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FINAL REPORT

Aerobic Biodegradation of Organic Chemicals in Environmental Media: A Summary of Field and Laboratory Studies

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. PURPOSE

In the following document, Syracuse Research Corporation (SRC) has reviewed the available aerobic biodegradation literature for several common organic chemicals and identified biodegradation rate constants from these studies. Unlike the anaerobic biodegradation rate constant database previously compiled (Aronson and Howard, 1997), the aerobic biodegradation rate constant database includes rate constant information from soil, surface water, and sediment as well as aquifer environments. This project has been completed to demonstrate that in many cases, a large amount of data is available from a variety of studies showing either the ability or inability of a particular compound of interest to degrade in the environment.

2. TECHNICAL APPROACH

2.1. Literature Search

A list of 25 compounds was initially received from the U.S. EPA. A rapid search of the BIOLOG file of the Environmental Fate Data Base (EFDB) (Howard et. al., 1986) for compounds with aerobic studies revealed that four of the listed compounds did not have appropriate data available for input into the database (cyanide, vinyl acetate, methyl isobutyl ketone and cyanide). These compounds were dropped from the list. However, the compound “xylene” was separated into its three isomers and data were collected for each isomer individually. These changes resulted in a final list of 23 compounds (Table 1) for which biodegradation rate information was then summarized.

The literature compilation began with an electronic search of two files in SRC’s EFDB, DATALOG and BIOLOG, as sources of extensive biodegradation information. Currently, there are over 315,000 catalogued records for 15,965 compounds in DATALOG and nearly 62,000 records for 7,820 compounds in BIOLOG. BIOLOG search terms were used to identify aerobic studies with a mixed population of microbes from soil, sediment, or water. DATALOG was searched for useful field, ecosystem, and biodegradation studies. Relevant papers were retrieved and summarized in the database. In addition to the literature searches, the reference section of every retrieved paper was scanned in order to identify additional relevant articles. To be included in this database, the study was required: 1) to use soil, aquifer material, groundwater, aerobic sediment, or surface water and 2) to be incubated under aerobic conditions. Studies where the environmental material was seeded with microorganisms from other sources *(e.g.* sewage, anaerobic sediment, and enrichment culture experiments) were not included.

The database was constructed in PARADOX with fields for information about the site including location and type of site (*e.g.* spill site, industrial location, pristine site, landfill), the sampling protocol and method of analysis, the type of study (*e.g.* field, laboratory microcosm, *in situ* microcosm), whether the compound was present alone or found in the presence of others, pH, temperature, dissolved oxygen concentrations, redox conditions, initial and final concentrations of the compound, a published or calculated rate constant, length of the study, lag period, control results, identification of reaction products, general comments (to accommodate other important information) and an abbreviated reference from which the information was retrieved.

Table 1. Final list of compounds

Chemical Name	CAS Number
Acetone	000067-64-1
Benzene	000071-43-2
Benzo(a)anthracene	000056-55-3
Benzo(a)pyrene	000050-32-8
Bis(2-ethylhexyl)phthalate	000117-81-7
Chrysene	000218-01-9
m-Cresol	000108-39-4
o-Cresol	000095-48-7
p-Cresol	000106-44-5
Dichloromethane (methylene chloride)	000075-09-2
Ethylbenzene	000100-41-4
Fluoranthene	000206-44-0
Fluorene	000086-73-7
Methanol	000067-56-1
Methyl ethyl ketone	000078-93-3
Naphthalene	000091-20-3
Phenol	000108-95-2
Pyrene	000129-00-0
Tetrachloroethylene	000127-18-4
Toluene	000108-88-3
m-Xylene	000108-38-3
o-Xylene	000095-47-6
p-Xylene	000106-42-3

2.2. Definition and Use of Biodegradation Rate Constants

Over time, a compound will biodegrade at a particular rate and the biodegradation kinetics will be dependent on the environmental conditions and the availability and concentration of the substrate. The Monod equation was developed to describe the growth of a population of microbes in the presence of a carbon source. At low concentrations of substrate, the microbial population is small. With increasing substrate concentrations, the microbial population grows until a maximum growth rate is reached. This is mathematically described by:

$$\mu = \frac{\mu_{max} S}{K_s + S} \tag{1}$$

where μ=growth rate of the microbe, S=substrate concentration, μ_{max}=maximum growth rate of the microbe, and K_s=a constant defined as the value of S at which $\mu=0.5\mu_{max}$. The Monod equation is best used when the microbial population is growing in size in relation to the substrate concentration (Alexander, 1994).

Both first and zero-order rate constants are calculated when little to no increase in microbial cell numbers is seen (Schmidt et. al., 1985). This will occur where the cell density is high compared to the substrate concentration. In this case, biodegradation kinetics are better represented by the classic Michaelis-Menton equation for enzyme kinetics. This equation assumes that the reaction rate of the individual cells and not the microbial population is increasing in relation to increasing substrate concentrations:

$$v = \frac{V_{max} S}{K_m + S} \tag{2}$$

where v=reaction rate (μ in the Monod equation), V_{max}=maximum reaction rate (μ_{max} in the Monod equation), and K_m is the Michaelis constant (K_s in the Monod equation) (Alexander, 1994).

2.2.1. Zero-Order Rate Constants

A zero-order rate constant is calculated when the substrate concentration is much greater than K_m so that as the substrate is biodegraded, the rate of biodegradation is not affected, *i.e.* loss is independent of substrate concentration. The rate of a zero-order reaction is linear (a constant amount of the substrate is lost per unit of time) and is represented by the differential:

$$\frac{dS}{dt} = k_0 \tag{3}$$

and the integral:

$$k_0 = \frac{S_0 - S}{t} \tag{4}$$

where S_0=initial substrate concentration, S=substrate concentration at time=t, and k_0=the zero-order rate constant (expressed as concentration/time, *e.g.* µg/L/day).

In the aerobic biodegradation database, zero-order rate constants are reported where the author has determined this value. If the author did not specify that the zero-order rate constant was a better measurement of the kinetics, this value was placed in the rate constant comments field and a SRC calculated first-order rate constant was placed in the rate constant field. If it was specified that zero-order rate kinetics were superior in describing the loss of a compound in the measured system, the zero-order rate constant was placed in the rate constant field and a first-order rate constant calculated by SRC was reported in the rate constant comment field. When sufficient information was not present in the paper to convert the reported values to a first-order rate constant, then the zero-order rate constant was placed in the rate constant field.

If a rate constant was not reported by the study authors and a value could be determined from the presented experimental data, SRC assumed first-order rate kinetics. A more accurate but time consuming approach would have been to plot the substrate concentration versus time. A straight line would signify zero-order kinetics and an exponential curve (or a straight line on a log linear paper) would indicate first-order kinetics. Priority was given to the determination of a first-order rate constant as many environmental models require the input of a first-order rate constant. This may not be strictly correct in all situations, such as when the substrate is present at high concentrations (above K_m), when substrate concentrations are toxic to the microbial population, when another substrate(s) is limiting the biodegradation rate or when the microbial population is significantly increasing or decreasing in size (Chapelle et. al., 1996).

Recently, the common use of first-order rate constant values to describe the kinetics of biodegradation loss in natural systems has been criticized. Bekins et. al. (1998) suggest that the automatic use of first-order kinetics without first determining whether the substrate concentration is less than the half-saturation constant, K_m, is incorrect and can lead to substantial miscalculations of the biodegradation rate of a studied compound. Using first-order kinetics where the substrate concentration is higher than K_m will lead to an overprediction of the biodegradation rate, whereas in circumstances where the substrate concentration is much lower, the biodegradation rate is expected to be underestimated. Buscheck et. al. (1993) state that first-order rate constants are generally appropriate for soluble plumes where a contaminant concentration of less than 1 mg/L is present. However, a database of LUFT sites in California (Rice et. al., 1995) reports that benzene concentrations are greater than 2 mg/L at 625 of 1092 sites (Bekins et. al., 1998). This suggests that concentrations at spill sites may often exceed the

K_m value and that first-order kinetics may not adequately represent the biodegradation of the studied compound. First-order rate constants are, however, commonly used to describe kinetics in natural systems often because of the lack of sufficient data points and the ease with which these values can be calculated. Salanitro (1993) reports that several studies where BTEX concentrations range from <1 to 5000 ppb are adequately described by first-order kinetics.

2.2.2. First-Order Rate Constants

First-order rate constants are used as a convenient approximation of the kinetics of degradation of test substrates where there is no growth of the microbial population and a low concentration of the test substrate is present. Under these circumstances, the substrate concentration is lower than K_m and, over time, both the concentration of substrate and rate of degradation drop in proportion with each other. Thus, unlike zero-order kinetics, the rate of biodegradation in a first-order reaction is dependent on the substrate concentration and is represented by the differential:

$$\frac{dS}{dt} = k_1 S \qquad \textbf{(5)}$$

and the integral:

$$k_1 = \frac{\ln \frac{S_0}{S}}{t} \qquad \textbf{(6)}$$

where S_0=initial substrate concentration, S=substrate concentration at time=t, and k_1=the first-order rate constant. During first-order rate reactions, the loss of substrate is exponential and follows a logarithmic curve.

The rate constant is used to correlate the rate of the reaction with time. In a first-order reaction, a constant percent of the substrate is lost with time and the rate is described by either percent per time or the half-life. The half-life is easily visualized and is more commonly used. In contrast, a zero-order rate constant by definition equals the rate and is given in units of concentration/time. This is because the rate is linear and loss is constant with time.

2.2.3. Mineralization Rate Constants Versus Primary Biodegradation Rate Constants

Many experiments summarized in the aerobic biodegradation database measured mineralization, defined as the complete biodegradation of a compound to carbon dioxide (CO_2) and water, in contrast to experiments which measure primary biodegradation, defined as the loss of the parent compound. These values are labeled as such in the rate constant comment field. Mineralization rate constants, in general, represent a minimum estimate of the total degradation of the compound; some of the CO_2

produced during the degradation of the original compound can be assimilated into natural, often high molecular weight compounds and is then generally not measured. In addition, once produced, CO_2 can be bound as carbonate within the study system. Thus, it is expected that unless degradation proceeds rapidly and completely to CO_2 and water, that mineralization rate constant values will be less than those measured for primary biodegradation.

2.3. Calculation of First-Order Rate Constants

Rate constants were collected from eight types of studies: laboratory column, field, groundwater grab sample, groundwater inoculum, *in situ* microcosm, lysimeter, reactor systems, and laboratory microcosm studies. The majority of studies summarized in the aerobic biodegradation database were laboratory microcosm studies. Laboratory microcosm studies can be further subdivided by the type of grab sample used: soil, sediment, surface water (including freshwater, estuarine, and seawater), and aquifer sediment and groundwater mixtures. The information obtained from each of these studies ranged from published first-order rate constants to simply an indication or contraindication of biodegradation. In some cases, insufficient data were available to assess whether biodegradation had occurred; for these studies, the rate constant field was left blank. When published first-order rate constants were not available, but sufficient information was presented to calculate a value, the rate constant was calculated by SRC.

To ensure that loss of a contaminant was due to biodegradation and not just to abiotic or transport processes, an appropriate control was necessary to correct the data set. This can be a problem in laboratory studies that are incubated for a long period of time. Mercuric chloride is known to adsorb to the clay component of soil or aquifer sediment reducing its efficacy whereas sodium azide only inhibits bacteria containing cytochromes (Wiedemeier et. al., 1996). In addition, autoclaving may not be totally suitable, probably due to incomplete sterilization (Dobbins et. al., 1992). Information on the control used in the study, if available in the paper, is found in the database field “control results”. This field was used mainly to state the method of sterilization, or, in the case of field studies, whether a conservative tracer was used. If a control was used by the author(s) but the method not specified then “yes” was placed in the “control results” field (*e.g.* Davis and Madsen, 1996). If the paper does not state whether a control was used then this field was left blank.

In some instances, a value is also included in the control field. When reported, this represents the loss of compound in the control over the study period. Studies often did not specify the loss found in the control, or the half-life or rate constant was directly reported by the author(s) and it was assumed, unless stated otherwise, that these values had been corrected for abiotic loss.

2.3.1. Laboratory Studies

A control was used in laboratory studies to correct for non-biodegradation processes such as sorption to sediment or the glass jar, headspace volatilization, *etc.* Data from laboratory studies (column, groundwater grab sample, groundwater inoculum, reactor systems, and laboratory microcosm studies) were obtained from graphs or tables giving concentrations of the compound of interest at specific timepoints. Lag periods were observed at times which is usually attributed to the need for acclimation (Alexander, 1994). The initial microbial species present, their relative numbers, metabolic state and ability to acclimate once exposed to a chemical are likely to vary considerably depending upon environmental parameters such as temperature, conductivity, pH, oxygen concentration, redox potential, concentration, the presence/absence of electron acceptors and donors, and effects, both synergistic and antagonistic, of associated microflora (Howard and Banerjee, 1984).

Lag periods were established either from the discussion in the paper or from looking at the data, and an appropriate initial and final concentration was chosen. The value used for the initial concentration was the concentration present following the lag period; therefore, all rate calculations for this project are independent of the associated lag period. Where a value of "0 Og/L" was reached as a final timepoint, an earlier time was chosen for the kinetics calculation, if possible; the use of zero as a denominator in the first-order rate equation would result in an "infinite" value. If the concentration reached a value other than zero but leveled off at that point for the remainder of the experiment, the final concentration and time were chosen at the point where the concentration leveled off. In column studies, the time field in the database contains the retention time for the column, which is the value (Ot) used to calculate the rate constant; column experiments were usually run for long periods of time, which would allow for the development of an acclimated microbial population.

The initial and final concentrations of the control within the chosen time period were obtained and the experimental data corrected for the loss shown by the control using the following equation:

$$C_{f,corr} = C_f \frac{Z_i}{Z_f} \qquad \textbf{(7)}$$

where: $C_{f,corr}$=corrected final concentration of the contaminant (corrected for non-biodegradation loss
C_f=final contaminant concentration, uncorrected
Z_i=initial control concentration
Z_f=final control concentration.

A first-order rate constant was then calculated for laboratory data using the corrected final contaminant concentration as follows:

$$k_1 = \frac{\ln \frac{C_i}{C_{f,corr}}}{\Delta t} \qquad \textbf{(8)}$$

where: C_i=initial contaminant concentration

$C_{f,corr}$=corrected final concentration of the contaminant (corrected for non-biodegradation loss)

Ot=time interval

k_1=first-order rate constant.

2.3.2. Field and *in situ* Microcosm Studies

In situ microcosms were designed to isolate a portion of the aquifer in order to make measurements directly in the field. This device is essentially a pipe divided into a test chamber and an equipment chamber, with two screens that permit water to be pumped both into and out of the interior of the pipe. More detailed information can be found in Gillham et. al. (1990). Groundwater is pumped to the surface, spiked with the compounds of interest plus other nutrients and/or electron acceptors if wanted, and then reinjected. Because the test zone is isolated from the main aquifer, advective and dispersive processes are not important to the study results. Often, this method is used to give very specific results for a particular redox regime within an aquifer (Nielsen et. al., 1995). The data obtained from this type of study was similar to that for a laboratory microcosm where loss of substrate is monitored with time; rate constants were calculated using the same method as for the laboratory studies.

In general, the field studies reported in this database are for aquifer environments. Only a limited number of aerobic aquifer studies were located, mainly because the oxygen initially present in groundwater will be rapidly used during oxidative degradation. This results in anaerobic conditions close to the source and within the contaminant plume. However, biodegradation data were reported for a few aerobic aquifer environments. Data from field studies were generally reported for 1) plume studies where monitoring wells were placed along the centerline of a contaminant plume or for 2) continuous injection experiments where monitoring wells were placed in fences along the flow path fairly close to the injection point (often 2 and 5 meters away). Loss of a contaminant over distance does not necessarily indicate that the compound has undergone biodegradation. Significant loss in concentration along a flow path is often reported for compounds simply due to non-biological processes such as advection, dispersion, sorption, and dilution. However, degradation is the only mechanism which leads to an actual loss of the contaminant.

The most convenient way to correct for non-biodegradation processes in both plume and injection studies is to use compounds present in the contaminant plume or injection mixture that are 1) biologically recalcitrant and 2) have similar properties, such as Henry's Law constant and soil sorption coefficient, as the contaminant of interest (Wiedemeier et. al., 1995). Most studies summarized in the aerobic biodegradation database used either chloride or bromide ion as a tracer satisfying the first condition of biological recalcitrance. The procedure for obtaining a normalized data set from an aquifer field study was taken from Wiedemeier et. al. (1996) and is again outlined in the report accompanying the anaerobic biodegradation database (Aronson and Howard, 1997). This method requires measurements of tracer and contaminant concentrations from a minimum of two points along a flow path in order to correct for the loss of the compound of interest due to transport processes.

A mass balance approach has also been used by some researchers (Barker et. al., 1987) to determine the rate of biodegradation of specific contaminants in groundwater during a field study. Mass flux of the studied contaminant through a line/cluster of wells (a transect) is recorded instead of monitoring loss of the contaminant at specific points down the middle of a plume, as is typical for a plume centerline study. Wiedemeier et. al. (1996), suggests that the calculations involved are approximate and that often many of the required parameters necessary for the modeling are not available.

3. RESULTS

Biodegradation of organic compounds under aerobic conditions most often occurs when bacteria catalyze the breakdown of these molecules and then recover some of this chemical energy as ATP (adenosine triphosphate) which is absolutely necessary for maintenance of the bacterial cell. ATP is generated through a series of oxidation-reduction reactions (the electron transport chain) where electrons are sequentially transferred from one compound, the electron donor, to an electron acceptor. The final or terminal electron acceptor in aerobic respiration is oxygen. Dissolved oxygen concentrations of 1 mg/L or greater are considered to define aerobic conditions. During aerobic respiration, the oxygen present in the environment is converted to water and thus the dissolved oxygen content can decrease. This is particularly significant in closed systems, as in a confined aquifer, where conditions can quickly become anaerobic with the metabolism of high concentrations of organic chemicals.

Thermodynamically, the reduction of molecular oxygen to water is very favorable for the participating microorganisms. Because hydrocarbons are generally chemically reduced (chlorinated aliphatics are an exception within the group of compounds in this paper) and stable, this is a preferred pathway over other redox pathways such as anaerobic chemical reduction. Aerobic biodegradation results in the oxidation of the original compound. Metabolism of aliphatic compounds generally proceeds initially by production of the alcohol and then oxidation to the carboxylic acid which is susceptible to beta-oxidation. In pure culture studies, aromatic hydrocarbons have been shown to biodegrade generally with the addition of one molecule of oxygen giving the dihydrodiol intermediate, usually with a cis-stereochemistry. This intermediate is then oxidized forming the catechol which then allows for *ortho*- or *meta*- cleavage of the aromatic ring structure (Gibson, 1977).

The data collected during this project were mainly from laboratory microcosm studies, a classification including grab sample studies (except for groundwater grab samples) for the purposes of this database. Groundwater grab samples were considered separately as it has been shown that a large majority of microorganisms responsible for biodegradation in the subsurface environment are associated with the aquifer sediment surface (Thomas et. al., 1987). Therefore, rates collected during groundwater grab studies may not be as rapid as those where aquifer sediment is included. Laboratory microcosm studies are believed to give very good evidence of biodegradation at a specific location and can provide an “absolute mass balance” on a particular contaminant. In addition, the formation and measurement of metabolites can definitively show the biodegradation of the contaminant of interest. However, results from a laboratory microcosm can be greatly influenced by many factors such as the source, collection, and condition of the grab sample (*e.g.* what is a representative source of material for that site?), the ratio of soil/sediment/aquifer sediment to water used in the microcosm, the type of sampling (repetitive or sacrificed), incubation conditions (*e.g.* substrate concentration, temperature), and the length of the study period (and its effect particularly on the initial microbial population during a long study period) (Wiedemeier et. al., 1996). If a sufficient supply of oxygen is not available to completely biodegrade the added organic compound/s then anaerobic conditions may prevail. The mixing of a natural sample during its collection or the construction of a microcosm may also result in a “disturbance artifact” which is seen as an increase in the microbial activity of the sample (Davis and Olsen, 1990). However, the influence of transport processes such as volatilization and adsorption cannot be measured in a microcosm experiment. If consideration of these processes is important, then field studies can be used to provide environmentally relevant data for a specific site, essentially showing whether the compound of interest can or cannot be biodegraded at that location.

The results for each compound are presented in the following sections. Separation of the data into mineralization and primary degradation studies was initially completed and each category was considered separately. A range was given to represent the dispersion of the data within the group as well as a median value, representing the central tendency of the data. In addition, frequency distribution histograms for the two types of studies are given for each compound with sufficient data. Within the subcategories of mineralization and primary degradation, each study was given equal weighting despite differences in how the study was carried out. Rate constants which were given as zero-order and could not be converted to first-order rate constants were not included in the statistical analysis.

3.1. BTEX Compounds

The BTEX group is composed of the water-soluble and monoaromatic compounds benzene, toluene, ethylbenzene, o-xylene, m-xylene, and p-xylene. In both laboratory and field studies, the biodegradation of all the BTEX compounds has been shown under aerobic conditions (Tables 2 to 7). There is a stoichometric requirement of 3 ppm O_2 to 1 ppm BTEX for the aerobic degradation of fuel hydrocarbons with rates of biodegradation appearing to slow for dissolved oxygen concentrations below 1 to 2 ppm in microcosm and field studies and below 1 ppm for soil column studies (Salanitro, 1993; Chiang et. al., 1989). Laboratory studies where 8 mg/L dissolved oxygen is initially present have been shown to rapidly biodegrade 2 mg/L or less of a BTEX mixture or a particular BTEX compound (Salanitro, 1993).

The majority of studies located for the BTEX compounds were for aquifer environments. As reported earlier, many aquifers become anaerobic during contaminant biodegradation due to the use of oxygen in aerobic respiration. Replacement of this oxygen from upgradient of the source, plume edges, infiltration of precipitation, or from vadose or saturated zone recharge is slower than its use during aerobic metabolism. Thus, the concentration of oxygen often becomes the rate-limiting factor in the biodegradation of the BTEX compounds in aquifer environments. During laboratory studies this can be controlled by the addition of oxygen or hydrogen peroxide. Extrapolation of laboratory rate constants to field environments which are confined or semi-confined systems, however, should be made with caution both because oxygen conditions cannot be controlled as readily and because laboratory rates are often higher (up to an order of magnitude) than those reported from field experiments.

3.1.1. Benzene

While benzene is considered recalcitrant under anaerobic conditions, most evidence currently available shows that this compound is moderately degradable in the presence of oxygen (Table 2). Degradation is thought to proceed via catechol to CO_2 (Ribbons and Eaton, 1992). 3.08 mg of oxygen are necessary to biodegrade 1 mg of benzene to CO_2 and water (Wiedemeier et. al., 1995). This calculation does not include the energy requirement for cell maintenance and thus is not a conservative value. However, the value of 3.1 mg oxygen to degrade 1 mg benzene is suggested as a conservative estimate (Wiedemeier et. al., 1995).

Most of the located data for benzene under aerobic conditions were for aquifer environments. Field studies at six different locations consistently reported the biodegradation of benzene, giving half-life values ranging from 58 to 693 days. The longer half-life was associated with an uncontaminated aquifer study (American Petroleum Institute, 1994). Initial concentrations of up to 25 mg/L were biodegraded under field conditions (Davis et. al., 1994). Biodegradation of benzene was observed as well during *in situ* microcosm studies at two locations. Half-lives ranged from 1.4 (Nielsen et. al., 1996) to 103 (Holm et. al., 1992) days with an average half-life of 4 days. The high half-life value represents biodegradation in the groundwater only section of the *in situ* microcosm; half-life values obtained in the aquifer sediment + groundwater section were significantly lower.

By far the most common type of study used to observe the biodegradation of benzene under aerobic conditions is the laboratory microcosm. Mineralization half-lives for benzene in lab microcosm studies ranged from 7 (Kemblowski et. al., 1987) to 1195 days (Thomas et. al., 1990) with the high value representing a study from an uncontaminated site. Microcosms established with sediment from a contaminated and a biostimulated region in the aquifer, measured during the same study, showed more rapid mineralization rates. The average half-life for mineralization was 53 days. In comparison, microcosm studies measuring primary biodegradation reported half-lives ranging from 0.2 (Kjeldsen et. al., 1997) to 679 (Pugh et. al., 1996) days with an average value of 1.5 days. Initial concentrations of up to 50 mg/L (Kemblowski et. al., 1987) were reported in these experiments without obvious deleterious effect. In general, however, initial concentrations of 5 mg/L or less were utilized.

No biodegradation was reported for four lab microcosm studies. A study by the American Petroleum Institute, 1994A, reports that benzene was not biodegraded in the presence of 85% methanol over 278 days. This result was not unexpected as sufficient oxygen was available to degrade only 5% of the initially added methanol. This suggests that anaerobic conditions may have occurred rapidly within this microcosm. Hunt and Alvarez, 1997 also report that benzene in the presence of 300 mg/L ethanol was not biodegraded over a period of 3 days. However, aquifer material collected from the same site and incubated without ethanol and either with or without nutrients was able to rapidly degrade benzene. Pristine aquifer sediment was unable to biodegrade benzene over a 7-day period; however, when creosote-contaminated aquifer sediment was used, greater than 31% of the initially added benzene was biodegraded over 7 days (Wilson et. al., 1986). While benzene was degraded in groundwater alone and in river water during a study by Vaishnav and Babeu (1987), it was not biodegraded in the presence of harbor water collected in Lake Superior. The addition of both nutrients and an enriched microbial culture isolated from sewage resulted in the biodegradation of this compound indicating that bacteria capable of biodegrading benzene were either not present or not present in sufficient numbers to significantly remove benzene in the natural harbor water over a 20-day period. Laboratory column experiments by Anid et. al. (1991) and Alvarez et. al. (1998) report that benzene was not biodegraded under certain circumstances. Anid et. al. (1991) reported that columns supplemented with hydrogen peroxide but not columns supplemented with nitrate were able to degrade benzene. The nitrate-amended columns may have exhibited nitrate-reducing conditions as over 60 mg/L BTEX mixture was initially added. However, no attempt was made by the authors to distinguish through end product measurements whether conditions remained aerobic or became nitrate-reducing. Alvarez et. al. (1998) showed biodegradation of benzene in laboratory columns fed with acetate and benzoate as cosubstrates. However, preacclimated sediment exposed to acetate and sediment columns which received no preacclimation period were unable to biodegrade benzene while a column which had been preacclimated to benzoate readily biodegraded this column.

The median for the primary biodegradation rate constant of benzene, considering all studies, is 0.096/day (N = 118); a range of not biodegraded to 3.3/day is reported. The median for the mineralization rate constant of benzene is 0.0013/day (N = 30); a range of not biodegraded to 0.087/day is reported. The frequency distribution histograms for this data are shown in figures 1a and 1b. Benzene is expected to biodegrade fairly readily under most aerobic environmental conditions.

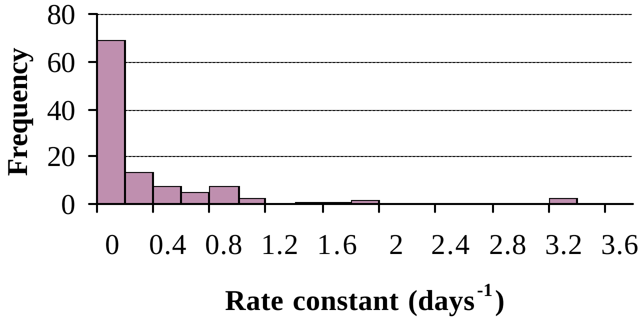

Figure 1a. Frequency histogram for the published primary biodegradation rate constant values for benzene.

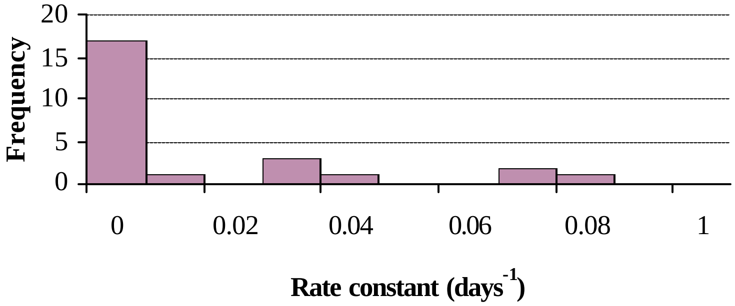

Figure 1b. Frequency histogram for the published mineralization rate constant values for benzene.

