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PROPOSED VALUES OF BIODEGRADATION RATE FOR ORGANIC CHEMICALS FOR USE IN THE BRITISH COLUMBIA CSST MODEL

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SUMMARY

This document developed recommended conservative groundwater biodegradation rates for use in the British Columbia Ministry of Environment Contaminated Sites Soil Task Group (CSST) model for developing Matrix Soil Standards. Recommended values are summarized in Table 1, and the rationale is provided in the remainder of this document.

Table 1. Summary of Recommended Values of Biodegradation Rate and Half-Life

Chemical	Rate (days^{-1})	Half-Life (days)	Rationale	Notes
BTEX				
Benzene	0.0018	390	5	
Toluene	0.0054	130	1	
Ethylbenzene	0.0024	290	1	
Xylenes	0.0024	290	5	A
PAHs				
Naphthalene	0.002	350	1	
Acenaphthene	0.0024	290	1	
Acenaphthylene	0.007	100	2b	
Fluorene	0.002	350	2b	
Fluoranthene	0.003	230	2b	
Phenanthrene	0	-	2b	
Anthracene	0.0018	390	5	
Hydrocarbon Fractions				
VPH_w	0.0039	180	1	
$LEPH_w$	0.002	350	1	
Chlorinated Ethenes				
Tetrachloroethylene (PCE)	0.00064	1,080	1	B
Trichloroethylene (TCE)	0.0003	2,310	1	B
Dichloroethylene	0.0012	580	2a	A
Vinyl Chloride	0.0013	530	2a	
Chlorinated Methanes				
Carbon Tetrachloride	0.0630	11	2b	B
Chloroform	0.011	63	2b	
Dichloromethane	0.0064	110	3	

Table 1 (cont). Summary of Recommended Values of Biodegradation Rate and Half-Life

Chemical	Rate (days^{-1})	Half-Life (days)	Rationale	Notes
Chlorinated Ethanes				
1,1,1-Trichloroethane	0.0044	160	2b	
1,2-Dichloroethane	0.006	120	3	
1,1-Dichloroethane	0.003	230	3	
Chloroethane	0.011	60	3	
Ketones				
Acetone	0.0037	190	4	
Methyl Ethyl Ketone (MEK)	0.0054	130	4	
Methyl Isobutyl Ketone (MIBK)	0.00013	5,330	4	
Other Compounds				
2,4-Dichlorophenol	0.00055	3,640	4	
Cresol [c]	0.0004	1,730	4	
Ethylene Glycol	0.0034	210	5	
Methanol	0.0028	250	2b	
MTBE	0.001	690	2a	
Nitrobenzene	0.0037	190	4	
Pentachlorophenol (PCP)	0	-	4	
Phenol	0.0013	530	4	
Trichlorofluoromethane	0.00016	4,330	4	

Notes:
See text for discussion on all compounds
A. Applies to all isomers
B. May only be applied in suitable anaerobic conditions – see Section 10 for details.
Rationale for recommended rate (refers to anaerobic field studies unless specified in text):
1. Based on the lower of i) the 25th percentile of all studies and ii) the lowest of the "High Quality" studies.
2a. Based on the 25th percentile of all studies.
2b. Based on the lowest of the "High Quality" studies.
3. Based on the lowest value from any study.
4. Lower end of the range of recommended rates presented in Aronson and Howard (1997).
5. Special case – see text for discussion.

1 INTRODUCTION

Axiom Environmental Inc. (Axiom) was retained by the British Columbia Ministry of Environment, under contract #CEMB11-160, to develop recommended conservative values for the groundwater biodegradation rate for a range of organic chemicals in groundwater. The intent is for these biodegradation rate values to be used as input parameters into the British Columbia Contaminated Sites Soil Task Group (CSST) model for developing soil standards.

1.1 Objective and Scope of Work

The objective of this project was to develop a dataset of recommended biodegradation rate values for selected organic chemicals for input into the CSST model.

The scope of work for this project was as follows.

- Review and briefly summarize relevant background material on biodegradation.
- Considering the variability in the type, amount, and quality of biodegradation rate data, develop a pragmatic approach to developing recommended biodegradation rate values which will be conservative for the majority, but not necessarily all sites.
- Project chemicals are organic chemicals for which Contaminated Sites Regulation Schedule 5 “groundwater flow to surface water” soil standards are calculated together with selected chemicals listed in Table 1 of the British Columbia Ministry of Environment document “Protocol 13 for Contaminated Sites – Screening Level Risk Assessment” for which suitable data are available.
- Abiotic degradation mechanisms are excluded from the scope of work of this project.
- For project chemicals, compile and consider available information on biodegradation rate, and, where appropriate, recommend a biodegradation rate for use in the CSST model.
- Generate a report summarizing the above.

2 BACKGROUND

2.1 Role of Biodegradation in Calculating Matrix Soil Standards

The BC Contaminated Sites Regulation (CSR) includes matrix numerical soil standards for a range of potential contaminant chemicals. These matrix numerical soil standards are provided in Schedule 5 of the CSR, and include values for several exposure pathways. The models on which the calculations for these exposure pathways are based are provided in a document entitled "*Overview of CSST procedures for the derivation of soil quality matrix standards for contaminated sites*" (BCE, 1996). Several of the models rely on predicting soil concentrations in a source area that will be protective of water quality at a downgradient location. One of the factors that enters into this model is the assumed biodegradation rate of the chemical in the subsurface. The CSST model assumes that biodegradation of chemicals occurs under first order kinetics. The recommended biodegradation rates developed in this document are intended for use in the CSST model.

2.2 Biodegradation Processes

Much has been written on the postulated mechanisms for biodegradation of chemicals in the subsurface. A very brief summary is provided here and the interested reader is directed to any of the detailed studies of this subject including Alexander (1999), Wiedemeier et al. (1999), and Neilson and Allard (2008).

A range of processes can result in the reduction of contaminant concentrations in the subsurface. Advection, dispersion, diffusion, dilution/recharge and volatilization can all change contaminant concentrations, but do not result in removal of contaminant mass. Various abiotic processes may occur that do result in the removal of contaminant mass including hydrolysis and dehydrohalogenation. This document is specifically focused on biologically mediated transformations of organic chemicals to daughter products, and the rate at which such transformations can be assumed to occur in the subsurface.

Fundamentally, bacteria break down organic chemicals because in doing so they gain energy for growth and activity. The energy is released by coupling oxidation and reduction reactions. During these growth-promoting reactions, electrons are transferred from one group of compounds, called electron donors to another group called electron acceptors. This process results in the oxidation of the electron donor and the reduction of the electron acceptor. The organic carbon undergoing biodegradation can act as the electron donor, the electron receptor, or both in a range of scenarios that are described below.

2.2.1 Biological Oxidation

One of the most common type of reaction is where an organic compound in a relatively reduced state (e.g., natural organic carbon, petroleum hydrocarbons, and lightly chlorinated aliphatics) acts as an electron donor and is degraded by oxidation. A range of potential electron acceptors may be available in the subsurface, including oxygen, nitrate, manganese (IV), iron (III), sulphate, and carbon dioxide. The thermodynamic favourability of using these different electron acceptors varies, with oxygen yielding the most energy (and typically the fastest reaction kinetics) and carbon dioxide (methanogenesis) the least energy and often the slowest rates. Bacteria utilizing the most energy-rich reaction will generally be able to out-compete others, and thus oxidation using oxygen ("aerobic biodegradation") will predominate so long as oxygen is available, with the remaining electron acceptors being used sequentially as more favoured electron acceptors are depleted.

While oxygen is the most energetically favourable electron acceptor, its availability is limited by its relatively low solubility in water. Significantly greater resources of other electron acceptors such as sulphate and carbon dioxide may be available in many cases. Wiedemeier et al. (1999) calculated the "expressed biodegradation capacity" of each for each of the electron acceptors at 38 petroleum hydrocarbon contaminated sites across the USA. They found that 95% of the capacity to degrade BTEX compounds at these sites could be attributed to anaerobic biodegradation based on iron or sulphate reduction and methanogenesis, and that only 5% of the capacity was due to use of oxygen or nitrate. This study emphasizes why biodegradation rates for use in the development of generic soil standards will normally need to be based on anaerobic biodegradation rates, particularly studies conducted under iron reducing, sulphate reducing or methanogenic conditions.

2.2.2 Biological Reduction

Biological reduction of organic compounds occurs when a chemical acts as an electron acceptor, and there is an external electron donor (often H_2). One example of this is reductive dechlorination of some chlorinated aliphatic compounds. Some more highly chlorinated aliphatics (e.g., tetrachloroethylene (PCE), trichloroethylene (TCE), and carbon tetrachloride) are already sufficiently highly oxidized that biological oxidation is thermodymically unfeasible, and reductive dechlorination may be the primary or only mechanism of biodegradation. Note that reductive dechlorination requires the presence of dissolved hydrogen, which in turn would be generated through the fermentation of other organic compounds (see below). Reductive dechlorination also requires a highly reducing environment and will not occur in either aerobic or nitrate-reducing conditions.

2.2.3 Fermentation

In fermentation reactions, different parts of the organic compound act both as electron donors and acceptors. During fermentation, organic compounds are converted to simpler molecules such as acetate, water carbon dioxide and dissolved hydrogen through a series of internal electron transfers catalyzed by microorganisms. Hydrogen is a high energy electron donor and thus is very important in a range of different processes, including reductive dechlorination.

2.2.4 Cometabolism

Cometabolism occurs when organic chemicals are degraded by an enzyme that is fortuitously produced by organisms for other purposes. Typically the biodegradation is incidental to the organism concerned. While biodegradation of chlorinated solvents can occur through cometabolism, the reaction is typically limited under natural conditions and is not a significant process at most field sites.

2.3 Rate Kinetics

The rate of a biodegradation reaction is often assumed or approximated to occur under first order kinetics. In first order decay, the rate of loss of a chemical substrate is proportional to the current concentration of that substrate, and thus degradation starts at a high rate and the rate constantly decreases thereafter in an exponential fashion. First order kinetics are described by the following equation:

(1)

Where:

C = current (time dependant) concentration of chemical
C_0 = initial concentration of chemical
k = degradation rate (units of time^{-1})
T = time (same time units as k)

In first order degradation, the half life of a chemical ($t_{1/2}$, time for the concentration to decrease to half of the starting concentration) is constant and is related to k as follows:

—— (2)

While other kinetics are possible for biodegradation (e.g., zero order kinetics, Michelis-Menten kinetics), the current project is focused on first order kinetics, since this is an assumption of the CSST model.

2.4 Units

Consistent with the standard procedure in the research literature for this field, first order biodegradation rates are generally presented and discussed in units of days^{-1}. Recommended rates are summarized in Table 1, and corresponding half lives (in days) are also tabulated to allow these values to be put more easily into context.

Degradation half lives (in units of days) are easily computed from degradation rate values (in units of days^{-1}) using equation (2). Some examples are shown in Table 2.

Table 2. Example Corresponding Values of Degradation Rate and Half-Life

Degradation Rate (days^{-1})	Corresponding Half-Life (days)
0.0001	6,931
0.0002	3,466
0.0003	2,310
0.0005	1,386
0.001	693
0.002	347
0.003	231
0.005	139
0.01	69
0.02	35
0.03	23
0.05	14
0.1	7

3 BIODEGRADATION RATES USED BY CANADIAN AND US JURISDICTIONS

Canadian and selected US regulatory agencies were polled to determine what values for biodegradation rate might already be in use in the development of soil standards. Relatively few independent values are in use, as indicated in the following summary. Values are expressed in the same format (biodegradation rate or half life) in which they are presented in the source.

In 1996, the British Columbia Ministry of Environment released its CSST protocol, and included the biodegradation half lives for saturated and unsaturated soils indicated in Table A-1. The rules used to calculate these rates were that the half life for saturated conditions ($t_{1/2\ sat}$) was calculated as 50% of the “anaerobic rate low”. The half life for unsaturated conditions ($t_{1/2\ unsat}$) was calculated from the greater of the “anaerobic rate high” and 25% of the “anaerobic rate low”. Unless $t_{1/2\ unsat} > t_{1/2\ sat}$, then $t_{1/2\ unsat}$ equals $t_{1/2\ sat}$. The database from which these values were calculated is no longer available.

In 2000, the CCME (2000) developed the Canada-Wide Standards for Petroleum Hydrocarbons (PHC CWS) using the BC CSST model for groundwater pathways. They conducted a literature review of petroleum hydrocarbon biodegradation rates and developed biodegradation half lives of 712 days and 1,750 days for petroleum hydrocarbon fractions F1 and F2, respectively (applicable to both saturated and unsaturated conditions). In 2006, the CCME developed a groundwater biodegradation half life of 800 days for TCE based on research carried out for a revised soil quality guideline for that chemical (Table A-2).

The 2010 Alberta Environment Tier 1 soil remediation guidelines document (AENV, 2010) includes groundwater biodegradation half lives for a range of compounds. In this document, biodegradation half lives for BTEX were adopted from BC CSST $t_{1/2\ sat}$, values. Rates for F1 and F2 were adopted from the PHC CWS. The rate for TCE was adopted from the CCME TCE guideline. Rates for other chemicals were developed independently (Table A-3).

In 2008, the British Columbia Ministry of Environment finalized *Protocol 13 for Contaminated Sites – Screening Level Risk Assessment*. This included biodegradation rates for eight compounds (Table A-4).

In 2008, Health Canada developed a spreadsheet for use with its PQRA risk assessment tool for Federal Contaminated Sites which included biodegradation half lives adopted from CCME or BC CSST sources, as indicated in Table A-5.

Other information from North American regulatory agencies is as follows.

- The Ontario Ministry of the Environment indicated that they do not use soil or groundwater biodegradation rates in the calculation of their soil standards, but did at one point compile a list of soil biodegradation rates, based primarily on Table 9.9 in Dragun (1988).
- Manitoba Environment indicated that they follow CCME guidance and do not use any independent values of biodegradation rate.
- Yukon Environment indicated that they generally follow BC guidance on soil standards, and do not use any independent values of biodegradation rate.
- The Saskatchewan and Nunavut environment ministries indicated that they do not use biodegradation rates in their regulatory framework.
- The Massachusetts Department of Environmental Protection indicated that they do not use biodegradation rates in the calculation of their soil standard values.

4 APPROACH

Many compounds have a large database of studies that can indicate a large range of biodegradation rates. The observed range in values can be partly due to inherently differing rates seen under differing redox conditions, in addition to effects from a large range of site and/or test-specific factors, many of which will not be known in a particular case.

4.1 Types of Study

Essentially, biodegradation studies can be categorized into three main groups, though there are a number of standard sub-types within each group. These are ranked below in order of relevance to the objectives of this project.

1. Field studies involve monitoring contaminant concentrations over time and space within a plume and interpreting the data to yield a biodegradation rate. Studies may use chemicals already present in an existing plume, or chemicals injected into groundwater (typically within an existing plume). Care must be taken to distinguish biodegradation from other processes that change contaminant concentrations including advection and dispersion.
2. In situ microcosms (or “in-situ column studies”) involve setting up an apparatus to withdraw groundwater from within a contaminant plume, add contaminant chemical(s), reintroduce the spiked water to the plume and monitor contaminant concentrations over time. Typically this is undertaken using a column driven into the plume, but may use hydraulic isolation to achieve the same goal.
3. Laboratory microcosm studies essentially involve monitoring chemical concentrations over time in a laboratory microcosm (container) that includes the chemical of interest, water, and a source of bacteria which would often be soil/aquifer material. The most relevant laboratory microcosm data would ideally duplicate the conditions in a groundwater plume as closely as possible, in terms of redox conditions, temperature, dark, lack of agitation, and lack of additional nutrients etc.

Literature values for lab biodegradation studies can often be orders of magnitude higher than for field-generated studies, calling into question the relevance of lab-generated values for characterizing the persistence of organic contaminants in the environment (Washington and Cameron, 2001). Therefore, where possible, in this project, biodegradation rates are developed based on field study data. In general, in-situ microcosm data were not included in the dataset, though data from some “push-pull” field experiments were included. These tests are essentially very large scale in-situ microcosms using hydraulic isolation, and thus are a hybrid between an in-situ microcosm and a field injection test. Where field data were unavailable or inadequate, laboratory data were considered on a case-specific basis.

4.2 Redox Regime

As noted in Section 2.2.1, the majority of environmentally relevant chemicals that are biodegraded in the subsurface (with the notable exception of chlorinated aliphatic chemicals) undergo biological oxidation, i.e., they act as electron donors, and utilize an electron acceptor. For compounds in this group, the thermodynamic favourability, and hence very often the biodegradation rate decreases through the following series of typical electron acceptors: oxygen, nitrate, iron (III), sulphate, and carbon dioxide (Wiedemeier et al., 1999). The biodegradation rate data for many compounds support this trend, with rates for aerobic biodegradation and nitrate reduction being more rapid than rates for biodegradation under iron reducing, sulphate reducing, or methanogenic conditions. The US EPA (1999) consider only studies conducted under iron reducing, sulphate reducing, or methanogenic conditions to be suitable for developing biodegradation rates for modelling natural attenuation of groundwater plumes.

For ease of reference, in this report, the redox conditions using oxygen, nitrate, iron, sulphate, and carbon dioxide as electron acceptors are referred to, respectively, using the following shorthand: aerobic, NO_3, Fe, SO_4 and methanogenic conditions, with the last four being collectively referred to as anaerobic.

In addition, Wiedemeier et al. (1999) calculated the “expressed biodegradation capacity” of 38 sites based on the amount of BTEX that could be biodegraded by the available electron acceptors at each site. These authors found that iron Fe, SO_4 and methanogenic conditions accounted for 95% of the total capacity of a site to degrade BTEX, and that aerobic biodegradation and nitrate reduction were relatively insignificant.

Considering the above, for chemicals that degrade by biological oxidation, the current project focuses as far as possible on data relating to Fe, SO_4 and methanogenic conditions.

As noted in Section 2.2.2, some of the more highly chlorinated aliphatic compounds, including tetrachloroethylene, trichloroethylene, and carbon tetrachloride, are themselves sufficiently highly oxidized that biological oxidation is thermodynamically unfeasible (Wiedemeier et al., 1999). These compounds may degrade by reductive dechlorination. For such compounds, careful consideration was given to data for all possible redox conditions to select an appropriate biodegradation rate for the current project.

4.3 Studies Indicating "No Biodegradation"

Some compilations of biodegradation rate data for field studies include one or more studies where no biodegradation could be inferred from the study results. These studies are sometimes erroneously interpreted to indicate that the effective biodegradation rate for the chemical in question was, in fact, zero. Closer consideration of these studies will, in many cases, provide an alternative, and more appropriate interpretation.

Consider a compound that degrades at a rate of approximately 0.001 day^{-1} (corresponding half life 693 days). A study with an effective duration of 5 years would show almost an order of magnitude decrease in concentration over this time frame, and would likely provide the data to allow a realistic estimate of this biodegradation rate to be calculated. A study with an effective duration of 90 days, however, would observe less than a 10% decrease in chemical concentration, which likely would not be considered significant. The best interpretation of the data from the second study might be something like "the biodegradation rate for the compound studied appears to be less than 0.004 day^{-1}". But the second study cannot conclude that the biodegradation rate is zero.

In general, no study can demonstrate that the biodegradation rate of a particular compound is zero. In most cases, studies that do not allow the calculation of a biodegradation rate should be interpreted as indicating a rate less than a certain value.

Care must be taken in assessing the effective study duration. In the early 1990s, several field studies were conducted by injecting contaminants into existing plumes and monitoring chemical contaminants at a "fence" of downgradient piezometers, often at 1, 2 or 5 m downgradient. Sometimes these studies were conducted over an extended period of 1-2 years, but the effective duration was much shorter, often a few tens of days, controlled by the residence/transit time of a chemical between injection well and fence.

In this report, studies that do not allow a degradation rate to be calculated were generally not included, since they typically do not add to the understanding of biodegradation kinetics in the subsurface. Exceptions were made for a few high quality studies for a small number of chemicals which had solid data supporting a particularly low degradation rate for a given chemical under specific conditions. These cases are discussed individually for each chemical as appropriate.

4.4 Saturated and Unsaturated Biodegradation Rates

No attempt was made to develop separate biodegradation rates for saturated and unsaturated conditions. The conservative assumption was made that anaerobic conditions can develop either in groundwater or in a source area in the vadose zone, and therefore the biodegradation rates developed based on the least favourable redox conditions for each chemical are applicable to both saturated and unsaturated zones.

4.5 Data Screening

Available studies that provide a first order anaerobic biodegradation rate from a field-based study are summarized for each project chemical in Appendix B. Essentially all datapoints (i.e., calculated biodegradation rates) from such studies are included without any screening. Only field studies are included in the listing, except in the special case of ethylene glycol, where laboratory studies are included (no field studies were available for this Schedule 5 compound).

Consistent with the approach of Aronson and Howard (1997), where multiple biodegradation rate values are available for one study (typically either relating to different portions of the same plume, or different analyses of the same data), all calculated values are included. Obvious duplications of the dame data are excluded.

Studies that indicated that biodegradation occurred, but no rate could be (or was) calculated are not included, as these studies provide no quantitative data. Studies that were included in other data compilations (see Section 5) and were reported as indicating “no biodegradation”, were reviewed, and most often excluded from the data compilation based on the reasons given in Section 4.3. Where a rate of “0” appears in appendix B, that study has been carefully reviewed and interpreted to genuinely indicate an effectively zero rate of biodegradation under those test conditions.

4.6 Study Quality

Fundamentally, all field studies that develop biodegradation rates for organic chemicals in groundwater try to determine the actual chemical distribution, compare that to the distribution that would have been expected under the influence of advection and dispersion alone, and calculate the biodegradation rate that is required to account for the difference.

Many studies (explicitly or implicitly) use measured hydraulic gradient, a few measurements of hydraulic conductivity, and generic assumptions about dispersivity to calculate the contaminant distribution that would have developed under advection and dispersion alone. However, due to the heterogeneity of many shallow groundwater systems, there can be significant uncertainty introduced by this approach. Measured hydraulic conductivity from a single groundwater unit within the boundaries of a site can often have an order of magnitude or more of variability/uncertainty. This uncertainty is reflected in a corresponding uncertainty in the calculated biodegradation rate when this approach is used.

A few studies, particularly those involving injection of contaminants into a groundwater system use a conservative tracer, such as bromide, chloride, or a range of synthetic dye compounds. Use of a tracer allows an accurate determination of how a contaminant plume would have evolved under the influence of advection and dispersion alone. Then the difference between the location and distribution of the tracer and that of the chemical under investigation can be attributed to biodegradation processes, and a biodegradation rate calculated with much greater confidence.

For this reason, studies which employed a conservative tracer to determine the groundwater flow field are designated "High Quality" studies, are indicated in the tables in Appendix B with a "+" symbol and bold text, and are accorded more weight than other studies. Studies which, in addition to using a tracer, included an unusually high number of monitoring points, and/or were conducted over an unusually long duration, are accorded even higher confidence and are designated with a "++" symbol.

