SYBRON CHEMICALS INC.

TREATABILITY STUDY WORK PLAN

FOR

RENORA SITE REMEDIATION


67025

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I. SUPPORT DOCUMENTATION

A. Site Location and Description

The Renora Inc. site, located at 83 South Main Street, in the Bonhamtown section of Edison Township, Middlesex County, New Jersey is an approximately one acre parcel of land in an area zoned for light industrial use (Figure 1). Adjacent to the site is a complex which includes an auto repair and body shop, welding, machinery, and electric supply shops. The surrounding area is residential with three sensitive uses, (a nursery school, senior citizens center and an apartment complex), within two thousand feet of the site (Figure 2).

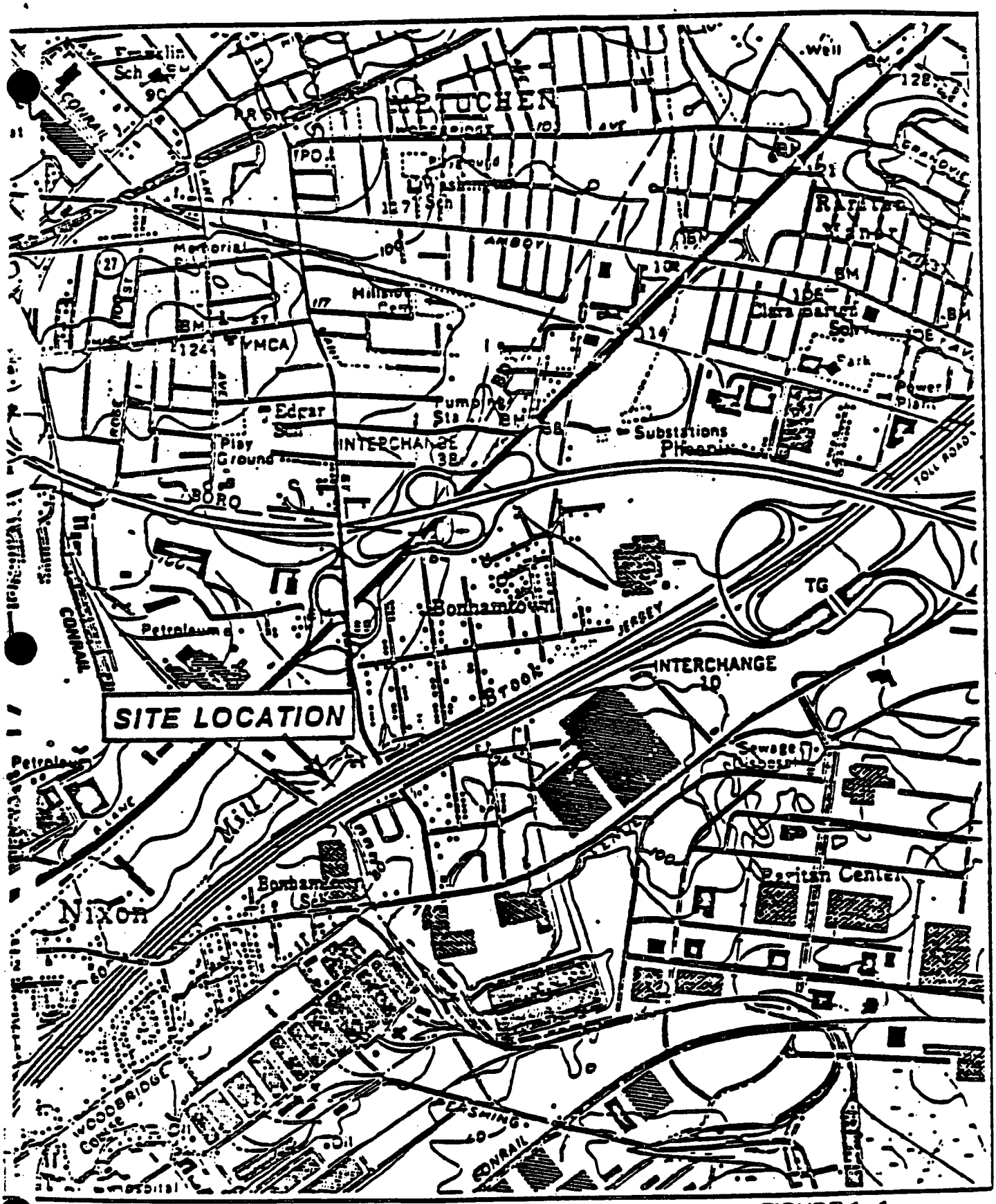
The site is bordered on the north by Mill Brook, on the south by the New Jersey Turnpike, on the east by South Main Street and on the west by the Conrail railroad. The only structure at the site is a perimeter chain link fence with locking gates. Figures 1-1 and 1-2 depict the location of the site and surrounding land use respectively.

The site is relatively flat land built up from flood plain with three to twelve feet of what appears to be demolition debris and underlain by a one to six foot thick layer of sand and clayey silt. The fine grained sediments are partially overlain by gravelly sand to sandy gravel, which pinches out near Mill Brook. Highly weathered, clay-rich Brunswick shales underlie the alluvial deposits. Surface elevations range from 62.5 feet above mean sea level in the eastern corner of the site, to approximately 66 feet above mean sea level along the southeastern perimeter. The site lies within the regulatory (but not actual since the land was built up from the flood plain) 100 year flood plain and within the actual 500 year flood plain.

While there are no public supply well fields within one-half mile of the site, a well search tentatively identified twelve wells within one mile of the site of which eight are believed to be residential but no longer used for potable purposes. Edison Township maintains several public supply wells four to eight miles from the site but has reserved their use for emergency situations only.

All groundwater from the site discharges into Mill Brook, which has a drainage area of 3.1 square miles. The watershed is drained by Bonhamtown Creek, which is upgradient of the site, and Mill Brook.

From November 1980 through July 1981, numerous site inspections by the NJDEP and the Edision Township Department of Health revealed that conditions at the site had progressively deteriorated. In late July 1981, NJDEP filed a Verified Complaint, supporting



BCM Eastern Inc.
ENGINEERS, PLANNERS, and SCIENTISTS

BCM Project No. 88-4378-03

750 1500 Feet

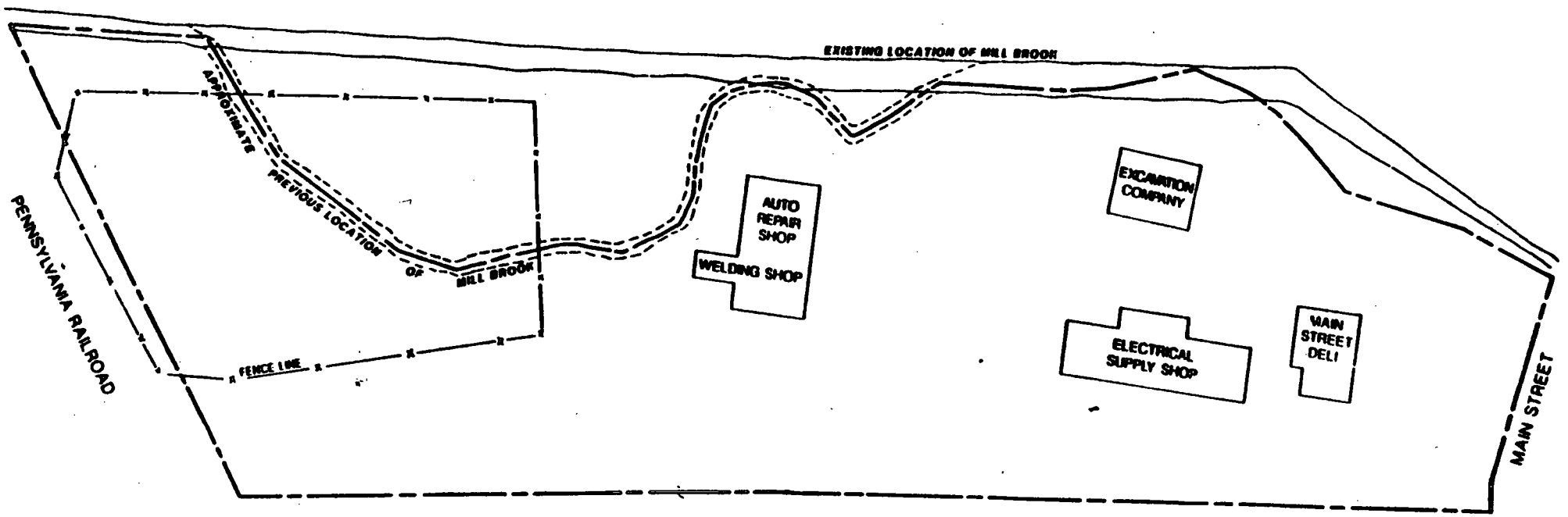
FIGURE 1-1

Pitney, Hardin, Kipp & Szuch

Feasibility Study
RENORA, INC. SITE
Edison Township, New Jersey

SITE MAP

REN 002 1867



STUDY AREA BOUNDARY (FENCE LINE)

CLEMENTI PROPERTY LINE

0 30 60 120 Feet

FIGURE 1-2

Pitney, Hardin, Kipp & Szuch

FEASIBILITY STUDY
RENORA, INC. SITE
Edison Township, New Jersey

STUDY AREA/SITE

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BCM Project No. 00-4376-02

Note: The study area boundary encompasses the approximate extent of former renora operations

affidavits and an Order to Show Cause against Kaschner, Renora and the Clementis' requesting closure of the facility, unannounced access by NJDEP, requiring that the facility be secured, and requiring posting of a performance bond. The business records of Renora were seized by NJDEP in September 1981.

The facility was placed on EPA's National Priority List in December, 1982.

The Clementis subsequently filed a third-party action against a number of the PRPs (potential responsible parties) who were involved in the RI/FS. On or about August 1, 1983, a consent order was entered pursuant to which further proceedings were stayed while NJDEP and the other parties attempted to negotiate a settlement of the lawsuit. Currently, the litigation is in an inactive status.

Negotiations between NJDEP and a group of responsible parties continued until August 1984. In April 1984, NJDEP had sent a directive letter to the responsible parties requesting a cleanup proposal, which was submitted in June 1984.

However, in August 1984 the NJDEP, in consultation with EPA determined the need for a removal action at the Renora site based on the potential for imminent and substantial endangerment to the public health, welfare and the environment.

EPA sent official notification to approximately seventy (70) PRPs on September 17, 1984 that EPA would conduct an Immediate Removal Action (Removal Action) as defined in the National Contingency Plan, 40 C.F.R. Part 300 at the site. On September 28, 1984 EPA issued an Administrative Order pursuant to §106 of the Comprehensive Environmental Response, Compensation and Liability Act, 42 U.S.C. §9606 (Docket No.: II-CERCLA-50112) to conduct the Removal Action. The PRPs immediately formed the Renora Surficial Cleanup Trust (Cleanup Trust) and entered into negotiations with EPA concerning the Removal Action at the site.

On October 22, 1984 EPA initiated the Removal Action by installing a perimeter fence and securing leaks from drums and tankers. On October 28, 1984 the Removal Action was assumed by a contractor for the Cleanup Trust.. The Removal Action was completed in compliance with the Administrative Order on April 17, 1985.

A cost recovery action was initiated against PRPs who elected not to participate in the removal action. The case was referred for litigation by EPA to the Department of Justice in September 30, 1985. A lawsuit was filed on September 4, 1986. A settlement has been reached between the United States and a group of recalcitrant parties for approximately

$78,000 costs incurred by EPA. In addition, the State of New Jersey and the defendants reached a settlement for $10,500 representing State cost expenditures. There are other recalcitrant parties to be pursued for remaining costs incurred by EPA.

In December 1984, negotiations were initiated between EPA and the PRPs to discuss performance of the RI/FS by the PRPs. On May 29, 1985, an Administrative Consent Order (Docket Number: II-CERCLA-50112) was entered into between EPA and a group of thirty-five (35) PRPs to have the PRPs conduct the RI/FS under oversight by EPA. The RI/FS report was submitted to EPA in August, 1987.

Based on the feasibility study submitted and the on-going discussions between EPA and the PRPs; there appears to be a strong interest on the part of the PRPs to implement the proposed remedy. Special notice will be expected to be issued to the PRPs in October or November, 1987. It is expected that a "good faith offer" would be submitted by the PRPs during the initial sixty day moratorium period and that an agreement for RD/RA can be consummated during the subsequent sixty day period allowed by the special notice procedures of SARA.

Site History

From 1950 to 1952 the New Jersey Turnpike (NJTP) Authority acquired parcels of land that form the present site. Between 1969 and 1974 the area underlying the present site was filled with what appears to be demolition debris and the Mill Brook stream channel was relocated at various points approximately 25 to 100 feet north to its present position. In November, 1976 Clementi Brothers Inc. acquired the site from the NJTP Authority.

In October, 1977 the New Jersey Board of Public Utilities Commissioners issued Renora, Inc. a Certificate of Public Convenience and Necessity as a collector/hauler of waste oils and in 1978 Ronal Kaschner, President of Renora, Inc. leased the site from Clementi Bros. Inc., via an oral agreement.

From 1978 to 1982 Renora Inc., transported and accepted material containing hazardous substances for transfer, storage, blending and ultimately, disposal through abandonment at the site.

New Jersey Department of Environmental Protection (NJDEP) and Edison Township Department of Health and Human Resources (DOH) inspection reports indicate that the site was poorly maintained throughout the period of its operation. An NJDEP inspection in July, 1978 detected several minor spills and determined that Renora Inc., was acting as a Special

Waste Transfer Station without proper registration. At that time Kaschner was advised to register with NJDEP Solid Waste Administration (SWA). In October, 1978, an oil spill at the site was reported to the DOH. NJDEP and the DOH conducted an investigation which led to an order to remove all contaminated soil and drums.

A Temporary Operating Authorization (TOA) was issued to Kaschner in December, 1978 with an expiration date of April 30, 1979. An NJDEP investigation of May, 1979 reported leaking drums on the property. In June, 1979, NJDEP SWA sent formal notification of the expiration of Renora Inc.'s TOA.

In March, 1980, NJDEP SWA issued a Notice of Prosecution to Renora, Inc., ordering the cessation of all operations and the implementation of remedial actions at the site. A subsequent NJDEP inspection of the site in June, 1980 indicated that, although operations had ceased, no remedial action had taken place. In July, 1980 NJDEP issued Renora Inc. a Directive/Notice of Violation. The Directive/Notice was not complied with and a meeting was arranged between Kaschner/Renora and NJDEP. In August, 1980, Kaschner/Renora and NJDEP entered into an Order and Settlement Agreement for site cleanup with a scheduled completion date of October, 1980. In November, 1980, the NJDEP revoked Kaschner's registration to collect and haul solid waste for Renora, effectively putting him out of business. Kascher abandoned cleanup activities in December, 1980 due to lack of funds.

On or about July 19, 1981, NJDEP sued Renora, Kaschner and Anthony and Catherine Clementi, and obtained an injunction requiring them to do the following:

1. end and remedy all statutory violations at the facility,
2. cease accepting wastes, petroleum products, and hazardous substances,
3. permit NJDEP to enter the facility for inspections and other investigative activities, and,
4. post a performance bond.