Table 2. Aerobic biodegradation rate constant values for benzene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.001/day		American Petroleum Institute (1994)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.003/day		American Petroleum Institute (1994)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.004/day		American Petroleum Institute (1994)
Benzene	Columbus Air Force Base, Columbus, Miss.		Aquifer sediment + groundwater	Field		224	0.0066/day		Stauffer,TB et. al. (1994)
Benzene	Michigan	Gas plant facility	Aquifer sediment + groundwater	Field			0.0088-0.0095/day		Chiang,CY et. al. (1986)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Field	1.25 mg/L		0.012/day		Kemblowski,MW et. al. (1987)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field	2.36 mg/L	374-434	30 mg/day		Barker,JF et. al. (1987)
Benzene	Amsterdam, The Netherlands	Dune infiltration site	Sediment	Field	<0.05 ug/L	7-49	Biodegrades		Bosma,TNP et. al. (1996)
Benzene	Eastern seaboard	Contaminated	Aquifer sediment + groundwater	Field	25 mg/L		Biodegrades		Davis,JW et. al. (1994)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	Groundwater grab sample	120 ug/L	90	0.0017/day		Holm,PE et. al. (1992)
Benzene	Traverse City, Michigan	Jet fuel contamination	Groundwater	Groundwater grab sample	800 ug/L	28	0.003/day		Thomas,JM et. al. (1987)
Benzene		Contaminated	Groundwater	Groundwater grab sample	100 mg/L	24	0.0082/day	3	Chang,BV et. al. (1997)
Benzene		Contaminated	Groundwater	Groundwater grab sample	100 mg/L	33	0.0084/day	5	Chang,BV et. al. (1997)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.016/day		Morgan,P et. al. (1993)
Benzene	12 km north of Lake Superior, Minnesota		Groundwater	Groundwater grab sample		20	0.025/day		Vaishnav,DD & Babeu,L (1987)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.027/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		0.032/day		Morgan,P et. al. (1993)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	Groundwater grab sample	120 ug/L	90	0.033/day		Holm,PE et. al. (1992)
Benzene	Traverse City, Michigan	Jet fuel contamination	Groundwater	Groundwater grab sample	800 ug/L	28	0.035/day		Thomas,JM et. al. (1987)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.037/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.038/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.039/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.043/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.045/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	17.5 mg/L		0.05/day		Morgan,P et. al. (1993)
Benzene	NW Gainesville, Florida		Groundwater	Groundwater grab sample	1 mg/L	16	0.107/day	8	Delfino,JJ & Miles,CJ (1985)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		0.11/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		0.13/day		Morgan,P et. al. (1993)
Benzene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater	Groundwater grab sample	100 ug/L	23	0.13/day		Albrechtsen,HJ et. al. (1996)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		0.16/day		Morgan,P et. al. (1993)
Benzene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	12	0.268/day		Albrechtsen,HJ et. al. (1996)
Benzene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	30	0.297/day	23	Albrechtsen,HJ et. al. (1996)
Benzene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	7	0.329/day		Albrechtsen,HJ et. al. (1996)
Benzene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater	Groundwater grab sample	100 ug/L	32	0.338/day	25	Albrechtsen,HJ et. al. (1996)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		0.35/day		Morgan,P et. al. (1993)
Benzene	Los Angeles, California	Gasoline contamination	Groundwater	Groundwater grab sample	477 ug/L	2	0.38/day		Karlson,U & Frankenberger,WTJr (1989)
Benzene		Industrial site	Groundwater	Groundwater grab sample	32 mg/L	16.25	0.467/day	10.4	Williams,RA et. al. (1997)
Benzene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	23	0.70/day	19	Albrechtsen,HJ et. al. (1996)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		1.1/day		Morgan,P et. al. (1993)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		180 ug/L/day		Morgan,P et. al. (1993)
Benzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	0.478 mg/L		200 ug/L/day		Morgan,P et. al. (1993)
Benzene	Los Angeles, California	Gasoline contamination	Groundwater	Groundwater grab sample	477 ug/L	1	3.3/day		Karlson,U & Frankenberger,WTJr (1989)
Benzene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	100	0.047/day	3	Lyngkilde,J et. al. (1988)
Benzene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	13	0.419/day	2	Lyngkilde,J et. al. (1988)
Benzene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	8	0.658/day	1	Lyngkilde,J et. al. (1988)
Benzene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	8	0.658/day	1	Lyngkilde,J et. al. (1988)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	In situ microcosm	120 ug/L		0.0067/day		Holm,PE et. al. (1992)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	In situ microcosm	120 ug/L		0.0067/day		Holm,PE et. al. (1992)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L		0.033/day		Holm,PE et. al. (1992)
Benzene	Canadian Forces Base, Borden, Ontario		Aquifer sediment + groundwater	In situ microcosm	345 ug/L	8	0.046/day		Gillham,RW et. al. (1990)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L		0.058/day		Holm,PE et. al. (1992)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.2/day	5	Nielsen,PH et. al. (1996)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.3/day	1	Nielsen,PH et. al. (1996)
Benzene	Vejen City, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	48	0.5/day	6	Bjerg,PL et. al. (1996)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.5/day	6	Nielsen,PH et. al. (1996)
Benzene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	20 mg/L	4.6	0.501/day		Anid,PJ et. al. (1993)
Benzene		Uncontaminated	Aquifer sediment	Lab column	193 ug/L	>8	1-5 ug/day	3	Alvarez,PJJ et. al. (1998)
Benzene		Uncontaminated	Aquifer sediment	Lab column	193 ug/L	2	2-9 ug/day		Alvarez,PJJ et. al. (1998)
Benzene		Uncontaminated	Aquifer sediment	Lab column	193 ug/L	>8	3-7 ug/day	3	Alvarez,PJJ et. al. (1998)
Benzene	Swan Coastal Plain, Australia	Uncontaminated	Aquifer sediment + groundwater	Lab column	1060 ug/L		9.5/day		Patterson,BM et. al. (1993)
Benzene	Swan Coastal Plain, Australia	Uncontaminated	Aquifer sediment + groundwater	Lab column	1060 ug/L		9.5/day		Patterson,BM et. al. (1993)
Benzene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	2.5	Biodegrades		Alvarez,PJJ et. al. (1998)
Benzene	Amsterdam, The Netherlands	Dune infiltration site	Sediment	Lab column	0.5 ug/L		Biodegrades		Bosma,TNP et. al. (1996)
Benzene	Amsterdam, The Netherlands	Dune infiltration site	Sediment	Lab column	10-20 ug/L		Biodegrades		Bosma,TNP et. al. (1996)
Benzene	Skaelskor, Denmark	Uncontaminated	Fractured clay	Lab column		3.2	Biodegrades		Broholm,K et. al. (1995)
Benzene	Wageningen, The Netherlands		Sediment	Lab column	10-20 ug/L		Biodegrades		Bosma,TNP et. al. (1996)
Benzene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	No biodegradation		Alvarez,PJJ et. al. (1998)
Benzene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	No biodegradation		Alvarez,PJJ et. al. (1998)
Benzene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	20 mg/L	4.6	No biodegradation		Anid,PJ et. al. (1993)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.00058/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.00065-0.00087/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.00072/day		Thomas,JM et. al. (1990)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	0.002 ug/L	42	0.00077/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0008/day		Thomas,JM et. al. (1990)
Benzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00102/day		Pugh,LB et. al. (1996)
Benzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00102/day		Pugh,LB et. al. (1996)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0012/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0012/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0012/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0013/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0013/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0016/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0017/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0019/day		Thomas,JM et. al. (1990)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.002/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0021/day		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	0.002 ug/L	42	0.00315/day		Thomas,JM et. al. (1990)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	50 mg/L	70	0.0035/day		Kemblowski,MW et. al. (1987)
Benzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.0039/day		Pugh,LB et. al. (1996)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	50 mg/L	70	0.0044/day		Kemblowski,MW et. al. (1987)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	2538 ug/L	114	0.006/day	21	American Petroleum Institute (1994A)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	5.5 mg/L	80	0.006/day	13	Barker,JF et. al. (1987)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	500 ug/L	14	0.016/day		Kemblowski,MW et. al. (1987)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	2491 ug/L	232	0.021/day	<7	American Petroleum Institute (1994A)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1903 ug/L	232	0.024/day	<7	American Petroleum Institute (1994A)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	5 mg/L		0.025-0.0866/day		Kemblowski,MW et. al. (1987)
Benzene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.030/day		Wilson,JT et. al. (1983B)
Benzene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.030/day		Wilson,JT et. al. (1983B)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	50 ug/L	14	0.031/day		Kemblowski,MW et. al. (1987)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	2.6 mg/L	80	0.032/day		Barker,JF et. al. (1987)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.033/day		Holm,PE et. al. (1992)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.033/day		Holm,PE et. al. (1992)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	5 mg/L	14	0.036-0.043/day		Kemblowski,MW et. al. (1987)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.042/day		Holm,PE et. al. (1992)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	5 mg/L		0.043-0.139/day		Kemblowski,MW et. al. (1987)
Benzene	Traverse City, Michigan	Jet fuel contamination	Aquifer sediment	Lab microcosm	800 ug/L	28	0.043/day		Thomas,JM et. al. (1987)
Benzene	Lester River, St. Louis County, MN		River water	Lab microcosm		20	0.044/day		Vaishnav,DD & Babeu,L (1987)
Benzene	Conroe, Texas	Creosote waste site	Aquifer sediment	Lab microcosm		7	0.046/day		Wilson,JT et. al. (1986)
Benzene	Eastern seaboard	Contaminated	Aquifer sediment + groundwater	Lab microcosm	10 mg/L	35	0.0495/day	10	Davis,JW et. al. (1994)
Benzene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	5000 ug/L	35	0.05/day		Chiang,CY et. al. (1986)
Benzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		45	0.0535/day		Pugh,LB et. al. (1996)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.058/day		Holm,PE et. al. (1992)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	50 ug/L	14	0.065-0.075/day		Kemblowski,MW et. al. (1987)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	500 ug/L	14	0.065-0.075/day		Kemblowski,MW et. al. (1987)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.07/day		Nielsen,PH et. al. (1996)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	5 mg/L	14	0.075-0.099/day		Kemblowski,MW et. al. (1987)
Benzene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	325 ug/L	14	0.085/day		Chiang,CY et. al. (1986)
Benzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.096/day		Pugh,LB et. al. (1996)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	140 ug/L	31.5	0.121/day	2-7	Nielsen,PH & Christensen,TH (1994B)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1.7 mg/L	43	0.122/day		Barker,JF et. al. (1987)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	10 ug/L		0.154/day		Kemblowski,MW et. al. (1987)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	50 ug/L		0.154/day		Kemblowski,MW et. al. (1987)
Benzene	Gloucester landfill, Ottawa, Canada	Landfill site	Aquifer sediment + groundwater	Lab microcosm	580 ug/L	21	0.16/day		Berwanger,DJ & Barker,JF (1988)
Benzene	Eastern seaboard	Contaminated	Aquifer sediment + groundwater	Lab microcosm	1 mg/L	8	0.173/day		Davis,JW et. al. (1994)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	10 ug/L		0.198/day		Kemblowski,MW et. al. (1987)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	50 ug/L		0.198/day		Kemblowski,MW et. al. (1987)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	500 ug/L		0.198/day		Kemblowski,MW et. al. (1987)
Benzene	Skidaway River, Georgia		River water	Lab microcosm	6 ug/L	1	0.2 ug/L/day		Lee,RF (1977)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.2/day	5	Nielsen,PH et. al. (1996)
Benzene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.2/day	5	Nielsen,PH et. al. (1996)
Benzene	Skidaway River, Georgia		River water	Lab microcosm	12 ug/L	1	0.26 ug/L/day		Lee,RF (1977)
Benzene	Indian River County, Florida	Gasoline spill	Aquifer sediment + groundwater	Lab microcosm	500 ug/L		0.277/day		Kemblowski,MW et. al. (1987)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene			Soil	Lab microcosm	132 mg VOC/kg soil	9	0.292 mg/day	5	English,CW & Loehr,RC (1991)
Benzene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	420 ug/L	14	0.326/day		Wilson,BH et. al. (1990)
Benzene	Skidaway River, Georgia		River water	Lab microcosm	24 ug/L	1	0.33 ug/L/day		Lee,RF (1977)
Benzene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	16	0.33/day		Borden,RC et. al. (1997)
Benzene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	450 ug/L	14	0.38/day		Wilson,BH et. al. (1990)
Benzene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	9	0.46/day		Hunt,CS & Alvarez,PJJ (1997)
Benzene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	10	0.53/day		Borden,RC et. al. (1997)
Benzene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	340 ug/L	7	0.56/day		Chiang,CY et. al. (1986)
Benzene	Grindsted, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	5	0.576/day		Albrechtsen,HJ et. al. (1996)
Benzene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	11	0.65/day	4.5	Hunt,CS & Alvarez,PJJ (1997)
Benzene	Grindsted, Jutland, Denmark	Grindsted landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	5	0.701/day		Albrechtsen,HJ et. al. (1997)
Benzene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	50 ug/L	35	0.8/day		Chiang,CY et. al. (1986)
Benzene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	3.7 mg/L	7	0.84/day		Hutchins,SR (1991)
Benzene	Grindsted, Jutland, Denmark	Grindsted landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.877/day		Albrechtsen,HJ et. al. (1997)
Benzene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.877/day		Albrechtsen,HJ et. al. (1997)
Benzene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.877/day		Albrechtsen,HJ et. al. (1997)
Benzene	Jurere Beach, Florianopolis, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	5	0.922/day		Corseuil,HX et. al. (1997)
Benzene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	1000 ug/L	35	0.95/day		Chiang,CY et. al. (1986)
Benzene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	500 ug/L	35	0.95/day		Chiang,CY et. al. (1986)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	3	1.0/day		Albrechtsen,HJ et. al. (1996)
Benzene	Northen Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	10-110 mg/L		1.09/day		Alvarez,PJJ et. al. (1991)
Benzene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	2.6	1.5/day		Hunt,CS & Alvarez,PJJ (1997)
Benzene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	2	1.75/day		Albrechtsen,HJ et. al. (1997)
Benzene	Holbaek,Western Sealand, Denmark	Skellingsted landfill	Soil	Lab microcosm	800-900 ug/L	2.5	1.9/day	0.63	Kjeldsen,P et. al. (1997)
Benzene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	2.25	1.9/day	1	Hunt,CS & Alvarez,PJJ (1997)
Benzene	Holbaek,Western Sealand, Denmark	Skellingsted landfill	Soil	Lab microcosm	600 ug/L	0.83	3.3/day		Kjeldsen,P et. al. (1997)
Benzene	Holbaek,Western Sealand, Denmark	Skellingsted landfill	Soil	Lab microcosm	800-900 ug/L	2.8	3.3/day	1.67	Kjeldsen,P et. al. (1997)
Benzene	North Charleston, South Carolina	JP-4 jet fuel contamination site	Aquifer sediment	Lab microcosm	30 ng/g	105	Limited		Aelion,CM & Bradley,PM (1991)
Benzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	4528 ug/L	278	No biodegradation		American Petroleum Institute (1994A)
Benzene	Conroe, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	No biodegradation		Wilson,JT et. al. (1986)
Benzene	NE of Barker's Island, Superior Bay, WI		Lake water	Lab microcosm		20	No biodegradation		Vaishnav,DD & Babeu,L (1987)
Benzene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	3	No biodegradation		Hunt,CS & Alvarez,PJJ (1997)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	1 ug/L	35	No mineralization		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	10 ug/L	35	No mineralization		Thomas,JM et. al. (1990)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	100 ug/L	35	No mineralization		Thomas,JM et. al. (1990)
Benzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	1000 ug/L	35	No mineralization		Thomas,JM et. al. (1990)
Benzene	North Charleston, South Carolina	JP-4 jet fuel contamination site	Aquifer sediment	Lab microcosm	7 ng/g	120	No mineralization		Aelion,CM & Bradley,PM (1991)
Benzene	North Charleston, South Carolina	JP-4 jet fuel contamination site	Aquifer sediment	Lab microcosm	7 ng/g	120	No mineralization		Aelion,CM & Bradley,PM (1991)
Benzene	Denmark	Municipal landfill	Leachate	Reactor system	50 mg COD/L		Biodegrades		Lyngkilde,J et. al. (1992)

3.1.2. Toluene

Biodegradation of toluene is expected to occur readily in aerobic environments (Table 3). Degradation is believed to proceed via 3-methylcatechol to CO_2 (Ribbons and Eaton, 1992). 3.13 mg of oxygen are necessary to biodegrade 1 mg of toluene to CO_2 and water (Wiedemeier et. al., 1995). This calculation does not include the energy requirement for cell maintenance and thus is not a conservative value.

Most of the located data for toluene under aerobic conditions were for aquifer or soil environments. Aquifer field studies at two different locations reported the biodegradation of toluene giving half-life values ranging from 1.3 (McCarty et. al., 1998) to 77 (American Petroleum Institute, 1994) days. The longer half-life was associated with an uncontaminated aquifer study. Rate constants measured during a stream field study were very high giving half-lives less than 1 day in every case (Kim et. al., 1995). Biodegradation of toluene was observed as well during several *in situ* microcosm studies at Vejen City, Denmark. Half-lives ranged from 1.7 (Nielsen et. al., 1996) to 103 (Holm et. al., 1992) days with an average half-life of 4.5 days. The high half-life value represents biodegradation in the groundwater only section of the *in situ* microcosm; half-life values reached in the aquifer sediment + groundwater section were significantly lower.

By far the most common type of study used to observe the biodegradation of toluene under aerobic conditions is the laboratory microcosm. Mineralization half-lives for toluene in lab microcosm studies ranged from 5 (Fan and Scow, 1993) to 693 days (Aelion et. al., 1989). The average half-life for mineralization was 36 days. In comparison, microcosm studies measuring primary biodegradation reported half-lives ranging from <1 (numerous studies, see Table 3) to 495 (Wilson et. al., 1984) days with an average value of 0.5 days.

No biodegradation was reported for nine lab microcosm studies. A study by the American Petroleum Institute, 1994A, reports that toluene was not biodegraded in the presence of 85% methanol over 278 days. This result was not unexpected as sufficient oxygen was available to degrade only 5% of the initially added methanol. This suggests that anaerobic conditions may have occurred rapidly within this microcosm. In addition, the bacteria may have preferentially degraded the structurally simpler methanol or the concentration of methanol added may have been toxic to the indigenous bacterial population. Davis and Madsen, 1996, reported the biodegradation of toluene in three different soils under varying moisture and concentration levels. No biodegradation of toluene was reported in air-dried soils over 30 days; however, toluene added to the same soil, when 100% moisture was present, was biodegraded with a half-life of less than 1 day. Fan and Scow (1993) reported that toluene was not biodegraded in soil which had been incubated at a moisture level of 2.5%; however, half-lives of 2 and 71 days were measured for moisture levels of >16 and 5%, respectively.

Initial concentrations of up to 50 mg/L (Davis and Madsen, 1996) were reported in these experiments without obvious deleterious effect. In general, however, initial concentrations of 5 mg/L or less were utilized. Concentrations of 500 mg/kg soil were shown to be inhibitory to the biodegradation of toluene

(Davis and Madsen, 1996) while at concentrations of 50 mg/kg soil or less, half-lives of less than 1 day were again measured. Similarly, Mu and Scow, 1994 reported that this compound was not degraded in soil samples exposed to 1000 mg/L toluene. Half-lives reported for the same soil but with toluene concentrations at 250 and 625 mg/L were 3 and 4 days, respectively. Inhibition of toluene degradation (present at 20 mg/L) in soil was shown when trichloroethylene was also present at concentrations of 20, 30, 50, and 60 mg/L giving half-lives of 2 days, 5 days, 60 days, and no biodegradation over the study period (42 days), respectively (Mu and Scow, 1994).

Degradation of toluene may also be limited by concentrations of inorganic nutrients in its immediate environment. Allen-King et. al. (1994) reports that nitrogen limitation caused the degradation rate of toluene to be almost immeasurably slow in uncontaminated soil grab samples without added nutrients. However, when nitrogen was added, a half-life of 4.5 days was obtained for this compound in the same soil. Pristine aquifer sediment was unable to biodegrade benzene over a 7 day period; however, when creosote-contaminated aquifer sediment was used, greater than 18-22% of the initially added toluene was biodegraded over 7 days (Wilson et. al., 1986).

Laboratory column experiments by Alvarez et. al. (1998) report that toluene was not biodegraded under certain circumstances. Biodegradation of toluene was observed in laboratory columns fed with acetate and benzoate as cosubstrates. However, preacclimated sediment exposed to acetate and columns which received no preacclimation were unable to biodegrade toluene while a column which had been preacclimated to benzoate readily biodegraded this compound.

The median for the primary biodegradation rate constant of toluene is 0.2/day (N = 182); a range of not biodegraded to 42.5/day is reported. The median for the mineralization rate constant of toluene is 0.00895/day (N = 31); a range of not biodegraded to 0.149/day is reported. The frequency distribution histograms for this data are shown in figures 2a and 2b. Toluene is expected to biodegrade readily under most aerobic environmental conditions.

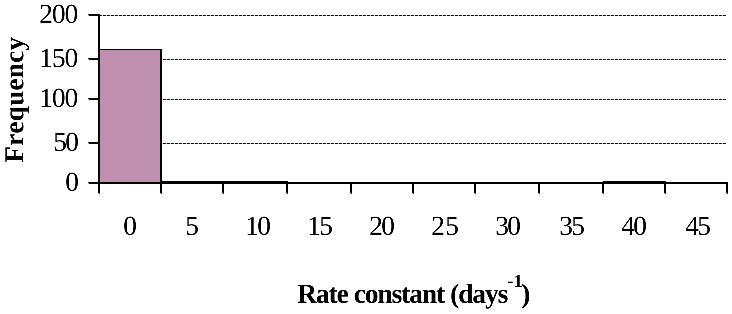

Figure 2a. Frequency histogram for the published primary biodegradation rate constant values for toluene.

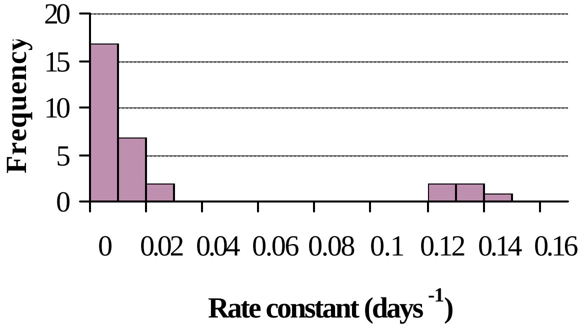

Figure 2b. Frequency histogram for the published mineralization rate constant values for toluene.

Table 3. Aerobic biodegradation rate constant values for toluene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.009/day		American Petroleum Institute (1994)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.009/day		American Petroleum Institute (1994)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.013/day		American Petroleum Institute (1994)
Toluene	Edwards AFB, California	TCE-contaminated GW plume	Aquifer sediment + groundwater	Field	1.8-2.7 mg/L	10	0.52-0.56/day		McCarty,PL et. al. (1998)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Field	172-381 mg/m3		13.7/day		Kim,H et. al. (1995)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Field	59-214 mg/m3		19.44/day		Kim,H et. al. (1995)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field	1.75 mg/L	270	37 mg/day		Barker,JF et. al. (1987)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Field	127-332 mg/m3		4.8/day		Kim,H et. al. (1995)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Field	149-325 mg/m3		41.52/day		Kim,H et. al. (1995)
Toluene		Contaminated	Groundwater	Groundwater grab sample	100 mg/L	24	0.0018/day		Chang,BV et. al. (1997)
Toluene		Contaminated	Groundwater	Groundwater grab sample	100 mg/L	24	0.00214/day		Chang,BV et. al. (1997)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	Groundwater grab sample	120 ug/L	90	0.0025/day		Holm,PE et. al. (1992)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	24.4 ug/L	3	0.031/day		Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	26.4 ug/L	3	0.031/day		Armstrong,AQ et. al. (1991)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	37.2 ug/L	3	0.032/day		Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	24.9 ug/L	3	0.037/day	0.5-1	Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	31.4 ug/L	3	0.037/day		Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	30.6 ug/L	3	0.040/day	0.5-1	Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	21.4 ug/L	3	0.043/day		Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	29.7 ug/L	3	0.044/day		Armstrong,AQ et. al. (1991)
Toluene	Clarke County, Georgia	University of Georgia landfill	Groundwater	Groundwater grab sample	27.4 ug/L	3	0.046/day		Armstrong,AQ et. al. (1991)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	Groundwater grab sample	120 ug/L	90	0.05/day		Holm,PE et. al. (1992)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.087/day		Morgan,P et. al. (1993)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.093/day		Morgan,P et. al. (1993)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.10/day		Morgan,P et. al. (1993)
Toluene	Ottawa, Canada	South Gloucester landfill	Groundwater	Groundwater grab sample	1000 ug/L	18	0.105/day		Harrison,EM & Barker,JF (1987)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	30	0.11/day		Albrechtsen,HJ et. al. (1996)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.12/day		Morgan,P et. al. (1993)
Toluene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater	Groundwater grab sample	100 ug/L	23	0.126/day		Albrechtsen,HJ et. al. (1996)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.13/day		Morgan,P et. al. (1993)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.14/day		Morgan,P et. al. (1993)
Toluene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	23	0.172/day	10	Albrechtsen,HJ et. al. (1996)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.19/day		Morgan,P et. al. (1993)
Toluene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	1.7 mg/L		0.19/day		Morgan,P et. al. (1993)
Toluene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater	Groundwater grab sample	100 ug/L	33	0.254/day	24	Albrechtsen,HJ et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	12	0.276/day		Albrechtsen,HJ et. al. (1996)
Toluene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	9	0.303/day		Albrechtsen,HJ et. al. (1996)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene		Industrial site	Groundwater	Groundwater grab sample	32 mg/L	16.25	0.327/day	12.5	Williams,RA et. al. (1997)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	110 ug/L	38	0.39/day	14	Aamand,J et. al. (1989)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	110 ug/L	78	0.42/day	56	Aamand,J et. al. (1989)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	110 ug/L	18	0.65/day	3.7	Aamand,J et. al. (1989)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	110 ug/L	18	0.65/day	3.7	Aamand,J et. al. (1989)
Toluene	Ottawa, Canada	South Gloucester landfill	Groundwater	Groundwater grab sample	1100 ug/L	6	0.898/day		Harrison,EM & Barker,JF (1987)
Toluene	Grindsted, Denmark	Heavy oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	6.2	1.0-1.11/day		Arvin,E et. al. (1988)
Toluene	Sandbjerg and Gassehaven, Denmark	Fuel oil + gasoline contamination	Groundwater	Groundwater grab sample	110 ug/L	10	1.0/day	0.7	Aamand,J et. al. (1989)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	110 ug/L	9	1.03/day		Aamand,J et. al. (1989)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	110 ug/L	11	1.26/day	3.6	Aamand,J et. al. (1989)
Toluene	Ottawa, Canada	South Gloucester landfill	Groundwater	Groundwater grab sample	1500 ug/L	4	1.38/day		Harrison,EM & Barker,JF (1987)
Toluene	Denmark		Groundwater	Groundwater grab sample	200-1000 ug/L	5	2.65-3.45/day	3	Arvin,E et. al. (1988)
Toluene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	2.3	2.67-2.96/day		Arvin,E et. al. (1988)
Toluene	Los Angeles, California	Gasoline contamination	Groundwater	Groundwater grab sample	561 ug/L	0.96	3.8/day		Karlson,U & Frankenberger,WTJr (1989)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Los Angeles, California	Gasoline contamination	Groundwater	Groundwater grab sample	561 ug/L	0.71	5.7/day		Karlson,U & Frankenberger,WTJr (1989)
Toluene	Ganlose, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	6	No biodegradation		Arvin,E et. al. (1988)
Toluene	Horsholm, Denmark	Gasoline contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	6	No biodegradation		Arvin,E et. al. (1988)
Toluene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	14	0.354/day	1	Lyngkilde,J et. al. (1988)
Toluene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	14	0.354/day	1	Lyngkilde,J et. al. (1988)
Toluene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	14	0.354/day	1	Lyngkilde,J et. al. (1988)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	In situ microcosm	120 ug/L		0.0067/day		Holm,PE et. al. (1992)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L		0.033/day		Holm,PE et. al. (1992)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	In situ microcosm	120 ug/L		0.039/day		Holm,PE et. al. (1992)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L		0.042/day		Holm,PE et. al. (1992)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.1/day	7	Nielsen,PH et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.2/day	1	Nielsen,PH et. al. (1996)
Toluene	Vejen City, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.4/day	5	Bjerg,PL et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.4/day	5	Nielsen,PH et. al. (1996)
Toluene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	20 mg/L	4.6	0.651/day		Anid,PJ et. al. (1993)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	20 mg/L	4.6	0.651/day		Anid,PJ et. al. (1993)
Toluene		Uncontaminated	Aquifer sediment	Lab column	183 ug/L	2	1-8 ug/day		Alvarez,PJJ et. al. (1998)
Toluene		Uncontaminated	Aquifer sediment	Lab column	183 ug/L	9	3-6 ug/day	3	Alvarez,PJJ et. al. (1998)
Toluene		Uncontaminated	Aquifer sediment	Lab column	183 ug/L	8	4-6 ug/day	3	Alvarez,PJJ et. al. (1998)
Toluene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	2.5	Biodegrades		Alvarez,PJJ et. al. (1998)
Toluene	Ada, Oklahoma		Soil	Lab column	0.20 mg/L		Biodegrades		Wilson,JT et. al. (1981)
Toluene	Ada, Oklahoma		Soil	Lab column	0.90 mg/L		Biodegrades		Wilson,JT et. al. (1981)
Toluene	Eastern Pennsylvania	Gasoline contaminated site	Soil	Lab column		3	Biodegrades		Venkatraman,SN et. al. (1998)
Toluene	Eastern Pennsylvania	Gasoline contaminated site	Soil	Lab column		3	Biodegrades		Venkatraman,SN et. al. (1998)
Toluene	Skaelskor, Denmark	Uncontaminated	Fractured clay	Lab column		3.2	Biodegrades		Broholm,K et. al. (1995)
Toluene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	No biodegradation		Alvarez,PJJ et. al. (1998)
Toluene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	No biodegradation		Alvarez,PJJ et. al. (1998)
Toluene	Traverse City, Michigan	Uncontaminated landfill site	Aquifer sediment	Lab microcosm	0.1-100 ng/g	68	0.001/day	10	Aelion,CM et. al. (1989)
Toluene	Pickett, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm		7	0.0014/day		Wilson,JT et. al. (1984)
Toluene	Fort Polk, Louisiana	Uncontaminated	Aquifer sediment	Lab microcosm		7	0.0019/day		Wilson,JT et. al. (1984)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0019/day		Thomas,JM et. al. (1990)
Toluene	Fort Polk, Louisiana	Uncontaminated	Aquifer sediment	Lab microcosm		7	0.003/day		Wilson,JT et. al. (1984)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0032/day		Thomas,JM et. al. (1990)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	1000 ug/L	42	0.0033/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0033/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0035/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	10 ug/L	42	0.00362/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	267 ug/L	42	0.0037/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	100 ug/L	28	0.0040/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	1 ug/L	42	0.0043/day		Thomas,JM et. al. (1990)
Toluene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00503/day		Pugh,LB et. al. (1996)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	35 ug/L	42	0.0054/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0061/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0061/day		Thomas,JM et. al. (1990)
Toluene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00786/day		Pugh,LB et. al. (1996)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0083/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0096/day		Thomas,JM et. al. (1990)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	35	0.0097/day	16.7	Fan,S & Scow,KM (1993)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.011-0.017/day		Thomas,JM et. al. (1990)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0115/day		Thomas,JM et. al. (1990)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	27.7	0.0115/day	10	Mu,DY & Scow,KM (1994)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0117/day		Thomas,JM et. al. (1990)
Toluene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.013/day		Pugh,LB et. al. (1996)
Toluene		Uncontaminated	Soil	Lab microcosm	0.5 ug/g	30	0.013/day		Davis,JW & Madsen,S (1996)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0135/day		Thomas,JM et. al. (1990)
Toluene	Traverse City, Michigan	Contaminated with aviation fuel	Aquifer sediment	Lab microcosm	0.1-100 ng/g	68	0.014/day		Aelion,CM et. al. (1989)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0162/day		Thomas,JM et. al. (1990)
Toluene	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm	104 ug/kg	11	0.0169/day		Swindoll,CM et. al. (1988)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		0.017 mg/kg sed/hr		Cohen,BA et. al. (1995)
Toluene		Uncontaminated	Soil	Lab microcosm	50 ug/g	30	0.017/day		Davis,JW & Madsen,S (1996)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.02 ng/L/day		Button,DK et. al. (1981A)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	2 ng/L	28	0.0218/day		Thomas,JM et. al. (1990)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g	30	0.022/day	1.9	Davis,JW & Madsen,S (1996)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Hanahan, South Carolina	Uncontaminated	Aquifer sediment	Lab microcosm	10 umol/kg		0.022/day		Bradley,PM & Chapelle,FH (1995)
Toluene	Conroe, Texas	Creosote waste site	Aquifer sediment	Lab microcosm		7	0.023-0.029/day		Wilson,JT et. al. (1986)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	230 ug/L	0.33	0.025 mg/kg sed/hr		Cohen,BA et. al. (1995)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g	30	0.025/day		Davis,JW & Madsen,S (1996)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		0.026 mg/kg sed/hr		Cohen,BA et. al. (1995)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	7.4	0.026/day	2.5	Fuller,ME et. al. (1995)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g	30	0.027/day	5.7	Davis,JW & Madsen,S (1996)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g	30	0.027/day		Davis,JW & Madsen,S (1996)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	2.5 mg/L	74	0.029/day		Barker,JF et. al. (1987)
Toluene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.03-0.035/day		Wilson,JT et. al. (1983B)
Toluene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.03-0.035/day		Wilson,JT et. al. (1983B)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	91	0.0312/day		Fuller,ME et. al. (1995)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	3.8 mg/L	80	0.032/day	13	Barker,JF et. al. (1987)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	839 ug/L	120	0.037/day	<7	American Petroleum Institute (1994A)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	100 ug/L		0.038 mg/kg sed/hr		Cohen,BA et. al. (1995)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Cooper River, South Carolina	Oil contamination	River water	Lab microcosm	6 ug/L	1	0.041 ug/L/day		Lee,RF (1977)
Toluene	Lula, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	0.041/day		Wilson,JT et. al. (1986)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1261 ug/L	120	0.047/day	<7	American Petroleum Institute (1994A)
Toluene	Cooper River, South Carolina	Oil contamination	River water	Lab microcosm	6 ug/L	1	0.048 ug/L/day		Lee,RF (1977)
Toluene	Georgia coast		Seawater	Lab microcosm	20 ug/L	1	0.05 ug/L/day		Lee,RF & Ryan,C (1976)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.05/day		Holm,PE et. al. (1992)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.05/day		Holm,PE et. al. (1992)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	48.5 mg/L	7.5	0.052/day	2	Allen-King,RM et. al. (1994)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	91	0.0576/day		Fuller,ME et. al. (1995)
Toluene	Cooper River, South Carolina	Oil contamination	River water	Lab microcosm	6 ug/L	1	0.058 ug/L/day		Lee,RF (1977)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.06 ng/L/day		Button,DK et. al. (1981A)
Toluene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm	32 mg/L	45	0.0625/day		Pugh,LB et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.067/day		Holm,PE et. al. (1992)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		0.068 mg/kg rock/hr		Cohen,BA et. al. (1995)
Toluene	Hanahan, South Carolina	Petroleum contaminated site	Aquifer sediment	Lab microcosm	10 umol/kg		0.071/day		Bradley,PM & Chapelle,FH (1995)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	48.5 mg/L	7.5	0.080/day		Allen-King,RM et. al. (1994)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	350 ug/L	21	0.083/day		Thomas,JM et. al. (1990)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.083/day		Holm,PE et. al. (1992)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1242 ug/L	50	0.088/day	7	American Petroleum Institute (1994A)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	7.4	0.088/day	2.5	Fuller,ME et. al. (1995)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.09/day		Nielsen,PH et. al. (1996)
Toluene		Uncontaminated	Soil	Lab microcosm	200 ug/g		0.098/day	4.8	Davis,JW & Madsen,S (1996)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	230 ug/L		0.1 mg/kg sed/hr		Cohen,BA et. al. (1995)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	200 ug/L	21	0.107/day		Thomas,JM et. al. (1990)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.11 ng/L/day		Button,DK et. al. (1981A)
Toluene	Skidaway River, Georgia		River water	Lab microcosm	20 ug/L	0.5	0.12 ug/L/day		Lee,RF & Ryan,C (1976)
Toluene	Skidaway River, Georgia		River water	Lab microcosm	20 ug/L	0.75	0.12 ug/L/day		Lee,RF & Ryan,C (1976)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	48.5 mg/L	12.5	0.123/day	9	Allen-King,RM et. al. (1994)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	27.7	0.136/day	10.8	Mu,DY & Scow,KM (1994)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	10	0.137/day	3.3	Fan,S & Scow,KM (1993)
Toluene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	240 ug/L	14	0.140/day		Thomas,JM et. al. (1990)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	5 mg/L	10	0.149/day	3.3	Fan,S & Scow,KM (1993)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		0.15 mg/kg rock/hr		Cohen,BA et. al. (1995)
Toluene	Skidaway River, Georgia		River water	Lab microcosm	20 ug/L	1	0.150 ug/L/day		Lee,RF (1977)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	48.5 mg/L	8	0.150/day		Allen-King,RM et. al. (1994)
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1.25 mg/L	32	0.156/day		Barker,JF et. al. (1987)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	25 mg/L	24	0.156/day	12.5	Allen-King,RM et. al. (1994)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		0.16 mg/kg rock/hr		Cohen,BA et. al. (1995)
Toluene	Gloucester landfill, Ottawa, Canada	Landfill site	Aquifer sediment + groundwater	Lab microcosm			0.16/day		Berwanger,DJ & Barker,JF (1988)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	48.5 mg/L	12.5	0.161/day		Allen-King,RM et. al. (1994)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	625 mg/L	42	0.169/day	13.3	Mu,DY & Scow,KM (1994)
Toluene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.192/day		Pugh,LB et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.2/day	3	Nielsen,PH et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.2/day	5	Nielsen,PH et. al. (1996)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.22 ng/L/day		Button,DK et. al. (1981A)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	36.5	0.224/day	13.3	Fan,S & Scow,KM (1993)
Toluene	Livermore, California	Gasoline spill site	Soil	Lab microcosm	20 mg/L	9.2	0.229/day		Fuller,ME et. al. (1995)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		0.23 mg/kg rock/hr		Cohen,BA et. al. (1995)
Toluene	Naval Air Station, Adak, Alaska	JP-5 Jet fuel contamination	Aquifer sediment	Lab microcosm	10 umol/kg		0.23/day		Bradley,PM & Chapelle,FH (1995)
Toluene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	143 ug/L	26.6	0.233/day	2-7	Nielsen,PH & Christensen,TH (1994B)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	250 mg/L	25	0.236/day	8.3	Mu,DY & Scow,KM (1994)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.38 ug/L		0.24 ng/L/day		Button,DK et. al. (1981A)
Toluene	Naval Air Station, Adak, Alaska	Uncontaminated	Aquifer sediment	Lab microcosm	10 umol/kg		0.24/day		Bradley,PM & Chapelle,FH (1995)
Toluene		Contaminated	Soil	Lab microcosm	5 ug/g		0.26/day		Davis,JW & Madsen,S (1996)
Toluene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	310 ug/L	14	0.28/day		Chiang,CY et. al. (1986)
Toluene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	13	0.31/day	5	Hunt,CS & Alvarez,PJJ (1997)
Toluene	Grindsted, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	7	0.322/day		Albrechtsen,HJ et. al. (1996)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	7.4	0.325/day		Fuller,ME et. al. (1995)
Toluene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	380 ug/L	14	0.327/day		Wilson,BH et. al. (1990)
Toluene		Uncontaminated	Soil	Lab microcosm	0.2-0.4 mg/L	7	0.329/day		McNabb,JF et. al. (1981)
Toluene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	16	0.33/day		Borden,RC et. al. (1997)
Toluene	Lula, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	0.344/day		Wilson,JT et. al. (1986)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	25.6	0.354/day	9.4	Mu,DY & Scow,KM (1994)
Toluene	Lula, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	0.36/day		Wilson,JT et. al. (1986)
Toluene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	420 ug/L	14	0.363/day		Wilson,BH et. al. (1990)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	25 mg/L	5	0.380/day		Allen-King,RM et. al. (1994)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	5	0.383/day		Fan,S & Scow,KM (1993)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	5	0.383/day		Fan,S & Scow,KM (1993)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	5	0.436/day		Fan,S & Scow,KM (1993)
Toluene		Uncontaminated	Soil	Lab microcosm	0.5 ug/g		0.46/day	5.7	Davis,JW & Madsen,S (1996)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.48 ng/L/day		Button,DK et. al. (1981A)
Toluene		Uncontaminated	Soil	Lab microcosm	200 ug/g		0.49/day	7.8	Davis,JW & Madsen,S (1996)
Toluene		Uncontaminated	Soil	Lab microcosm	0.5 ug/g		0.53/day		Davis,JW & Madsen,S (1996)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g		0.53/day	0.71	Davis,JW & Madsen,S (1996)
Toluene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	10	0.53/day		Borden,RC et. al. (1997)
Toluene		Uncontaminated	Soil	Lab microcosm	50 ug/g		0.57/day	2.8	Davis,JW & Madsen,S (1996)
Toluene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	325 ug/L	7	0.60/day		Chiang,CY et. al. (1986)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	16.7	0.60/day	12.5	Fan,S & Scow,KM (1993)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.62 ng/L/day		Button,DK et. al. (1981A)
Toluene	Grindsted, Jutland, Denmark	Grindsted landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.63/day		Albrechtsen,HJ et. al. (1997)
Toluene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.63/day		Albrechtsen,HJ et. al. (1997)
Toluene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.63/day		Albrechtsen,HJ et. al. (1997)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.65 ng/L/day		Button,DK et. al. (1981A)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		0.65 ng/L/day		Button,DK et. al. (1981A)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	2.5 mg/L	1.4	0.654/day		Allen-King,RM et. al. (1994)
Toluene	Grindsted, Jutland, Denmark	Grindsted landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	7	0.701/day		Albrechtsen,HJ et. al. (1997)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g		0.72/day	5.9	Davis,JW & Madsen,S (1996)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	7.5	0.737/day		Mu,DY & Scow,KM (1994)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	100 mg/L	8.75	0.746/day		Mu,DY & Scow,KM (1994)
Toluene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	2.8 mg/L	7	0.80/day		Hutchins,SR (1991)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	48.5 mg/L	12	0.853/day	8.3	Allen-King,RM et. al. (1994)
Toluene	Northen Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	10-100 mg/L		0.91/day		Alvarez,PJJ et. al. (1991)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g		1.04/day	2.5	Davis,JW & Madsen,S (1996)
Toluene	Holbaek,Western Sealand, Denmark	Skellingsted landfill	Soil	Lab microcosm	450-600 ug/L	2.5	1.15/day		Kjeldsen,P et. al. (1997)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	3.9 ug/L		1.2 ng/L/day		Button,DK et. al. (1981A)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	2.5 mg/L	32 hours	1.29/day		Allen-King,RM et. al. (1994)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	2.5 mg/L	1.4	1.29/day		Allen-King,RM et. al. (1994)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		1.5 mg/kg sed/hr		Cohen,BA et. al. (1995)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g		1.5/day	1.9	Davis,JW & Madsen,S (1996)
Toluene	East Drainage Ditch, Massachusetts	Tanning and chemical manufacture	Stream water	Lab microcosm	250 ug/L		1.6 mg/kg sed/hr		Cohen,BA et. al. (1995)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	2.5	1.66/day		Fuller,ME et. al. (1995)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Sandbjerg and Gassehaven, Denmark	Fuel oil + gasoline contamination	Aquifer sediment + groundwater	Lab microcosm	110 ug/L	6	1.76/day	0.7	Aamand,J et. al. (1989)
Toluene	Jurere Beach, Florianopolis, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	2	1.90/day		Corseuil,HX et. al. (1997)
Toluene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	3	1.96/day		Albrechtsen,HJ et. al. (1996)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	25 mg/L	7.5 hours	11.4/day		Allen-King,RM et. al. (1994)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		14.4 ng/L/day		Button,DK et. al. (1981A)
Toluene	Holbaek,Western Sealand, Denmark	Skellingsted landfill	Soil	Lab microcosm	450-600 ug/L	3.5	2.0/day	2.5	Kjeldsen,P et. al. (1997)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	6.25	2.07/day	3.75	Mu,DY & Scow,KM (1994)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	25 mg/L	8 hours	2.08/day		Allen-King,RM et. al. (1994)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	45.8 mg/L		21.7 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Riverside, California	Uncontaminated	Soil	Lab microcosm	140 mg/L		34.2/day		Jin,Y et. al. (1994)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	18.2 mg/L		35.3 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	8.32 mg/L		35.6 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	2.	4.61/day		Albrechtsen,HJ et. al. (1997)
Toluene	Holbaek,Western Sealand, Denmark	Skellingsted landfill	Soil	Lab microcosm	400-500 ug/L	0.83	4.7/day		Kjeldsen,P et. al. (1997)
Toluene	Livermore, California	Uncontaminated	Soil	Lab microcosm	20 mg/L	1	4.71/day		Fuller,ME et. al. (1995)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	2.5 mg/L	10 hours	4.73/day		Allen-King,RM et. al. (1994)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Riverside, California	Uncontaminated	Soil	Lab microcosm	140 mg/L		42.5/day		Jin,Y et. al. (1994)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		58 ng/L/day		Button,DK et. al. (1981A)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	2.5 mg/L	5 hours	7.22/day		Allen-King,RM et. al. (1994)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	10.57 mg/L		8.67 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	24 mg/L		9.07 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Canadian Forces Base, Borden, Ontario	Contaminated	Soil + groundwater	Lab microcosm	2.5 mg/L	10 hours	9.39/day		Allen-King,RM et. al. (1994)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	23.7 mg/L		9.61 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	4.24 mg/L		9.85 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	9 mg/L		9.86 mg/kg/day		Allen-King,RM et. al. (1996)
Toluene	Port Valdez, Alaska	Oil contamination	Seawater	Lab microcosm	0.33-0.42 ug/L		>170-210 ng/L/day		Button,DK et. al. (1981A)
Toluene	Riverside, California	Uncontaminated	Soil	Lab microcosm	11.1 mg/L	6	Biodegrades		Jin,Y et. al. (1994)
Toluene	Riverside, California	Uncontaminated	Soil	Lab microcosm	25.1 mg/L	12	Biodegrades		Jin,Y et. al. (1994)
Toluene	Riverside, California	Uncontaminated	Soil	Lab microcosm	27.6 mg/L	2.5	Biodegrades		Jin,Y et. al. (1994)
Toluene	North Charleston, South Carolina	JP-4 jet fuel contamination site	Aquifer sediment	Lab microcosm	43 ng/g	105	Limited		Aelion,CM & Bradley,PM (1991)
Toluene		Uncontaminated	Soil	Lab microcosm	5 ug/g		No biodegradation		Davis,JW & Madsen,S (1996)
Toluene		Uncontaminated	Soil	Lab microcosm	500 ug/g		No biodegradation		Davis,JW & Madsen,S (1996)

