AEROBIC BIODEGRADATION OF ORGANIC CHEMICALS IN ENVIRONMENTAL MEDIA: A SUMMARY OF FIELD AND LABORATORY STUDIES

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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.

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:

$$\mu = \frac{\mu_{max} S}{K_s + S} \quad \textbf{(1)}$$

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:

$$v = \frac{V_{max} S}{K_m + S} \quad \textbf{(2)}$$

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

and the integral:

$$k_0 \frac{S_0 - S}{t} \qquad \textbf{(4)}$$

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.* Fg/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

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:

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

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,

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

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 µg/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 (? t) 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:

where: C_i=initial contaminant concentration
$C_{f,corr}$=corrected final concentration of the contaminant (corrected for non-biodegradation loss)
? t=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

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

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-

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

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.

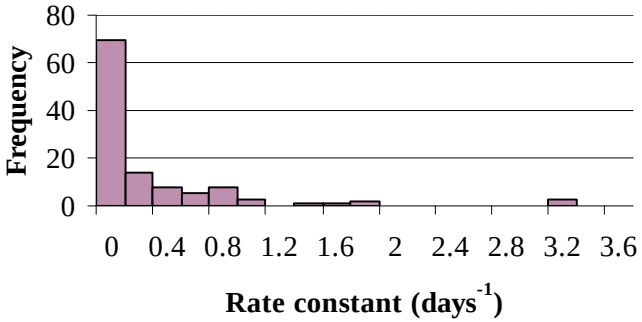

Figure 1a. Frequency histogram for the published primary biodegradation rate constant values

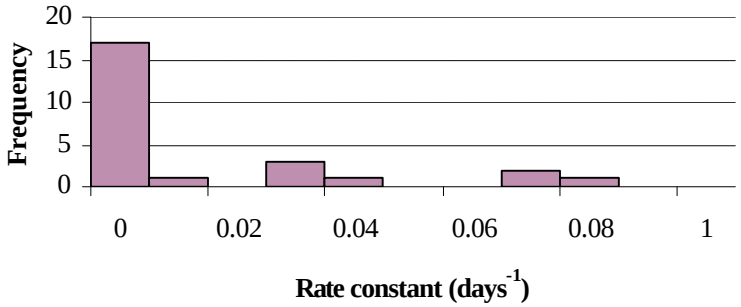

Figure 1b. Frequency histogram for the published mineralization rate constant values for benzene.

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)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
Benzene	NW Gainesville, Florida		Groundwater	Groundwater grab sample	1 mg/L	16	0.107/day	8	Delfino,JJ & Miles,CJ (1985)
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)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
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)
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)

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	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)
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)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
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)
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)

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	0.0013/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)
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)

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		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)
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)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
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)
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)

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	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)
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)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
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)
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)

Table 2. (Continued)

Compound	Site Name	Site Type	Inoculum	Study Type	Initial Concn.	Time Period (days)	Rate Constant	Lag Time (days)	Reference
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)
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)