In June of 1982 the site was abandoned and in December, 1982 the site was included on the EPA's National Priorities List (NPL).

On September 28, 1984 EPA issued an Administrative Order to conduct surficial cleanup at the site to all the known potentially responsible parties (PRPs). A group of these PRPs then formed the Renora Surficial Cleanup Trust (Trust).

A removal action was initiated in October, 1984 and continued through April, 1985. During the cleanup, approximately 33,000 gallons of liquid waste and 28,000 gallons of PCB contaminated waste oil along with approximately 500 cubic yards of non-PCB contaminated

soils and 560 cubic yards of PCB-contaminated soils were shipped off-site for proper disposal.

On September 17, 1984 EPA sent Notice Letters to all the members of the Trust to perform a Remedial Investigation/Feasibility Study (RI/FS).

In May 1985, an Administrative Consent Order was signed between EPA and a group of potential responsible parties (Renora RI/FS Trust) who volunteered to undertake the studies. The RI/FS was conducted by BCM Eastern Inc. under contract to the Trust between May 1985 and May 1987. The work was conducted under EPA oversight. In support of the RI/FS, Camp, Dresser & McKee under contract to EPA conducted an endangerment assessment in order to determine the magnitude of risk to public health and the environment posed by the site.

B. Current Site Status

The RI, completed May, 1987, includes investigations of soil, groundwater, surface water, sediment and air. Findings and conclusions as a result of the RI are as follows:

1. Surficial soils (0-2 feet) are primarily contaminated with polychlorinated biphenyl (PCBs) and polynuclear aromatic hydrocarbons (PAHs) and to a lesser extent with volatile organic compounds (VOCs), acid extractable compounds (AECs), other base/neutral organic compounds (BNCs) and heavy metals. The southwest corner of the site contains greatest contamination at the site.
2. Shallow groundwater beneath the site is contaminated with low levels of chloroethane, (a volatile organic compound) and heavy metals.
3. Surface water and sediment samples show levels of heavy metals, tetrachloroethene, phenols and pesticides.
4. No evidence of air contamination was found at the site.
5. No buried drums were found at the site.

A detailed analysis of each aspect of the RI is presented below.

C. Soil Investigation

Twelve sampling locations were selected based on the site history, test pit program results, removal action observations and results, and field observations. Two to three depths were sampled at each location to determine the degree of vertical contamination. The bulk of the contamination is limited to surficial soil as a result of the contaminants high rate of adsorption and low solubility. Concentrations and locations of soil/fill samples are depicted on Figure 3. A summary of the chemical analysis of soil samples is presented in Table 1.

TABLE 1

SUMMARY OF ORGANIC COMPOUNDS IN SOIL

RENORA SITE
EDISON, NEW JERSEY

Sample Identification	Sample Material	Total Group Concentration								
		Volatile Organics				Base Neutrals				
		Halogenated Aliphatics ug/kg	Monocyclic Aromatics ug/kg	Other Volatiles ug/kg	Acid Extractables ug/kg	PAHs ug/kg	Phthalates ug/kg	Chlorinated Benzenes ug/kg	PCBs ug/kg	TPH mg/kg
RB-1-2	A	2.9	---	---	---	4,000	900	---	---	*
RB-1-6	B	---	---	---	---	---	---	---	---	---
RB-2-2	A	---	---	---	---	140,200	2,000	---	---	*
RB-2-6	B	*	*	*	---	8,200	850	---	*	239
RB-2-10	B	2.6	---	2.6	*	*	*	*	---	---
RB-3-2	A	91	4.4	---	---	9,300	4,100	47 J	---	*
RB-3-10	B	---	---	---	---	103,600	---	---	---	1,112
RB-4-2	A,C	---	---	---	86	26,300	490	350 J	7,800	*
RB-4-10	B	---	11.0 J	---	---	4,500	320	---	480.90	1,053
RB-5-2	A,C	2,200	73,400	2,300	420	20,000	3,200	1,500	37,000	*
RB-5-10	B	7.2	20.5	72	1,270	11,700	5,750	752	182.26	6,706
RB-6-2	A	---	---	---	---	29,400	---	---	760	*
RB-6-6	A,C	*	*	*	50	8,400	---	---	562.72	3,097
RB-6-8	B	---	---	---	*	*	*	*	*	---
RB-7-2	A	---	---	---	13,600	59,100	---	---	3,000	*
RB-7-10	A,B	---	---	940	---	3,600	170	---	---	1,989
RB-8-2	A	237	59.0	---	590	13,700	3,000	1,300	3,800	*
RB-8-12	B	---	---	51	---	---	390	---	---	976
RB-9-2	A,C	---	---	---	150	8,500	170	---	---	*
RB-9-6	A,C	*	*	*	---	15,900	360	---	*	1,799
RB-9-10	A,B	---	---	---	*	*	*	*	---	---
RB-10-2	A	---	---	---	56	9,100	130 B	---	270.65	2,637
RB-10-8	A	---	---	---	783	4,000	300	---	---	759
RB-10-12	B	---	---	4.3	211	1,500	464	---	---	79
RB-11-2	A	277	---	---	6,900	22,400	8,000	2,100	3,583.37	7,196
RB-11-6	A	31.0	298	1,210	132,400	43,500	1,100 B	---	12,724.14	1,410
RB-11-12	B	1.5	46.2	645	54,900	50,200	2,400 B	---	179.03	1,580
RB-12-2	A,C	---	203	---	700	27,100	4,200	1,100	1,208.79	12,585
RB-12-6	A	27.6	25.8	85.8	124,100	80,200	1,800	---	583.52	6,133
RB-12-12	B	4.9	---	236	36,400	42,700	700 B	---	---	432

A Fill material
B Natural material
C Cinders or asphalt noted in sample
* Not analyzed for
--- Analyzed but not detected
Note: Where duplicate samples were analyzed, only the highest concentration is shown.

Source: BCM Eastern Inc. (BCM Project No. 00-4376-02)

Elevated concentrations of all five of the analytical parameter groups (PCBs, PAHs, VOCs, AECs, BNCs, and heavy metals) were detected at the site with the major constituents being PCBs and PAHs. Distribution of these contaminants was not uniform; the greatest concentrations of contaminants were generally found in the southwest portion of the site. PAHs were found at each sampling location. Concentrations of PAH's were present in all twelve surface to 2' depth samples and were present in nearly every test well at depths greater than six feet. Generally, the west portion of the site comprising approximately one third of the total area was most heavily contaminated with PAH compounds.

Volatile organic compounds were found on site in low ppb concentrations for the most part. However, high ppb and ppm levels were obvious in four soil boring wells on the western corner of the site (Figure 3).

D. **Groundwater Investigation**

The groundwater investigation assessed the degree of existing contamination. five groundwater monitoring wells were installed at the site to provide on site groundwater quality data and help determine the direction of groundwater flow at the site. A seep in the stream bank was also sampled to supplement groundwater quality data. Three piezometers were installed in and adjacent to Mill Brook to monitor water table elevations close to the Brook (Figure 4).

The results of this investigation revealed that the groundwater on-site is contaminated with low levels of chloroethane and heavy metals. While chloroethane was not found in soil samples it is potentially a byproduct of degradation from 1,1,1-trichloroethane which was found in out site soils previously sampled. For metals, cadmium and chromium slightly exceeded Federal and State requirements by 1 and 4 ppb respectively, in one of two sampling episodes and were not detected in the second sampling episode. Alternatively, there could be an upgradient source(s) of contamination. A summary of groundwater contamination is presented in Table 2. There were no elevated concentrations of PAH compounds found in the groundwater.

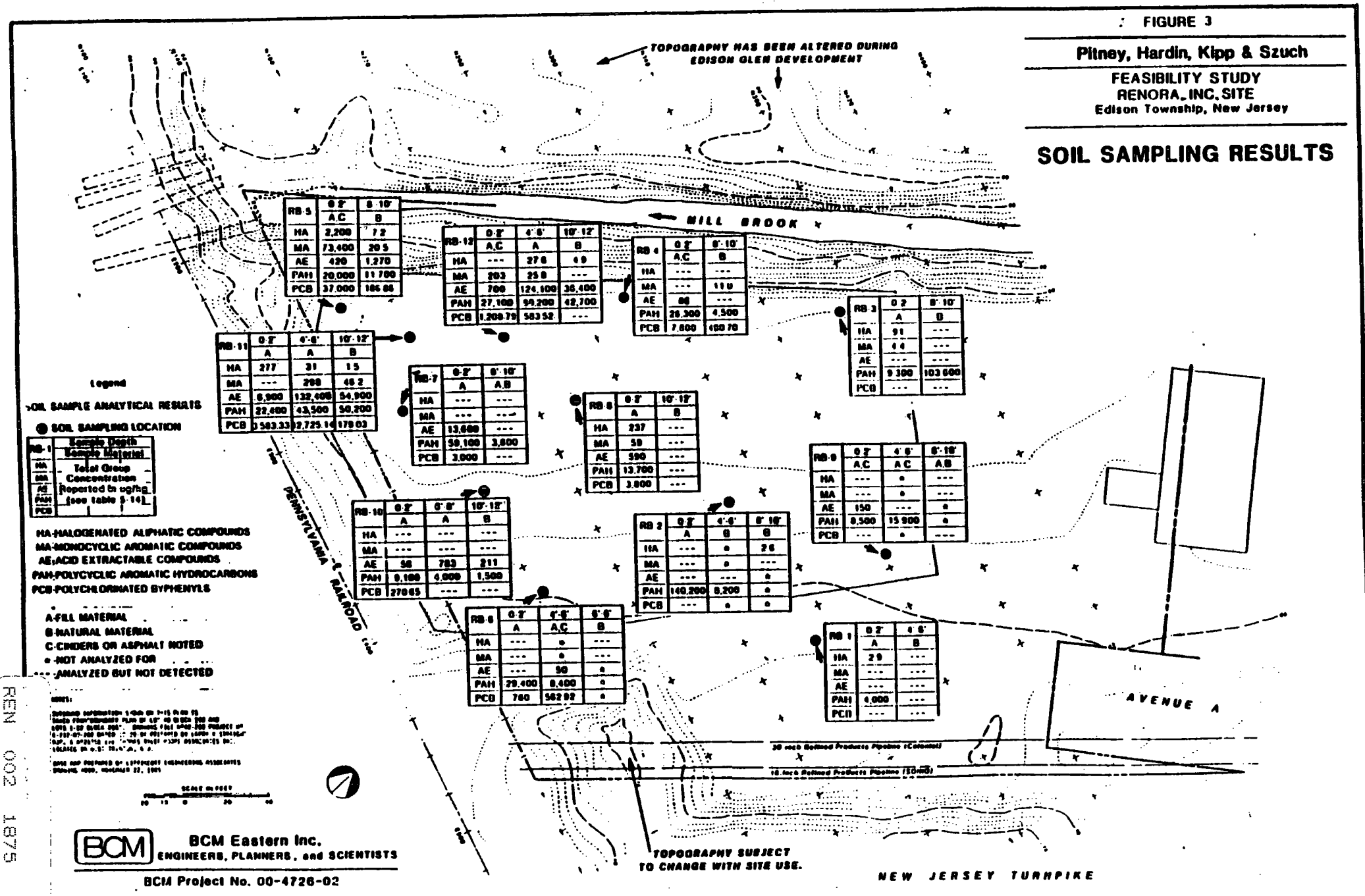
The fate of the organic compounds at the site is largely controlled by the nature of the fill material, alluvium and weathered bedrock beneath the site. Many of the compounds detected at the site will absorb moderately to very strongly to fine-grained solid particles containing organic matter prevalent in the fill/soil. In addition, the limited solubility of most

FIGURE 3

Pitney, Hardin, Kipp & Szuch

FEASIBILITY STUDY
RENORA, INC. SITE
Edison Township, New Jersey

SOIL SAMPLING RESULTS



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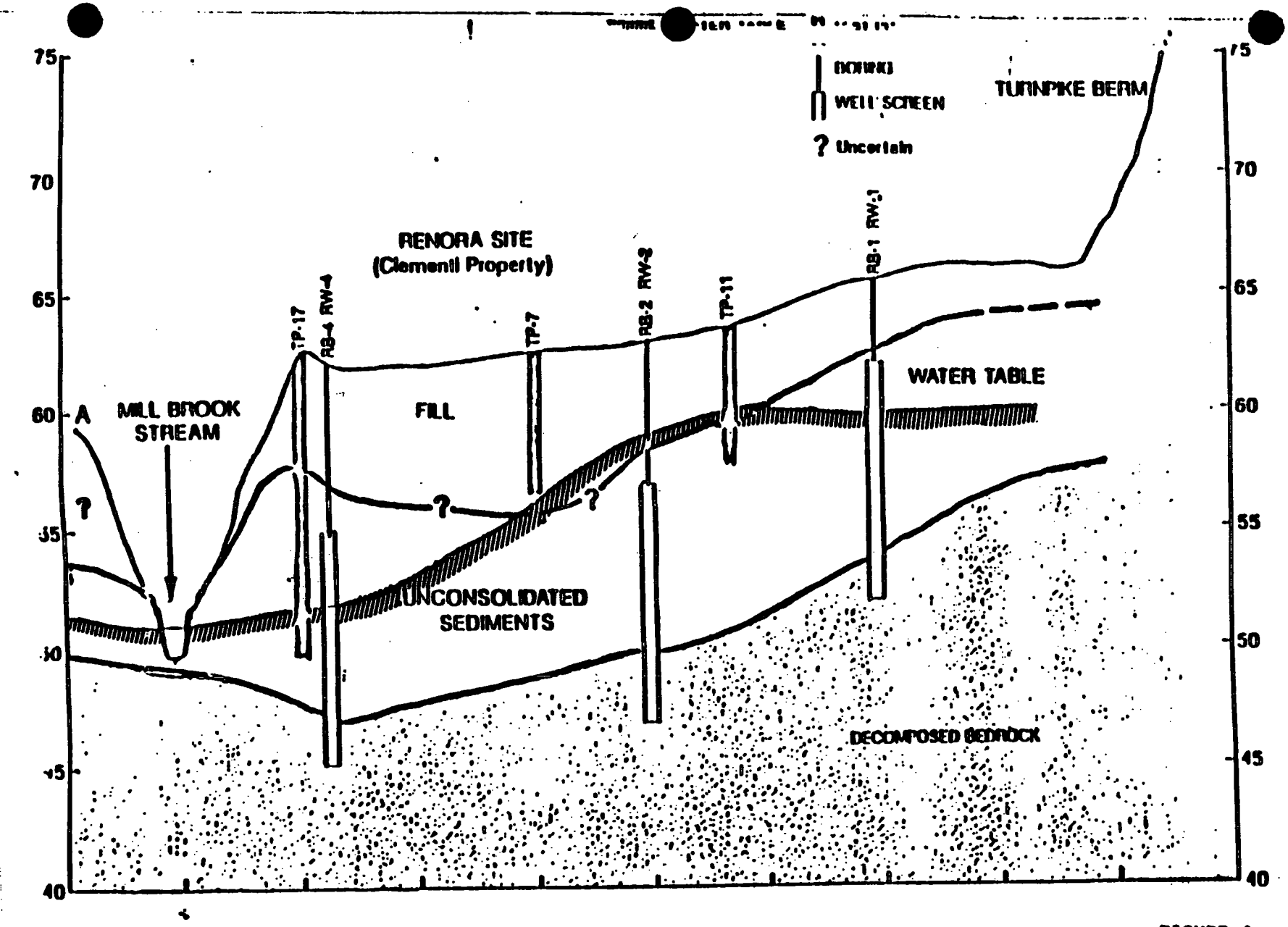