Table 3. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Toluene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	2846 ug/L	278	No biodegradation		American Petroleum Institute (1994A)
Toluene	Canadian Forces Base, Borden, Ontario	Uncontaminated	Soil + groundwater	Lab microcosm	25 mg/L	33	No biodegradation		Allen-King,RM et. al. (1994)
Toluene	Conroe, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	No biodegradation		Wilson,JT et. al. (1986)
Toluene	Pickett, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm		7	No biodegradation		Wilson,JT et. al. (1984)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	32	No biodegradation		Fan,S & Scow,KM (1993)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	1000 mg/L	42	No biodegradation		Mu,DY & Scow,KM (1994)
Toluene	Yolo County, California	Agricultural soil	Soil	Lab microcosm	20 mg/L	27.7	No biodegradation		Mu,DY & Scow,KM (1994)
Toluene	North Charleston, South Carolina	JP-4 jet fuel contamination site	Aquifer sediment	Lab microcosm	17 ng/g	120	No mineralization		Aelion,CM & Bradley,PM (1991)
Toluene	Denmark	Municipal landfill	Leachate	Reactor system	50 mg COD/L		Biodegrades		Lyngkilde,J et. al. (1992)

3.1.3. Ethylbenzene

Ethylbenzene is moderately degradable in the presence of oxygen (Table 4). Degradation is thought to proceed via 3-ethylcatechol to CO_2 (Ribbons and Eaton, 1992). 3.17 mg of oxygen are necessary to biodegrade 1 mg of ethylbenzene to CO_2 and water (Wiedemeier et. al., 1995).

As for the other BTEX compounds, most of the located data for ethylbenzene under aerobic conditions were from aquifer environments. Field studies at two different locations reported the biodegradation of ethylbenzene. Half-life values ranged from 87 to 231 days for an uncontaminated aquifer study (American Petroleum Institute, 1994). No *in situ* microcosm studies were found for this compound. Only one study was found which measured the rate of mineralization for ethylbenzene. A mineralization half-life of 19 days was calculated in river water (Ludzack and Ettinger, 1963).

By far the most common type of study used to observe the biodegradation of ethylbenzene under aerobic conditions is the laboratory microcosm. Half-lives ranging from 1 (Hutchins, 1991) to 231 (American Petroleum Institute, 1994A) days with an average value of 4.4 days were measured. The high half-life reported by the American Petroleum Institute represents a microcosm study where 85% methanol was present. When methanol was not present, a half-life of 22 days was obtained. Initial concentrations of up to 20.6 mg/L (Ludzack and Ettinger, 1963) were reported in these experiments without obvious deleterious effect. In general, however, initial concentrations of less than 2 mg/L were utilized. No biodegradation was reported for one lab column study. Anid et. al. (1991) reports that columns supplemented with nitrate were unable to degrade ethylbenzene as well as meta- and para-xylenes and benzene. The nitrate-amended columns may have exhibited nitrate-reducing conditions as over 60 mg/L total BTEX mixture was added. However, no attempt was made by the authors to distinguish through end product measurements whether conditions remained aerobic or became nitrate-reducing.

The median for the primary biodegradation rate constant of ethylbenzene, considering all studies, is 0.113/day (N = 21). A range of 0.003 to 4.8/day is reported. The frequency distribution histogram for this data is shown in figure 3. Ethylbenzene is expected to biodegrade fairly readily under most aerobic environmental conditions.

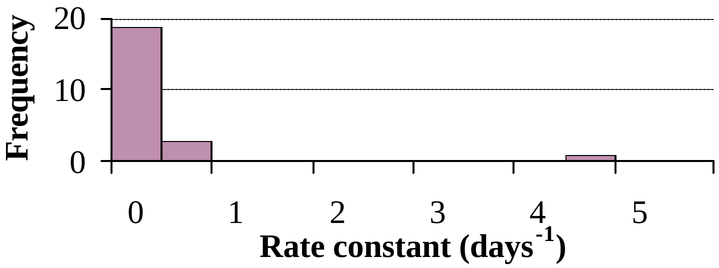

Figure 3. Frequency histogram for the published primary biodegradation rate constant values of ethylbenzene.

Table 4. Aerobic biodegradation rate constant values for ethylbenzene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.003/day		American Petroleum Institute (1994)
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.007/day		American Petroleum Institute (1994)
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.008/day		American Petroleum Institute (1994)
Ethylbenzene	Amsterdam, The Netherlands	Dune infiltration site	Sediment	Field	<0.05 ug/L	7-49	Biodegrades		Bosma,TNP et. al. (1996)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		0.14/day		Morgan,P et. al. (1993)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		0.17/day		Morgan,P et. al. (1993)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		25 ug/L/day		Morgan,P et. al. (1993)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		32 ug/L/day		Morgan,P et. al. (1993)
Ethylbenzene	Industrial facility, New Jersey	Vinyl wall covering facility	Groundwater	Groundwater grab sample	50 mg/L	1.67	4.8/day		Graves,DA et. al. (1994)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		40 ug/L/day		Morgan,P et. al. (1993)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		41 ug/L/day		Morgan,P et. al. (1993)

Table 4. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site- BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		46 ug/L/day		Morgan,P et. al. (1993)
Ethylbenzene	Uiterburen, The Netherlands	Natural gas production site- BTEX contamination	Groundwater	Groundwater grab sample	169 ug/L		59 ug/L/day		Morgan,P et. al. (1993)
Ethylbenzene	Amsterdam, The Netherlands	Dune infiltration site	Sediment	Lab column	0.5 ug/L		Biodegrades		Bosma,TNP et. al. (1996)
Ethylbenzene	Amsterdam, The Netherlands	Dune infiltration site	Sediment	Lab column	10-20 ug/L		Biodegrades		Bosma,TNP et. al. (1996)
Ethylbenzene	Wageningen, The Netherlands		Sediment	Lab column	10-20 ug/L		Biodegrades		Bosma,TNP et. al. (1996)
Ethylbenzene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	3 mg/L	4.6	No biodegradation		Anid,PJ et. al. (1993)
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	359 ug/L	278	0.003/day		American Petroleum Institute (1994A)
Ethylbenzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.018/day		Pugh,LB et. al. (1996)
Ethylbenzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.022/day		Pugh,LB et. al. (1996)
Ethylbenzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.025/day		Pugh,LB et. al. (1996)
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	92 ug/L	120	0.031/day	7	American Petroleum Institute (1994A)
Ethylbenzene	Ohio River		River water	Lab microcosm	20.6 mg/L	15	0.036/day		Ludzack,FJ & Ettinger,MB (1963)

Table 4. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Ethylbenzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	225 ug/L	21	0.074/day		Thomas,JM et. al. (1990)
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	134 ug/L	25	0.077/day	<7	American Petroleum Institute (1994A)
Ethylbenzene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	139 ug/L	50	0.088/day	<7	American Petroleum Institute (1994A)
Ethylbenzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	205 ug/L	21	0.0915/day		Thomas,JM et. al. (1990)
Ethylbenzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.111/day		Pugh,LB et. al. (1996)
Ethylbenzene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm	2 mg/L	16	0.115/day		Pugh,LB et. al. (1996)
Ethylbenzene	Gloucester landfill, Ottawa, Canada	Landfill site	Aquifer sediment + groundwater	Lab microcosm			0.16/day		Berwanger,DJ & Barker,JF (1988)
Ethylbenzene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	240 ug/L	7	0.202/day		Thomas,JM et. al. (1990)
Ethylbenzene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	16	0.33/day		Borden,RC et. al. (1997)
Ethylbenzene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	10	0.53/day		Borden,RC et. al. (1997)
Ethylbenzene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	1.85 mg/L	7	0.75/day		Hutchins,SR (1991)

3.1.4. o-Xylene

o-Xylene is moderately degradable in the presence of oxygen (Table 5). Degradation is thought to proceed via 3,4-dimethylcatechol to CO_2 (Gibson and Subramanian, 1984). 3.17 mg of oxygen are necessary to biodegrade 1 mg of o-xylene to CO_2 and water (Wiedemeier et. al., 1995).

As for the other BTEX compounds, most of the located data for o-xylene under aerobic conditions were for aquifer environments. Two different field studies from the same location reported the biodegradation of o-xylene giving half-life values ranging from 116 to 173 days (American Petroleum Institute, 1994). Biodegradation of o-xylene was observed as well during *in situ* microcosm studies at Vejen City, Denmark. Half-lives ranged from 7 (Nielsen et. al., 1996) to 408 days (Holm et. al., 1992) days with an average half-life of 18 days. The high half-life value represents biodegradation in the groundwater only section of the *in situ* microcosm; half-life values obtained in the aquifer sediment + groundwater section were significantly lower.

By far the most common type of study used to observe the biodegradation of o-xylene under aerobic conditions is the laboratory microcosm. Half-lives ranging from 1 (Hutchins, 1991) to 41 (Holm et. al., 1992) days with an average value of 4.3 days (rate constant of 2.42/day reported by Aamand et. al., 1989 was not used in this calculation) were measured. Initial concentrations of up to 20 mg/L were reported in these experiments without obvious deleterious effect. In general, however, initial concentrations of less than 2 mg/L were utilized.

No biodegradation was reported for several microcosm studies. A study by the American Petroleum Institute (1994A) reports that o-xylene, as well as benzene, toluene and both *meta*- and *para*-xylene, were not biodegraded in the presence of 85% methanol over 278 days. This result was not unexpected as sufficient oxygen was available to degrade only 5% of the initially added methanol (over 7 grams were initially added). This suggests that anaerobic conditions may have occurred rapidly within this microcosm. In addition, the bacteria may have preferentially degraded the structurally simpler methanol or the concentration of methanol added may have been toxic to the indigenous bacterial population. Pristine aquifer sediment was unable to biodegrade o-xylene over a 7 day period; however, when creosote-contaminated aquifer sediment was used, greater than 19-21% of the initially added o-xylene was biodegraded over 7 days. Thomas et. al. (1990) reported that o-xylene was readily biodegraded in uncontaminated aquifer material with a half-life of 7 days but when either contaminated or biostimulated aquifer material was used instead, no biodegradation was reported over 21 days. Laboratory microcosms which contained double concentrations of nitrogen and phosphorus nutrients were able to significantly biodegrade a xylene mixture; however, unamended and single nutrient amendments to the microcosm were insufficient to encourage biodegradation of this mixture (Pugh et. al., 1996).

Laboratory column experiments by Broholm et. al. (1995) and Alvarez et. al. (1998) report that o-xylene was not biodegraded under certain circumstances. Alvarez et. al. (1998) showed biodegradation of o-xylene in laboratory columns fed with acetate and benzoate as cosubstrates. However, preacclimated sediment exposed to acetate and columns which received no preacclimation period were unable to biodegrade o-xylene while a column which had been preacclimated to benzoate readily biodegraded o-xylene. Broholm et. al. (1995) were not able to explain their results showing no to slight biodegradation of o-xylene over an experimental period of 3.5 days. It may be that this time period was not sufficient for acclimation of the bacterial population within the clay column.

The median for the primary biodegradation rate constant of o-xylene, considering all studies, is 0.054/day (N = 92); a range of not biodegraded to 7.625 is reported. The frequency distribution histogram for this data is shown in figure 4. o-Xylene is expected to biodegrade readily under most aerobic environmental conditions.

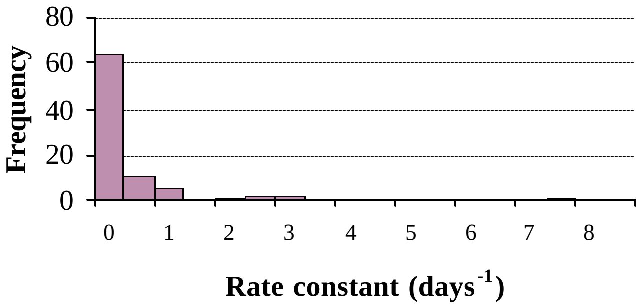

Figure 4. Frequency histogram for the published primary biodegradation rate constant values for o-xylene.

Table 5. Aerobic biodegradation rate constant values for o-xylene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.004/day		American Petroleum Institute (1994)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.005/day		American Petroleum Institute (1994)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.006/day		American Petroleum Institute (1994)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field	1.29 mg/L	270	47 mg/day		Barker,JF et. al. (1987)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	Groundwater grab sample	120 ug/L	90	0.0017/day		Holm,PE et. al. (1992)
o-Xylene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	48	0.0067/day	8	Albrechtsen,HJ et. al. (1996)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.0073/day		Morgan,P et. al. (1993)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	Groundwater grab sample	120 ug/L	90	0.0083/day		Holm,PE et. al. (1992)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.014/day		Morgan,P et. al. (1993)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.020/day		Morgan,P et. al. (1993)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.021/day		Morgan,P et. al. (1993)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.023/day		Morgan,P et. al. (1993)

Table 5. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Uiterburen, The Netherlands	Natural gas production site- BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.031/day		Morgan,P et. al. (1993)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site- BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		0.038/day		Morgan,P et. al. (1993)
o-Xylene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater	Groundwater grab sample	100 ug/L	48	0.040/day	8	Albrechtsen,HJ et. al. (1996)
o-Xylene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater	Groundwater grab sample	100 ug/L	48	0.0444/day	23	Albrechtsen,HJ et. al. (1996)
o-Xylene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	28	0.125/day		Albrechtsen,HJ et. al. (1996)
o-Xylene	Grindsted, Denmark	Uncontaminated landfill site	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	23	0.132/day	5	Albrechtsen,HJ et. al. (1996)
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	160 ug/L	65	0.16-0.54/day	14	Aamand,J et. al. (1989)
o-Xylene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	12	0.201/day		Albrechtsen,HJ et. al. (1996)
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	160 ug/L	18	0.62/day	2.4	Aamand,J et. al. (1989)
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	160 ug/L	38	0.69/day	24	Aamand,J et. al. (1989)
o-Xylene	Industrial facility, New Jersey	Vinyl wall covering facility	Groundwater	Groundwater grab sample	50 mg/L	7.5	0.70/day		Graves,DA et. al. (1994)
o-Xylene	Grindsted, Denmark	Heavy oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	5.2	1.2-1.33/day		Arvin,E et. al. (1988)
o-Xylene	Sandbjerg and Gassehaven, Denmark	Fuel oil + gasoline contamination	Groundwater	Groundwater grab sample	160 ug/L	10	1.21/day	2	Aamand,J et. al. (1989)
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	160 ug/L	10	1.27/day	2.4	Aamand,J et. al. (1989)

Table 5. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	160 ug/L	11	1.42/day	4.2	Aamand,J et. al. (1989)
o-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	295 ug/L		180 ug/L/day		Morgan,P et. al. (1993)
o-Xylene	Horsholm, Denmark	Gasoline contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	2.4	2.6-2.88/day		Arvin,E et. al. (1988)
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	160 ug/L	6	2.69/day	2.4	Aamand,J et. al. (1989)
o-Xylene	Ganlose, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	2.1	2.96-3.29/day		Arvin,E et. al. (1988)
o-Xylene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	2.1	2.96-3.29/day		Arvin,E et. al. (1988)
o-Xylene	Denmark		Groundwater	Groundwater grab sample	200-1000 ug/L	4.3	6.62-8.63/day	3.5	Arvin,E et. al. (1988)
o-Xylene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	60	0.0808/day	3	Lyngkilde,J et. al. (1988)
o-Xylene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	60	0.089/day	8	Lyngkilde,J et. al. (1988)
o-Xylene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	75	0.0903/day	24	Lyngkilde,J et. al. (1988)
o-Xylene	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	50	0.154/day	20	Lyngkilde,J et. al. (1988)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	In situ microcosm	120 ug/L		0.0017/day		Holm,PE et. al. (1992)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Groundwater	In situ microcosm	120 ug/L		0.0033/day		Holm,PE et. al. (1992)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L		0.0083/day		Holm,PE et. al. (1992)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L		0.011/day		Holm,PE et. al. (1992)

Table 5. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.04/day		Nielsen,PH et. al. (1996)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.04/day	3	Nielsen,PH et. al. (1996)
o-Xylene	Vejen City, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	100	0.1/day	7	Bjerg,PL et. al. (1996)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.1/day	7	Nielsen,PH et. al. (1996)
o-Xylene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	4 mg/L	4.6	0.0625/day	30	Anid,PJ et. al. (1993)
o-Xylene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	4 mg/L	4.6	0.262/day		Anid,PJ et. al. (1993)
o-Xylene		Uncontaminated	Aquifer sediment	Lab column	192 ug/L	9	1-3 ug/day	3	Alvarez,PJJ et. al. (1998)
o-Xylene		Uncontaminated	Aquifer sediment	Lab column	192 ug/L	2	1-8 ug/day		Alvarez,PJJ et. al. (1998)
o-Xylene		Uncontaminated	Aquifer sediment	Lab column	192 ug/L	9	2-4 ug/day	3	Alvarez,PJJ et. al. (1998)
o-Xylene			Aquifer sediment	Lab column	0.5 uM	17	Biodegrades		Kuhn,EP et. al. (1985)
o-Xylene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	Biodegrades		Alvarez,PJJ et. al. (1998)
o-Xylene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	No biodegradation		Alvarez,PJJ et. al. (1998)
o-Xylene		Uncontaminated	Aquifer sediment	Lab column	150 ug/L	3	No biodegradation		Alvarez,PJJ et. al. (1998)
o-Xylene	Skaelskor, Denmark	Uncontaminated	Fractured clay	Lab column		3.2	No biodegradation		Broholm,K et. al. (1995)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00136/day		Pugh,LB et. al. (1996)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.00677/day		Pugh,LB et. al. (1996)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.017/day		Holm,PE et. al. (1992)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.017/day		Holm,PE et. al. (1992)

Table 5. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.017/day		Holm,PE et. al. (1992)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.02/day		Nielsen,PH et. al. (1996)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	141 ug/L	82	0.0248/day	2-7	Nielsen,PH & Christensen,TH (1994B)
o-Xylene	Conroe, Texas	Creosote waste site	Aquifer sediment	Lab microcosm		7	0.025-0.028/day		Wilson,JT et. al. (1986)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	120 ug/L	90	0.025/day		Holm,PE et. al. (1992)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.03/day		Nielsen,PH et. al. (1996)
o-Xylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.03/day		Nielsen,PH et. al. (1996)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	168 ug/L	120	0.030/day	<7	American Petroleum Institute (1994A)
o-Xylene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.030/day		Wilson,JT et. al. (1983B)
o-Xylene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.030/day		Wilson,JT et. al. (1983B)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.033/day		Pugh,LB et. al. (1996)
Xylene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	285 ug/L	14	0.035/day		Chiang,CY et. al. (1986)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	248 ug/L	50	0.047/day	<7	American Petroleum Institute (1994A)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	228 ug/L	25	0.048/day	<7	American Petroleum Institute (1994A)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	20 mg/L	58	0.054/day		Barker,JF et. al. (1987)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	2 mg/L	54	0.056/day	13	Barker,JF et. al. (1987)

Table 5. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Gloucester landfill, Ottawa, Canada	Landfill site	Aquifer sediment + groundwater	Lab microcosm			0.057/day		Berwanger,DJ & Barker,JF (1988)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		16	0.077/day		Pugh,LB et. al. (1996)
o-Xylene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	250 ug/L	14	0.099/day		Thomas,JM et. al. (1990)
o-Xylene	Grindsted, Jutland, Denmark	Grindsted landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	23	0.10/day		Albrechtsen,HJ et. al. (1997)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	900 ug/L	25	0.14/day	10	Barker,JF et. al. (1987)
o-Xylene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	19	0.158/day		Albrechtsen,HJ et. al. (1997)
o-Xylene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	19	0.158/day		Albrechtsen,HJ et. al. (1997)
o-Xylene	Grindsted, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	23	0.163/day	5	Albrechtsen,HJ et. al. (1996)
o-Xylene			Soil	Lab microcosm	123 mg VOC/kg soil		0.227 mg/day	10	English,CW & Loehr,RC (1991)
Xylene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L		0.25/day	5	Hunt,CS & Alvarez,PJJ (1997)
o-Xylene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	370 ug/L	14	0.296/day		Wilson,BH et. al. (1990)
o-Xylene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	16	0.33/day		Borden,RC et. al. (1997)
o-Xylene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	390 ug/L	14	0.33/day		Wilson,BH et. al. (1990)
o-Xylene	Grindsted, Jutland, Denmark	Grindsted landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	13	0.333/day		Albrechtsen,HJ et. al. (1997)
o-Xylene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	10	0.53/day		Borden,RC et. al. (1997)
Xylene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	300 ug/L	7	0.56/day		Chiang,CY et. al. (1986)
o-Xylene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	5	0.60/day		Albrechtsen,HJ et. al. (1996)

Table 5. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Xylene	Vejen City, Jutland, Denmark	Vejen landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	4	0.75/day		Albrechtsen,HJ et. al. (1997)
o-Xylene	Jurere Beach, Florianopolis, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L	8	0.750/day	3	Corseuil,HX et. al. (1997)
o-Xylene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	2.3 mg/L	15	0.78/day		Hutchins,SR (1991)
o-Xylene	Sandbjerg and Gassehaven, Denmark	Fuel oil + gasoline contamination	Aquifer sediment + groundwater	Lab microcosm	160 ug/L	6	2.42/day	2	Aamand,J et. al. (1989)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	No biodegradation		Pugh,LB et. al. (1996)
o-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	544 ug/L	278	No biodegradation		American Petroleum Institute (1994A)
o-Xylene	Conroe, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	No biodegradation		Wilson,JT et. al. (1986)
o-Xylene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	260 ug/L	21	No biodegradation		Thomas,JM et. al. (1990)
o-Xylene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	270 ug/L	21	No biodegradation		Thomas,JM et. al. (1990)
o-Xylene	Denmark	Municipal landfill	Leachate	Reactor system	50 mg COD/L		Biodegrades		Lyngkilde,J et. al. (1992)

3.1.5. m-Xylene

m-Xylene is moderately degradable in the presence of oxygen (Table 6). Degradation is thought to proceed via 2,4-dimethylcatechol to CO_2 (Gibson and Subramanian, 1984). 3.13 mg of oxygen are necessary to biodegrade 1 mg of m-xylene to CO_2 and water (Wiedemeier et. al., 1995).

As for the other BTEX compounds, most of the located data for m-xylene under aerobic conditions were for aquifer environments. Two different field studies from the same location reported the biodegradation of m-xylene giving half-life values ranging from 50 to 77 days (American Petroleum Institute, 1994). No *in situ* microcosm studies were found for this compound.

By far the most common type of study used to observe the biodegradation of m-xylene under aerobic conditions is the laboratory microcosm. Half-lives ranging from 1 (Hutchins, 1991) to 27 (Wilson et. al., 1986) days with an average value of 4.3 days were measured. Initial concentrations of up to 20 mg/L (Hunt and Alvarez, 1997) were reported in these experiments without obvious deleterious effect. In general, however, initial concentrations of less than 2 mg/L were utilized.

No biodegradation was reported for several microcosm studies. A study by the American Petroleum Institute, 1994A, reports that m-xylene was not biodegraded in the presence of 85% methanol over 278 days. This result was not unexpected as sufficient oxygen was available to degrade only 5% of the initially added methanol. In addition, the bacteria may have preferentially degraded the structurally simpler methanol or the concentration of methanol added may have been toxic to the indigenous bacterial population. Laboratory microcosms which contained double concentrations of nitrogen and phosphorus nutrients were able to significantly biodegrade a xylene mixture; however, unamended and single nutrient amendments to the microcosm were insufficient to encourage biodegradation of this mixture (Pugh et. al., 1996). Pristine aquifer sediment was unable to biodegrade m-xylene over a 7-day period; however, when creosote-contaminated aquifer sediment was used, greater than 19-22% of the initially added m-xylene was biodegraded over 7 days. Anid et. al. (1991) report that columns supplemented with hydrogen peroxide but not columns supplemented with nitrate were able to degrade m-xylene. The nitrate-amended columns may have exhibited nitrate-reducing conditions as over 60 mg/L BTEX mixture was added. However, no attempt was made by the authors to distinguish through end product measurements whether conditions remained aerobic or became nitrate-reducing.

The median for the primary biodegradation rate constant of m-xylene is 0.057/day (N = 32); a range from not biodegraded to 0.76/day is reported. The frequency distribution histogram for this data is shown in figure 5. m-Xylene is expected to biodegrade fairly readily under most aerobic environmental conditions.

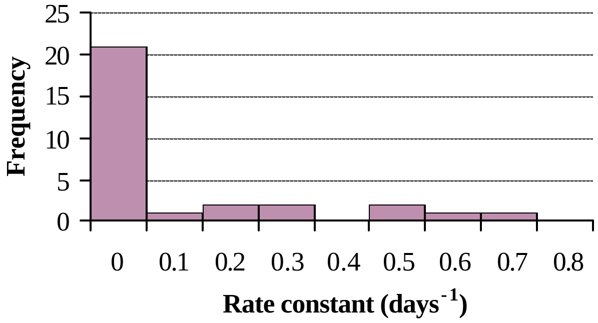

Figure 5. Frequency histogram for the published primary biodegradation rate constant values of m-xylene.

