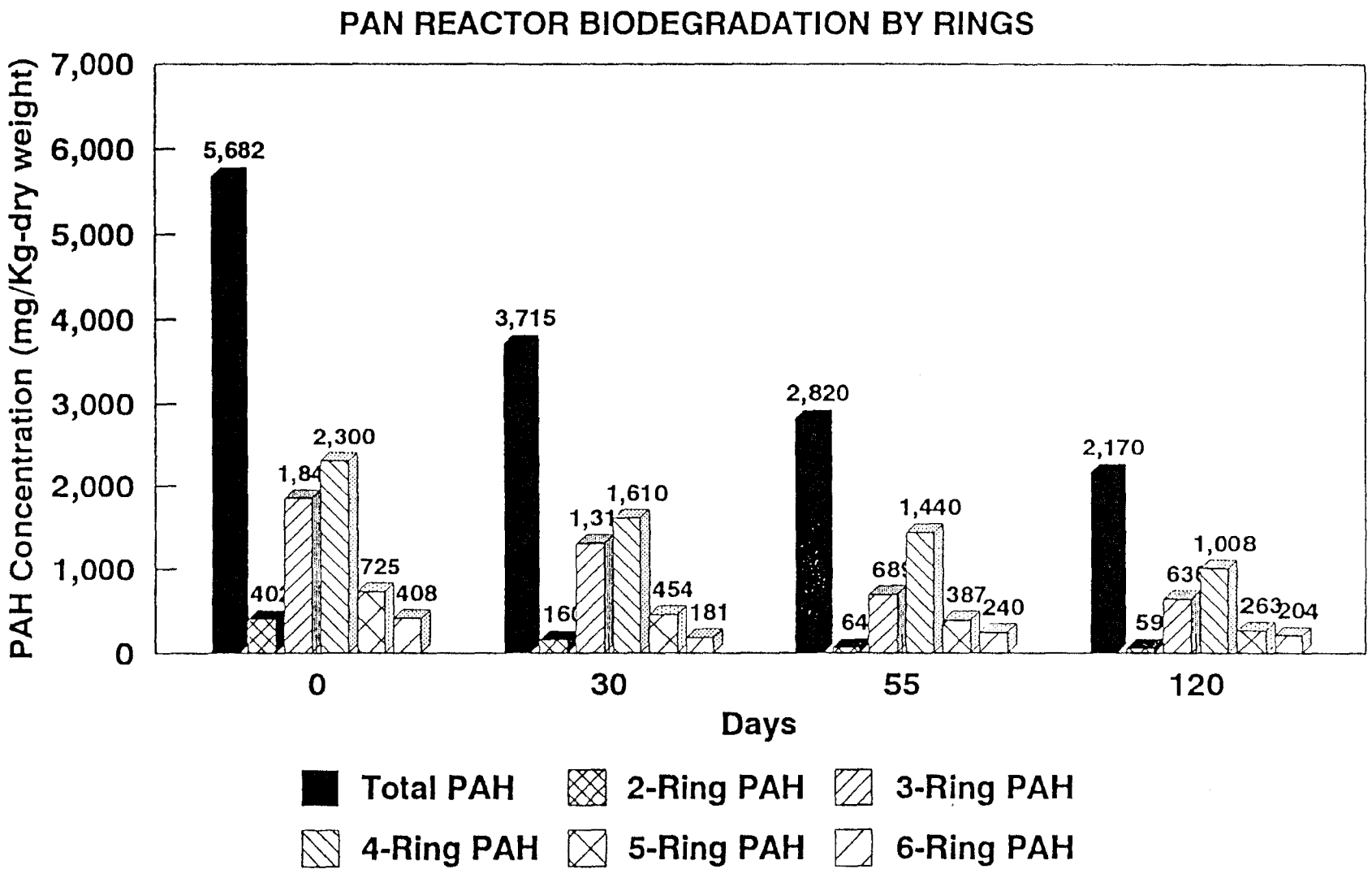

PAN REACTOR BIODEGRADATION BY RINGS
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
5,682
402
1,84
2,300
725
408
3,715
16
1,31
1,610
454
181
2,820
64
68
1,440
387
240
2,170
59
63
1,008
263
204
0
30
55
120
Days
Total PAH
2-Ring PAH
3-Ring PAH
4-Ring PAH
5-Ring PAH
6-Ring PAH

FIGURE 5-7

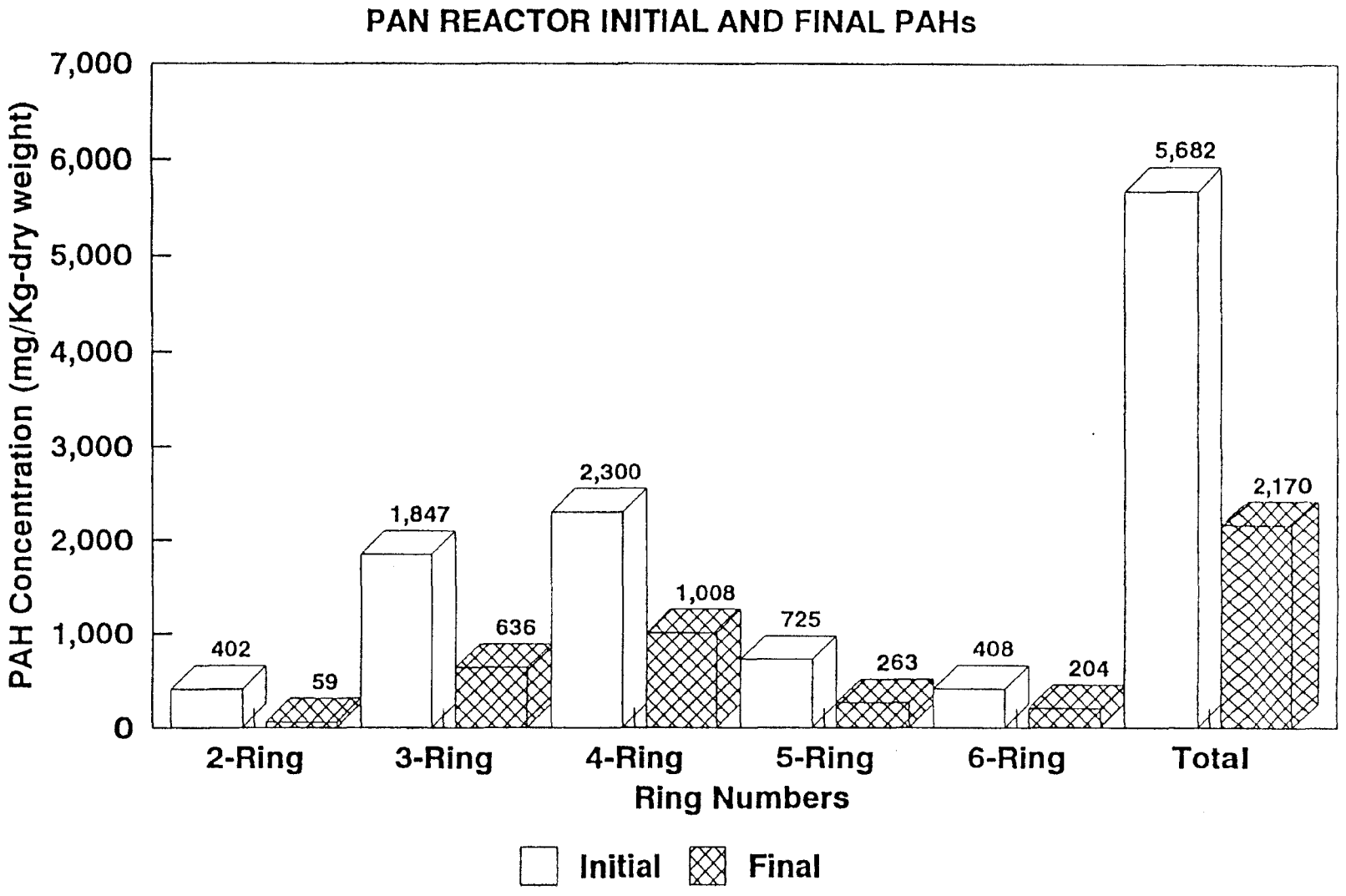
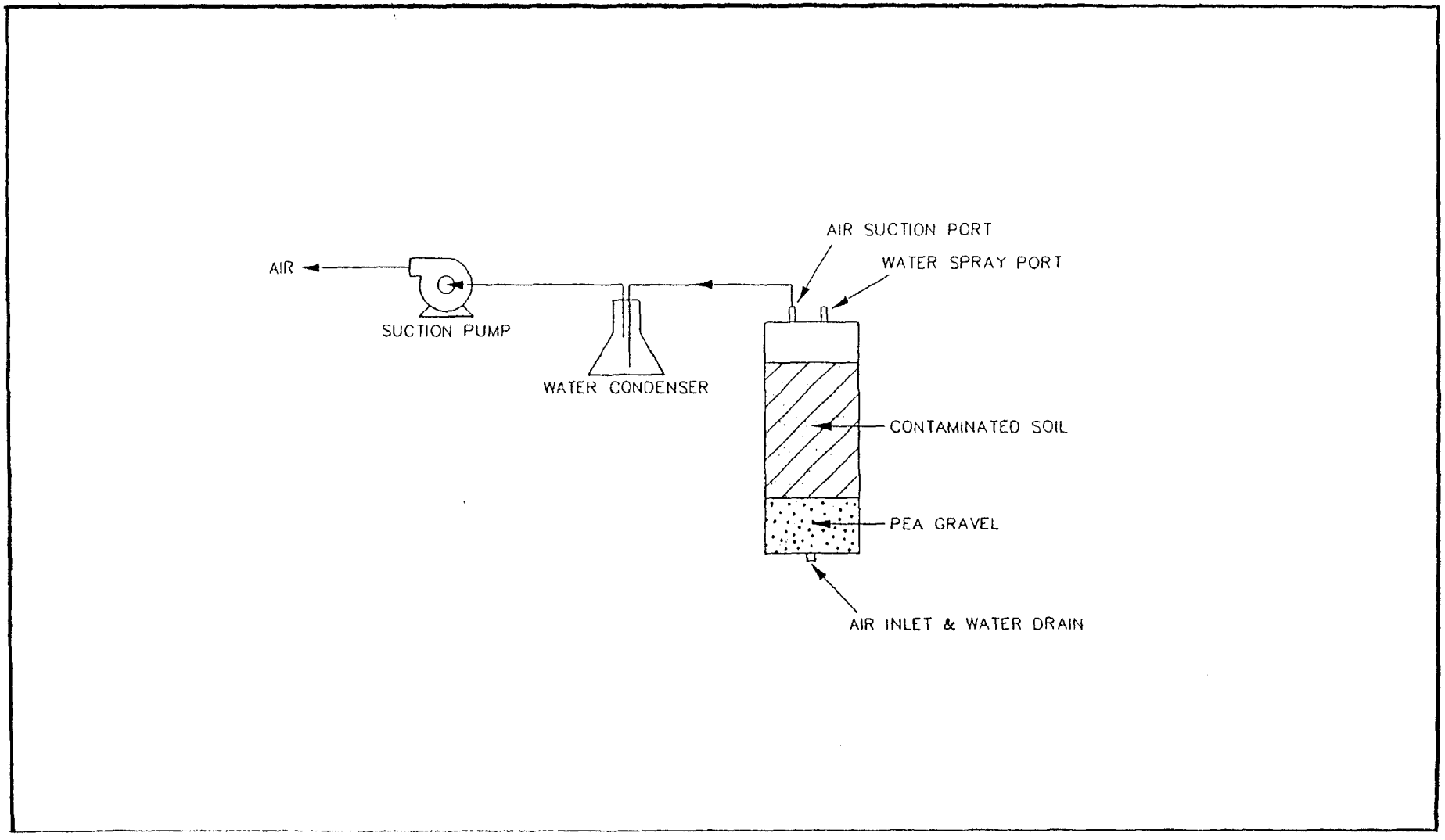

PAN REACTOR INITIAL AND FINAL PAHs
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
402
59
1,847
636
2,300
1,008
725
263
408
204
5,682
2,170
2-Ring
3-Ring
4-Ring
5-Ring
6-Ring
Total
Ring Numbers
Initial
Final

FIGURE 5-8

COMPOST REACTOR SCHEMATIC



approximately 18 inches. The reactor was then closed with its lid and the air suction pump was initiated. The initial contents of the reactors are given in Table 5-15.

Tables 5-16 and 5-17 give details of maintenance and sampling schedules for the compost reactor study. The maintenance work involved visually examining the soil daily to add sufficient water to keep the soil wet but not saturated. The air flow was checked everyday and adjusted to keep the flow between 4 and 6 L/min. Percent moisture, pH and nutrients were determined whenever a soil sample was taken for PAH analysis.

Operational Monitoring

The data presented in Table 5-18 show that the reactor was operated under environmental conditions suitable for microbial growth. The table shows that the reactor had sufficient moisture and nutrients. The average moisture content of the soil was 18.8 percent which represents 69 percent field capacity of the soil. The monitoring data for nitrogen and phosphorus show that there was always sufficient nutrients. The pH of the soil averaged to 7.4.

Analytical Monitoring

Analytical results for the compost reactor study are presented in Table 5-19 and 5-20. Since the compost reactor contents consisted of 90% dry soil and 10% wood chips, (by dry weight) the measured values have to be multiplied by 1.11 (i.e., 100/90 to compute the concentration of PAHs in 100% dry soil); this is needed for direct comparison to slurry reactor and pan reactor results. It can be seen from these tables that composting treatment reduced the total PAH concentration approximately value from 5,682 mg/Kg to 1,774 mg/Kg. All analytical testing results related to the compost reactor are provided in Appendix B4.

The analytical results are graphically illustrated in Figure 5-9 for total PAH and Figures 5-10 and 5-11 for different PAH ring classes. As shown, the majority of the soil PAH biodegradation occurred during the first month of treatment, with little additional treatment achieved during months 2 through 4.

TABLE 5-15

COMPOST REACTOR CONTENTS

Weight of Soil Used (wet)	=	2400 g
Moisture Content of "Soil As Is"	=	14 % (w/w)
Computed Weight of Dry Soil	=	2064 g
Weight of Manure Added	=	239 g
Ammonium Nitrate Added	=	11.0 g
Trisodium Phosphate Added	=	15.0 g
Field Capacity of Compost Blend	=	73.6 %
Initial pH	=	7.3
Adjusted Moisture Content of Soil	=	20.1%
Nutrients (Test Kits)		
Phosphate as P	=	500 mg/Kg
Nitrate as N	=	10000 mg/Kg
Ammonia as N	=	1200 mg/Kg

TABLE 5-16

COMPOST REACTOR MAINTENANCE SCHEDULE

Water Addition	Visual examination of soil daily and add water as necessary.
Moisture Content	Whenever soil sample is taken for PAH analysis.
Nutrients	Whenever soil sample is taken for PAH analysis.
pH	Whenever soil sample is taken for PAH analysis.

NOTE: All parameters were adjusted as needed.

TABLE 5-17

COMPOST REACTOR SAMPLING SCHEDULE

DESCRIPTION OF TEST	INITIAL[a]	MONTH			
		1	2	3	4
ANALYTICAL					
% Moisture	4X	1X	1X	—	2X
PAH	4X	1X	1X	—	2X

[a]Analyzed as part of the initial soil characterization (See Section 4.2).

TABLE 5-18

COMPOST REACTOR MONITORED PARAMETERS

MONTH	WATER ADDED (mL/d)[a]	pH[b]	NO_3^-N[b] (mg/Kg)	NH_3^-N[b] (mg/Kg)	PO_4^-P[b] (mg/Kg)	% MOISTURE[b]
1	65	7.4	1,100	35	300	17.6
2	47	7.3	600	30	400	16.5
4	50	7.4	1,200	24	330	22.2

NOTE: [a]Average values for 0-1, 0-2 and 2-4 month periods.
[b]Measured values at the end of 1, 2 and 4 months.

TABLE 5-19

COMPOST REACTOR BIODEGRADATION RESULTS

PAHs (mg/Kg)[a]	INITIAL SOIL[b]	MONTH 1		MONTH 2		MONTH 4[c]	
		Measured[c]	Computed[d]	Measured[c]	Computed[d]	Measured[c]	Computed[d]
Naphthalene	402.5 ± 35.3	100.0	111.1	86.0	95.5	52.0	57.8
TOTAL 2-RINGS	402.5 ± 35.3	100.0	111.1	86.0	95.5	52.0	57.8
Acenaphthylene	12.3 ± 0.8	76.0	84.4	44.0	48.9	84.0	93.3
Acenaphthene	557.5 ± 60.1	89.0	98.9	120.0	133.3	114.5	127.2
Fluorene	275.0 ± 84.7	49.0	54.4	29.0	32.2	15.0	16.7
Phenanthrene	625.0 ± 107.5	100.0	111.1	91.0	101.1	42.5	47.2
Anthracene	377.5 ± 35.3	72.0	80.0	55.0	61.1	42.5	47.2
TOTAL 3-RINGS	1847.3 ± 278.6	386.0	428.8	339.0	376.6	298.5	331.6
Fluoranthene	720.0 ± 50.3	190.0	211.1	180.0	200.0	145.0	161.1
Pyrene	765.0 ± 84.7	210.0	233.3	420.0	466.7	300.0	333.3
Benzo(a)anthracene	320.0 ± 22.5	110.0	122.2	120.0	133.3	100.5	111.7
Chrysene	495.0 ± 27.6	160.0	177.7	170.0	188.9	150.0	166.7
TOTAL 4-RINGS	2300.0 ± 107.9	670.0	744.3	890.0	988.9	695.5	772.8
Benzo(b)fluoranthene	222.5 ± 15.2	85.0	94.4	110.0	122.2	94.5	105.0
Benzo(k)fluoranthene	110.0 ± 13.0	45.0	50.0	57.0	63.3	52.0	57.8
Benzo(a)pyrene	270.0 ± 13.0	110.0	122.2	140.0	155.6	115.0	127.8
Dibenzo(a,h)anthracene	122.5 ± 15.2	33.0	36.7	55.0	61.1	50.0	55.6
TOTAL 5-RINGS	725.0 ± 47.7	273.0	303.3	362.0	402.2	311.5	346.2

TABLE 5-19
(Continued)

COMPOST REACTOR BIODEGRADATION RESULTS

PAHs (mg/Kg)[a]	INITIAL SOIL[b]	MONTH 1		MONTH 2		MONTH 4[e]	
		Measured[c]	Computed[d]	Measured[c]	Computed[d]	Measured[c]	Computed[d]
Benzo(g,h,i)perylene	202.5 ± 7.6	67.0	74.4	110.0	122.2	78.5	87.2
Indeno(1,2,3-cd)pyrene	205.0 ± 12.7	49.0	54.4	130.0	144.4	160.0	177.8
TOTAL 6-RINGS	407.5 ± 23.9	116.0	128.8	240.0	266.6	238.5	265.0
TOTAL PAHS	**5682.3 ± 191.2**	**1545.0**	**1716.3**	**1917.0**	**2219.6**	**1596.0**	**1773.4**

NOTE: All raw analytical results given in Appendix B4.
[a]On dry weight basis.
[b]Average values ± 95% confidence intervals on four results (See Table 4-5).
[c]Analytical results.
[d]Analytical values multiplied by 100/90 to give 100% soil basis for direct comparison purposes.
[e]Average values of two data points.