FIGURE 4

BCM Eastern Inc.
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BCM Project No. 00-4378-02

SCALE
0 50'
5'

Pliney, Hardin, Kipp & Szuch

REMEDIAL INVESTIGATION
RENORA, INC. SITE
Edison Township, New Jersey

WATER TABLE

TABLE 2

SUMMARY OF CHEMICAL ANALYSES
SEEP AND GROUNDWATER

REMOVA SITE
EDISON TOWNSHIP, NEW JERSEY

CompuChem No.:	92881	115134	92883	115123	92885	115124	115125	92888	115126	92889	115127	92891	115128
BCM No.:	86-12736	87-00971	86-12737	87-00960	86-12738	87-00961	87-00962	86-12740	87-00963	86-12741	87-00964	86-12742	87-00965
BCM I.D.:	SP-1	SP-1	RW-1-13	RW-1-13	RW-2-16	RW-2-16	RW-2D-16	RW-3-15	RW-3-15	RW-4-17	RW-4-17	RW-5-17	RW-5-17
Sampling Date:	07/09/86	01/14/87	07/09/86	01/14/87	07/09/86	01/14/87	01/14/87	07/09/86	01/14/87	07/09/86	01/14/87	07/09/86	01/15/87
Volatile Organics (ug/l)													
Acetone	---	---	---	---	---	7.9 J**	---	---	16**	---	---	---	---
Benzene	---	---	---	---	---	---	---	---	2.1 J	---	---	---	---
Chloroethane	---	---	---	---	15	7.5 J	7.1 J	240	130	42	37	16	7.5 J
Total Xylenes	---	---	---	---	16	---	---	---	---	---	---	---	---
Acid Extractables (ug/l)													
No compounds detected	*	*	---	*	---	*	*	---	*	---	*	---	*
Base/Neutral Extractables (ug/l)													
Acenaphthene	---	*	---	*	---	*	*	2.4 J	*	---	*	---	*
Bis(2-Ethylhexyl)phthalate	2.6 J	*	---	*	---	*	*	---	*	---	*	---	*
Isophorone	---	*	---	*	---	*	*	4.4 J	*	---	*	2.0 J	*
Naphthalene	---	*	---	*	---	*	*	6.2 J	*	---	*	---	*
Pesticides and PCBs (ug/l)													
No compounds detected	---	*	---	*	---	*	*	---	*	---	*	---	*
Metals (mg/l)													
Antimony	0.004	---	---	---	---	---	---	---	---	---	---	---	---
Arsenic	0.04	0.024	0.009	---	---	0.011	0.011	0.031	0.070	0.011	0.006	0.025	0.016
Cadmium	0.011	---	---	---	0.0005	---	---	0.0009	---	---	---	---	---
Chromium	0.054	---	0.002	---	0.001	---	---	---	---	---	---	---	---
Copper	0.239	---	---	0.029	---	0.025	0.026	---	0.026	---	0.025	---	0.028
Lead	0.295	---	0.002	---	0.038	---	---	0.036	---	0.059	---	0.010	---
Mercury	---	---	---	0.0005	---	---	---	---	0.0002	0.0005	0.0007	---	0.0002
Selenium	---	---	0.009	---	0.006	---	---	0.006	---	0.009	---	0.007	---
Zinc	1.67	0.076	---	0.178	--	0.099	0.178	0.02	0.167	---	0.201	0.04	0.201
Miscellaneous													
Phenols as phenol (ug/l)	36	90	7	---	35	8	15	22	25	9	58	8	49

* Compounds not analyzed for
** Analyte was detected at a concentration less than 10 times that found in any blank. The result is, therefore, questionable.
--- Compound analyzed for but not detected
J Estimated value

Source: BCM Eastern Inc. (BCM Project No. 80-4376-02)

of the contaminants and the limited vertical permeability due to the highly weathered, clay-rich bedrock underlying the site inhibit the vertical migration route and focuses groundwater toward Mill Brook.

Groundwater flows northwest and discharges into Mill Brook. Analysis of water level data collected from three different periods revealed fluctuations in water table elevations of less than 1 foot. Such slight differences in water elevations suggests minimal horizontal movement of groundwater occurs beneath the site. The stability of the water table combined with the low permeability of the soil has kept contamination of groundwater low. There has been no offsite migration of contaminants through groundwater.

E. Existing Literature

The degradation pathways and biokinetic constants of many polynuclear aromatic compounds (PAHs) are known. Two books and one major research publication exist that comprehensively review PAH studies (1, 2, 3). A plethora of organisms exist that can degrade PNA compounds. However, it is apparent that the limiting factor to degradation in all cases is the solubility of PAH in water (3, 4). Solubility decreases as molecular weight increases. Compounds consisting of more than four rings are generally considered insoluble in water. A complete review of the literature as it relates to microbial degradation of aromatic compounds can be reviewed in Appendix I.

As in all soil systems volatilization and sorption are considered important parameters in controlling the fate of contaminants. Volatization is not considered to be a significant transport or removal process for PAHs other than naphthalene. Sorption, however, is more important and is affected by the soil type, moisture, temperature, pH and the presence of other organic compounds. PAHs are considered to be strongly sorbed in most cases. Table 3 describes adsorption data for PAHs as they relate to soil. Additionally, data for selected VOC's, phthalates, and phenolics are also described.

Microbial degradation has been shown to be a very slow but important process in the removal of PAHs, VOCs and other environmentally sensitive compounds (Table 4). Degradation rates were found to be independent of PAH concentrations (3). This implies a zero-order rate for biokinetics and is supported by the limiting solubility factors (4). However, in an American Petroleum Institute study, selected PAHs, VOC's, phthalates, and monoaromatics were reported to follow first order degradative kinetics (Table 5) (3).

TABLE 3

SUMMARY OF SOIL ADSORPTION DATA FOR ORGANIC CONSTITUENTS

Compound	Aqueous Solubility (mg/l)	log octanol/ water parti- Coefficient Kow	Organic Carbon Partition Coefficient Koc
Monoaromatics			
Benzene	1780-1800 (25°C)	1.95-2.13	83[a]
Toluene	535 (25°C)	2.69	No Data
Nitrobenzene	1000 (20°C)	1.85	No Data
2,4-Dinitrotoluene	270 (22°C)	2.01	No Data
2,6-Dinitrotoluene	No Data	2.05	No Data
Phenolics			
Phenol	93,000 (25°C)	1.46	No Data
2,4-Dimethylphenol	4,200 (20°C)	2.30	No Data
4,6-Dinitro-o-cresol		2.85	No Data
4-Nitrophenol	16,000 (25°C)	1.91	No Data
2,4-Dinitrophenol	5,600 (18°C)	1.53	No Data
Phthalate Esters			
Bis (2-ethylhexyl)	0.4 (25°C)	5.3-8.7	31,700[b]
Butyl Benzyl	2.9	4.8-5.8	21,900[b]
Diethyl	896 (25°C)	3.22	1,870[b]
Di-n-octyl	3.0 (25°C)	9.2	No Data
Dimethyl	4320 (25°C)	2.12	No Data
Polynuclear Aromatic Hydrocarbons			
Benz(c)acridine	No Data	No Data	No Data
Benz(a)Anthracene	0.014	5.61	1,871,400[c]
Benzo(b)-Fluoranthene	0.0012	6.57	No Data
Benzo(j)-Fluoranthene	No Data	No Data	No Data
Benzo(a)Pyrene	0.003	6.04	4,510,650[d]
Chrysene	0.0018	5.61	No Data
Dibenz(a,h)Acridine	No Data	No Data	No Data
Dibenz(a,j)Acridine	No Data	No Data	No Data
Dibenz(a,h)-Anthracene	0.0005	5.97	2,029,000[e]
7H Dibenzo(c-g)Carbazole	No Data	No Data	No Data
Dibenzo(a,e)Pyrene	No Data	No Data	No Data
Dibenzo(a,h)Pyrene	No Data	No Data	No Data
Dibenzo(a,i)Pyrene	No Data	No Data	No Data
7,12-Dimethylbenz(a)-Anthracene	0.0244	5.97	225,308[e]
Fluoranthene	0.26	5.33	No Data
Indeno(1,2,3-cd)-Pyrene	0.0002	7.66	No Data
Naphthalene	31.7	3.37	1,300[d]

[a] Karickhoff et al., 1979
[b] McDuffie and Russell, 1982
[c] Nasset et al., 1980
[d] Reinbold et al., 1978
[e] Means et al., 1979

TABLE 4

KINETIC PARAMETERS DESCRIBING RATES OF DEGRADATION OF ORGANIC COMPOUNDS IN SOIL SYSTEMS

Substance	Initial Concentration (ug/g soil)	K (day^{-1})	1/2 Life (days)	Reference
Toluene	5,000-20,000	0.60-1.0	0.7-1.7	Donnelly (1979)
Toluene	-	0.10	7	Borkowitz et al (1981)
Pyridine	-	> 0.10	< 7	Borkowitz et al (1981)
Phenol	500	0.693	1.0	Medvedev & Davidov (1972)
Phenol	500	0.315*	2.2*	Medvedev & Davidov (1972)
2,4-dimethylphenol	500	0.35-0.69	1-2	Medvedev & Davidov (1972)
4,6-dinitro-o-cresol	-	> 0.023	< 30	Versar, Inc. (1977)
2,4-dinitrophenol	5-50	0.025	28	Overcash et al. (1982)
2,4-dinitrophenol	20-25	>0.099-0.23	<3-7	Sudharkar-Sarik & Sethunathan (1978)
4-nitrophenol	-	> 0.043	< 16	Verschueren (1977)
Bis(2-ethylhexyl phthalate)	-	0.050	14	Johnsen and Lulves (1975)
Diethyl Phthalate	10	>0.173	< 4	McDuffie & Russell (1982)
Napthalene	7	5.78	0.12	Herbes & Schwall (1978)
Napthalene	7	0.005*	125*	Herbes & Schwall (1978)
Napthalene	7	0.173	4**	Herbes & Schwall (1978)
Benz(a)anthracene	0.12	0.046*	15.2*	Herbes & Schwall (1978)
Benz(a)anthracene	0.12	0.0001	6,250	Herbes & Schwall (1978)
Benz(a)anthracene	3.5	0.007	102	Groenewegen & Stolp (1976)
Benz(a)anthracene	20.8	0.003	231	Gardner et al. (1979)
Benz(a)anthracene	25.8	0.005	133	Gardner et al. (1979)
Benz(a)anthracene	17.2	0.008	199	Gardner et al. (1979)
Benz(a)anthracene	22.1	0.006	118	Gardner et al. (1979)
Benz(a)anthracene	42.6	0.003	292	Gardner et al. (1979)
Benz(a)anthracene	72.8	0.004	196	Gardner et al. (1979)
Benz(a)anthracene	0.07	0.005	134	Sims (1982)
Benz(a)anthracene	0.10	0.005	142	Sims (1982)
Benz(a)anthracene	0.15	0.005	154	Sims (1982)
Benz(a)anthracene	7	0.016	43	Sims (1982)

*Low temperature (<15°C)

**High temperature (>25°C)

TABLE 4 (Continued)

Substance	Initial Concentration (µg/g soil)	K (day^{-1})	1/2 Life (days)	Reference
Benz(a)anthracene	8.2	0.017	41	Sims (1982)
Benz(a)anthracene	9.7	0.017	41	Sims (1982)
Chrysene	4.4	0	-	Groenewegen & Stolp (1976)
Chrysene	300	0.067	10.5	Medvedev & Davidov (1972)
Chrysene	5	0.126	5.5	Medvedev & Davidov (1972)
Dibenz(a,j)-acridine	0.57	0.015	44	Sims (1982)
Dibenz(a,j)-acridine	0.71	0.017	40	Sims (1982)
Dibenz(a,j)-acridine	0.69	0.012	55	Sims (1982)
Dibenz(a,j)-acridine	57	0.016	43	Sims (1982)
Dibenz(a,j)-acridine	64	0.017	41	Sims (1982)
Dibenz(a,j)-acridine	73	0.015	46	Sims (1982)
Indeno(1,2,3-cd)-pyrene	0.57	0.001	600	Sims (1982)
Indeno(1,2,3-cd)-pyrene	1.14	0.002	360	Sims (1982)
Indeno(1,2,3-cd)-pyrene	1.30	0.003	200	Sims (1982)
Indeno(1,2,3-cd)-pyrene	57	0.001	600	Sims (1982)
Indeno(1,2,3-cd)-pyrene	114	0.001	600	Sims (1982)
Indeno(1,2,3-cd)-pyrene	168	0.001	600	Sims (1982)
Dibenz(a,h)-anthracene	9700	0.033**	21**	Lijinsky & Quastel (1956)
Dibenz(a,h)-anthracene	5.7	0.004	183	Sims (1982)
Dibenz(a,h)-anthracene	4.5	0.005	141	Sims (1982)
Dibenz(a,h)-anthracene	3.5	0.004	190	Sims (1982)
Dibenz(a,h)-anthracene	57	0.005	130	Sims (1982)
Dibenz(a,h)-anthracene	93	0.007	99	Sims (1982)
Dibenz(a,h)-anthracene	147	0.007	119	Sims (1982)

*Low temperature (<15°C)

**High temperature (>25°C)

TABLE 4 (Continued)

Substance	Initial Concentration (ug/g soil)	K (day^{-1})	1/2 Life (days)	Reference
Fluoranthene	3.9	0.016	44	Groenewegen & Stolp (1976)
Fluoranthene	18.0	0.004	182	Gardner et al. (1979)
Fluoranthene	23.0	0.007	105	Groenewegen & Stolp (1976)
Fluoranthene	16.5	0.005	143	Gardner et al. (1979)
Fluoranthene	20.9	0.006	109	Groenewegen & Stolp (1976)
Fluoranthene	44.5	0.004	175	Gardner et al. (1979)
Fluoranthene	72.8	0.005	133	Gardner et al. (1979)
Benzo(b)fluoranthene	0.33	0.007	98	Sims (1982)
Benzo(b)fluoranthene	0.57	0.006	123	Sims (1982)
Benzo(b)fluoranthene	0.80	0.006	130	Sims (1982)
Benzo(b)fluoranthene	33	0.010	67	Sims (1982)
Benzo(b)fluoranthene	46	0.008	85	Sims (1982)
Benzo(b)fluoranthene	53	0.010	73	Sims (1982)
Benz(a)pyrene	0.048	0.014*	50*	Herbes & Schwall (1978)
Benz(a)pyrene	0.01	0.001*	694*	Herbes & Schwall (1978)
Benz(a)pyrene	3.4	0.012	57	Groenewegen & Stolp (1976)
Benz(a)pyrene	9.5	0.002	294	Gardner et al. (1979)
Benz(a)pyrene	12.3	0.005	147	Gardner et al. (1979)
Benz(a)pyrene	7.6	0.003	264	Gardner et al. (1979)
Benz(a)pyrene	18.5	0.023	30	Gardner et al. (1979)
Benz(a)pyrene	17.0	0.002	420	Gardner et al. (1979)
Benz(a)pyrene	32.6	0.004	175	Gardner et al. (1979)
Benz(a)pyrene	1.0	0.347**	2**	Shabad et al. (1975)
Benz(a)pyrene	0.515	0.347**	2**	Shabad et al. (1975)
Benz(a)pyrene	0.00135	0.139**	5**	Shabad et al. (1975)
Benz(a)pyrene	0.0094	0.002*	406*	Shabad et al. (1975)
Benz(a)pyrene	0.345	0.011	66	Shabad et al. (1975)
Benz(a)pyrene	28.5	0.019*	37*	Shabad et al. (1975)
Benz(a)pyrene	29.2	0	-	Shabad et al. (1975)