Table 6. Aerobic biodegradation rate constant values for m-xylene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.009/day		American Petroleum Institute (1994)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.010/day		American Petroleum Institute (1994)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.014/day		American Petroleum Institute (1994)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field	1.09 mg/L	270	33 mg/day		Barker,JF et. al. (1987)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.056/day		Morgan,P et. al. (1993)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.06/day		Morgan,P et. al. (1993)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.065/day		Morgan,P et. al. (1993)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.088/day		Morgan,P et. al. (1993)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.1/day		Morgan,P et. al. (1993)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		37 ug/L/day		Morgan,P et. al. (1993)
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		79 ug/L/day		Morgan,P et. al. (1993)

Table 6. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
m-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		91 ug/L/day		Morgan,P et. al. (1993)
m-Xylene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	13 mg/L	4.6	0.350/day		Anid,PJ et. al. (1993)
m-Xylene			Aquifer sediment	Lab column	0.5 uM	17	Biodegrades		Kuhn,EP et. al. (1985)
m-Xylene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	13 mg/L	4.6	No biodegradation		Anid,PJ et. al. (1993)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00136/day		Pugh,LB et. al. (1996)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.00677/day		Pugh,LB et. al. (1996)
m-Xylene	Conroe, Texas	Creosote waste site	Aquifer sediment	Lab microcosm		7	0.025-0.029/day		Wilson,JT et. al. (1986)
m-Xylene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.030/day		Wilson,JT et. al. (1983B)
m-Xylene	East Texas	Wood-creosoting plant	Aquifer sediment	Lab microcosm		84	0.030/day		Wilson,JT et. al. (1983B)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.033/day		Pugh,LB et. al. (1996)
Xylene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	285 ug/L	14	0.035/day		Chiang,CY et. al. (1986)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	216 ug/L	120	0.038/day	<7	American Petroleum Institute (1994A)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1.1 mg/L	63	0.048/day		Barker,JF et. al. (1987)
m-Xylene	Gloucester landfill, Ottawa, Canada	Landfill site	Aquifer sediment + groundwater	Lab microcosm			0.057/day		Berwanger,DJ & Barker,JF (1988)

Table 6. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	361 ug/L	50	0.058/day	<7	American Petroleum Institute (1994A)
m-Xylene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	200 ug/L	21	0.061/day		Thomas,JM et. al. (1990)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	290 ug/L	25	0.076/day	<7	American Petroleum Institute (1994A)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		16	0.077/day		Pugh,LB et. al. (1996)
m-Xylene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	210 ug/L	7	0.213/day		Thomas,JM et. al. (1990)
Xylene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L		0.25/day	5	Hunt,CS & Alvarez,PJJ (1997)
m-Xylene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	16	0.33/day		Borden,RC et. al. (1997)
m-Xylene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	10	0.53/day		Borden,RC et. al. (1997)
Xylene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	300 ug/L	7	0.56/day		Chiang,CY et. al. (1986)
m-Xylene	Granger, Indiana	Unleaded gasoline spill site	Aquifer sediment	Lab microcosm	250 ug/L	7	0.687/day		Thomas,JM et. al. (1990)
m-Xylene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	2 mg/L	7	0.76/day		Hutchins,SR (1991)
m-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	872 ug/L	278	No biodegradation		American Petroleum Institute (1994A)
m-Xylene	Conroe, Texas	Uncontaminated	Aquifer sediment	Lab microcosm		7	No biodegradation		Wilson,JT et. al. (1986)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	No biodegradation		Pugh,LB et. al. (1996)

3.1.6. p-Xylene

p-Xylene is moderately degradable in the presence of oxygen (Table 7). Degradation is thought to proceed via 3,6-dimethylcatechol to CO_2 (Gibson and Subramanian, 1984). 3.13 mg of oxygen are necessary to biodegrade 1 mg of p-xylene to CO_2 and water (Wiedemeier et. al., 1995).

As for the other BTEX compounds, most of the located data for p-xylene under aerobic conditions were for aquifer environments. Three field studies from two different locations reported the biodegradation of p-xylene giving half-life values ranging from 49 (Staffer et. al., 1994) to 231 days (American Petroleum Institute, 1994). No *in situ* microcosm studies were found for this compound.

By far the most common type of study used to observe the biodegradation of p-xylene under aerobic conditions is the laboratory microcosm. Half-lives ranging from 1 (Chiang et. al., 1986) to 28 (American Petroleum Institute, 1994A) days with an average value of 4.4 days were reported. Initial concentrations of up to 20 mg/L were reported in these experiments without obvious deleterious effect. In general, however, initial concentrations of less than 2 mg/L were utilized.

No biodegradation was reported for two microcosm studies. A study by the American Petroleum Institute, 1994A, reports that p-xylene was not biodegraded in the presence of 85% methanol over 278 days. This result was not unexpected as sufficient oxygen was available to degrade only 5% of the initially added methanol. In addition, the bacteria may have preferentially degraded the structurally simpler methanol or the concentration of methanol added may have been toxic to the indigenous bacterial population. Laboratory microcosms which contained double concentrations of nitrogen and phosphorus nutrients were able to significantly biodegrade a xylene mixture; however, unamended and single nutrient amendments to the microcosm were insufficient to encourage biodegradation of this mixture (Pugh et. al., 1996). Anid et. al. (1991) reports that columns supplemented with hydrogen peroxide but not columns supplemented with nitrate were able to degrade p-xylene. The nitrate-amended columns may have exhibited nitrate-reducing conditions as over 60 mg/L BTEX mixture was added. However, no attempt was made by the authors to distinguish through end product measurements whether conditions remained aerobic or became nitrate-reducing.

The median for the primary biodegradation rate constant of p-xylene, considering all studies, is 0.052/day (N = 27); a range of not biodegraded to 0.56/day is reported. The frequency distribution histogram for this data is shown in figure 6. p-Xylene is expected to biodegrade fairly readily under most aerobic environmental conditions.

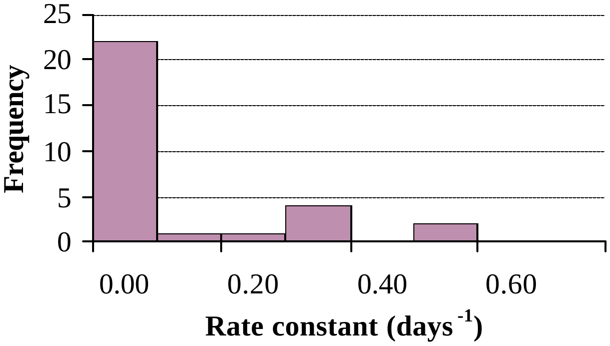

Figure 6. Frequency histogram for the published primary biodegradation rate constant values of p-xylene.

Table 7. Aerobic biodegradation rate constant values for p-xylene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.003/day		American Petroleum Institute (1994)
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.006/day		American Petroleum Institute (1994)
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field		476	0.007/day		American Petroleum Institute (1994)
p-Xylene	Columbus Air Force Base, Columbus, Miss.		Aquifer sediment + groundwater	Field		224	0.0141/day		Stauffer,TB et. al. (1994)
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field	1.08 mg/L	270	55 mg/day		Barker,JF et. al. (1987)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.056/day		Morgan,P et. al. (1993)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.060/day		Morgan,P et. al. (1993)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.065/day		Morgan,P et. al. (1993)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.088/day		Morgan,P et. al. (1993)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		0.10/day		Morgan,P et. al. (1993)

Table 7. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		37 ug/L/day		Morgan,P et. al. (1993)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		79 ug/L/day		Morgan,P et. al. (1993)
p-Xylene	Uiterburen, The Netherlands	Natural gas production site-BTEX contamination	Groundwater	Groundwater grab sample	310 ug/L		91 ug/L/day		Morgan,P et. al. (1993)
p-Xylene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	13 mg/L	4.6	0.350/day		Anid,PJ et. al. (1993)
p-Xylene			Aquifer sediment	Lab column	0.5 uM	17	Biodegrades		Kuhn,EP et. al. (1985)
p-Xylene	Northern Michigan	Gas plant facility	Aquifer sediment	Lab column	13 mg/L	4.6	No biodegradation		Anid,PJ et. al. (1993)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.00136/day		Pugh,LB et. al. (1996)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.00677/day		Pugh,LB et. al. (1996)
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	85 ug/L	120	0.025/day	<7	American Petroleum Institute (1994A)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.033/day		Pugh,LB et. al. (1996)
Xylene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	285 ug/L	14	0.035/day		Chiang,CY et. al. (1986)
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	133 ug/L	50	0.044/day	<7	American Petroleum Institute (1994A)

Table 7. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	143 ug/L	25	0.048/day	<7	American Petroleum Institute (1994A)
p-Xylene	Gloucester landfill, Ottawa, Canada	Landfill site	Aquifer sediment + groundwater	Lab microcosm	300 ug/L	21	0.057/day	5	Berwanger,DJ & Barker,JF (1988)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		16	0.077/day		Pugh,LB et. al. (1996)
Xylene	Santa Catarina Island, Brazil	Uncontaminated	Aquifer sediment	Lab microcosm	20 mg/L		0.25/day	5	Hunt,CS & Alvarez,PJJ (1997)
p-Xylene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	370 ug/L	14	0.30/day		Wilson,BH et. al. (1990)
p-Xylene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	16	0.33/day		Borden,RC et. al. (1997)
p-Xylene	Traverse City, MI	JP-4 jet fuel spill	Aquifer sediment	Lab microcosm	390 ug/L	14	0.382/day		Wilson,BH et. al. (1990)
p-Xylene	Sampson County, North Carolina	Gasoline contaminated site	Aquifer sediment	Lab microcosm	2 mg/L	10	0.53/day		Borden,RC et. al. (1997)
Xylene	Michigan	Gas plant facility	Aquifer sediment	Lab microcosm	300 ug/L	7	0.56/day		Chiang,CY et. al. (1986)
p-Xylene	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	319 ug/L	278	No biodegradation		American Petroleum Institute (1994A)
Xylene		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	No biodegradation		Pugh,LB et. al. (1996)

3.2. PAH (Polycyclic Aromatic Hydrocarbon) Compounds

PAH compounds are ubiquitous compounds in the environment due to their production during incomplete combustion and pyrolytic processes. In addition, effluents from wood-preserving (creosoting sites), refinery and oil waste, waste incineration, coal gasification and liquification, and coal tar distillation sites often provide high concentrations of PAH compounds (Cerniglia, 1992).

Structurally, PAHs are considered to have two or more fused benzene ring structures in various arrangements. This database includes several PAHs including naphthalene (2 rings), fluorene (3 rings), benzo(a)anthracene, chrysene, fluoranthene, and pyrene (4 rings), and benzo(a)pyrene (5 rings). Based on pure culture studies, bacterial biodegradation of PAHs is believed to proceed via oxidation of the ring structure using dioxygenase enzymes in the presence of molecular oxygen. The cis-dihydrodiol is then dehydrogenated forming the catechol which leaves the aromatic ring open to enzymatic cleavage by another dioxygenase activity (Cerniglia, 1992). The two hydroxyl groups must be located either *ortho* or *para* to each other for ring cleavage to occur.

The lower molecular weight PAH compounds are generally more rapidly degraded than the higher molecular weight PAH compounds. This was shown by Park et. al. (1990), in a study investigating the biodegradation of 14 PAH compounds in two different soils. Compounds with two or three rings were extensively degraded while, in general, compounds with four or five rings were resistant to biodegradation. Sorption of the PAH compound to the soil or sediment appears to strongly affect its ability to be biodegraded. Maliszewska-Kordybach (1998) examined the physical properties and their correlation to the biodegradation rate reported for four PAH compounds in ten different soils varying in pH and organic matter content. The length of time the PAH was in contact with the soil had a strong effect on the importance of the physical property/properties relationship to persistence. Initially, volatilization, reflected by Henry's Law constant was correlated to loss of the PAH in soil. However, over time, other properties such as water solubility and sorption became more important in determining the resistance of a particular PAH to degradation. Lower water solubilities were correlated to lower biodegradation rates. Sorption properties, however, showed the strongest influence in determining PAH persistence in soil.

Loehr and Webster (1996) reviewed the current literature examining the effect exposure time had on the biodegradation in soil of compounds ranging from chlorinated aliphatics to PAHs. They proposed that studies using soil freshly amended with a compound cannot fairly reflect the biodegradative ability of a compound which has been in contact with soil for a long period of time and has thus undergone weathering processes. Sorption of compounds mainly by soil organic matter has been indicated, with increasing organic matter generally resulting in increasing sorption (Manilal and Alexander, 1991; Maliszewska-Kordybach, 1998). It is believed that a compound in contact with soil for a long time will be more strongly sorbed, have a lesser ability to desorb and will be generally less bioavailable that a compound that was recently spiked into the same soil environment. This is reflected experimentally by an initial period of relatively rapid biodegradation followed by a phase of little to no further loss.

Keck et. al. (1989) looked at PAH disappearance as the single compound, in a defined mixture of PAH compounds, in oil refinery waste, and in a creosote wood-preserving waste. The degradation of 3-ring PAH compounds was similar in all four systems; however, PAH compounds with 4 or more rings were more rapidly degraded in the oil-refinery and the wood-preserving waste. This suggested to the authors that co-oxidation of these larger PAH compounds was occurring. Rates of biodegradation also appear to be higher in environments where the medium is contaminated when compared to sites which are initially pristine (Herbes and Schwall, 1978; Cerniglia, 1992).

3.2.1. Naphthalene

Naphthalene is a PAH with a 2-ring structure. In general, PAHs that contain three or fewer rings tend to be biodegraded more rapidly than compounds containing four or five benzene rings. First-order rate constants for naphthalene ranged from 0.0064/day to 5.0/day, with the majority of the values occurring between 0.1 to 1.0/day. These values correspond to half-lives of <1 to 108 days. The highest rate constant (5.0/day) resulted from polluted groundwater obtained downgradient from a landfill (Albrechtsen et. al., 1996) while the lowest rate constant was calculated from a field experiment in which naphthalene was injected into a series of wells and its concentration was measured over time (MacIntyre et. al., 1993). The primary biodegradation of naphthalene resulted in the following products: cis-1,2-dihydroxy-1,2-dihydronaphthalene, 1-naphthol, salicylic acid and catechol (Heitkamp & Cerniglia, 1987).

Naphthalene will be degraded rapidly by indigenous microorganisms in soils and groundwater that have previously been exposed to PAHs. The rate constant determined from sediment in an oil polluted stream was 3.36/day while the rate constant determined from sediment in a non-polluted stream was less than 0.0096/day (Herbes and Schwall, 1978) .

The median for the primary biodegradation rate constant of naphthalene is 0.308/day (N = 49); a range of 0 to 5.0/day is reported. The median for the mineralization rate constant of naphthalene is 0.023/day (N = 47); a range of 0 to 3.34/day is reported. The frequency distribution histograms for this data are shown in figures 7a and 7b.

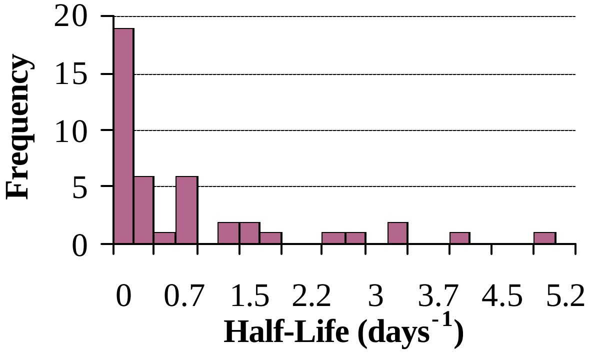

Figure 7a. Frequency distribution histogram for the published primary biodegradation rate constant values of naphthalene.

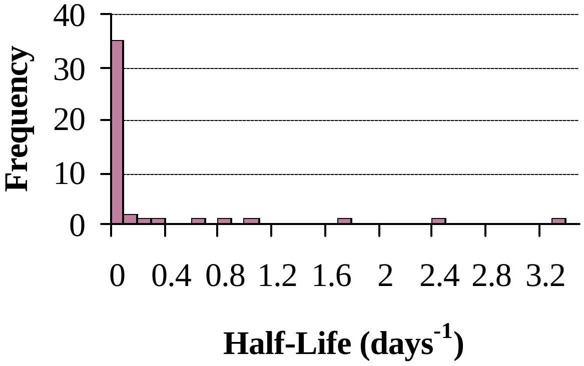

Figure 7b. Frequency distribution histogram for the published mineralization rate constant values of naphthalene.

Table 8. Aerobic biodegradation rate constant values for naphthalene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Columbus AFB, Mississippi	Aquifer	Aquifer sediment + groundwater	Field	7.23 mg/L	440	0.0064/day		MacIntyre,WG et. al. (1993)
Naphthalene	Grindsted, Denmark	Landfill	Groundwater	Groundwater grab sample	100 ug/L	50	0.028/day		Albrechtsen,HJ et. al. (1996)
Naphthalene	Vejen, Denmark	Landfill	Groundwater	Groundwater grab sample	100 ug/L	10	0.56/day		Albrechtsen,HJ et. al. (1996)
Naphthalene	Gainesville, Florida	Groundwater	Groundwater	Groundwater grab sample	1.5 mg/L	8	0.77/day	5	Delfino,JJ & Miles,CJ (1985)
Naphthalene	Denmark		Groundwater	Groundwater grab sample	200-1000 ug/L	4.1	1.29-1.68/day		Arvin,E et. al. (1988)
Naphthalene	Grindsted, Denmark	Heavy oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	4.4	1.44-1.57/day		Arvin,E et. al. (1988)
Naphthalene	Vejen, Denmark	Landfill	Groundwater + sterile quartz	Groundwater grab sample	100 ug/L	10	2.5/day		Albrechtsen,HJ et. al. (1996)
Naphthalene	Horsholm, Denmark	Gasoline contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	2.1	2.96-3.29/day		Arvin,E et. al. (1988)
Naphthalene	Ganlose, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	1.5	4.14-4.61/day		Arvin,E et. al. (1988)
Naphthalene	Grindsted, Denmark	Heavy oil contamination	Groundwater	Groundwater grab sample			4/day		Arvin,E et. al. (1988)
Naphthalene	Vejen, Denmark	Landfill	Groundwater + sterile rock wool	Groundwater grab sample	100 ug/L	10	5.0/day		Albrechtsen,HJ et. al. (1996)
Naphthalene	Gassehaven, Denmark	Fuel oil contamination	Groundwater	Groundwater grab sample	500-1000 ug/L	1.2	5.18-5.76/day		Arvin,E et. al. (1988)
Naphthalene	Vejen, Denmark	Landfill	Groundwater	Groundwater grab sample	160 ug/L	90	7-13 ug/L/day	15	Holm,PE et. al. (1992)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	15	0.069/day		Nielsen,PH & Christensen,TH (1994)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	150	0.2/day and 0.9/day	6-12	Nielsen,PH et. al. (1996)
Naphthalene	Vejen, Denmark	Landfill	Groundwater	In situ microcosm	120 ug/L	90	0.5-0.8 ug/L/day		Holm,PE et. al. (1992)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Vejen City, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.8/day	6	Bjerg,PL et. al. (1996)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	150	0.8/day	6	Nielsen,PH et. al. (1996)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	In situ microcosm	120 ug/L	90	1.5-2.0 ug/L/day		Holm,PE et. al. (1992)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.00048-0.0022/day		Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.00073-0.010/day		Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.001/day		Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0015/day	6	Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.002-0.0068/day		Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0022/day	12	Durant,ND et. al. (1995)
Naphthalene	Narragansett Bay, Rhode Island	Uncontaminated	Seawater	Lab microcosm	50 ug/L		0.0022/day		Lee,RF & Ryan,C (1983)
Naphthalene	Narragansett Bay, Rhode Island	Uncontaminated	Seawater	Lab microcosm	25 ug/L		0.0023/day		Lee,RF & Ryan,C (1983)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0032/day	6	Durant,ND et. al. (1995)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0039-0.0085/day		Durant,ND et. al. (1995)
Naphthalene	Skidaway River, Savannah, Georgia	Oil-contamination	River water	Lab microcosm	2.5 ug/L		0.0039/day		Lee,RF & Ryan,C (1983)
Naphthalene		Manufactured gas plant	Soil	Lab microcosm	0.36 ug/g	3	0.00432 ug/g/day		Fleming,JT et. al. (1993)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0051/day	6	Durant,ND et. al. (1995)
Naphthalene	Narragansett Bay, Rhode Island	Uncontaminated	Seawater	Lab microcosm	10 ug/L		0.0055/day		Lee,RF & Ryan,C (1983)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0065/day		Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.0065/day		Durant,ND et. al. (1995)
Naphthalene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	1 mg/kg	77	0.007/day	7	Mueller,JG et. al. (1991A)
Naphthalene	Conroe, Texas	Landfill	Aquifer sediment + groundwater	Lab microcosm		56	0.0073/day		Wilson,JT et. al. (1985)
Naphthalene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	1 mg/kg	84	0.011/day		Mueller,JG et. al. (1991A)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.011/day		Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.011/day		Durant,ND et. al. (1995)
Naphthalene		Uncontaminated	Soil	Lab microcosm	12 mg/kg soil	130	0.016/day	75	Pott,BM & Henrysson,T (1995)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.021/day		Durant,ND et. al. (1995)
Naphthalene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	3924.5 mg/kg	84	0.022/day		Mueller,JG et. al. (1991A)
Naphthalene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	300 mg/kg	28	0.022/day		Ellis,B et. al. (1991)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.023/day		Durant,ND et. al. (1995)
Naphthalene	Degray Resevoir, Arkansas	Unpolluted freshwater reservoir	Lake water + sediment	Lab microcosm	500 ng/g	56	0.023/day		Heitkamp,MA & Cerniglia,CE (1987)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.026/day	6	Durant,ND et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	0.030/day		Durant,ND et. al. (1995)
Naphthalene	Lake Chicot, Arkansas	Freshwater lake	Lake water + sediment	Lab microcosm	500 ng/g	56	0.030/day		Heitkamp,MA & Cerniglia,CE (1987)
Naphthalene		Plasticizer manufacturing site	Soil	Lab microcosm	340 mg/kg	42	0.035/day		Fogel,S et. al. (1995)
Naphthalene	Marquette, Michigan	Aquifer near a charcoal manufacturing plant	Aquifer sediment + groundwater	Lab microcosm	500 ug/L	24	0.038/day		Klecka,GM et. al. (1990)
Naphthalene	Georgia coast	Seawater	Seawater	Lab microcosm	130 ppb	1	0.04 ug/L/day		Lee,RF & Ryan,C (1979)
Naphthalene	Redfish Bay, Texas	Estuary	Estuarine water + sediment	Lab microcosm	500 ng/g	56	0.040/day		Heitkamp,MA & Cerniglia,CE (1987)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm			0.041/day		Mueller,JG et. al. (1991A)
Naphthalene	Tamar Estuary, England	Estuary	Estuarine water + sediment	Lab microcosm	3 ug/L	1	0.041/day		Readman,JW et. al. (1982)
Naphthalene	Tamar Estuary, England	Estuary	Estuarine water + sediment	Lab microcosm	3 ug/L	1	0.041/day		Readman,JW et. al. (1982)
Naphthalene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	300 mg/kg	63	0.043/day		Ellis,B et. al. (1991)
Naphthalene	Marquette, Michigan	Aquifer near a charcoal manufacturing plant	Aquifer sediment + groundwater	Lab microcosm	500 ug/L	24	0.043/day		Klecka,GM et. al. (1990)
Naphthalene	Lula, Oklahoma	Aquifer	Soil	Lab microcosm	0.01-622 ug/g		0.044/day		Swindoll,CM et. al. (1988)
Naphthalene		Uncontaminated	Soil	Lab microcosm	12 mg/kg soil	80	0.046/day		Pott,BM & Henrysson,T (1995)
Naphthalene		Plasticizer manufacturing site	Soil	Lab microcosm	3800 mg/kg	98	0.049/day		Fogel,S et. al. (1995)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	40 ppb	2	0.05 ug/L/day		Lee,RF & Ryan,C (1979)
Naphthalene	Cooper River, Charleston, South Carolina	Oil-contamination	River water	Lab microcosm	2.5 ug/L		0.05/day		Lee,RF & Ryan,C (1983)
Naphthalene	Tamar Estuary, England	Estuary	Estuarine water + sediment	Lab microcosm	3 ug/L	1	0.055/day		Readman,JW et. al. (1982)
Naphthalene	Marquette, Michigan	Aquifer near a charcoal manufacturing plant	Aquifer sediment + groundwater	Lab microcosm	500 ug/L	24	0.063/day		Klecka,GM et. al. (1990)
Naphthalene	Saucon Creek, Bethlehem, Pennsylvania	Polluted stream	Stream water	Lab microcosm		4	0.077/day		Herbes,SE (1981)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	30 ug/L	1	0.07ug/L/day		Lee,RF (1977)
Naphthalene	Grindsted, Denmark	Landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	20	0.089/day		Albrechtsen,HJ et. al. (1996)
Naphthalene	Narragansett Bay, Rhode Island	Oil-contamination	Seawater	Lab microcosm	50 ug/L		0.099/day		Lee,RF & Ryan,C (1983)
Naphthalene	Skidaway River, Savannah, Georgia	Oil-contamination	River water	Lab microcosm	2.5 ug/L		0.099/day		Lee,RF & Ryan,C (1983)
Naphthalene		Coal-tar contaminated	Soil	Lab microcosm	186 mg/kg soil	105	0.10/day		Wischmann,H & Steinhart,H (1997)
Naphthalene		Plasticizer manufacturing site	Soil	Lab microcosm	1018 mg/kg	49	0.12/day		Fogel,S et. al. (1995)
Naphthalene	Narragansett Bay, Rhode Island	Oil-contamination	Seawater	Lab microcosm	25 ug/L		0.14/day		Lee,RF & Ryan,C (1983)
Naphthalene	Narragansett Bay, Rhode Island	Oil-contamination	Seawater	Lab microcosm	10 ug/L		0.17/day		Lee,RF & Ryan,C (1983)
Naphthalene	Lincolnshire, UK	Unpolluted soil	Soil	Lab microcosm	0.5 mg/g		0.20/day		Smith,MJ et. al. (1997)
Naphthalene	Sufflok, UK	Unpolluted sand	Soil	Lab microcosm	0.5 mg/g		0.20/day		Smith,MJ et. al. (1997)
Naphthalene	Uttar Pradesh, India	Soil receiving effluent from an oil refinery	Soil	Lab microcosm	20 mg/kg	60	0.23/day		Ashok,BT et. al. (1995)
Naphthalene	Hudson River Estuary, New York	Estuary	Estuarine water	Lab microcosm	1 ug/L	2	0.26/day		Hudak,JP et. al. (1988)
Naphthalene	Mississippi	Uncontaminated	Soil	Lab microcosm	101 mg/kg	105	0.308/day		Park,KS et. al. (1990)
Naphthalene	Paleudult, Mississippi	Pristine soil	Soil	Lab microcosm	101 mg/kg	105	0.308/day		Park,KS et. al. (1990)
Naphthalene	Calciaquoll, Utah	Pristine soil	Soil	Lab microcosm	101 mg/kg	196	0.337/day		Park,KS et. al. (1990)
Naphthalene	Utah	Uncontaminated	Soil	Lab microcosm	101 mg/kg	196	0.3370/day		Park,KS et. al. (1990)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Skidaway River, Savannah, Georgia	Oil-contamination	River water	Lab microcosm	2.5 ug/L		0.35/day		Lee,RF & Ryan,C (1983)
Naphthalene	Cass County, North Dakota	Agricultural soil	Soil	Lab microcosm	7 mg/L	10	0.39/day		Mihelcic,JR & Luthy,RG (1988)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	Lab microcosm	150 ug/L	150	0.4/day	10	Nielsen,PH et. al. (1996)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	15 ug/L	1	0.42 ug/L/day		Lee,RF (1977)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	40 ppb	0.33	0.56 ug/L/day		Lee,RF & Ryan,C (1975)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	30 ug/L	1	0.68 ug/L/day		Lee,RF (1977)
Naphthalene	Tamar Estuary, England	Estuary	Estuarine water + sediment	Lab microcosm	3 ug/L	1	0.693/day		Readman,JW et. al. (1982)
Naphthalene	Unspecified site	Polluted pond	Pond water + sediment	Lab microcosm	10 mg/L	2	0.77/day		Meyer,JS et. al. (1984)
Naphthalene	Unspecified site	Polluted pond	Pond water + sediment	Lab microcosm	10 mg/L	10	0.77/day	8	Meyer,JS et. al. (1984)
Naphthalene	Tamar Estuary, England	Estuary	Estuarine water + sediment	Lab microcosm	3 ug/L	1	0.80/day		Readman,JW et. al. (1982)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	30 ug/L	1	0.82 ug/L/day		Lee,RF (1977)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	Lab microcosm	150 ug/l	150	0.9/day	8-9	Nielsen,PH et. al. (1996)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	40 ppb	1	0.90 ug/L/day		Lee,RF & Ryan,C (1975)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	60 ug/L	1	1.2 ug/L/day		Lee,RF (1977)
Naphthalene		Manufactured gas plant	Soil	Lab microcosm	0.36 ug/g	3	1.22 ug/g/day		Fleming,JT et. al. (1993)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Long Island Sound, New York	Estuary	Estuarine water	Lab microcosm	1 ug/L	2	1.63/day		Hudak,JP et. al. (1988)
Naphthalene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	28.7 ug/L	14	1.85/day		Mueller,JG et. al. (1991)
Naphthalene	Saucon Creek, Bethlehem, Pennsylvania	Polluted stream	Sediment	Lab microcosm	1 ug/g	24	1.87/day		Herbes,SE (1981)
Naphthalene	Tamar Estuary, England	Estuary	Estuarine water + sediment	Lab microcosm	3 ug/L	1	1/day		Readman,JW et. al. (1982)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	Lab microcosm	160 ug/L	90	12-13 ug/L/day	15	Holm,PE et. al. (1992)
Naphthalene		Creosote contaminated soil	Soil	Lab microcosm	0.36 ug/g	3	18.7 ug/g/day		Fleming,JT et. al. (1993)
Naphthalene	Hudson River Estuary, New York	Estuary	Estuarine water	Lab microcosm	1 ug/L	2	2.4/day		Hudak,JP et. al. (1988)
Naphthalene	Cooper River, South Carolina	Estuary	Estuarine water	Lab microcosm	30 ug/L	1	2.8 ug/L/day		Lee,RF (1977)
Naphthalene	Fort Point Channel, Boston Harbor	Estuary	Sediment	Lab microcosm	20 ng/g	2.5	2277.6 ng/g/day		Shiaris,MP (1989)
Naphthalene	Weymouth Back River, Boston Harbor	Estuary	Sediment	Lab microcosm	20 ng/g	2.5	27.84 ng/g/day		Shiaris,MP (1989)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	Lab microcosm	100 ug/L	10	3.3/day		Albrechtsen,HJ et. al. (1996)
Naphthalene	Knoxville, Tennessee	Oil-contaminated stream	Sediment	Lab microcosm		2	3.36/day		Herbes,SE & Schwall,LR (1978)
Naphthalene	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	130 ppb	1	4.4 ug/L/day		Lee,RF & Ryan,C (1975)

Table 8. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Naphthalene	Cooper River, South Carolina	Estuary	Estuarine water	Lab microcosm	60 ug/L	1	4.7 ug/L/day		Lee,RF (1977)
Naphthalene	Lower Neck Quincy Bay, Boston Harbor	Estuary	Sediment	Lab microcosm	20 ng/g	2.5	41.28 ng/g/day		Shiaris,MP (1989)
Naphthalene	Conroe, Texas	Landfill	Aquifer sediment + groundwater	Lab microcosm	200 ug/L	8	67.2 ug/L/day		Thomas,JM et. al. (1986)
Naphthalene		Manufactured gas plant	Soil	Lab microcosm	0.36 ug/g	3	7.7X10-4 ug/g/day		Fleming,JT et. al. (1993)
Naphthalene	Vejen, Denmark	Landfill	Aquifer sediment + groundwater	Lab microcosm	160 ug/L	90	9-10 ug/L/day	15	Holm,PE et. al. (1992)
Naphthalene	Walker Branch, Oakridge, Tennessee	Non-polluted stream	Sediment	Lab microcosm		5	< 0.0096/day		Herbes,SE & Schwall,LR (1978)
Naphthalene	Conroe, Texas	Landfill	Aquifer sediment + groundwater	Lab microcosm		56	> 0.32/day		Wilson,JT et. al. (1985)
Naphthalene	Conroe, Texas	Landfill	Aquifer sediment + groundwater	Lab microcosm		56	> 0.51/day		Wilson,JT et. al. (1985)
Naphthalene		Plasticizer manufacturing site	Soil	Lab microcosm	34-35 mg/kg	63	No biodegradation		Fogel,S et. al. (1995)
Naphthalene	Baltimore Gas & Electric Spring Gardens	Former manufactured gas plant facility	Aquifer sediment	Lab microcosm	4 mg/L	42	No mineralization		Durant,ND et. al. (1995)

3.2.2. Fluorene

Fluorene is a PAH with a 3-ring structure, that is virtually insoluble in water. In general, PAHs that contain three or fewer rings tend to be biodegraded more rapidly than compounds containing four or five benzene rings. First-order rate constants were in the range of 0.0018/day to 0.33/day, corresponding to half-lives of about 2 to 385 days. The smallest rate constant was observed in a pristine soil with no history of pollution (Park et. al., 1990), while the largest rate constant was observed in creosote-contaminated aquifer material obtained from a wood preserving site (Mueller et. al., 1991). One study reported 9-fluorenone as a primary biodegradation product of fluorene (Wischmann and Steinhart, 1997).

The median for the primary biodegradation rate constant of fluorene is 0.015/day (N = 28); a range of 0.0018 to 0.33/day is reported. The median for the mineralization rate constant of fluorene is 0.019/day (N = 7); a range of 0.00385 to 0.05/day is reported. The frequency distribution histograms for this data are shown in figures 8a and 8b. For the most part, fluorene is expected to biodegrade slowly under aerobic conditions in the environment.

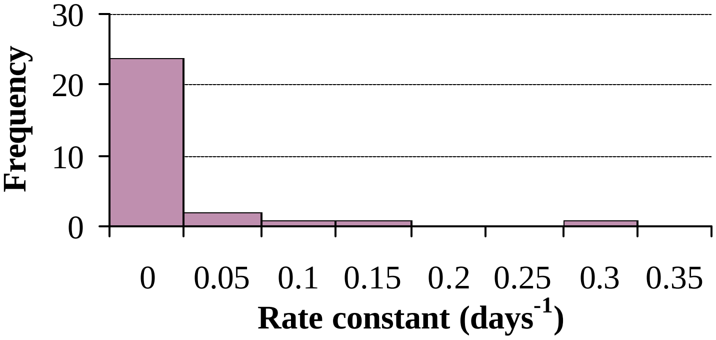

Figure 8a. Frequency distribution histogram for the published primary biodegradation rate constant values of fluorene.