TABLE 5-20

COMPOST REACTOR PERCENT REMOVALS
BY PAH RING GROUPINGS

PAH RING GROUPING	INITIAL SOIL (mg/Kg)	FINAL SOIL (mg/Kg)	REMOVAL (%)
2-Ring	402	58	86
3-Ring	1847	332	82
4-Ring	2300	773	66
5-Ring	725	346	52
6-Ring	407	265	35
TOTAL	**5682**	**1774**	**69**

NOTE: Based on data given in Table 5-15.

FIGURE 5-9

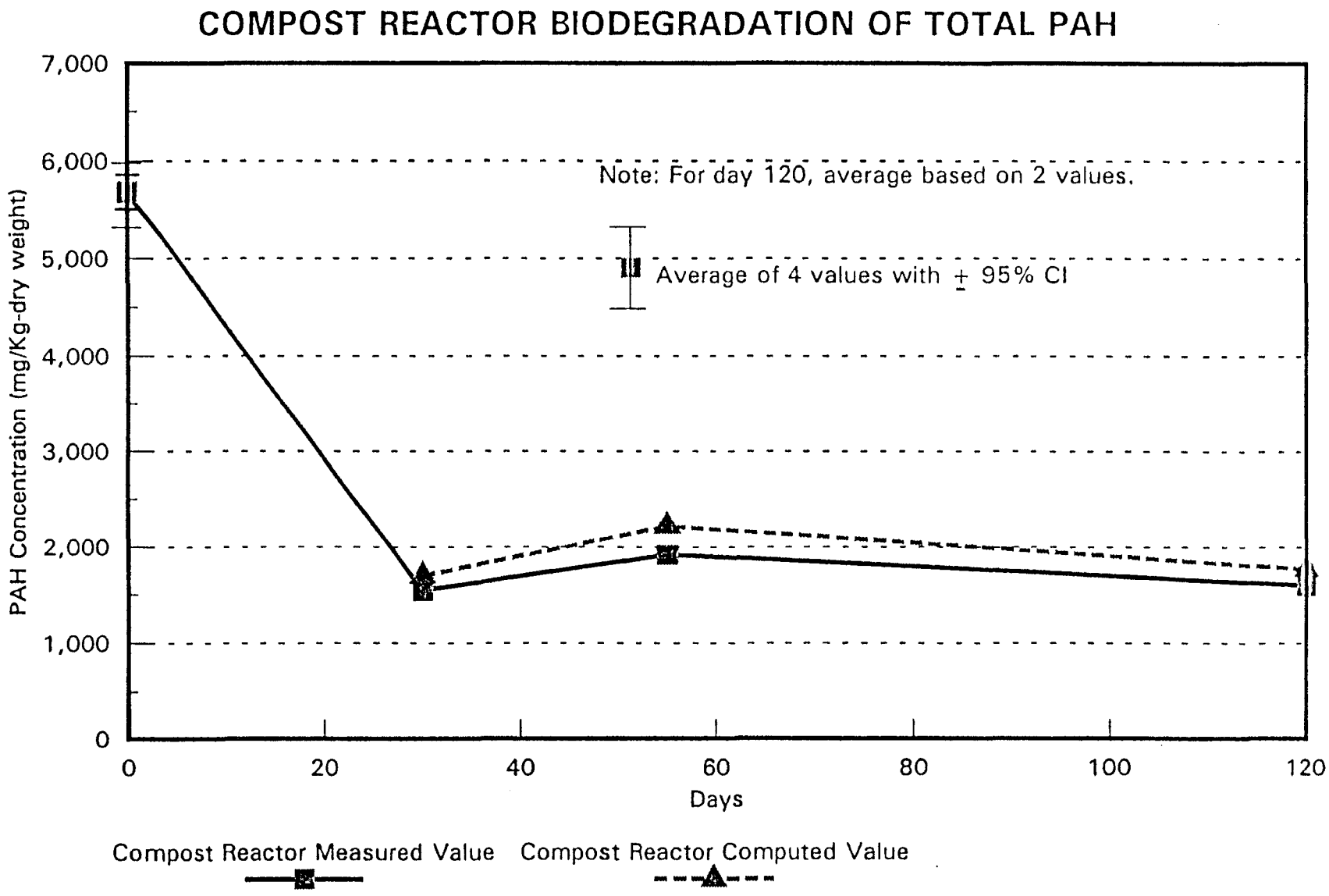

COMPOST REACTOR BIODEGRADATION OF TOTAL PAH
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Note: For day 120, average based on 2 values.
Average of 4 values with ± 95% CI
0
20
40
60
80
100
120
Days
Compost Reactor Measured Value
Compost Reactor Computed Value

FIGURE 5-10

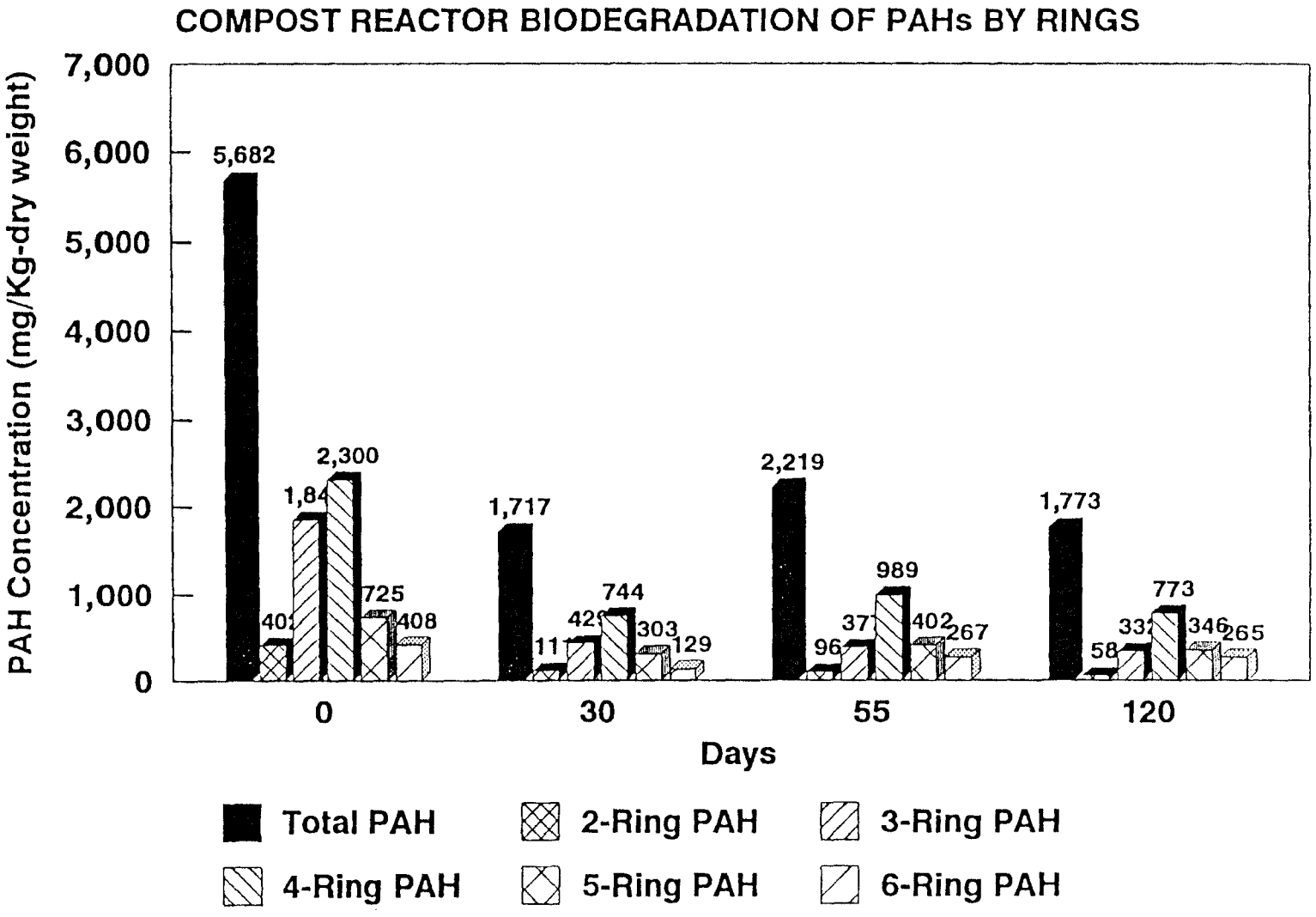
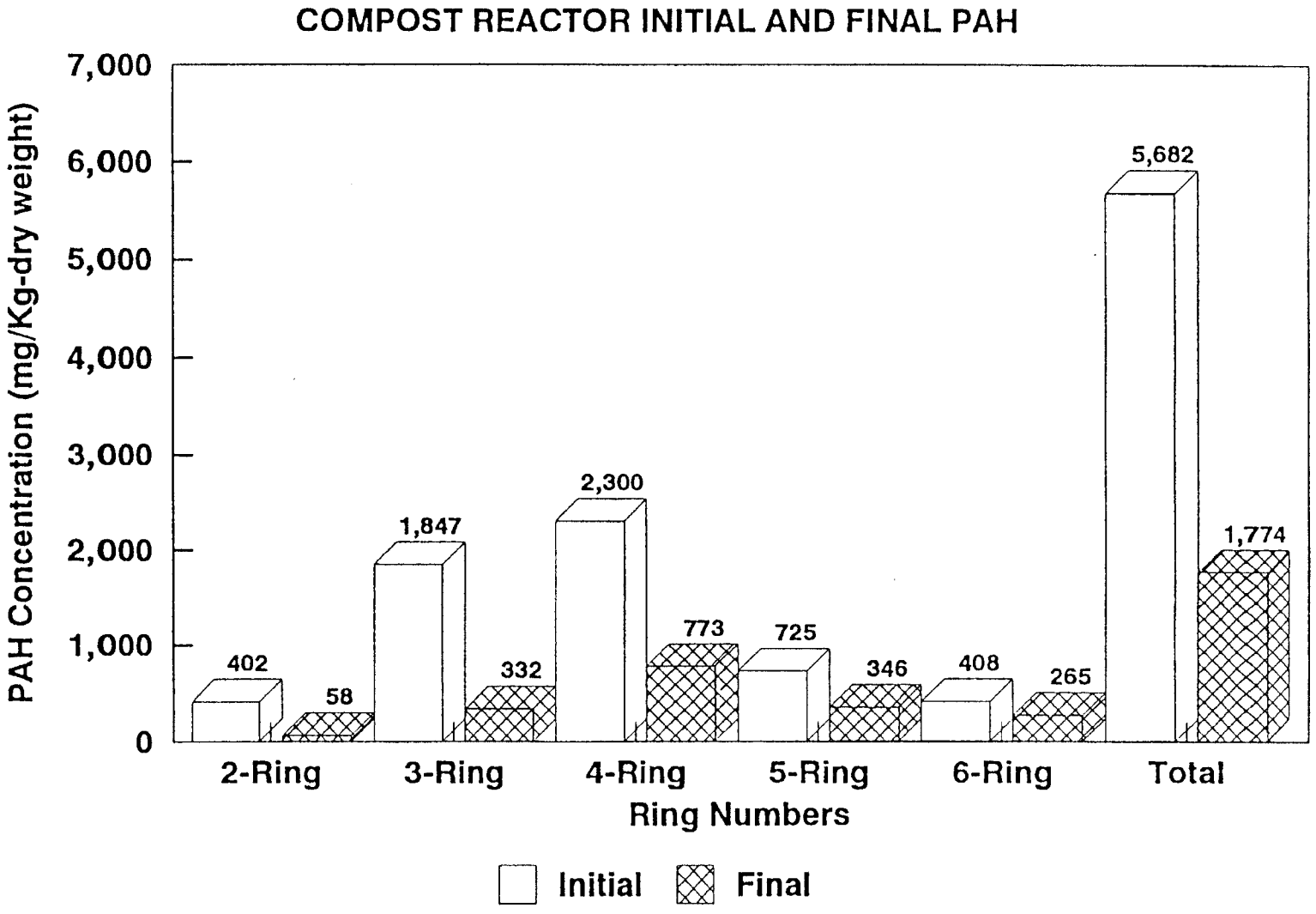

COMPOST REACTOR BIODEGRADATION OF PAHs BY RINGS
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
5,682
1,717
2,219
1,773
2,300
744
989
773
725
408
303
129
267
265
0
30
55
120
Days
Total PAH
2-Ring PAH
3-Ring PAH
4-Ring PAH
5-Ring PAH
6-Ring PAH

FIGURE 5-11


COMPOST REACTOR INITIAL AND FINAL PAH
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
402
58
1,847
332
2,300
773
725
346
408
265
5,682
1,774
2-Ring
3-Ring
4-Ring
5-Ring
6-Ring
Total
Ring Numbers
Initial
Final

6.0 DISCUSSION OF RESULTS

6.1 BIODEGRADATION SCREENING - SLURRY REACTOR TREATMENT

The results presented in section 5.1 show that the PAHs in the site soils are very biodegradable. The majority of PAH reductions occurred during the first month of treatment with degradation appearing to level off near 2000 mg/kg total PAH after the initial month of treatment. Degradation was directly proportional to the solubility of the PAH compounds with the most soluble compounds being degraded most completely. Table 5-6 summarized PAH removals and aqueous solubility data for different PAH compounds. In summary, the 2-ring and 3-ring PAHs were degraded to low ppm levels with average reductions of 97 percent and 89 percent, respectively. 4-ring PAHs were degraded approximately 69 percent and 5-ring and 6-ring PAH reductions were negligible (Table 6-1).

These results are consistent with those observed in other bioremediation studies conducted by ReTeC. In over 50 treatability studies conducted by ReTeC with PAH contaminated soils, there is always a plateau concentration at which the decrease in PAH concentration levels out. Research conducted by ReTeC on behalf of the Gas Research Institute (GRI) indicates that the level of the plateau concentration is influenced by the quantity and composition of non-aqueous phase liquid (NAPL) present in the soil and the quantity and composition of fines (i.e., silts and clays) in the soil. Appendix D includes a technical paper which provides additional information on this plateau phenomenom.

Although the slurry reactor study indicates the maximum level of treatment for the site soil will be approximately 2000 mg/kg total PAHs, this result needs further explanation. First, worst case soils were used in the treatability study. It is quite likely that full scale remediation would start at much lower soil PAH concentrations and treatment endpoints would be correspondingly lower. Second, the residual PAHs are not bioavailable to soil microorganisms for biodegradation due to mass transport limitations or insolubility. Thus, the water-mobile PAHs have been degraded and the remaining constituents are insoluble and virtually immobile. This "biostabilization" of the treated soil is illustrated by the data shown in Table 5-6 which shows that final aqueous phase concentrations in the slurry reactor were reduced to low ppb levels for all PAHs. The aqueous phase data shown in Table 5-6 would be even lower if the analytical samples had been filtered with a smaller 0.45 um filter to remove micro particulates (i.e., the micro particulates, which are not mobile, contributed significantly to the aqueous phase concentrations for the 4-ring, 5-ring, and 6-ring PAHs).

TABLE 6-1

BIODEGRADATION SUMMARY

PAHs	REMOVAL EFFICIENCIES[a] (%)		
	Slurry Reactor	Pan Reactor	Compost Reactor
2-Ring	97	85	86
3-Ring	89	66	82
4-Ring	69	56	66
5-Ring	0	64	52
6-Ring	3	50	35
TOTAL	**64**	**62**	**69**

NOTE: [a]Based on initial and final soil results.