*Low temperature (<15°C)

**High temperature (>25°C)

TABLE 4 (Continued)

Substance	Initial Concentration (ug/g soil)	K (day^{-1})	1/2 Life (days)	Reference
Benz(a)pyrene	9,100	0.018**	39**	Liginsky & Quastel (1956)
Benz(a)pyrene	19.5	0.099	7	Poglazova et al. (1967b)
Benz(a)pyrene	19.5	0.139	5	Poglazova et al. (1967b)
Benz(a)pyrene	19.5	0.231	3	Poglazova et al. (1967b)
Benz(a)pyrene	130.6	0.173	4	Poglazova et al. (1967b)
Benz(a)pyrene	130.6	0.116	6	Poglazova et al. (1967b)
Benz(a)pyrene	0.36	0.009	79	Sims (1982)
Benz(a)pyrene	0.41	0.008	83	Sims (1982)
Benz(a)pyrene	0.75	0.006	120	Sims (1982)
Benz(a)pyrene	36	0.008	92	Sims (1982)
Benz(a)pyrene	55	0.007	100	Sims (1982)
Benz(a)pyrene	69	0.008	92	Sims (1982)

*Low temperature (<15°C)

**High temperature (>25°C)

TABLE 5

ESTIMATES OF DEGRADATION AND IMMOBILIZATION CONSTANTS

	First Order[a] Kinetic Constant, K ($days^{-1}$)	Carbon Partion[b] Coefficient, K_{oc} (ml/g)
MONOAROMATICS		
Benzene	0.1-1.0[e]	83
Toluene	0.40-1.0	100-1000[e]
Nitrobenzene	0.01-0.1[e]	10-100[e]
2,4 Dinitrotoluene	0.01-0.1[e]	10-100[e]
2,6 Dinitrotoluene	0.01-0.1[e]	10-100[e]
PHENOLICS		
Phenol	0.69	10-100[e]
2,4-dimethylphenol	0.35-0.69	100-1000[e]
4,6-dinitro-o-cresol	>0.023	100-1000[e]
4-nitrophenol	>0.043	10-100[e]
2,4-dinitrophenol	>0.025	10-100[e]
PHTHALATE ESTERS		
Bis(2-ethylhexyl)	>0.05	31,700
Butyl Benzyl	0.1-1.0[e]	21,900[e]
Diethyl	>0.17	1,870
Di-n-octyl	0.01-0.10[e]	>1,000,000[e]
Dimethyl	0.1-1.0[e]	100-1000[e]
PAH		
Benz(c)acridine	0.001-0.10[e]	100,000-1,000,000[e]
Benz(a)anthracene	0.003[d]-0.017	1,871,400
Benzo(b)fluoranthene	0.006-0.010	>1,000,000[e]
Benzo(j)fluoranthene	0.001-0.10[e]	>1,000,000[e]
Benzo(a)pyrene	0.002-0.023	4,510,650
Chrysene	0.067-0.126	100,000-1,000,000[e]
Dibenz(a,h)acridine	0.001-0.10[e]	100,000-1,000,000[e]
Dibenz(a,j)acridine	0.12-0.017	100,000-1,000,000[e]
Dibenz(a,h)anthracene	0.004-0.007	1,668,800

TABLE 5 (Continued)

ESTIMATES OF DEGRADATION AND IMMOBILIZATION CONSTANTS

	First Order[a] Kinetic Constant, K ($days^{-1}$)	Carbon Partion[b] Coefficient, K_{oc} (ml/g)
PAH (Continued)		
7,H Dibenzo(c,g)carbazole	0.001-0.10[e]	100,000-1,000,000[e]
Dibenzo(a,e)Pyrene	0.001-0.10[e]	100,000-1,000,000[e]
Dibenzo(a,h)Pyrene	0.001-0.10[e]	100,000-1,000,000[e]
Dibenzo(a,i)Pyrene	0.001-0.10[e]	100,000-1,000,000[e]
7,12-Dimethylbenz(a)-anthracene	0.001-0.10[e]	225,308
Fluoranthene	0.004-0.016	100,000-1,000,000[e]
Indeno(1,2,3,cd)pyrene	0.001-0.003	> 1,000,000[e]
Napthalene	0.005-0.173[f]	1300

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a,b experimental values from Table 4-19
d dropped low experimental value
e estimated value (see Appendix I).
f dropped high experimental value

Cometabolism of PAHs in a mixed PAH system is considered to be an important process as in microbial acclimation (3). Biodegradation has not been successfully demonstrated with 5-membered and greater ring compounds. The half-lives for PAHs up to 5 rings ranged from 18 - 190 days, while a six-membered ring compound, indeno (1, 2, 3-CD) pyrene had a half-life of 600 days (3). A review of the literature indicates that a number of different investigators have determined biodgradability of many different environmentally sensitive compounds. Table 6 outlines a compilation of the results of these studies.

F. **Soil Characterization**

Soil characteristics can be expressed physically and chemically. The present study will involve both liquid and gas movement through the soil. Therefore, thorough investigation is necessary. A heterogeneous soil is often more difficult to evaluate, as is the case with fill material, and in some cases all tests are not applicable. However, without having seen the soil to be studied, only a list of potential examinations may be given.

Parameters critical to evaluating soil to be treated by the movement of liquids or gases:

Physical (5, 6)	Chemical (5, 7)
Hydraulic conductivity	Anions - C1, Br, NO3, NO2, SO4, PO4
Diffusivity	
Porosity	Cations - Ca, Mg, Na, K, Fe (total), Mn (total)
Consistency	
Gas movement	Toxic metals
Aggregate stability	Total organic carbon
Particle size	Alkalinity/pH

Chemical evaluations can be obtained by extracting soil with distilled water and performing the appropriate analyses. The integrity of ion analyses is assured if the milliequivalents of anions and cations are found to be equal in the examined water. Anion analyses may be performed by ion chromatography or wet chemistry methods. Cations will be determined by atomic absorption spectrophotometry.

It has been recently reported that the chemistry of the soil environment is critical in the determination of the potential for contaminant biodegradation (8).

TABLE 6

Biodegradation of Organic Chemicals by Indigenous Soil Microorganisms

Compound	System[a]	Initial Concentration[b]	Biodegradation[c]	Ref[d]
Alcohols				
methanol	S, sm, x	1-1000	RD	1
	S, sm, c, x	100-1000	RD	2
	S, sm, x, n	20	RD	3
ethanol	S, sm, x, n	20	RD	3
1-propanol	S, sm, x, n	20	RD	3
1-butanol	S, sm, x, n	20	RD	3
1-pentanol	S, sm, x, n	20	RD	3
t-butanol	S, sm, x, n	$10-10^3$	RD-R	3
	S, sm, x	1-100	SD-R	1
	S, sm, c, x	1-100	RD-SD, L	2
Aliphatics				
tetrachloromethane	S, as, x	4.5	--	4
bromodichloromethane	S, sm, a	--	SD-R	5
1,2-dibromoethane (EDB)	S, ss, a	0.007	RD	6
		0.017	SD, L	6
	S, sm, m	0.19	RD	7
1,1,1-trichloroethane	S, as, x	4.5	--	4
trichloroethene (TCE)	S, as, x	4.5	--	4
	S, sm, c, m	0.16	SD, L	7
	S, sm, c, x	2	--	8
1,1-dichloroethene	S, sm, c, m	0.12	SD, L	7
cis-1,2-dichloroethene	S, sm, c, m	0.12	RD, L	7
trans-1,2-dichlorocthene	S, sm, c, m	0.12	SD, L	7
tetrachloroethene	S, as, x	1.5	RD	9
		4.5	--	4
Alicyclics				
α-hexachlorocyclohexane	S, ss, a	400 mg/kg	RD	10
	S, ss, n, s, m	350 mg/kg	R	10

TABLE 6 (Cont.)

Compound	System[a]	Initial Concentration[b]	Biodegradation[c]	Ref[d]
Benzenes				
benzene	S, sm, c, m	0.6	R, LL	7
	S, sm, c, a, m	0.45	RD	11
	S, sm, c, a	0.1-0.6	RD-SD	12
	S, sm, a, n	3	RD	13
	S, sm, x	3	SD	13
toluene	S, sm, a	1	SD	14
	S, sm, a	--	RD	5
	S, sm, c, m	0.5	RD	7
	S, sm, c, a, m	0.4	RD	11
	S, sm, a	0.1-0.6	RD-R	12
	S, sm, c, a	0.1-0.6	RD-SD	12
	S, sm, a, n	3	RD	13
	S, sm, x	3	SD	13
	F, as, c, n	18.4	RD	15
o-xylene	S, sm, c, m	0.3	R, LL	7
	S, sm, c, a, m	0.4	RD	11
	S, sm, c, a	0.1-0.6	RD-SD	12
	S, sm, c, a, n	3	RD	13
	S, sm, x	3	SD	13
	F, as, c, a	12	SD	16
m-xylene	S, sm, c, a	0.1-0.6	RD-SD	12
	S, sm, a, n	3	RD	13
	S, sm, x	3	SD	13
	F, as, c, a, n	12-21	RD	15,16
	F, as, a	12	RD	16
m- and *p*-xylene	S, sm, c, a, m	0.4	RD	11
	F, as, a	12	RD	16
chlorobenzene	S, sm, a	1	R	14
	S, sm, a	--	RD-R	5
	S, sm, a	0.1-0.6	RD-R	12
p-dichlorobenzene	F, as, a	15	RD	16
ethylbenzene	S, sm, c, m	0.3	R, LL	7
3-ethyltoluene	F, as, c, n	0.2mM	RD	15
styrene	S, sm, a	1	RD-SD	14
Phenoxyacetates				
phenoxyacetate	S, sm, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17

TABLE 6 (Cont.)

Compound	System[a]	Initial Concentration[b]	Biodegradation[c]	Ref[d]
2,4-dichlorophenoxyacetate (2,4-D)	S, sm, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
2,4,5-trichlorophenoxy-acetate (2,4,5-T)	S, sm, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
Benzoates				
benzoate	S, sm, c, a, x	1 mg/kg	RD	17
	S, sm, c, s, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
2-bromobenzoate	S, as, m	0.1-0.8	RD, L	19
3-bromobenzoate	S, as, c, m	0.1-0.8	RD	19
3-iodobenzoate	S, as, c, m	0.1-0.8	RD	19
3-chlorobenzoate	S, as, x	0.3-0.5mM	RD	17
	S, sm, c, m	0.3-0.5mM	RD	17
3,4-dichlorobenzoate	S, as, x	0.3-0.5mM	RD	17
	S, sm, c, m	0.3-0.5mM	RD	17
3,5-dichlorobenzoate	S, as, c, m	0.1-0.8	RD	19
	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
2,3,6-trichlorobenzoate	S, as, c, m	0.1-0.8	RD	19
4-amino-3,5-dichloro-benzoate	S, as, m	0.1-0.8	RD, L	19
Phenols				
phenol	F, sm, c, a	0.05-0.1	RD	20
	S, sm, c, s, m	30	RD	20
	S, sm, c, s, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
	S, sm, x	100	RD	21
	S, sm, x, n	1-200	RD	3
2-chlorophenol	F, sm, c, a	0.05-0.1	RD	20
	S, sm, c, m	30	RD	20
	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
	S, sm, x	100	RD	21
3-chlorophenol	S, sm, c, m	30	RD, L	20
	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17

TABLE 6 (Cont.)

Compound	System[a]	Initial Concentration[b]	Biodegradation[c]	Ref[d]
4-chlorophenol	S, sm, c, m	30	RD, L	20
	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
2,4-dichlorophenol	F, sm, c, a	0.05-0.1	RD	20
	S, sm, c, m	30	RD	20
	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
	S, sm, x	100	RD	21
	S, sm, x, n	15	RD	3
2,5-dichlorophenol	S, sm, c, m	30	RD	20
	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
3,4-dichlorophenol	S, as, x	0.3-0.5mM	RD	17
2,4,5-trichlorophenol	S, sm, c, m	0.3-0.5mM	RD	17
	S, as, x	0.3-0.5mM	RD	17
2,4,6-trichlorophenol	F, sm, c, a	0.05-0.1	RD	20
	S, sm, x	100	RD	21
pentachlorophenol	S, ss, a	0.15	RD	22
	S, sm, x	10	RD	21
p-nitrophenol	S, as, a	0.15	RD	23
p-cresol	S, sm, c, s	0.2mM	RD	24
	S, sm, c, m	0.2mM	RD, L	24
m-cresol	S, sm, c, s	0.2mM	RD, L	24
	S, sm, c, m	0.2mM	SD, L	24
o-cresol	S, sm, c, s, m	0.2mM	SD, LL	24
Organophosphates				
methyl parathion	S, sm, ss, a	1 mg/kg	RD	18
PAHs				
naphthol	S, ss, a, x, n	9	RD	25
naphthalene	F, as, a	0.66	RD	26
	S, ss, a	7	RD	25
	S, ss, n	7	RD, L	25
	S, ss, c, a	0.1-1.0	RD	27

TABLE 6 (Cont.)

Compound	System[a]	Initial Concentration[b]	Biodegradation[c]	Ref[d]
acenaphthene	S, ss, a	1	RD	25
	S, ss, n	0.4	RD, L	25
	S, ss, c, a	0.1-1.0	RD	27
1-methylnaphthalene	S, ss, c, a	0.1-1.0	RD	27
2-methylnaphthalene	S, ss, c, a	0.1-1.0	RD	27
Dibenzofuran	S, ss, c, a	0.1-1.0	RD	27
Fluorene	S, ss, c, a	0.1-1.0	RD	27

[a]S = static; F = flow-through; as = aquatic sediment; ss = surface soil; sm = subsurface material; c = soil from contaminated site and/or microcosms pre-acclimated to compound; a = aerobic; x = anoxic (conditions unknown); n = nitrate-reducing/denitrifying; s = sulfate-reducing; m = methanogenic conditions

[b]mg/L except where otherwise noted

[c]RD = readily degraded, $t_{1/2}$ < 84d; SD = slowly degraded, 84d < $t_{1/2}$ < 168d; R = recalcitrant but degradation apparent, $t_{1/2}$ > 168d; L = lag period; LL = long lag period, > 84d

-- = unknown

[d]References:

1. Goldsmith 1985
2. White 1986
3. Morris 1988
4. Parsons & Lage 1985
5. Wilson et al. 1983
6. Pignatello 1986
7. Wilson et al. 1986a
8. Kleopfer et al. 1985
9. Parsons et al. 1984
10. Bachmann et al. 1988
11. Wilson et al. 1986b
12. Wilson et al. 1986c
13. Major et al. 1988
14. Wilson et al. 1982
15. Kuhn et al. 1988
16. Kuhn et al. 1985
17. Gibson & Suflita 1986
18. Ward 1985
19. Horowitz et al. 1983
20. Suflita & Miller 1985
21. Smith & Novak 1987
22. Edgehill & Finn 1983
23. Spain et al. 1984
24. Smolenski & Suflita 1987
25. Mihelcic & Luthy 1988a
26. Heitkamp et al. 1987
27. Wilson et al. 1985

G. Chemical Analyses

PAH analyses will be performed by USEPA Method 8100 and extracted by USEPA Method 3550. USEPA Method 3630 will be used for sample cleanup if required. Methods for cadmium (7130, 7131), zinc (7950), volatile organics (8010, 8015, 8020) and total petroleum hydrocarbons (418.1) are attached. Analyses will be performed by Centec Analytical Services, Inc., Salem, VA. A Statement of Qualifications is attached in Appendix III.