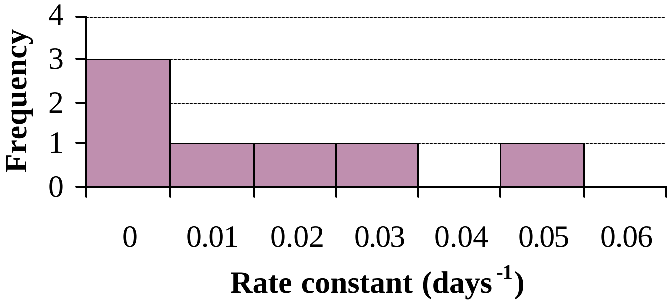

Figure 8b. Frequency distribution histogram for the published mineralization rate constant values of fluorene

Table 9. Aerobic biodegradation rate constant values for fluorene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Fluorene	Brookhaven, Mississippi	Wood-preserving site	Soil	Field	225 ug/g	56	0.025/day		Lamar,RT & Glaser,JA (1994)
Fluorene	Calciaquoll, Utah	Pristine soil	Soil	Lab microcosm	883 mg/kg	196	0.0018/day		Park,KS et. al. (1990)
Fluorene	Paleudult, Mississippi	Pristine soil	Soil	Lab microcosm	913 mg/kg	105	0.0026/day		Park,KS et. al. (1990)
Fluorene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	1792.1 mg/kg	84	0.003/day		Mueller,JG et. al. (1991A)
Fluorene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.00385/day		Lee,RF & Ryan,C (1983)
Fluorene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	1792.1 mg/kg	84	0.004/day		Mueller,JG et. al. (1991A)
Fluorene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	3.1 mg/kg	84	0.004/day		Mueller,JG et. al. (1991A)
Fluorene	Musi River, India	Hazardous waste site	Soil	Lab microcosm	1000 ppm	450	0.0041/day		Mahmood,SK & Rao,PR (1993)
Fluorene	Skidaway Institute of Oceanography, GA	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment	3	0.006/day		Lee,RF & Silva,M (1994)
Fluorene	Montreal, Quebec	Uncontaminated	Soil	Lab microcosm	100 mg/L	120	0.0069/day		Leduc,R et. al. (1992)
Fluorene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	29 ug/g		0.007/day		Keck,J et. al. (1989)
Fluorene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	124 mg/kg	28	0.0071/day		Ellis,B et. al. (1991)
Fluorene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	124 mg/kg	63	0.0073/day		Ellis,B et. al. (1991)
Fluorene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.00845/day		Lee,RF & Ryan,C (1983)
Fluorene		Coal-tar contaminated	Soil	Lab microcosm	198 mg/kg soil	175	0.0085/day		Wischmann,H & Steinhart,H (1997)
Fluorene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0099/day		Maliszewska-Kordybach,B (1993)

Table 9. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Fluorene	Conroe, Texas	Landfill	Aquifer sediment + groundwater	Lab microcosm		56	0.012/day		Wilson,JT et. al. (1985)
Fluorene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	100 ug/g	240	0.012/day		Coover,MP & Sims,RC (1987)
Fluorene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	100 ug/g	240	0.015/day		Coover,MP & Sims,RC (1987)
Fluorene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	100 ug/g		0.015/day		Keck,J et. al. (1989)
Fluorene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	3.1 mg/kg	84	0.019/day		Mueller,JG et. al. (1991A)
Fluorene	Narragansett Bay, Rhode Island	Uncontaminated	Sediment	Lab microcosm	1 ug/g sediment		0.019/day		Lee,RF & Ryan,C (1983)
Fluorene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.022/day		Maliszewska-Kordybach,B (1993)
Fluorene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	100 ug/g	240	0.022/day		Coover,MP & Sims,RC (1987)
Fluorene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.025/day		Maliszewska-Kordybach,B (1993)
Fluorene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	5 ug/g sediment		0.025/day		Lee,RF & Ryan,C (1983)
Fluorene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	180 ug/g		0.027/day		Keck,J et. al. (1989)
Fluorene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0277/day		Maliszewska-Kordybach,B (1993)
Fluorene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.029/day		Maliszewska-Kordybach,B (1993)
Fluorene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0335/day		Maliszewska-Kordybach,B (1993)
Fluorene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.035/day		Lee,RF & Ryan,C (1983)

Table 9. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Fluorene	Skidaway Institute of Oceanography, GA	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment	3	0.05/day		Lee,RF & Silva,M (1994)
Fluorene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	181 mg/kg soil	77	0.061/day		Deschenes,L et. al. (1996)
Fluorene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	1 ug/g sediment		0.063/day		Lee,RF & Ryan,C (1983)
Fluorene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	240 mg/kg soil	14	0.11/day		Deschenes,L et. al. (1995)
Fluorene	Conroe, Texas	Landfill	Aquifer sediment + groundwater	Lab microcosm		56	0.18/day		Wilson,JT et. al. (1985)
Fluorene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	11.6 ug/mL	14	0.33/day		Mueller,JG et. al. (1991)

3.2.3. Benzo(a)anthracene

Benzo(a)anthracene is a PAH with a 4-ring structure, that is virtually insoluble in water. In general, PAHs that contain more than 3 rings tend to be biodegraded rather slowly in the environment. First-order rate constants were in the range of 0.000033/day to 0.116/day, corresponding to half-lives of about 6 to 21,000 days. The majority of the rate constants were less than 0.01/day. There were also several studies for which no rate constant was reported or could be calculated since the compound was not observed to biodegrade during the course of the study. This included an experiment where no measurable biodegradation was observed in a coal-tar polluted soil over a 80 day incubation period (Grosser et. al., 1995). Similar results were obtained from other studies with shorter incubation periods (Carmichael and Pfaender, 1997; Lee et. al., 1978; Herbes, 1981). Biodegradation reaction products were reported as benzo(a)anthracene-7,12-dione (Wischmann and Steinhart, 1997) and unspecified phenol and quinone metabolites (Hinga et. al., 1980).

The median for the primary biodegradation rate constant of benzo(a)anthracene, considering all studies, is 0.0035/day (N = 27); a range of 0.000096 to 0.072/day is reported. The median for the mineralization rate constant of benzo(a)anthracene is 0.0029/day (N = 32); a range of not biodegraded to 0.116/day is reported. The frequency distribution histograms for the data are shown in figures 9a and 9b. For the most part, benzo(a)anthracene is expected to biodegrade slowly under aerobic conditions or be recalcitrant in the environment.

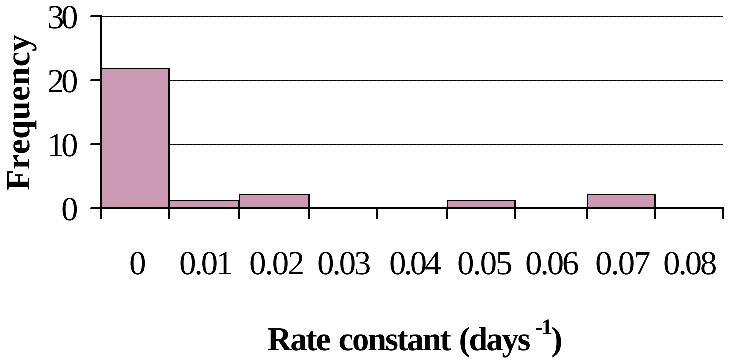

Figure 9a. Frequency distribution histogram for the published primary biodegradation rate constant values of benzo(a)anthracene.

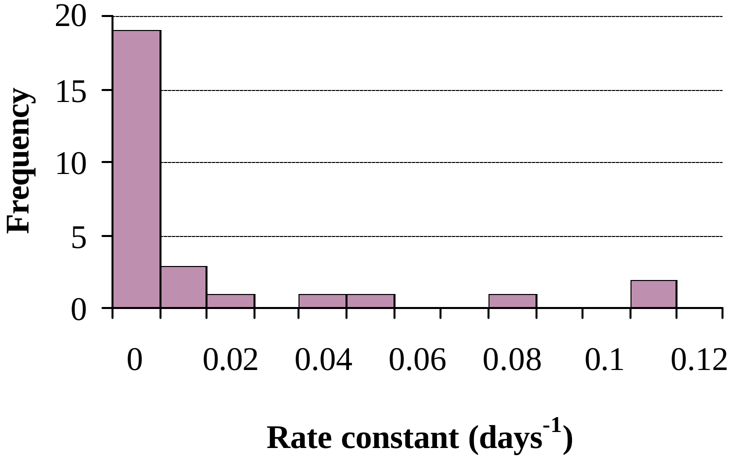

Figure 9b. Frequency distribution histogram for the published mineralization rate constant values of benzo(a)anthracene.

Table 10. Aerobic biodegradation rate constant values for benzo(a)anthracene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)anthracene	Brookhaven, Mississippi	Wood-preserving site	Soil	Field	74 ug/g	56	0.0021/day		Lamar,RT & Glaser,JA (1994)
Benzo(a)anthracene	Wiroa Island, Auckland, New Zealand	Uncontaminated	Sediment	Field		256	<0.00693/day		Wilcock,RJ et. al. (1996)
Benzo(a)anthracene	Narragansett Bay, Rhode Island	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment		0.000033/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Walker Branch, Oak Ridge, Tennessee	Uncontaminated	Sediment	Lab microcosm		26	0.000096/day		Herbes,SE & Schwall,LR (1978)
Benzo(a)anthracene	Narragansett Bay, Rhode Island	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment		0.00029/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene		Uncontaminated	Soil	Lab microcosm		480	0.0005/day	120	Bossert,ID & Bartha,R (1986)
Benzo(a)anthracene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	1.2 ng/g	80	0.0006/day		Grosser,RJ et. al. (1995)
Benzo(a)anthracene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	1.2 ng/g	80	0.0006/day		Grosser,RJ et. al. (1995)
Benzo(a)anthracene	Narragansett Bay, Rhode Island	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment		0.00063/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	11.9 mg/kg	84	0.001/day		Mueller,JG et. al. (1991A)
Benzo(a)anthracene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	30.1 ug/g	240	0.001/day		Coover,MP & Sims,RC (1987)
Benzo(a)anthracene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	1.2 ng/g	80	0.0015-0.0058/day		Grosser,RJ et. al. (1995)
Benzo(a)anthracene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.0015/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	30.1 ug/g	240	0.0016/day		Coover,MP & Sims,RC (1987)

Table 10. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)anthracene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	214 ng/g	56	0.0019/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.002/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	30.1 ug/g		0.002/day		Keck,J et. al. (1989)
Benzo(a)anthracene	Calciaquoll, Utah	Pristine soil	Soil	Lab microcosm	33 mg/kg	196	0.0022/day		Park,KS et. al. (1990)
Benzo(a)anthracene		Uncontaminated	Soil	Lab microcosm	21.5 mg/kg soil	175	0.0023/day	80	Pott,BM & Henrysson,T (1995)
Benzo(a)anthracene	Knoxville, Tennessee	Oil contaminated	Sediment	Lab microcosm		26	0.0024/day		Herbes,SE & Schwall,LR (1978)
Benzo(a)anthracene	Calciaquoll, Utah	Pristine soil	Soil	Lab microcosm	107 mg/kg	196	0.0026/day		Park,KS et. al. (1990)
Benzo(a)anthracene	Utah	Uncontaminated	Soil	Lab microcosm	107 mg/kg	196	0.0026/day		Park,KS et. al. (1990)
Benzo(a)anthracene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	30.1 ug/g	240	0.0029/day		Coover,MP & Sims,RC (1987)
Benzo(a)anthracene	Skidaway Institute of Oceanography, GA	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment	3	0.0029/day		Lee,RF & Silva,M (1994)
Benzo(a)anthracene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	22.6 mg/kg	84	0.003/day		Mueller,JG et. al. (1991A)
Benzo(a)anthracene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	107 ug/g		0.003/day		Keck,J et. al. (1989)
Benzo(a)anthracene	Paleudult, Mississippi	Pristine soil	Soil	Lab microcosm	33 mg/kg	105	0.0030/day		Park,KS et. al. (1990)
Benzo(a)anthracene	Central Narragansett Bay	Uncontaminated	Seawater + sediment	Lab microcosm		230	0.0035/day		Hinga,KR et. al. (1980)
Benzo(a)anthracene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	22.6 mg/kg	84	0.004/day		Mueller,JG et. al. (1991A)

Table 10. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)anthracene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	11.9 mg/kg	84	0.004/day		Mueller,JG et. al. (1991A)
Benzo(a)anthracene	Mississippi	Uncontaminated	Soil	Lab microcosm	99 mg/kg	105	0.0043/day		Park,KS et. al. (1990)
Benzo(a)anthracene	Paleudult, Mississippi	Pristine soil	Soil	Lab microcosm	99 mg/kg	105	0.0043/day		Park,KS et. al. (1990)
Benzo(a)anthracene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	1.2 ng/g	80	0.0045-0.012/day		Grosser,RJ et. al. (1995)
Benzo(a)anthracene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.0058/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	128 mg/kg soil	315	0.0073/day		Deschenes,L et. al. (1996)
Benzo(a)anthracene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	180 mg/kg soil	315	0.0076/day		Deschenes,L et. al. (1995)
Benzo(a)anthracene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	53 ug/g		0.008/day		Keck,J et. al. (1989)
Benzo(a)anthracene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	214 ng/g	56	0.009/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	214 ng/g	56	0.009/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	130.1 ug/g		0.009/day		Keck,J et. al. (1989)
Benzo(a)anthracene	Reilly Tar & Chemical,St. Louis Park, MN	Contaminated	Soil	Lab microcosm	214 ng/g	56	0.0091/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	214 ng/g	56	0.012/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Dubose Oil Recycling, Cantonment, FL	Contaminated	Soil	Lab microcosm	214 ng/g	56	0.014/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene		Uncontaminated	Soil	Lab microcosm	24 mg/kg soil	130	0.016/day		Pott,BM & Henrysson,T (1995)

Table 10. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)anthracene	Skidaway Institute of Oceanography, GA	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment	3	0.019/day		Lee,RF & Silva,M (1994)
Benzo(a)anthracene	Reilly Tar & Chemical,St. Louis Park, MN	Contaminated	Soil	Lab microcosm	214 ng/g	56	0.022/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Central Narragansett Bay	Uncontaminated	Seawater + sediment	Lab microcosm	270 ng/L	202	0.024/day		Hinga,KR & Pilson,MEQ (1987)
Benzo(a)anthracene		Uncontaminated	Soil	Lab microcosm	23 mg/kg soil	130	0.027/day	20	Pott,BM & Henrysson,T (1995)
Benzo(a)anthracene	Cooper River, Charleston, South Carolina	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.043/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Dubose Oil Recycling, Cantonment, FL	Contaminated	Soil	Lab microcosm	214 ng/g	56	0.05/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	2.9 ug/mL	14	0.052/day		Mueller,JG et. al. (1991)
Benzo(a)anthracene	Saucon Creek, Bethlehem, PA	Contaminated	Sediment	Lab microcosm	1 ug/g sediment	4	0.072/day		Herbes,SE (1981)
Benzo(a)anthracene	Saucon Creek, Bethlehem, PA	Uncontaminated	Sediment	Lab microcosm	1 ug/g sediment	4	0.072/day		Herbes,SE (1981)
Benzo(a)anthracene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	5 ug/g sediment		0.087/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	1 ug/g sediment		0.116/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.116/day		Lee,RF & Ryan,C (1983)
Benzo(a)anthracene		Coal-tar contaminated	Soil	Lab microcosm	<0.2 mg/kg soil	175	Biodegrades		Wischmann,H & Steinhart,H (1997)

Table 10. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)anthracene	Alaskan continental shelf	Uncontaminated	Seawater + sediment	Lab microcosm		42	No mineralization		Roubal,G & Atlas,RM (1978)
Benzo(a)anthracene	Bozeman, MT	Pristine soil	Soil	Lab microcosm	214 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Bozeman, Montana	Uncontaminated	Soil	Lab microcosm	214 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)anthracene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	1.2 ng/g	80	No mineralization		Grosser,RJ et. al. (1995)
Benzo(a)anthracene	Saanich Inlet, western Canada	Uncontaminated	Seawater + sediment	Lab microcosm		3	No mineralization		Lee,RF et. al. (1978)
Benzo(a)anthracene	Saanich Inlet, western Canada	Uncontaminated	Seawater + sediment	Lab microcosm		3	No mineralization		Lee,RF et. al. (1978)
Benzo(a)anthracene	Saucon Creek, Bethlehem, PA	Contaminated	Creek water	Lab microcosm		4	No mineralization		Herbes,SE (1981)

3.2.4. Chrysene

Chrysene is a PAH with a 4-ring structure, that is virtually insoluble in water. In general, PAHs that contain more than 3 rings tend to be biodegraded rather slowly in the environment. First-order rate constants were in the range of 0.0005/day to 0.037/day, corresponding to half-lives of about 19 to 1,400 days. The majority of the rate constants were smaller than 0.01/day. There were also several studies for which no rate constant was reported or could be calculated since the compound was not observed to biodegrade during the course of the study. This included an experiment where no measurable biodegradation was observed in an uncontaminated soil over a 56-day incubation period (Carmichael and Pfaender, 1997). Similar results were obtained from other studies with shorter incubation periods (Ellis et. al., 1991; Hungspreugs et. al., 1984). No reaction products were reported for the degradation of chrysene.

The median for the primary biodegradation rate constant of chrysene is 0.003/day (N = 31); a range of not biodegraded to 0.037/day is reported. The median for the mineralization rate constant of chrysene is 0.0037/day (N = 20); a range from not biodegraded to 0.035/day is reported. The frequency distribution histograms for this data are shown in figures 10a and 10b. Chrysene is expected to biodegrade slowly under aerobic conditions or to be recalcitrant in the environment.

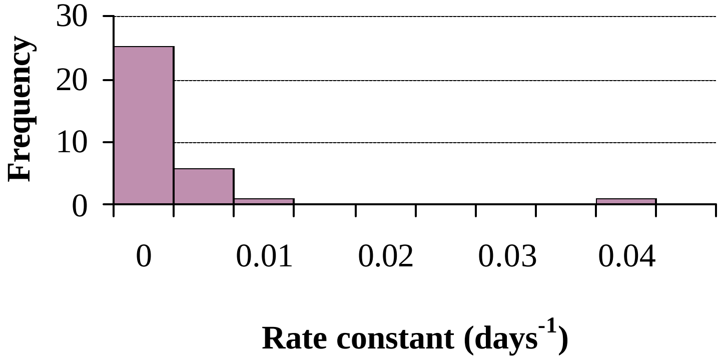

Figure 10a. Frequency distribution histogram for the published primary biodegradation rate constant values of chrysene.

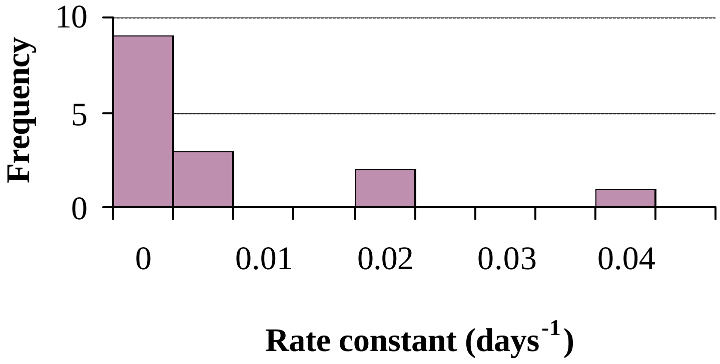

Figure 10b. Frequency distribution histogram for the published mineralization rate constant values of chrysene.

Table 11. Aerobic biodegradation rate constant values for chrysene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Chrysene	Brookhaven, Mississippi	Wood-preserving site	Soil	Field	90 ug/g	56	0.0011/day		Lamar,RT & Glaser,JA (1994)
Chrysene	Wiroa Island, Auckland, New Zealand	Uncontaminated	Sediment	Field		256	<0.00693/day		Wilcock,RJ et. al. (1996)
Chrysene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.0005/day		Lee,RF & Ryan,C (1983)
Chrysene	Uttar Pradesh, India	Soil receiving effluent from an oil refinery	Soil	Lab microcosm	20 mg/kg	90	0.00068/day		Ashok,BT et. al. (1995)
Chrysene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	200 ug/g		0.000693/day		Keck,J et. al. (1989)
Chrysene		Uncontaminated	Soil	Lab microcosm		480	0.0007/day	120	Bossert,ID & Bartha,R (1986)
Chrysene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	200 ug/g	240	0.0007/day		Coover,MP & Sims,RC (1987)
Chrysene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	200 ug/g	240	0.00071/day		Coover,MP & Sims,RC (1987)
Chrysene	Musi River, India	Hazardous waste site	Soil	Lab microcosm	1000 ppm	459	0.00072/day		Mahmood,SK & Rao,PR (1993)
Chrysene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	200 ug/g	240	0.00095/day		Coover,MP & Sims,RC (1987)
Chrysene	Narragansett Bay, Rhode Island	Uncontaminated	Sediment	Lab microcosm	2.5 ug/g sediment		0.0014/day		Lee,RF & Ryan,C (1983)
Chrysene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0017/day		Maliszewska-Kordybach,B (1993)
Chrysene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0017/day		Maliszewska-Kordybach,B (1993)
Chrysene	Mississippi	Uncontaminated	Soil	Lab microcosm	105 mg/kg	105	0.0018/day		Park,KS et. al. (1990)
Chrysene	Paleudult, Mississippi	Pristine soil	Soil	Lab microcosm	105 mg/kg	105	0.0018/day		Park,KS et. al. (1990)

Table 11. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Chrysene	Calciaquoll, Utah	Pristine soil	Soil	Lab microcosm	100 mg/kg	196	0.0019/day		Park,KS et. al. (1990)
Chrysene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	237 ng/g	56	0.0019/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Utah	Uncontaminated	Soil	Lab microcosm	100 mg/kg	196	0.0019/day		Park,KS et. al. (1990)
Chrysene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	100 ug/g		0.0019/day		Keck,J et. al. (1989)
Chrysene	Reilly Tar & Chemical Co., St. Louis, MN	Contaminated	Soil	Lab microcosm	1.6-2.8 ug/L		0.002 ug/L/hr		Carmichael,LM et. al. (1997)
Chrysene	Skidaway River, Savannah, Georgia	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.0028/day		Lee,RF & Ryan,C (1983)
Chrysene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	481.2 mg/kg	84	0.003/day		Mueller,JG et. al. (1991A)
Chrysene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0030/day		Maliszewska-Kordybach,B (1993)
Chrysene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0035/day		Maliszewska-Kordybach,B (1993)
Chrysene	Narragansett Bay, Rhode Island	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.0036/day		Lee,RF & Ryan,C (1983)
Chrysene	Upper Gulf of Thailand		Seawater + sediment	Lab microcosm		3	0.0037/day		Hungspreugs,M et. al. (1984)
Chrysene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	481.2 mg/kg	84	0.004/day		Mueller,JG et. al. (1991A)
Chrysene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	237 ng/g	56	0.004/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Reilly Tar & Chemical,St. Louis Park, MN	Contaminated	Soil	Lab microcosm	237 ng/g	56	0.0044/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Chao Phraya River		Seawater + sediment	Lab microcosm		3	0.0045/day		Hungspreugs,M et. al. (1984)

Table 11. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Chrysene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	51 ug/g		0.0047/day		Keck,J et. al. (1989)
Chrysene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	81 mg/kg	63	0.0048/day		Ellis,B et. al. (1991)
Chrysene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	165 mg/kg soil	315	0.0052/day		Deschenes,L et. al. (1995)
Chrysene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	127 mg/kg soil	315	0.0053/day	14	Deschenes,L et. al. (1996)
Chrysene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0054/day		Maliszewska-Kordybach,B (1993)
Chrysene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	237 ng/g	56	0.006/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0062/day		Maliszewska-Kordybach,B (1993)
Chrysene	Cooper River, Charleston, South Carolina	Oil-contamination	Sediment	Lab microcosm	2.5 ug/g sediment		0.0088/day		Lee,RF & Ryan,C (1983)
Chrysene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	38 mg/kg	84	0.009/day		Mueller,JG et. al. (1991A)
Chrysene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	237 ng/g	56	0.009/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	140 ug/g		0.009/day		Keck,J et. al. (1989)
Chrysene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	38 mg/kg	84	0.011/day		Mueller,JG et. al. (1991A)
Chrysene	Reilly Tar & Chemical,St. Louis Park, MN	Contaminated	Soil	Lab microcosm	237 ng/g	56	0.016/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Dubose Oil Recycling, Cantonment, FL	Contaminated	Soil	Lab microcosm	237 ng/g	56	0.019/day		Carmichael,LM & Pfaender,FK (1997)

Table 11. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Chrysene	Dubose Oil Recycling, Cantonment, FL	Contaminated	Soil	Lab microcosm	237 ng/g	56	0.035/day		Carmichael,LM & Pfaender,FK (1997)
Chrysene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	2.7 ug/mL	14	0.037/day		Mueller,JG et. al. (1991)
Chrysene	Dubose Oil Recycling site, Cantonment,FL	Contaminated	Soil	Lab microcosm	1.6-2.8 ug/L		0.04 ug/L/hr		Carmichael,LM et. al. (1997)
Chrysene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	81 mg/kg	28	No biodegradation		Ellis,B et. al. (1991)
Chrysene	Bozeman, MT	Pristine soil	Soil	Lab microcosm	237 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Bozeman, Montana	Uncontaminated	Soil	Lab microcosm	237 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Chrysene	Chao Phraya River		River water	Lab microcosm		3	No mineralization		Hungspreugs,M et. al. (1984)
Chrysene	Upper Gulf of Thailand		Seawater	Lab microcosm		3	No mineralization		Hungspreugs,M et. al. (1984)

3.2.5. Fluoranthene

Fluoranthene is a PAH with a 4-ring structure. In general, PAHs that contain more than 3 rings tend to be biodegraded rather slowly in the environment. The primary biodegradation rate constant for fluoranthene ranges from 0.0015/day to 0.045/day, corresponding to half-lives of about 15 to 462 days. The lowest rate constant is derived from an unpolluted pristine soil (Keck et. al., 1989), while the largest rate constant was observed in aquifer material from a heavily-polluted wood-preserving facility (Mueller et. al., 1991). The half-life of fluoranthene in pristine sediment obtained from New Zealand was reported as greater than 100 days (Wilcock et. al., 1996), further illustrating that biodegradation will be extremely slow in non-acclimated environments. No reaction products have been reported from the primary biodegradation of fluoranthene.

The median for the primary biodegradation rate constant of fluoranthene is 0.0048/day (N = 20); a range of not biodegraded to 0.045/day is reported. No mineralization data are available. The frequency distribution histogram for this data is shown in figure 11. Fluoranthene is expected to biodegrade slowly or be recalcitrant under most environmental conditions.

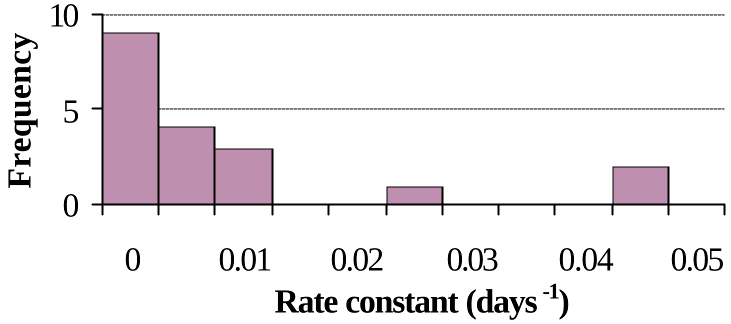

Figure 11. Frequency histogram for the published primary biodegradation rate constant values of fluoranthene.

Table 12. Aerobic biodegradation rate constant values for fluoranthene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Fluoranthene	Brookhaven, Mississippi	Wood-preserving site	Soil	Field	972 ug/g	56	0.0047/day		Lamar,RT & Glaser,JA (1994)
Fluoranthene	Wiroa Island, Auckland, New Zealand	Uncontaminated	Sediment	Field		256	<0.00693/day		Wilcock,RJ et. al. (1996)
Fluoranthene	Southern Uintah County, Utah	Uncontaminated	Soil	Lab column	1.61 ug/g soil	90	0.004/day		Grenney,WJ et. al. (1987)
Fluoranthene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	400 ug/g		0.0015/day		Keck,J et. al. (1989)
Fluoranthene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	400 ug/g	240	0.0016/day		Coover,MP & Sims,RC (1987)
Fluoranthene	Utah	Uncontaminated	Soil	Lab microcosm	883 mg/kg	196	0.0018/day		Park,KS et. al. (1990)
Fluoranthene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	883 ug/g		0.0018/day		Keck,J et. al. (1989)
Fluoranthene	Mississippi	Uncontaminated	Soil	Lab microcosm	913 mg/kg	105	0.0026/day		Park,KS et. al. (1990)
Fluoranthene		Coal-tar contaminated	Soil	Lab microcosm	53 mg/kg soil	175	0.0029/day		Wischmann,H & Steinhart,H (1997)
Fluoranthene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	1628.7 mg/kg	84	0.003/day		Mueller,JG et. al. (1991A)
Fluoranthene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	286 mg/kg	28	0.004/day		Ellis,B et. al. (1991)
Fluoranthene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	286 mg/kg	63	0.0048/day		Ellis,B et. al. (1991)
Fluoranthene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	1628.7 mg/kg	84	0.005/day		Mueller,JG et. al. (1991A)
Fluoranthene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	400 ug/g	240	0.005/day		Coover,MP & Sims,RC (1987)
Fluoranthene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	34.7 mg/kg	84	0.006/day		Mueller,JG et. al. (1991A)

Table 12. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Fluoranthene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	705 mg/kg soil	315	0.0095/day		Deschenes,L et. al. (1996)
Fluoranthene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	34.7 mg/kg	84	0.010/day		Mueller,JG et. al. (1991A)
Fluoranthene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	810 mg/kg soil	315	0.010/day		Deschenes,L et. al. (1995)
Fluoranthene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	570 ug/g		0.012/day		Keck,J et. al. (1989)
Fluoranthene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	787 ug/g		0.027/day		Keck,J et. al. (1989)
Fluoranthene	Lancaster, UK	Agricultural soil	Soil	Lab microcosm		205	0.043/day		Wild,SR & Jones,KC (1993)
Fluoranthene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	16.2 ug/mL	14	0.045/day		Mueller,JG et. al. (1991)
Fluoranthene	Hamburg, Germany	Tar oil contaminated site	Soil	Lab microcosm	1480 mg/kg soil	70	No biodegradation		Mahro,B et. al. (1994)
Fluoranthene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	400 ug/g	240	No biodegradation		Coover,MP & Sims,RC (1987)

3.2.6. Pyrene

Pyrene is a PAH with a 4-ring structure. In general, PAHs that contain more than 3 rings tend to be biodegraded rather slowly in the environment. First-order rate constants were in the range of 0.00036/day to 0.143/day, with the majority of the rate constant values less than 0.01/day. These values correspond to half-lives of 5 to 1,925 days. The smallest rate constant was observed in an unpolluted sandy loam that had a mixture of 16 other PAHs. This rate constant was derived from the reported half-life of 1,900 days (Coover and Sims, 1987). The largest rate constants (0.136/day and 0.143/day) were observed in unpolluted soil with roughly 80% moisture content (Schwab et. al., 1995). These two rate constants are much larger than those of any other study including those obtained from material at industrial locations with acclimated microbes. There were also several studies for which no rate constant was reported or could be calculated since the compound was not observed to biodegrade over the course of the study. This included one experiment where no measurable biodegradation was observed in an unpolluted sandy loam during a 240-day incubation period (Coover and Sims, 1987). Similar results were obtained from other studies with shorter incubation periods (Carmichael and Pfander, 1997; Mahro et. al., 1994; Heitkamp and Cerniglia, 1987; Heitkamp and Cerniglia, 1989). No reaction products were reported for the biodegradation of pyrene.

The median for the primary biodegradation rate constant of pyrene, considering all studies, is 0.00345/day (N = 40); a range of not biodegraded to 0.052day is reported. The median for the mineralization rate constant of pyrene is 0.006/day (N = 18); a range of not biodegraded to 0.143/day is reported. The frequency distribution histograms for this data are shown in figures 12a and 12b. Pyrene is expected to biodegrade slowly under aerobic conditions or to be recalcitrant in the environment.

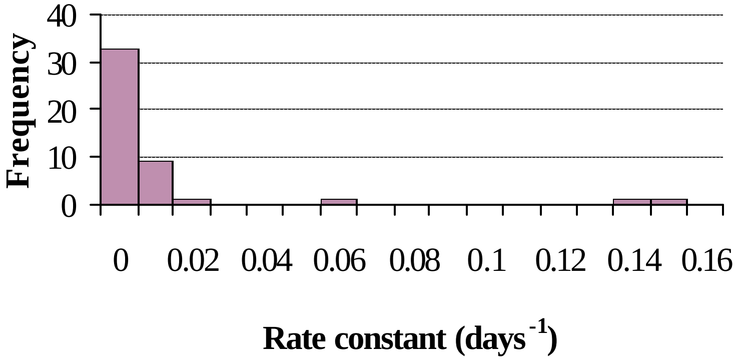

Figure 12a. Frequency distribution histogram for the published primary biodegradation rate constant values of pyrene.

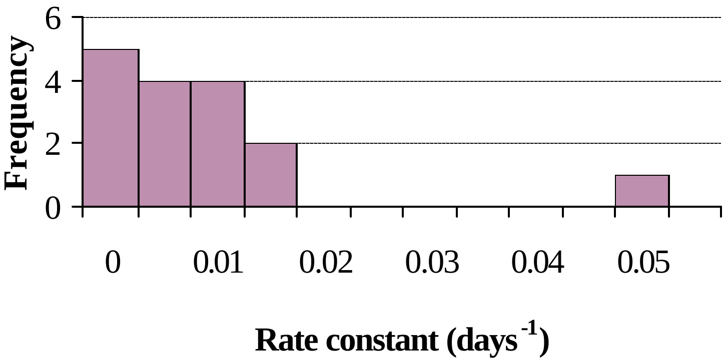

Figure 12b. Frequency distribution histogram for the published mineralization rate constant values of pyrene.