Note that, particularly in studies from the mid 1990s, some of the trimethyl benzene compounds were considered to be recalcitrant, and suitable for use as an in-situ tracer. However, more recent studies (Table B-13; Figures 1 and 3) seem to indicate that trimethylbenzenes can degrade about as rapidly as other BTEX components, and accordingly, studies using a trimethylbenzene tracer are not included in the "High Quality" group.

4.7 Methodology for Developing Recommended Biodegradation Rates

The scope of this project involves developing biodegradation rates for a wide range of chemicals. Some of these chemicals have been thoroughly studied and have a large dataset. Others have a very limited dataset. For this reason, a multi-level approach was adopted with the overriding goal of making the most appropriate use of the available data.

The following methodology was used in most cases to develop a recommended biodegradation rate (see Table 1 for values). All available field-based studies yielding anaerobic groundwater biodegradation rates for each compound were tabulated in Appendix B, arranged in order of increasing rate. Wherever ten or more data points were available, the 25th percentile of the distribution of biodegradation rates was calculated (A; values summarized in Table B-1). Where one or more "High Quality" data points (see Section 4.6 above) were available, the lowest biodegradation rate from a High Quality" study was identified (B). The recommended biodegradation rate was developed using the following procedures in order of preference (the same numbering scheme is used in the rationale column of Table 1, and is explained in the notes to that table).

1. If both “A” and “B” values were available, the lower was adopted as the recommended biodegradation rate.
2. If either “A” or “B” values were available, that value was adopted as the recommended biodegradation rate.
3. If neither “A” nor “B” values were available, but anaerobic field groundwater biodegradation rate data were available, then the lowest of the rates was used (C).
4. If neither “A” nor “B” values were available, and no anaerobic field groundwater biodegradation rate data were available, then the low end of the recommended range of values given in Aronson and Howard (1997) was used, where available.

In a few cases it was considered appropriate to deviate from the above procedure. Rationale for such special cases is provided in the discussion for that chemical (and indicated as “5” in the rationale column of Table 1).

Where available, values from other comparable compilations were used for comparison purposes.

For chlorinated aliphatics, consideration is also given to aerobic studies, where available. For compounds where aerobic biodegradation is very limited or non-existent, the recommended rate is only applicable at sites where sufficiently anaerobic conditions can be demonstrated. The procedure for demonstrating sufficiently anaerobic conditions is provided in Section 10.

5 COMPILATION STUDIES

A number of large compilations of data for groundwater biodegradation rates have been compiled and some of these compilations are a key resource for this study. Selected compilations are described here and the results for individual chemicals are discussed in the relevant section. In some cases the biodegradation rates in Appendix B were taken directly from tabulated values in the compilation studies. In other cases, the original paper was consulted. In all cases, this is indicated in the “Source” column of the Tables in Appendix B.

Howard et al. (1991) generated one of the earliest compilations of environmental biodegradation rate data for soil, air, surface water and groundwater for a large database of 336 chemicals. However, many of the groundwater biodegradation rates are from professional judgement based on a few aerobic grab samples, and this compilation is now dated since so much research has been done since this time, and is only considered in the current study where other data are lacking.

Wilson et al. (1996a) compiled and/or recalculated first order degradation groundwater rates for chlorinated ethene compounds from eleven sites.

Aronson and Howard (1997) conducted a thorough review of a large amount of the literature on anaerobic biodegradation for 44 compounds including BTEX, PAHs, chlorinated aliphatics, phenols, ketones and others. Key study parameters including rate constants were collected from eight types of groundwater study: batch reactor, batch reactor with a groundwater inoculum, column studies, field studies, groundwater grab sample, groundwater inoculum, in situ microcosm and laboratory microcosm studies. Studies conducted under all anaerobic regimes were considered – NO_3, Fe, SO_4 and methanogenic conditions. Aerobic studies were not included. The data for each chemical were reviewed, and a range of recommended groundwater biodegradation rates was provided. The low end of the range was typically the lowest anaerobic field rate, and the upper end of the recommended range was typically the mean value of the entire anaerobic field and laboratory anaerobic dataset.

Aronson et al. (1999) conducted a thorough review of the literature on aerobic biodegradation for 23 compounds including BTEX, PAHs, chlorinated aliphatics, phenols, ketones and others. Aerobic biodegradation data were compiled for soil, surface water, and sediment as well as aquifer environments. The data for each chemical were reviewed, and the overall range and median biodegradation rates were summarized. Separate values were provided, where possible, for primary biodegradation and complete mineralization.

Suarez and Rifai (1999) reviewed a total of 133 studies on the biodegradation of fuel hydrocarbons, and 138 studies on chlorinated aliphatics. They sorted the data for each chemical by biodegradation mechanism (aerobic, anaerobic, broken down by electron acceptor, reductive dechlorination etc.) and compiled statistics for each compound and each process. The authors generated summary statistics including minimum, maximum, median, 25th and 75th percentiles of the distribution of biodegradation rates. Their study does not provide either references to the studies used or any tabulation of individual rate values. Accordingly, relatively little use is made of this study since it is difficult to evaluate its relevance to the current project.

The United States Environmental Protection Agency (US EPA, 1999) generated a compilation of anaerobic biodegradation rates based on the data in Aronson and Howard (1997), but applying more restrictive screening criteria, and limiting the compilation to Fe, SO_4 and methanogenic conditions.

Wilson and Kolhatkar (2002) compiled and/or recalculated first order degradation groundwater rates for MTBE compounds from five sites.

Ulrich et al. (2010) compiled first order biodegradation rates for BTEX components that were specific to cold groundwater temperatures. They used a combination of studies that were conducted at low temperatures and a correction algorithm to develop minimum (95% confidence interval) biodegradation rates for BTEX at 5ºC, 10ºC, and ambient temperatures. This compilation is of particular interest and relevance to the current study since the temperatures considered are relevant to typical groundwater temperatures in British Columbia and several previously unpublished studies from Western Canada are included.

6 HYDROCARBONS

6.1 BTEX

The BTEX compounds – benzene, toluene, ethylbenzene, and xylenes – are some of the most frequently found organic compounds at contaminated sites due to their ubiquitous presence in fuel hydrocarbons. The biodegradation kinetics of these compounds in groundwater have been correspondingly well studied.

In addition to the compilation studies discussed in Section 5, there are a number of studies available which compile statistics from a large number of BTEX plumes in various areas of the United States. These studies summarize key parameters, such as plume length, concentration trends, and plume composition, but not necessarily explicit compound biodegradation rates for a group of groundwater plumes. These studies are useful, since they can be used to make generalizations about how the vast majority of BTEX plumes behave. These studies include:

- Newell et al. (1990) – plume data from 400 US sites for a wide range of contaminant chemicals based on a questionnaire sent out to National Groundwater Association members ("The HGDB database").
- Rice et al. (1995) – plume data for 271 leaking underground fuel tank sites in California, ("the California LUFT Study").
- Mace et al. (1997) – plume data from 217 fuel hydrocarbon release sites in Texas ("The Texas Study").
- Groundwater Services Inc. (1997) – plume data from 117 leaking underground storage tank sites in Florida ("the Florida Study").

Newell and Connor (1998) compiled BTEX data from the four studies above to give a combined dataset of 604 sites and found the following:

- Median BTEX plume length was 40 m.
- 90th percentile plume length was 97 m.
- 98.1% of plumes were less than or equal to 274 m long.
- Approximately 75% of plumes were stable or shrinking.

Various authors, including Wiedemeier et al. (1999) have considered these compilations, and concluded that overall, the data are consistent with biodegradation of BTEX being active at the vast majority of real world contaminated sites.

Based on the mean values for multiple studies presented in Aronson et al. (1999) it appears that for aerobic biodegradation, toluene is the most readily degraded BTEX component, and xylenes the least, with benzene and ethylbenzene at similar, intermediate values. For anaerobic biodegradation, based on information in Aronson and Howard (1997), Suarez and Rifai (1999), and Ulrich (2010), toluene again appears to be the most readily degraded, followed by ethylbenzene and xylenes at similar rates, then benzene. It is noted that the recommended biodegradation rates for BTEX compounds in Table 1 follow this same order.

Available data on BTEX groundwater biodegradation rate from anaerobic field studies are summarized in Tables B-2 to B-5, and are illustrated in Figure 1.

6.1.1 Benzene

Benzene biodegradation rate data from anaerobic field studies are summarized in Table B-2.

Benzene has generally been shown to degrade readily under aerobic conditions. Aronson et al. (1999) found a median aerobic biodegradation rate of 0.096 day^{-1} (n=118). Benzene also degrades under anaerobic conditions. Aronson and Howard (1997) indicate that mean anaerobic biodegradation rates under NO_3, Fe, SO_4 and methanogenic conditions were 0.023, 0.035, 0.016, and 0.005 day^{-1}, respectively, with mean rates generally decreasing in the order that would be expected by thermodynamics. This project is looking for a conservative value to apply to real-world groundwater plumes so focused on the anaerobic dataset.

Under anaerobic conditions, benzene appears to be the most slowly degraded of the BTEX compounds. It has been speculated that this is partly due to the symmetry of the electron distribution in the aromatic ring (Gibson and Subramanian, 1984). Laboratory microcosm data compiled in Aronson and Howard (1997) indicate that biodegradation rates have been measured in microcosms under all anaerobic regimes. However, quite a number of laboratory microcosm studies have also shown benzene not to biodegrade under various anaerobic conditions. It is unclear to what extent this may be due to the test durations not being long enough to be able to quantify the slow rate of anaerobic benzene biodegradation.

A similarly complex picture comes out of the database of field studies, with some showing biodegradation for benzene, and others no biodegradation. However, for practical purposes, Aronson and Howard (1997) point out that in large databases from hundreds of sites, the vast majority of benzene plumes do not extend beyond approximately 100 m (with 5 or 10 ppb being used to define plume limits), and thus benzene biodegradation does seem to be active at the majority of field sites. Aronson and Howard (1997) speculate that aerobic biodegradation at the periphery of the plume may contribute to benzene biodegradation. Wiedemeier et al. (1999) looked for, but did not find, a “chromatographic effect” (where benzene plumes would typically extend further than the plumes of other BTEX components) by plotting benzene concentrations against concentrations of other BTEX components for large datasets of hydrocarbon plumes.

Based on this, Wiedemeier et al. (1999) concluded that, in practice, benzene did biodegrade in the majority of plumes associated with leaking underground fuel tanks.

For the purposes of the current project, therefore, it appears that benzene does, in practice, degrade at the vast majority of real world field sites, and thus it is considered appropriate to select a non-zero biodegradation rate. Relevant data on anaerobic benzene biodegradation rates from field studies conducted under Fe, SO_4 and methanogenic conditions, are discussed below.

Aronson and Howard (1997) made an extensive compilation of anaerobic laboratory microcosm, in-situ microcosm and field biodegradation studies for benzene. The authors recommended values of benzene groundwater biodegradation rate in the range 0 day^{-1} to 0.0036 day^{-1}. The former was the lowest measured field value, and the latter was the mean value for the field and in-situ microcosm dataset. This compilation included 13 data points from 9 studies that either provided, or were interpreted to yield groundwater biodegradation rates from field studies of groundwater plumes under Fe, SO_4 or methanogenic conditions.

In addition the authors list a number of studies that are reported as showing no biodegradation for benzene in field studies. Three of these studies (Barbaro et al., 1992; Rugge et al., 1995; and Acton and Barker 1992) have piezometer fences at 1, 2, and 5 m from injection wells, and the residence time would likely have been insufficient to resolve biodegradation rates slower than perhaps 0.005 day^{-1}. Closer inspection of two other studies, Reinhard et al. (1984), and Beller et al. (1995) are actually consistent with benzene biodegradation occurring (though at a much slower rate than other BTEX components). One study using fully deuterated benzene (Thierrin et al, 1995) showed no measurable biodegradation in the plume core, but biodegradation occurring at the plume margins. Overall, the field data for benzene appear consistent with benzene biodegradation occurring at the majority of sites, albeit slowly in some cases.

Ulrich et al. (2010) compiled 26 anaerobic biodegradation rates (19 field and 7 lab studies, including previously unpublished data from BC and Alberta) for benzene that were either measured at lower groundwater temperatures, or were converted to low temperature values. The lower 95% confidence limit on the mean value for the anaerobic biodegradation rate for benzene for ambient temperature, 10ºC and 5ºC were reported as 0.002, 0.002, and 0.001 $days^{-1}$, respectively.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-2 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume). They used a bromide tracer to compensate for the effects of advections and dispersion. They found no significant benzene biodegradation over the 924 days of their experiment relative to a bromide tracer. Assuming that they could have detected a 5% change in plume mass, then the lowest biodegradation rate that they could have measured would have been perhaps in the range 0.0001 to 0.00005 day^{-1}. Thus the benzene biodegradation rate from this study is considered to be <0.00005 day^{-1}. For the purposes of completing statistics, the value included in Table B-2 is 0.00005 day^{-1}. The rate from this study seems to be inconsistent with the findings of Wiedemeier et al. (1999) and others, since in practice, benzene *does* biodegrade in the vast majority of BTEX plumes in the real world. Part of the answer may lie in the potential for benzene degradation in the margins of small to medium sized BTEX plumes due to slow migration of oxygen from surrounding aerobic areas (as confirmed by the elegant Thierrin et al. (1995) study, see below). Therefore, while the Rugge et al. (1999) rate may be relevant to conditions in the core of a large landfill plume, it is likely not, in practice, particularly relevant to the vast majority of moderate sized hydrocarbon releases, and is therefore not used directly in determining a recommended degradation rate for benzene.

Reinhard et al. (2005) conducted a “push-pull” study into the anaerobic portion of a BTEX plume in a shallow sand and silt unit at Seal Beach, California. Groundwater was extracted from the plume, organic carbon, sulphate, iron, nitrate and oxygen were removed, and BTEX compounds were reintroduced at known concentrations. A bromide tracer was included, and a hydraulic buffer was injected into the well prior to the injection of the spiked groundwater. Pure methanogenic conditions were ensured by the removal of all other possible electron acceptors. Three sequential tests were run using the same injection well, injecting approximately 700 to 1,400 L of spiked groundwater, and each test was monitored periodically for 73 to 159 days. The authors calculated an overall methanogenic benzene biodegradation rate based on all three experiments of 0.003 day^{-1} (Table B-2).

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany. The redox regime in the area of interest was SO_4 and Fe reducing. Their monitoring network was relatively sparse, just 12 wells monitoring wells, but the flow field was accurately known following multiple tracer tests. Date were analyzed using three different techniques (the “centerline” method of Buscheck and Alcantar (1995); the “groundwater fence” method used by a number of authors, including Borden et al. (1997), and a new integral method involving extracting plume groundwater from pumping wells). The anaerobic biodegradation rates calculated for benzene using the various techniques and from various parts of the plume ranged from 0.046 to 0.13 day^{-1}.

Thierrin et al. (1995) conducted a study in which fully deuterated aromatic compounds (BTEX and naphthalene) were injected into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The use of deuterated compounds allows the injected chemiclas to be distinguished from background concentrations. Bromide was used as an inert tracer to minimize the uncertainty in the groundwater flow field. The data for benzene are particularly interesting, in that the vertical sampling resolution is sufficient to show biodegradation in the top and bottom portions of the plume, but little or no biodegradation in the core of the plume. This supports the Wiedemeier et al. (1999) theory that migration of oxygen into the margins of an anaerobic plume may be a factor in the field-scale biodegradation of benzene. The mean benzene biodegradation rate taken across the plume is 0.0058 day^{-1}.

One other source of information which may provide a useful insight into typical behaviour at real world field sites is the Rice et al. (1995) compilation of data from 1,094 leaking underground fuel tank sites in California. Rice et al. (1995) computed the temporal trend in the average benzene concentration in the plumes in their study. The averaging was done using a planar triangular interpolation technique based on $\log_{10}$ of benzene concentrations. Only 7.7% of the sites in the study showed increasing trends in benzene concentration (assumed to be recent releases with sources still in place). 32.8% of sites showed no significant trend in benzene concentration, assumed to represent cases where input of benzene into the plume was approximately balanced by biodegradation within the plume. 59.4% of sites showed a significant decreasing trend. For these sites with a significant decreasing trend, the median rate and 10th percentile of decrease were 0.0029 day^{-1} and 0.0015 day^{-1}, respectively (values converted from the base 10 values provided in Rice and al. (1995) to an exponential basis by multiplying by 10/e). Note that, while these values represent rates of decrease in average benzene concentration over a whole plume, they would be expected to be conservative relative to actual benzene biodegradation rate in cases where plume was stable or shrinking in size (91.9% of the plumes in the study were stable or shrinking in length).

Values considered in the derivation of a recommended groundwater biodegradation rate for benzene are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for benzene is 0.0018 day^{-1} (Table B-2).
- The lowest rate from the high quality studies listed in Table B-2, excluding Rugge et al. (1999) is 0.003 day^{-1}.
- The lower 95% confidence intervals on the mean biodegradation rates in Ulrich et al. (2010) corrected for groundwater temperature are 0.002 day^{-1} (10ºC) and 0.001 day^{-1} (5ºC).

Overall, these values are considered to be consistent, and 0.0018 day^{-1} (half life 390 days), based on the 25th percentile of the dataset compiled in this study is recommended as the groundwater biodegradation rate for benzene (Table 1).

6.1.2 Toluene

Toluene biodegradation rate data from anaerobic field studies are summarized in Table B-3.

Toluene has generally been shown to degrade readily under aerobic conditions. Aronson et al. (1999) found a median aerobic biodegradation rate of 0.2 day^{-1} (n=182). Toluene also degrades under anaerobic conditions, though rates are slower. Ulrich et al. (2010) indicated the mean toluene anaerobic biodegradation rate under Fe, SO_4 and methanogenic conditions was in the range of approximately 0.01 to 0.06 day^{-1}, while mean rates under NO_3 conditions were significantly faster, approximately 0.4 day^{-1}. Anaerobic data presented in Aronson and Howard (1997) show a similar pattern and values.

This review is focused on field studies conducted under Fe, SO_4 and methanogenic conditions, as these are expected to be the most relevant to developing a conservative biodegradation rate applicable to real-world plumes. The following compilation studies provide values or ranges for the biodegradation rate of toluene.

Aronson and Howard (1997) made an extensive compilation of anaerobic laboratory microcosm, in-situ microcosm and field biodegradation studies. The authors recommended a value of toluene groundwater biodegradation rate in the range 0.00099 day^{-1} to 0.059 day^{-1}. This compilation included 22 data points from 16 studies that either provided, or were interpreted to yield groundwater biodegradation rates from field studies of groundwater plumes under Fe, SO_4 or methanogenic conditions. One field study in their compilation indicated no biodegradation for toluene. However, this study (Rugge et al., 1995) was based on monitoring at a piezometer fence 2 m downgradient of the injection point, and the residence time was likely insufficient to see significant toluene biodegradation, and thus the results of this study are discounted for present purposes.

The slowest biodegradation rate calculated for the remaining field studies in the Aronson and Howard (1997) compilation came from data at the Tibbetts Road Superfund site near Barrington in New Hampshire (Wilson et al., 1996b). These authors calculated toluene biodegradation rates of 0.00099 day^{-1}, >0.0023 day^{-1}, and >0.0039 day^{-1} for different parts of the contaminant plume. However, the level of confidence applied to these rate values is particularly low, based on the fact that a single value for groundwater flow velocity was assumed for the whole site, while in reality, based on the glacial till stratigraphy, it is likely that there was considerable variation in this parameter, which would have affected the rate calculations.

Ulrich et al. (2010) compiled 26 anaerobic biodegradation rates (19 field and 7 lab studies, including previously unpublished data from BC and Alberta) for toluene that were either measured at, or were converted to low temperature values. The lower 95% confidence limits on the mean values for the anaerobic biodegradation rate for toluene for ambient temperature, 10ºC and 5ºC were reported as 0.009, 0.008, and 0.005 days^{-1}, respectively.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-3 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study with a bromide tracer in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume) that is described in the benzene section. These authors found a biodegradation rate for toluene under these conditions in the range of 0.028 to 0.039 day^{-1} (Table B-3).

Reinhard et al. (2005) conducted a “push-pull” study into the anaerobic portion of a BTEX plume in a shallow sand and silt unit at Seal Beach, California, described in the benzene section. The authors calculated an overall methanogenic toluene biodegradation rate based on three experiments of 0.057 day^{-1} (Table B-3).

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for toluene using the various techniques and from various parts of the plume ranged from 0.022 to 0.032 day^{-1} (Table B-3).

Thierrin et al. (1995) conducted a study in which fully deuterated aromatic compounds (BTEX and naphthalene) were injected into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The study is described in the benzene section. The rate for toluene biodegradation is in the range 0.0058 to 0.0077 day^{-1}.

Values considered in the derivation of a recommended groundwater biodegradation rate for toluene are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for toluene is 0.0054 day^{-1} (Table B-3).
- The lowest rate from the high quality studies listed in Table B-3 is 0.0058 day^{-1}.

- The lower 95% confidence interval on the mean biodegradation rate in Ulrich et al. (2010) corrected for groundwater temperature is 0.008 day^{-1} (10ºC) and 0.005 day^{-1} (5ºC).

Overall, these values are considered to be consistent, and 0.0054 day^{-1} (half life 130 days), based on the 25th percentile of the dataset compiled in this study is recommended as the groundwater biodegradation rate for toluene (Table 1).

6.1.3 Ethylbenzene

Ethylbenzene biodegradation rate data from anaerobic field studies are summarized in Table B-4.

Ethylbenzene has generally been shown to degrade readily under aerobic conditions. Aronson et al. (1999) found a median aerobic biodegradation rate of 0.113 day^{-1} (n=21). Ethylbenzene also degrades under anaerobic conditions. Aronson and Howard (1997) indicate that mean anaerobic biodegradation rates under NO_3 conditions were 0.28 day^{-1} (n=34), while mean rates for Fe, SO_4 and methanogenic conditions were significantly lower, in the range of approximately 0.011 to 0.05 day^{-1}.

This summary of the anaerobic biodegradation rate of ethylbenzene is focused on field studies conducted under Fe, SO_4 and methanogenic conditions, as these are expected to be the most relevant to developing a conservative biodegradation rate applicable to real-world plumes. The following compilation studies provide values or ranges for the biodegradation rate of ethylbenzene.