H. Soil Sampling Methods

1. EPA

The EPA methods are described by Wilson et al (9). Basically, the sampling apparatus consisted of a heavy bronze cutting shoe fitted to a thick-walled sample tube. The shoe has a sharp edge at the penetration end and flares to a solid cylindrical shape into which the tube is inserted. The entire apparatus was designed to be pushed into the ground. Because the bronze cylindrical head is one inch larger than the tube, a gap is created around the tube as the unit is advanced into the soil. To keep the specimen from falling out of the tube, a six-finger sample "catcher" is inserted between the bottom of the sample tube and the flared section of the cutting shoe. The particular sample catcher employed is used conventionally to retain rock cor during oil well drilling. EPA personnel indicated good success with their sampling apparatus. However, they had only used it in local clean river bed sands at relatively shallow depths.

It is felt that the EPA methodology is inappropriate when:

1. The soils are dense, and simple pushing procedures would likely not penetrate enough distance for sampling.
2. Some of the soils are gravelly, and this would likely damage the sharp edge of the bronze cutting shoe.
3. Below the water table, the soil would likely collapse into the gap created between the cutting shoe and the tube causing withdrawal problems and possible loss of the cutting shoe.

2. Alternative Sampling Techniques

At least four alternatives are available: 1) an Osterberg hydraulic sampler; 3) a Denison sampler; 3) a Pitcher Barrel sampler; and 4) a Dames and Moore sampler. A split-spoon sampler is often used in preliminary drilling.

The split-spoon sampler is also known as the split barrel or split tube sampler. There are several modified versions of this sampler but basically it has a sample retainer located immediately above the barrel shoe and the barrel in which the sample is held and split longitudinally for easy sample removal. Split-spoon sampling is accomplished by driving the sampler with a 140-300 lb. hammer. It is common practice to record the number of blows for each six inches of sampler penetration. The number of blows required for a 1.5 inch sampler to driven 12 inches with a given hammer weight can be used to determine the Standard Penetration Resistance (SPR) of the soil. Split-spoon sampling is generally used where it is necessary to determine stratification, identification, consistency, and density of soils at a site (10).

The Osterberg piston sampler (Hydraulic sampler) consists of an actuating piston and a pressure cylinder. Introduction of fluid pressure on top of the actuating piston executes the sampling by pushing a Shelby tube into the soil (10). Shelby tubes are made of brass or steel.

A Dennison sampler relies on a combination of jacking and coring to obtain the sample. It is made of an outer rotating core barrel with a bit, an inner stationary sample barrel with a cutting shoe, inner and outer barrel heads, an inner barrel liner and an optional core retainer (10).

The Pitcher sampler is basically a Denison sampler in which the inner barrel is spring loaded to provide automatic adjustment of the distance by which the cutting edge of the barrel leads the coring bit (10).

Table 7 lists the advantages and disadvantages of each sampling method.

Drilling mud is used to maintain hole stability, especially in sands below the groundwater table, and is required for rotary drilling, as in the case of the Denison and Pitcher Barrel samplers, to return cuttings to the surface. While the mud serves to enhance the basic drilling process, a primary concern is that it might contaminate the soils. This is thought to be remote because the mud is very viscous and unlikely to flow freely. As a quality control measure, lithium chloride may be added as a tracer to the mud. Lithium is easily analyzed by AA.

Careful observations should be made for drilling mud penetration into the samples. Generally, no drilling mud is found inside the soil cores.

Table 7. Samplers considered for program.

Sampler	Insertion Method	Advantages	Disadvantages
Hydraulic	Hydraulic Push	Minimal disturbance	Limited to looser sands, no gravel
Denison	Rotary Drilling	Can drill into hard materials	Must use drilling mud
Pitcher Barrel	Rotary Drilling or Spring Push	Can drill into hard soil, push into soft soil	Must use drilling mud
Dames and Moore	Driven	Can penetrate hard soils	Must be driven by hammering

3. Soil Extrusion Apparatus

The extrusion device consists of hydraulically powered piston capable of generating in excess of 1000 psi, a dual clamp bed for holding the sampling tube, and a paring device (Figure 5). As the soil core is extruded from the sample tube, the first few centimeters are cut away with a flame sterilized spatula to remove any possibly contaminated material. The core is then forced through the sterilized, stainless steel, paring device, which trims away the outer one centimeter so that soil in contact with the sample tube walls is discarded. The final portion of the core sample is also discarded. The samples are extruded into acid-washed, sterile, one quart containers with Teflon-lined lids, and transported in iced coolers to the laboratory for refrigeration.

I. **Soil Microbial Characterization**

There is no single method of quantifying microbial populations that is not inadequate in some way. Three methods will be used to characterize the existing soil system. These will be soil extract and nutrient agar spread plate total viable counts (7, 11), acridine-orange epifluorescence direct counts (12, 5b), and substrate specific MPNs (most probable number) for naphthalene and anthracene (7, 11). These three methods are included in the attached Appendix V.

J. **Conceptual Design**

The actual design of the system will be determined based upon the results of the treatability study. Conceptual figures of the recirculating leachbed and soil ventilation systems are attached (Figures 6-9). A more detailed explanation will be given in the Treatability Design.

Conventional sanitary engineering design models will be used to size the bioreactor, while conventional engineering methods will be used to design the leachfield or soil ventilation system to provide the most rapid treatment in any case.

K. **Reporting**

Monthly progress reports will be issued on each phase of the treatability study. A final report will be issued on all phases of the study within four weeks after completion.

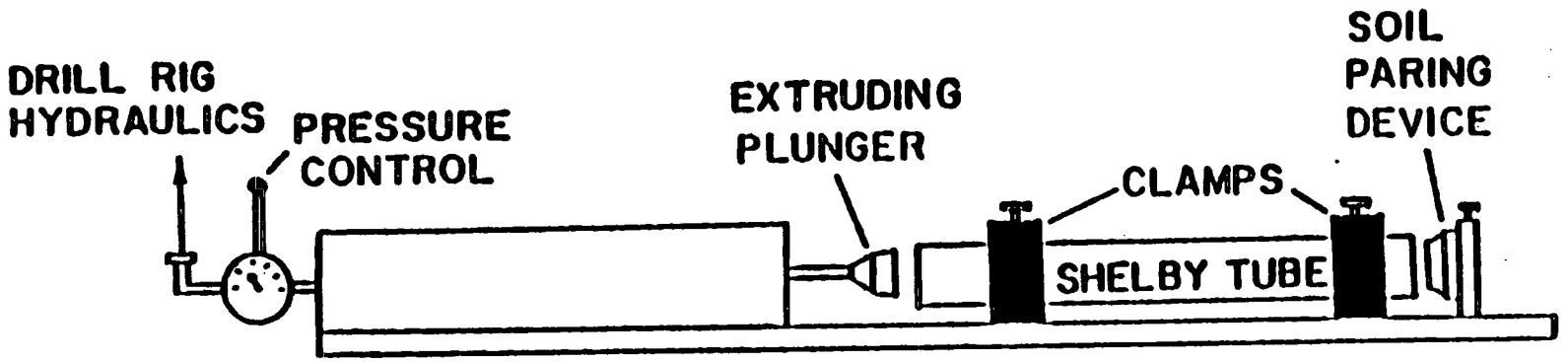
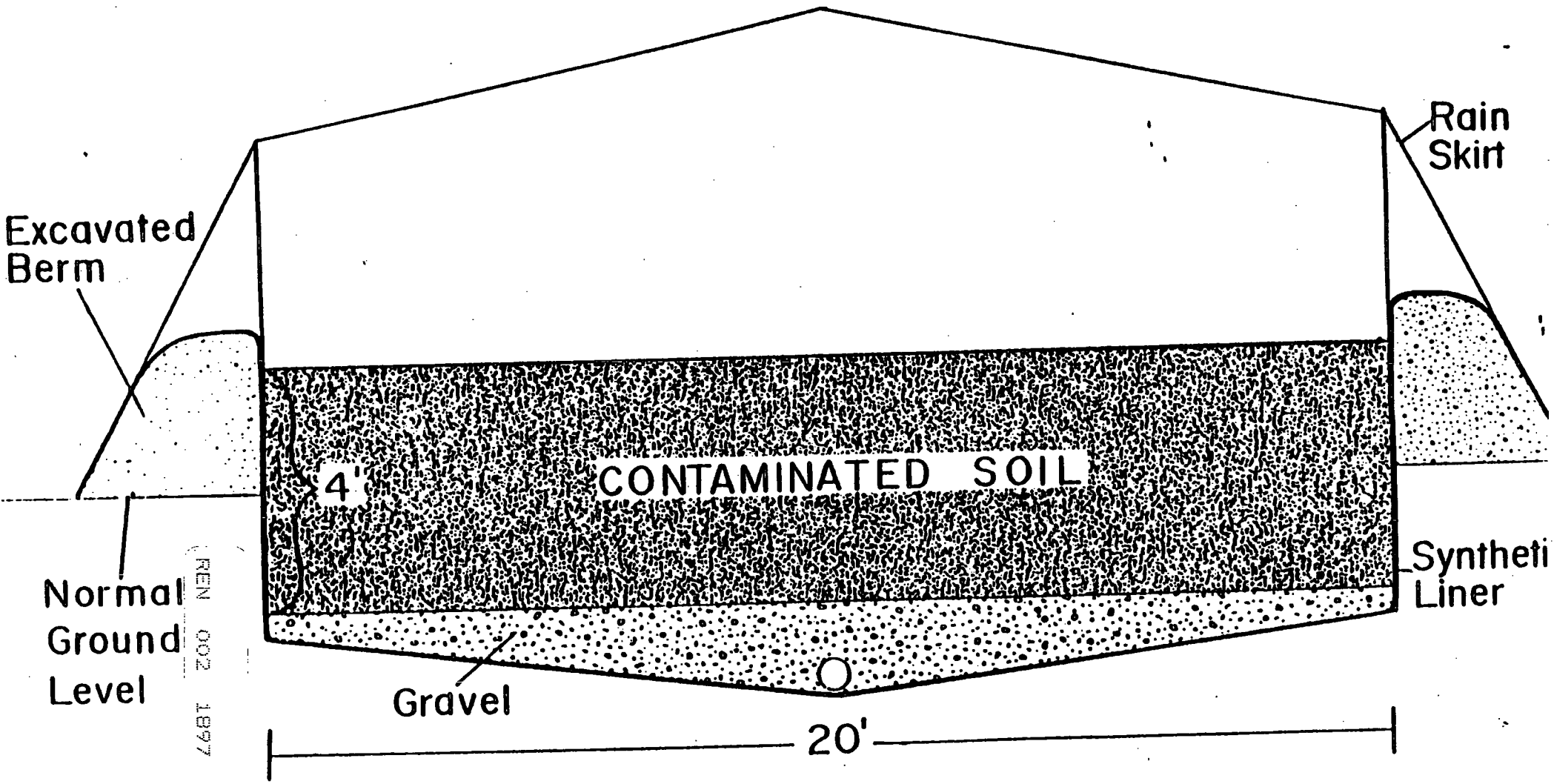


Figure 5. Soil extrusion apparatus.