Table 13. Aerobic biodegradation rate constant values for pyrene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Pyrene	Brookhaven, Mississippi	Wood-preserving site	Soil	Field	572 ug/g	56	0.0019/day		Lamar,RT & Glaser,JA (1994)
Pyrene	Champion Intnt'l site, Libby, Montana	Contaminated industrial site	Soil	Field	84.9-90.5 mg/kg	54-60	0.0125-0.0155/day		Huling,SG et. al. (1995)
Pyrene	Wiroa Island, Auckland, New Zealand	Uncontaminated	Sediment	Field		256	<0.00693/day		Wilcock,RJ et. al. (1996)
Pyrene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	400 ug/g	240	0.00036/day		Coover,MP & Sims,RC (1987)
Pyrene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	323 mg/kg	63	0.0004/day		Ellis,B et. al. (1991)
Pyrene	Lake Chicot, Arkansas	Freshwater lake	Lake water + sediment	Lab microcosm	500 ng/g	56	0.001/day		Heitkamp,MA & Cerniglia,CE (1987)
Pyrene	Southern Illinois	Unpolluted soil	Soil	Lab microcosm	8.5	65	0.002/day		Grosser,RJ et. al. (1991)
Pyrene	Southern Illinois	Unpolluted soil	Soil	Lab microcosm	8.5 ng/g	65	0.002/day		Grosser,RJ et. al. (1991)
Pyrene		Coal-tar contaminated	Soil	Lab microcosm	17 mg/kg soil	175	0.0025/day		Wischmann,H & Steinhart,H (1997)
Pyrene	Calciaquoll, Utah	Pristine soil	Soil	Lab microcosm	686 mg/kg	196	0.0027/day		Park,KS et. al. (1990)
Pyrene	Utah	Uncontaminated	Soil	Lab microcosm	686 mg/kg	196	0.0027/day		Park,KS et. al. (1990)
Pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	1015.9 mg/kg	84	0.003/day		Mueller,JG et. al. (1991A)
Pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	1015.9 mg/kg	84	0.003/day		Mueller,JG et. al. (1991A)
Pyrene	Dover, Ohio	Polluted soil	Soil	Lab microcosm	8.5 ng/g	85	0.003/day		Grosser,RJ et. al. (1995)
Pyrene	Dover, Ohio	Unpolluted soil	Soil	Lab microcosm	8.5 ng/g	85	0.003/day		Grosser,RJ et. al. (1995)
Pyrene	Redfish Bay, Texas	Estuary	Estuarine water + sediment	Lab microcosm	500 ng/g	56	0.003/day		Heitkamp,MA & Cerniglia,CE (1987)

Table 13. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	686 ug/g		0.003/day		Keck,J et. al. (1989)
Pyrene	Uttar Pradesh, India	Soil receiving effluent from an oil refinery	Soil	Lab microcosm	20 mg/kg	90	0.0031/day		Ashok,BT et. al. (1995)
Pyrene	Lincolnshire, UK	Uncontaminated soil	Soil	Lab microcosm	0.5 mg/g		0.0032/day		Smith,MJ et. al. (1997)
Pyrene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	400 ug/g	240	0.0033/day		Coover,MP & Sims,RC (1987)
Pyrene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0034/day		Maliszewska-Kordybach,B (1993)
Pyrene		Uncontaminated	Soil	Lab microcosm		480	0.0034/day		Bossert,ID & Bartha,R (1986)
Pyrene	Mississippi	Uncontaminated	Soil	Lab microcosm	697 mg/kg	105	0.0035/day		Park,KS et. al. (1990)
Pyrene	Paleudult, Mississippi	Pristine soil	Soil	Lab microcosm	697 mg/kg	105	0.0035/day		Park,KS et. al. (1990)
Pyrene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	100 ng/g	56	0.004/day		Carmichael,LM & Pfaender,FK (1997)
Pyrene	Southern Illinois	Polluted soil	Soil	Lab microcosm	8.5 ng/g	65	0.004/day		Grosser,RJ et. al. (1991)
Pyrene	Suffolk, UK	Uncontaminated sand	Soil	Lab microcosm	0.5 mg/g		0.0045/day		Smith,MJ et. al. (1997)
Pyrene		Uncontaminated	Soil	Lab microcosm	95-100 mg/kg soil	97	0.0047/day		Mahro,B et. al. (1994)
Pyrene	Dover, Ohio	Polluted soil	Soil	Lab microcosm	8.5 ng/g	85	0.005/day		Grosser,RJ et. al. (1995)
Pyrene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	100 ng/g	56	0.005/day		Carmichael,LM & Pfaender,FK (1997)
Pyrene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	100 ng/g	56	0.006/day		Carmichael,LM & Pfaender,FK (1997)
Pyrene	Southern Illinois	Unpolluted soil	Soil	Lab microcosm	8.5 ng/g	65	0.006/day		Grosser,RJ et. al. (1991)

Table 13. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Pyrene	Musi River, India	Hazardous waste site	Soil	Lab microcosm	1000 ppm	450	0.0062/day		Mahmood,SK & Rao,PR (1993)
Pyrene	Southern Illinois	Polluted soil	Soil	Lab microcosm	8.5 ng/g	65	0.008/day		Grosser,RJ et. al. (1991)
Pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	49.4 mg/kg	84	0.009/day		Mueller,JG et. al. (1991A)
Pyrene	Dover, Ohio	Polluted soil	Soil	Lab microcosm	8.5 ng/g	85	0.009/day		Grosser,RJ et. al. (1995)
Pyrene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	550 mg/kg sol	315	0.0092/day		Deschenes,L et. al. (1995)
Pyrene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	485 mg/kg soil	315	0.0095/day		Deschenes,L et. al. (1996)
Pyrene	Southern Illinois	Polluted soil	Soil	Lab microcosm	8.5 ng/g	65	0.011/day		Grosser,RJ et. al. (1991)
Pyrene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0114/day		Maliszewska-Kordybach,B (1993)
Pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	49.4 mg/kg	84	0.012/day		Mueller,JG et. al. (1991A)
Pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	570 ug/g		0.013/day		Keck,J et. al. (1989)
Pyrene	DeGray Reservoir, Arkadelphia, Arkansas	Uncontaminated	Sediment + water	Lab microcosm		28	0.014/day		Heitkamp,MA & Cerniglia,CE (1989)
Pyrene	Lancaster, UK	Agricultural soil	Soil	Lab microcosm		205	0.014/day		Wild,SR & Jones,KC (1993)
Pyrene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0143/day		Maliszewska-Kordybach,B (1993)
Pyrene	Dover, Ohio	Polluted soil	Soil	Lab microcosm	8.5 ng/g	85	0.015/day		Grosser,RJ et. al. (1995)
Pyrene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0152/day		Maliszewska-Kordybach,B (1993)

Table 13. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	640 ug/g		0.016/day		Keck,J et. al. (1989)
Pyrene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0198/day		Maliszewska-Kordybach,B (1993)
Pyrene		Agricultural soil	Soil	Lab microcosm	20 ug/g	180	0.0202/day		Maliszewska-Kordybach,B (1993)
Pyrene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	100 ng/g	56	0.049/day		Carmichael,LM & Pfaender,FK (1997)
Pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	10.4 ug/mL	14	0.052/day		Mueller,JG et. al. (1991)
Pyrene		Uncontaminated	Soil	Lab microcosm	10 mg/kg	100	0.136/day		Schwab,AP et. al. (1995)
Pyrene		Uncontaminated	Soil	Lab microcosm	10 mg/kg	100	0.143/day		Schwab,AP et. al. (1995)
Pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	400 ug/g		3.6X10-4/day		Keck,J et. al. (1989)
Pyrene	Blekholmstorget, Stockholm, Sweden	Creosote production facility	Soil	Lab microcosm	323 mg//kg	28	No biodegradation		Ellis,B et. al. (1991)
Pyrene	Bozeman, MT	Pristine soil	Soil	Lab microcosm	100 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Pyrene	Degray Resevoir, Arkansas	Unpolluted freshwater reservoir	Lake water + sediment	Lab microcosm	500 ng/g	56	No biodegradation		Heitkamp,MA & Cerniglia,CE (1987)
Pyrene	Hamburg, Germany	Tar oil contaminated site	Soil	Lab microcosm	1250 mg/kg soil	70	No biodegradation		Mahro,B et. al. (1994)
Pyrene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	400 ug/g	240	No biodegradation		Coover,MP & Sims,RC (1987)
Pyrene	DeGray Reservoir, Arkadelphia, Arkansas	Uncontaminated	Sediment + water	Lab microcosm		28	No mineralization		Heitkamp,MA & Cerniglia,CE (1989)

3.2.7. Benzo(a)pyrene

Benzo(a)pyrene is a PAH with a 5-ring structure that is virtually insoluble in water. In general, PAHs that contain more than 3 rings tend to be biodegraded rather slowly in the environment. Biodegradation of benzo(a)pyrene appears to occur at an extremely slow rate when compared to other PAHs. First-order rate constants ranged from 0.00006/day to 0.057/day. These values correspond to half-lives of 12 to 11,552 days. The smallest rate constant was observed in soil that contained 8 other PAHs (Grosser et. al., 1995). The biodegradation rate of benzo(a)pyrene was slower than the other compounds, indicating microbes may selectively degrade PAH compounds. The largest rate constant was observed in creosote-contaminated groundwater obtained from a wood-preserving facility (Mueller et. al., 1991). There were also several studies for which no rate constant was reported or could be calculated since the compound was not observed to biodegrade over the course of the study. This included an experiment where no measurable biodegradation was observed in a polluted sandy loam over a 315-day incubation period (Deschenes et. al., 1996). Similar results were obtained from other studies with shorter incubation periods (Carmichael and Pfaender, 1997; Lee et. al., 1978; Heitkamp and Cerniglia, 1987A; Grosser et. al., 1995). No reaction products were reported for the degradation of benzo(a)pyrene.

The median for the primary biodegradation rate constant of benzo(a)pyrene is 0.0027/day (N = 23); a range of not biodegraded to 0.057/day is reported. The median for the mineralization rate constant of benzo(a)pyrene is 0.00015/day (N = 25); a range of not biodegraded to 0.0037/day is reported. The frequency distribution histograms for this data are shown in figures 13a and 13b. For the most part, benzo(a)pyrene is expected to be recalcitrant under most environmental conditions.

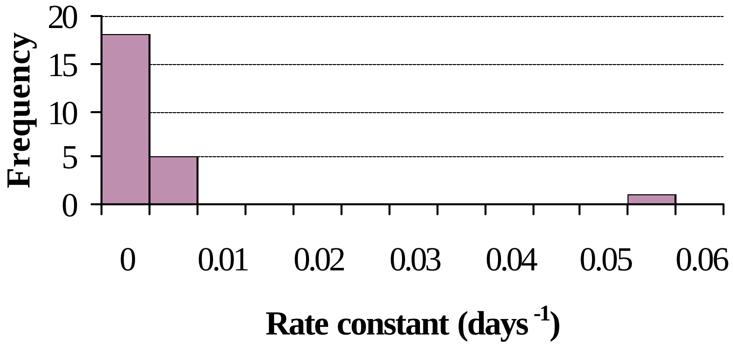

Figure 13a. Frequency histogram for the published primary biodegradation rate constant values of benzo(a)pyrene.

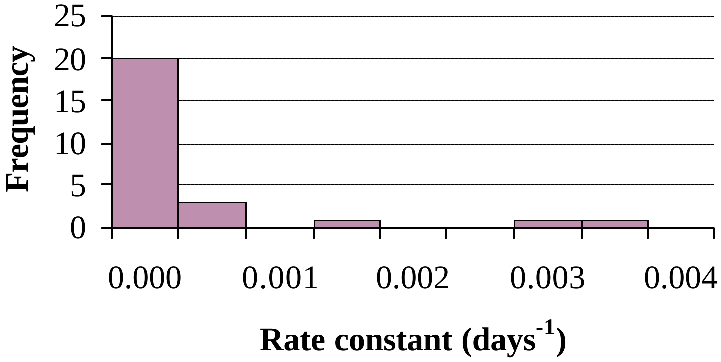

Figure 13b. Frequency histogram for the published mineralization rate constant values of benzo(a)pyrene.

Table 14. Aerobic biodegradation rate constant values for benzo(a)pyrene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)pyrene	Wiroa Island, Auckland, New Zealand	Uncontaminated	Sediment	Field		256	<0.00693/day		Wilcock,RJ et. al. (1996)
Benzo(a)pyrene		Uncontaminated	Soil	Lab microcosm	10 ug/g soil	28			Lu,PY et. al. (1977)
Benzo(a)pyrene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	105 ng/g	80	0.00006/day		Grosser,RJ et. al. (1995)
Benzo(a)pyrene	Southern Illinois	Uncontaminated coal gasification plant site	Soil	Lab microcosm	84.4 ng/g	225	0.00024/day		Grosser,RJ et. al. (1991)
Benzo(a)pyrene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	105 ng/g	80	0.0003/day		Grosser,RJ et. al. (1995)
Benzo(a)pyrene	Southern Illinois	Contaminated coal gasification plant site	Soil	Lab microcosm	84.4 ng/g	225	0.00032/day		Grosser,RJ et. al. (1991)
Benzo(a)pyrene	Southern Illinois	Contaminated coal gasification plant site	Soil	Lab microcosm	84.4 ng/g	225	0.00032/day		Grosser,RJ et. al. (1991)
Benzo(a)pyrene		Uncontaminated	Soil	Lab microcosm		480	0.0005/day	120	Bossert,ID & Bartha,R (1986)
Benzo(a)pyrene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	105 ng/g	160	0.0006/day		Grosser,RJ et. al. (1995)
Benzo(a)pyrene	Southern Illinois	Uncontaminated coal gasification plant site	Soil	Lab microcosm	84.4 ng/g	225	0.00065/day		Grosser,RJ et. al. (1991)
Benzo(a)pyrene	Southern Illinois	Uncontaminated coal gasification plant site	Soil	Lab microcosm	84.4 ng/g	225	0.0009/day		Grosser,RJ et. al. (1991)
Benzo(a)pyrene	Reilly Tar & Chemical,St. Louis Park, MN	Contaminated	Soil	Lab microcosm	136 ng/g	56	0.0011/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	Reilly Tar & Chemical,St. Louis Park, MN	Contaminated	Soil	Lab microcosm	136 ng/g	56	0.0012/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	10.76 ug/g	240	0.0013/day		Coover,MP & Sims,RC (1987)

Table 14. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)pyrene	Southern Illinois	Contaminated coal gasification plant site	Soil	Lab microcosm	84.4 ng/g	225	0.0013/day	25	Grosser,RJ et. al. (1991)
Benzo(a)pyrene	DeGray Reservoir, Arkadelphia, Arkansas	Uncontaminated	Sediment + water	Lab microcosm		28	0.0015/day		Heitkamp,MA & Cerniglia,CE (1989)
Benzo(a)pyrene	Utah	Uncontaminated	Soil	Lab microcosm	33 mg/kg	196	0.0022/day		Park,KS et. al. (1990)
Benzo(a)pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	33 ug/g		0.0022/day		Keck,J et. al. (1989)
Benzo(a)pyrene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	10.76 ug/g	240	0.0024/day		Coover,MP & Sims,RC (1987)
Benzo(a)pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	10.8 ug/g		0.0024/day		Keck,J et. al. (1989)
Benzo(a)pyrene	Mississippi	Uncontaminated	Soil	Lab microcosm	33 mg/kg	105	0.0030/day		Park,KS et. al. (1990)
Benzo(a)pyrene	Kaysville, Utah	Uncontaminated	Soil	Lab microcosm	10.76 ug/g	240	0.0032/day		Coover,MP & Sims,RC (1987)
Benzo(a)pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	28.1 mg/kg	84	0.0034/day		Mueller,JG et. al. (1991A)
Benzo(a)pyrene	Dubose Oil Recycling, Cantonment, FL	Contaminated	Soil	Lab microcosm	136 ng/g	56	0.0034/day		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	82.2 mg/kg	84	0.0035/day		Mueller,JG et. al. (1991A)
Benzo(a)pyrene	Dubose Oil Recycling, Cantonment, FL	Contaminated	Soil	Lab microcosm	136 ng/g	56	0.0037/day	28	Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	82.2 mg/kg	84	0.0038/day		Mueller,JG et. al. (1991A)
Benzo(a)pyrene	Utah State University, Kaysville, Utah	Uncontaminated soil	Soil	Lab microcosm	13 ug/g		0.0046/day		Keck,J et. al. (1989)

Table 14. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)pyrene	Lancaster, UK	Agricultural soil	Soil	Lab microcosm		205	0.0062/day		Wild,SR & Jones,KC (1993)
Benzo(a)pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Soil	Lab microcosm	28.1 mg/kg	84	0.0068/day		Mueller,JG et. al. (1991A)
Benzo(a)pyrene	Uttar Pradesh, India	Soil receiving effluent from an oil refinery	Soil	Lab microcosm	20 mg/kg	90	0.0068/day		Ashok,BT et. al. (1995)
Benzo(a)pyrene	Saucon Creek, Bethlehem, PA	Contaminated	Sediment	Lab microcosm	1 ug/g sediment	4	0.00816/day		Herbes,SE (1981)
Benzo(a)pyrene	Saucon Creek, Bethlehem, PA	Uncontaminated	Sediment	Lab microcosm	1 ug/g sediment	4	0.00816/day		Herbes,SE (1981)
Benzo(a)pyrene	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + soil	Lab microcosm	2.1 ug/mL	14	0.057/day.		Mueller,JG et. al. (1991)
Benzo(a)pyrene	Fort Point Channel, Boston Harbor	Estuary	Sediment	Lab microcosm	20 ng/g	5	1188 ng/g/day		Shiaris,MP (1989)
Benzo(a)pyrene	Weymouth Back River, Boston Harbor	Estuary	Sediment	Lab microcosm	20 ng/g	5	3.6 ng/g/day		Shiaris,MP (1989)
Benzo(a)pyrene	Lower Neck Quincy Bay, Boston Harbor	Estuary	Sediment	Lab microcosm	20 ng/g	5	41.28 ng/g/day		Shiaris,MP (1989)
Benzo(a)pyrene	Lake Chicot, Arkansas		Sediment + water	Lab microcosm	500 ng/g	56	<0.00033/day		Heitkamp,MA & Cerniglia,CE (1987A)
Benzo(a)pyrene	Redfish Bay, Texas		Sediment + water	Lab microcosm	500 ng/g	56	<0.0005/day		Heitkamp,MA & Cerniglia,CE (1987A)
Benzo(a)pyrene	Knoxville, Tennessee	Oil contaminated	Sediment	Lab microcosm		26	<0.00072/day		Herbes,SE & Schwall,LR (1978)
Benzo(a)pyrene	Walker Branch, Oak Ridge, Tennessee	Uncontaminated	Sediment	Lab microcosm		26	<0.00072/day		Herbes,SE & Schwall,LR (1978)
Benzo(a)pyrene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	46 mg/kg soil	315	No biodegradation		Deschenes,L et. al. (1996)

Table 14. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzo(a)pyrene	Delson, Quebec, Canada	Wood-preserving industrial site	Soil	Lab microcosm	90 mg/kg soil	315	No biodegradation		Deschenes,L et. al. (1995)
Benzo(a)pyrene	Bozeman, MT	Pristine soil	Soil	Lab microcosm	136 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	Bozeman, Montana	Uncontaminated	Soil	Lab microcosm	136 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	DeGray Reservoir, Arkadelphia, Arkansas	Uncontaminated	Sediment + water	Lab microcosm	500 ng/g	56	No mineralization		Heitkamp,MA & Cerniglia,CE (1987A)
Benzo(a)pyrene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	105 ng/g	80	No mineralization		Grosser,RJ et. al. (1995)
Benzo(a)pyrene	Dover, Ohio	Coal tar refining plant	Soil	Lab microcosm	105 ng/g	80	No mineralization		Grosser,RJ et. al. (1995)
Benzo(a)pyrene	Dubose Oil Recycling, Cantonment, FL	Industrial location	Soil	Lab microcosm	136 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	136 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	Reilly Tar & Chemical,St. Louis Park, MN	Industrial location	Soil	Lab microcosm	136 ng/g	56	No mineralization		Carmichael,LM & Pfaender,FK (1997)
Benzo(a)pyrene	Saanich Inlet, western Canada	Uncontaminated	Seawater + sediment	Lab microcosm		3	No mineralization		Lee,RF et. al. (1978)
Benzo(a)pyrene	Saanich Inlet, western Canada	Uncontaminated	Seawater + sediment	Lab microcosm		3	No mineralization		Lee,RF et. al. (1978)
Benzo(a)pyrene	Saucon Creek, Bethlehem, PA	Contaminated	Creek water	Lab microcosm		4	No mineralization		Herbes,SE (1981)

3.3. Chlorinated Aliphatic Compounds

While anaerobic biodegradation of highly chlorinated aliphatic compounds generally proceeds readily in strong reducing, anaerobic environments, aerobic degradation of these compounds is less likely. The degree of chlorination of the aliphatic compound will determine its ability to be aerobically biodegraded. Compounds such as tetrachloroethylene and carbon tetrachloride, which are highly oxidized and highly chlorinated, will not be readily biodegraded under aerobic conditions while less oxidized and less highly chlorinated compounds such as dichloromethane and vinyl chloride will. The major route of degradation for these less chlorinated compounds is via a cometabolic pathway using broad specificity bacterial oxygenases. In this case, the chlorinated aliphatic is not used as a growth substrate but is fortuitously degraded during the biodegradation of other non-chlorinated compounds (or methane) present in the bacterial environment. Methanotrophs (methane-oxidizing bacteria) are able to metabolize some chlorinated aliphatics during a cometabolic process due to the methane monooxygenase enzyme complex. However, the rate of aerobic degradation by methanotrophs also appears to lessen with an increasing number of chlorine atoms on the molecule (Broholm et. al., 1991; Henson et. al., 1988). Tetrachloroethylene is apparently not susceptible to degradation by methanotrophs (Broholm et. al., 1991; Henson et. al., 1988; Lige et. al., 1995). In aerobic environments, as found in unsaturated soil or surface water, processes such as leaching or volatilization may be more important in the loss of highly-chlorinated aliphatic compounds than biodegradation.

3.3.1. Tetrachloroethylene

This compound, while readily biodegraded under anaerobic conditions through reductive dechlorination processes, is resistant to biodegradation under aerobic conditions (Table 15). Reductive dechlorination does not occur at oxygen concentrations greater than 0.5 mg/L (Wiedemeier et. al., 1996).

Enzien et. al. (1994) studied the degradation of tetrachloroethylene in laboratory columns where the measured dissolved oxygen concentration did not drop below 1.6 mg/L. Significant degradation of this compound occurred and the authors postulated that anaerobic microsites were responsible although the column was kept under bulk aerobic conditions. MPN counts of both aerobic and anaerobic bacteria showed that abundant populations of each existed in the aquifer sediment. Methane was measured in the column indicating that methanogens were present and providing more evidence that anaerobic conditions, as microsites, may have been present. Finally, cis-dichloroethylene was reported as the major metabolite of tetrachloroethylene degradation, again suggesting that anaerobic biodegradation was responsible for the breakdown of this compound during the experiment. A groundwater recharge field study by Roberts et. al. (1982) reporting the biodegradation of tetrachloroethylene, injected water with dissolved oxygen concentrations of 1.86 mg/L which may not have been sufficient to prevent anaerobic conditions from developing in the aquifer.

In both oxygen-saturated and methanotrophic lab microcosm conditions, tetrachloroethylene was minimally degraded from 0 to 6% over a 56-day period (Lige et. al., 1995). No measurable oxygen consumption or carbon dioxide production was seen in these microcosms relative to the control microcosms; however, some loss of methane in the methanotrophic microcosms, in excess of that found in the controls, was reported suggesting possible unmeasurable transformation by a methanotrophic population.

The remainder of the studies summarized in the database show that aerobic biodegradation of tetrachloroethylene does not occur even given time frames of over 700 days (Roberts et. al., 1986). Studies incorporating methane and oxygen in the microcosm atmosphere also reported that tetrachloroethylene was not biodegraded, again showing that this compound is not susceptible to methanotrophic cometabolism.

Table 15. Aerobic biodegradation rate constant values for tetrachloroethylene

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Tetrachloroethylene	Palo Alto Baylands, California	Injection site of municipal wastewater	Aquifer sediment + groundwater	Field	2.5 ug/L	350	0.0021/day		Roberts,PV et. al. (1982)
Tetrachloroethylene	Canadian Forces Base, Borden, Ontario		Aquifer sediment + groundwater	Field	30.2 ug/L	709	No biodegradation		Roberts,PV et. al. (1986)
Tetrachloroethylene	Lower Glatt River Valley, Switzerland	River infiltration site	Aquifer sediment + groundwater	Field	0.60 ug/L		No biodegradation		Schwarzenbach,RP et. al. (1983)
Tetrachloroethylene	Victoria, Texas	DuPont Plant West Landfill	Aquifer sediment + groundwater	Field	10 uM	203	No biodegradation		Beeman,RE et. al. (1994)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Contaminated landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L	90	No biodegradation		Nielsen,PH et. al. (1992)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Contaminated landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L	90	No biodegradation		Nielsen,PH et. al. (1992)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	70	No biodegradation		Nielsen,PH et. al. (1996)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	70	No biodegradation		Nielsen,PH et. al. (1996)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L	70	No biodegradation		Nielsen,PH et. al. (1996)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Uncontaminated landfill site	Aquifer sediment + groundwater	In situ microcosm	120 ug/L	90	No biodegradation		Nielsen,PH et. al. (1992)
Tetrachloroethylene	Savannah River Site, South Carolina		Soil + groundwater	Lab column	500 ug/L	1.25	0.139/day		Enzien,MV et. al. (1994)
Tetrachloroethylene	Ada, Oklahoma		Soil	Lab column	0.15 mg/L		No biodegradation		Wilson,JT et. al. (1981)
Tetrachloroethylene	Ada, Oklahoma	Rapid infiltration site	Soil	Lab column	2.6 umol/L	196	No biodegradation		Piwoni,MD et. al. (1986)
Tetrachloroethylene	Glatt River, Switzerland	River/Groundwater infiltration zone	Aquifer sediment	Lab column	30 mg/L	270	No biodegradation		Kuhn,EP et. al. (1985)

Table 15. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Tetrachloroethylene	Rhine River sediment	River infiltration site	Sediment	Lab column	0.5-60 ug/L		No biodegradation		Bosma,TNP et. al. (1990)
Tetrachloroethylene	Skrydstrup, Denmark	Uncontaminated	Soil	Lab column	1.1 mg/kg wet soil	289	No biodegradation		Broholm,K et. al. (1991)
Tetrachloroethylene	Swan Coastal Plain, Australia	Uncontaminated	Aquifer sediment + groundwater	Lab column	490 ug/L		No biodegradation		Patterson,BM et. al. (1993)
Tetrachloroethylene	Swan Coastal Plain, Australia	Uncontaminated	Aquifer sediment + groundwater	Lab column	490 ug/L		No biodegradation		Patterson,BM et. al. (1993)
Tetrachloroethylene	Swan Coastal Plain, Australia	Uncontaminated	Aquifer sediment + groundwater	Lab column	540 ug/L		No biodegradation		Patterson,BM et. al. (1993)
Tetrachloroethylene	Swan Coastal Plain, Australia	Uncontaminated	Aquifer sediment + groundwater	Lab column	580 ug/L		No biodegradation		Patterson,BM et. al. (1993)
Tetrachloroethylene	The Netherlands	Infiltration area	Sediment	Lab column	40-60 ug/L		No biodegradation		van der Meer,JR et. al. (1992)
Tetrachloroethylene	Dover AFB, Dover, Delaware	Contaminated	Aquifer sediment + groundwater	Lab microcosm	1 mg/L	56	0.000361/day		Lige,JE et. al. (1995)
Tetrachloroethylene	Dover AFB, Dover, Delaware	Contaminated	Aquifer sediment + groundwater	Lab microcosm	1 mg/L	56	0.000916/day		Lige,JE et. al. (1995)
Tetrachloroethylene	Dover AFB, Dover, Delaware	Contaminated	Aquifer sediment + groundwater	Lab microcosm	1 mg/L	56	0.0011/day		Lige,JE et. al. (1995)
Tetrachloroethylene	Dover AFB, Dover, Delaware	Contaminated	Aquifer sediment + groundwater	Lab microcosm	1 mg/L	56	No biodegradation		Lige,JE et. al. (1995)
Tetrachloroethylene	Fort Polk, Louisiana		Aquifer sediment	Lab microcosm	600-800 ug/L	63	No biodegradation		Wilson,JT et. al. (1983)
Tetrachloroethylene	Fort Polk, Louisiana		Aquifer sediment	Lab microcosm	600-800 ug/L	63	No biodegradation		Wilson,JT et. al. (1983)
Tetrachloroethylene	Iowa River, Iowa	Freshwater	River water	Lab microcosm	20.1 mg/L	4.5	No biodegradation		Mudder,TI (1981)

Table 15. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Tetrachloroethylene	Lula, Oklahoma		Aquifer sediment	Lab microcosm	600-800 ug/L	63	No biodegradation		Wilson,JT et. al. (1984)
Tetrachloroethylene	Lula, Oklahoma		Aquifer sediment	Lab microcosm	600-800 ug/L	63	No biodegradation		Wilson,JT et. al. (1984)
Tetrachloroethylene	Pickett, Oklahoma		Aquifer sediment	Lab microcosm	600-800 ug/L	189	No biodegradation		Wilson,JT et. al. (1983)
Tetrachloroethylene	Pickett, Oklahoma		Aquifer sediment	Lab microcosm	600-800 ug/L	189	No biodegradation		Wilson,JT et. al. (1983)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L	150	No biodegradation		Nielsen,PH et. al. (1996)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L	150	No biodegradation		Nielsen,PH et. al. (1996)
Tetrachloroethylene	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L	150	No biodegradation		Nielsen,PH et. al. (1996)
Tetrachloroethylene	Denmark	Municipal landfill	Leachate	Reactor system	50 mg COD/L		No biodegradation		Lyngkilde,J et. al. (1992)

3.3.2. Dichloromethane

Several studies using pure cultures or mixed defined bacterial cultures show that dichloromethane, unlike the more highly chlorinated aliphatic compounds can be utilized by bacteria as a carbon and energy source for growth (Davis and Madsen, 1991). Biodegradation of this compound is believed to be catalyzed initially by a dehalogenase resulting in the formation of formaldehyde and hydrochloric acid (Davis and Madsen, 1991). Only three papers were located reporting the biodegradation of dichloromethane in environmental media (Table 16). Based on this data, dichloromethane is expected to be moderately degradable under aerobic conditions.

Davis and Madsen (1991) investigated the aerobic degradation of dichloromethane in several soils without the addition of methane. The rate of degradation was dependent on the soil type, substrate concentration, organic carbon availability and redox condition of the particular soil studied. Rates were significantly higher for concentrations between 0.5 mg/L ($T_{1/2}$ of 1.3 days) and 5 mg/L ($T_{1/2}$ of 191 days) for the same soil although degradation was shown at concentrations up to 50 mg/L. Henson et. al. (1988) reported the biodegradation of dichloromethane following the addition of methane to stimulate the naturally occurring population of methanotrophs. Without the prior addition of methane only 43% of the initially added dichloromethane was degraded in 6 days whereas the enrichment procedure, with methane added over the 6 weeks before the addition of dichloromethane, showed 98% loss over 6 days.

The median for the primary biodegradation rate constant of dichloromethane, considering all studies, is 0.0546/day (N = 8); a range of 0.00362 to 0.533/day is reported. The frequency distribution histogram for this data is shown in figure 14. Dichloromethane is expected to be fairly readily biodegraded under most aerobic environmental conditions.

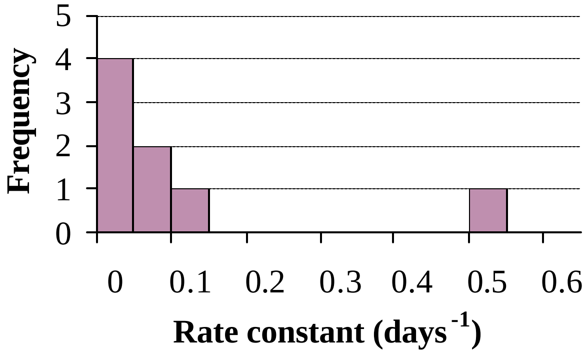

Figure 14. Frequency histogram for the published primary biodegradation rate constant values of dichloromethane.

Table 16. Aerobic biodegradation rate constant values for dichloromethane

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Dichloromethane	Rhine River, The Netherlands	Uncontaminated	River water	Field	5 ug/L	80	0.0182/day		Zoeteman,BCJ et. al. (1980)
Dichloromethane	Rhine River, The Netherlands	Uncontaminated	River water	Field	5 ug/L	132	0.021/day		Zoeteman,BCJ et. al. (1980)
Dichloromethane	Midland County, Michigan	Uncontaminated	Soil	Lab microcosm	5 mg/L	220	0.00362/day		Davis,JW & Madsen,SS (1991)
Dichloromethane	Midland County, Michigan	Uncontaminated	Soil	Lab microcosm	5 mg/L	196	0.00645/day		Davis,JW & Madsen,SS (1991)
Dichloromethane	Bay County, Michigan	Uncontaminated	Soil	Lab microcosm	0.5 mg/L	140	0.0126/day		Davis,JW & Madsen,SS (1991)
Dichloromethane	Midland County, Michigan	Uncontaminated	Soil	Lab microcosm	5 mg/L	31	0.043/day		Davis,JW & Madsen,SS (1991)
Dichloromethane	Midland County, Michigan	Uncontaminated	Soil	Lab microcosm	0.5 mg/L	36	0.0546/day		Davis,JW & Madsen,SS (1991)
Dichloromethane	Bay County, Michigan	Uncontaminated	Soil	Lab microcosm	0.5 mg/L	21	0.0737/day		Davis,JW & Madsen,SS (1991)
Dichloromethane	Midland County, Michigan	Uncontaminated	Soil	Lab microcosm	0.5 mg/L	68	0.096/day	50	Davis,JW & Madsen,SS (1991)
Dichloromethane	Ada, Oklahoma	Uncontaminated	Soil	Lab microcosm	275 ug/L	6	0.101/day		Henson,JM et. al. (1988)
Dichloromethane	Midland County, Michigan	Uncontaminated	Soil	Lab microcosm	0.16 mg/L	5.25	0.533/day		Davis,JW & Madsen,SS (1991)

3.4. Phenol and Substituted Phenols

Both phenol and the cresol isomers are readily degraded under aerobic conditions in environmental media (see Tables 17, 18, 19, and 20). The cresols are monosubstituted phenols commonly used in disinfectants and fumigants, in photographic developers, as a manufacturing intermediate in the production of synthetic resins and in explosives. Because of their common usage, these compounds are often found in the environment and are listed as priority pollutants by the U.S. EPA. Phenol is expected to biodegrade more rapidly than the cresol isomers. Phenols with *ortho*- or *para*- substituents were shown to be preferentially degraded over those with *meta*- substitution (Medvedev and Davidov, 1981). m-Cresol is thought to exhibit a greater stability of the benzene ring making it more difficult to biodegrade than the other two isomers.