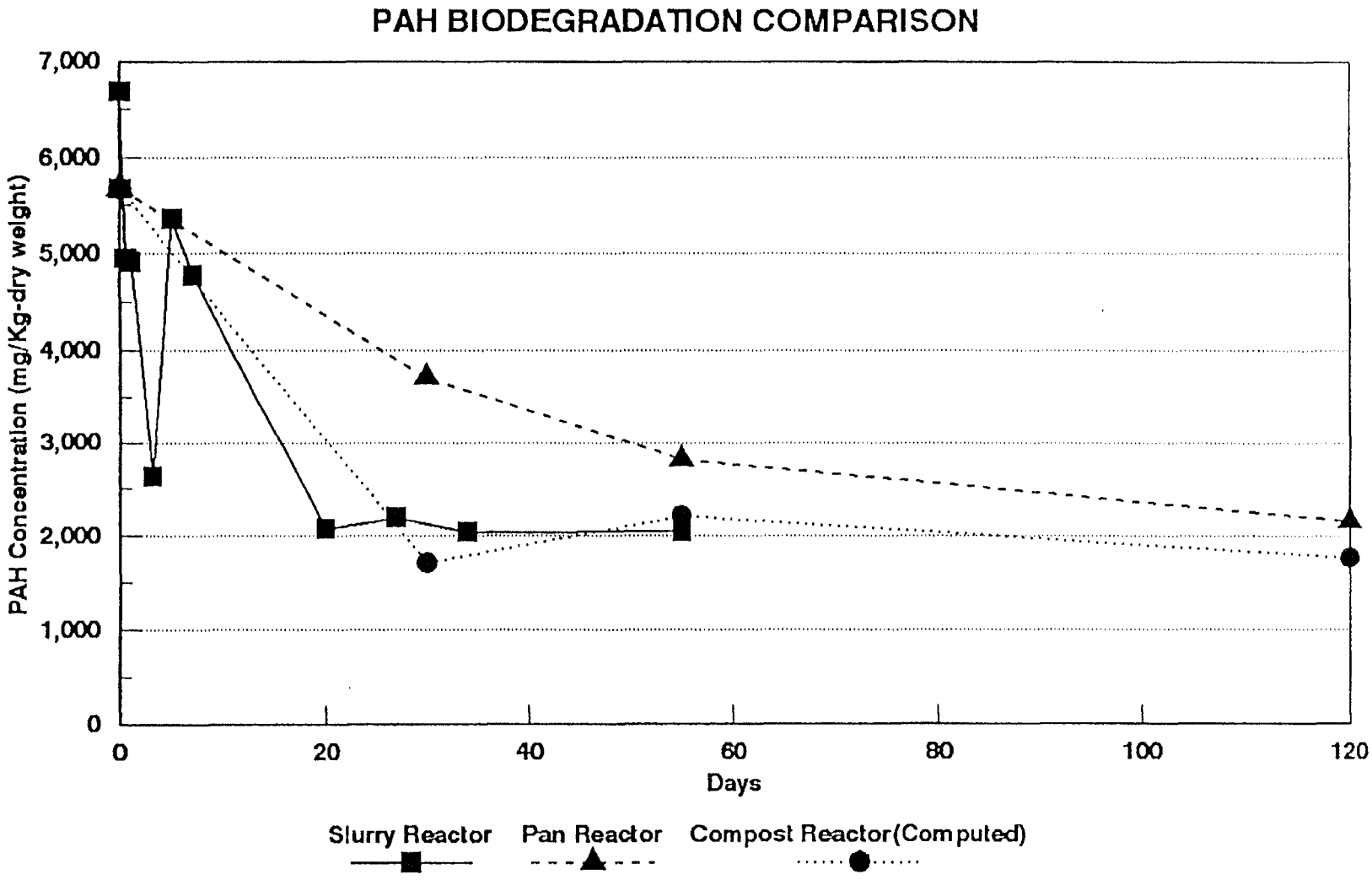
These micro particulates would not be present in leachate generated from water passing through the treated soil.

6.2 SOLID PHASE BIOREMEDIATION

Table 6-1 summarizes PAH reductions for the compost and pan reactors. The table shows that removal efficiencies for the compost and pan reactors were generally similar to those observed in the slurry reactors. One notable exception is removal efficiencies for the 5 and 6 ring PAHs. For these compounds, the compost and pan reactors both achieved measurable reductions in 5-ring and 6-ring PAHs.

Figure 6-1 compares PAH degradation with time for the slurry, pan, and compost reactors. As expected, the rate of degradation was slowest for the pan reactor. In all three cases, degradation appeared to level off near 2000 mg/kg total PAHs. As discussed previously, this plateau concentration represents a "biostabilized" soil, i.e.,the water-mobile PAHs have been degraded and the remaining constituents are insoluble and virtually immobile.

FIGURE 6-1


PAH BIODEGRADATION COMPARISON
PAH Concentration (mg/Kg-dry weight)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0
20
40
60
80
100
120
Days
Slurry Reactor
Pan Reactor
Compost Reactor(Computed)

7.0 SUMMARY AND CONCLUSIONS

Significant findings and observations of the laboratory testing are summarized below:

1. The site soil was determined to be defined as a "coarse-grained soil with clayey fines." This is based on the fact that the soil was measured to contain 8.6 percent coarse sand, 37.1 percent medium sand, 21.3 percent fine sand, 14 percent silt and 19 percent clay.

2. The site soil "as received" contained approximately 5,680 mg/Kg total PAH consisting of 7 percent 2-ring PAHs, 33 percent 3-ring PAHs, 40 percent 4-ring PAHs, 13 percent 5-ring PAHs and 7 percent 6-ring PAHs. The initial concentration of oil and grease was measured at 7,400 mg/Kg and the initial concentration of phenols (4-AAP) was measured at 1.6 mg/Kg. These values are typical of other sites which have been impacted by creosote wood treating operations.

3. Soil PAH concentrations in the slurry, compost, and pan reactors were reduced from 5700 ppm to a plateau of approximately 2000 mg/kg. At the termination of the studies, continued downward trends of PAH concentrations were observed in all of the reactors, although at much slower rates. This represents a PAH concentration whereby PAHs can no longer be desorbed from the soil and are unavailable to soil microorganisms for biodegradation. In essence, the treated soil can be viewed as being biostabilized.

4. Based on the above results, both solid phase bioremediation approaches (land treatment and composting) appear technically feasible for full-scale remediation of the site. Selection of a final alternative should be based on the space and schedule constraints placed on the full scale bioremediation system.

REFERENCES

[1] Brown, K.W., et. al. "Land Treatability of Refinery and Petrochemical Sludges." EPA Project Summary, EPA-600/52-83-074, November, 1983.

[2] ETR, 1983. "Land Treatment Practices in the Petroleum Industry." Prepared for the American Petroleum Institute, Washington, D.C.

[3] Loehr, R.C., et. al. "Land Treatment of an Oily Waste—Degradation, Immobilization, and Bioaccumulation." EPA/600/285/009, February 1985.

[4] Hunter J.V. and M.S. Finstein, 1986. "Microbial Decomposition of Hazardous Industrial Compounds Through Composting." Interim Project Report, The Rutgers University.

[5] Savage, G.M., et. al. "Disposing of Organic Wastes by Composting." Biocycle, January/February, 1985.

[6] Dahl and Associates, 1990. Phase II Property Evaluation Report, Southeast Minneapolis Yards, Report #MN776-003.

[7] American Society for Testing and Materials, 1985. Standard Test Method for Classification of Soils for Engineering Purposes. D 2487-85.

APPENDIX A

LABORATORY DATA FOR GRAIN-SIZE ANALYSIS

Appendix A1

Dry Sieve Analysis

DRY SIEVE ANALYSIS

ID: Dahl & Associates

DATE: Feburary 21, 1991

Air Dried Weight: 251.3 g

U.S. STANDARD SIEVE NO.	MESH OPENING (mm)	PERCENT FINER
4	4.76	100.0
10	2.00	73.14
20	0.84	73.14
40	0.42	54.68
60	0.25	25.35
80	0.18	11.98
100	0.149	8.56
200	0.075	4.74

DRY SIEVE ANALYSIS

ID: Dahl & Associates

DATE: Feburary 21, 1991

Air Dried Weight: 254.0 g

U.S. STANDARD SIEVE NO.	MESH OPENING (mm)	PERCENT FINER
4	4.76	100.0
10	2.00	91.81
20	0.84	73.66
40	0.42	53.82
60	0.25	25.12
80	0.18	13.86
100	0.149	9.13
200	0.075	5.00

Appendix A2

Hydrometer Analysis

HYDROMETER ANALYSIS

ID: Dahl & Associates

DATE: Feburary 22, 1991

Weight of Sample: 76.1 g dry weight, 91.5% passing No. 10 sieve

TIME (Min.)	PERCENT SUSPENDED (%)	PARTICLE DIAMETER (mm)
1/4	37.02	0.084
1/2	34.62	0.060
1	32.21	0.045
2	31.00	0.032
3	29.81	0.026
4	28.61	0.023
5	27.40	0.021
6	26.20	0.019
7	25.60	0.018
8	25.30	0.016
10	25.00	0.015
15	23.80	0.012
20	22.60	0.011
40	20.20	0.008
80	19.00	0.005

APPENDIX B

LABORATORY ANALYTICAL RESULTS

Appendix B1

Initial Soil Characterization

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2413-23289
MATRIX: SOIL

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE-SOIL-INITIAL 1 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 16

Naphthalene	410000
Acenaphthylene	ND
Acenaphthene	590000
Fluorene	330000
Phenanthrene	710000
Anthracene	390000
Fluoranthene	740000
Pyrene	800000
Benzo(a)anthracene	300000
Chrysene	510000
Benzo(b)fluoranthene	230000
Benzo(k)fluoranthene	110000
Benzo(a)pyrene	280000
Dibenzo(a,h)anthracene	130000
Benzo(g,h,i)perylene	210000
Indeno(1,2,3-cd)pyrene	210000
2-Methylnaphthalene/ Dibenzofuran	410000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 12000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2413-23290
MATRIX: SOIL

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE-SOIL-INITIAL 2 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 15

Naphthalene	420000
Acenaphthylene	ND
Acenaphthene	590000
Fluorene	310000
Phenanthrene	640000
Anthracene	400000
Fluoranthene	750000
Pyrene	730000
Benzo(a)anthracene	330000
Chrysene	510000
Benzo(b)fluoranthene	230000
Benzo(k)fluoranthene	120000
Benzo(a)pyrene	270000
Dibenzo(a,h)anthracene	130000
Benzo(g,h,i)perylene	200000
Indeno(1,2,3-cd)pyrene	200000
2-Methylnaphthalene/ Dibenzofuran	220000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 12000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2413-23291
MATRIX: SOIL

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE-SOIL-INITIAL 3 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 15

Naphthalene	370000
Acenaphthylene	ND
Acenaphthene	520000
Fluorene	220000
Phenanthrene	550000
Anthracene	350000
Fluoranthene	680000
Pyrene	710000
Benzo(a)anthracene	330000
Chrysene	480000
Benzo(b)fluoranthene	220000
Benzo(k)fluoranthene	110000
Benzo(a)pyrene	260000
Dibenzo(a,h)anthracene	120000
Benzo(g,h,i)perylene	200000
Indeno(1,2,3-cd)pyrene	200000
2-Methylnaphthalene/ Dibenzofuran	360000
Carbazole	ND

NOTE:
- ND (None Detected, lower detectable limit = 12000 ug/kg)dry weight
- ND* (None Detected, lower detectable limit = ug/kg)dry weight
- ND** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*** (None Detected, lower detectable limit = ug/kg)dry weight
- ND**** (None Detected, lower detectable limit = ug/kg)dry weight
- ND***** (None Detected, lower detectable limit = ug/kg)dry weight
- ND****** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*******(None Detected, lower detectable limit = ug/kg)dry weight
- J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2413-23292
MATRIX: SOIL

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE-SOIL-INITIAL 4 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 17

Naphthalene	410000
Acenaphthylene	ND
Acenaphthene	530000
Fluorene	240000
Phenanthrene	600000
Anthracene	370000
Fluoranthene	710000
Pyrene	820000
Benzo(a)anthracene	320000
Chrysene	480000
Benzo(b)fluoranthene	210000
Benzo(k)fluoranthene	100000
Benzo(a)pyrene	270000
Dibenzo(a,h)anthracene	110000
Benzo(g,h,i)perylene	200000
Indeno(1,2,3-cd)pyrene	190000
2-Methylnaphthalene/ Dibenzofuran	210000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 13000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. DATE RECEIVED: 2/20/91
LAB #: 2426-23396
MATRIX : SOLID

SAMPLE ID : CRESOTE-SOIL-INITIAL 5/1/SOIL 2-19-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Oil and Grease	2/26/91	7400	50	mg/kg

NOTE: ND (None Detected)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. **DATE RECEIVED:** 2/20/91
LAB #: 2413-23289
MATRIX : SOIL

SAMPLE ID : CRESOTE-SOIL-INITIAL 1 2-19-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Percent Water	2/20/91	16		%
Total Recoverable Phenolics	2/20- 2/21/91	1.6	0.30	mg/kg

NOTE: ND (None Detected)
Results are on a dry weight basis.

REMEDIATION
TECHNOLOGIES INC

3040 William Pitt Way
Pittsburgh, PA 15238
Telephone: (412) 826-3340
Facsimile: (412) 826-3409

DAHL ASSOCIATES I R RESULTS
APRIL 24,1991

Extract sample 2655-25799 exhibits IR absorptions characteristic of a mixture of high molecular weight coal tar hydrocarbons, typical of the "heavy" ends of a creosote fraction. Also detected were the same components found in the Freon blank, viz. a dialkyl phthalate ester and and aliphatic hydrocarbon (petroleum) oil. Relative IR absorptions indicate more aliphatic hydrocarbon oil in the blank than in the soil extracts (?).

Appendix B2

Slurry Reactor Results

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2413-23293
MATRIX: SOIL

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE-SLURRY-15 MIN.-SOIL 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 33

Naphthalene	540000
Acenaphthylene	ND
Acenaphthene	800000
Fluorene	340000
Phenanthrene	880000
Anthracene	450000
Fluoranthene	850000
Pyrene	940000
Benzo(a)anthracene	310000
Chrysene	540000
Benzo(b)fluoranthene	220000
Benzo(k)fluoranthene	110000
Benzo(a)pyrene	270000
Dibenzo(a,h)anthracene	87000
Benzo(g,h,i)perylene	180000
Indeno(1,2,3-cd)pyrene	160000
2-Methylnaphthalene/ Dibenzofuran	620000
Carbazole	ND

NOTE:
- ND (None Detected, lower detectable limit = 16000 ug/kg)dry weight
- ND* (None Detected, lower detectable limit = ug/kg)dry weight
- ND** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*** (None Detected, lower detectable limit = ug/kg)dry weight
- ND**** (None Detected, lower detectable limit = ug/kg)dry weight
- ND***** (None Detected, lower detectable limit = ug/kg)dry weight
- ND****** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*******(None Detected, lower detectable limit = ug/kg)dry weight
- J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2414-23298
MATRIX: WATER

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/21/91
DATE ANALYZED: 2/25/91

SAMPLE ID: CRESOTE-SLURRY-15 MIN.-WATER 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 610 LIST - HPLC

Naphthalene	630
Acenaphthylene	22
Acenaphthene	370
Fluorene	140
Phenanthrene	140
Anthracene	22
Fluoranthene	33
Pyrene	39
Benzo(a)anthracene	5.6
Chrysene	8.9
Benzo(b)fluoranthene	3.4
Benzo(k)fluoranthene	1.8
Benzo(a)pyrene	4.2
Dibenzo(a,h)anthracene	0.74
Benzo(g,h,i)perylene	2.9
Indeno(1,2,3-cd)pyrene	2.4
2-Methylnaphthalene/ Dibenzofuran	270
Carbazole	39

NOTE:
ND (None Detected, lower detectable limit = ug/l)as rec'd
ND* (None Detected, lower detectable limit = ug/l)as rec'd
ND** (None Detected, lower detectable limit = ug/l)as rec'd
ND*** (None Detected, lower detectable limit = ug/l)as rec'd
ND**** (None Detected, lower detectable limit = ug/l)as rec'd
ND***** (None Detected, lower detectable limit = ug/l)as rec'd
ND******(None Detected, lower detectable limit = ug/l)as rec'd
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	95	(40-140)	(30-130)
2-Fluorobiphenyl	Interference	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. DATE RECEIVED: 2/20/91
LAB #: 2414-23298
MATRIX : WATER

SAMPLE ID : CRESOTE-SLURRY-15 MIN.-WATER 2-19-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Total Recoverable Phenolics	2/20- 2/21/91	0.012	0.005	mg/l

NOTE: ND (None Detected)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2427-23401
MATRIX: SOIL

DATE RECEIVED: 2/21/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE SLURRY 12H SOIL 2-19-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 37

Naphthalene	390000
Acenaphthylene	ND
Acenaphthene	550000
Fluorene	230000
Phenanthrene	610000
Anthracene	310000
Fluoranthene	620000
Pyrene	700000
Benzo(a)anthracene	240000
Chrysene	390000
Benzo(b)fluoranthene	170000
Benzo(k)fluoranthene	85000
Benzo(a)pyrene	210000
Dibenzo(a,h)anthracene	100000
Benzo(g,h,i)perylene	170000
Indeno(1,2,3-cd)pyrene	170000
2-Methylnaphthalene/ Dibenzofuran	350000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 17000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2428-23406
MATRIX: SOIL

DATE RECEIVED: 2/20/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE SLURRY 24H SOIL/2-20-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 34

Naphthalene	410000
Acenaphthylene	ND
Acenaphthene	580000
Fluorene	250000
Phenanthrene	660000
Anthracene	360000
Fluoranthene	630000
Pyrene	490000
Benzo(a)anthracene	220000
Chrysene	430000
Benzo(b)fluoranthene	170000
Benzo(k)fluoranthene	88000
Benzo(a)pyrene	200000
Dibenzo(a,h)anthracene	99000
Benzo(g,h,i)perylene	150000
Indeno(1,2,3-cd)pyrene	170000
2-Methylnaphthalene/ Dibenzofuran	360000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 16000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

10,307,006

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2437-23477
MATRIX: SOIL

DATE RECEIVED: 2/25/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE SLURRY 72H SOIL 2-22-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 25

Naphthalene	200000
Acenaphthylene	ND
Acenaphthene	270000
Fluorene	140000
Phenanthrene	280000
Anthracene	180000
Fluoranthene	350000
Pyrene	380000
Benzo(a)anthracene	140000
Chrysene	220000
Benzo(b)fluoranthene	87000
Benzo(k)fluoranthene	50000
Benzo(a)pyrene	120000
Dibenzo(a,h)anthracene	43000
Benzo(g,h,i)perylene	82000
Indeno(1,2,3-cd)pyrene	79000
2-Methylnaphthalene/ Dibenzofuran	140000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 14000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