Aronson and Howard (1997) made an extensive compilation of anaerobic laboratory microcosm, in-situ microcosm and field biodegradation studies for ethylbenzene. The authors recommended values of ethylbenzene groundwater biodegradation rate in the range 0.0006 day^{-1} to 0.015 day^{-1}. The former was the lowest measured field value, and the latter was the mean value for the field and in-situ microcosm dataset. This compilation included 18 data points from 11 studies that either provided, or were interpreted to yield groundwater biodegradation rates from field studies of groundwater plumes under Fe, SO_4 or methanogenic conditions. In addition the authors list four studies that are reported to show no biodegradation for ethylbenzene in field studies. Three of these studies (Barbaro et al., 1992; Rugge et al., 1995; and Acton and Barker 1992) have piezometer fences at 1, 2, and 5 m from injection wells, and the residence time would likely have been insufficient to resolve biodegradation rates slower than perhaps 0.005 day^{-1}. Review of the fourth study, Reinhard et al. (1984), clearly indicates anaerobic biodegradation of ethylbenzene relative to chloride as a tracer in the anaerobic parts of plumes from two landfills (Woolwich, and North Bay, both in Ontario). The authors' assessment of "no biodegradation' appears in this case to be erroneous.

The slowest biodegradation rate calculated for the remaining field studies in the Aronson and Howard (1997) compilation came from data at the Tibbetts Road Superfund site near Barrington in New Hampshire (Wilson et al., 1996b). These authors calculated ethylbenzene biodegradation rates of 0.00060 day^{-1}, >0.0018 day^{-1}, and 0.0032 day^{-1} for different parts of the contaminant plume. With the same rationale as discussed for toluene above, this study is accorded very low weight.

Ulrich et al. (2010) compiled 17 anaerobic field study biodegradation rates for ethylbenzene, including previously unpublished data for 6 sites in BC and Alberta. These data were either measured at, or were converted to low temperature values. The lower 95$^{\%}$ confidence limits on the mean values for the anaerobic biodegradation rate for ethylbenzene for ambient temperature, 10ºC and 5ºC were reported as 0.002, 0.002, and 0.001 days^{-1}, respectively.

Ulrich et al. (2010) indicate three studies with "not significant" ethylbenzene biodegradation. The first of these studies, Beller et al. (1995) suggests that benzene and ethylbenzene did not decrease during the duration of the experiment in the text of the paper, however the data provided indicate that, while much slower than toluene or xylenes loss, ethylbenzene concentrations do in fact decrease consistent with a first order biodegradation rate of approximately 0.007 day^{-1} in this relatively short (60 day) study. Source data were not available for the second and third of the three studies with "not significant" ethylbenzene biodegradation in Ulrich et al. (2010), however, it is assumed, based on the other studies reviewed, that these other two studies also represent situations where the test duration was insufficient to resolve the actual biodegradation rate.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-4 and discussed below.

Reinhard et al. (2005) conducted a "push-pull" study into the anaerobic portion of a BTEX plume in a shallow sand and silt unit at Seal Beach, California, described in the benzene section. The authors calculated an overall methanogenic ethylbenzene biodegradation rate based on three experiments of 0.003 day^{-1} (Table B-4).

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for ethylbenzene using the various techniques and from various parts of the plume ranged from 0.03 to 0.125 day^{-1} (Table B-4).

Thierrin et al. (1995) conducted a study in which fully deuterated aromatic compounds (BTEX and naphthalene) were injected into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The study is described in the benzene section. The rate for ethylbenzene biodegradation is 0.003 day^{-1}.

Values considered in the derivation of a recommended groundwater biodegradation rate for ethylbenzene are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for ethylbenzene is 0.0024 day^{-1}(Table B-4).
- The lowest rate from the high quality studies listed in Table B-4 is 0.003 day^{-1}.
- The lower 95% confidence interval on the mean biodegradation rate in Ulrich et al. (2010) corrected for groundwater temperature is 0.002 day^{-1} (10ºC) and 0.001 day^{-1} (5ºC).

Overall, these values are considered to be consistent, and 0.0024 day^{-1} (half life 290 days), based on the 25th percentile of the dataset compiled in this study is recommended as the groundwater biodegradation rate for ethylbenzene (Table 1).

6.1.4 Xylenes

The biodegradation rate data from anaerobic field studies for xylenes (all three isomers are considered together in this analysis) are summarized in Table B-5.

Xylenes have generally been shown to degrade readily under aerobic conditions. Aronson et al. (1999) found median aerobic biodegradation rates in the range of 0.052 day^{-1} to 0.057 day^{-1} (n=151). Xylenes also degrade under anaerobic conditions. Aronson and Howard (1997) indicate that mean anaerobic biodegradation rates under NO_3 conditions were in the range 0.04 to 0.12 day^{-1} for the three isomers (n=91), while mean rates for Fe, SO_4 and methanogenic conditions were lower, in the range of approximately 0.005 to 0.09 day^{-1}.

This summary of the anaerobic biodegradation rate of xylenes is focused on field studies conducted under Fe, SO_4 and methanogenic conditions, as these are expected to be the most relevant to developing a conservative biodegradation rate applicable to real-world plumes. The following compilation studies provide values or ranges for the biodegradation rate of xylenes.

Aronson and Howard (1997) made an extensive compilation of anaerobic laboratory microcosm, in-situ microcosm and field biodegradation studies for xylenes. The authors recommended values of groundwater biodegradation rate in the range 0.00082 day^{-1} to 0.021 day^{-1} for the three xylenes isomers. The former was the lowest measured field value, and the latter was the highest mean value for the three isomers for the field and in-situ microcosm dataset. This compilation included 59 data points from 15 studies that either provided, or were interpreted to yield groundwater biodegradation rates from field studies of groundwater plumes under Fe, SO_4 or methanogenic conditions. In addition the authors list three studies (Barbaro et al., 1992; Rugge et al., 1995; and Acton and Barker 1992) that are reported to show no biodegradation for one or more xylenes isomers in field studies. However, the finding of “no biodegradation” in these studies is not considered relevant to the current project for the same reasons as those given in the discussion on ethylbenzene.

The slowest biodegradation rate calculated for the remaining field studies in the Aronson and Howard (1997) compilation came from data at the Tibbetts Road Superfund site near Barrington in New Hampshire (Wilson et al., 1996b). However, with the same rationale as discussed for toluene and ethylbenzene above, this study is accorded very low weight.

Ulrich et al. (2010) compiled 25 anaerobic field study biodegradation rates for xylenes, including previously unpublished data for 6 sites in BC and Alberta. These data were either measured at, or were converted to low temperature values. The lower $95^{\%}$ confidence limit on the mean value for the anaerobic biodegradation rate for xylenes for ambient temperature, 10ºC and 5ºC were reported as 0.003, 0.002, and 0.002 $days^{-1}$, respectively for m/p-xylenes, and 0.003, 0.002, and 0.001 $days^{-1}$, respectively for o-xylene.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-5 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study with a bromide tracer in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume) that is described in the benzene section. These authors found a biodegradation rate for o-xylene under these conditions in the range of 0.0014 to 0.0028 day^{-1} (Table B-5).

Reinhard et al. (2005) conducted a “push-pull” study into the anaerobic portion of a BTEX plume in a shallow sand and silt unit at Seal Beach, California, described in the benzene section. The authors calculated an overall methanogenic xylenes biodegradation rate based on three experiments ranging from 0.03 to 0.054 day^{-1} for the three xylene isomers (Table B-5).

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for toluene using the various techniques and from various parts of the plume ranged from 0.0125 to 0.12 day^{-1} (Table B-5).

Thierrin et al. (1995) conducted a study in which fully deuterated aromatic compounds (BTEX and naphthalene) were injected into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The study is described in the benzene section. The rate for xylenes biodegradation is in the range 0.0031 to 0.0055 day^{-1}.

Values considered in the derivation of a recommended groundwater biodegradation rate for xylenes are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for xylenes is 0.0024 day^{-1} (Table B-5).
- The lowest rate from the high quality studies listed in Table B-5 is in Rugge et al. (1999) which gives 0.0014 to 0.0028 day^{-1} as the range for for o-xylene.
- The lower 95% confidence interval on the mean biodegradation rate in Ulrich et al. (2010) corrected for groundwater temperature is 0.002 day^{-1} (10ºC) and 0.001 day^{-1} (5ºC).

Overall, these values are considered to be consistent, and 0.0024 day^{-1} (half life 290 days), based on the 25th percentile of the dataset compiled in this study is recommended as the groundwater biodegradation rate for xylenes (Table 1). The 25th percentile of the overall dataset is, in this case, given more weight than the lowest rate from the high quality studies for the same reasons discussed in the benzene section in relation to the Rugge et al. (1999) study.

6.2 Polycyclic Aromatic Hydrocarbons (PAHs)

Available data for anaerobic groundwater field biodegradation studies for PAHs is much more limited than that for BTEX. Data were available for seven PAH compounds, naphthalene, acenaphthene, acenaphthylene, fluorene, fluoranthene, phenanthrene, and anthracene. Studies which evaluated PAH biodegradation in soil, rather than groundwater were not included. The PAH compounds for which data were available comprise some of the more commonly analyzed two and three ring PAHs. All these PAHs with the exception of fluoranthene have equivalent carbon numbers in the range 10 to 20, and thus are included in $LEPH_w$.

No anaerobic groundwater biodegradation rate data were available for PAHs with four or more aromatic rings. These PAHs all have equivalent carbon numbers greater than 20, and thus are included in $HEPH_w$. In addition, these 4+ ring PAHs all have low solubility ($<150\ \mu g/L$) and high Koc values ($>2 \times 10^4$ L/kg). Accordingly, the 4+ ring PAHs are expected to have very low mobility, and thus will rarely be a concern for groundwater mediated pathways.

Available data on PAH groundwater biodegradation rate from anaerobic field studies are summarized in Tables B-6 to B-12, and are illustrated in Figure 2.

6.2.1 Naphthalene

Available data on naphthalene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-6.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-6 and discussed below.

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for acenaphthene using the various techniques and from various parts of the plume ranged from 0.002 to 0.035 day^{-1} (Table B-6).

Thierrin et al. (1995) conducted an injection study with fully deuterated aromatic compounds (BTEX and naphthalene) into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The study is described in the benzene section. The rate for naphthalene biodegradation was in the range 0.021 to 0.043 day^{-1}.

Values considered in the derivation of a recommended groundwater biodegradation rate for xylenes are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for xylenes is 0.0028 day^{-1} (Table B-6).
- The lowest rate from the high quality studies listed in Table B-6 is in Brockelmann et al. (2003) which gives a range of 0.002 to 0.035 day^{-1}.

Overall, these values are considered to be consistent, and 0.002 day^{-1} (half life 350 days), based on the lowest value from a high quality study is recommended as the groundwater biodegradation rate for naphthalene (Table 1).

6.2.2 Acenaphthene

Available data on acenaphthene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-7.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-7 and discussed below.

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for naphthalene using the various techniques and from various parts of the plume ranged from 0.01 to 0.078 day^{-1} (Table B-7).

Values considered in the derivation of a recommended groundwater biodegradation rate for acenaphthene are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for acenaphthene is 0.0024 day^{-1} (Table B-7).
- The lowest rate from the high quality studies listed in Table B-7 is in Brockelmann et al. (2003) which gives a range of 0.01 to 0.78 day^{-1}.

Of these two options, the 25th percentile approach is more conservative for this compound, and 0.0024 day^{-1} (half life 290 days), based on the 25th percentile of the dataset compiled in this study is recommended as the groundwater biodegradation rate for acenaphthene (Table 1).

6.2.3 Acenaphthylene

Available data on acenaphthylene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-8. Five data points from two studies are available for this compound, including the high quality Brockelmann et al. (2003) study.

The lowest rate from the high quality studies listed in Table B-8 is 0.007 day^{-1} (half life 100 days), and this value is adopted as the recommended groundwater biodegradation rate for acenaphthylene (Table 1).

6.2.4 Fluorene

Available data on fluorene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-9. Eight data points from five studies are available for this compound, including the high quality Brockelmann et al. (2003) study.

The lowest rate from the high quality studies listed in Table B-9 is 0.002 day^{-1} (half life 350 days), and this value is adopted as the recommended groundwater biodegradation rate for fluorene (Table 1).

6.2.5 Fluoranthene

Available data on fluoranthene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-10. Just two data points are available for this compound, both from the high quality Brockelmann et al. (2003) study.

The lowest rate from the high quality studies listed in Table B-10 is 0.003 day^{-1} (half life 230 days), and this value is adopted as the recommended groundwater biodegradation rate for fluoranthene (Table 1).

6.2.6 Phenanthrene

Available data on phenanthrene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-11. Three data points from two studies are available for this compound, including the high quality Brockelmann et al. (2003) study.

The lowest rate from the high quality studies listed in Table B-11 is 0, and it appears that this compound can be recalcitrant in groundwater under some conditions, and accordingly the recommended groundwater biodegradation rate for phenanthrene is 0 day^{-1} (Table 1).

6.2.7 Anthracene

Available data on anthracene groundwater biodegradation rate from anaerobic field studies are summarized in Table B-12. Four data points are available for this compound, all from the high quality Brockelmann et al. (2003) study.

The lowest rate from the high quality studies listed in Table B-12 is 0.018 day^{-1}. This rate appears inconsistent with the recommended rates for the other PAH compounds. Given the small size of the database, an uncertainty factor of 10 is applied to the lowest rate for this compound to give a recommended groundwater biodegradation rate of 0.0018 day^{-1} for anthracene (half life 390 days) (Table 1).

6.3 VPH$_w$ and LEPH$_w$

Available data on groundwater biodegradation rates for VPH$_w$ and LEPH$_w$ components from anaerobic field studies are summarized in Tables B-13 and B-14, and are illustrated in Figure 3.

6.3.1 VPH_w

VPH_w is defined as volatile hydrocarbons in water eluting between n-hexane and n-decane (C6 to C10) with BTEX compounds excluded. VPH_w includes both aliphatic and aromatic hydrocarbon compounds. No groundwater biodegradation studies were found specifically for VPH_w. However, anaerobic groundwater biodegradation rate studies were available for a range of VPH_w components, and a total of 29 data points are summarized in Table B-13.

Note that all the studies relate to aromatic hydrocarbons (trimethylbenzenes and propyl benzenes) and none to aliphatic hydrocarbons. However, this is not a great concern, since, due to the higher solubility of the aromatic hydrocarbons, for groundwater in contact with a soil or free product source of VPH, the majority of the VPH_w dissolved in groundwater will be in the aromatic fractions.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-13 and discussed below.

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for various VPH_w components using the various techniques and from various parts of the plume ranged from 0.0039 to 0.11 day^{-1} (Table B-13).

Thierrin et al. (1995) conducted a study injecting fully deuterated aromatic compounds into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The study is described in the benzene section. The mean rate for 1,3,5-trimethylbenzene biodegradation was 0.039 day^{-1}.

Values considered in the derivation of a recommended groundwater biodegradation rate for xylenes are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for VPH_w components is 0.0098 day^{-1} (Table B-13).
- The lowest rate from the high quality studies listed in Table B-13 is 0.0039 day^{-1} from the study by Thierrin et al. (1995) (Table B-13).

In this case, the lowest value from the high quality studies appears to be significantly lower than the 25th percentile of the whole distribution, and this value, 0.0039 day^{-1} (half life 180 days), is recommended as the groundwater biodegradation rate for VPH_w (Table 1).

6.3.2 $LEPH_w$

$LEPH_w$ is defined as extractable hydrocarbons in water eluting between n-decane and n-eicosane (C10 to C20) with specified PAH compounds (acenaphthene, acridine, anthracene, fluorene, naphthalene, and phenanthrene) excluded. $LEPH_w$ includes both aliphatic and aromatic hydrocarbon compounds. No groundwater biodegradation studies were found specifically for $LEPH_w$. However, anaerobic groundwater biodegradation rate studies were available for a range of aromatic hydrocarbons eluting in the $LEPH_w$ range. A total of 45 data points are summarized in Table B-14.

Note that all the studies relate to aromatic hydrocarbons (PAHs with two or three rings) and none to aliphatic hydrocarbons. However, this is not a great concern, since, due to the higher solubility of the aromatic hydrocarbons, for groundwater in contact with a soil or free product source of LEPH, the majority of the $LEPH_w$ dissolved in groundwater will be in the aromatic fractions. Note also that data for the specified PAH compounds are included. Removing data for these compounds would significantly deplete the dataset, and the specified PAH compounds are considered to be surrogates for other, similar, PAH compounds.

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-14 and discussed below.

Brockelmann et al. (2003) conducted a careful analysis of natural attenuation in a plume of BTEX and PAH compounds at a former manufactured gas plant (MGP) situated in a Quaternary river valley in southwest Germany, described in the benzene section. The anaerobic biodegradation rates calculated for various $LEPH_w$ components using the various techniques and from various parts of the plume ranged from 0.002 to 0.11 day^{-1} with the exception of the rate for phenanthrene, which was evaluated to be zero (Table B-14).

Thierrin et al. (1995) conducted a study injecting fully deuterated aromatic compounds into an existing BTEX plume under SO_4 reducing conditions near Perth, Australia. The study is described in the benzene section. The biodegradation rate for naphthalene ranged from 0.017 to 0.043 day^{-1} (Table B-14).

Values considered in the derivation of a recommended groundwater biodegradation rate for $LEPH_w$ are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for $LEPH_w$ components is 0.0020 day^{-1} (Table B-14).
- The lowest rate from the high quality studies listed in Table B-14, excluding the data for phenanthrene, which is expected to be a very minor contributor to $LEPH_w$ based on

limited solubility, is 0.002 day^{-1} for naphthalene data from the study by Brockelmann et al. (2003).

These values are consistent, and 0.002 day^{-1} (half life 350 days), based on the 25th percentile of the dataset compiled in this study, is recommended as the groundwater biodegradation rate for LEPH$_w$ (Table 1).

7 CHLORINATED ALIPHATICS

Many of the chlorinated aliphatic compounds degrade by reductive dechlorination (Section 2.2.2). For the more oxidized compounds (e.g., tetrachloroethylene (PCE), trichloroethylene (TCE), trichloromethane (TCA), and carbon tetrachloride (CT), reductive dechlorination may be the only biodegradation process which is thermodynamically feasible. In reductive dechlorination, the chlorinated compound acts as the electron acceptor, and the electron donor is dissolved hydrogen, which in is generated by the anaerobic fermentation of other (less oxidized) carbon sources (Wiedemeier et al., 1999).

Based on reaction kinetics and field data analysis, Wiedemeier et al. (1999) consider that reductive dechlorination probably accounts for the majority of chlorinated solvent biodegradation at sites where biodegradation is significantly attenuating the plume. For reductive dechlorination to occur, the following conditions must exist Wiedemeier et al. (1999).

- The subsurface environment must be anaerobic, with a redox potential lower than that required for nitrate reduction.
- Chlorinated solvents amenable to reductive dechlorination must be present.
- There must be an adequate supply of fermentation substrates (e.g., hydrocarbon compounds, natural organic carbon, other readily oxidizable organic compounds) for production of dissolved hydrogen.

Wiedemeier (1996) proposed a classification scheme for chlorinated solvent plume environments based on the amount and origin of fermentation substrates available to produce dissolved hydrogen.

- Type 1 environments are anaerobic due to the presence of sufficient anthropogenic carbon sources which are fermented to produce hydrogen. Type 1 plumes will be characterized by very low redox potentials, very low concentrations of dissolved oxygen, nitrate and sulphate, high dissolved iron, and typically the presence of methane. The more highly chlorinated aliphatics such as PCE, TCE, and CT will be rapidly degraded in Type 1 plumes, however, less chlorinated daughter products, such as vinyl chloride will be degraded slower, and may form longer plumes.
- Type 2 environments are anaerobic due to the presence of sufficient naturally occurring organic material sources which are fermented to produce hydrogen. Redox conditions characterizing Type 2 plumes and the fate of chlorinated solvents are similar to those in Type 1 plumes.
- A Type 3 environment is characterized by a well oxygenated groundwater system and little or no organic matter. In such an environment, reductive dechlorination will not

occur, and chlorinated solvents such as PCE, TCE, TCA and CT will not biodegrade (Wiedemeier et al., 1999).

It is possible for more than one type of environment to exist at a site, for example, a Type 1 environment to be present close to a source area, and a Type 3 environment further downgradient.

Reductive dechlorination tends to lead to a series of daughter products with decreasing chlorination, e.g., PCE → TCE → cis-DCE → VC → ethene. This can complicate the monitoring of biodegradation, since for example TCE may be produced by the biodegradation of PCE at one rate and degrade into cis-DCE at another rate, and both these rates may be dependent on the redox regime.

Reductive dechlorination is most rapid for the most highly chlorinated compounds (e.g., PCE and TCE, and relatively slower for dichloroethylene (DCE) and vinyl chloride (VC). This means that in an anaerobic plume, DCE and VC can accumulate, since they are biodegradation products of PCE and TCE, and may degrade more slowly.

Some chlorinated solvents can also be oxidized biologically in groundwater systems. In this case, the chlorinated compound acts as the electron donor, and oxygen, nitrate, iron (III), sulphate or other compounds act as the electron acceptor. Typically, this biodegradation process is available to the less chlorinated compounds with one, or perhaps two chlorine atoms, but not to fully chlorinated compounds.

7.1 Chlorinated Ethenes

Available data on groundwater biodegradation rate for chlorinated ethenes from anaerobic field studies are summarized in Tables B-15, B-17, B-19, and B-21, and are illustrated in Figure 4. Available data on groundwater biodegradation rate for chlorinated ethenes from aerobic field studies are summarized in Tables B-16, B-18, B-20, and B-22.

7.1.1 Tetrachloroethylene (PCE)

Available data on PCE groundwater biodegradation rates from anaerobic field studies are summarized in Table B-15 (16 data points).

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-15 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study with a bromide tracer in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume) that is described in the benzene section. These authors found a biodegradation rate for PCE under these conditions in the range of 0.0012 to 0.0038 day^{-1} (Table B-15).

Values considered in the derivation of a recommended groundwater biodegradation rate for PCE <u>in anaerobic conditions</u> are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for PCE is 0.00064 day^{-1} (Table B-15).
- The lowest rate from the high quality studies listed in Table B-15 is 0.0012 day^{-1} from Rugge et al. (1999).

Of these values, the 25th percentile is more conservative, and the value of 0.00064 day^{-1} (half life 1080 days) is recommended as the groundwater biodegradation rate for PCE <u>under anaerobic conditions</u> (Table 1).

Field studies of PCE biodegradation conducted under aerobic conditions are summarized in Table B-16. One of these studies shows no aerobic biodegradation of PCE. This information, together with other information in Aronson et al. (1999), and thermodynamic considerations presented in Wiedemeier et al. (1999) suggest that PCE does not generally degrade under aerobic conditions. Accordingly, the groundwater biodegradation rate for PCE of 0.00064 day^{-1} developed above will only generally be applicable to anaerobic sites. Practical implementation of this guideline is discussed further in Section 10.

7.1.2 Trichloroethylene (TCE)

Available data on TCE groundwater biodegradation rate from anaerobic field studies are summarized in Table B-17 (68 data points).