FIGURE 6

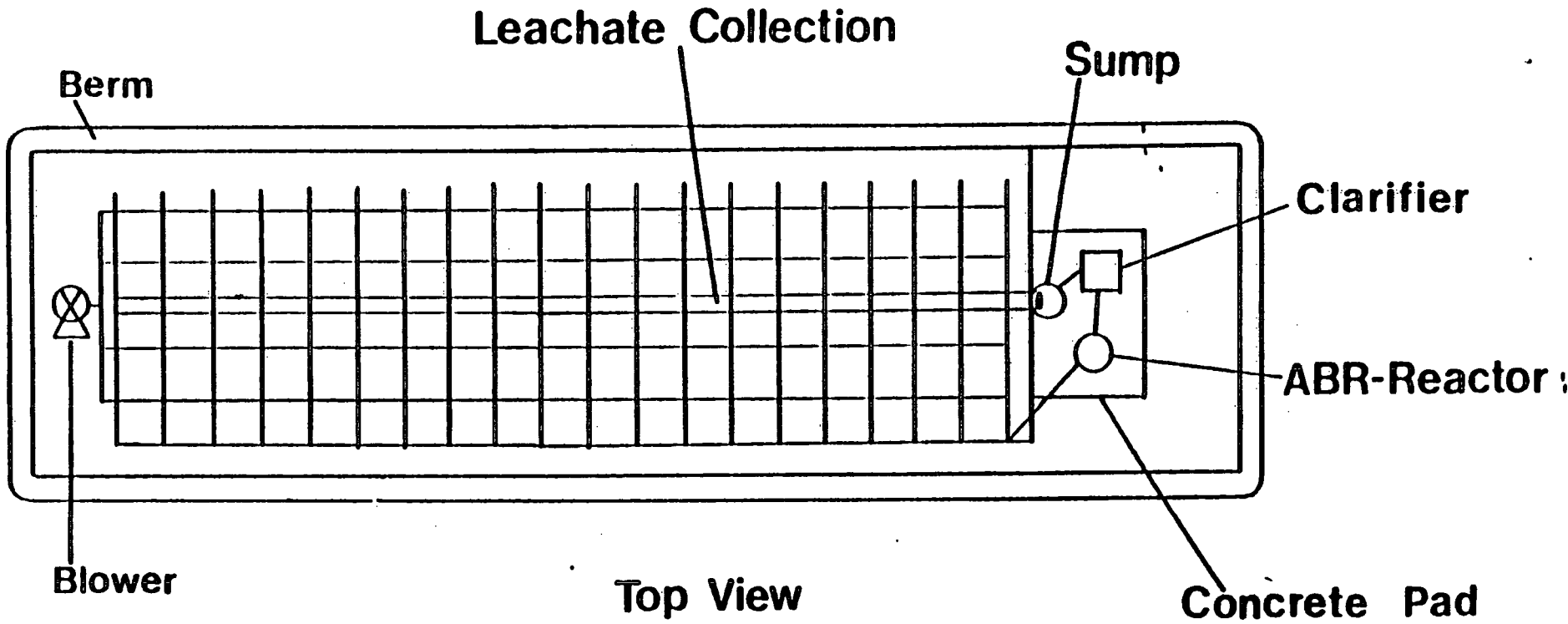
RECIRCULATING LEACHBED



CROSS SECTION

FIGURE 7

RECIRCULATING LEACHBED

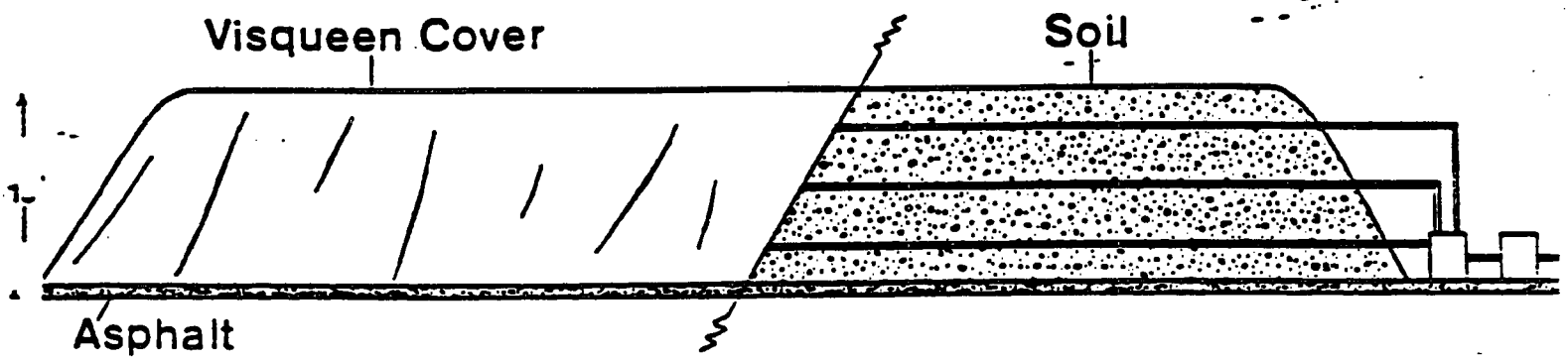


SYBRON
BIOCHEMICAL

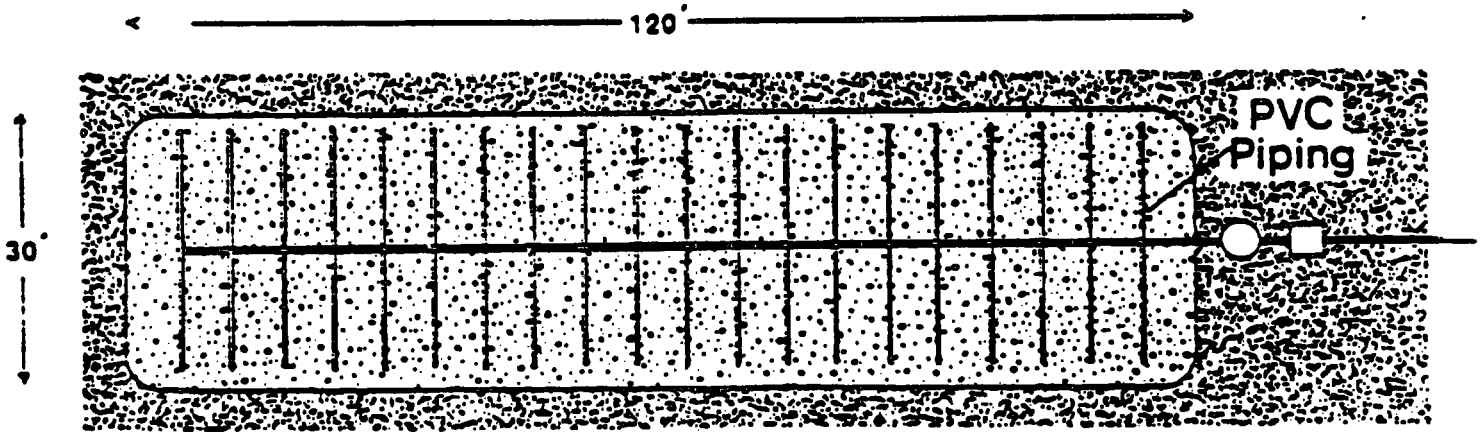
FIGURE 8

SOIL VENTILATION

Note: Dimensions are conceptual only.



Side View



Top View

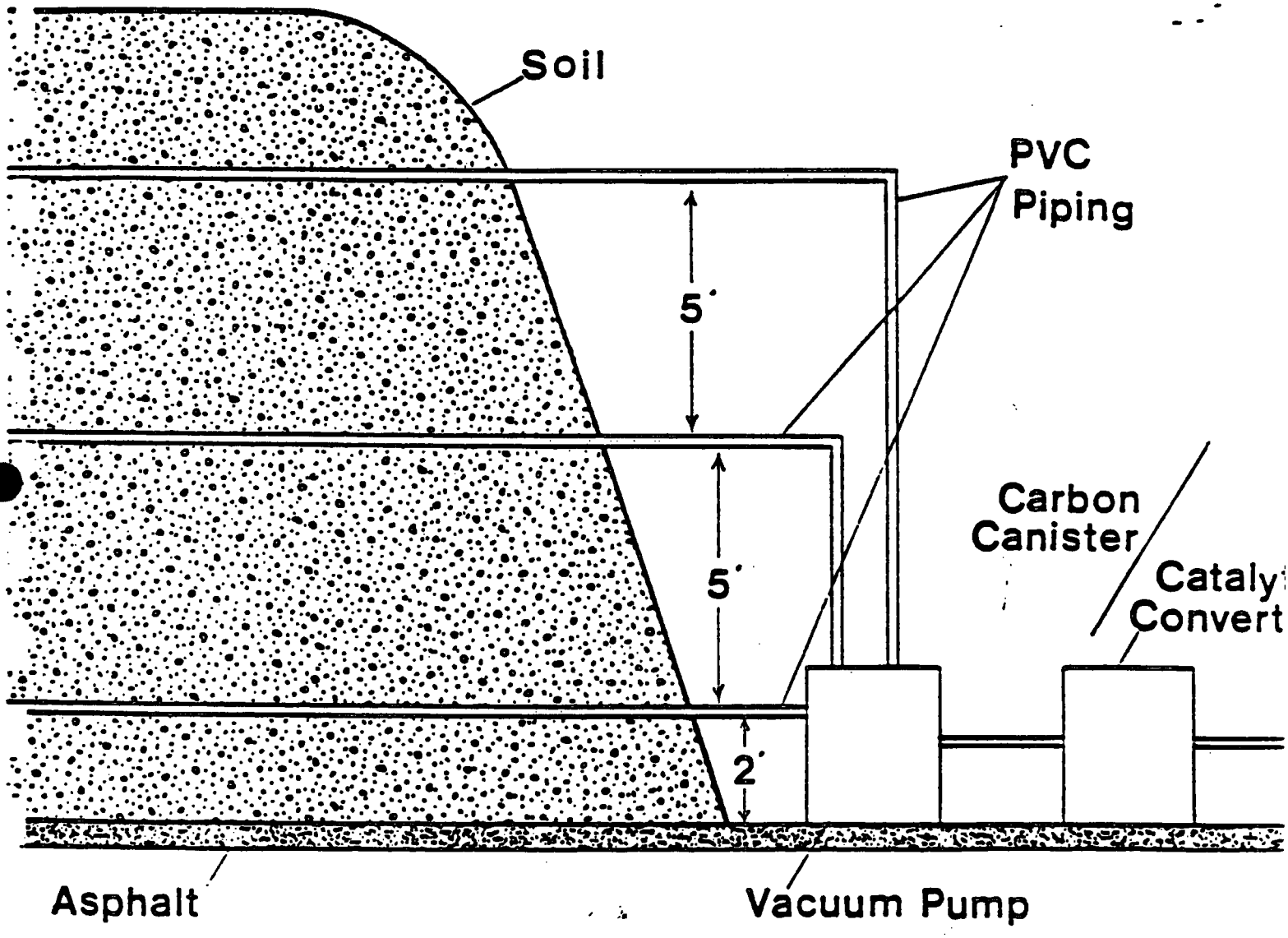
Sybron Chemicals

G

FIGURE 9

SOIL VENTILATION

Note: Dimensions are conceptual only.



Cross Section

L. **Scheduling for Performance**

Phase I - Sacrificial Shake Flask Study - 14 weeks.

Phase II - Recirculating Leachfield and Soil Ventilation - 18 weeks. May be done concurrent with Phase I.

See attached graphics.

II. TREATABILITY DESIGN

A. Shake Flask Study

Objective:

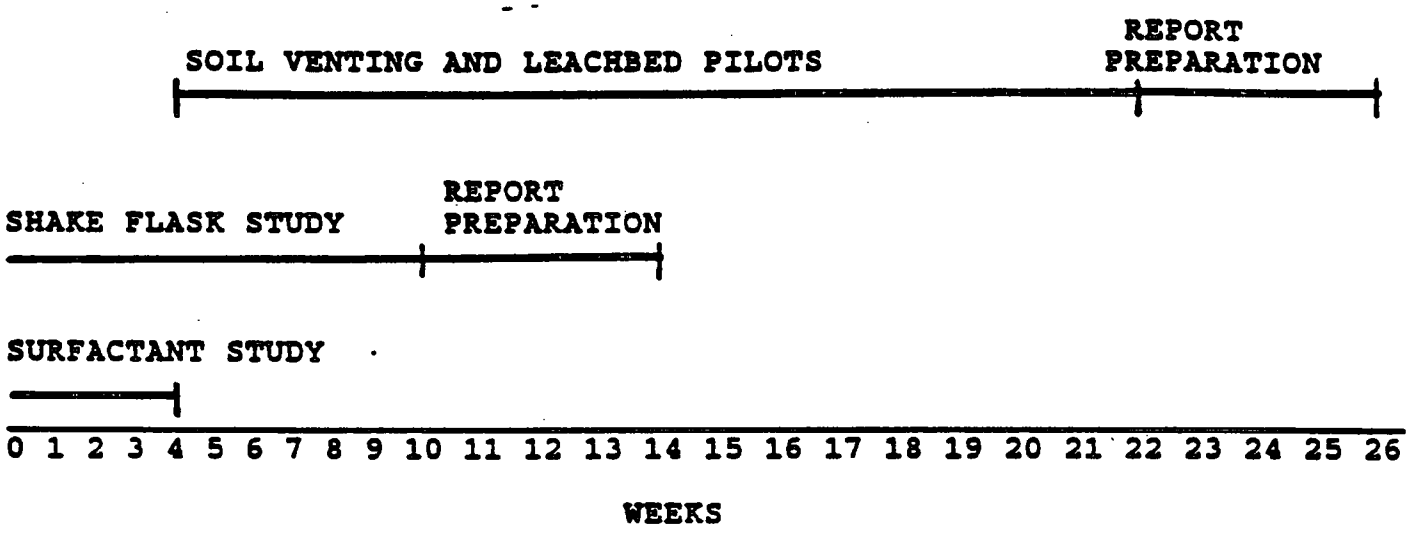
Determine the biodegration potential for soil containing polynuclear aromatic hydrocarbons under aerobic conditions in an aqueous media, and also for volatile organic compounds.

Treatments

1. Sterile Control
2. Indigenous organisms, no N & P
3. Indigenous organisms with N & P
4. Indigenous organisms and PAH specific organisms with N & P

A composite sample of the soil of interest is added at ten grams per shake flask. Sterile microbiological techniques will be followed during the handling and transfer of materials within the lab. The shake flask to be used in this microbial investigation simply consists of 250 mL Erlenmeyer flasks containing 100 mL of minimal media (Sorenson's buffer or water containing a carbonate buffer). These are pH 7 and plugged with a cotton-gauze stopper to allow air to move into the flask, while preventing the entry of airborne bacterial contaminants. Aeration is enhanced by placing the flasks on a rotary shaker incubator at 100 rpm. This creates a swirling motion of the liquid within the flask which increases oxygen transfer to the liquid media.

Multiple flasks will be sacrificed as indicated in Table 8. Sixteen PAH compounds are quantified by Method 8100. Flasks will be sacrificed and analyzed by an independent laboratory for PAHs to determine the utilization rate of these compounds. Four treatments with five flasks per treatment will result in the sacrifice of twenty flasks at each measurement


SOIL VENTING AND LEACHBED PILOTS
REPORT PREPARATION
SHAKE FLASK STUDY
REPORT PREPARATION
SURFACTANT STUDY
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
WEEKS

point. Only initial and final determinations will be made for total petroleum hydrocarbons, cadmium and zinc. Microbial assays will be performed as previously described and do not require the sacrifice of a discrete flask, since subsampling can be performed. This is also true of pH and nutrient measurements. Ten weeks (70 days) should provide sufficient utilization rate data and microbial growth rate data based upon results presented in the literature.

Table 8. Sacrificial shake flask testing schedule giving number of flasks required over time.

	Monitored Parameters				
Week	Microorganism Counts	pH/N & P	PAHs	VOs	Total
Initial	20	20	20	20	80
1					
2			20		20
4			20		20
6			20		20
8			20		20
10			20	20	40
					200

The data collected from the shake flask study can be used for a biokinetic evaluation. Biodegradation kinetic values, once obtained, can be used in the design of full-scale treatment systems. Kinetics can be briefly explained. For a general chemical reaction:

$$aA + bB \rightarrow cC + dD \quad (1)$$

where A and B are reactants, C and D are products, and a, b, c, and d are stoichiometric quantities the reaction rate may be expressed as the rate of reactant disappearance or product appearance. For example disappearance of A might be expressed as:

$$-\frac{d(A)}{dt} = K(A)^a(B)^b \quad (2)$$

where k is the reaction rate constant. For this equation, the order of the reaction, n, equals a + b. The disappearance of a single reactant, such as an organic substrate (C = concentration), might be given by:

$$-\frac{dC}{dt} = kC^n \tag{3}$$

The exponents constituting rate order usually are simple positive integers, but may be fractional or negative numbers, depending on the complexity of the reaction. The exponents represent the molecularity of the reaction and are intended to indicate the number of molecules involved in a simple collisional reaction process. Molecularity is a theoretical concept whereas reaction order is empirical. Consequently, a unimolecular reaction is first order, a bimolecular reactions is second order, etc.; however, the converse is not necessarily true.

A reaction which proceeds at a rate observed to be independent of reactant concentration is said to be zero order. A first order reaction proceeds at a rate which is directly proportional to the concentration of one reactant. Rate equations for reactions of different order are shown in Table 9. Reaction rate constants can be determined as the slope of plots of C vs. t (zero order), in C vs. t (first order), and $\frac{1}{C}$ vs. t (second order type I) (Benefield and Randall, 1980).