276000

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2441-23501
MATRIX: SOIL

DATE RECEIVED: 2/25/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE SLURRY 120H SOIL 2-24-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 39

Naphthalene	87000
Acenaphthylene	ND
Acenaphthene	640000
Fluorene	140000
Phenanthrene	54000
Anthracene	380000
Fluoranthene	900000
Pyrene	1000000
Benzo(a)anthracene	340000
Chrysene	570000
Benzo(b)fluoranthene	250000
Benzo(k)fluoranthene	120000
Benzo(a)pyrene	300000
Dibenzo(a,h)anthracene	130000
Benzo(g,h,i)perylene	220000
Indeno(1,2,3-cd)pyrene	220000
2-Methylnaphthalene/ Dibenzofuran	210000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 17000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
ND****** (None Detected, lower detectable limit = ug/kg)dry weight
ND*******(None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

5,461,000

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2444-23518
MATRIX: SOIL

DATE RECEIVED: 2/26/91
DATE EXTRACTED: 2/27/91
DATE ANALYZED: 3/01/91

SAMPLE ID: CRESOTE SLURRY 168H SOIL 2-26-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 39

Naphthalene	39000
Acenaphthylene	ND
Acenaphthene	400000
Fluorene	34000
Phenanthrene	38000
Anthracene	61000
Fluoranthene	870000
Pyrene	1100000
Benzo(a)anthracene	350000
Chrysene	580000
Benzo(b)fluoranthene	230000
Benzo(k)fluoranthene	140000
Benzo(a)pyrene	320000
Dibenzo(a,h)anthracene	140000
Benzo(g,h,i)perylene	230000
Indeno(1,2,3-cd)pyrene	230000
2-Methylnaphthalene/ Dibenzofuran	85000
Carbazole	ND

NOTE:
- ND (None Detected, lower detectable limit = 17000 ug/kg)dry weight
- ND* (None Detected, lower detectable limit = ug/kg)dry weight
- ND** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*** (None Detected, lower detectable limit = ug/kg)dry weight
- ND**** (None Detected, lower detectable limit = ug/kg)dry weight
- ND***** (None Detected, lower detectable limit = ug/kg)dry weight
- ND****** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*******(None Detected, lower detectable limit = ug/kg)dry weight
- J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

4,617,000

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB#: 2506-24070
MATRIX: SOIL

DATE RECEIVED: 3/13/91
DATE EXTRACTED: 3/13/91
DATE ANALYZED: 3/14/91

SAMPLE ID: CRESOTE SLURRY SOIL D20 3-11-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 49

Naphthalene	31000
Acenaphthylene	ND
Acenaphthene	58000
Fluorene	4400
Phenanthrene	11000
Anthracene	7000
Fluoranthene	150000
Pyrene	420000
Benzo(a)anthracene	82000
Chrysene	220000
Benzo(b)fluoranthene	230000
Benzo(k)fluoranthene	100000
Benzo(a)pyrene	280000
Dibenzo(a,h)anthracene	98000
Benzo(g,h,i)perylene	200000
Indeno(1,2,3-cd)pyrene	180000
2-Methylnaphthalene/ Dibenzofuran	210000
Carbazole	ND

NOTE:
- ND (None Detected, lower detectable limit = 10000 ug/kg)dry weight
- ND* (None Detected, lower detectable limit = ug/kg)dry weight
- ND** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*** (None Detected, lower detectable limit = ug/kg)dry weight
- ND**** (None Detected, lower detectable limit = ug/kg)dry weight
- ND***** (None Detected, lower detectable limit = ug/kg)dry weight
- J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: DAHL & ASSOCIATES
and
REMEDIATION TECHNOLOGIES INC.

LAB #: 2528-24292
MATRIX: SOIL

DATE RECEIVED: 3/18/91
DATE EXTRACTED: 3/23/91
DATE ANALYZED: 4/04/91

SAMPLE ID: CRESOTE-SLURRY-WK 4 SOIL 3-18-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 48

Naphthalene	27000
Acenaphthylene	130000
Acenaphthene	110000
Fluorene	8800
Phenanthrene	13000
Anthracene	10000
Fluoranthene	140000
Pyrene	480000
Benzo(a)anthracene	85000
Chrysene	190000
Benzo(b)fluoranthene	200000
Benzo(k)fluoranthene	100000
Benzo(a)pyrene	240000
Dibenzo(a,h)anthracene	78000
Benzo(g,h,i)perylene	200000
Indeno(1,2,3-cd)pyrene	190000
2-Methylnaphthalene/ Dibenzofuran	140000
Carbazole	ND

NOTE:
- ND (None Detected, lower detectable limit = 8500 ug/kg)dry weight
- ND* (None Detected, lower detectable limit = ug/kg)dry weight
- ND** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*** (None Detected, lower detectable limit = ug/kg)dry weight
- ND**** (None Detected, lower detectable limit = ug/kg)dry weight
- ND***** (None Detected, lower detectable limit = ug/kg)dry weight
- J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: DAHL & ASSOCIATES AND
REMEDIATION TECHNOLOGIES INC.
LAB #: 2566-24727
MATRIX: SOIL

DATE RECEIVED: 3/26/91
DATE EXTRACTED: 4/02/91
DATE ANALYZED: 4/05/91

SAMPLE ID: CRESOTE SLURRY WK5 3-25-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 48

Naphthalene	15000
Acenaphthylene	99000
Acenaphthene	76000
Fluorene	9300
Phenanthrene	11000
Anthracene	9200
Fluoranthene	150000
Pyrene	430000
Benzo(a)anthracene	86000
Chrysene	210000
Benzo(b)fluoranthene	210000
Benzo(k)fluoranthene	100000
Benzo(a)pyrene	270000
Dibenzo(a,h)anthracene	85000
Benzo(g,h,i)perylene	150000
Indeno(1,2,3-cd)pyrene	140000
2-Methylnaphthalene/ Dibenzofuran	ND
Carbazole	ND

NOTE:
- ND (None Detected, lower detectable limit = 11000 ug/kg)dry weight
- ND* (None Detected, lower detectable limit = ug/kg)dry weight
- ND** (None Detected, lower detectable limit = ug/kg)dry weight
- ND*** (None Detected, lower detectable limit = ug/kg)dry weight
- ND**** (None Detected, lower detectable limit = ug/kg)dry weight
- ND***** (None Detected, lower detectable limit = ug/kg)dry weight
- J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2656-25804
MATRIX: SOLID

DATE RECEIVED: 4/17/91
DATE EXTRACTED: 4/18/91
DATE ANALYZED: 4/19/91

SAMPLE ID: CRESOTE SLURRY FINAL SOIL 1 4-15-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 46

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	16000	7600
Acenaphthylene	130000	7600
Acenaphthene	75000	7600
Fluorene	6200	1500
Phenanthrene	12000	3800
Anthracene	6700	3800
Fluoranthene	130000	1500
Pyrene	420000	1500
Benzo(a)anthracene	88000	150
Chrysene	190000	1100
Benzo(b)fluoranthene	260000	150
Benzo(k)fluoranthene	120000	150
Benzo(a)pyrene	330000	150
Dibenzo(a,h)anthracene	120000	230
Benzo(g,h,i)perylene	240000	380
Indeno(1,2,3-cd)pyrene	240000	380
2-Methylnaphthalene/ Dibenzofuran	140000	7600
Carbazole	ND	7600

NOTE: ND (None Detected)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. DATE RECEIVED: 4/17/91
LAB #: 2656-25804
MATRIX : SOLID

SAMPLE ID : CRESOTE SLURRY FINAL SOIL 1 4-15-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Percent Water	4/17/91	46		%
Total Recoverable Phenolics	4/18- 4/22/91	4.6	0.90	mg/kg

NOTE: ND (None Detected)
Results are on a dry wt. basis

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2656-25805
MATRIX: SOLID

DATE RECEIVED: 4/17/91
DATE EXTRACTED: 4/18/91
DATE ANALYZED: 4/20/91

SAMPLE ID: CRESOTE SLURRY FINAL SOIL 2 4-15-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 42

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	12000	7100
Acenaphthylene	120000	7100
Acenaphthene	96000	7100
Fluorene	8500	1400
Phenanthrene	11000	3600
Anthracene	6700	3600
Fluoranthene	130000	1400
Pyrene	420000	1400
Benzo(a)anthracene	120000	140
Chrysene	190000	1100
Benzo(b)fluoranthene	240000	140
Benzo(k)fluoranthene	110000	140
Benzo(a)pyrene	310000	140
Dibenzo(a,h)anthracene	110000	210
Benzo(g,h,i)perylene	210000	360
Indeno(1,2,3-cd)pyrene	220000	360
2-Methylnaphthalene/ Dibenzofuran	130000	7100
Carbazole	ND	7100

NOTE: ND (None Detected)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. **DATE RECEIVED:** 4/17/91
LAB #: 2656-25805
MATRIX : SOLID

SAMPLE ID : CRESOTE SLURRY FINAL SOIL 2 4-15-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Percent Water	4/17/91	42		%

NOTE: ND (None Detected)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2656-25806
MATRIX: SOLID

DATE RECEIVED: 4/17/91
DATE EXTRACTED: 4/18/91
DATE ANALYZED: 4/20/91

SAMPLE ID: CRESOTE SLURRY FINAL SOIL 3 4-15-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 43

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	11000	7100
Acenaphthylene	89000	7100
Acenaphthene	82000	7100
Fluorene	6800	1400
Phenanthrene	9500	3600
Anthracene	6000	3600
Fluoranthene	110000	1400
Pyrene	350000	1400
Benzo(a)anthracene	87000	140
Chrysene	200000	1100
Benzo(b)fluoranthene	310000	140
Benzo(k)fluoranthene	100000	140
Benzo(a)pyrene	290000	140
Dibenzo(a,h)anthracene	110000	210
Benzo(g,h,i)perylene	200000	360
Indeno(1,2,3-cd)pyrene	210000	360
2-Methylnaphthalene/ Dibenzofuran	120000	7100
Carbazole	ND	7100

NOTE: ND (None Detected)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. DATE RECEIVED: 4/17/91
LAB #: 2656-25806
MATRIX : SOLID

SAMPLE ID : CRESOTE SLURRY FINAL SOIL 3 4-15-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Percent Water	4/17/91	43		%

NOTE: ND (None Detected)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2656-25807
MATRIX: SOLID

DATE RECEIVED: 4/17/91
DATE EXTRACTED: 4/18/91
DATE ANALYZED: 4/20/91

SAMPLE ID: CRESOTE SLURRY FINAL SOIL 4 4-15-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 43

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	7800	7200
Acenaphthylene	56000	7200
Acenaphthene	52000	7200
Fluorene	4200	1400
Phenanthrene	6200	3600
Anthracene	3700	3600
Fluoranthene	69000	1400
Pyrene	210000	1400
Benzo(a)anthracene	52000	140
Chrysene	120000	1100
Benzo(b)fluoranthene	190000	140
Benzo(k)fluoranthene	64000	140
Benzo(a)pyrene	180000	140
Dibenzo(a,h)anthracene	64000	210
Benzo(g,h,i)perylene	130000	360
Indeno(1,2,3-cd)pyrene	130000	360
2-Methylnaphthalene/ Dibenzofuran	76000	7200
Carbazole	ND	7200

NOTE: ND (None Detected)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. DATE RECEIVED: 4/17/91
LAB #: 2656-25807
MATRIX : SOLID

SAMPLE ID : CRESOTE SLURRY FINAL SOIL 4 4-15-91

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Percent Water	4/17/91	43		%

NOTE: ND (None Detected)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2657-25812
MATRIX: WATER

DATE RECEIVED: 4/17/91
DATE EXTRACTED: 4/22/91
DATE ANALYZED: 4/25/91

SAMPLE ID: CRESOTE SLURRY FINAL WATER 4-15-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

PARAMETER	RESULT (ug/l)	DETECTION LIMIT
Naphthalene	21	2.3
Acenaphthylene	ND	2.3
Acenaphthene	ND	2.3
Fluorene	ND	0.23
Phenanthrene	1.4	0.58
Anthracene	0.94	0.58
Fluoranthene	7.3	0.23
Pyrene	28	0.23
Benzo(a)anthracene	2.6	0.02
Chrysene	5.6	0.17
Benzo(b)fluoranthene	6.9	0.02
Benzo(k)fluoranthene	2.7	0.02
Benzo(a)pyrene	7.8	0.02
Dibenzo(a,h)anthracene	2.4	0.03
Benzo(g,h,i)perylene	5.7	0.06
Indeno(1,2,3-cd)pyrene	6.3	0.06
2-Methylnaphthalene/ Dibenzofuran	30	2.3
Carbazole	ND	2.3

NOTE: ND (None Detected)as rec'd
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Interference	(40-140)	(30-130)
2-Fluorobiphenyl	Interference	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY : REMEDIATION TECHNOLOGIES INC. DATE RECEIVED: 4/17/91
LAB #: 2657-25812
MATRIX : WATER

SAMPLE ID : CRESOTE SLURRY FINAL WATER 4-15-91
(FILTERED)

ANALYTICAL REPORT

PARAMETER	PREPARATION - ANALYSIS DATE	RESULT	DETECTION LIMIT	
Total Recoverable Phenolics	4/25/91	ND	0.025	mg/l

NOTE: ND (None Detected)

Table 1

Number of Total and PAH degrading microorganisms in
Dahl Associates samples
The samples were analyzed in duplicate.

Sample ID[1]	Total Numbers cells/g of soil[2] (10^5)	PAH Degraders cells/g of soil[2] (10^5)
Creosote slurry D-20		
Mean	614.0	75.8
Std. Dev.	15.0	10.3
Creosote slurry wk4		
Mean	0.8	< 0.0001
Std. Dev.	0.2	
Creosote slurry wk5		
Mean	0.3	< 0.0001
Std. Dev.	0.08	
Creosote slurry final soil		
Mean	1.6	< 0.0001
Std. Dev.	0.4	

[1] Results represent the mean value and standard deviation of duplicate samples.

[2] Reported as cells/g sample on a dry weight basis.

Released by: Heidi Anderson

Heidi Anderson
Microbiologist

Table 1

Number of Total and PAH degrading microorganisms in
Dahl Associates slurry sample (collected on 3-5).
The sample was analyzed in duplicate.

Sample ID[1]	Total Numbers cells/g of soil[2] (10^6)	PAH Degraders cells/g of soil[2] (10^6)
Creosote slurry 338H		
Mean	59.9	18.5
Std. Dev.	1.6	0.2

[1] Results represent the mean value and standard deviation of duplicate samples.

[2] Reported as cells/g sample on a dry weight basis.

Released by: Heidi Anderson

Heidi Anderson
Microbiologist

REIEC

Table 1

Number of Total and PAH degrading microorganisms in
Dahl Associates soil and slurry samples (collected on 2-19).
Each sample was analyzed in duplicate.

Sample ID[1]	Total Numbers cells/g of soil[2] (10^6)	PAH Degraders cells/g of soil[2] (10^4)
Creosote-soil ini1		
Mean	2.3	< 0.1 (10^2)
Std. Dev.	0.2	
Creosote-soil ini2		
Mean	1.9	< 0.1 (10^2)
Std. Dev.	0.3	
Creosote slurry 12H		
Mean	35.3	0.3
Std. Dev.	7.4	0.08
Creosote-slurry 24H		
Mean	41.8	0.8
Std. Dev.	1.1	0.1
Creosote-slurry 72H		
Mean	45.0	< 0.1 (10^2)
Std. Dev.	2.6	
Creosote slurry 120H		
Mean	72.2	< 0.1 (10^2)
Std. Dev.	0.4	
Creosote slurry 168H		
Mean	52.0	< 0.1 (10^2)
Std. Dev.	8.4	

[1] Results represent the mean value and standard deviation of duplicate samples.

[2] Reported as cells/g sample on a dry weight basis.

Released by: Heidi Anderson

Heidi Anderson
Microbiologist

REMEDIATION
TECHNOLOGIES INC

3040 William Pitt Way
Pittsburgh, PA 15238
Telephone: (412) 826-3340
Facsimile: (412) 826-3409

DAHL ASSOCIATES I R RESULTS
MARCH 5,1991

The sample exhibits IR absorptions characteristic of a mixture of polynuclear aromatic hydrocarbons typical of a coal tar creosote; a small amount of an aliphatic hydrocarbon (petroleum oil) is also indicated. The ratio of creosote/petroleum oil is estimated to be 90/10, assuming a mixture of Grade 1 creosote and a mineral oil is present.

Also detected in the sample were carbonyl absorptions in the 5.9 - 6.0 micrometer spectral region, indicating the petroleum oil and the creosote components to be partially oxidized.