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-17 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study with a bromide tracer in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume) that is described in the benzene section. These authors found a biodegradation rate for TCE under these conditions in the range of 0.0003 to 0.001 day^{-1} (Table B-17).

Values considered in the derivation of a recommended groundwater biodegradation rate for TCE <u>in anaerobic conditions</u> are summarized below:

- The 25th percentile of the entire anaerobic field biodegradation rate database for TCE is 0.00089 day^{-1} (Table B-17).
- The lowest rate from the high quality studies listed in Table B-17 is 0.0003 day^{-1} from Rugge et al. (1999).

Of these values, the rate from Rugge et al. (1999) is the most conservative. Since this study was of such high quality, the value of 0.0003 day^{-1} (half life 2,310 days) is recommended as the groundwater biodegradation rate for TCE <u>under anaerobic conditions</u> (Table 1).

Field studies of TCE biodegradation conducted under aerobic conditions are summarized in Table B-18. Two out of three of these studies show slower aerobic biodegradation of TCE, than the anaerobic rate developed above. Accordingly, it is recommended that the groundwater biodegradation rate for TCE of 0.0003 day^{-1} developed above will only generally be applicable to anaerobic sites. Practical implementation of this guideline is discussed further in Section 10.

7.1.3 Dichloroethylene (DCE)

Three isomers exist for dichloroethylene: 1,1-dichloroethylene, cis-1,2-dichloroethylene, and trans-1,2-dichloroethylene. The predominant isomer formed via reductive dechlorination of TCE is cis-DCE. Accordingly, the majority of the available field biodegradation rate data are for cis-DCE. However, the rate developed based on cis-DCE data is assumed to be applicable to all three DCE isomers.

Available data on cis-DCE groundwater biodegradation rates from anaerobic field studies are summarized in Table B-19 (68 data points). Available data on cis-DCE groundwater biodegradation rates from aerobic field studies are summarized in Table B-20 (5 data points).

None of the studies met the criteria for inclusion in the high quality category, and accordingly all studies are treated equally.

- The 25th percentile of the entire anaerobic field biodegradation rate database for cis-DCE is 0.0012 day^{-1} (Table B-19).
- The lowest value of the aerobic field biodegradation rate data set is 0.004 (Table B-20).

Considering the above, it appears that anaerobic biodegradation of DCE may be the limiting situation, and accordingly the 25th percentile of the anaerobic biodegradation rate database, 0.0012 day^{-1}, (corresponding half life 580 days) is recommended as the groundwater biodegradation rate for all three DCE isomers under any redox conditions (Table 1).

7.1.4 Vinyl Chloride (VC)

Available data on vinyl chloride groundwater biodegradation rates from anaerobic field studies are summarized in Table B-21 (27 data points). Available data on vinyl chloride groundwater biodegradation rates from aerobic field studies are summarized in Table B-22 (1 data point).

None of the studies met the criteria for inclusion in the high quality category, and accordingly all studies are treated equally.

- The 25th percentile of the entire anaerobic field biodegradation rate database for vinyl chloride is 0.0013 day^{-1} (Table B-21).
- The lowest value of the aerobic field biodegradation rate data set is 0.002 (Table B-22).

Considering the above, and information in Wiedemeier et al. (1999) and other sources that indicates aerobic biodegradation of vinyl chloride is feasible and observed at a range of field sites, it appears that anaerobic biodegradation of vinyl chloride may be the limiting situation, and accordingly the 25th percentile of the anaerobic biodegradation rate database, 0.0013 day^{-1}, (corresponding half life 530 days) is recommended as the groundwater biodegradation rate for vinyl chloride under any redox conditions (Table 1).

7.2 Chlorinated Methanes

Available data on groundwater biodegradation rate for chlorinated ethenes from anaerobic field studies are summarized in Tables B-23, B-24, and B-26, and are illustrated in Figure 5. Available data on groundwater biodegradation rate for chloroform in aerobic field studies are summarized in Table B-25. No aerobic field studies relating to other chlorinated methane compounds were found.

7.2.1 Carbon Tetrachloride (CT)

Three data points from three studies were available for anaerobic field biodegradation rates for carbon tetrachloride (Table B-23).

Studies that appear to be of higher quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-23 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study with a bromide tracer in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume) that is described in the benzene section. These authors found a biodegradation rate for carbon tetrachloride under these conditions of 0.7 day^{-1} (Table B-23).

Devlin et al. (2004) conducted an in-situ remediation experiment in the Borden aquifer in Ontario. A control setup run to evaluate natural attenuation at the same time is relevant to the current study. A bromide tracer was used to quantify the flow field. Methanogenic, SO_4 and Fe reducing zones were established in the plumes during the experiment. These authors found an anaerobic field biodegradation rate for carbon tetrachloride of 0.063 day^{-1} (Table B-23).

The lowest biodegradation rate from the high quality studies, 0.063 day^{-1} (half life 11 days) is recommended as the groundwater biodegradation rate for carbon tetrachloride <u>under anaerobic conditions</u> (Table 1).

Thermodynamic considerations presented in Wiedemeier et al. (1999) suggest that carbon tetrachloride does not generally degrade under aerobic conditions. Accordingly, the groundwater biodegradation rate for carbon tetrachloride of 0.063 day^{-1} developed above will only generally be applicable to anaerobic sites. Practical implementation of this guideline is discussed further in Section 10.

7.2.2 Chloroform (Trichloromethane)

Available data on chloroform groundwater biodegradation rates from anaerobic field studies are summarized in Table B-24 (2 data points). Available data on chloroform groundwater biodegradation rates from aerobic field studies are summarized in Table B-25 (2 data points).

One of the anaerobic studies, Devlin et al. (2004), and the aerobic study, Pavelic et al. (2005) were considered high quality studies.

Based on the available data, it appears that chloroform can degrade by aerobic or anaerobic pathways. Accordingly, the recommended biodegradation rate was set at the lowest rate for either an aerobic or an anaerobic study. In this case the lowest rate was 0.011 day^{-1} (half life 63 days), which was the lowest rate from the Pavelic et al. (2005) aerobic study (Table 1).

7.2.3 Dichloromethane (Methylene Chloride)

Only one data point was available for an anaerobic field biodegradation rate for dichloromethane (Table B-26). In the absence of other information, this value, 0.0064 day^{-1}

(half life 110 days) was adopted as the recommended biodegradation rate for dichloromethane (Table 1).

The median aerobic degradation rate for dichloromethane in Aronson et al. (1999) is 0.0546 day^{-1}. Thus the recommended anaerobic biodegradation rate for dichloromethane is assumed to be conservative for aerobic degradation, and accordingly is applicable in any redox conditions.

7.3 Chlorinated Ethanes

Available data on groundwater biodegradation rate for chlorinated ethenes from anaerobic field studies are summarized in Tables B-27 to B-30 and are illustrated in Figure 6. No aerobic field study data were available for chlorinated ethanes.

7.3.1 1,1,1-Trichloroethane

Available data on 1,1,1-trichlorethane groundwater biodegradation rates from anaerobic field studies are summarized in Table B-27 (7 data points).

Studies that appear to be of particularly high quality, and therefore have a correspondingly lower degree of uncertainty are indicated in Table B-27 and discussed below.

Rugge et al. (1999) conducted a very careful, lengthy (924 days), and well instrumented (~700 sample locations) natural gradient injection study with a bromide tracer in the first 65 m of the plume from the Grindsted landfill in Denmark (methanogenic, SO_4 and Fe reducing zone of plume) that is described in the benzene section. These authors found a biodegradation rate for 1,1,1-trichlorethane under these conditions in the range of 0.0044 to 0.0054 day^{-1} (Table B-27).

The number of data points was below the threshold value for calculating percentiles, and the recommended biodegradation rate was set at 0.0044 day^{-1} (half life 160 days), based on the lowest biodegradation rate from a high quality study (Table 1).

7.3.2 1,1-Dichloroethane

Only one data point was available for an anaerobic field biodegradation rate for 1,1-dichloroethane (Table B-28). In the absence of other information, this value, 0.006 day^{-1} (half life 120 days) was adopted as the recommended biodegradation rate for 1,1-dichloroethane (Table 1).

7.3.3 1,2-Dichloroethane

Three data points from two studies were available for anaerobic field biodegradation rates for 1,2-dichloroethane (Table B-29). In the absence of other information, the lowest of these three values, 0.003 day^{-1} (half life 230 days) was adopted as the recommended biodegradation rate for 1,2-dichloroethane (Table 1).

7.3.4 Chloroethane

Only one data point was available for an anaerobic field biodegradation rate for chloroethane (Table B-30). In the absence of other information, this value, 0.011 day^{-1} (half life 60 days) was adopted as the recommended biodegradation rate for chloroethane (Table 1).

8 KETONES

No field biodegradation rate studies were available for the ketones. Recommended biodegradation rates for acetone, methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK) were adopted from the low end of the recommended range in Aronson and Howard (1997), which in turn were based on laboratory microcosm data and appropriate uncertainty factors. Adopted values are summarized in Table 1.

9 OTHER COMPOUNDS

Available data on groundwater biodegradation rate for other compounds from field studies are summarized in Tables B-31 to B-33 and are illustrated in Figure 7.

9.1 Methyl tert-Butyl Ether (MTBE)

Available data on MTBE groundwater biodegradation rates from field studies are summarized in Table B-31. It is unclear for this compounds whether aerobic or anaerobic conditions will be limiting in developing recommended biodegradation rates, and accordingly both aerobic and anaerobic studies are included in Table B-31.

None of the studies meet the criteria for a High Quality study. The 25th percentile of the entire aerobic and anaerobic field biodegradation rate database for MTBE is 0.001 day^{-1} (half life 690 days), and this value is recommended as the groundwater biodegradation rate for MTBE (Table 1).

9.2 Phenol

Only one anaerobic field study was available for phenol (Table B-32). Given the minimal dataset and the relatively rapid rate seen in this study, a more conservative value (0.0013 day^{-1} (half life 530 days; Table 1) was adopted from the lower end of the range of recommended rates provided by Aronson and Howard (1997).

9.3 Methanol

Available data on methanol groundwater biodegradation rate from anaerobic field studies are summarized in Table B-33. Just one data point is available for this compound, from the high quality Hubbard et al. (1994) study.

The rate this study is 0.0028 day^{-1} (half life 250 days), and this value is adopted as the recommended groundwater biodegradation rate for methanol (Table 1).

9.4 Ethylene Glycol

No groundwater field studies were available for ethylene glycol. Since this compound is included in Schedule 5, it was considered desirable to develop a recommended groundwater biodegradation rate, and accordingly anaerobic laboratory biodegradation rates are compiled in Table B-34. An uncertainty factor of 2 was applied to the lowest biodegradation rate in Table B-34 to give a recommended groundwater biodegradation rate of 0.0034 day^{-1} (half life 210 days; Table 1),

9.5 Other Compounds

No field biodegradation rate studies were available for 2,4-dichlorophenol, cresol, nitrobenzene, pentachlorophenol, or trichlorofluoromethane. Recommended biodegradation rates for these compounds were adopted from the low end of the recommended range in Aronson and Howard (1997) (Table 1).

10 SPECIAL CONSIDERATIONS FOR PCE, TCE, AND CT

For three of the compounds considered in this document, tetrachloroethylene (PCE), trichloroethylene (TCE), and carbon tetrachloride (CT), aerobic biodegradation has been shown, or is expected to be much slower than anaerobic biodegradation or possibly non-existent. The recommended biodegradation rates for these three chemicals are based on anaerobic conditions. If anaerobic conditions are not developed in the source area, then a biodegradation rate of zero should be assumed.

Wiedemeier et al. (1999) identifies three types of behaviour at sites with these three chemicals. At Type 1 or Type 2 sites, there is sufficient anthropogenic or natural organic carbon present that Fe, or SO4 reducing or methanogenic conditions are developed, and biodegradation of these chlorinated aliphatics occurs. At Type 3 sites, insufficient organic carbon is present, anaerobic conditions are not developed, and biodegradation of these chlorinated aliphatics does not occur.

The following two conditions are used to determine whether groundwater conditions are appropriate for biodegradation of PCE, TCE, and/or CT to be assumed. If both of these conditions are met, then the groundwater biodegradation rates for these compounds in Table 1 can be used. If either condition is not met, then the biodegradation rates of these three compounds should be assumed to be zero. The two conditions are:

1. Sufficient readily fermentable carbon (such as BTEX, VPH_w, alcohols, ketones or other readily degradable carbon sources) is available in groundwater in the source area. The concentration of fermentable carbon is considered sufficient if it is equal to or greater than the greater of:
   a. 20 mg/L of fermentable carbon compounds in the source zone, based on being approximately 5x the concentration of dissolved hydrocarbon required to exhaust the dissolved oxygen in oxygen-saturated groundwater at 10ºC; and,
   b. A concentration of fermentable carbon in the source zone equal to or greater than the total concentration of chlorinated aliphatics in the source zone. This is based on the stoichiometry presented in Wiedemeier et al. (1999) required to provide sufficient hydrogen for reductive dechlorination of all the chlorinated aliphatics together with an uncertainty factor of 5.
2. The redox potential measured in groundwater throughout the source zone indicates at least Fe-reducing conditions.

For other chlorinated aliphatic compounds listed in Table 1, the biodegradation rates provided are considered to be appropriate in any redox conditions.

11 REFERENCES

(References for Appendix B are at the back of that Appendix)

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12 CLOSURE AND DISCLAIMER

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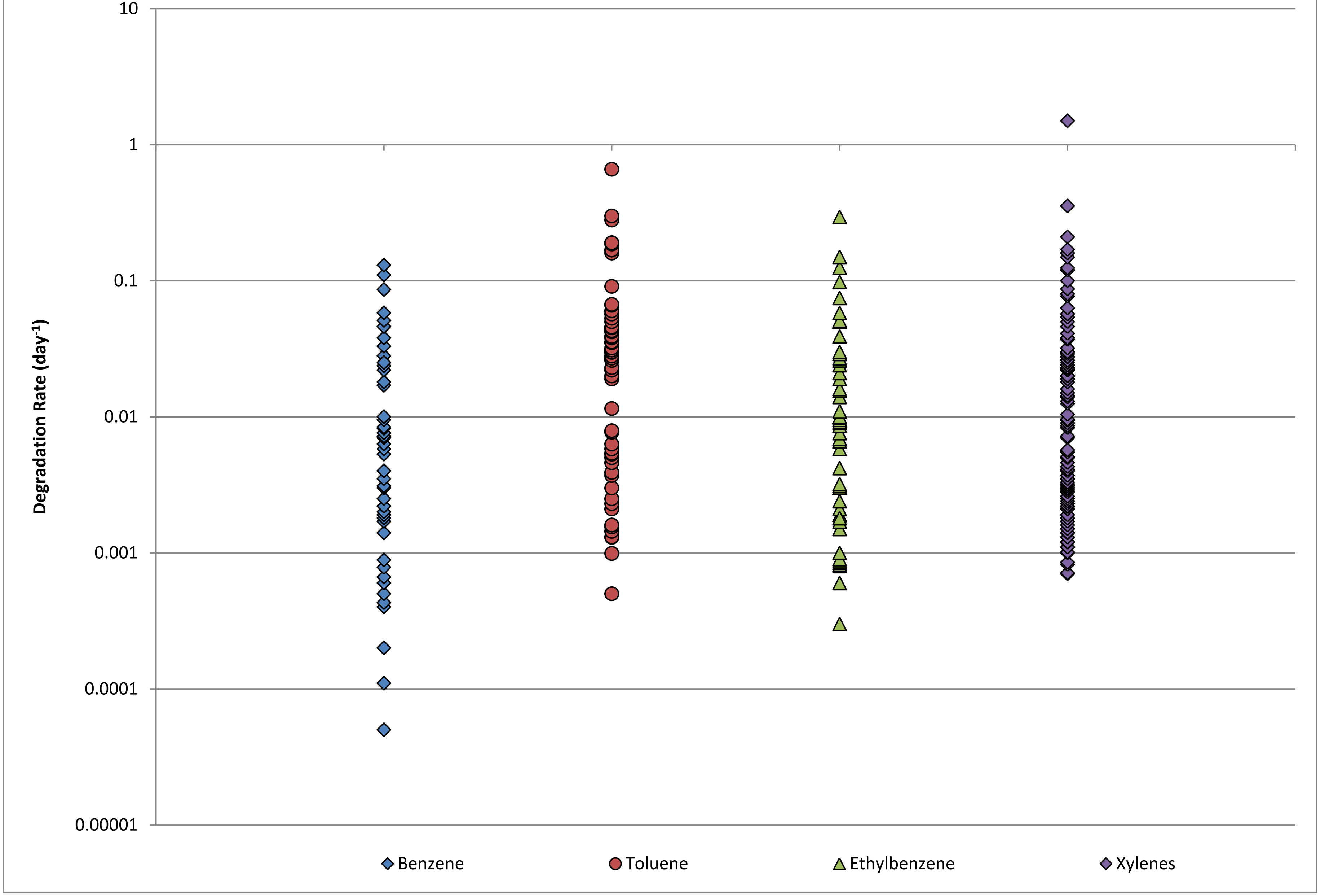
Axiom has exercised reasonable skill, care, and diligence to assess the information acquired during the preparation of this report. Information has been compiled from a range of sources in the preparation of this report. This information is believed to be accurate, but cannot be guaranteed. This report represents a scientific analysis of published literature data. It is written with the intention of providing conservative values for groundwater biodegradation rate that are towards the lower end of the range of values that might be present on a wide range of sites for a given organic compound.

Please do not hesitate to contact Miles Tindal at (403) 678 4790 or mtindal@axiomenvironmental.ca with any questions you may have concerning this report.

FIGURES

Figure 1. Anaerobic Field Study Biodegradation Rates - BTEX



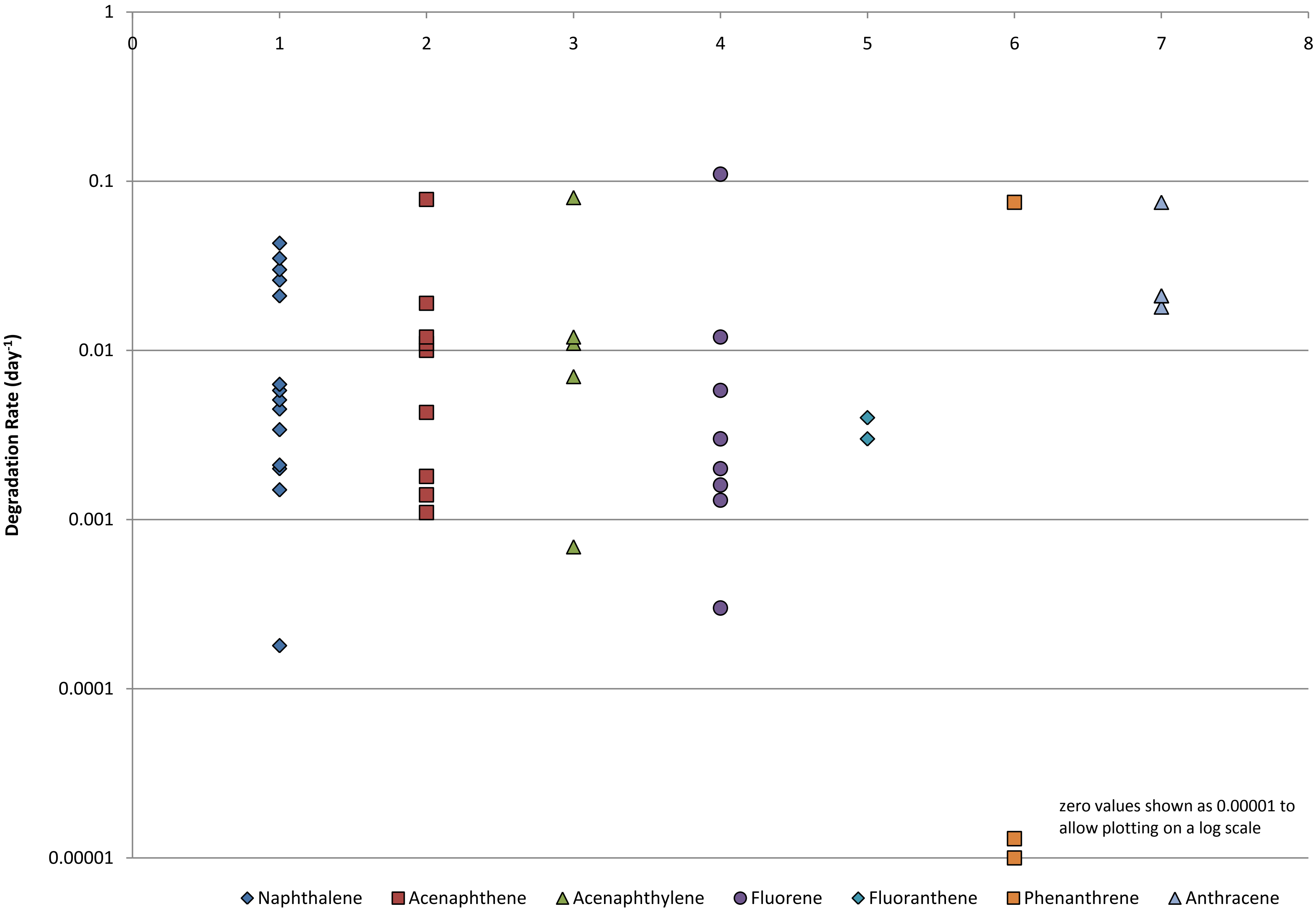
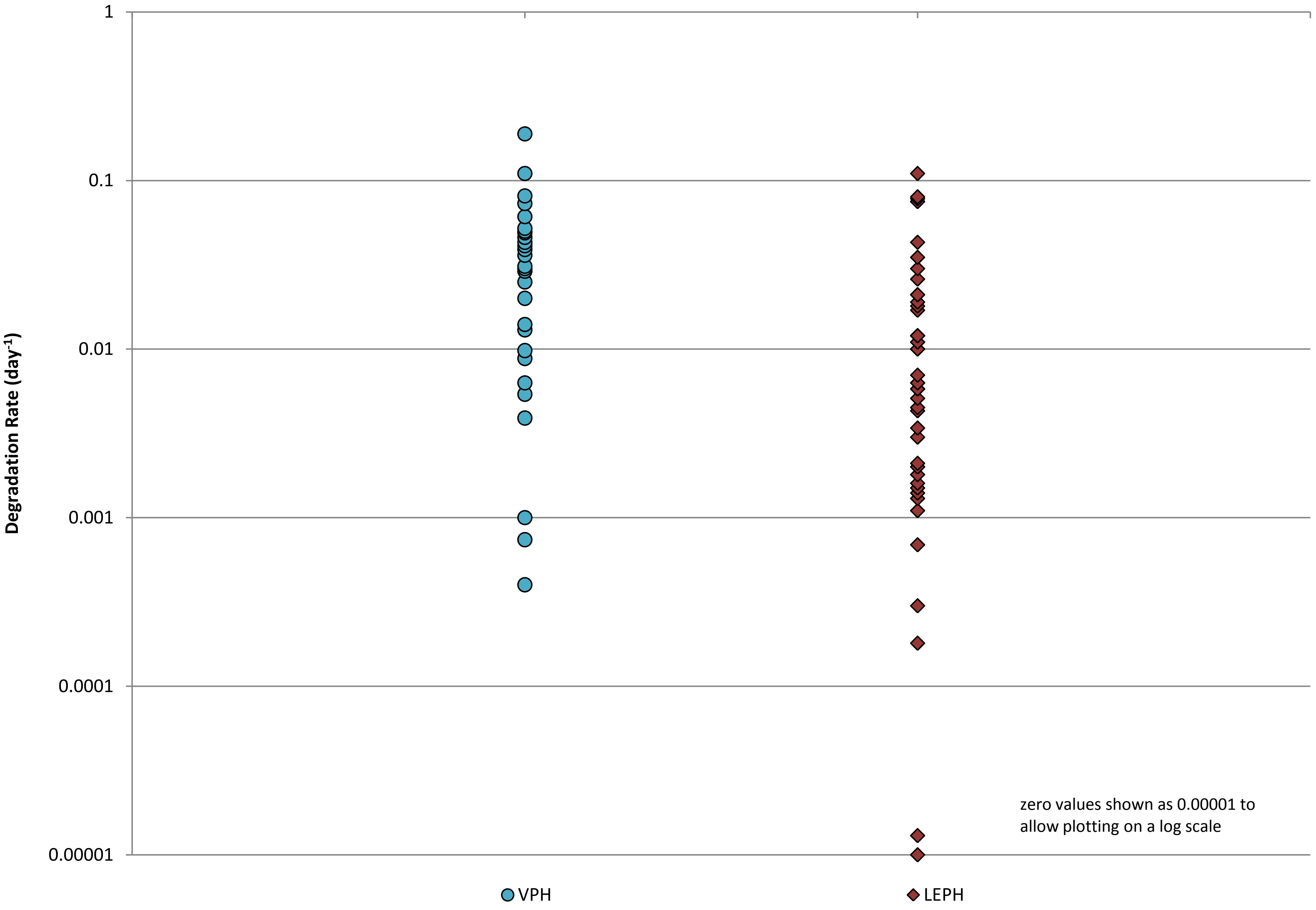