For many enzyme-catalyzed reactions, the relationship between reaction rate, v, and substrate concentration, S, can be described by the Michaelis-Menten equation:

$$v = \frac{V_{max}S}{K_m + S} \tag{4}$$

where V_{max} = maximum reaction rate and K_m = the Michaelis constant (half-saturation constant, the substrate concentration at which the reaction proceeds at half its maximum rate). This equation is based on the so-called Michaelis-Menten mechanism in which a molecule of substrate and enzyme reversibly join to form an enzyme-substrate complex followed by the irreversible breakdown of ES to product and free enzyme:

$$S + E \underset{k_2}{\overset{k_1}{\rightleftharpoons}} ES \rightarrow P + E \tag{5}$$

In this case, K_m = the dissociation constant of the ES complex ($K_m = k_2 + k_3)/k_1$). The Michaelis-Menten relationship is shown graphically in Figure 10A. The biokinetic constants V_{max} and K_m are commonly determined by one of the linearizations (reciprocal plots) shown in Figures 10B and 10D.

The effect of a limiting substrate or nutrient on microbial growth or substrate utilization rates can be described by the Monod (1949) relationship (Figures 10E and 10F):

Table 9

Rate equations for Simple Irreversible Reactions (Source: Metcalf & Eddy 1979)

Reaction	Order	Rate equation	Integrated forms
$A \rightarrow B$	Zero	$\frac{d[A]}{dt} = -k_0$	$[A] = [A]_0 - k_0 t$ $t_{1/2} = \frac{[A]_0}{2k_0}$
$A \rightarrow B$	First	$\frac{d[A]}{dt} = -k_1[A]$	$\ln \frac{[A]}{[A]_0} = k_1 t$ $t_{1/2} = \frac{1}{k_1} \ln 2$
$A + A \rightarrow P$	Second, type I	$\frac{d[A]}{dt} = -k_2[A]^2$	$\frac{1}{[A]} - \frac{1}{[A]_0} = k_2 t$ $t_{1/2} = \frac{1}{k_2[A]_0}$
$aA + bB \rightarrow P$	Second, type II	$\frac{d[A]}{dt} = -k_2[A][B]$	$\ln \frac{[A]_0 - [B]}{[B]_0 - b/a[X]} = \ln \frac{[A]}{[B]}$ $= \frac{b[A]_0 - a[B]_0}{a} k_2 t + \ln \frac{[A]_0}{[B]_0}$ $t_{1/2} = \frac{a}{k_2(b[A]_0 - a[B]_0)}$ $\times \ln \frac{a[B]_0}{2a[B]_0 - b[A]_0}$

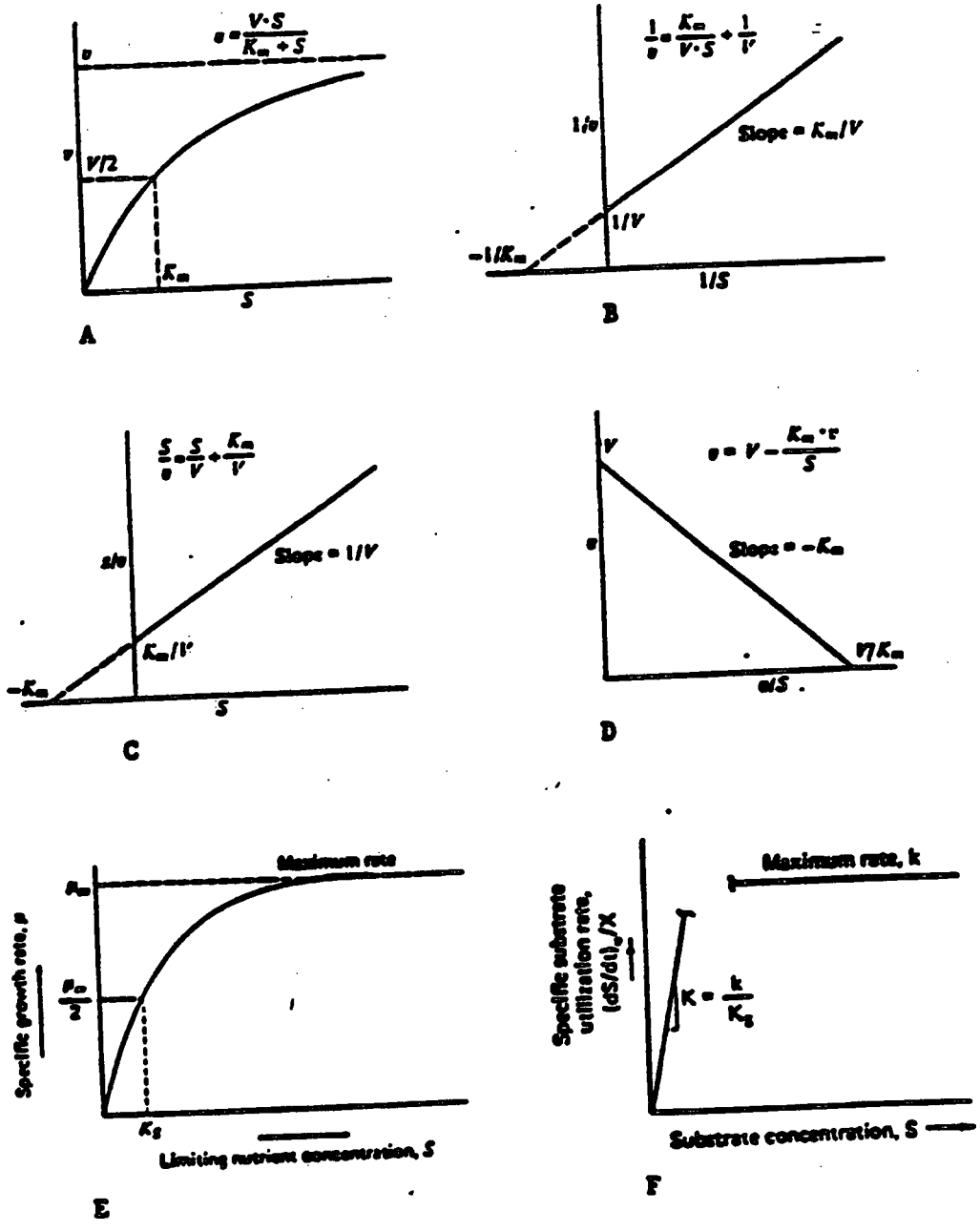


Figure 10 Michaelis-Menten plot (A) and linearizations (B-D), Monod plot (E), and "discontinuous model" (F). Sources: Gaudy & Gaudy 1980; Metcalf & Eddy 1979; Benefield & Randall 1980.

$$\mu = \frac{\mu_m S}{K_s + S} \tag{6}$$

$$q = \frac{q_m S}{K_s + S} \tag{7}$$

where μ = specific growth rate = (dX/dt)/X, q = specific substrate utilization rate = (dS/dt)/X; X = active biomass concentration, μ_m and q_m are maximum values of μ and q, K_s = half-saturation constant analogous to K_m, and S = concentration of limiting substrate or nutrient. Two special cases of equation 7 (as well as 4 and 6) exist: When $S << K_s$, equation 7 reduces to the first-order expression $q = q_m S/K_s$ and when $S >> K_s$, equation 7 reduces to the zero-order equation, $q = q_m$. A mixed reaction order (between 0 and 1) results when $K_s \approx S$ (Figure 1F).

The Michaelis-Menton model does not consider inhibitory effects; reaction rate increases asymptotically to V_{max} as substrate concentration increases. But at high concentrations of a nutrient or substrate, particularly toxic ones, inhibition frequently occurs. Haldane proposed an equation to account for the inhibition resulting from the formation of an inactive enzyme-substrate complex involving two substrate molecules per enzyme molecule (Edwards, 1970):

$$(a)\ S + E \underset{k_2}{\overset{k_1}{\rightleftharpoons}} ES \rightarrow P + E \tag{8}$$

$$(b)\ S + ES \underset{k_4}{\overset{k_3}{\rightarrow}} ES_2(inactive) \tag{9}$$

The Haldane expression is:

$$v = \frac{V_{max} S}{(K_s + S)(1 + S/K_i)} \tag{10}$$

where K_i = inhibition constant. Note that this is identical to the Michaelis-Menten equation except that the denominator has been altered by a factor of $(1 + S/K_i)$. Like the Monod relationship, the Haldane equation has been applied to microbial growth:

$$\mu = \frac{\mu_m S}{S + K_s + S^2/K_i} \tag{11}$$

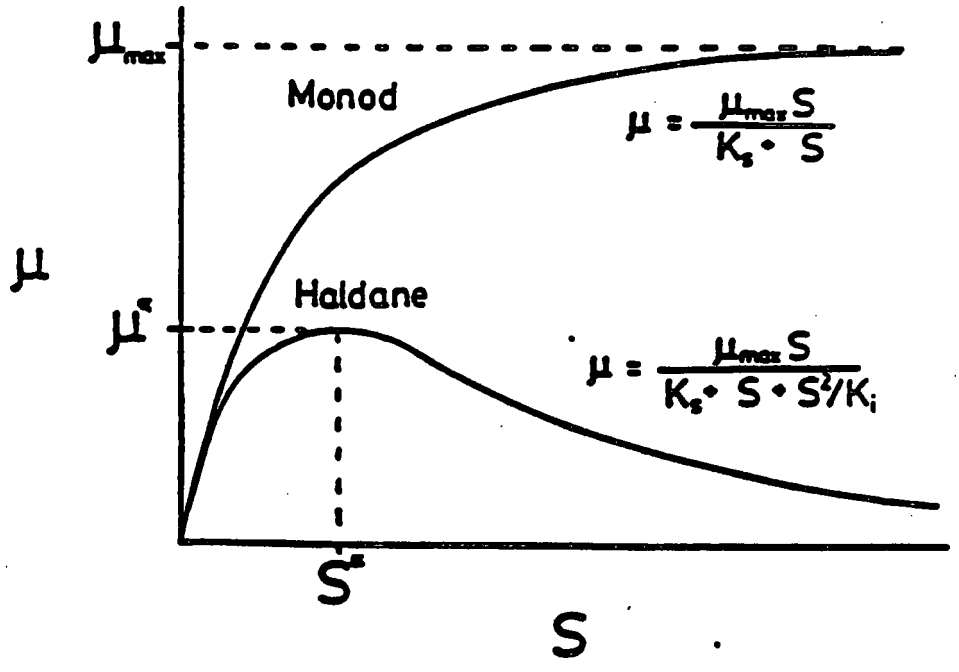


Figure 10A Comparison of Monod and Haldane (inhibitory) growth kinetics. Source: Colvin & Rozich 1986.

(Note that a term was lost from the denominator somewhere during the evolution of this equation). The Monod and Haldane models are compared in Figure 10. Equation 11 has been successfully used to describe the utilization kinetics of inhibitory substrates (reactants) such as nitrite (Boon and Laudelout, 1962), phenol (Rozich et al., 1985), 2,4-dinitrophenol, and 2-chlorophenol (Gaudy et al., 1986).

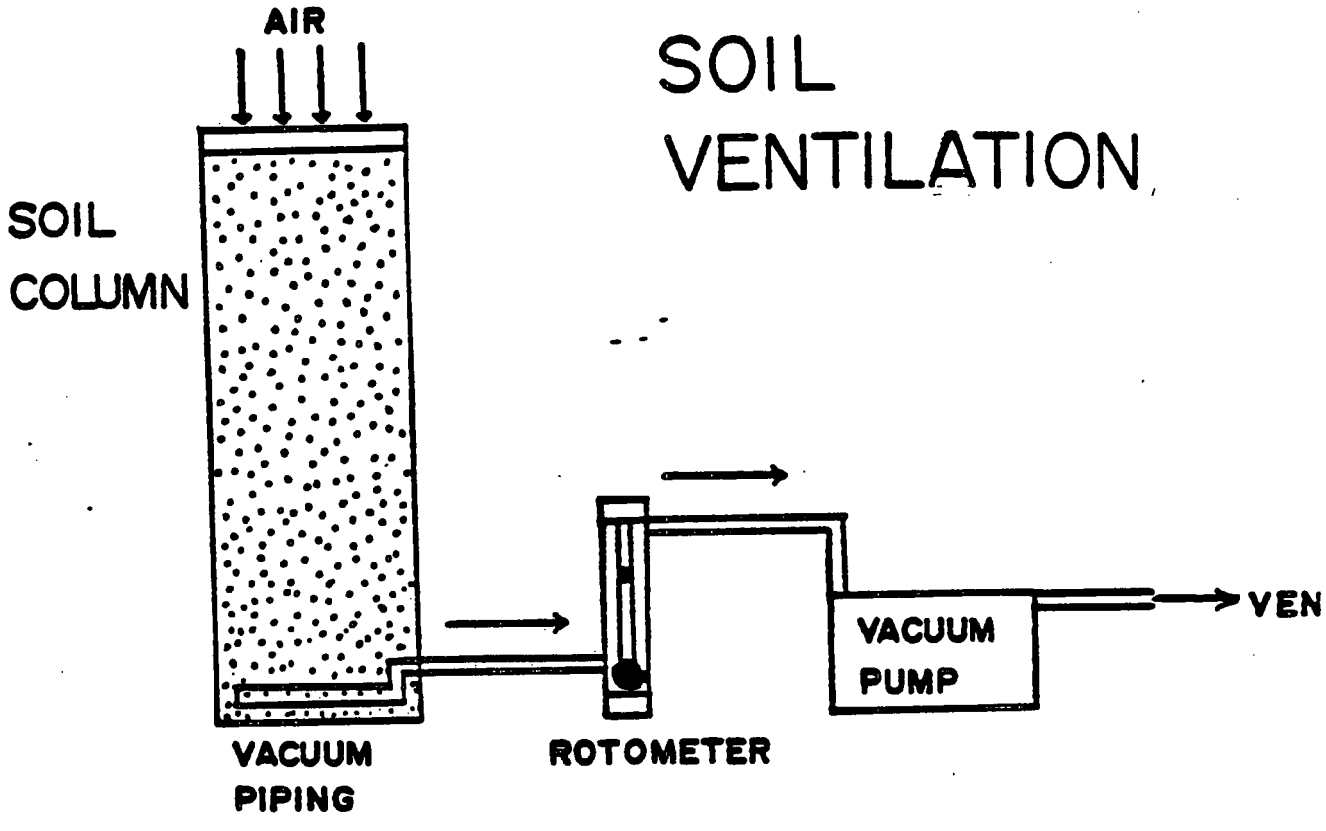
B. **Brief Description of the Technologies to be Tested**

Two technologies will be evaluated for their respective effectiveness in treating organic contaminants within the Renora Site. While PAHs constitute the majority of the problem at Renora, volatile organics are also present. The technologies to be studied, recirculating leachfield and soil ventilation, are designed to provide an environment conducive to biodegradation of the contaminating organics.

In actual field use, the recirculating leachfield will heap contaminated soil onto a PVC lined basin. The basin will also contain a French drain system for the recovery of leachate trickling through the contaminated pile. This leachate water will contain the necessary nutrients and oxygen concentration to promote the bioreduction of the contaminating organics (i.e. the organisms will use the organic contaminant as a source of carbon). Leachate will be pumped from the French drain collection system back to the surface of the pile where it will be sprayed back over the top of the pile for recirculation. Oxygen is dissolved back into the water as it is sprayed over the pile. Nutrients, oxygen, microbial growth, and contaminant concentrations are monitored regularly. Nutrient concentration is adjusted as needed. A clarifier placed in-line between the French system to remove silt they may blind the surface of the pile. Figure 11 depicts a laboratory model of the system and Figure 6 and 7 the scale up version.