Appendix B3

Pan Reactor Results

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: DAHL & ASSOCIATES AND
REMEDIATION TECHNOLOGIES INC.
LAB #: 2566-24728
MATRIX: SOIL

DATE RECEIVED: 3/26/91
DATE EXTRACTED: 4/02/91
DATE ANALYZED: 4/05/91

SAMPLE ID: CRESOTE PAN MONTH 1 3-25-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 16

Naphthalene	160000
Acenaphthylene	220000
Acenaphthene	380000
Fluorene	130000
Phenanthrene	350000
Anthracene	230000
Fluoranthene	530000
Pyrene	520000
Benzo(a)anthracene	230000
Chrysene	330000
Benzo(b)fluoranthene	140000
Benzo(k)fluoranthene	78000
Benzo(a)pyrene	180000
Dibenzo(a,h)anthracene	56000
Benzo(g,h,i)perylene	100000
Indeno(1,2,3-cd)pyrene	81000
2-Methylnaphthalene/ Dibenzofuran	190000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 10000 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2729-26452
MATRIX: SOLID

DATE RECEIVED: 4/25/91
DATE EXTRACTED: 5/01/91
DATE ANALYZED: 5/01/91

SAMPLE ID: CRESOTE PAN MONTH 2 4-25-91 DAHL Associates

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 17

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	64000	2500
Acenaphthylene	190000	2500
Acenaphthene	220000	2500
Fluorene	49000	500
Phenanthrene	110000	1300
Anthracene	120000	1300
Fluoranthene	360000	500
Pyrene	680000	500
Benzo(a)anthracene	170000	50
Chrysene	230000	380
Benzo(b)fluoranthene	120000	50
Benzo(k)fluoranthene	62000	50
Benzo(a)pyrene	150000	50
Dibenzo(a,h)anthracene	55000	75
Benzo(g,h,i)perylene	110000	130
Indeno(1,2,3-cd)pyrene	130000	130
2-Methylnaphthalene/ Dibenzofuran	83000	2500
Carbazole	ND	2500

NOTE: ND (None Detected)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 3175-30584
MATRIX: SOLID

DATE RECEIVED: 7/17/91
DATE EXTRACTED: 7/17/91
DATE ANALYZED: 7/27/91

SAMPLE ID: CRESOTE PAN FINAL 6-27-91

POLYNUCLEAR AROMATIC HYDROCARBONS -- METHOD 8310

% MOISTURE: 16

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	46000	10000
Acenaphthylene	83000	10000
Acenaphthene	160000	10000
Fluorene	29000	2000
Phenanthrene	46000	5000
Anthracene	86000	5000
Fluoranthene	210000	2000
Pyrene	410000	2000
Benzo(a)anthracene	95000	200
Chrysene	140000	1500
Benzo(b)fluoranthene	63000	200
Benzo(k)fluoranthene	36000	200
Benzo(a)pyrene	92000	200
Dibenzo(a,h)anthracene	20000	300
Benzo(g,h,i)perylene	45000	500
Indeno(1,2,3-cd)pyrene	92000	500
2-Methylnaphthalene/ Dibenzofuran	50000	10000
Carbazole	ND	10000

NOTE: ND (None Detected) dry weight
J (Detected, but below quantitation limit; estimated value)

SURROGATE RECOVERY:	ACCEPTABLE LIMITS WATER	SOLID	%
Benzo(e)pyrene	(33-128)	(35-138)	Diluted Out
2-Fluorobiphenyl	(28-111)	(41-137)	Diluted Out

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 3043-29326
MATRIX: SOLID

DATE RECEIVED: 6/27/91
DATE EXTRACTED: 6/28/91
DATE ANALYZED: 7/10/91

SAMPLE ID: CRESOTE PAN FINAL 6-27-91

POLYNUCLEAR AROMATIC HYDROCARBONS -- METHOD 8310

% MOISTURE: 16

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	71000	8300
Acenaphthylene	220000	8300
Acenaphthene	380000	8300
Fluorene	43000	1700
Phenanthrene	94000	4200
Anthracene	130000	4200
Fluoranthene	260000	1700
Pyrene	540000	1700
Benzo(a)anthracene	140000	170
Chrysene	220000	1200
Benzo(b)fluoranthene	94000	170
Benzo(k)fluoranthene	56000	170
Benzo(a)pyrene	110000	170
Dibenzo(a,h)anthracene	55000	250
Benzo(g,h,i)perylene	72000	420
Indeno(1,2,3-cd)pyrene	200000	420
2-Methylnaphthalene/ Dibenzofuran	74000	8300
Carbazole	ND	8300

NOTE: ND (None Detected) dry weight
J (Detected, but below quantitation limit; estimated value)

SURROGATE RECOVERY:	ACCEPTABLE LIMITS WATER	SOLID	%
Benzo(e)pyrene	(40-140)	(30-130)	Diluted Out
2-Fluorobiphenyl	(40-140)	(30-130)	Diluted Out

Appendix B4

Compost Reactor Results

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: DAHL & ASSOCIATES AND
REMEDIATION TECHNOLOGIES INC.

LAB #: 2566-24729
MATRIX: SOIL

DATE RECEIVED: 3/26/91
DATE EXTRACTED: 4/02/91
DATE ANALYZED: 4/05/91

SAMPLE ID: CRESOTE COMPOST MONTH 1 3-25-91

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 25

Naphthalene	100000
Acenaphthylene	76000
Acenaphthene	89000
Fluorene	49000
Phenanthrene	100000
Anthracene	72000
Fluoranthene	190000
Pyrene	210000
Benzo(a)anthracene	110000
Chrysene	160000
Benzo(b)fluoranthene	85000
Benzo(k)fluoranthene	45000
Benzo(a)pyrene	110000
Dibenzo(a,h)anthracene	33000
Benzo(g,h,i)perylene	67000
Indeno(1,2,3-cd)pyrene	49000
2-Methylnaphthalene/ Dibenzofuran	100000
Carbazole	ND

NOTE:
ND (None Detected, lower detectable limit = 7500 ug/kg)dry weight
ND* (None Detected, lower detectable limit = ug/kg)dry weight
ND** (None Detected, lower detectable limit = ug/kg)dry weight
ND*** (None Detected, lower detectable limit = ug/kg)dry weight
ND**** (None Detected, lower detectable limit = ug/kg)dry weight
ND***** (None Detected, lower detectable limit = ug/kg)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 2729-26453
MATRIX: SOLID

DATE RECEIVED: 4/25/91
DATE EXTRACTED: 5/01/91
DATE ANALYZED: 5/01/91

SAMPLE ID: CRESOTE COMPOST MONTH 2 4-25-91 DAHL Associates

POLYNUCLEAR AROMATIC HYDROCARBONS
METHOD 8310 LIST - HPLC

% MOISTURE: 26

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	86000	2800
Acenaphthylene	44000	2800
Acenaphthene	120000	2800
Fluorene	29000	560
Phenanthrene	91000	1400
Anthracene	55000	1400
Fluoranthene	180000	560
Pyrene	420000	560
Benzo(a)anthracene	120000	56
Chrysene	170000	420
Benzo(b)fluoranthene	110000	56
Benzo(k)fluoranthene	57000	56
Benzo(a)pyrene	140000	56
Dibenzo(a,h)anthracene	55000	84
Benzo(g,h,i)perylene	110000	140
Indeno(1,2,3-cd)pyrene	130000	140
2-Methylnaphthalene/ Dibenzofuran	54000	2800
Carbazole	ND	2800

NOTE: ND (None Detected)dry weight
J (Detected, but below quantitation limit; quantitation suspect)

SURROGATE RECOVERY	%	ACCEPTABLE LIMITS WATER	SOLID
Benzo(e)pyrene	Diluted Out	(40-140)	(30-130)
2-Fluorobiphenyl	Diluted Out	(40-140)	(30-130)

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 3175-30583
MATRIX: SOLID

DATE RECEIVED: 7/17/91
DATE EXTRACTED: 7/17/91
DATE ANALYZED: 7/26/91

SAMPLE ID: CRESOTE COMPOST FINAL 6-27-91

POLYNUCLEAR AROMATIC HYDROCARBONS -- METHOD 8310

% MOISTURE: 19

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	42000	10000
Acenaphthylene	28000	10000
Acenaphthene	69000	10000
Fluorene	13000	2000
Phenanthrene	32000	5000
Anthracene	36000	5000
Fluoranthene	120000	2000
Pyrene	290000	2000
Benzo(a)anthracene	81000	200
Chrysene	130000	1500
Benzo(b)fluoranthene	79000	200
Benzo(k)fluoranthene	42000	200
Benzo(a)pyrene	110000	200
Dibenzo(a,h)anthracene	25000	300
Benzo(g,h,i)perylene	57000	500
Indeno(1,2,3-cd)pyrene	70000	500
2-Methylnaphthalene/ Dibenzofuran	51000	10000
Carbazole	ND	10000

NOTE: ND (None Detected) dry weight
J (Detected, but below quantitation limit; estimated value)

SURROGATE RECOVERY:	ACCEPTABLE LIMITS WATER	SOLID	%
Benzo(e)pyrene	(33-128)	(35-138)	Diluted Out
2-Fluorobiphenyl	(28-111)	(41-137)	Diluted Out

WADSWORTH/ALERT
LABORATORIES, INC.

COMPANY: REMEDIATION TECHNOLOGIES INC.
LAB #: 3043-29325
MATRIX: SOLID

DATE RECEIVED: 6/27/91
DATE EXTRACTED: 6/28/91
DATE ANALYZED: 7/10/91

SAMPLE ID: CRESOTE COMPOST FINAL 6-27-91

POLYNUCLEAR AROMATIC HYDROCARBONS -- METHOD 8310

% MOISTURE: 16

PARAMETER	RESULT (ug/kg)	DETECTION LIMIT
Naphthalene	62000	8400
Acenaphthylene	140000	8400
Acenaphthene	160000	8400
Fluorene	17000	1700
Phenanthrene	53000	4200
Anthracene	49000	4200
Fluoranthene	170000	1700
Pyrene	310000	1700
Benzo(a)anthracene	120000	170
Chrysene	170000	1300
Benzo(b)fluoranthene	110000	170
Benzo(k)fluoranthene	62000	170
Benzo(a)pyrene	120000	170
Dibenzo(a,h)anthracene	75000	250
Benzo(g,h,i)perylene	100000	420
Indeno(1,2,3-cd)pyrene	250000	420
2-Methylnaphthalene/ Dibenzofuran	52000	8400
Carbazole	ND	8400

NOTE: ND (None Detected) dry weight
J (Detected, but below quantitation limit; estimated value)

SURROGATE RECOVERY:	ACCEPTABLE LIMITS WATER	SOLID	%
Benzo(e)pyrene	(40-140)	(30-130)	Diluted Out
2-Fluorobiphenyl	(40-140)	(30-130)	Diluted Out

APPENDIX C

ENVIRONMENTAL FATE MECHANISMS

ENVIRONMENTAL FATE MECHANISMS

Based on a review of available literature, Sims and Overcash[6] and the U.S. EPA[8] cite volatilization, sorption, and biological oxidation as the three primary environmental fate mechanisms influencing PAHs in the environment. While photolysis, chemical oxidation, and bioaccumulation of PAHs may occur, they are not considered to be significant relative to the other three. As discussed later in this section, sorption refers to the combined and simultaneously occurring effects of adsorption/desorption, dissolution, and diffusion within the soil matrix.

Figure C-1 schematically illustrates that PAH biodegradation is a water-based process influenced by chemical partitioning among the solid, air, and water phases. In this model, biological oxidation can occur only if a particular PAH compound within or on a soil particle (C_s) desorbs and diffuses into the bulk water phase (C_l). Once in solution, volatilization (C_g) can also occur. In many instances, PAH desorption and diffusion into the bulk water phase may be the rate-limiting step controlling both volatilization and biological oxidation. This model is supported by Annokkee[9] who cites that *the biodegradation reaction is rate-limited primarily by diffusion of the organic material to the surface of the soil particles*.

The three environmental fate mechanisms cited in Figure C-1 depict a very complex process influenced by the physical/chemical characteristics of the particular PAH compound, the physical/chemical characteristics of the particular media (e.g., soil, sludge, water), and the particular biological treatment system design and operation. Of the three fate mechanisms, sorption and biological oxidation are believed to be the more predominant related to PAH compounds. While volatilization of the 2- and 3-ring PAHs may occur, such emissions can be controlled in a properly operated biological treatment process[10]. For this reason, an overview of only mechanisms governing sorption and biological oxidation follow. Additional discussions of these fate mechanisms are provided elsewhere[10,11,12,13].

For reference purposes, Table C-1 lists the specific PAH compounds given focused attention in this report, along with their respective physical/chemical properties.

C.1 MECHANISMS GOVERNING DESORPTION OF PAHS FROM SOIL

It has been well documented in the literature that the extent and rate of reductions of PAH concentration in soils by different liquid-based soil treatment processes, such as biological slurry and soil washing processes, depend on the extent and rate of PAH

FIGURE C-1

ROLE OF DESORPTION/DIFFUSION IN
PAH BIODEGRADATION

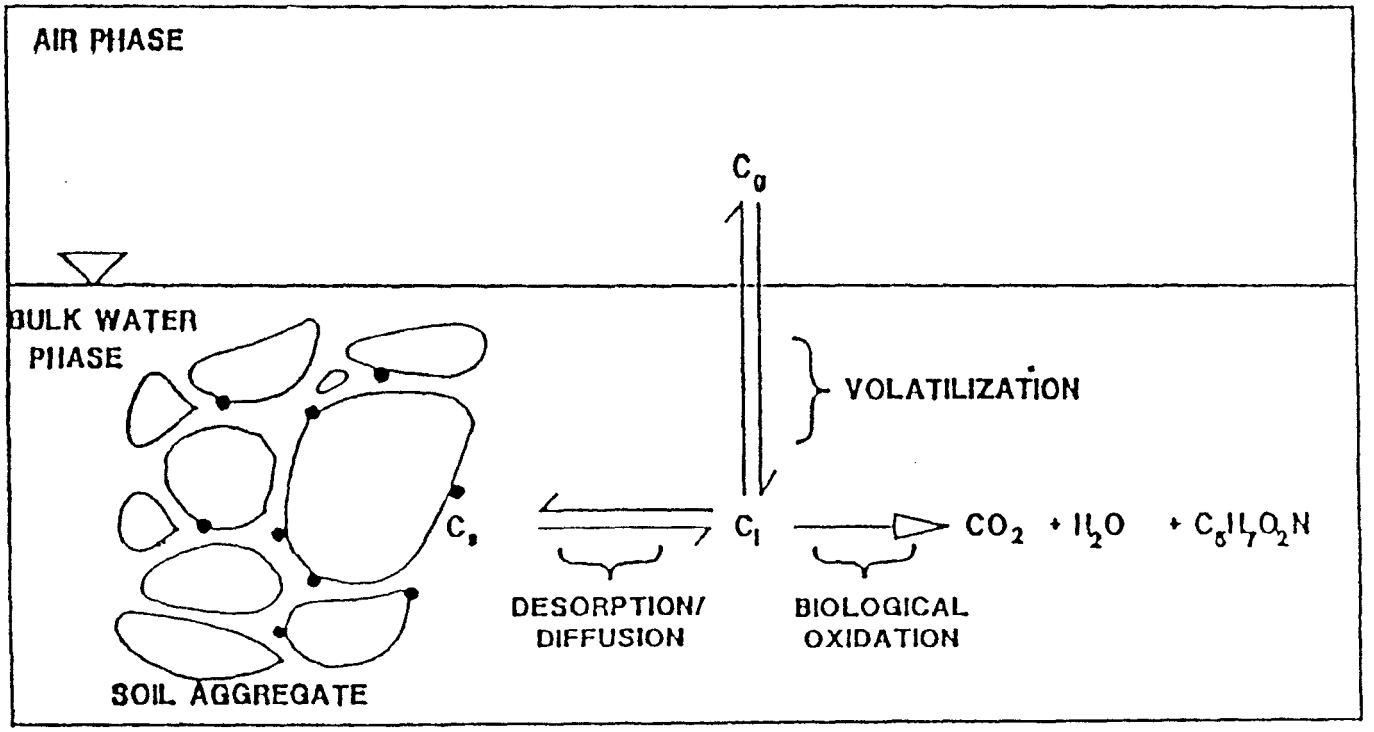


TABLE C-1

PHYSICAL/CHEMICAL PROPERTIES OF SELECTED PAH COMPOUNDS

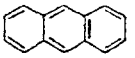
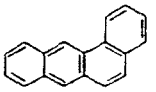
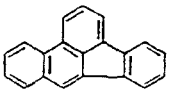
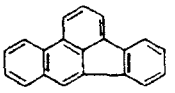
Name (and Synonyms) (a)	CAS Reg. No.	# of Rings	Formula	Mol. Wt.	Physical Property (b)	Structure
* Acenaphthene 1, 2-Dihydroacenaphthylene Peri-Ethylenenaphthylene 1:8 Dimethylene-naphthalene	83-32-9	3	$C_{12}H_{10}$	154	Sol = 3.42 M.P. = 95°C B.P. = 278°C H = 9.2×10^{-5} V.P. = 1.55×10^{-3} Koc = 4,600 log Kow = 4.0	
* Acenaphthylene	208-96-8	3	$C_{12}H_8$	152	Sol = 3.93 M.P. = 92°C B.P. = 265°C H = 1.48×10^{-3} V.P. = 2.90×10^{-2} Koc = 2,500 log Kow = 3.70	
* Anthracene	120-12-7	3	$C_{14}H_{10}$	178	Sol = 0.045 M.P. = 217°C B.P. = 340°C H = 1.02×10^{-3} V.P. = 1.95×10^{-4} Koc = 14,000 log Kow = 4.45	
* = Benz (a) Anthracene tetraphene 1, 2-Benzanthracene 2, 3-Benzophenanthrene	56-55-3	4	$C_{18}H_{12}$	228	Sol = 0.0057 M.P. = 157-162°C B.P. = 438°C H = 1.16×10^{-6} V.P. = 2.2×10^{-8} Koc = 1,380,000 log Kow = 5.6	
* = Benzo (b) fluoranthene Benzo (e) acephenanthrylene 2, 3-Benzofluoranthene	205-99-2	5	$C_{20}H_{12}$	252	Sol = 0.0014 M.P. = 167°C B.P. = 481°C V.P. = 5.0×10^{-7} H = 1.19×10^{-5} Koc = 550,000 log Kow = 6.06	
* Benzo (k) fluoranthene 8,9-Benzofluoranthene 11, 12-Benzofluoranthene	207-08-9	5	$C_{20}H_{12}$	252	Sol = 0.0043 M.P. = 215°C B.P. = 480°C V.P. = 5.6×10^{-7} H = 3.94×10^{-5} Koc = 550,000 log Kow = 6.06	