3.4.1. Phenol

Phenol is rapidly biodegraded in the environment under aerobic conditions, usually without any apparent lag time. First-order biodegradation rate constants were in the range of 0.006/day $T_{1/2}$=116 days) to 11/day ($T_{1/2}$<1 day), with the majority of the values greater than 1/day. The lowest rate constant was derived from unpolluted aquifer material 12-12.6 m below the soil surface and had a lag period of 16 days. Substantially larger rate constants were calculated for aquifer material collected at different depths in this study (Konopka and Turco, 1991).

A field study in Terrebonne Bay and Barataria Bay, LA was conducted in which the half-lives of phenol in sediment cores were reported as 1.9 and 4.1 days. These half-lives were in good agreement with half-lives determined in laboratory experiments using continuous flow reactor systems (Portier, 1985).

Biodegradation of phenol in soils under aerobic conditions was also rapid. First-order rate constants of 4.5/day to 7.3/day were determined in unpolluted Captina and Palouse soils at initial concentrations of $1X10^{-6}$ M to $1X10^{-9}$ M (Scott et. al., 1983).

The median for the primary biodegradation rate constant of phenol, considering all studies, is 0.21/day (N = 38). The median for the mineralization rate constant of phenol, considering all studies, is 1.56/day (N = 26). The frequency histograms for this data are shown in figures 15a and 15b.

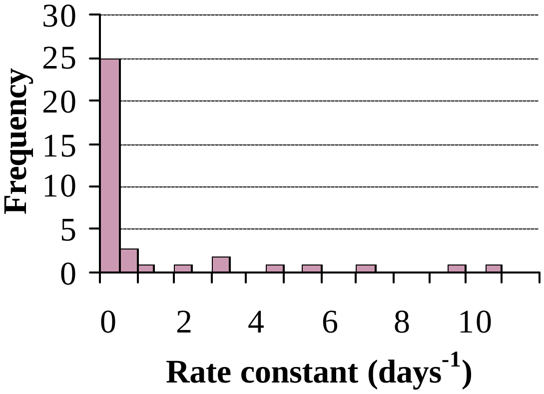

Figure 15a. The frequency histogram for the published primary biodegradation rate constant values of phenol.

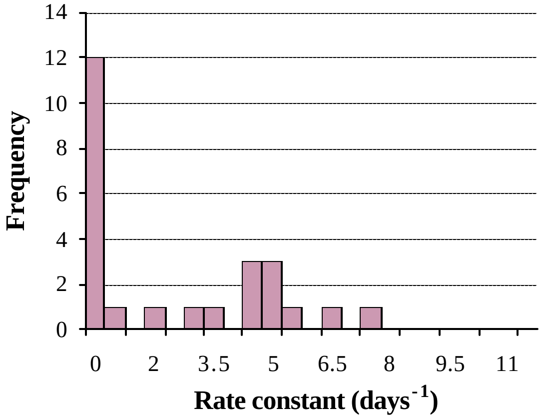

Figure 15b. The frequency histogram for the published mineralization rate constant values of phenol.

Table 17. Aerobic biodegradation rate constant values for phenol

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	Terrebonne Bay and Barataria Bay, LA	Estuary	Bay water + sediment	Field	5 mg/L		0.17/day		Portier,RJ (1985)
Phenol	Terrebonne Bay and Barataria Bay, LA	Estuary	Bay water + sediment	Field	5 mg/L		0.36/day		Portier,RJ (1985)
Phenol	Lake Superior, WI	Groundwater	Groundwater	Groundwater grab sample	0-3.2 mg/L	20	0.035/day		Vaishnav,DD & Babeu,L (1987)
Phenol	Purdue University, W. Lafayette, Indiana	Aquifer	Aquifer sediment	Lab microcosm	10 uM	32	0.006/day	16	Konopka,A & Turco,R (1991)
Phenol	Memorial Park pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.024-0.14/day		Paris,DF & Rogers,JE (1986)
Phenol	Wiggins, Mississippi	Acidic soil	Soil	Lab microcosm	350 mg/kg	30	0.030/day		Loehr,RC & Matthews,JE (1992)
Phenol	Lula, Oklahoma	Aquifer	Aquifer sediment	Lab microcosm	9 ng/g	250	0.035/day		Aelion,CM et. al. (1987)
Phenol	Lula, Oklahoma	Aquifer	Aquifer sediment	Lab microcosm	461 ng/g	250	0.036/day		Aelion,CM et. al. (1987)
Phenol	Purdue University, W. Lafayette, Indiana	Aquifer	Aquifer sediment	Lab microcosm	10 uM	32	0.047/day	2	Konopka,A & Turco,R (1991)
Phenol	Hickory Hills pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.048-0.072/day		Paris,DF & Rogers,JE (1986)
Phenol	Water Works pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.048-0.096/day		Paris,DF & Rogers,JE (1986)
Phenol	Hickory Hills pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.048-4.8/day		Paris,DF et. al. (1983)
Phenol	Park pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.058-5.8/day		Paris,DF et. al. (1983)
Phenol	Chernozen, Ukraine	Industrial location	Soil	Lab microcosm	1000 mg/kg	16	0.058/day		Medvedev,VA & Davidov,VD (1981A)
Phenol	Lester River, MN	River water	River water	Lab microcosm	0-3.2 mg/L	20	0.065/day		Vaishnav,DD & Babeu,L (1987)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	Williams pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.072-7.2/day		Paris,DF et. al. (1983)
Phenol	Skidaway River, Georgia	Estuary	Estuarine water	Lab microcosm	25 ug/L	2	0.079/day		Lee,RF & Ryan,C (1979)
Phenol	Oconee River, Athens, Georgia	Pristine river	River water	Lab microcosm	1 mg/L		0.10-10/day		Paris,DF et. al. (1983)
Phenol	Overlook pond, Athens, Georgia	Pristine pond	Pond water	Lab microcosm	1 mg/L		0.11-11/day		Paris,DF et. al. (1983)
Phenol	Oconee River, Athens, Georgia	Pristine river	River water	Lab microcosm	1 mg/L		0.14-0.21/day		Paris,DF & Rogers,JE (1986)
Phenol	Purdue University, W. Lafayette, Indiana	Aquifer	Aquifer sediment	Lab microcosm	10 uM	32	0.15/day		Konopka,A & Turco,R (1991)
Phenol	Austin, Texas	Basic soil	Soil	Lab microcosm	700 mg/kg	12	0.17/day		Loehr,RC & Matthews,JE (1992)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	20 ppm	7	0.17/day		Borighem,G & Vereecken,J (1978)
Phenol	Purdue University, W. Lafayette, Indiana	Aquifer	Aquifer sediment	Lab microcosm	10 uM	32	0.2/day		Konopka,A & Turco,R (1991)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	20 ppm	6.7	0.21/day		Borighem,G & Vereecken,J (1978)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	20 ppm	5	0.22/day		Borighem,G & Vereecken,J (1978)
Phenol	Lake Superior Harbor, WI	Lake water	Lake water	Lab microcosm	0-3.2 mg/L	12	0.247/day		Vaishnav,DD & Babeu,L (1986)
Phenol	Purdue University, W. Lafayette, Indiana	Aquifer	Aquifer sediment	Lab microcosm	10 uM	32	0.25/day	1	Konopka,A & Turco,R (1991)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	10 ppm	4	0.32/day		Borighem,G & Vereecken,J (1978)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	10 ppm	4	0.34/day		Borighem,G & Vereecken,J (1978)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	10 ppm	4	0.42/day		Borighem,G & Vereecken,J (1978)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	5 ppm	2.9	0.59/day		Borighem,G & Vereecken,J (1978)
Phenol	Purdue University, W. Lafayette, Indiana	Aquifer	Aquifer sediment	Lab microcosm	10 uM	32	0.72/day		Konopka,A & Turco,R (1991)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	5 ppm	2.6	0.76/day		Borighem,G & Vereecken,J (1978)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	5 ppm	2	0.92/day		Borighem,G & Vereecken,J (1978)
Phenol	Lake Superior Harbor, WI	Lake water	Lake water	Lab microcosm	0-3.2 mg/L	12	1.03/day		Vaishnav,DD & Babeu,L (1986)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		1.0X10-5 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.1X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.1X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		1.2X10-5 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.2X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		1.2X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		1.3X10-5 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.5X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.5X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		1.5X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.6X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		1.6X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		1.9X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		1.9X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		1.9X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		2.0X10-5 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.1X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.1X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		2.2X10-5 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.2X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	0.5 ppm	0.5	2.4/day		Borighem,G & Vereecken,J (1978)
Phenol	Unspecified site	Soil	Soil	Lab microcosm	1X10-7 mols/g	1	2.4/day		Dao,TH & Lavy,TL (1987)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		2.4X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		2.4X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.4X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.4X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		2.4X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.5X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		2.6X10-5 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.6X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.9X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		2.9X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		3.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Brians Pond, Summit, New Jersey	Pond water	Pond water	Lab microcosm	1000 ng/mL	1	3.2/day		Chesney,RH et. al. (1985)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	0.5 ppm	0.5	3.3/day		Borighem,G & Vereecken,J (1978)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		3.3X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Samber River, Belgium	Polluted river	River water	Lab microcosm	0.5 ppm	0.5	3.4/day		Borighem,G & Vereecken,J (1978)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		3.6X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		4.3X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		4.3X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Brians Pond, Summit, New Jersey	Pond water	Pond water	Lab microcosm	10 ng/mL	1	4.4/day		Chesney,RH et. al. (1985)
Phenol	Whitman County, Washington	Unpolluted Palouse soil	Soil	Lab microcosm	1X10-9 M		4.5/day		Scott,HD et. al. (1983)
Phenol	Whitman County, Washington	Unpolluted Palouse soil	Soil	Lab microcosm	1X10-6 M		4.6/day		Scott,HD et. al. (1983)
Phenol	Whitman County, Washington	Unpolluted Palouse soil	Soil	Lab microcosm	1X10-7 M		4.8/day		Scott,HD et. al. (1983)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		4.8X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		4.8X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		4.8X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		4.8X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	White Rocks Branch, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		4.8X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		4.9X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		4.9X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Whitman County, Washington	Unpolluted Palouse soil	Soil	Lab microcosm	1X10-8 M		5.0/day		Scott,HD et. al. (1983)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		5.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Jefferson National Forest, Virginia	Pristine stream	Stream water + seston	Lab microcosm	1 ug/L		5.0X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Brians Pond, Summit, New Jersey	Pond water	Pond water	Lab microcosm	100 ng/mL	1	5.4/day		Chesney,RH et. al. (1985)
Phenol	Washington County, Arkansas	Unpolluted Captina soil	Soil	Lab microcosm	1X10-9 M		5.4/day		Scott,HD et. al. (1983)
Phenol	Brians Pond, Summit, New Jersey	Pond water	Pond water	Lab microcosm	1 ng/mL	1	5.5/day		Chesney,RH et. al. (1985)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		6.0X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Washington County, Arkansas	Unpolluted Captina soil	Soil	Lab microcosm	1X10-8 M		6.1/day		Scott,HD et. al. (1983)
Phenol	Washington County, Arkansas	Unpolluted Captina soil	Soil	Lab microcosm	1X10-7 M		6.2/day		Scott,HD et. al. (1983)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		7.2X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Washington County, Arkansas	Unpolluted Captina soil	Soil	Lab microcosm	1X10-6 M		7.3/day		Scott,HD et. al. (1983)
Phenol	New River, Virginia	Pristine river	River water + sediment	Lab microcosm	1 ug/L		7.5X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)

Table 17. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Phenol	St. Lawrence River, Canada	River water	River water	Lab microcosm	125 ppb	0.2	7.99/day		Visser,SA et. al. (1977)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		8.0X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Stoney Creek, Virginia	Pristine stream	Stream water + sediment	Lab microcosm	1 ug/L		9.0X10-7 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	New River, Virginia	Pristine river	River water + seston	Lab microcosm	1 ug/L		9.6X10-6 mg/mg/day		Peters,GT & Colwell,FS (1989)
Phenol	Chernozen, Ukraine	Industrial location	Soil	Lab microcosm	100 mg/kg	5	Biodegrades		Medvedev,VA & Davidov,VD (1981A)
Phenol	Chernozen, Ukraine	Industrial location	Soil	Lab microcosm	100 mg/kg	3	Biodegrades		Medvedev,VA & Davidov,VD (1981A)
Phenol	Chernozen, Ukraine	Industrial location	Soil	Lab microcosm	500 mg/kg	6	Biodegrades		Medvedev,VA & Davidov,VD (1981B)
Phenol	Chernozen, Ukraine	Industrial location	Soil	Lab microcosm	500 mg/kg	16	Biodegrades		Medvedev,VA & Davidov,VD (1981B)
Phenol	Waterloo, Ontario	Uncultivated soil	Soil	Lab microcosm	100 ug/g	5	Biodegrades		Baker,MD & Mayfield,CI (1980)
Phenol	Chernozen, Ukraine	Industrial location	Soil	Lab microcosm	1000 mg/kg	44	No biodegradation		Medvedev,VA & Davidov,VD (1981A)
Phenol	Terrebonne Bay and Barataria Bay, LA	Estuary	Sediment	Reactor system	5 mg/L		0.18/day		Portier,RJ (1985)
Phenol	Terrebonne Bay and Barataria Bay, LA	Estuary	Sediment	Reactor system	5 mg/L		0.31/day		Portier,RJ (1985)

3.4.2. o-Cresol

o-Cresol is readily degraded under aerobic conditions (Table 18). Biodegradation of this compound is believed to proceed via hydroxylation to 2-methylcatechol followed by ring cleavage (Paris et. al., 1983).

While no field studies were located for this compound, *in situ* microcosm studies conducted at Vejen City, Denmark showed that o-cresol was readily degraded in an aquifer environment with an average half-life of 2.6 days (Nielsen et. al., 1996). Rate constants were mainly collected for laboratory microcosm studies with calculated half-lives ranging from less than 1 day (several studies, see Table 18) to 10 days (Mueller et. al., 1991A). The average half-life for these data was less than 1 day. Rate constants reported for a study using groundwater as an inoculum for the degradation of o-cresol were considerably higher than those reported in other study types.

The median for the primary biodegradation rate constant of o-cresol, considering all studies, is 0.4/day (N = 22); a range of 0.069 to 4.61/day is reported. The frequency distribution histogram for the data is shown in figure 16. The mean for the lab microcosm studies alone is 0.49/day. o-Cresol is expected to be readily biodegraded under most aerobic environmental conditions.

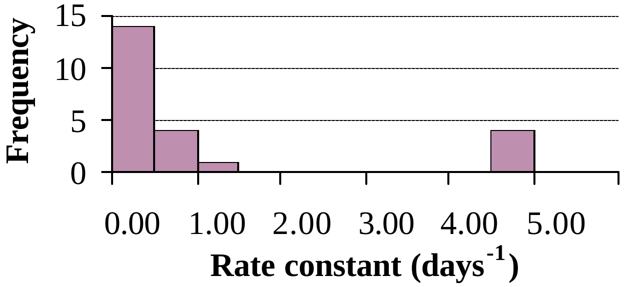

Figure 16. Frequency histogram for the published primary biodegradation rate constant values of o-cresol.

Table 18. Aerobic biodegradation rate constant values for o-cresol

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Cresol	Denmark		Groundwater	Groundwater grab sample	200-1000 ug/L	20	0.33-0.43/day	4	Arvin,E et. al. (1988)
o-Cresol	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	1	4.61/day		Lyngkilde,J et. al. (1988)
o-Cresol	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	1	4.61/day		Lyngkilde,J et. al. (1988)
o-Cresol	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	1	4.61/day		Lyngkilde,J et. al. (1988)
o-Cresol	Forlev landfill, Korsoer, Zealand	Sanitary landfill	Leachate	Groundwater inoculum	100 ug/L	1	4.61/day		Lyngkilde,J et. al. (1988)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.2/day		Nielsen,PH et. al. (1996)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.2/day		Nielsen,PH et. al. (1996)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	In situ microcosm	150 ug/L		0.4/day		Nielsen,PH et. al. (1996)
o-Cresol	Skaelskor, Denmark	Uncontaminated	Fractured clay	Lab column		3.2	Biodegrades	0.5	Broholm,K et. al. (1995)
o-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	9.7 mg/kg	56	0.069/day		Mueller,JG et. al. (1991A)
o-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	9.7 mg/kg	56	0.087/day	7	Mueller,JG et. al. (1991A)
o-Cresol	Wiggins, Mississippi		Soil	Lab microcosm	250 mg/kg soil		0.136/day		Loehr,RC & Matthews,JE (1992)
o-Cresol			River water	Lab microcosm			0.160/day	2	Kaplin,VT et. al. (1968)
o-Cresol	Cliffs-Dow Chemical Co., Marquette, MI	Charcoal manufacturing plant	Aquifer sediment	Lab microcosm	500 ug/L	21	0.19/day		Klecka,GM et. al. (1990)

Table 18. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
o-Cresol	Cliffs-Dow Chemical Co., Marquette, MI	Charcoal manufacturing plant	Aquifer sediment	Lab microcosm	500 ug/L	21	0.33/day		Klecka,GM et. al. (1990)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.4/day		Nielsen,PH et. al. (1996)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.4/day	1	Nielsen,PH et. al. (1996)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L		0.4/day	2	Nielsen,PH et. al. (1996)
o-Cresol	Austin, Texas		Soil	Lab microcosm	500 mg/kg soil		0.433/day		Loehr,RC & Matthews,JE (1992)
o-Cresol			Soil	Lab microcosm	1000 mg/kg soil	16	0.72-0.82/day		Medvedev,VA & Davidov,VD (1981)
o-Cresol	Cliffs-Dow Chemical Co., Marquette, MI	Charcoal manufacturing plant	Aquifer sediment	Lab microcosm	500 ug/L		0.77/day		Klecka,GM et. al. (1990)
o-Cresol	Vejen City, Jutland, Denmark	Landfill site	Aquifer sediment + groundwater	Lab microcosm	150 ug/L	10	0.877/day		Nielsen,PH & Christensen,TH (1994A)
o-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + groundwater	Lab microcosm	4.2 mg/L	3	0.88/day		Mueller,JG et. al. (1991)
o-Cresol			Soil	Lab microcosm	500 mg/kg soil	8	1.35-1.55/day		Medvedev,VA & Davidov,VD (1981B)
o-Cresol	Denmark	Municipal landfill	Leachate	Reactor system	50 mg COD/L		Biodegrades		Lyngkilde,J et. al. (1992)

3.4.3. m-Cresol

m-Cresol is rapidly degraded under aerobic conditions (Table 19). Biodegradation is believed to proceed via hydroxylation to 3-methylcatechol followed by ring cleavage (Paris et. al., 1983).

No field or *in situ* microcosm studies were located for this compound. Rate constants were exclusively collected for laboratory microcosm studies with calculated half-lives ranging from less than 1 day (several studies, see Table 19) to 198 days (Dobbins and Pfaender, 1988). The average half-life for this data was approximately 1.5 days. The high half-life was taken from a study measuring the biodegradation of m-cresol at different horizons in a sediment core from a pristine aquifer site. The half-lives measured for this core varied from 28 to 198 days depending on the location of the sediment used in the laboratory microcosm. A single mineralization study was reported giving a half-life of 714 days for m-cresol in uncontaminated aquifer sediment (Aelion et. al., 1987).

Loehr and Matthews (1992) reported that biodegradation of m-cresol was considerably slower in an acid soil (pH 4.8) when compared to degradation in a basic soil (pH 7.8) giving half-lives of 0.6 and 11.3 days, respectively. This difference was not seen in the same magnitude for the other cresol isomers although degradation of the cresols in the acidic soil was slower in all cases. Work by Palumbo et. al. (1988) showed that maximum uptake rates of m-cresol in environmental water samples were seasonal, with rates significantly slower in the winter months and then increasing through the summer months as water temperatures and microbial activity increased before declining again during the fall.

The median for the primary biodegradation rate constant of m-cresol, considering all studies, is 0.133/day (N = 19); a range of 0.0035 to 1.16/day is reported. The frequency distribution histogram for this data is shown in figure 17. m-Cresol is expected to be readily biodegraded under most aerobic environmental conditions.

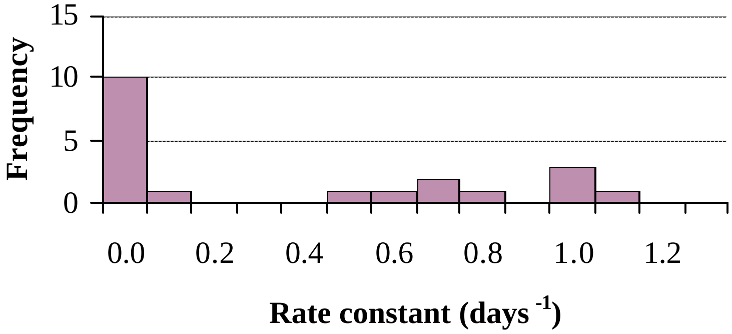

Figure 17. Frequency histogram for the published primary biodegradation rate constant values of m-cresol.

Table 19. Aerobic biodegradation rate constant values for m-cresol

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
m-Cresol	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm			0.00024-0.0024/day		Dobbins,DC & Pfaender,FK (1987)
m-Cresol	Lula, Oklahoma	Uncontaminated aquifer site	Aquifer sediment	Lab microcosm	39 ng/g	150	0.00097/day		Aelion,CM et. al. (1987)
m-Cresol	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm			0.0035/day		Dobbins,DC & Pfaender,FK (1988)
m-Cresol	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm			0.0073/day		Dobbins,DC & Pfaender,FK (1988)
m-Cresol	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm			0.012/day		Dobbins,DC & Pfaender,FK (1988)
m-Cresol	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm			0.012/day		Dobbins,DC & Pfaender,FK (1988)
m-Cresol	Lula, Oklahoma	Uncontaminated	Aquifer sediment	Lab microcosm			0.025/day		Dobbins,DC & Pfaender,FK (1988)
m-Cresol	Coastal water adjacent to the Newport R.	Uncontaminated	Seawater	Lab microcosm	1-35 ug/L	0.21-0.5	0.032/day		Palumbo,AV et. al. (1988)
m-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	21.1 mg/kg	84	0.057/day		Mueller,JG et. al. (1991A)
m-Cresol	Wiggins, Mississippi		Soil	Lab microcosm	130 mg/kg soil		0.061/day		Loehr,RC & Matthews,JE (1992)
m-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	21.1 mg/kg	56	0.078/day	7	Mueller,JG et. al. (1991A)
m-Cresol			River water	Lab microcosm			0.188/day	2	Kaplin,VT et. al. (1968)
m-Cresol			Soil	Lab microcosm	1000 mg/kg soil	27	0.43-0.49/day		Medvedev,VA & Davidov,VD (1981)

Table 19. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
m-Cresol	Lake Michie, Durham, North Carolina	Uncontaminated	Lake water	Lab microcosm	0-500 ug/L		0.576/day		Shimp,RJ & Pfaender,FK (1985)
m-Cresol	Lake Michie, Durham, North Carolina	Uncontaminated	Lake water	Lab microcosm	0-500 ug/L		0.624/day		Shimp,RJ & Pfaender,FK (1985)
m-Cresol	Newport River estuary, NC	Uncontaminated	Estuarine water	Lab microcosm	1-35 ug/L	0.21-0.5	0.70/day		Palumbo,AV et. al. (1988)
m-Cresol	Lake Michie, Durham, North Carolina	Uncontaminated	Lake water	Lab microcosm	0-500 ug/L		0.792/day		Shimp,RJ & Pfaender,FK (1985)
m-Cresol	Newport River, NC	Uncontaminated	River water	Lab microcosm	1-35 ug/L	0.21-0.5	0.82/day		Palumbo,AV et. al. (1988)
m-Cresol			Soil	Lab microcosm	500 mg/kg soil	11	0.98-1.13/day		Medvedev,VA & Davidov,VD (1981B)
m-Cresol	Lake Michie, Durham, North Carolina	Uncontaminated	Lake water	Lab microcosm	0-500 ug/L		1.01/day		Shimp,RJ & Pfaender,FK (1985)
m-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + groundwater	Lab microcosm	2.5 mg/L	3	1.07/day		Mueller,JG et. al. (1991)
m-Cresol	Austin, Texas		Soil	Lab microcosm	120 mg/kg soil		1.16/day		Loehr,RC & Matthews,JE (1992)
m-Cresol	Newport River estuary, North Carolina	Uncontaminated	Estuarine water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)
m-Cresol	Newport River estuary, North Carolina	Uncontaminated	Estuarine water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)

Table 19. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
m-Cresol	Newport River estuary, North Carolina	Uncontaminated	Estuarine water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)
m-Cresol	Newport River estuary, North Carolina	Uncontaminated	Estuarine water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)
m-Cresol	Newport River estuary, North Carolina	Uncontaminated	Estuarine water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)
m-Cresol	Newport River estuary, North Carolina	Uncontaminated	Estuarine water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)
m-Cresol	Newport River, North Carolina	Uncontaminated	River water	Lab microcosm			Biodegrades		Pfaender,FK & Bartholomew,GW (1982)
m-Cresol	Offshore, North Carolina	Uncontaminated	Seawater	Lab microcosm			Biodegrades slightly		Pfaender,FK & Bartholomew,GW (1982)

3.4.4. p-Cresol

p-Cresol is readily degraded under aerobic conditions (Table 20). Biodegradation is believed to proceed via hydroxylation to 4-methylcatechol followed by ring cleavage (Paris et. al., 1983).

No field or *in situ* microcosm studies were located for this compound. Rate constants were exclusively collected for laboratory microcosm studies aside from one groundwater grab study (Delfino and Miles, 1985) with calculated half-lives ranging from less than 1 day (several studies, see Table 20) to 27 days (Paris et. al., 1983). The average half-life for this data was less than 1 day. A single mineralization study was reported giving an approximate half-life of 10 days for p-cresol in aquifer sediment (Millette et. al., 1995). In a factorial experiment, it was found that the mineralization of p-cresol was unaffected by the presence of other compounds commonly found in creosote (Millette et. al., 1995).

The median for the primary biodegradation rate constant of p-cresol is 1.75/day (N = 28); a range of 0.079 to 13.15/day is reported. The frequency distribution histogram for this data is shown in figure 18. p-Cresol is expected to be readily biodegraded under most aerobic environmental conditions.

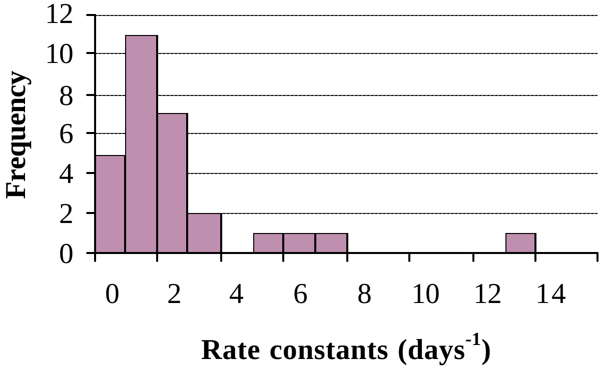

Figure 18. Frequency histogram for the published primary biodegradation rate constant values of p-cresol.

Table 20. Aerobic biodegradation rate constant values for p-cresol

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Cresol	NW Gainesville, Florida		Groundwater	Groundwater grab sample	2.2 mg/L	8	1.26/day	2	Delfino,JJ & Miles,CJ (1985)
p-Cresol	Lago Lake, Georgia	Uncontaminated	Lake water	Lab microcosm	1 ug/L		0.003 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Okefenokee Swamp, Mizell Prairie	Uncontaminated	Freshwater	Lab microcosm	1 ug/L		0.01 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Williams pond, Georgia		Pond water	Lab microcosm	1 mg/L		0.026-2.6/day		Paris,DF et. al. (1983)
p-Cresol	Mamma Rhoda Channel, Bahamas	Uncontaminated	Seawater	Lab microcosm	1 ug/L		0.027 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Park pond, Georgia		Pond water	Lab microcosm	1 mg/L		0.058-5.8/day		Paris,DF et. al. (1983)
p-Cresol	Hickory Hills, Georgia		Freshwater	Lab microcosm	1 mg/L		0.062-6.3/day		Paris,DF et. al. (1983)
p-Cresol	Oconee River, Georgia		River water	Lab microcosm	1 mg/L		0.072-7.2/day		Paris,DF et. al. (1983)
p-Cresol	Canadian Forces Base, Borden, Canada		Aquifer sediment	Lab microcosm	101.4 mg/L	15	0.0723/day	3	Millette,D et. al. (1995)
p-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	21.7 mg/kg	56	0.079/day		Mueller,JG et. al. (1991A)
p-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Sediment	Lab microcosm	21.7 mg/kg	56	0.084/day		Mueller,JG et. al. (1991A)
p-Cresol	Overlook pond, Georgia		Pond water	Lab microcosm	1 mg/L		0.11-11/day		Paris,DF et. al. (1983)
p-Cresol			River water	Lab microcosm			0.188/day	2	Kaplin,VT et. al. (1968)

Table 20. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Cresol	Mamma Rhoda Channel, Bahamas	Uncontaminated	Seawater	Lab microcosm	500 ug/L		0.22 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Lago Lake, Georgia	Uncontaminated	Lake water	Lab microcosm	1 ug/L		0.24 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Bay Bridge, Pensacola, Florida		Estuarine water	Lab microcosm	200 ug/L	4.1	0.384/day	2.5	Vanveld,PA & Spain,JC (1983)
p-Cresol	Lago Lake, Georgia	Uncontaminated	Lake water	Lab microcosm	1 ug/L		0.5 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	James River, Virginia		River water	Lab microcosm		4.2	0.842/day		Bourquin,AW (1984)
p-Cresol	Yakima River, Washington		River water	Lab microcosm	100 ug/L	0.75	0.98-1.22/day		Rogers,JE et. al. (1984)
p-Cresol	Sabine Island, Florida		Estuarine water + sediment	Lab microcosm	200 ug/L	2.5	1.06/day	0.42	Vanveld,PA & Spain,JC (1983)
p-Cresol	Sabine Island, Florida		Estuarine water	Lab microcosm	200 ug/L	1.5	1.08/day	1	Vanveld,PA & Spain,JC (1983)
p-Cresol			Soil	Lab microcosm	1000 mg/kg soil	9	1.28-1.46/day		Medvedev,VA & Davidov,VD (1981)
p-Cresol	Wiggins, Mississippi		Soil	Lab microcosm	45 mg/kg soil		1.39/day		Loehr,RC & Matthews,JE (1992)
p-Cresol	Bay Bridge, Pensacola, Florida		Estuarine sediment	Lab microcosm	200 ug/L	1.25	1.46/day	0.42	Vanveld,PA & Spain,JC (1983)
p-Cresol			Soil	Lab microcosm	500 mg/kg soil	7	1.55-1.78/day		Medvedev,VA & Davidov,VD (1981B)
p-Cresol	Yakima River, Washington		River water	Lab microcosm	1000 ug/L	2.25	1.7-2.64/day	1.6	Rogers,JE et. al. (1984)
p-Cresol	Bayou Chico, Florida		Estuarine water	Lab microcosm	200 ug/L	1.25	1.75/day		Vanveld,PA & Spain,JC (1983)

Table 20. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Cresol	331 Bldg Fish Pond, Richmond, WA		Pond water	Lab microcosm	1000 ug/L	3.5	1.94-1.99/day	2.75	Rogers,JE et. al. (1984)
p-Cresol	Walla Walla River, Washington		River water	Lab microcosm	1000 ug/L	2.5	1.97-2.57/day		Rogers,JE et. al. (1984)
p-Cresol	Yakima River, Washington		River water	Lab microcosm	100 ug/L		1.97-2.57/day		Rogers,JE et. al. (1984)
p-Cresol	Lago Lake, Georgia	Uncontaminated	Lake water	Lab microcosm	10000 ug/L		10.95 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Lago Lake, Georgia	Uncontaminated	Lake water	Lab microcosm	10000 ug/L		14.67 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Bayou Chico, Florida		Estuarine sediment	Lab microcosm	200 ug/L	1	2.02/day		Vanveld,PA & Spain,JC (1983)
p-Cresol	Bay Bridge, Pensacola, Florida		Estuarine water + sediment	Lab microcosm	200 ug/L	1.25	2.28/day		Vanveld,PA & Spain,JC (1983)
p-Cresol	331 Bldg Fish Pond, Richmond, WA		Pond water	Lab microcosm	100 ug/L	2.5	2.45-3.7/day	1.25-1.9	Rogers,JE et. al. (1984)
p-Cresol	Sabine Island, Florida		Estuarine sediment	Lab microcosm	200 ug/L	1	2.88/day		Vanveld,PA & Spain,JC (1983)
p-Cresol	331 Bldg Fish Pond, Richmond, WA		Pond water	Lab microcosm	1000 ug/L	2.9	2.98-10.4/day	2.3	Rogers,JE et. al. (1984)
p-Cresol	American Creosote Works, Pensacola, FL	Wood preserving site	Aquifer sediment + groundwater	Lab microcosm	2.0 mg/L	1	3.0/day		Mueller,JG et. al. (1991)
p-Cresol	Lago Lake, Georgia	Uncontaminated	Lake water	Lab microcosm	100000 ug/L		32.1 ug/L/day		Hwang,HM et. al. (1989)

Table 20. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
p-Cresol	Okefenokee Swamp, Mizell Prairie	Uncontaminated	Freshwater	Lab microcosm	100000 ug/L		38 ug/L/day		Hwang,HM et. al. (1989)
p-Cresol	Bayou Chico, Florida		Estuarine water + sediment	Lab microcosm	200 ug/L	0.79	5.52/day		Vanveld,PA & Spain,JC (1983)
p-Cresol	Columbia River, Washington		River water	Lab microcosm	1000 ug/L	2.67	7.3-19.0/day	0-2.4	Rogers,JE et. al. (1984)
p-Cresol	331 Bldg Fish Pond, Richmond, WA		Pond water	Lab microcosm	100 ug/L	1.8	7.7-8.2/day	1.5	Rogers,JE et. al. (1984)
p-Cresol	Austin, Texas		Soil	Lab microcosm	100 mg/kg soil		>100 mg/kg/day		Loehr,RC & Matthews,JE (1992)
p-Cresol	331 Bldg Fish Pond, Richmond, WA		Pond water	Lab microcosm	100 ug/L		Biodegrades		Rogers,JE et. al. (1984)
p-Cresol	Athens, Georgia		Freshwater	Lab microcosm	130 ug/L	0.38	Biodegrades		Hwang,HM & Maloney,SW (1996)
p-Cresol	Athens, Georgia		Freshwater	Lab microcosm	300 ug/L	0.38	Biodegrades		Hwang,HM & Maloney,SW (1996)
p-Cresol	Athens, Georgia		Freshwater	Lab microcosm	500 ug/L	0.38	Biodegrades		Hwang,HM & Maloney,SW (1996)
p-Cresol	Athens, Georgia		Freshwater	Lab microcosm	60 ug/L	0.38	Biodegrades		Hwang,HM & Maloney,SW (1996)
p-Cresol	Columbia River, Washington		River water	Lab microcosm	1000 ug/L		Biodegrades		Rogers,JE et. al. (1984)
p-Cresol	Yakima River, Washington		River water	Lab microcosm	1000 ug/L		Biodegrades		Rogers,JE et. al. (1984)

3.5. Ketones

Data were located for two of the three original members of this group, acetone, methyl ethyl ketone and methyl isobutyl ketone. No data were found for methyl isobutyl ketone and this compound was not included in this discussion. The ketones, in general, are readily biodegraded in soil and water and thus are expected to naturally attenuate in the environment.