Figure 2. Anaerobic Field Study Biodegradation Rates - PAHs

zero values shown as 0.00001 to allow plotting on a log scale

Figure 3. Anaerobic Field Study Biodegradation Rates - VPH and LEPH



zero values shown as 0.00001 to allow plotting on a log scale

Figure 4. Anaerobic Field Study Biodegradation Rates - Chlorinated Ethenes

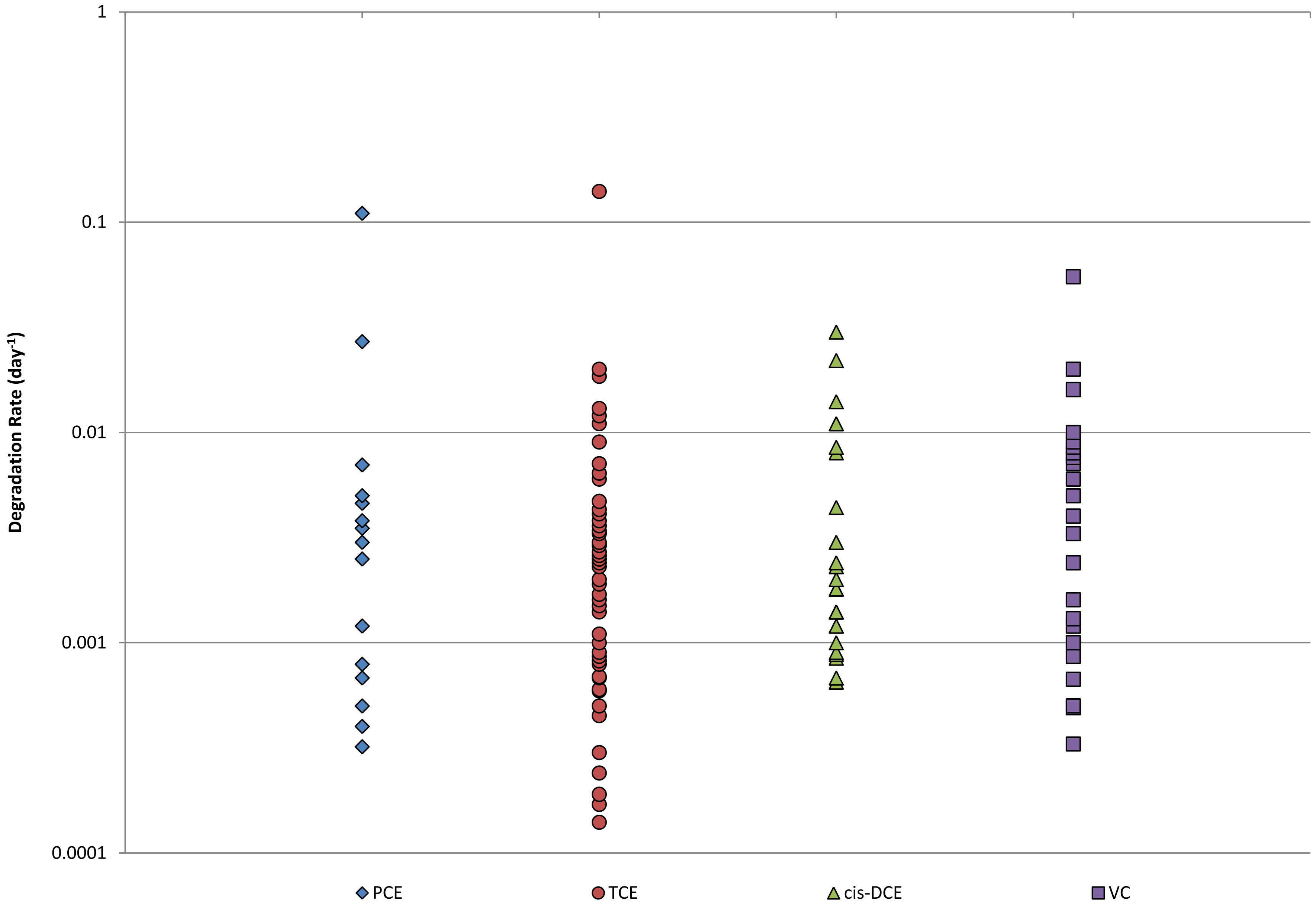


Figure 5. Anaerobic Field Study Biodegradation Rates - Chlorinated Methanes

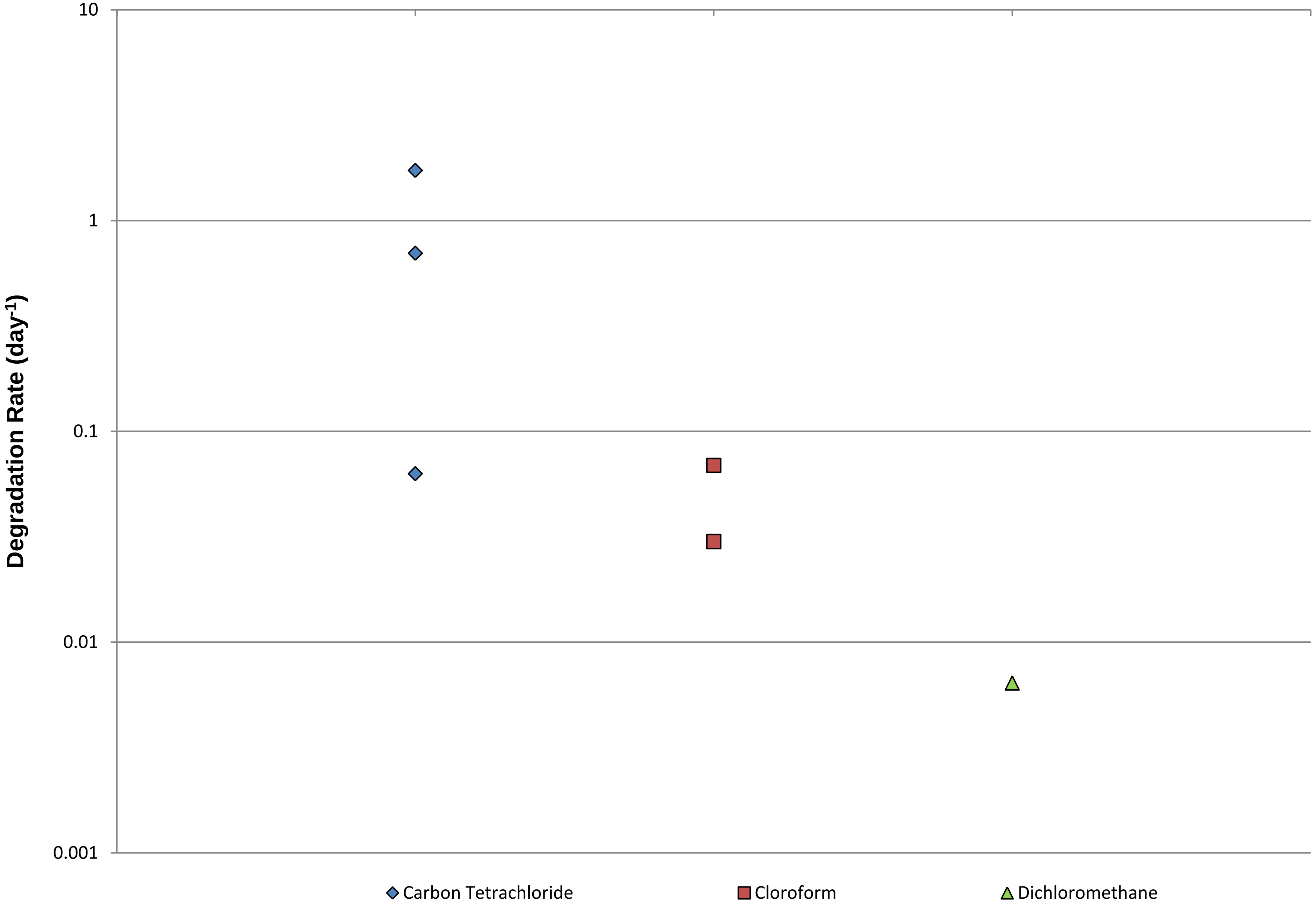


Figure 6. Anaerobic Field Study Biodegradation Rates - Chlorinated Ethanes

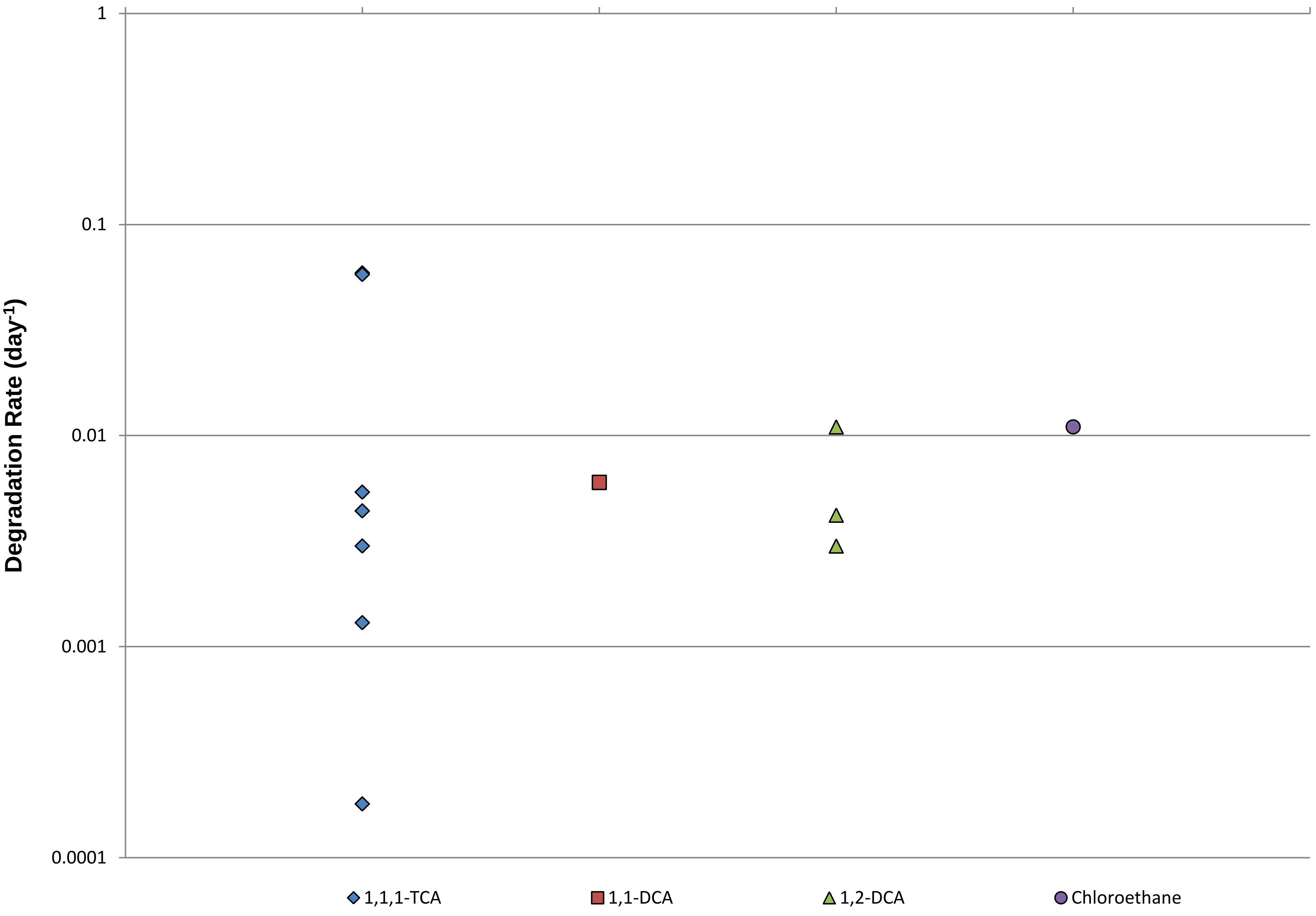
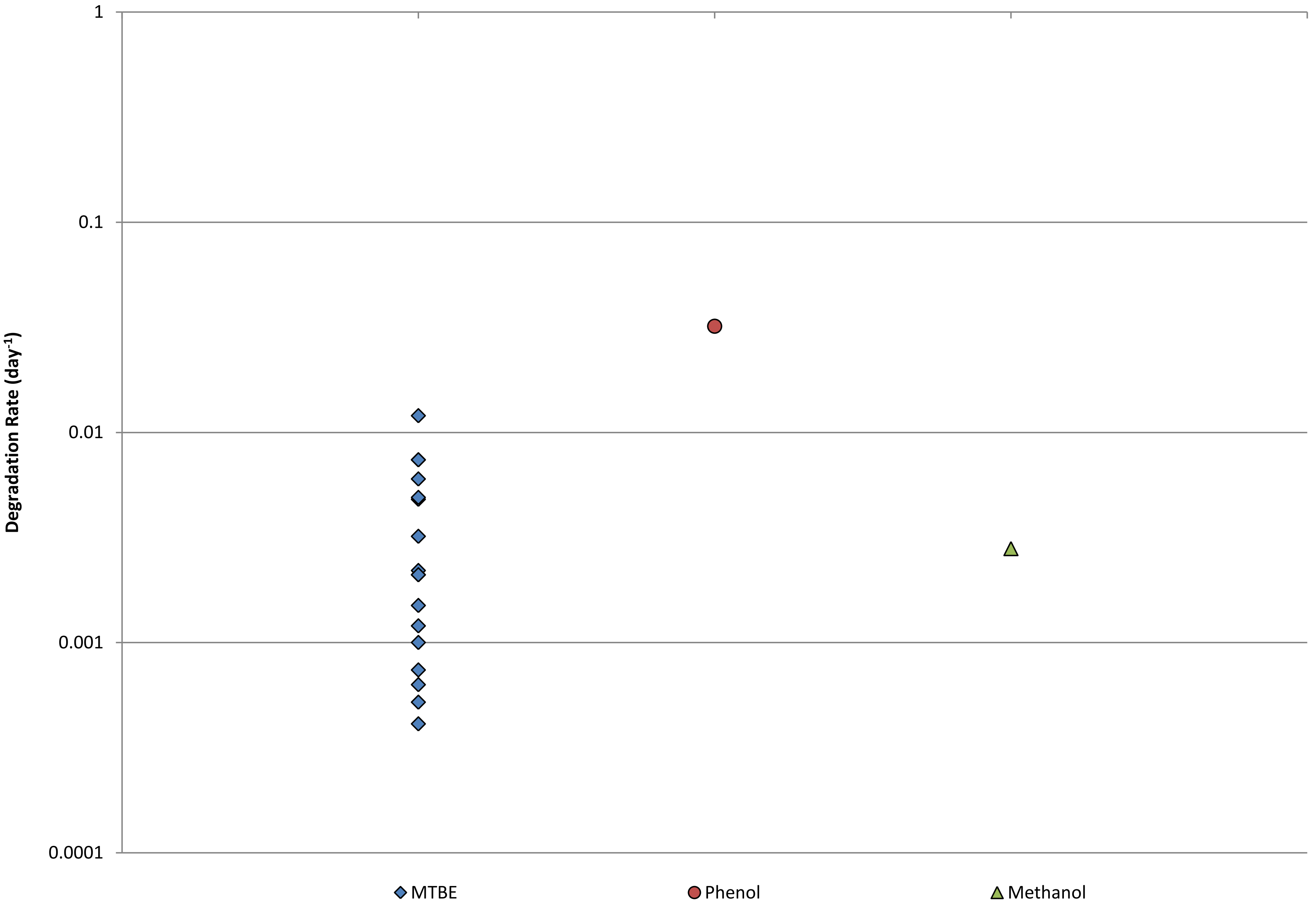


Figure 7. Anaerobic Field Study Biodegradation Rates - Other Compounds



APPENDIX A

SUMMARY OF GROUNDWATER BIODEGRADATION RATES ADOPTED BY REGULATORY AGENCIES

Table A-1. Biodegradation Half Lives from 1996 CSST Protocol

Chemical	$t1/2_{unsat}$ (days)	$t1/2_{sat}$ (days)
benzene	183	365
ethylbenzene	114	114
toluene	56	105
xylenes	183	183
benzo(a)pyrene	529	1,059
naphthalene	65	129
pyrene	1,898	3,796
tetrachloroethylene (PCE)	411	821
trichloroethylene (TCE)	411	821
pentachlorophenol	383	767

Table A-2. Biodegradation Half Lives developed by the CCME

Chemical	Half Life (days)
F1	712
F2	1750
trichlorethylene	800

Table A-3. Biodegradation Half Lives from Alberta Environment Tier 1 Guidelines

Chemical	t1/2 (years)	Comment
benzene	1	Adopted from BC CSST
ethylbenzene	0.288	Adopted from BC CSST
toluene	0.312	Adopted from BC CSST
xylenes	0.501	Adopted from BC CSST
F1	1.95	Adopted from CCME PHC CWS
F2	4.79	Adopted from CCME PHC CWS
trichloroethylene	2.19	Adopted from CCME Soil Guideline Doc.
diethanolamine	0.75	Derived by AENV
diethylene glycol	0.68	Derived by AENV
methanol	0.67	Derived by AENV
monoethanolamine	0.75	Derived by AENV
triethylene glycol	0.48	Derived by AENV

Table A-4. Biodegradation Half Lives for SLRA in Protocol 13

Chemical	Degradation Rate ($days^{-1}$)
benzene	0.027
ethylbenzene	0.00021
toluene	0.0062
xylenes	0.00021
naphthalene	0.000045
pyrene	0.00018
VPH	0.0004
LEPH	0.00097

Table A-5. Biodegradation Half Lives for PAHs Developed by Health Canada

Chemical	t1/2 (unsaturated)] (days)	t1/2 (saturated)] (days)	Comment
benzene	365	365	Adopted from CCME Soil Guideline Doc.
toluene	105	105	Adopted from CCME Soil Guideline Doc.
ethylbenzene	114	114	Adopted from CCME Soil Guideline Doc.
xylenes	183	183	Adopted from CCME Soil Guideline Doc.
acenaphthene	204	204	Developed based on CCME PHC CWS
acenaphthylene	120	120	Developed based on CCME PHC CWS
anthracene	913	913	Developed based on CCME PHC CWS
benz[a]anthracene	1,361	1,361	Developed based on CCME PHC CWS
benzo(a)pyrene	1,059	1,059	Developed based on CCME PHC CWS
benzo(b)fluoranthene	1,219	1,219	Developed based on CCME PHC CWS
chrysene	2,000	2,000	Developed based on CCME PHC CWS
fluoranthene	876	876	Developed based on CCME PHC CWS
fluorene	120	120	Developed based on CCME PHC CWS
naphthalene	65	129	Developed based on CCME PHC CWS
phenanthrene	32	402	Developed based on CCME PHC CWS
pyrene	3,796	3,796	Developed based on CCME PHC CWS
pentachlorophenol	383	767	Adopted from BC CSST values
tetrachloroethylene (PCE)	411	821	Adopted from BC CSST values
trichloroethylene (TCE)	411	821	Adopted from BC CSST values

APPENDIX B

GROUNDWATER BIODEGRADATION RATES FROM FIELD STUDIES

APPENDIX B

Groundwater Biodegradation Rates from Field Studies

(Data for Anaerobic Field Studies Except Where Specified)

Table B-1. Summary Statistics for Groundwater Anaerobic Field Degradation Rate Distributions

	Minimum Value		5th Percentile		10th Percentile		25th Percentile		
Chemical	**Rate (days^{-1})**	**Half-Life (days)**	**Rate (days^{-1})**	**Half-Life (days)**	**Rate (days^{-1})**	**Half-Life (days)**	**Rate (days^{-1})**	**Half-Life (days)**	**n**
BTEX									
Benzene	0.00005	13,860	0.00029	2,390	0.00049	1,410	0.0018	390	50
Toluene	0.0005	1,390	0.0013	530	0.0019	360	0.0054	130	67
Ethylbenzene	0.0003	2,310	0.00082	850	0.00089	780	0.0024	290	57
Xylenes	0.0007	990	0.001	690	0.0012	580	0.0024	290	124
PAHs									
Naphthalene	0.00018	3,850	0.0011	630	0.0017	410	0.0028	250	15
Acenaphthene	0.0011	630	0.0012	580	0.0014	500	0.0024	290	10
Acenaphthyne	0.00069	1,000							5
Flourene	0.0003	2,310							8
Fluoranthene	0.003	230							2
Phenanthrene	0	-							3
Anthracene	0.018	39							4
Hydrocarbon Fractions									
VPH	0.0004	1,730	0.00084	820	0.0033	210	0.0098	70	29
LEPH	0	-	0.0002	3,470	0.0009	770	0.002	350	45
Chlorinated Ethenes									
Tetrachloroethylene (PCE)	0.00019	3,650	0.00029	2,410	0.00036	1,930	0.00064	1,080	16
Trichloroethylene (TCE)	0.00014	4,950	0.00021	3,340	0.00045	1,540	0.00086	810	68
Dichloroethylene (DCE)	0.00065	1,070	0.00073	950	0.00087	800	0.0012	580	27
Vinyl Chloride (VC)	0.00033	2,100	0.00049	1,420	0.0005	1,390	0.0013	530	27
Chlorinated Methanes									
Carbon Tetrachloride	0.063	11							3
Chloroform	0.03	23							2
Dichloromethane	0.0064	110							1
Chlorinated Ethanes									
1,1,1-Trichloroethane	0.00018	3,850							7
1,1-Dichloroethane	0.006	120							1
1,2-Dichloroethane	0.003	230							3
Chloroethane	0.011	60							1
Other Compounds									
Methanol	0.0028	250							1
MTBE	0.00041	1,690	0.0005	1,390	0.00059	1,180	0.001	690	17
Phenol	0.032	22							1

Notes:

Percentiles calcualted only when at least 10 data points are available.