TABLE C-1
(Continued)

PHYSICAL/CHEMICAL PROPERTIES OF SELECTED PAH COMPOUNDS

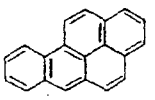
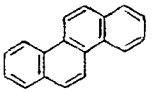
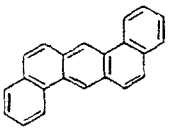
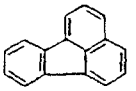
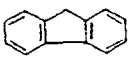
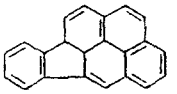
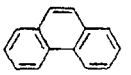
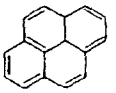
Name (and Synonyms) (a)	CAS Reg. No.	# of Rings	Formula	Mol. Wt.	Physical Property (b)	Structure
* Benzo (ghi) Perylene 1, 12-Benzoperylene	191-24-2	6	$C_{22}H_{12}$	276	Sol = 0.0007 M.P. = 273°C B.P. = +500°C V.P. = 1.03×10^{-10} H = 5.34×10^{-6} Koc = 1,600,000 log Kow = 6.51	
* ≠ Benzo (a) Pyrene 1, 2-Benzopyrene 3, 4-Benzopyrene	50-32-8	5	$C_{20}H_{12}$	252	Sol = 0.0012 M.P. = 178°C B.P. = 495°C H = 1.5×10^{-5} V.P. = 5.6×10^{-9} Koc = 5,500,000 log Kow = 6.06	
* ≠ Chrysene	218-01-9	4	$C_{18}H_{12}$	228	Sol = 0.0018 M.P. = 245-256°C B.P. = 436-448°C V.P. = 6.3×10^{-9} H = 1.05×10^{-6} Koc = 200,000 log Kow = 5.61	
* ≠ Dibenz (a,h) Anthracene 1,2:5, 6-Dibenzanthracene	53-70-3	5	$C_{22}H_{14}$	278	Sol = 0.0005 M.P. = 266°C B.P. = 524°C V.P = 1.0×10^{-10} H = 7.33×10^{-6} Koc = 3,300,000 log Kow = 6.80	
* ≠ Fluoranthene	206-44-0	4	$C_{16}H_{10}$	202	Sol = 0.206 M.P. = 110°C B.P. = 393°C V.P. = 5.0×10^{-6} H = 6.46×10^{-4} Koc = 38,000 log Kow = 4.90	
* Fluorene	86-73-7	3	$C_{13}H_{10}$	166	Sol = 1.69 M.P. = 115°C B.P. = 294°C V.P. = 7.1×10^{-4} H = 6.42×10^{-5} Koc = 7,300 log Kow = 4.20	

TABLE C-1
(Continued)

PHYSICAL/CHEMICAL PROPERTIES OF SELECTED PAH COMPOUNDS

Name (and Synonyms) (a)	CAS Reg. No.	# of Rings	Formula	Mol. Wt.	Physical Property (b)	Structure
* ≠ Indeno (1,2,3-CD) pyrene O-phenylenepyrene	193-39-5	6	$C_{22}H_{12}$	276	Sol = 0.00054 M.P. = 163°C B.P. = V.P. = 1.0×10^{-10} H = 6.86×10^{-8} Koc = 1,600,000 log Kow = 6.50	
* ≠ Napthalene	91-20-3	2	$C_{10}H_8$	128	Sol = 31.7 M.P. = 80°C B.P. = 218°C H = 2.6×10^{-4} V.P. = 4.92×10^{-2} Koc = 2300 log Kow = 3.01/3.45	
* Phenanthrene	85-01-3	3	$C_{14}H_{10}$	178	Sol = 1.0 M.P. = 101°C B.P. = 340°C H = 4.54×10^{-7} V.P. = 6.8×10^{-4} Koc = 14.2 log Kow = 1.46	
* Pyrene	129-00-0	4	$C_{16}H_{10}$	202	Sol = 0.132 M.P. = 149°C B.P. = 393°C H = 5.04×10^{-6} V.P. = 2.5×10^{-6} Koc = 38,000 log Kow = 4.88	

Notes:

(a) ≠ Indicates a RCRA Appendix VIII compound (40 CFR Part 26: Appendix VIII). Other PAH listed in Appendix VIII that are not given in this table are dibenz (a,h)-acridene, dibenz (a,j)-acridene, 7H-dibenzo (c,g) carbazole, dibenzo (a,e)pyrene, dibenzo (a,h) pyrene, and dibenzo (a, i) pyrene. Very little property data are available for these compounds and they are not commonly found.

* Indicates a priority pollutant compound (40 CFR part 122 Appendix D). All priority pollutant PAH are listed in this table.

(b) Sol = Solubility in mg/1 in distilled water at 25°C from EPA 1986.

M.P. = Melting point in °C as reported by Anderson and Wu (1963) unless otherwise noted.

B.P = Boiling point in °C as reported by Anderson and Wu (1963) unless otherwise noted.

V.P. = Vapor pressure in torr mm Hg at 20°C from U.S. EPA, 1986.

H = Henry's law constant in atm-m^3/mole at 25°C from EPA, 1986.

Koc = Organic carbon partition coefficient (ml/g) from EPA, 1986.

log Kow = Logarithm of octanol-water partition coefficient from EPA, 1986

desorption from soil.

Referring to Figure C-1, the soil matrix is conceptualized as a collection of porous, water-stable aggregates which are loosely associated with one another. Only a single soil aggregate is illustrated in this figure. The aggregates consist of organic and inorganic (e.g., clay) fractions which are ionicly bound together by metal cations such as aluminum. The size of the individual aggregates range from less than 1 to 250 microns in diameter. Soil water can exist in the macropores between the aggregates (bulk soil water) or within the micropores of the individual aggregates themselves (pore water).

It is believed that the micropores of the individual aggregates are large enough to permit some chemicals to move into, out of, and within the aggregate, but they are not sufficiently large to permit microorganisms to enter. Hence, for biodegradation to occur, the chemicals must migrate to the bacteria which exist at the surface of the aggregate or in the bulk soil water (macropores). The organic contaminant can be present in the soil system bound to the soil organic/inorganic fractions, in aqueous solution (either in the micropore water or the bulk soil water), or in free hydrocarbon phase. As such, migration to the bacteria requires some combination of the adsorption/desorption, dissolution, and diffusion processes. Desorption and dissolution are the mechanisms by which the contaminant enters the solution and diffusion is the mechanism which governs its movement in the aqueous phase.

While it is not entirely clear which of the transport processes dominate the movement of the contaminants, adsorption/desorption and diffusion are important for all soil systems. Dissolution is likely to be important only for very contaminated soil where substantial free phase hydrocarbons exist. Consequently, subsequent discussion focuses on sorption processes. Sorption is characterized by of both equilibrium and rate conditions. Equilibrium refers to the extent that a particular PAH compound partitions between soil and water. Rate refers to the time it takes for a chemical to reach equilibrium between the soil and water. Sorption equilibrium and kinetic relationships are addressed as follows.

C.1.1 Equilibrium Sorption Relationships

The equilibrium adsorption/desorption of PAHs on soil aggregates has been investigated by numerous researchers who have used a linear isotherm to model the partitioning of chemicals between the solid and liquid phases. This isotherm expresses the equilibrium concentration of a contaminant adsorbed on soil, C_s, in terms of a partition

coefficient, Kp, and the concentration of the contaminant in solution, C_l, as shown in Equation 2-1:

$$C_s = Kp \times C_l \qquad (2\text{-}1)$$

where,

C_s = equilibrium concentration of chemical adsorbed onto soil, g_c/g_s,

Kp = partition coefficient, L/g_s; and

C_l = equilibrium concentration of chemical in the aqueous phase, g_c.

The partition coefficient, Kp, for a specific contaminant can be expressed as the product of the fraction of organic carbon in the soil, foc, and the organic carbon partition coefficient, Koc, of the contaminant. When this relationship is substituted into Equation 2-1, the equilibrium relationship can be expressed as:

$$C_s = (Koc \times foc) \times C_l \qquad (2\text{-}2)$$

Hamaker and Thompson[14] and Karickhoff[15] suggest that Koc is independent of the nature of the solid and relatively constant for a given solute or contaminant. This would indicate that the adsorption of a specific PAH on the soil aggregate will increase with the organic carbon fraction (foc) of the aggregate.

Thus, Equation 2 can be used to estimate the extent to which a particular PAH compound will exist in solution based upon the soil concentration (C_s), the organic carbon content (foc) of the soil, and published Koc values cited by the U.S. EPA[8]. Along these lines, much research on PAH sorption processes has been done, and continues to be performed in soil/water systems. General conclusions of this work are that the lower molecular weight PAHs (i.e., 2- and 3-ring) have a tendency to desorb off soils to a greater extent and at a faster rate than the higher molecular weight PAHs (i.e., 4-, 5-, and 6-ring).

Due to their inherent physical/chemical properties, the concentrations of lower molecular weight PAHs in aqueous solution can be in the part per million (ppm) range while the higher molecular weight PAHs are typically in the part per trillion (ppt) to part per billion (ppb) range. These differences in solubilities result in more extensive and faster rates of biodegradation for the lower molecular weight PAHs.

C.1.2 Sorption Kinetics

The rate at which adsorption equilibrium is attainable in a soil-water system is believed to be controlled by intraggregate and intraparticle diffusion of the chemicals[15,16]. These kinetics can be described in terms of a radial diffusive penetration model modified by a retardation factor that reflects microscale partitioning of the sorbate between the pore fluids and the solids which make up the aggregate[17]. This model has been tested against experimental data for lower ring PAHs and moderately hydrophobic organic chemicals (e.g., pentachlorobenzene), but not for very large soil aggregates or very hydrophobic substances (e.g., 5- and 6-ring PAHs) due to the extended timeframe required for complete equilibration (i.e., months to years). This mathematical model suggests that the physical/chemical properties of the PAHs and the size of the soil aggregate are the major variables which influence the rate of PAH adsorption/desorption. The implication is that the PAHs may take considerably longer to become available to bacteria if the soil aggregates are larger and/or the number of aromatic rings in the PAHs are greater than 3. This time will be extended even further by the aging of soil-waste matrices which provides more time for diffusion of the PAHs into the aggregates.

An example of the range of time which many be required for equilibrium sorption/desorption to be achieved was estimated by Mihelcic[18] for 2-ring and 6-ring PAHs. Equilibrium adsorption for the 2-ring PAH naphthalene was predicted to be achieved in 15 minutes and one day, respectively, for soil aggregate diameters, of 17.5 and 175 microns. For the same particle diameters, a 6-ring PAH compound will require 50 days and 27 years, respectively, for adsorption/desorption equilibrium to be achieved.

The significance of the hypothesis presented is amplified by the fact that soil aggregates which may have been in contact with contaminants for 50 years or longer will contain PAHs which may have penetrated deep into individual aggregates. An equally long period of time may be required for the same PAH compounds to desorb and to become for biological oxidation. Thus, treatment processes which rely on the availability of the contaminant in the bulk liquid phase will most likely be rate-limited by this

desorption/diffusion process. However, this conceptual model suggests that the use of chemical amendments (e.g., surfactants) or naturally secreted biosurfactants may enhance soil desorption/diffusion of contaminants and thus enhance contaminant biodegradation.

APPENDIX D

TECHNICAL PAPER - THE INFLUENCE OF SOIL COMPOSITION ON BIOREMEDIATION OF PAH-CONTAMINATED SOILS

The Influence of Soil Composition on Bioremediation Of PAH-Contaminated Soils

Andrew C. Middleton • David V. Nakles • David G. Linz

Andrew C. Middleton and David V. Nakles are principals at Remediation Technologies in Pittsburgh, PA. David G. Linz is an environmental engineer and manager of Environment & Safety Research at the Gas Research Institute in Chicago, IL.

As a result of former industrial activities, many properties across the United States contain various chemicals in their soils at concentrations above background levels. Polynuclear aromatic hydrocarbons (PAHs) are often encountered at sites of gas manufacture, wood treating, tar refining, coke making, and petroleum refining. When the presence of PAHs in site soil is deemed to create a situation of unacceptable risk to public health or the environment, treatment or disposal is required to reduce concentrations to acceptable levels.

The ideal remedial process for PAHs in soils would destroy them to an environmentally sound level at relatively low cost without producing adverse by-products. In many cases bioremediation can accomplish these goals. The degree to which bioremediation can destroy PAHs in a particular soil, however, is highly dependent on the characteristics of that soil, including the nature of the hydrocarbon that is the source of the PAHs.

It is the objective of this article to describe efforts leading to this conclusion and to summarize how soil characteristics influence bioremediation of PAHs.

Bioremediation is the use of bacteria in engineered systems to destroy biodegradable contaminants in soils, waters, and sludges. The engineered system creates conditions to optimize the growth of bacteria on the chemical that is targeted for destruction. Bacteria use the chemical for food, oxidizing part for energy and synthesizing the remainder into new bacterial cells.

Many studies and full-scale remediations have found PAHs to be biodegradable (Mihelic and Luthy, 1988; Loehr and Malina, 1986; Sims and Overcash, 1983; Nakles and Smith, 1989; Smith and Weightman, 1988). Others have described the metabolic pathways for PAH degradation (Gibson and Subramanian, 1984). Unquestionably, bioremediation is a technology that should be initially considered for destruction of PAHs in contaminated soils. It cannot be assumed, however, that bioremediation will achieve a reduction in the soil PAH concentration to cleanup criteria in all situations.

TREATABILITY TESTS ON UNSATURATED SOILS

Four cases will serve to illustrate the conclusion. As part of a research

program for the Gas Research Institute on bioremediation of PAH-contaminated soils, a number of treatability tests were performed. Details on this work have been described elsewhere (Cushey and Morgan, 1990; Linz et al., 1990; Morgan et al., 1990).

Pan Reactor Tests

Initially, a series of soils were bioremediated in laboratory-scale pan reactors.

Initially, a series of soils were bioremediated in laboratory-scale pan reactors. Pan reactors simulate bioremediation of soils in an unsaturated state. Contaminated soils are placed into a pan of approximate dimensions 8 x 12 x 4 inches, and nitrogen, phosphorus, and water are added to optimize the growth of the indigenous soil bacteria. The reactor is operated for a relatively long period of time, in some cases in excess of 20 weeks. During operation, soil moisture is maintained by the addition of water to provide a moist but drained soil. Nitrogen and phosphorus are added, as necessary, for bacterial growth. The pH is adjusted with addition of lime to maintain it in the range of 6-8. The soils are mixed weekly for aeration and homogenization.

The soils are monitored for PAH concentration as a function of time. The reduction in PAH concentrations over time forms the basis for conclusions about the response of the PAH-contaminated soil to bioremediation.

This treatability test simulates the full-scale bioremediation technologies that operate in an unsaturated state. These include ex situ land treatment, in situ landfarming, and, to some degree, composting.

To return to the four cases, PAH-contaminated soils from four different sites were subjected to pan reactor treatability tests. Initial PAH concentrations were 160, 190, 20,000, and 29,000 mg/kg for the four soils, identified as Soils B, D, F, and J respectively. The sites were former manufactured-gas plants where coal and oil had been converted to gas for some period during the era of gas manufacture (1816-1960s). Tar ore lampblack, by-products of gas manufacture, contain high concentration of PAHs and were the likely source of PAHs in these soils.

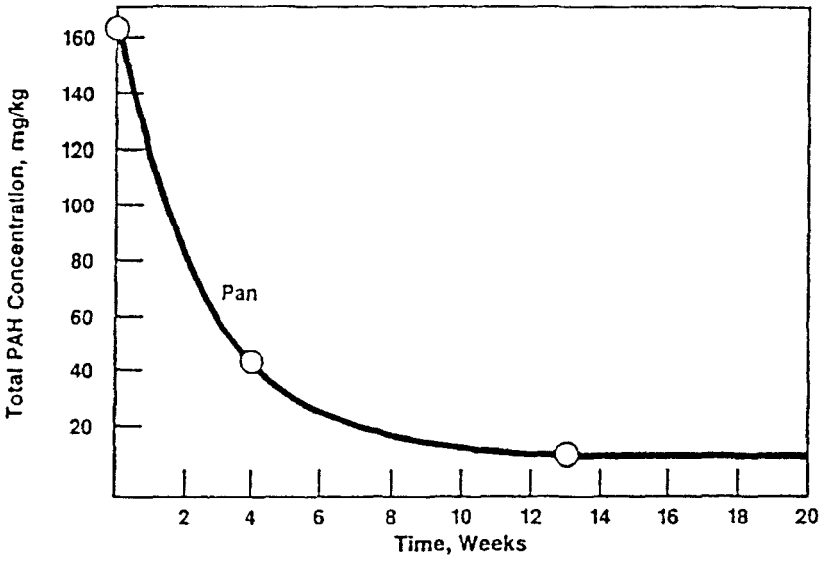
The individual soils responded very differently to bioremediation. Soil B responded very well. **Figure 1** shows the decrease in total PAH concentration with time for Soil B. PAHs decreased from the initial concentration of 160 mg/kg to less than 20 mg/kg within fourteen weeks, a reduction greater than 85 percent.

Soil F also responded well, but achieved a lower reduction of PAHs (75 percent) within 22 weeks. **Figure 2** shows the PAH concentration with time for Soil F. The concentration decreased from 20,000 mg/kg to 5,000 mg/kg within twenty-two weeks. The final concentration began to reach an asymptote or plateau concentration substantially above zero.

Soil J responded to bioremediation, but not as well as Soil F. **Figure 3** shows the PAH concentration with time for Soil J. The concentration decreased from 30,000 mg/kg to 17,000 mg/kg within sixteen weeks, a reduction of 43 percent. As with Soil F, the final concentration approached a plateau well above zero.