3.5.1. Acetone

Acetone is expected to biodegrade rapidly under aerobic conditions (Table 21). Only three papers were located, however, reporting the degradation of this compound in environmental media.

Hwang et. al. (1989) reported that mineralization of acetone in freshwater samples, varying time of collection and concentration, followed multiphasic kinetics which was best described by the Michaelis-Menton model. First-order biodegradation rate constants of 0.025/day to 7.3/day were calculated from these data. The largest values were observed for low initial concentrations of acetone (0.5 μg/L), while the smallest values were observed for high initial concentrations (500 μg/L). The plot of the calculated first-order rate constant versus the initial concentration of acetone used in this study is shown in figure 19.

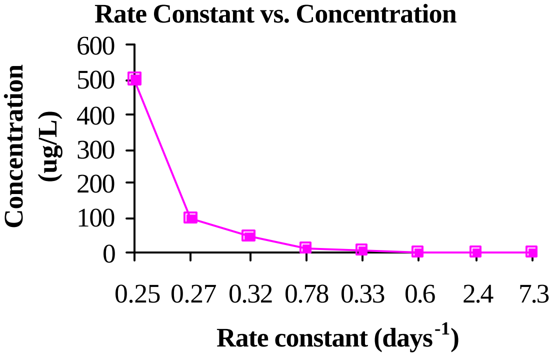

Figure 19. Rate constant versus initial concentration of acetone in a shallow stream.

A field study that measured the fate of acetone in a shallow stream reported a biodegradation rate constant of 1.2/day (Rathbun et. al., 1993). This rate constant was determined by subtracting the volatilization rate constant from the overall loss rate constant. A study by Pugh et. al. (1996) reports that acetone was not biodegraded over 30 days in a non-amended microcosm using soil and groundwater from an contaminated solvent storage site. When nitrogen and phosphorus were added, however, half-lives from 20 to 49.5 days were reported. A second study by the same authors using pre-acclimated soil (over 30 days), reported a half-life of 3.6 days for acetone.

The median for the primary biodegradation rate constant of acetone is 0.035/day (N = 5); a range of not biodegraded to 1.2/day is reported. The median for the mineralization rate constant of acetone is

0.078/day (N = 13); a range of 0.025 to 7.3/day is reported.. The mineralization rate constants were all measured in the same paper for lake water grab samples (Hwang et. al., 1989). The frequency histograms for this data are shown in figure 20a and 20b.

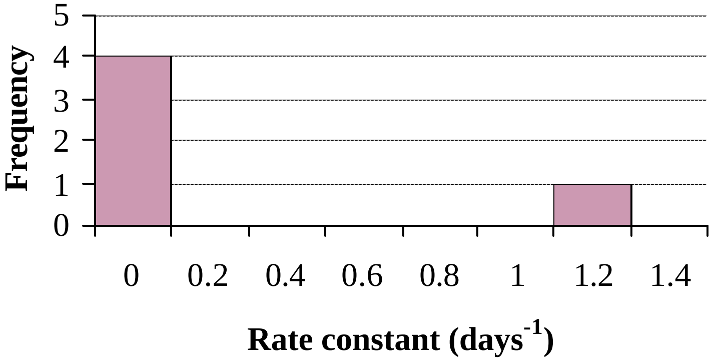

Figure 20a. The frequency histogram for the published primary biodegradation rate constant values of acetone.

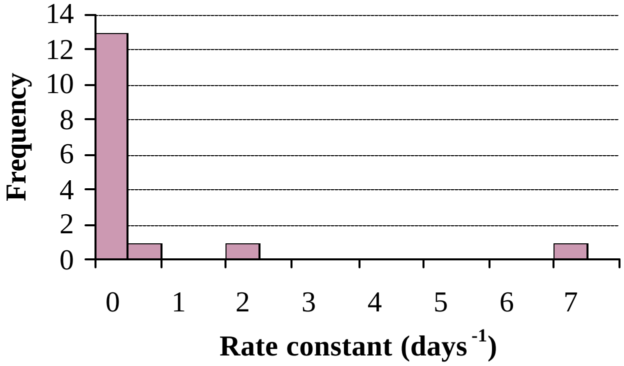

Figure 20b. The frequency histogram for the published mineralization rate constant values of acetone.

Table 21. Aerobic biodegradation rate constant values for acetone

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Acetone	Stennis Space Center, Mississippi	Surface water	Stream water	Field		30	1.2/day		Rathbun,RE et. al. (1993)
Acetone		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.014/day		Pugh,LB et. al. (1996)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	500 ug/L		0.025/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	100 ug/L		0.028/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	101 ug/L		0.028/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	105 ug/L		0.028/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	50 ug/L		0.032/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	51 ug/L		0.032/day		Hwang,HM et. al. (1989)
Acetone		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.035/day		Pugh,LB et. al. (1996)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	10 ug/L		0.078/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	9 ug/L		0.086/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	8 ug/L		0.097/day		Hwang,HM et. al. (1989)
Acetone		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.19/day		Pugh,LB et. al. (1996)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	3 ug/L		0.33/day		Hwang,HM et. al. (1989)

Table 21. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	2 ug/L		0.6/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	1 ug/L		2.4/day		Hwang,HM et. al. (1989)
Acetone	Lake Lago, Athens, Georgia	Surface water	Lake water	Lab microcosm	0.5 ug/L		7.3/day		Hwang,HM et. al. (1989)
Acetone		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	No biodegradation		Pugh,LB et. al. (1996)

3.5.2. Methyl ethyl ketone

Methyl ethyl ketone is expected to biodegrade rapidly under aerobic conditions (Table 22). Only two papers were located, however, reporting the degradation of this compound in environmental media. In pure culture experiments, methyl ethyl ketone was initially hydroxylated to acetoin, and then degraded to diacetyl and acetic acid (Lijmbach and Brinkhuis, 1973).

Dojlido (1979) reports that concentrations up to 800 mg/L were not toxic to microbial activity during typical screening tests using municipal wastewater. In river die-away studies, methyl ethyl ketone initially present at 20 mg/L was degraded within one to two days. A second addition of 20 mg/L methyl ethyl ketone to the same river water, once degradation from the first addition was complete, resulted in 100% degradation in less than one day. Delfino and Miles (1985) reported that methyl ethyl ketone, at 1 mg/L, was completely biodegraded in an aerated, previously anaerobic groundwater within 12 days including a 4 to 5 day lag phase.

A spill of methyl ethyl ketone, resulting in groundwater contamination, was remediated by air stripping and then by biological degradation. While there was insufficient information in the paper to report a rate constant, the authors stated that laboratory tests showed that the indigenous bacteria were capable of degrading this compound (Halvorsen and Ohneck, 1985).

The median for the primary biodegradation rate constant of methyl ethyl ketone, based on limited data, is 0.69/day (N = 3); a range of 0.4 to 1.4/day is reported.

Table 22. Aerobic biodegradation rate constant values for methyl ethyl ketone

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Methyl ethyl ketone	Gainesville, Florida	Groundwater	Groundwater	Groundwater grab sample	1 mg/L	12	0.40/day	4 days	Delfino,JJ & Miles,CJ (1985)
Methyl ethyl ketone	Vistula River, Warsaw, Poland	River water	River water	Lab microcosm	20 mg/L	2	19.2mg/L/day	0.8	Dojlido,JR (1979)
Methyl ethyl ketone	Vistula River, Warsaw, Poland	River water	River water	Lab microcosm	20 mg/L	1	28.8 mg/L/day		Dojlido,JR (1979)

3.6. Miscellaneous

This section contains the data for two compounds, bis(2-ethylhexyl)phthalate and methanol.

3.6.1. Bis(2-ethylhexyl)phthalate

Bis(2-ethylhexyl)phthalate, a plasticizer widely used in PVC, is a ubiquitous environmental contaminant. The current literature shows that this compound is considered to be "moderately" degradable (Scheunert et. al., 1987) under aerobic condtions. Half-life values from 3 to 630 days were reported for bis(2-ethylhexyl)phthalate (Table 23).

High CO_2 production measured during mineralization experiments as well as the inability to measure intermediates such as monoethylhexyl phthalate and phthalate indicate that this compound can be readily mineralized (Maag and Loekke, 1990; Ruedel et. al., 1993; Saeger and Tucker, 1973). Studies generally used a ^{14}C-radiolabeled carbonyl group; cleavage of the carbonyl group and release as CO_2 thus by itself does not indicate complete mineralization of the compound. Labeling of the ring, however, and subsequent CO_2 production does indicate that mineralization is occurring. Only 3 studies looked at the biodegradation of bis(2-ethylhexyl)phthalate in the presence of other organic compounds (Hattori et. al., 1975; Graves et. al., 1994; Schouten et. al., 1979). The rate constants obtained from these studies were, in general, greater that values reported for other studies using bis(2-ethylhexyl)phthalate as a single compound.

No biodegradation of bis(2-ethylhexyl)phthalate was reported in two studies. Ritsema et. al. (1989) reported no biodegradation of this compound at 4 °C over 10 days; however, at 20 °C, a half-life of 19 days was calculated. A second laboratory microcosm study by Rubin et. al. (1982) reported that water obtained from an oligotrophic lake was unable to mineralize bis(2-ethylhexyl)phthalate over 60 days. In the same study, water collected from a eutrophic lake readily biodegraded this compound at concentrations ranging from 40 ng/L to 200 µg/L without a lag phase.

The median for the primary biodegradation rate constant of bis(2-ethylhexyl)phthalate, considering all studies, is 0.0205/day (N = 36); a range of not biodegraded to 0.23/day is reported. The median for the mineralization rate constant of bis(2-ethylhexyl)phthalate, considering all studies, is 0.014/day (N = 28); a range of 0.0022 to 0.045/day is reported. The frequency distribution histograms for this data are shown in figures 21a and 21b.

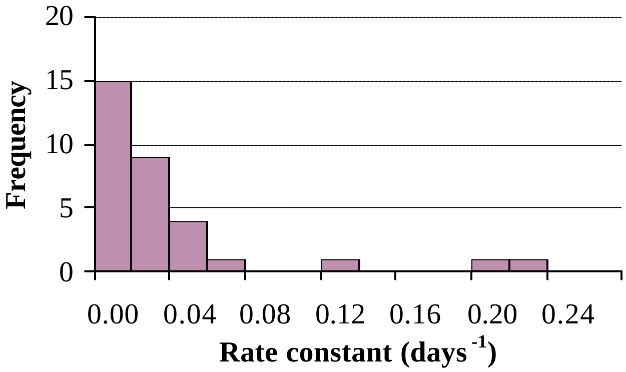

Figure 21a. Frequency histogram for the published primary biodegradation rate constant values of bis(2-ethylhexyl)phthalate.

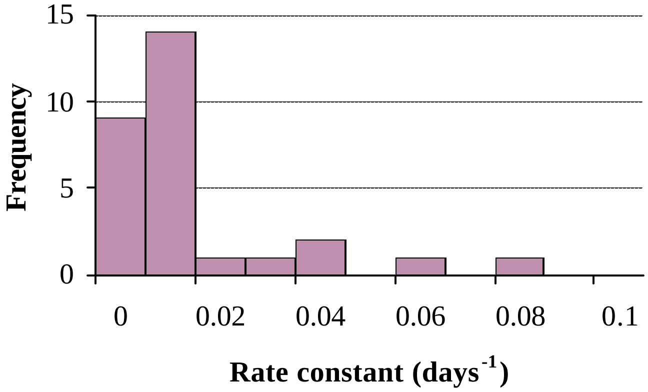

Figure 21b. Frequency histogram for the published mineralization rate constant values of bis(2-ethylhexyl)phthalate.

Table 23. Aerobic biodegradation rate constant values for bis(2-ethylhexyl)phthalate

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Bis(2-ethylhexyl)phthalate	Industrial facility, New Jersey	Contaminated	Groundwater	Groundwater grab sample	17 mg/L	21	0.00903/hr		Graves,DA et. al. (1994)
Bis(2-ethylhexyl)phthalate	White Lake, Old Forge, New York	Uncontaminated	Lake water	Lab microcosm		60			Subba-Rao,RV et. al. (1982)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm		28	0.0011/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm		28	0.0014/day	21	Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate		Contaminated industrial site	Soil	Lab microcosm	21940 mg/kg	70	0.002/day		Maag,J & Loekke,H (1990)
Bis(2-ethylhexyl)phthalate		Uncontaminated	Soil	Lab microcosm	15 ug	56	0.0022/day		Scheunert,I et. al. (1987)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm		28	0.0022/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm	1.82 mg/L	28	0.0032/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm	0.182 mg/L	28	0.0035/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm	0.0182 mg/L	28	0.0037/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm		28	0.004/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Lower Saxonia, Germany	Uncontaminated	Soil	Lab microcosm	1 mg/L	100	0.004/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.004/day	12	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.004/day	7	Wylie,GD et. al. (1982)

Table 23. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm	14.3 mg/L	28	0.005/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate		Contaminated industrial site	Soil	Lab microcosm	21940 mg/kg	70	0.006/day		Maag,J & Loekke,H (1990)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.006/day	3	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.006/day	7	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate		Uncontaminated	Soil	Lab microcosm		33	0.0073/day		Schmitzer,JL et. al. (1988)
Bis(2-ethylhexyl)phthalate	Little Dixie Lake, Columbia, Missouri	Uncontaminated	Sediment	Lab microcosm	10.0 mg/L	28	0.0079/day		Johnson,BT et. al. (1984)
Bis(2-ethylhexyl)phthalate	Germany	Uncontaminated	Soil	Lab microcosm	0.5 mg/kg	63	0.009-0.0134/day		Dorfler,U et. al. (1996)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	20 mg/kg	146	0.0096/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	20 mg/kg	146	0.0097/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	Lower Saxonia, Germany	Uncontaminated	Soil	Lab microcosm	1 mg/L	100	0.01/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.012/day	7	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	2 mg/kg	146	0.012/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	2 ng/mL	33	0.013/day		Subba-Rao,RV et. al. (1982)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.013/day	4	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	200 pg/mL	40	0.0137/day		Subba-Rao,RV et. al. (1982)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	2 mg/kg	146	0.014/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	20 mg/kg	146	0.0148/day		Fairbanks, BC et. al. (1985)

Table 23. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Bis(2-ethylhexyl)phthalate	Baierbrunn, Germany	Uncontaminated	Soil	Lab microcosm	0.5 mg/kg	28-63	0.015-0.019/day		Dorfler,U et. al. (1996)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	2 mg/kg	146	0.015/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	20 mg/kg	146	0.015/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	2 mg/kg	146	0.0156/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	20 mg/kg	146	0.0158/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	Germany	Uncontaminated	Soil	Lab microcosm	10 mg/kg	63	0.017-0.024/day		Dorfler,U et. al. (1996)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.017/day	3	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate	New Mexico	Uncontaminated	Soil	Lab microcosm	2 mg/kg	146	0.017/day		Fairbanks, BC et. al. (1985)
Bis(2-ethylhexyl)phthalate	Ebersberger Forst, Germany	Uncontaminated	Soil	Lab microcosm	0.5 mg/kg	28-63	0.018-0.028/day		Dorfler,U et. al. (1996)
Bis(2-ethylhexyl)phthalate	Northrhine-Westfalia, Germany	Uncontaminated	Soil	Lab microcosm	1 mg/L	100	0.02/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate		Plasticizer manufacturing site	Soil	Lab microcosm	5200 mg/kg	98	0.024/day		Fogel,S et. al. (1995)
Bis(2-ethylhexyl)phthalate	Mississippi River	Uncontaminated	River water	Lab microcosm	1 mg/L	35	0.029/day		Saeger,VW & Tucker,ES (1976)
Bis(2-ethylhexyl)phthalate	Northrhine-Westfalia, Germany	Uncontaminated	Soil	Lab microcosm	1 mg/L	100	0.03/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate		Plasticizer manufacturing site	Soil	Lab microcosm	310 mg/kg	42	0.033/day		Fogel,S et. al. (1995)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	200 ng/mL	28	0.035/day		Subba-Rao,RV et. al. (1982)
Bis(2-ethylhexyl)phthalate	Neuherberg, Germany	Uncontaminated	Soil	Lab microcosm	0.5 mg/kg	28-63	0.036-0.057/day		Dorfler,U et. al. (1996)

Table 23. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Bis(2-ethylhexyl)phthalate	Mississippi River, Missouri	Uncontaminated	River water	Lab microcosm	1 ppm	19	0.036/day		Saeger,VW & Gledhill,WE (1978)
Bis(2-ethylhexyl)phthalate	Mt. Pleasant, New York	Uncontaminated	Soil	Lab microcosm	1 ug/g dry soil	20	0.036/day		Efroymson,RA & Alexander,M (1994)
Bis(2-ethylhexyl)phthalate	Rhine River, the Netherlands	Uncontaminated	River water	Lab microcosm	3.3 ppb	10	0.036/day		Ritsema,R et. al. (1989)
Bis(2-ethylhexyl)phthalate	Missouri River, Easley, Missouri	Uncontaminated	River water	Lab microcosm	0.10 mg/L	32	0.037/day	4	Wylie,GD et. al. (1982)
Bis(2-ethylhexyl)phthalate	Mississippi River	Uncontaminated	River water	Lab microcosm	1.0 mg/L		0.040/day		Saeger,VW and Tucker,ES (1973a)
Bis(2-ethylhexyl)phthalate	Mississippi River	Uncontaminated	River water	Lab microcosm		42	0.041/day		Saeger,VW & Tucker,ES (1973b)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	21 pg/mL	28	0.045/day		Subba-Rao,RV et. al. (1982)
Bis(2-ethylhexyl)phthalate	Fish-Pesticide Research Laboratory, MO	Uncontaminated	Freshwater hydrosoil	Lab microcosm	1 m/L	30	0.045/day		Johnson,BT & Lulves,W (1975)
Bis(2-ethylhexyl)phthalate		Plasticizer manufacturing site	Soil	Lab microcosm	1120 mg/kg	49	0.051/day		Fogel,S et. al. (1995)
Bis(2-ethylhexyl)phthalate	Ogawa River, Japan	Uncontaminated	River water	Lab microcosm		17	0.064/day	3	Hattori,Y et. al. (1975)
Bis(2-ethylhexyl)phthalate	Osaka Bay, off Tomokeshima, Japan	Uncontaminated	Seawater	Lab microcosm		19	0.065/day	3	Hattori,Y et. al. (1975)
Bis(2-ethylhexyl)phthalate			Soil	Lab microcosm	480 ug/g	30	0.082/day		Shanker,R et. al. (1985)
Bis(2-ethylhexyl)phthalate	Ogawa River, Japan	Uncontaminated	River water	Lab microcosm		17	0.085/day	3	Hattori,Y et. al. (1975)
Bis(2-ethylhexyl)phthalate	the Netherlands	Uncontaminated	River water	Lab microcosm	50 ug/L	14	0.13/day		Schouten,MJ et. al. (1979)
Bis(2-ethylhexyl)phthalate	Osaka Bay, near costal factory, Japan	Uncontaminated	Seawater	Lab microcosm		19	0.23/day	2	Hattori,Y et. al. (1975)

Table 23. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	450 ng/L		100 pg/L/hr		Rubin,HE et. al. (1982)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	5 ug/L		2 ng/L/hr		Rubin,HE et. al. (1982)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	200 ug/L		450 ng/L/hr		Rubin,HE et. al. (1982)
Bis(2-ethylhexyl)phthalate	Beebe Lake, Ithaca, New York	Uncontaminated	Lake water	Lab microcosm	40 ng/L		50 pg/L/hr		Rubin,HE et. al. (1982)
Bis(2-ethylhexyl)phthalate	Rhine River, the Netherlands	Uncontaminated	River water	Lab microcosm	3.3 ppb	10	No biodegradation		Ritsema,R et. al. (1989)
Bis(2-ethylhexyl)phthalate	White Lake, Old Forge, New York	Uncontaminated	Lake water	Lab microcosm		60	No biodegradation		Rubin,HE et. al. (1982)
Bis(2-ethylhexyl)phthalate	Lower Saxonia, Germany	Uncontaminated	Soil	Lysimeter		100	0.003/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate	Lower Saxonia, Germany	Uncontaminated	Soil	Lysimeter		100	0.013/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate	Northrhine-Westfalia, Germany	Uncontaminated	Soil	Lysimeter		100	0.033/day		Ruedel,H et. al. (1993)
Bis(2-ethylhexyl)phthalate	Northrhine-Westfalia, Germany	Uncontaminated	Soil	Lysimeter		100	0.05/day		Ruedel,H et. al. (1993)

3.5.2. Methanol

Methanol is readily biodegraded under aerobic conditions in most cases (Table 24). First-order rate constants for biodegradation were less than or equal to 0.693/day in laboratory studies. The sole field study reported a rate constant of 0.019/day ($T_{1/2}$=36 days) (American Petroleum Institute, 1994).

Several experiments in two studies reported no biodegradation of methanol over the time period measured. Work by Pugh et. al. (1996) at a former pharmaceutical tank farm, showed that methanol concentrations did not uniformly decrease in laboratory microcosms. However, the presence of other compounds including acetone and isopropanol, suggest that methanol is being produced by the degradation of these compounds. Thus, the degradation of methanol may be masked by its concurrent production. The American Petroleum Institute (1994) reported that methanol was readily degraded in a field experiment following a lag phase of 100 days; however, in laboratory microcosm studies where methanol concentrations ranged from 1000 to over 7000 mg/L, no biodegradation of methanol was seen over time periods of up to 200 days (American Petroleum Institute, 1994A). These concentrations may be too high to allow microbial populations to exist readily. In addition, incomplete oxidation of methanol leading to the production of formaldehyde could act to inhibit microbial populations. In a field environment where physical processes such as dilution and dispersion initially act to lower concentrations, biodegradation appears to be facilitated.

The median for the primary biodegradation rate constant of methanol is 0.118/day (N = 20); a range of not biodegraded to 0.693/day is reported. The frequency distribution histogram for this data is shown in figure 22.

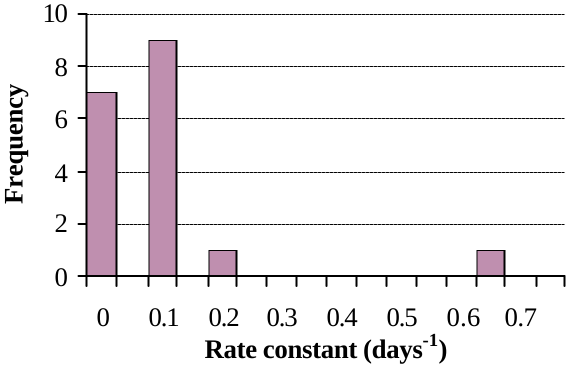

Figure 22. Frequency histogram for the published primary biodegradation rate constant values of methanol.

Table 24. Aerobic biodegradation rate constant values for methanol

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Methanol	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Field	7034 mg/L	476	0.019/day	100	American Petroleum Institute (1994)
Methanol		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		127			Pugh,LB et. al. (1996)
Methanol	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	7318 mg/L	278		>103	American Petroleum Institute (1994A)
Methanol	Mamma Rhoda Channel, Bahamas	Uncontaminated	Seawater	Lab microcosm	1 ug/L		0.00002 ug/L/day		Hwang,HM et. al. (1989)
Methanol		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	0.007/day		Pugh,LB et. al. (1996)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	750 mg/L	185	0.0134/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	750 mg/L	185	0.0134/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	820 mg/L	185	0.0159/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	700 mg/L	185	0.0179/day		Novak,JT et. al. (1985)
Methanol		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		24	0.027/day		Pugh,LB et. al. (1996)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	93 mg/L	26	0.125/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	100 mg/L	23	0.130/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	106 mg/L	26	0.131/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	107 mg/L	26	0.131/day		Novak,JT et. al. (1985)

Table 24. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	106 mg/L	26	0.131/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	102 mg/L	23	0.131/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	120 mg/L	23	0.138/day		Novak,JT et. al. (1985)
Methanol	Pennsylvania	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	120 mg/L	23	0.138/day		Novak,JT et. al. (1985)
Methanol		Uncontaminated	Soil	Lab microcosm		5	0.153/day		Scheunert,I et. al. (1987)
Methanol	Wiggins, Mississippi	Uncontaminated	Soil	Lab microcosm	740 mg/kg soil	65	0.216/day		Loehr,RC & Matthews, JE (1992)
Methanol	Mamma Rhoda Channel, Bahamas	Uncontaminated	Seawater	Lab microcosm	500 ug/L		0.63 ug/L/day		Hwang,HM et. al. (1989)
Methanol	Austin Texas	Uncontaminated	Soil	Lab microcosm	740 mg/kg soil	65	0.693/day		Loehr,RC & Matthews, JE (1992)
Methanol		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	No biodegradation		Pugh,LB et. al. (1996)
Methanol		Pharmaceutical plant underground tank farm	Soil + groundwater	Lab microcosm		30	No biodegradation		Pugh,LB et. al. (1996)
Methanol	Canada Forces Base, Borden, Ontario	Uncontaminated	Aquifer sediment + groundwater	Lab microcosm	1039 mg/L	232	No degradation	>114	American Petroleum Institute (1994A)
Methanol		Pharmaceutical plant underground tank farm	Soil + groundwater	Reactor system	23 mg/L	32	0.118/day		Pugh,LB et. al. (1996)

4. SUMMARY

Syracuse Research Corporation has compiled aerobic biodegradation rate constant information for 23 compounds in a single database. This database currently holds 1450 records from 194 different references. A summary of the aerobic biodegradation rate constant statistics for these compounds is presented in Table 25. If the compound had sufficient data, results were divided into primary biodegradation and mineralization studies, and values for median and range determined for each. No further division of the results was attempted although studies were completed under different conditions of temperature, substrate concentration, nutrients, environmental media, in the presence of other compounds, *etc*. Each of these conditions is expected to affect the outcome of the results, and in some cases will do so considerably. However, the results given in Table 25 are present to provide a data summary for this report as well as a comparison of rate constant values among compounds grouped together as shown. Mean values are not reported in this table as a number of very high rate constant values for some of the reported compounds had a strong weighting effect on the data.

A comparison of median rate constant values between groups is not advised as: 1. some groups of compounds appear to be studied almost exclusively in one particular environment (*e.g.* BTEX compounds in groundwater environments, PAHs in soil environments), and 2. limited data were located for some compounds. Studies completed in the same environment but by different authors may produce very different degradation rates, depending on the location, study conditions, whether other compounds were present, *etc*. Thus, the statistical data reported here may be skewed based on the studies available for a compound (*e.g.* more studies with large rate constants were summarized than those with smaller rate constants), particularly if only a few studies were found. The same papers tended to be reviewed within a group of compounds and thus differences within a group of similar compounds (such as within the BTEX compounds or within the PAH compounds) may be minimized.

Barker et. al. (1987) commented that the biodegradation rates of the BTEX compounds in a series of microcosm experiments were very similar to each other. The BTEX compounds, when arranged by median rate constant, show the order: toluene > ethylbenzene > benzene > m-xylene, o-xylene, p-xylene. In general, however, the differences in rate constant values between the BTEX compounds are not very great.

The PAH group, including compounds with two to five aromatic rings, had median values for primary degradation which were surprisingly similar once four rings were present in the structure. When arranged by median rate constant, the order: naphthalene > fluorene > fluoranthene > benzo(a)anthracene, pyrene, chrysene > benzo(a)pyrene is shown. This is predicted by the simple rule that compounds with fewer aromatic rings (lower molecular weight) have a more rapid biodegradation rate than those with more aromatic rings (higher molecular weight). Mineralization rate constants, when arranged by median values, followed the order: naphthalene > fluorene > pyrene > chrysene > benzo(a)anthracene >> benzo(a)pyrene. Insufficient mineralization data for fluoranthene were located to include this compound in this analysis. Individual compounds within this group had median values from primary biodegradation and mineralization studies which were surprisingly similar; benzo(a)pyrene was the only compound in this group to report at least an order of magnitude difference between study types. This result may be due to the tendency to run mineralization studies in the presence of the studied PAH only, while primary biodegradation studies tended to use a mixture of PAH compounds.

The phenol group had some of the highest median rate constant values within this report. These compounds are expected to biodegrade rapidly in the environment. The order of median primary biodegradation rate constant values follows: p-cresol > o-cresol > phenol > m-cresol. The median mineralization rate constant for phenol however, is much greater than that for primary degradation. If this value is used then the order is: p-cresol > phenol > o-cresol > m-cresol. The results from the cresol isomers follows the order predicted by Medvedev and Davidov (1981). Mean values for aerobic biodegradation rate constants for the cresol isomers were 2.49 day^{-1} (std. deviation=2.74 day^{-1}), 1.17 day^{-1} (std. deviation=1.64 day^{-1}), and 0.42 day^{-1} (std. deviation=0.44 day^{-1}) for p-cresol, o-cresol, and m-cresol, respectively. The extent of the difference in mean and median rate constant values seems high but may only be an artifact of the studies summarized in this database.

The determination of median values as a method of comparison between compounds in a group mainly has context within this compiled data set. As new data from other types of environmental media and other locations are added, these results may change, especially if relatively little information is currently available for a particular compound. In general, however, it is evident from these data that most of the studied compounds are susceptible to aerobic biodegradation in most environments. Within this set of compounds, only the highly chlorinated aliphatic compounds and the high molecular weight PAHs currently appear to be resistant to degradation in an oxygenated environment.

Table 25. Summary of median and range of aerobic biodegradation rate constant values for compounds listed in document

Group	Compound	Median(day^{-1})	Range (day^{-1})	N=
BTEX Compounds	Benzene (Mineralization)	0.0013	0-0.087	30
	Benzene (Primary degradation)	0.096	0-3.3	118
	Toluene (Mineralization)	0.00895	0-0.149	31
	Toluene (Primary degradation)	0.20	0-42.5	182
	Ethylbenzene (Primary degradation)	0.113	0.003-4.8	21
	o-Xylene (Primary degradation)	0.054	0-7.625	92
	m-Xylene (Primary degradation)	0.057	0-0.76	32
	p-Xylene (Primary degradation)	0.052	0-0.56	27
PAH Compounds	Naphthalene (Mineralization)	0.023	0-3.34	44
	Naphthalene (Primary degradation)	0.308	0-5.0	46
	Fluorene (Mineralization)	0.019	0.00385-0.05	7
	Fluorene (Primary degradation)	0.015	0.0018-0.33	28
	Benzo(a)anthracene (Mineralization)	0.0029	0-0.116	32
	Benzo(a)anthracene (Primary degradation)	0.0035	0.000096-0.072	27
	Chrysene (Mineralization)	0.0037	0-0.035	20
	Chrysene (Primary degradation)	0.003	0-0.037	31
	Fluoranthene (Primary degradation)	0.0048	0-0.045	20
	Pyrene (Mineralization)	0.006	0-0.143	18
	Pyrene (Primary degradation)	0.00345	0-0.052	40
	Benzo(a)pyrene (Mineralization)	0.00015	0-0.0037	25
	Benzo(a)pyrene (Primary degradation)	0.0027	0-0.057	23
Chlorinated Aliphatics	Tetrachloroethylene (Primary degradation)	0	0-0.139	36
	Dichloromethane (Primary degradation)	0.0546	0.00362-0.533	8
Phenol and Substituted Phenols	Phenol (Mineralization)	1.56	0.006-7.3	26
	Phenol (Primary degradation)	0.21	0.024-11.0	38
	o-Cresol (Primary degradation)	0.40	0.069-4.61	22
	m-Cresol (Primary degradation)	0.133	0.0035-1.16	19
	p-Cresol (Primary degradation)	1.75	0.079-13.15	28
Ketones	Acetone (Primary degradation)	0.035	0-1.2	5
	Acetone (Mineralization)*	0.078	0.025-7.3	13
	Methyl ethyl ketone (Primary degradation)	0.69	0.4-1.4	3
Miscellaneous	Bis(2-ethylhexyl)phthalate (Mineralization)	0.014	0.0022-0.045	28
	Bis(2-ethylhexyl)phthalate (Primary degradation)	0.0205	0-0.23	36
	Methanol (Primary degradation)	0.118	0-0.693	20

*****Results taken from one mineralization study only.

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