Table B-2. Benzene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**-**	**924**	**0.00005**	**Rugge et al. (1999)**	**a**	**++**
Tibbetts Road Site, Barrington, NH	Fe	493	876	0.00011	Wilson et al. (1996a)	a	
Arvida Research Site, NC	-	1326	-	0.0002	Borden et al. (1994)	c	
Ohio River Park, PA	-	200000	-	0.0004	Edwards et al. (1999)	c	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	230	35	0.00043	Wilson et al. (1994a)	b	
North Bay Landfill, ON	-	28	-	0.0005	Barker and Mayfield (1988)	c	
Sampson County, NC	NO3	-	-	0.0006	Borden et al. (1997)	b	
UST Site, Dublin NC	Meth/Fe	14900	-	0.000663	Kao and Wang (2000)	a	
UST Site, Dublin NC	Meth/Fe	14900	-	0.000781	Kao and Wang (2000)	a	
UST Site, Dublin NC	Meth/Fe	14900	-	0.000886	Kao and Wang (2000)	a	
Sampson County, NC	NO3	-	-	0.0014	Borden et al. (1997)	b	
Tibbetts Road Site, Barrington, NH	Fe	493	3650	0.0017	Wilson et al. (1996a)	a	
UST Site, Garysburg NC	Meth/Fe	9844	-	0.0018	Kao and Wang (2001)	a	
Central Alberta Gas Plant	-	120	-	0.0019	Unpub. data reported in (c)	c	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	3120	-	0.002	Barlaz et al. (1993)	b	
UST Site, Garysburg NC	Meth/Fe	29973	-	0.0022	Kao and Wang (2001)	a	
Tibbetts Road Site, Barrington, NH	Fe	510	2336	0.0022	Wilson et al. (1996a)	a	
UST Site, Garysburg NC	Meth/Fe	29973	-	0.0025	Kao and Wang (2001)	a	
Seal Beach, CA	**Meth**	**316**	**159**	**0.003**	**Reinhard et al. (2005)**	**a**	**+**
Former MGP, Midwest US	assumed anaerobic	10075	-	0.0031	Stenback et al. (2004)	a	
Former MGP, Midwest US	assumed anaerobic	10075	-	0.0035	Stenback et al. (2004)	a	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	3120	-	0.004	Barlaz et al. (1993)	b	
West Central Alberta Gas Plant	-	4300	-	0.004	Unpub. data reported in (c)	c	
West Central Alberta Gas Plant	-	7000	-	0.0053	Unpub. data reported in (c)	c	
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.0058**	**Thierrin et al. (1995)**	**a**	**+**
Noordwijk landfill, The Netherlands	-	100	3650	0.0063	Zoeteman et al. (1981)	b	
Traverse City, MI	-	-	-	0.007	Wilson et al. (1990)	c	
Traverse City, MI	Meth	-	70	0.00714	Wilson et al. (1990)	b	
Hill AFB, Utah	SO4	5600	228	0.0072	Wiedemeier et al. (1995)	b	
George AFB, CA	-	1620	-	0.0076	Wilson et al. (1995a)	c	
West Central Alberta Gas Plant	-	3400	-	0.0082	Unpub. data reported in (c)	c	
Former MGP	SO4/Fe	2200	27375	0.0084	Rogers et al. (2007)	a	
Gas Plant, MI	-	67	-	0.0095	Chiang et al. (1989)	c	

Table B-2. Benzene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Patrick AFB, FL	Meth	724	1200	0.01	Wiedemeier et al. (1995)	b	
Bemidji, MN	Meth/Fe/Mn	-	-	0.017	Cozzarelli et al. (1990)	b	
BC Gas Station	-	296	-	0.018	Unpub. data reported in (c)	c	
Tank Farm, Southern Taiwan	Meth	355	-	0.022	Kao et al. (2010)	a	
SE coastal plain, NC	-	2000	-	0.0237	Hunt et al. (1995)	c	
Tank Farm, Southern Taiwan	Meth	149	-	0.028	Kao et al. (2010)	a	
Hill AFB, Utah	SO4	5600	250	0.028	Wiedemeier et al. (1995)	b	
Hill AFB, Utah	-	-	-	0.033	Wiedemeier et al. (1999)	c	
Hill AFB, Utah	SO4	5600	250	0.038	Wiedemeier et al. (1995)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.046**	**Brockelmann et al. (2003)**	**a**	**+**
Hill AFB, Utah	SO4	5600	228	0.046	Wiedemeier et al. (1995)	b	
Tank Farm, Kaohsiung, Taiwan	Meth	170	-	0.051	Kao et al. (2006)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.058**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.086**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.11**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.13**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.13**	**Brockelmann et al. (2003)**	**a**	**+**
Tank Farm, Southern Taiwan	Meth	355	-	>0.025	Kao et al. (2010)	a	
Minimum				**0.00005**			
5th percentile				**0.00029**			
10th percentile				**0.00049**			
25th percentile				**0.0018**			
n				**50**			

Notes:

- = not specified (in the redox column, assumed to be anaerobic)

source: a = original paper consulted. b = Aronson and Howard (1997). c = Ulrich et al. (2010)

MGP = manufactured gas plant; UST = underground storage tank; AFB = air force base; CFB = Canadian forces base.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-3. Toluene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Sampson County, NC	NO3	-	-	0.0005	Borden et al. (1997)	b	
Tibbetts Road Site, Barrington, NH	Fe	3,850	876	0.00099	Wilson et al. (1996a)	a	
North Bay Landfill, ON	-	19	-	0.0013	Barker and Mayfield (1988)	c	
UST Site, Dublin NC	Meth/Fe	35040	-	0.00131	Kao and Wang (2000)	a	
UST Site, Dublin NC	Meth/Fe	35040	-	0.00144	Kao and Wang (2000)	a	
UST Site, Dublin NC	Meth/Fe	35040	-	0.00155	Kao and Wang (2000)	a	
Rocky Point NC	-	10436	-	0.0016	Borden et al. (1995)	c	
Arvida Research Site, NC	-	10436	-	0.0021	Borden et al. (1994)	c	
Rocky Point, NC	Fe	-	-	0.0021	Rifai et al. (1995)	b	
Tibbetts Road Site, Barrington, NH	Fe	3,850	3,650	0.0023	Wilson et al. (1996a)	a	
Central Alberta Gas Plant	-	550	-	0.0025	Unpub. data reported in (c)	c	
Patrick AFB, FL	Meth	737	1,200	0.003	Wiedemeier et al. (1995)	b	
West Central Alberta Gas Plant	-	56	-	0.0037	Unpub. data reported in (c)	c	
Tibbetts Road Site, Barrington, NH	Fe	10,000	2,336	0.0039	Wilson et al. (1996a)	a	
UST Site, Garysburg NC	Meth/Fe	14296	-	0.0046	Kao and Wang (2001)	a	
UST Site, Garysburg NC	Meth/Fe	14296	-	0.005	Kao and Wang (2001)	a	
Former MGP, Midwest US	-	1312	-	0.0053	Stenback et al. (2004)	a	
UST Site, Garysburg NC	Meth/Fe	1899	-	0.0054	Kao and Wang (2001)	a	
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.0058**	**Thierrin et al. (1995)**	**a**	**+**
Sampson County, NC	NO3	-	-	0.0063	Borden et al. (1997)	b	
Former MGP, Midwest US	-	1312	-	0.0063	Stenback et al. (2004)	a	
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.0077**	**Thierrin et al. (1995)**	**a**	**+**
West Central Alberta Gas Plant	-	8200	-	0.0079	Unpub. data reported in (c)	c	
SE coastal plain, NC	-	-	-	0.0115	Hunt et al. (1995)	c	
Eglin AFB, FL	Meth	5,150	35	0.013	Wilson et al. (1994b)	b	
Noordwijk landfill, TheNetherlands	-	300	3650	0.019	Zoeteman et al. (1981)	b	
Western New Mexico	NO3	7,600	7	0.02	Hilton et al. (1992)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.022**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.022**	**Brockelmann et al. (2003)**	**a**	**+**
Hill AFB, Utah	SO4	5,870	250	0.023	Wiedemeier et al. (1996a)	b	
Sleeping Bear Dunes NatlLakeshore, MI	Meth/NO3/SO4	5,300	70-105	0.023	Wilson et al. (1994a)	b	
Sleeping Bear Dunes NatlLakeshore, MI	Meth/NO3/SO4	8,200	70-105	0.026	Wilson et al. (1994a)	b	
Hill AFB, Utah	-	-	-	0.027	Wiedemeier et al. (1999)	c	
Grindsted Landfill, Denmark	**Fe**	**-**	**924**	**0.028**	**Rugge et al. (1999)**	**a**	**++**
West Central Alberta Gas Plant	-	8800	-	0.0297	Unpub. data reported in (c)	c	

Table B-3. Toluene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Tank Farm, Southern Taiwan	Meth	145	-	0.03	Kao et al. (2010)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.031**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.031**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.032**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.032**	**Brockelmann et al. (2003)**	**a**	**+**
Tank Farm, Southern Taiwan	Meth	145	-	0.035	Kao et al. (2010)	a	
West Central Alberta Gas Plant	-	21000	-	0.0356	Unpub. data reported in (c)	c	
CFB Borden aquifer, Ontario, Canada	NO3	2369	56	0.038	Barbaro et al. (1992)	b	
Seal Beach, CA	-	300	-	0.0385	Beller et al. (1995)	c	
Tank Farm, Southern Taiwan	Meth	57	-	0.039	Kao et al. (2010)	a	
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**-**	**924**	**0.039**	**Rugge et al. (1999)**	**a**	**++**
Sleeping Bear DunesNatl Lakeshore, MI	-	-	-	0.0421	Wilson et al. (1994a)	c	
Vejen city landfill, Denmark	Meth/SO4/Fe	39	71	0.043	Lyngkilde and Christensen (1992)	b	
Hill AFB, Utah	SO4	5,870	102	0.045	Wiedemeier et al. (1995)	b	
George AFB, CA	-	1500	-	0.0457	Wilson et al. (1995)	c	
Eglin AFB, FL	Meth	5,150	35	0.05	Wilson et al. (1994b)	b	
Sleeping Bear Dunes NatlLakeshore, MI	Meth/NO3/SO4	-	-	0.053	Barlaz et al. (1993)	b	
Sleeping Bear Dunes NatlLakeshore, MI	Meth/NO3/SO4	5,300	35	0.053	Wilson et al. (1994a)	b	
Seal Beach, CA	**Meth**	**289**	**159**	**0.057**	**Reinhard et al. (2005)**	**a**	**+**
BC Gas Station	-	4980	-	0.0602	Unpub. data reported in (c)	c	
North Bay landfill, OntarioCanada	Meth/SO4	~175	51	0.066	Acton and Barker (1992)	b	
Site Not Identified	SO4	200-300	45	0.066	Reinhard et al. (1996)	b	
Sleeping Bear Dunes NatlLakeshore, MI	Meth/NO3/SO4	-	-	0.067	Barlaz et al. (1993)	b	
Sleeping Bear Dunes NatlLakeshore, MI	Meth/NO3/SO4	8,200	35	0.067	Wilson et al. (1994a)	b	
Seal Beach, CA	SO4	184-276	60	0.091	Beller et al. (1995)	b	
North Bay landfill, OntarioCanada	Meth/SO4	73	17	0.16	Acton and Barker (1992)	b	
Tank Farm, Kaohsiung, Taiwan	Meth	89	-	0.168	Kao et al. (2006)	a	
Traverse City, MI	Meth	-	70	0.186	Wilson et al. (1990)	b	
Site Not Identified	NO3	210-290	16	0.19	Reinhard et al. (1996)	b	
CFB Borden aquifer, Ontario, Canada	NO3	2,296	11	0.28	Barbaro et al. (1992)	b	
CFB Borden aquifer, Ontario, Canada	NO3	2,587	11	0.3	Barbaro et al. (1992)	b	
Eglin AFB, FL	-	5150	-	0.66	Wilson et al. (1994b)	c	
Hill AFB, Utah	SO4	5870	250	>0.031	Wiedemeier et al. (1996a)	b	
Traverse City, MI	-	-	-	>0.19	Wilson et al. (1990)	c	
Minimum				**0.0005**			
5th percentile				**0.0013**			
10th percentile				**0.0019**			
25th percentile				**0.0054**			

Table B-3. Toluene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
n				**67**			

Notes:
- = not specified (in the redox column, assumed to be anaerobic)
source: a = original paper consulted. b = Aronson and Howard (1997). c = Ulrich et al. (2010)
MGP = manufactured gas plant; UST = underground storage tank; AFB = air force base; CFB = Canadian forces base.
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-4. Ethylbenzene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
North Bay Landfill, ON	-	60	-	0.0003	Barker and Mayfield (1988)	c	
Tibbetts Road Site, Barrington, NH	Fe	760	876	0.0006	Wilson et al. (1996a)	a	
Sampson County, NC	NO3	-	-	0.0008	Borden et al. (1997)	b	
UST Site, Dublin NC	Meth/Fe	2654	-	0.00082	Kao and Wang (2000)	a	
UST Site, Dublin NC	Meth/Fe	2654	-	0.000845	Kao and Wang (2000)	a	
UST Site, Dublin NC	Meth/Fe	2654	-	0.000867	Kao and Wang (2000)	a	
Central Alberta Gas Plant	-	680	-	0.0009	Unpub. data reported in (c)	c	
Rocky Point NC	-	1814	-	0.001	Borden et al. (1995)	c	
Arvida Research Site, NC	-	1814	-	0.0015	Borden et al. (1994)	c	
Rocky Point, NC	Fe	-	-	0.0015	Rifai et al. (1995)	b	
UST Site, Garysburg NC	Meth/Fe	1645	-	0.0017	Kao and Wang (2001)	a	
UST Site, Garysburg NC	Meth/Fe	4172	-	0.0019	Kao and Wang (2001)	a	
Former MGP, Midwest US	assumed anaerobic	2935	-	0.0019	Stenback et al. (2004)	a	
UST Site, Garysburg NC	Meth/Fe	4172	-	0.0021	Kao and Wang (2001)	a	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	1,500	70-105	0.0024	Wilson et al. (1994a)	b	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.003	Barlaz et al. (1993)	b	
Seal Beach, CA	**Meth**	**347**	**159**	**0.003**	**Reinhard et al. (2005)**	**a**	**+**
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.003**	**Thierrin et al. (1995)**	**a**	**+**
Patrick AFB, FL	Meth	823	1,200	0.0031	Wiedemeier et al. (1995)	b	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	1,700	35	0.0031	Wilson et al. (1994a)	b	
Tibbetts Road Site, Barrington, NH	Fe	1,300	2,336	0.0032	Wilson et al. (1996a)	a	
Former MGP, Midwest US	assumed anaerobic	2935	-	0.0042	Stenback et al. (2004)	a	
Sampson County, NC	NO3	-	-	0.0058	Borden et al. (1997)	b	
Seal Beach, CA	SO4	212-319	60	0.0066	Beller et al. (1995)	b	
Sleeping Bear DunesNatl Lakeshore, MI	-	-	-	0.0066	Wilson et al. (1994a)	c	
West Central Alberta Gas Plant	-	-	-	0.0069	Unpub. data reported in (c)	c	
Former MGP	SO4/Fe	1700	27375	0.0076	Rogers et al. (2007)	a	
George AFB, CA	-	210	-	0.0086	Wilson et al. (1995)	c	
Hill AFB, Utah	SO4	955	250	0.009	Wiedemeier et al. (1996a)	b	
Western New Mexico	NO3	475	7	0.0092	Hilton et al. (1992)	b	
Hill AFB, Utah	-	-	-	0.0095	Wiedemeier et al. (1999)	c	
West Central Alberta Gas Plant	-	300	-	0.0099	Unpub. data reported in (c)	c	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	1500	35	0.0099	Wilson et al. (1994a)	b	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.01	Barlaz et al. (1993)	b	
Hill AFB, Utah	SO4	955	250	0.01	Wiedemeier et al. (1996a)	b	

Table B-4. Ethylbenzene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	1700	70-105	0.011	Wilson et al. (1994a)	b	
Site Not Identified	SO4	200-300	60	0.014	Reinhard et al. (1996)	b	
West Central Alberta Gas Plant	-	2200	-	0.0155	Unpub. data reported in (c)	c	
Tank Farm, Southern Taiwan	Meth	31	-	0.016	Kao et al. (2010)	a	
Noordwijk landfill, TheNetherlands	-	300	3650	0.019	Zoeteman,BCJ et al. (1981)	b	
Tank Farm, Southern Taiwan	Meth	79	-	0.021	Kao et al. (2010)	a	
Vejen city landfill, Denmark	Meth/SO4/Fe	96	71	0.024	Lyngkilde and Christensen (1992)	b	
CFB Borden aquifer, Ontario, Canada	NO3	374	11	0.026	Barbaro et al. (1992)	b	
Tank Farm, Southern Taiwan	Meth	79	-	0.027	Kao et al. (2010)	a	
Hill AFB, Utah	SO4	955	228	0.029	Wiedemeier et al. (1995)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.03**	**Brockelmann et al. (2003)**	**a**	**+**
Eglin AFB, FL	Meth	1,700	35	0.03	Wilson et al. (1994b)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.039**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.05**	**Brockelmann et al. (2003)**	**a**	**+**
Eglin AFB, FL	Meth	1,700	35	0.05	Wilson et al. (1994b)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.051**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.058**	**Brockelmann et al. (2003)**	**a**	**+**
BC Gas Station	-	1680	-	0.0748	Unpub. data reported in (c)	c	
Tank Farm, Kaohsiung, Taiwan	Meth	183	-	0.098	Kao et al. (2006)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.125**	**Brockelmann et al. (2003)**	**a**	**+**
Site Not Identified	NO3	210-290	16	0.15	Reinhard et al. (1996)	b	
Eglin AFB, FL	-	1700	-	0.295	Wilson et al. (1994b)	c	
Tibbetts Road Site, Barrington, NH	Fe	760	3,650	>0.0018	Wilson et al. (1996a)	a	
Minimum				**0.0003**			
5th percentile				**0.00082**			
10th percentile				**0.00089**			
25th percentile				**0.0024**			
n				**57**			

Notes:

- = not specified (in the redox column, assumed to be anaerobic)

source: a = original paper consulted. b = Aronson and Howard (1997). c = Ulrich et al. (2010)

MGP = manufactured gas plant; UST = underground storage tank; AFB = air force base; CFB = Canadian forces base.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-5. Xylenes
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Compound	Quality
Sampson County, NC	NO3	-	-	0.0007	Borden et al. (1997)	b	o-xylene	
UST Site, Dublin NC	Meth/Fe	5057	-	0.00071	Kao and Wang (2000)	a	o-xylene	
Tibbetts Road Site, Barrington, NH	Fe	240	876	0.00082	Wilson et al. (1996a)	a	o-xylene	
Tibbetts Road Site, Barrington, NH	Fe	1,100	876	0.00085	Wilson et al. (1996a)	a	p-xylene	
North Bay Landfill, ON	-	109	-	0.001	Barker and Mayfield (1988)	c	total xylenes	
Rocky Point NC	-	8179	-	0.001	Borden et al. (1995)	c	m/p-xylenes	
UST Site, Dublin NC	Meth/Fe	9152	-	0.001	Kao and Wang (2000)	a	m/p-xylenes	
UST Site, Dublin NC	Meth/Fe	5057	-	0.00101	Kao and Wang (2000)	a	o-xylene	
UST Site, Dublin NC	Meth/Fe	9152	-	0.0011	Kao and Wang (2000)	a	m/p-xylenes	
Sleeping Bear Dunes Natl Lakeshore, MI	Meth/NO3/SO4	2,300	70-105	0.0011	Wilson et al. (1994a)	b	o-xylene	
UST Site, Dublin NC	Meth/Fe	9152	-	0.00119	Kao and Wang (2000)	a	m/p-xylenes	
Sampson County, NC	NO3	-	-	0.0012	Borden et al. (1997)	b	m-xylene	
Sampson County, NC	NO3	-	-	0.0012	Borden et al. (1997)	b	p-xylene	
West Central Alberta Gas Plant	-	28000	-	0.0012	Unpub. data reported in (c)	c	total xylenes	
Tibbetts Road Site, Barrington, NH	Fe	360	876	0.0012	Wilson et al. (1996a)	a	m-xylene	
Arvida Research Site, NC	-	8179	-	0.0013	Borden et al. (1994)	c	m/p-xylenes	
Rocky Point, NC	Fe	-	-	0.0013	Rifai et al. (1995)	b	m-xylene	
Rocky Point, NC	Fe	-	-	0.0013	Rifai et al. (1995)	b	p-xylene	
Rocky Point NC	-	3873	-	0.0014	Borden et al. (1995)	c	o-xylene	
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**-**	**924**	**0.0014**	**Rugge et al. (1999)**	**a**	**o-xylene**	**++**
UST Site, Dublin NC	Meth/Fe	5057	-	0.00141	Kao and Wang (2000)	a	o-xylene	
Tibbetts Road Site, Barrington, NH	Fe	240	3,650	0.0015	Wilson et al. (1996a)	a	o-xylene	
Tibbetts Road Site, Barrington, NH	Fe	360	3,650	0.0016	Wilson et al. (1996a)	a	m-xylene	
Sampson County, NC	NO3	-	-	0.0017	Borden et al. (1997)	b	o-xylene	
Tibbetts Road Site, Barrington, NH	Fe	1,400	2,336	0.0018	Wilson et al. (1996a)	a	p-xylene	
Tibbetts Road Site, Barrington, NH	Fe	1,100	3,650	0.0019	Wilson et al. (1996a)	a	p-xylene	
Arvida Research Site, NC	-	3873	-	0.0021	Borden et al. (1994)	c	o-xylene	
Rocky Point, NC	Fe	-	-	0.0021	Rifai et al. (1995)	b	o-xylene	
UST Site, Garysburg NC	Meth/Fe	5099	-	0.00218	Kao and Wang (2001)	a	m/p-xylenes	
Tibbetts Road Site, Barrington, NH	Fe	1,400	2,336	0.0022	Wilson et al. (1996a)	a	o-xylene	
West Central Alberta Gas Plant	-	699	-	0.0023	Unpub. data reported in (c)	c	total xylenes	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	1,400	70-105	0.0024	Wilson et al. (1994a)	b	p-xylene	
Central Alberta Gas Plant	-	10300	-	0.0025	Unpub. data reported in (c)	c	total xylenes	
UST Site, Garysburg NC	Meth/Fe	1357	-	0.0026	Kao and Wang (2001)	a	m/p-xylenes	
Grindsted Landfill, Denmark	**Fe**	**-**	**924**	**0.0028**	**Rugge et al. (1999)**	**a**	**o-xylene**	**++**
Patrick AFB, FL	Meth	1,220	1,200	0.0029	Wiedemeier et al. (1995)	b	p-xylene	
UST Site, Garysburg NC	Meth/Fe	5099	-	0.003	Kao and Wang (2001)	a	m/p-xylenes	
Patrick AFB, FL	Meth	2,410	1,200	0.003	Wiedemeier et al. (1995)	b	m-xylene	