Soil D, however, did not respond in any obvious manner to

Figure 1. Soil B.



bioremediation. **Figure 4** shows the PAH concentration with time for Soil D. The initial concentration of 190 mg/kg was similar to that of Soil B, but subsequent concentrations over the twenty-five weeks of testing oscillated with no apparent functional relationship.

The Effects of Soil Characteristics on Bioremediation

These results clearly illustrate the varying responses of PAH-contaminated soils to bioremediation. Some soils responded with varying degrees of PAH reductions to less than 20 mg/kg in the best case, but only to around 17,000 mg/kg in the least responsive case. One soil did not respond at all with no apparent reduction in PAH concentrations. The obvious question was why.

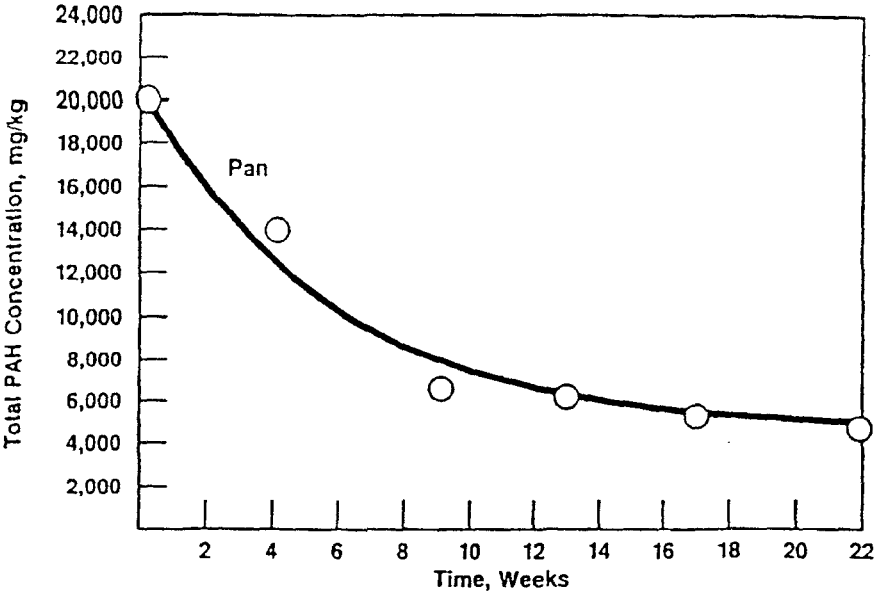
Soil characteristics provided some insight into the phenomena that were causing these variations. **Table 1** lists fines content and organic carbon fraction for the four soils. Fines content, as used here, is the percent by weight of soil that passes a 0.075-mm sieve and primarily represents the amount of silt and clay present in the soil. The organic carbon fraction is the percent by weight of organic carbon present in the soil. It is a measure of the natural organic carbon as well as that from the hydrocarbons present.

Table 1. Soil Characteristics.

SOIL	INITIAL PAH CONCENTRATION mg/kg	FINES CONTENT PERCENT	ORGANIC CARBON FRACTION PERCENT
B	160	3	0.6
D	190	26	4.3
F	20,000	7	16
J	29,000	27*	58

*Includes lampblack fines

Figure 2. Soil F.



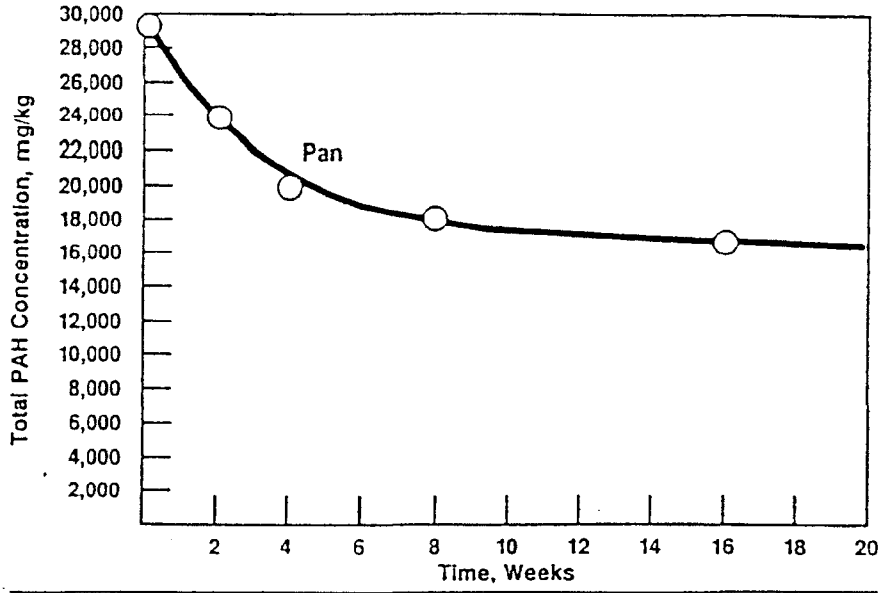
Soil B had both the lowest fines content and organic carbon fraction. Soil J had the highest fines content and organic carbon fraction. However, it contained a substantial amount of lampblack, which accounted for a portion of both. Soil D had the highest amount of fines due solely to silts and clays. The organic carbon fraction was next to the lowest. Finally, Soil F had the second to lowest fines content and next to highest organic carbon fraction. Tar, which was visibly present in this soil, accounted for a portion of the organic carbon fraction.

These four soils covered a wide range of values of fines content and organic carbon fraction. Similarly, they responded to bioremediation in an unsaturated state in a widely varying manner. The apparent potential for a relationship between bioremediation response and these characteristics motivated development of a conceptual model of soil bioremediation.

THE CONCEPTUAL MODEL

Site soils are mixtures of cohesive and noncohesive inorganic soil, natural organics, and often separate phase hydrocarbons. The noncohesive soils include sands and gravels; the cohesive soils include silts and clays. The cohesive soils are made up of aggregates of the individual silt and clay particles. Natural organics include the humus and other remnants of decayed vegetation. The separate phase hydrocarbons are pockets of oils, tars, and other nonaqueous phase liquids (NAPLs). **Figure 5** is a schematic diagram of a conceptual model of a site soil showing the mixture of NAPLs, sand particles, and fines aggregates. In a saturated state, the void space is filled with water; in an unsaturated state, it is filled with air.

Figure 3. Soil J.

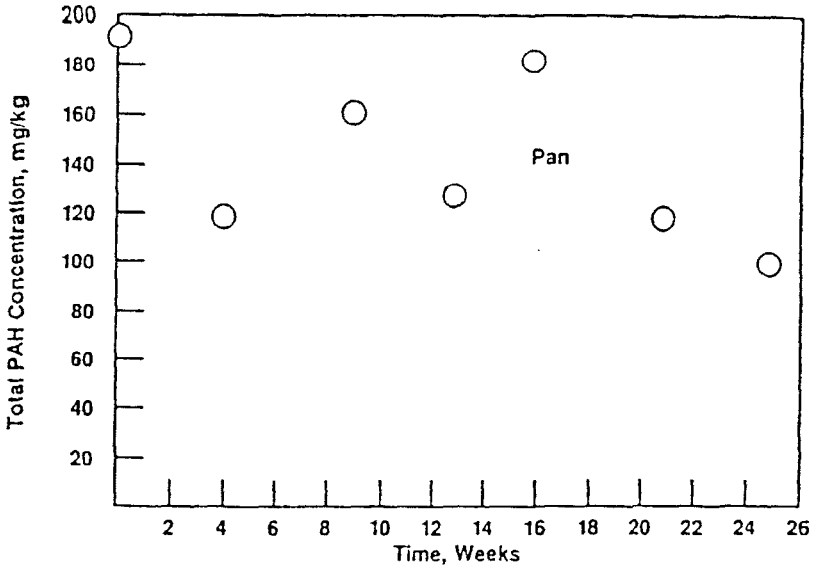


Greater magnification of this model provides details that permit the development of a conceptual model. **Figure 6** shows a magnification of three key components: NAPLs, sand grains, and final aggregates. Where active biodegradation is occurring, a biofilm exists around each of these as shown in Figure 6. A biofilm is simply a layer of bacterial cells and other soil microorganisms adhered to a surface. Biodegradable organics diffuse through water or soil moisture into the biofilm where they are degraded by the microorganisms (Rittman et al., 1990). Microorganisms cannot penetrate to the interior of a pocket of NAPL or a sand grain because of the liquid or crystalline nature of the material. Nor can they penetrate into the micropore structure of a fines aggregate because the micropore diameters are too small. Hence, active biodegradation must occur in the biofilms surrounding the surfaces of these materials.

Biodegradation of NAPLs

In the case of the pocket of tar-NAPL, the biofilm is a mixture of PAHs. As the PAHs at the surface are degraded, mobile PAHs from within the NAPL diffuse to the surface to the biofilm. The first circle in Figure 6 depicts this schematically. In this process the nature of the NAPL changes to a mixture of mobile PAHs. Depending on the composition of the NAPL with respect to the relative presence of mobile and immobile PAHs, it may be substantially biodegraded or converted to an insoluble, inert NAPL like a roofing or road tar. If it is converted to an insoluble, inert NAPL, the soil may have a substantial concentration of PAHs remaining after bioremediation (i.e., a relatively high plateau concentration as discussed earlier). Hence, the quantity and composition of a NAPL in soil is clearly a factor influencing the response to bioremediation.

Figure 4. Soil D.



Biodegradation of Sand Grains

In the case of a sand grain, PAHs are adsorbed to the surface of the particle. They desorb and diffuse into the biofilm in the bioremediation process. The second circle in Figure 6 depicts this schematically. This situation contrasts significantly from that of the NAPL. The biofilm and adsorbed PAHs are in close proximity, and the relatively thin layer of adsorbed PAHs do not significantly change in composition during

Figure 5. Conceptual Model.

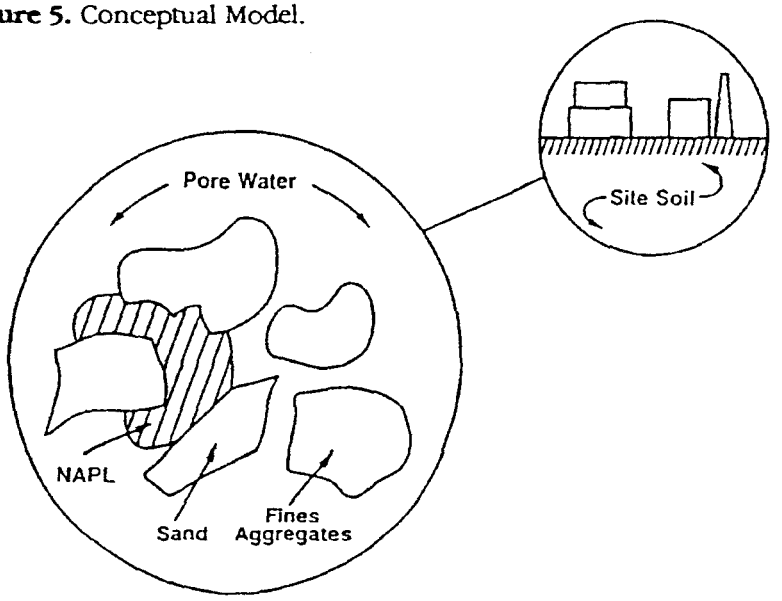
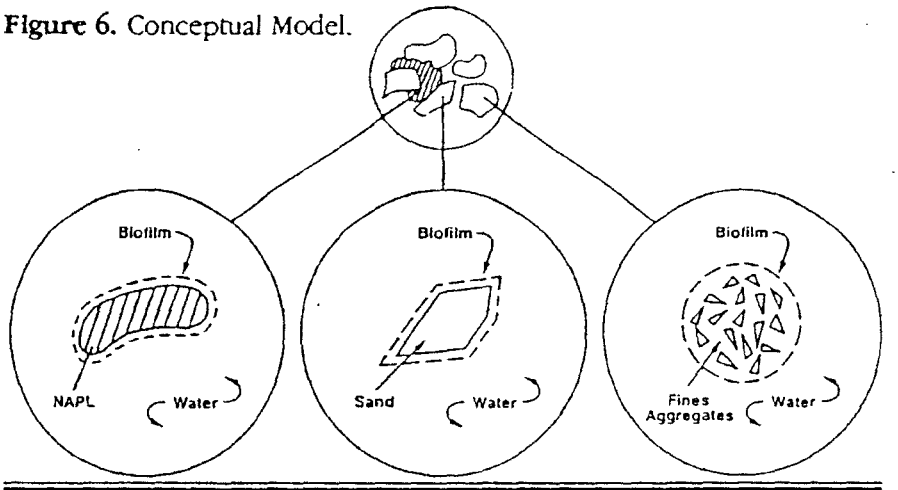


Figure 6. Conceptual Model.



bioremediation as does that of tar NAPL. They desorb, diffuse a short distance into the biofilm, and are degraded. Bioremediation of PAHs in sand probably represents the most straightforward and rapid process of these three situations.

Biodegradation of Fines Aggregates

The situation for the fines aggregate is the most complex of the three. The third circle in Figure 6 depicts this schematically. The fines aggregate is made up of individual particles (i.e., silts and clays) adhering in a cohesive mass. The surface area of the particles within the aggregate is orders of magnitude higher than that of an equivalent volume of sand. The micropores within the fines are typically water saturated and too small for bacterial cells to enter.

When subjected to bioremediation, PAHs on the exterior surface of the aggregate have a much shorter pathway to the surrounding biofilm than those within the fines.

PAHs will adhere to the interior and exterior surfaces of the individual particles making up the aggregate. When subjected to bioremediation, PAHs on the exterior surface of the aggregate have a much shorter pathway to the surrounding biofilm than those within the fines. The ones within must desorb from the microsurface and diffuse through the micropore structure to the outer surface where the biofilm is located. This pathway is further complicated by the continuous opportunity for surface adsorption and desorption along the micropore (Brusseau and Rao, 1989). The presence of fines in the soil represents a situation where bioremediation will be limited by the transport of PAHs through the micropore structure to the surface.

The Prediction for Bioremediation of Unsaturated Soils

In summary, this conceptual model predicts that bioremediation of soils in an unsaturated state will depend on two additional factors as well as classical biodegradation factors such as pH and temperature. The additional factors are

- The quantity and composition of NAPL present in the soil, and

- The quantity and composition of fines (i.e., silts and clays) in the soil.

The conceptual model also predicts that in certain situations bioremediation of soil in a saturated, well-mixed state should improve the response. In situations where there is a substantial amount of fines present in the soil, part of the limitation to bioremediation is the relatively slow transport rate of contaminants from the interior of the fines aggregate to the outer surface biofilm. If the fines aggregate were dispersed in a well-mixed water slurry, the interior surfaces would be exposed to the bulk water and should be much more available for bioremediation. If the water were also aerated and supplemented with nutrients, then conditions should be optimal for bioremediation of the PAHs in the soil.

If the water were also aerated and supplemented with nutrients, then conditions should be optimal for bioremediation of the PAHs in the soil.

Similarly, where pockets of NAPL are present in the soil, dispersal in a well-mixed water slurry should produce a better situation for bioremediation than in an unsaturated state because of the mixing and exposure of more surface area to the water that supports the biofilm.

Hence, better and faster treatment of PAH-contaminated soils should occur in a water-slurry bioremediation system.

Quantitation of experimental results provides a means to better compare and contrast the various responses to bioremediation. The variation of PAH concentration as a function of time for these pan treatability studies can be described mathematically with a modified first-order equation:

$$C = C_R + (C_o - C_R)e^{-kt} \qquad (1)$$

in which,

C	=	PAH concentration, M/L^3;
C_o	=	initial PAH concentration, M/L^3;
C_R	=	PAH concentration resistant to biodegradation or not bioavailable, M/L^3;
k	=	first-order decay coefficient, T^{-1}; and,
t	=	time, T.

In this equation the term C_R represents the plateau concentration at which the decrease in PAH concentration levels out.

It is recognized that mathematically describing the total PAH concentration rather than the concentration of individual PAH compounds is a simplifying assumption. The intent here, however, is to determine whether the conceptual model is supported by the experimental data, and this simplification will facilitate this analysis. Future work will refine the analysis by examining individual compounds.

Values of C_R and k can be estimated by fitting this model to the experimental data using a least-squares technique. When this is done, the values for Soil B in response to unsaturated bioremediation in a pan were 0.054 day^{-1} and 11 mg/kg for k and C_R, respectively. Those for Soil F were 0.024 day^{-1} and 4,500 mg/kg, and for Soil J, 0.041 day^{-1} and 16,800 mg/kg.

No values for Soil D were estimated because the data did not show a clear decrease in concentration with time. The curves plotted through the data points in Figures 1-3 were determined using Equation 1 and the above values.

SLURRY REACTOR EXPERIMENTS

To test the prediction of better and faster treatment in a saturated state, the four soils were also bioremediated in laboratory-scale slurry reactors. The apparatus and procedures were developed as part of protocol for accelerated biotreatability testing for Gas Research Institute and have been described in detail elsewhere (Cushey and Morgan, 1990). Briefly, a soil-water slurry (20 percent soil) was added to a twelve-liter stainless-steel vessel equipped with a high-speed mixer, aeration devices, and means to sample volatiles in the off-gas exiting the reactor. Nitrogen and phosphorus nutrients were added to the water to provide the supplemental macro-nutrients for bacterial growth. The reactor was operated as a batch reactor for typically four to eight weeks. During this time soil samples were collected for PAH analysis. Additionally, if nutrients or pH control were required, appropriate chemical additions were made.

The apparatus and procedures were developed as part of protocol for accelerated biotreatability testing for Gas Research Institute and have been described in detail elsewhere.

Application of the Results to the Conceptual Model

Results of the response of the four soils (B, D, F, and J) to bioremediation in a saturated state provide a basis for evaluating the conceptual model. **Figure 7** shows the PAH concentration with time for Soil B in both the pan and slurry reactors. The concentration in the slurry reactor decreased more rapidly than in the pan, but approached a similar plateau concentration. Values of C_r and k in Equation 1 were also estimated for the slurry reactor

Figure 7. Soil B.