The soil venting system is designed to utilize vacuum pumps to pull air through a manifold system buried inside of a pile of contaminated soil. The soil is contained in PVC lined basins in scale up versions. Moisture and nutrients are applied to the surface of the heap to supply the necessary requirements for stimulated growth of microorganisms on the organic contaminants in the soil. Moisture, microbial growth, nutrients, and contaminant concentrations are monitored regularly. Figure 12 depicts the laboratory pilot unit anticipated for this project and Figures 8 and 9 depict a scaled up version.

FIGURE 12



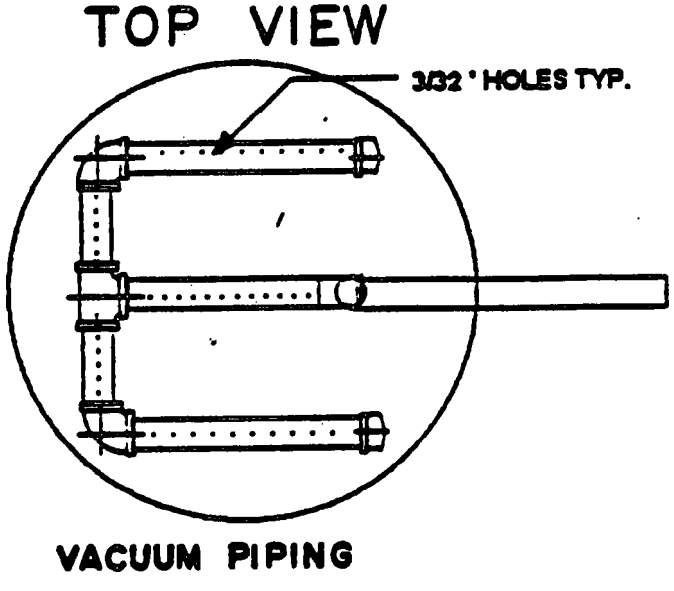
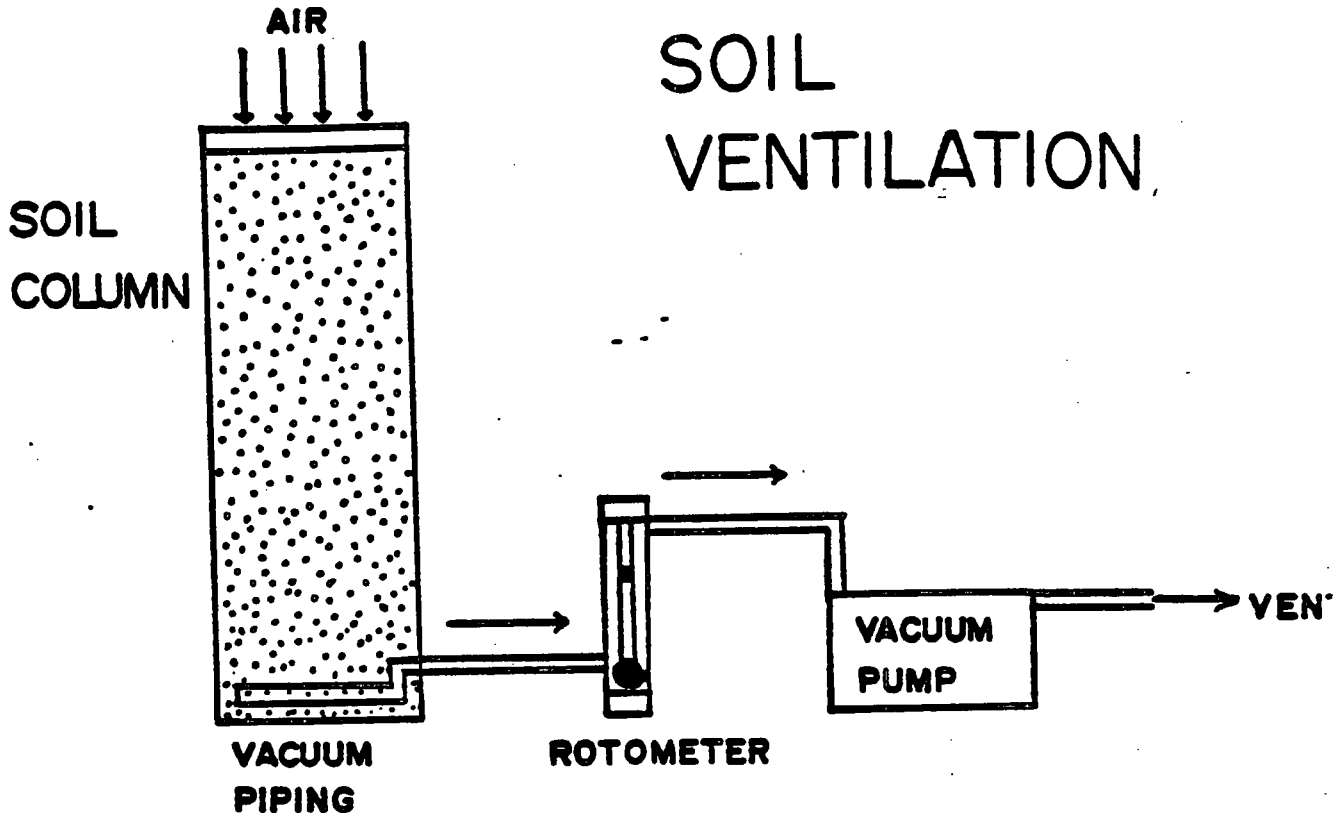
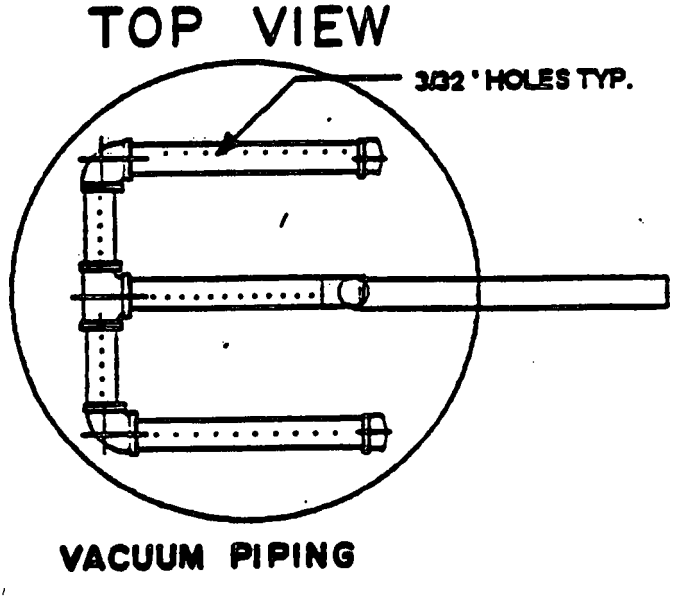


FIGURE 12





C. Experimental Pilot Unit Design and Treatment Protocol

1. Recirculating Leachfield

The objective of this study is to determine degradation rates for PAHs and VOCs treated in a recirculating leachfield system for the purpose of designing a full scale treatment unit.

Water will be allowed to flow by gravity through vertical soil columns constructed of PVC pipe (3 ft. x 10 in.). Sampling ports will be placed at intervals to allow for an oxygen profile, i.e., how much oxygen remains at a given depth. This will ensure that the microbial action at each point will be known as aerobic or anoxic. The base of the column will contain three inches of pea gravel over a perforated plate to allow discharge of the effluent to an aerated biological reactor. Compounds removed from the soil by the water can be further utilized by microbes in the reactor before the water is pumped back to the top of the soil column by a persitaltic pump. A clarifier for solids removal may be required to prevent blinding of the top of the column. The bioreactor will be operated as a SBR (sequential batch reactor). The HRT (hydraulic retention time) of the reactor will be controlled by the soil, since soil characteristics will dictate flow rate. A pumpout tube will be set at depth from the surface of the reactor that will not result in hydraulic overloading of the soil column. The flow rate may be reduced with time due to the formation of a microbial biofilm on soil particles.

Analyses to be performed are given in the following tables.

Treatments

1. Indigenous organisms, no N & P
2. Indigenous organisms with N & P
3. Indigenous organisms and PAH and VOC specific organisms with N & P

Table 11. Recirculating Leachfield Soil Column Testing Schedule

Time	Parameters		
	Microbial Counts*	D.O.	PAHS and VOCs**
Initial	x	x	x
Daily		x	
Week 2	x		x
Week 4	x		x
Week 6	x		x
Week 8	x		x
Week 10	x		x
Week 12	x		x

Table 12. Recirculating Leachfield Bioreactor Testing Schedule

Time	Parameters						
	Micro Counts*	pH	D.O	N&P	Suspended Solids	Volatile Suspended Solids	PAHs & VOCs
Initial	x	x	x	x	x	x	x
Daily		x	x				
Weekly				x	x	x	
Week 2	x				x	x	x
Week 4	x				x	x	x
Week 6	X				x	x	x
Week 8	X				x	x	x
Week 10	x				x	x	x
Week 12	x				x	x	x

* 1. Soil extract and nutrient agar spread plate counts
  2. A-0 epifluorescence
  3. MPN's (PAHs)

**7 subsamples -> one composite

2. Soil Ventilation

The objective of this study is to determine the degradation rates for PAHs and VOCs in a soil ventilation system under moist conditions for the purpose of determining the design parameters for a full scale unit.

Ventilation piping will be installed in the bottom of soil columns to provide aeration to the soil through the top of the column as shown in Figure 12. A 0.75 hp vacuum pump will be used to draw air through the soil system. Rotometers (0.5 - 5 cfh) will be installed in line to monitor the air flow through each column. Off gases will be passed through

Calgon Carbon Canisters prior to emission through the solvent hood. Thermometers will be installed in the column center to monitor temperature changes that may be associated with enhanced biological activity. Soil moisture will be maintained by surface addition of water as necessary when soil drying occurs to guarantee good microbial conditions.

Treatments

1. Indigenous organisms, no N & P
2. Indigenous organisms with N & P
3. Indigenous organisms and PAH and VOC specific organisms with N & P

Table 13. Soil Ventilation Testing Schedule

	Parameters					
Time	% Moisture	Micro Counts	Temp.	pH	N&P	PAHs & VOCs
Initial	x	x	x	x	x	x
Daily	x		x			
Weekly	x			x	x	
Week 2	x	x				x
Week 4	x	x				x
Week 6	x	x				x
Week 8	x	x				x
Week 10	x	x				x
Week 12	x	x				x

D. **Significance of Data Evaluation**

The primary focus in this project is in reducing the concentration of contaminate in the soil matrix to levels acceptable to environmental concern. Results throughout the two treatability studies will be analyzed to formulate the design criteria for a full scale treatment unit.

1. Recirculation Leachfield Data Evaluation

Data to be collected.

The pilot system data will be essential to the proper design of a full-scale treatment unit. The recirculating leachfield columns will provide useful information pretaining to the maximum depth that can be employed and to the steady state flow of contaminated

water per unit volume of soil. The dissolved oxygen levels of various depths in the soil column will be monitored by a YSI Clark electrode type oxygen probe. The small size will allow a direct union with the sampling parts by use of an O-ring. Since aerobic systems have been demonstrated to be the most efficient method of eliminating PAHs, the quantification of dissolved oxygen residuals are critical.

The hydraulic conductivity of the soil will dictate the measurable flow to the bioreactor. The bioreactor is simply an aerated chemostat which will serve to degrade the incoming contaminants and reaerate the water before reintroduction to the top of the soil column. The growth rate of the microorganisms in the bioreactor is controlled by the influent substrate concentration and hydraulic retention time. By monitoring the influent organics to the reactor (soil column effluent) and the effluent organics, the removal efficiency of this system may be determined. Reactor size will be determined from these data.

The soil column will also serve as a treatment unit in that it will act as a biofilm. As microbial growth increases it will eventually reach a constant film thickness. The PAHs may then become more soluble with time due to the microbial dissolution of these compounds as recently reported by Stucki and Alexander (1987).

Finally, the clarification unit is essential to the prevention of blinding in the soil column. Fine particles, upon moving through the column, would eventually slow the liquid flow through the column and decrease the efficiency of the entire system.

Generally, it is hoped that the system as described will not only result in the biological cleansing of soil, but also in the passive removal of contaminants from the groundwater used in the operation of the system.

2. Soil Venting Data Evaluation

Data gathered from the soil venting pilot unit will primarily consist of PAH and VOC concentration data over time for exhaust gases through the unit and column soils. Temperature will be monitored and correlated to reduction of contamination as an indicator of microbial activity. Moisture, nutrients and pH will be monitored in order to maintain consistency. Microbial population data will be compared to reduction of contaminant levels in order to make some rough assessments concerning microbe preference and kinetic activity.

Overall, assessment of the rate of destruction of the contaminants under the selected conditions of pilot study will allow for approximation of the rate of contaminant destruction per unit time per unit volume of contaminated soil.

LITERATURE CITED

Gibson, D. T., and V. Subramanian, Microbial Degradation of Aromatic Compounds, in Microbial Degradation of Organic Compounds, ed, D. T. Gibson, pp. 181-252, Marcel Dekker, Inc., New York, 1984.

Cerniglia, C. E., Microibal Transformation of Aromatic Hydrocarbons, in Petroleum Microbiology, ed, R. M. Atlas, pp. 99-128, Macmillian Publishing Company, New York, 1984.

Environmental Research and Technology, Inc., The Land Treatability of Appendix VIII Constituents Present in Petroleum Industry Wastes, API Pub. No. 4379, API, Washington, D.C., May 1984.

Stucki, G. and M. Alexander, Role of Dissolution Rate and Solubility in Biodegradation of Aromatic Compounds, Applied and Environmental Microbiology, 53(2), pp. 292-297, 1987.

Black, C. A., Ed-in-Cheif, Methods of Soil Analysis Part I, American Society of Agronomy, Madison, WI, 1965.

Black, C. A., Ed-in-Chief, Methods of Soil Analysis Part II, American Society of Agronomy, Madison, WI, 1965.

Freeze, R. A. and J. A. Cherry, Groundwater, Prentice-Hall Inc., Englewood Cliffs, NJ, 1979.

APHA, AWWA, WPCF, Standard Methods for the Examination of Water and Wastewater, 16th Ed., American Public Health Association Washington, D.C., 1985.

Hickman, G. T., Variations in the Biodegradation Potential of Subsurface Environments for Organic Contaminants, Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1988.

Wilson, J. T., McNabb, J. R., Blackwill, D. L., and Ghiorse, W. C., "Enumeration and Characterization of Bacteria Indigenous to a Shallow Water-Table Aquifer." Groundwater 21, 134142 (1983).

Winterkorn, H. F., and Fang, H. Y., eds., Foundation Engineering Handbook. Van Norstrand Reinhold Company, New York, NY (1975).

ASM, Manual of Methods for General Bacteriology, American Society for Microbiology, Washington, D.C., 1981.

Troildenier, G. The use of fluorexcence microscopy for counting microorganisms, in Modern Methods in the Study of Microbial Ecology, Bull. Ecol. Res. Comm., Swedish Nat. Res. Council, Stockholm, 17, pp. 53-55, 1973.