Table B-5. Xylenes
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Compound	Quality
Patrick AFB, FL	Meth	1,390	1,200	0.003	Wiedemeier et al. (1995)	b	o-xylene	
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.0031**	**Thierrin et al. (1995)**	**a**	**p-xylene**	**+**
UST Site, Garysburg NC	Meth/Fe	895	-	0.0032	Kao and Wang (2001)	a	o-xylene	
Tibbetts Road Site, Barrington, NH	Fe	2,500	2,336	0.0033	Wilson et al. (1996a)	a	m-xylene	
Sampson County, NC	NO3	-	-	0.0035	Borden et al. (1997)	b	m-xylene	
Sampson County, NC	NO3	-	-	0.0035	Borden et al. (1997)	b	p-xylene	
UST Site, Garysburg NC	Meth/Fe	4669	-	0.0035	Kao and Wang (2001)	a	o-xylene	
UST Site, Garysburg NC	Meth/Fe	4669	-	0.0037	Kao and Wang (2001)	a	o-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	3,400	70-105	0.0037	Wilson et al. (1994a)	b	m-xylene	
Traverse City, MI	-	-	-	0.004	Wilson et al. (1990)	c	total xylenes	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2,400	70-105	0.004	Wilson et al. (1994a)	b	o-xylene	
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.0041**	**Thierrin et al. (1995)**	**a**	**m/p-xylenes**	**+**
Traverse City, MI	Meth	-	70	0.0043	Wilson et al. (1990)	b	o-xylene	
Traverse City, MI	Meth	-	70	0.0043	Wilson et al. (1990)	b	p-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2,500	35	0.0046	Wilson et al. (1994a)	b	m-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.005	Barlaz et al. (1993)	b	m-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.005	Barlaz et al. (1993)	b	p-xylene	
West Central Alberta Gas Plant	-	37000	-	0.0051	Unpub. data reported in (c)	c	m/p-xylenes	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2100	35	0.0051	Wilson et al. (1994a)	b	p-xylene	
Gas Station, Perth, Western Australia	**SO4**	**-**	**-**	**0.0055**	**Thierrin et al. (1995)**	**a**	**o-xylene**	**+**
Former MGP	SO4/Fe	1000	27375	0.0057	Rogers et al. (2007)	a	total xylenes	
Hill AFB, Utah	-	-	-	0.007	Wiedemeier et al. (1999)	c	total xylenes	
Sleeping Bear Dunes Natl Lakeshore, MI	-	51800	-	0.0072	Wilson et al. (1994a)	c	total xylenes	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2,500	70-105	0.0083	Wilson et al. (1994a)	b	m-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2,300	35	0.0086	Wilson et al. (1994a)	b	o-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.009	Barlaz et al. (1993)	b	o-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	1400	35	0.0094	Wilson et al. (1994a)	b	p-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2,100	70-105	0.0096	Wilson et al. (1994a)	b	p-xylene	
West Central Alberta Gas Plant	-	6800	-	0.0104	Unpub. data reported in (c)	c	total xylenes	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.0125**	**Brockelmann et al. (2003)**	**a**	**p-xylene**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.013**	**Brockelmann et al. (2003)**	**a**	**p-xylene**	**+**
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.014	Barlaz et al. (1993)	b	m-xylene	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.014	Barlaz et al. (1993)	b	p-xylene	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.014**	**Brockelmann et al. (2003)**	**a**	**p-xylene**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.014**	**Brockelmann et al. (2003)**	**a**	**o-xylene**	**+**
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	3,400	35	0.014	Wilson et al. (1994a)	b	m-xylene	
SE coastal plain, NC	-	-	-	0.0143	Hunt et al. (1995)	c	m/p-xylenes	
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	2,400	35	0.015	Wilson et al. (1994a)	b	o-xylene	

Table B-5. Xylenes
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Compound	Quality
Sleeping Bear DunesNatl Lakeshore, MI	Meth/NO3/SO4	-	-	0.016	Barlaz et al. (1993)	b	o-xylene	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.018**	**Brockelmann et al. (2003)**	**a**	**p-xylene**	**+**
Tank Farm, Southern Taiwan	Meth	41	-	0.019	Kao et al. (2010)	a	o-xylene	
Noordwijk landfill, The Netherlands	-	300	3,650	0.019	Zoeteman et al. (1981)	b	m-xylene	
Noordwijk landfill, The Netherlands	-	300	3,650	0.019	Zoeteman et al. (1981)	b	p-xylene	
Tank Farm, Southern Taiwan	Meth	98	-	0.02	Kao et al. (2010)	a	o-xylene	
Hill AFB, Utah	SO4	2,300	102	0.02	Wiedemeier et al. (1995)	b	o-xylene	
Eglin AFB, FL	Meth	6,750	35	0.02	Wilson et al. (1994b)	b	m-xylene	
Eglin AFB, FL	Meth	3,120	35	0.02	Wilson et al. (1994b)	b	p-xylene	
George AFB, CA	-	377	-	0.02	Wilson et al. (1995a)	c	o-xylene	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.022**	**Brockelmann et al. (2003)**	**a**	**p-xylene**	**+**
Tank Farm, Southern Taiwan	Meth	98	-	0.022	Kao et al. (2010)	a	o-xylene	
West Central Alberta Gas Plant	-	3400	-	0.0224	Unpub. data reported in (c)	c	o-xylene	
George AFB, CA	-	704	-	0.0229	Wilson et al. (1995a)	c	m/p-xylenes	
Tank Farm, Southern Taiwan	Meth	41	-	0.023	Kao et al. (2010)	a	m/p-xylenes	
Tank Farm, Southern Taiwan	Meth	98	-	0.024	Kao et al. (2010)	a	m/p-xylenes	
Hill AFB, Utah	SO4	5,130	228	0.024	Wiedemeier et al. (1995)	b	m-xylene	
Tank Farm, Southern Taiwan	Meth	98	-	0.025	Kao et al. (2010)	a	m/p-xylenes	
CFB Borden aquifer, Ontario, Canada	NO3	943	11	0.026	Barbaro et al. (1992)	b	m-xylene	
CFB Borden aquifer, Ontario, Canada	NO3	551	11	0.026	Barbaro et al. (1992)	b	o-xylene	
CFB Borden aquifer, Ontario, Canada	NO3	367	11	0.026	Barbaro et al. (1992)	b	p-xylene	
BC Gas Station	-	10050	-	0.0275	Unpub. data reported in (c)	c	total xylenes	
Seal Beach, CA	-	300	-	0.0277	Beller et al. (1995)	c	m/p-xylenes	
Vejen city landfill, Denmark	Meth/SO4/Fe	16	71	0.029	Lyngkilde and Christensen (1992)	b	o-xylene	
Seal Beach, CA	**Meth**	**218**	**159**	**0.03**	**Reinhard et al. (2005)**	**a**	**m-xylene**	**+**
Hill AFB, Utah	SO4	1,620	228	0.032	Wiedemeier et al. (1995)	b	p-xylene	
Seal Beach, CA	**Meth**	**302**	**159**	**0.037**	**Reinhard et al. (2005)**	**a**	**p-xylene**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.038**	**Brockelmann et al. (2003)**	**a**	**o-xylene**	**+**
Site Not Identified	NO3	210-290	80	0.041	Reinhard et al. (1996)	b	o-xylene	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.046**	**Brockelmann et al. (2003)**	**a**	**p-xylene**	**+**
Site Not Identified	SO4	200-300	45	0.05	Reinhard et al. (1996)	b	m-xylene	
Seal Beach, CA	**Meth**	**367**	**159**	**0.054**	**Reinhard et al. (2005)**	**a**	**o-xylene**	**+**
Vejen city landfill, Denmark	Meth/SO4/Fe	224	71	0.057	Lyngkilde and Christensen (1992)	b	m-xylene	
Vejen city landfill, Denmark	Meth/SO4/Fe	224	71	0.057	Lyngkilde and Christensen (1992)	b	p-xylene	

Table B-5. Xylenes
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Compound	Quality
Noordwijk landfill, The Netherlands	-	100	3,650	0.063	Zoeteman et al. (1981)	b	o-xylene	
Site Not Identified	SO4	200-300	45	0.077	Reinhard et al. (1996)	b	o-xylene	
Eglin AFB, FL	Meth	3,120	35	0.08	Wilson et al. (1994b)	b	p-xylene	
North Bay landfill, Ontario Canada	Meth/SO4	~165	51	0.087	Acton and Barker (1992)	b	m-xylene	
Eglin AFB, FL	Meth	6,750	35	0.1	Wilson et al. (1994b)	b	m-xylene	
Seal Beach, CA	SO4	212-319	60	0.12	Beller et al. (1995)	b	m-xylene	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.12**	**Brockelmann et al. (2003)**	**a**	**o-xylene**	**+**
Tank Farm, Kaohsiung, Taiwan	Meth	9.5	-	0.124	Kao et al. (2006)	a	o-xylene	
Tank Farm, Kaohsiung, Taiwan	Meth	202	-	0.149	Kao et al. (2006)	a	m/p-xylenes	
Seal Beach, CA	SO4	212-319	60	0.16	Beller et al. (1995)	b	o-xylene	
Site Not Identified	NO3	210-290	10	0.17	Reinhard et al. (1996)	b	m-xylene	
Eglin AFB, FL	Meth	5,480	35	0.21	Wilson et al. (1994b)	b	o-xylene	
Eglin AFB, FL	-	9870	-	0.355	Wilson et al. (1994b)	c	m/p-xylenes	
Eglin AFB, FL	-	5480	-	1.5	Wilson et al. (1994b)	c	o-xylene	
Minimum				**0.0007**				
5th percentile				**0.0010**				
10th percentile				**0.0012**				
25th percentile				**0.0024**				
n				**124**				

Notes:
- = not specified (in the redox column, assumed to be anaerobic)
source: a = original paper consulted. b = Aronson and Howard (1997). c = Ulrich et al. (2010)
MGP = manufactured gas plant; UST = underground storage tank; AFB = air force base; CFB = Canadian forces base.
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-6. Naphthalene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Conroe,TX	anaerobic	649.3	15000	0.00018	Bedient et al. (1984)	b	
Conroe,TX	anaerobic	650-1600	2963	0.0015	Wilson et al. (1985)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.002**	**Brockelmann et al. (2003)**	**a**	**+**
Conroe,TX	anaerobic	650-1600	2963	0.0021	Wilson et al. (1985)	b	
Former MGP, Midwest US	assumed anaerobic	4946	-	0.0034	Stenback et al. (2004)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.0045**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, Midwest US	assumed anaerobic	4946	-	0.0051	Stenback et al. (2004)	a	
Former MGP	SO4/Fe	6900	27375	0.0058	Rogers et al. (2007)	a	
South Glens Falls MGP NY	anaerobic/aerobic	52000	5110	0.0063	Neuhauser et al. (2009)	a	
Noordwijk landfill, The Netherlands	anaerobic	30	3650	0.0063	Zoeteman et al. (1981)	b	
Gas Station, Perth, Western Australia	**SO4/Fe**	**1200**	**71**	**0.021**	**Thierrin et al. (1995)**	**a**	**+**
Vejen city landfill, Denmark	Meth/SO4/Fe	24	71	0.026	Lyngkilde and Christensen (1992)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.03**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.035**	**Brockelmann et al. (2003)**	**a**	**+**
Gas Station, Perth, Western Australia	**SO4/Fe**	**1200**	**71**	**0.043**	**Thierrin et al. (1995)**	**a**	**+**
Minimum				**0.00018**			
5th percentile				**0.0011**			
10th percentile				**0.0017**			
25th percentile				**0.0028**			
n				**15**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-7. Acenaphthene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Former MGP	SO4/Fe	6900	27375	0.0011	Rogers et al. (2007)	a	
Former MGP, Midwest US	assumed anaerobic	183	-	0.0014	Stenback et al. (2004)	a	
Former MGP, Midwest US	assumed anaerobic	183	-	0.0018	Stenback et al. (2004)	a	
Pensacola, FL	Meth	520	125	0.0043	Godsy et al. (1992)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.01**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.01**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.011**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.012**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.019**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.078**	**Brockelmann et al. (2003)**	**a**	**+**
Minimum				**0.0011**			
5th percentile				**0.0012**			
10th percentile				**0.0014**			
25th percentile				**0.0024**			
n				**10**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-8. Acenaphthylene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Former MGP	SO4/Fe	6900	27375	0.00069	Rogers et al. (2007)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.007**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.011**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.012**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.08**	**Brockelmann et al. (2003)**	**a**	**+**
Minimum				**0.00069**			
n				**5**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-9. Fluorene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate $(days^{-1})$	Study Author	Source	Quality
Conroe,TX	anaerobic	123.8	15000	0.0003	Bedient et al. (1984)	b	
Conroe,TX	anaerobic	120-230	2963	0.0013	Wilson et al. (1985)	b	
Conroe,TX	anaerobic	120-230	2963	0.0016	Wilson et al. (1985)	b	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.002**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.003**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP	SO4/Fe	6900	27375	0.0058	Rogers et al. (2007)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.012**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.11**	**Brockelmann et al. (2003)**	**a**	**+**
Minimum				**0.0003**			
n				**8**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-10. Fluoranthene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate ($days^{-1}$)	Study Author	Source	Quality
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.003**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.004**	**Brockelmann et al. (2003)**	**a**	**+**
Minimum				**0.003**			
n				**2**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-11. Phenanthrene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0**	**Brockelmann et al. (2003)**	**a**	**+**
Former MGP	SO4/Fe	6900	27375	0.000013	Rogers et al. (2007)	a	
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.075**	**Brockelmann et al. (2003)**	**a**	**+**
Minimum				**0**			
n				**3**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-12. Anthracene
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.018	Brockelmann et al. (2003)	a	+
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.021	Brockelmann et al. (2003)	a	+
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.021	Brockelmann et al. (2003)	a	+
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.075	Brockelmann et al. (2003)	a	+
Minimum				0.018			
n				4			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant.

Quality: + = High Quality study.

Table B-13. VPH Components
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality	Compound
UST Site, Garysburg NC	Meth/Fe	2925	-	0.0004	Kao and Wang (2001)	a		1,2,4-trimethylbenzene
UST Site, Garysburg NC	Meth/Fe	2925	-	0.0007	Kao and Wang (2001)	a		1,2,4-trimethylbenzene
UST Site, Garysburg NC	Meth/Fe	2459	-	0.001	Kao and Wang (2001)	a		1,2,4-trimethylbenzene
Gas Station, Perth, Western Australia	SO4	520	71	0.0039	Thierrin et al. (1995)	a	+	1,3,5-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.0054	Brockelmann et al. (2003)	a	+	1,2,4-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.0063	Brockelmann et al. (2003)	a	+	1,2,3-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.0088	Brockelmann et al. (2003)	a	+	1,2,4-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.0098	Brockelmann et al. (2003)	a	+	1,3,5-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.013	Brockelmann et al. (2003)	a	+	isopropylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.014	Brockelmann et al. (2003)	a	+	1,2,3-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.02	Brockelmann et al. (2003)	a	+	1,3,5-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.025	Brockelmann et al. (2003)	a	+	propylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.029	Brockelmann et al. (2003)	a	+	propylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.03	Brockelmann et al. (2003)	a	+	propylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.03	Brockelmann et al. (2003)	a	+	isopropylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.031	Brockelmann et al. (2003)	a	+	isopropylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.036	Brockelmann et al. (2003)	a	+	1,3,5-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.039	Brockelmann et al. (2003)	a	+	isopropylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.041	Brockelmann et al. (2003)	a	+	1,2,3-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.043	Brockelmann et al. (2003)	a	+	isopropylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.046	Brockelmann et al. (2003)	a	+	1,2,4-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.049	Brockelmann et al. (2003)	a	+	propylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.05	Brockelmann et al. (2003)	a	+	propylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.052	Brockelmann et al. (2003)	a	+	1,2,4-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.061	Brockelmann et al. (2003)	a	+	1,3,5-trimethylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.073	Brockelmann et al. (2003)	a	+	isopropylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.081	Brockelmann et al. (2003)	a	+	propylbenzene
Former MGP, SW Germany	SO4/Fe	NAPL	-	0.11	Brockelmann et al. (2003)	a	+	1,2,3-trimethylbenzene
Tank Farm, Kaohsiung, Taiwan	Meth	35	-	0.189	Kao et al. (2006)	a		1,2,4-trimethylbenzene
Minimum				**0.0004**				
5th percentile				**0.00084**				
10th percentile				**0.0033**				
25th percentile				**0.0098**				
n				**29**				

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant; UST = underground storage tank.

Quality: + = High Quality study (bold). See text for discussion.

Table B-14. LEPH Components
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality	Compound
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0**	**Brockelmann et al. (2003)**	**a**	**+**	**phenanthrene**
Former MGP	SO4/Fe	6900	27375	0.000013	Rogers et al. (2007)	a		phenanthrene
Conroe,TX	anaerobic	649.3	15000	0.00018	Bedient et al. (1984)	b		naphthalene
Conroe,TX	anaerobic	123.8	15000	0.0003	Bedient et al. (1984)	b		fluorene
Former MGP	SO4/Fe	6900	27375	0.00069	Rogers et al. (2007)	a		acenaphthylene
Former MGP	SO4/Fe	6900	27375	0.0011	Rogers et al. (2007)	a		acenaphthene
Conroe,TX	anaerobic	120-230	2963	0.0013	Wilson et al. (1985)	b		fluorene
Former MGP, Midwest US	assumed anaerobic	183	-	0.0014	Stenback et al. (2004)	a		acenaphthene
Conroe,TX	anaerobic	650-1600	2963	0.0015	Wilson et al. (1985)	b		naphthalene
Conroe,TX	anaerobic	120-230	2963	0.0016	Wilson et al. (1985)	b		fluorene
Former MGP, Midwest US	assumed anaerobic	183	-	0.0018	Stenback et al. (2004)	a		acenaphthene
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.002**	**Brockelmann et al. (2003)**	**a**	**+**	**fluorene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.002**	**Brockelmann et al. (2003)**	**a**	**+**	**naphthalene**
Conroe,TX	anaerobic	650-1600	2963	0.0021	Wilson et al. (1985)	b		naphthalene
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.003**	**Brockelmann et al. (2003)**	**a**	**+**	**fluorene**
Former MGP, Midwest US	assumed anaerobic	4946	-	0.0034	Stenback et al. (2004)	a		naphthalene
Pensacola, FL	Meth	520	125	0.0043	Godsy et al. (1992)	b		acenaphthene
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.0045**	**Brockelmann et al. (2003)**	**a**	**+**	**naphthalene**
Former MGP, Midwest US	assumed anaerobic	4946	-	0.0051	Stenback et al. (2004)	a		naphthalene
Former MGP	SO4/Fe	6900	27375	0.0058	Rogers et al. (2007)	a		fluorene
Former MGP	SO4/Fe	6900	27375	0.0058	Rogers et al. (2007)	a		naphthalene
South Glens Falls MGP NY	anaerobic/aerobic	52000	5110	0.0063	Neuhauser et al. (2009)	a		naphthalene
Noordwijk landfill, The Netherlands	anaerobic	30	3650	0.0063	Zoeteman et al. (1981)	b		naphthalene
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.007**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthylene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.01**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.01**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.011**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.011**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthylene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.012**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.012**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthylene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.012**	**Brockelmann et al. (2003)**	**a**	**+**	**fluorene**
Swan Coastal Plain, Western Australia	**SO4/Fe**	**1200**	**71**	**0.017**	**Thierrin et al. (1995)**	**a**	**+**	**naphthalene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.018**	**Brockelmann et al. (2003)**	**a**	**+**	**anthracene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.019**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.021**	**Brockelmann et al. (2003)**	**a**	**+**	**anthracene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.021**	**Brockelmann et al. (2003)**	**a**	**+**	**anthracene**
Vejen city landfill, Denmark	Meth/SO4/Fe	24	71	0.026	Lyngkilde and Christensen (1992)	b		naphthalene
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.03**	**Brockelmann et al. (2003)**	**a**	**+**	**naphthalene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.035**	**Brockelmann et al. (2003)**	**a**	**+**	**naphthalene**

Table B-14. LEPH Components
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality	Compound
Swan Coastal Plain, Western Australia	**SO4/Fe**	**1200**	**71**	**0.043**	**Thierrin et al. (1995)**	**a**	**+**	**naphthalene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.075**	**Brockelmann et al. (2003)**	**a**	**+**	**anthracene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.075**	**Brockelmann et al. (2003)**	**a**	**+**	**phenanthrene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.078**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.08**	**Brockelmann et al. (2003)**	**a**	**+**	**acenaphthylene**
Former MGP, SW Germany	**SO4/Fe**	**NAPL**	**-**	**0.11**	**Brockelmann et al. (2003)**	**a**	**+**	**fluorene**
Minimum				**0**	**-**			
5th percentile				**0.0002**	**3,398**			
10th percentile				**0.0009**	**812**			
25th percentile				**0.0020**	**347**			
n				**45**				

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

MGP = manufactured gas plant; UST = underground storage tank.

Quality: + = High Quality study (bold). See text for discussion.