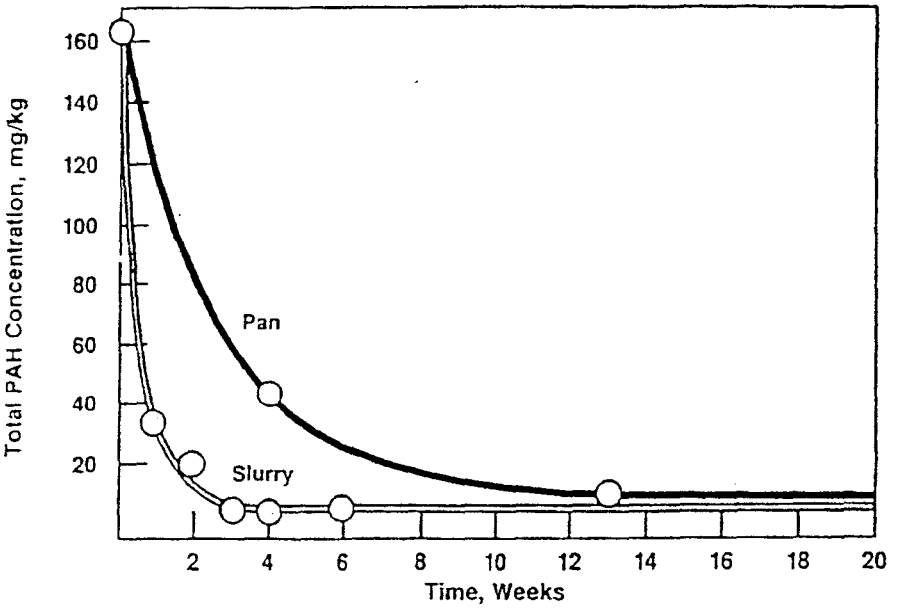
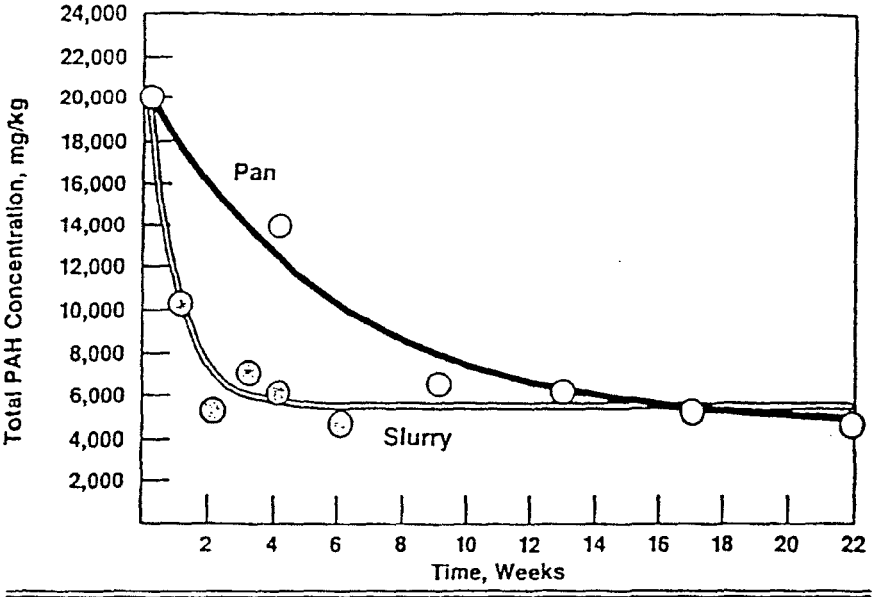


Figure 8. Soil F.



data. For Soil B's response to saturated bioremediation in a slurry reactor, the values of k and C_R were 0.24 day^{-1} and 7 mg/kg, respectively.

Figure 8 shows the PAH concentration with time for Soil F in both the pan and slurry reactors. The relative response of the two reactors was similar to that for Soil B. The slurry reactor concentrations decreased more rapidly than in the pan, but approached a similar plateau concentration well above zero. Values of k and C_R for the slurry reactor were estimated

Figure 9. Soil J.

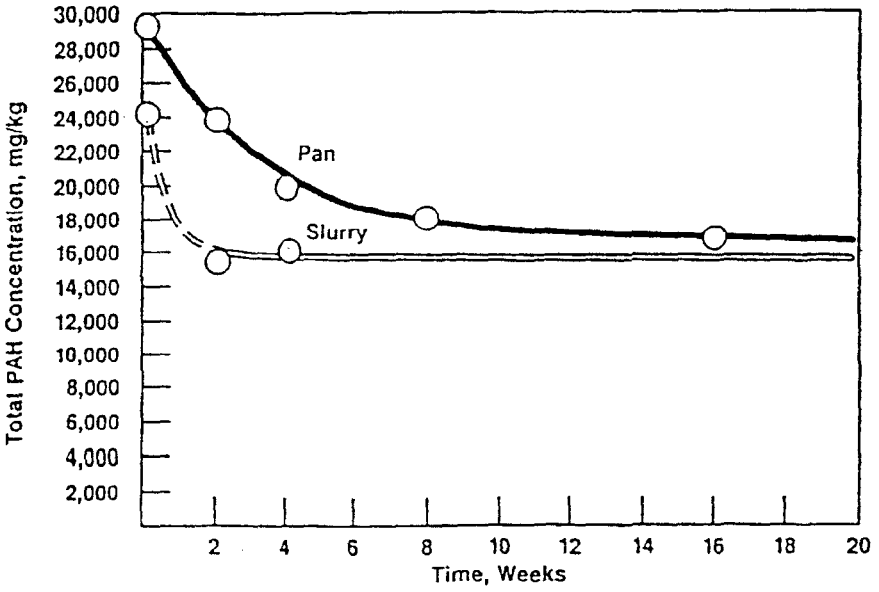
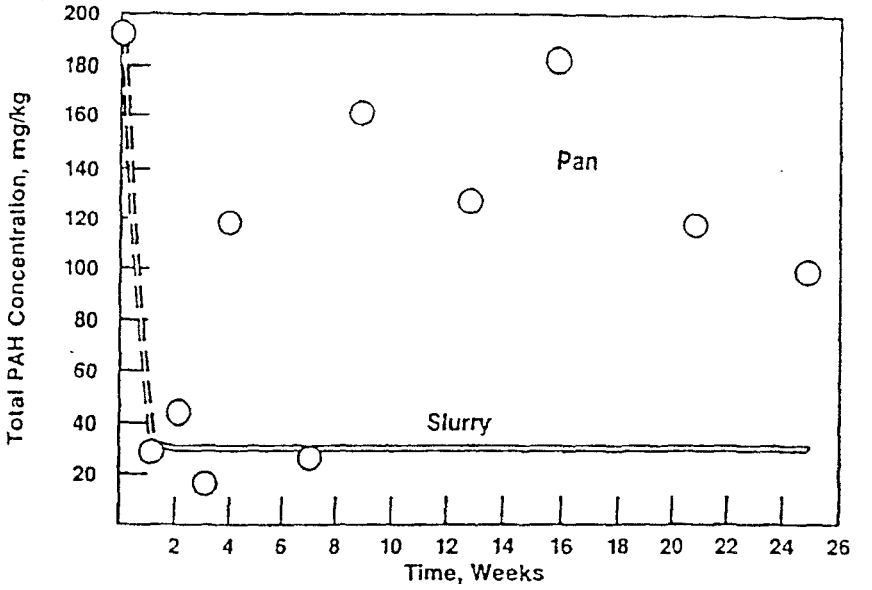


Figure 10. Soil D.



to be 0.19 day^{-1} and 5,200 mg/kg, respectively.

Figure 9 shows the PAH concentration with time for Soil J in both the pan and slurry reactors. Again the relative response was similar to that of both Soil B and Soil F. Values of k and C_R for the slurry reactor were estimated to be 0.24 day^{-1} and 15,700 mg/kg, respectively.

Figure 10 shows the PAH concentration with time for Soil D in both the pan and slurry reactors. The difference between the responses of the two was dramatic. There was essentially no response of Soil D to bioremediation in an unsaturated state. In the slurry reactor, however, the PAH concentration rapidly dropped to a relatively low plateau concentration. Values of k and C_R for the slurry reactor were estimated to be 0.57 day^{-1} and 31 mg/kg, respectively.

These results motivate the discussion as to whether they are consistent with the conceptual model.

THE RELIABILITY OF THE CONCEPTUAL MODEL

The response to bioremediation in both a saturated and unsaturated state of four soils of different characteristics and tar NAPL produced a broad range of results. **Table 2** summarizes the soil characteristics and estimated modified first-order coefficients for the four soils. Examination of this table yields several trends supporting the conceptual model.

Rates of Bioremediation: Saturated versus Unsaturated States

The first-order decay rates (k) for saturated bioremediation (i.e., slurry reactors) are consistently higher by an approximate order-of-magnitude than the rates for unsaturated (i.e., pan reactors). One of the basic premises of the conceptual model is that soil bioremediation is a water-based

Table 2. Summary of Soil Characteristics and Modified First-Order Coefficients.

SOIL	INITIAL PAH CONCENTRATION (C_o), mg/kg	FINES CONTENT, (Percent)	ORGANIC CARBON FRACTION, (Percent)	FIRST-ORDER DECAY RATE (k), DAY^{-1}		PAH CONCENTRATION RESISTANT TO BIODEGRADATION (C_R), mg/kg	
				Unsaturated	Saturated	Unsaturated	Saturated
B	160	3	0.6	0.054	0.24	11	7
F	190	26	6.5	**	0.57	**	31
G	20,000	7	16	0.024	0.19	4,500	5,200
J	29,000	27*	58	0.041	0.24	16,800	15,700

process. Water provides the medium of transport for the PAHs, the NAPLs, and the soil to the biofilm. The ratio of water to soil in a slurry reactor is thirty to fifty times greater than in a pan reactor. This water is aerated and supplemented with nutrients to optimize bacterial growth. Hence, with the excess water and mixing present and the water being an optimal bacterial growth medium, it is logical to expect degradation rates to be faster than in an unsaturated state.

The Potential Contribution of the Slurry Reactor

One of the basic premises of the conceptual model is that soil bioremediation is a water-based process.

This finding has two implications. First, the slurry reactor can be used as an accelerated treatability test. If degradation is going to occur, it will do so in a two-to-six-week period rather than a two-to-six-month period as is often required in pan reactor tests. This accelerated test is a key benefit of the protocol developed by GRI to shorten the time necessary to evaluate the potential response of soils to bioremediation (Linz et al., 1990).

Slurry reactor testing can also help with technology screening. The slurry reactor represents an optimal situation for bioremediation of soils; if results from it do not achieve desired cleanup levels, then other forms of bioremediation are unlikely to do so either. In this situation bioremediation may be screened out as an applicable remedial technology. If the results do achieve desired cleanup levels, then bioremediation should be retained as a potential remedial technology. As will be discussed below, additional treatability may be required to confirm that unsaturated bioremediation would achieve similar levels.

Second, the results support the concept of slurry reactor bioremediation as a potentially viable full-scale treatment technology for soils as it has been used for organic sludges. Clearly, treatment times could be shortened in a slurry reactor. However, substantial evaluation of the mechanical requirements for slurry handling, mixing, and dewatering would be necessary to determine the economic competitiveness of it compared to other remedial technologies for soils.

Bioavailability of PAHs

The estimated values of the PAH concentration resistant to bioremediation (C_R) also supports the validity of the conceptual model. C_R represents the PAH concentration that is not bioavailable because of mass transport limitations or insolubility.

In unsaturated bioremediation, PAHs deep within micropores of fines aggregates may not be subject to transport to the outer surface in any relatively short period of time desired for treatment. Soils higher in fines content will not respond very well to unsaturated bioremediation. In saturated bioremediation, however, where the surfaces of the fines are exposed by dispersion, bioremediation may readily proceed. Soil D illustrated this situation. There was no clear trend of bioremediation in the unsaturated test. Concentrations oscillated in the vicinity of the initial concentration of 190 mg/kg. When dispersed in a slurry, however, bioremediation was rapid and produced a relatively low plateau concentration (C_R) of 31 mg/kg.

Similar Plateau Concentrations

The plateau concentrations (C_R) for the other three soils were similar between the saturated and unsaturated treatment. For Soil B, values of C_R were 11 and 7 mg/kg for unsaturated and saturated treatment, respectively; for Soil F, 4,500 and 5,200 mg/kg; and, for Soil J, 16,800 and 15,700 mg/kg. Soils B and F had the lowest fines contents of 3 percent and 7 percent, respectively. Soil J had a fines content of 27 percent, but some of this was due to lampblack, which made it difficult, if not virtually impossible, to estimate the fines caused only by silts and clays. The similarity of C_R for these soils between the saturated and unsaturated states suggests that mass transport from the interiors of fines aggregates did not significantly influence bioremediation in the unsaturated state. Based on the results for Soils B, D, and F, the fines content threshold above which unsaturated bioremediation can be significantly influenced lies between 7 percent and 27 percent. Until this threshold level is more precisely defined, the round number of 10 percent should be reasonable as an initial definition.

One hypothesis consistent with the conceptual model is that during the course of bioremediation, the mobile constituents are degraded, leaving behind a relatively immobile, insoluble material not subject to further attack by a water-based technology.

Hence, if a soil's fines content is above 10 percent, the certainty of extrapolation of saturated bioremediation test data to unsaturated treatment should clearly be questioned. As the value decreases below 10 percent, certainty of this assumption significantly increases. As mentioned earlier, in cases of uncertainty about such extrapolation, additional treatability testing simulating the unsaturated state should be performed to provide a final basis for decision making.

Although plateau concentrations for saturated and unsaturated bioremediation were similar for the same soil, these varied greatly between the soils for B, F, and J. Soil B had the lowest values of C_R, 7 and 11 mg/kg. Soil F was next at 4,500 and 5,200 mg/kg, with Soil J the highest at 16,800 and 15,700 mg/kg. If mass transport from the interiors of fines aggregates was not a significant influence, why did the total PAH concentration not decrease to similar plateau concentrations? These results

suggest that bioremediation of the tar-NAPL in Soils F and J were significantly influenced by the composition of the NAPL itself. The NAPL constituents were not available for further bioremediation in these soils.

One hypothesis consistent with the conceptual model is that during the course of bioremediation, the mobile constituents are degraded, leaving behind a relatively immobile, insoluble material not subject to further attack by a water-based technology. Another would be that the NAPL initially contained a fraction that was already immobile and insoluble. An example of such a tar-NAPL would be a coal-tar roof, pipeline coating, or driveway sealer. These are produced by distilling off the lighter fractions of coal tar to produce a heavier fraction that is virtually immobile and insoluble. Planned future work is targeted at identifying the composition of the NAPL both before and after bioremediation to determine its similarity to these commercial products consisting of heavier tar fractions.

These results illustrate that a water-based remedial technology, such as bioremediation, can attack the water-mobile portion of a NAPL present in the soil. The water mobility varies in saturated and unsaturated states and with the composition of both the soils and the NAPL. Slurry reactor treatment represents the most aggressive water-based treatment because the soils and pockets of NAPL are highly mixed for weeks in an excess of water where constituents dissolving into the water are removed by biodegradation. When the soils concentration of PAHs levels out at a plateau concentration (C_R) in a slurry reactor after weeks of treatment, the limits of a water-based technology have been reached. Transport of constituents from the remaining NAPL to water is virtually insignificant after this plateau has been reached.

This conclusion suggests that bioremediation, especially in a saturated state, may consistently produce a treated soil that is protective of human health and the environment where the contaminant is a hydrocarbon NAPL, like tar.

This conclusion suggests that bioremediation, especially in a saturated state, may consistently produce a treated soil that is protective of human health and the environment where the contaminant is a hydrocarbon NAPL, like tar. If the water-mobile constituents of the NAPL have been degraded so that remaining constituents are virtually immobile, then the treated soil should not be a source of further groundwater contamination through leaching. Hence, the threat of exposure from ingestion of contaminated groundwater from this treated soil should be alleviated.

If the soil itself were ingested, the water-mobile constituents would not be present; hence, a significant reduction in exposure potential would be achieved. However, the availability of other non-water mobile constituents in a biotreated soil when ingested has not been determined definitively. A conservative approach therefore would be to cover biotreated soils so that exposure through ingestion is unlikely. Future research is targeted at determining the bioavailability of PAH-contaminated soils treated by bioremediation.

The Conceptual Model Applied to Other Hydrocarbons

As a final part of the discussion, extrapolation of these results to other hydrocarbon NAPLs (e.g., petroleum products) should be considered. Clearly, the water-based conceptual model plausibly explains experimental

observations with tar-NAPL. There is no apparent reason why these findings are not generally applicable to other hydrocarbons. A petroleum hydrocarbon in soil should respond analogously to a tar hydrocarbon. If mass transport of constituents from the interior of fines aggregates is limiting for tar-contaminated soil, then this should also be the case for petroleum-contaminated soil. If the soil is high in fines, bioremediation of petroleum compounds in an unsaturated state should result in higher plateau concentrations than a more sandy soil or a saturated state. If the petroleum hydrocarbons are composed of immobile, insoluble substances (e.g., asphaltic compounds), then the plateau concentration can be expected to be at a significant level above zero.

CONCLUSIONS

The results of this work allow the following conclusions to be made:

- Bioremediation of PAH-contaminated soils is a viable remedial technology;
- The composition of the soils and NAPL can significantly influence the response of PAH-contaminated soils to bioremediation;
- Bioremediation of soils containing higher fines contents, greater than 10 percent, in an unsaturated state can be limited because of mass transport restrictions from the interiors of the fine aggregates; and
- Bioremediation of soil containing pockets of NAPL can be limited by the immobile, insoluble constituents of the NAPL. ■

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