Table B-15. Tetrachloroethylene (PCE)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Otis AFB, MA	NO3	133.6	-	0.00019	Ala and Domenico (1992)	b	
Dover AFB, DE	Meth	-	-	0.00032	Clement et al. (2000)	a	
Dover AFB, DE	Meth	-	-	0.0004	Clement et al. (2000)	a	
Zetor site, Czech Republic	SO4	681	-	0.0005	Kutchovsky and Sracek (2007)	a	
Dover AFB, DE	Meth	-	-	0.00068	Ellis et al. (1996)	a	
Dover AFB, DE	Meth	-	-	0.00079	Ellis et al. (1996)	a	
Grindsted landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.0012**	**Rugge et al. (1999)**	**a**	**++**
Dolni Tresnovec landfill, Czech Republic	Fe/NO3	690	-	0.0025	Kutchovsky and Sracek (2007)	a	
Palo Alto, CA	-	2.5	350	0.003	Roberts et al. (1982)	b	
Seattle, WA	NO3/Fe/SO4/Meth	-	-	0.0035	Nelson (1996)	b	
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.0038**	**Rugge et al. (1999)**	**a**	**++**
Seattle, WA	NO3/Fe/SO4/Meth	-	-	0.0046	Nelson (1996)	b	
Dry cleaning site	-	84	3650	0.005	Ling and Rifai (2007)	a	
Dry cleaning site	-	84	3650	0.007	Ling and Rifai (2007)	a	
Zetor site, Czech Republic	SO4	681	-	0.027	Kutchovsky and Sracek (2007)	a	
Landfill, SE PA	SO4	-	3000	0.11	Washington and Cameron (2001)	a	
Minimum				**0.00019**			
5th percentile				**0.00029**			
10th percentile				**0.00036**			
25th percentile				**0.00064**			
n				**16**			

Notes:

- = not specified (in the redox column, assumed to be anaerobic)

source: a = original paper consulted. b = Aronson and Howard (1997).

AFB = air force base.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-16. Tetrachloroethylene (PCE)
Degradation Rates from Aerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate ($days^{-1}$)	Study Author	Source	Quality
Fractured bedrock site, SW Germany	Aerobic	5400	-	0	Pooley et al. (2009)	a	
Fractured bedrock site, SW Germany	Aerobic	5400	-	0	Pooley et al. (2009)	a	
Dubnica site, Slovak Republic	Aerobic	130	-	0.00027	Kutchovsky and Sracek (2007)	a	
Dubnica site, Slovak Republic	Aerobic	130	-	0.0011	Kutchovsky and Sracek (2007)	a	
Minimum				**0**			
n				**4**			

Notes:
- = not specified.
source: a = original paper consulted.
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-17. Trichloroethylene (TCE)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Picatinny Arsenal, NJ	SO4/Fe	15-16	-	0.00014	Ehlke et al. (1994)	b	
Tacoma, WA	-	2,890	2,008	0.00014	Silka and Wallen (1988)	b	
Otis AFB, MA	NO3	95	-	0.00017	Ala & Domenico (1992)	b	
Tacoma, WA	-	2,890	2,008	0.00019	Silka and Wallen (1988)	b	
Tacoma, WA	-	2,890	2,008	0.00024	Silka and Wallen (1988)	b	
Grindsted landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.0003**	**Rugge et al. (1999)**	**a**	**++**
Dover AFB, DE	Meth	-	-	0.00045	Clement et al. (2000)	a	
Dover AFB, DE	Meth	-	-	0.00045	Ellis et al. (1996)	a	
Eielson Air Force Base, AK	-	40.1 kg	420	0.0005	Dupont et al. (1996)	a	
Cape Canaveral Air Station, FL	Fe/Meth/SO4	-	-	0.00059	Swanson et al. (1996)	b	
Zetor site, Czech Republic	SO4	2250	-	0.0006	Kutchovsky and Sracek (2007)	a	
Dover AFB, DE	Meth	-	-	0.00068	Ellis et al. (1996)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.00069	Rifai et al. (1995)	b	
Cape Canaveral Air Station, FL	Fe/Meth/SO4	-	-	0.00079	Swanson et al. (1996)	b	
St. Joseph site, MI	Meth/SO4	7,411	-	0.00082	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	7,411	2,374	0.00082	Weaver et al. (1996)	a	
Picatinny Arsenal, NJ	Fe/Meth/SO4	1,900	1,096	0.00086	Imbrigiotta et al. (1996)	a	
Dover AFB, DE	Meth	-	-	0.0009	Clement et al. (2000)	a	
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.001**	**Rugge et al. (1999)**	**a**	**++**
St. Joseph site, MI	Meth/SO4	6,500	2,373	0.001	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	6,700	2,380	0.0011	Wilson et al. (1994c)	b	
Tibbitt's Road, NH	-	200	2,338	0.0011	Wilson et al. (1996a)	a	
Plattsburg AFB, Plattsburg, NY	NO3/Fe/SO4/Meth	-	692	0.0014	Wiedemeier et al. (1996b)	a	
Tibbitt's Road, NH	-	710	3,650	0.0015	Wilson et al. (1996a)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.0016	Rifai et al. (1995)	b	
St. Joseph site, MI	Meth/SO4	-	-	0.0016	Rifai et al. (1995)	b	
Tibbitt's Road, NH	-	710	877	0.0016	Wilson et al. (1996a)	a	
Picatinny Arsenal, NJ	SO4/Fe	-	-	0.0017	Ehlke and Imbrigiotta (1996)	b	
Necco Park, NY	-	-	584	0.0019	Lee et al. (1995)	d	
Necco Park, NY	-	-	657	0.0019	Lee et al. (1995)	d	
Eielson Air Force Base, AK	-	-	-	0.002	Gorder et al. (1996)	b	
St. Joseph site, MI	Meth/SO4	-	-	0.0023	Rifai et al. (1995)	b	
Tacoma, WA	-	2,890	2,008	0.0024	Silka and Wallen (1988)	b	
St. Joseph site, MI	Meth/SO4	15	1,971	0.0025	Semprini et al. (1995)	d	
Eielson Air Force Base, AK	-	90,000	-	0.0026	Dupont et al. (1996)	b	

Table B-17. Trichloroethylene (TCE)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Picatinny Arsenal, NJ	SO4/Fe	-	1,533	0.0027	Wilson et al. (1995b)	b	
Picatinny Arsenal, NJ	SO4/Fe	-	-	0.0029	Ehlke and Imbrigiotta (1996)	b	
Sacramento, CA	-	-	658	0.003	Cox et al. (1995)	d	
Palo Alto, CA	-	10	350	0.003	Roberts et al. (1982)	b	
Picatinny Arsenal, NJ	SO4/Fe	10,000	475	0.0033	Ehlke et al. (1994)	d	
St. Joseph site, MI	Meth/SO4	-	-	0.0033	Rifai et al. (1995)	b	
Plattsburg AFB, Plattsburg, NY	NO3/Fe/SO4/Meth	-	2,487	0.0033	Wiedemeier et al. (1996b)	a	
St. Joseph site, MI	Meth/SO4	504	1,015	0.0034	Wilson et al. (1994c)	b	
St. Joseph site, MI	Meth/SO4	520	1,022	0.0036	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	-	730	0.0038	Semprini et al. (1995)	d	
Picatinny Arsenal, NJ	SO4/Fe	25,000	730	0.0038	Wilson et al. (1995b)	b	
Dolni Tresnovec landfill, Czech Republic	Fe/NO3	23000	-	0.0041	Kutchovsky and Sracek (2007)	a	
Picatinny Arsenal, NJ	SO4/Fe	25,000	244-733	0.0043	Wilson et al. (1991)	b	
Picatinny Arsenal, NJ	SO4/Fe	10,000	156-467	0.0043	Wilson et al. (1991)	b	
St. Joseph site, MI	Meth/SO4	864	-	0.0047	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	30	-	0.0047	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.0047	Rifai et al. (1995)	b	
St. Joseph site, MI	Meth/SO4	864	1,023	0.0047	Weaver et al. (1996)	a	
St. Joseph site, MI	Meth/SO4	30	1,972	0.0047	Weaver et al. (1996)	a	
Dry cleaning site	-	200	3650	0.006	Ling and Rifai (2007)	a	
Eielson Air Force Base, AK	-	-	-	0.0064	Gorder et al. (1996)	b	
Picatinny Arsenal, NJ	SO4/Fe	15-16	-	0.0071	Ehlke et al. (1994)	b	
Cecil Field NAS, FL	-	-	438	0.009	Chapelle and Bradley (1996)	d	
Dry cleaning site	-	200	3650	0.009	Ling and Rifai (2007)	a	
Picatinny Arsenal, NJ	SO4/Fe	25,000	244-733	0.011	Wilson et al. (1991)	b	
San Francisco Bay Area, CA	-	-	-	0.012	Buscheck and O'Reilly (1996)	d	
Picatinny Arsenal, NJ	SO4/Fe	10,000	156-467	0.013	Wilson et al. (1991)	b	
Zetor site, Czech Republic	SO4	2250	-	0.0185	Kutchovsky and Sracek (2007)	a	
Cecil Field NAS, FL	-	-	438	0.02	Chapelle and Bradley (1996)	d	
Landfill, SE PA	SO4	-	3000	0.14	Washington and Cameron (2001)	a	

Table B-17. Trichloroethylene (TCE)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Minimum				**0.00014**			
5th percentile				**0.00020**			
10th percentile				**0.00045**			
25th percentile				**0.00086**			
n				**65**			

Notes:
- = not specified (in the redox column, assumed to be anaerobic)
source: a = original paper consulted. b = Aronson and Howard (1997). d = Wilson et al. (1996b).
AFB = air force base; NAS = Naval Air Station
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-18. Trichloroethylene (TCE)
Degradation Rates from Aerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Dover AFB, DE	Aerobic	-	-	0.00001	Clement et al. (2000)	a	
Dubnica site, Slovak Republic	Aerobic	3320	-	0.00011	Kutchovsky and Sracek (2007)	a	
Dubnica site, Slovak Republic	Aerobic	3320	-	0.00027	Kutchovsky and Sracek (2007)	a	
Fractured bedrock site, SW Germany	Aerobic	1200	-	0.015	Pooley et al. (2009)	a	
Fractured bedrock site, SW Germany	Aerobic	1200	-	0.02	Pooley et al. (2009)	a	
Minimum				**0.00001**			
n				**5**			

Notes:

- = not specified.

source: a = original paper consulted.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-19. cis-1,2-Dichloroethylene (cis-DCE) Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Dover AFB, DE	Meth	-	-	0.00065	Clement et al. (2000)	a	
Dover AFB, DE	Meth	-	-	0.00068	Ellis et al. (1996)	a	
Dover AFB, DE	Meth	-	-	0.000845	Clement et al. (2000)	a	
Perth, Australia	-	-	5,114	0.00088	Benker et al. (1994)	d	
Landfill, SE PA	SO4	-	3000	0.0009	Washington and Cameron (2001)	a	
Dolni Tresnovec landfill, Czech Republic	Fe/NO3	100000	-	0.001	Kutchovsky and Sracek (2007)	a	
Dry cleaning site	-	1768	3650	0.0012	Ling and Rifai (2007)	a	
Tibbitt's Raod, NH	-	220	3,650	0.0012	Wilson et al. (1996a)	a	
Picatinny Arsenal, NJ	SO4/Fe	-	256	0.0014	Ehlke et al. (1994)	d	
Dover AFB, DE	Meth	-	-	0.0014	Ellis et al. (1996)	a	
St. Joseph site, MI	Meth/SO4	-	2,373	0.0014	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	9,117	-	0.0018	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	9,117	2,374	0.0018	Weaver et al. (1996)	a	
Tibbitt's Raod, NH	-	740	2,338	0.0018	Wilson et al. (1996a)	a	
Plattsburg AFB, Plattsburg, NY	NO3/Fe/SO4/Meth	14,968	692	0.002	Wiedemeier et al. (1996b)	a	
St. Joseph site, MI	Meth/SO4	-	1,022	0.0023	Semprini et al. (1995)	d	
Sacramento, CA	-	-	658	0.0024	Cox et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	1,453	-	0.003	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	1,453	1,023	0.003	Weaver et al. (1996)	a	
Picatinny Arsenal, NJ	SO4/Fe	-	256	0.0044	Ehlke et al. (1994)	d	
Zetor site, Czech Republic	SO4	820	-	0.008	Kutchovsky and Sracek (2007)	a	
St. Joseph site, MI	Meth/SO4	-	1,971	0.0085	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	281	-	0.011	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	281	1,972	0.011	Weaver et al. (1996)	a	
San Francisco Bay Area, CA	-	-	-	0.014	Buscheck and O'Reilly (1996)	d	
Zetor site, Czech Republic	SO4	820	-	0.022	Kutchovsky and Sracek (2007)	a	
Dry cleaning site	-	1768	3650	0.03	Ling and Rifai (2007)	a	
Minimum				**0.00065**			
5th percentile				**0.00073**			
10th percentile				**0.00087**			
25th percentile				**0.0012**			
n				**27**			

Notes:

- = not specified (in the redox column, assumed to be anaerobic)

source: a = original paper consulted. d = Wilson et al. (1996b).

AFB = air force base.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-20. cis-1,2-Dichloroethylene (cis-DCE)
Degradation Rates from Aerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate ($days^{-1}$)	Study Author	Source	Quality
Dover AFB, DE	Aerobic	-	-	0.004	Clement et al. (2000)	a	
Dubnica site, Slovak Republic	Aerobic	66	-	0.00465	Kutchovsky and Sracek (2007)	a	
Dubnica site, Slovak Republic	Aerobic	66	-	0.0164	Kutchovsky and Sracek (2007)	a	
Fractured bedrock site, SW Germany	Aerobic	3600	-	0.023	Pooley et al. (2009)	a	
Fractured bedrock site, SW Germany	Aerobic	3600	-	0.027	Pooley et al. (2009)	a	
Minimum				**0.004**			
n				**5**			

Notes:

- = not specified

source: a = original paper consulted.

AFB = air force base.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-21. Vinyl Chloride (VC)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
St. Joseph site, MI	Meth/SO4	-	-	0.00033	Rifai et al. (1995)	b	
St. Joseph site, MI	Meth/SO4	6,500	2,373	0.00049	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	930	2373	0.00049	Wilson et al. (1994c)	b	
Dry cleaning site	-	670	3650	0.0005	Ling and Rifai (2007)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.00067	Rifai et al. (1995)	b	
Dover AFB, DE	Meth	-	-	0.00086	Ellis et al. (1996)	a	
Dover AFB, DE	Meth	-	-	0.001	Ellis et al. (1996)	a	
Plattsburg AFB, Plattsburg, NY	NO3/Fe/SO4/Meth	-	692	0.0012	Wiedemeier et al. (1996b)	a	
Plattsburg AFB, Plattsburg, NY	NO3/Fe/SO4/Meth	-	3385	0.0013	Wiedemeier et al. (1996b)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.0016	Rifai et al. (1995)	b	
St. Joseph site, MI	Meth/SO4	520	1,022	0.0024	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	450	1022	0.0024	Wilson et al. (1994c)	b	
St. Joseph site, MI	Meth/SO4	-	-	0.0033	Rifai et al. (1995)	b	
Dover AFB, DE	Meth	-	-	0.004	Clement et al. (2000)	a	
Zetor site, Czech Republic	SO4	520	-	0.005	Kutchovsky and Sracek (2007)	a	
Dry cleaning site	-	670	3650	0.006	Ling and Rifai (2007)	a	
St. Joseph site, MI	Meth/SO4	15	1,971	0.006	Semprini et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	106	1971	0.006	Wilson et al. (1994c)	b	
St. Joseph site, MI	Meth/SO4	998	-	0.0071	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	998	2,374	0.0071	Weaver et al. (1996)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.0076	Rifai et al. (1995)	b	
Dover AFB, DE	Meth	-	-	0.008	Clement et al. (2000)	a	
St. Joseph site, MI	Meth/SO4	473	-	0.0085	An et al. (2004)	a	
Sacramento, CA	-	-	658	0.0085	Cox et al. (1995)	d	
St. Joseph site, MI	Meth/SO4	473	1,023	0.0085	Weaver et al. (1996)	a	
Cecil Field NAS, FL	-	-	438	0.009	Chapelle and Bradley (1996)	d	
Dolni Tresnovec landfill, Czech Republic	Fe/NO3	2100	-	0.01	Kutchovsky and Sracek (2007)	a	
St. Joseph site, MI	Meth/SO4	-	-	0.016	Rifai et al. (1995)	b	
Cecil Field NAS, FL	-	-	438	0.02	Chapelle and Bradley (1996)	d	
St. Joseph site, MI	Meth/SO4	98	-	0.055	An et al. (2004)	a	
St. Joseph site, MI	Meth/SO4	98	1,972	0.055	Weaver et al. (1996)	a	

Table B-21. Vinyl Chloride (VC)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Minimum				**0.00033**			
5th percentile				**0.00049**			
10th percentile				**0.0005**			
25th percentile				**0.0013**			
n				**27**			

Notes:

- = not specified (in the redox column, assumed to be anaerobic)

source: a = original paper consulted. b = Aronson and Howard (1997). d = Wilson et al. (1996b).

AFB = air force base; NAS = Naval Air Station

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-22. Vinyl Chloride (VC)
Degradation Rates from Aerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate ($days^{-1}$)	Study Author	Source	Quality
Dover AFB, DE	Aerobic	-	-	0.002	Clement et al. (2000)	a	
Minimum				**0.002**			
n				**1**			

Notes:
- = not specified.
source: a = original paper consulted.
AFB = air force base.
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-23. Carbon Tetrachloride (CT)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Borden Aquifer, ON	**Meth/SO4/Fe**	**200-600**	**339**	**0.063**	**Devlin et al. (2004)**	**a**	**+**
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.7**	**Rugge et al. (1999)**	**a**	**++**
Moffett Field NavalAir Station, CA	NO3/SO4	45	1.8	1.73	Semprini et al. (1992)	b	
Minimum				**0.063**			
n				**3**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-24. Chloroform (CF)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Palo Alto, CA	-	20	350	0.03	Roberts et al. (1982)	b	
Borden Aquifer, ON	**Meth/SO4/Fe**	**-**	**339**	**0.069**	**Devlin et al. (2004)**	**a**	**+**
Minimum				**0.03**			
n				**2**			

Notes:

- = not specified (in the redox column, assumed to be anaerobic)

source: a = original paper consulted. b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-25. Chloroform (CF)
Degradation Rates from Aerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Bolivar ASR site, South Australia	**Aerobic**	**-**	**110**	**0.046**	**Pavelic et al. (2005)**	**a**	**+**
Bolivar ASR site, South Australia	**Aerobic**	**-**	**110**	**0.011**	**Pavelic et al. (2005)**	**a**	**+**
Minimum				**0.011**			
n				**2**			

Notes:

- = not specified

source: a = original paper consulted.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-26. Dichlolomethane (DCM)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Hawkesbury, Ontario, Canada	Meth	37,000	906	0.0064	Fiorenza,S et al. (1994)	b	
Minimum				**0.0064**			
n				**1**			

Notes:

- = not specified

source: b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-27. 1,1,1-Trichloroethane (1,1,1-TCA)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Santa Clara, CA	-	-	-	0.00018	Wing,MR (1997)	b	
Hawkesbury, Ontario, Canada	Meth	5500	906	0.0013	Fiorenza,S et al. (1994)	b	
Palo Alto, CA	-	10	350	0.003	Roberts,PV et al. (1982)	b	
Moffett Field Naval Air Station, CA	NO3/SO4	50	1.8	0.059	Semprini,L et al. (1992)	b	
Grindsted landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.0044**	**Rugge et al. (1999)**	**a**	**++**
Grindsted Landfill, Denmark	**Meth/SO4/Fe**	**150**	**924**	**0.0054**	**Rugge et al. (1999)**	**a**	**++**
Landfill, SE PA	SO4	-	3000	0.058	Washington and Cameron (2001)	a	
Minimum				**0.00018**			
n				**7**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-28. 1,1-Dichloroethane (1,1-DCA)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Landfill, SE PA	SO4	-	3000	0.006	Washington and Cameron (2001)	a	
Minimum				**0.006**			
n				**1**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-29. 1,2-Dichloroethane (1,2-DCA)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Gulf Coast site	Meth	-	-	0.0042	Lee et al. (1996)	b	
Gulf Coast site	Meth	-	-	0.011	Lee et al. (1996)	b	
NE Brazil site	SO4	-	-	0.003	Nobre and Nobre (2004)	a	
Minimum				**0.003**			
n				**3**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-30. Chloroethane (CA)
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Landfill, SE PA	SO4	-	3000	0.011	Washington and Cameron (2001)	a	
Minimum				**0.011**			
n				**1**			

Notes:

- = not specified

source: a = original paper consulted. b = Aronson and Howard (1997).

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-31. Methyl tert-Butyl Ether (MTBE)
Degradation Rates from Aerobic and Anaerobic Field Studies

Site Name	**Redox Regime**	**Max. Conc. ug/L**	**Duration (days)**	**Rate (days^{-1})**	**Study Author**	**Source**	**Quality**
Elizabeth City NC	-	-	-	0.00041	Wilson et al. (2000)	f	
Parsippany NJ	-	-	-	0.00052	Kolhatkar et al. (2000)	f	
Prot Hueneme CA	-	-	-	0.00063	Wilson and Kolhatkar (2002)	f	
Brandon FL	-	-	-	0.00074	Wilson and Kolhatkar (2002)	f	
Site Not Identified	NO3/aerobic	-	-	0.001	Borden et al. (1997)	e	
Site Not Identified	Aerobic	-	2920	0.0012	Schirmer et al. (2003)	e	
Prot Hueneme CA	-	-	-	0.0015	Wilson and Kolhatkar (2002)	f	
Oil Refining Plant, S. Taiwan	Meth	145000	-	0.0021	Chen et al. (2005)	a	
Long Island NY	-	-	-	0.0021	Wilson and Kolhatkar (2002)	f	
Long Island NY	Multiple redox zones	-	-	0.0022	Wilson and Kolhatkar (2002)	f	
Parsippany NJ	-	-	-	0.0032	Kolhatkar et al. (2000)	f	
Oil Tank Farm, S. Taiwan	Meth	265	-	0.0048	Chen et al. (2005)	a	
Elizabeth City NC	-	-	-	0.0049	Wilson et al. (2000)	f	
Brandon FL	-	-	-	0.006	Wilson and Kolhatkar (2002)	f	
Site Not Identified	Meth	-	1642	0.0074	Wilson et al. (2000)	e	
Site Not Identified	Meth	-	-	0.0074	Wilson et al. (2000)	e	
Long Island NY	Meth	-	-	0.012	Wilson and Kolhatkar (2002)	f	
Minimum				**0.00041**			
5th percentile				**0.00050**			
10th percentile				**0.00059**			
25th percentile				**0.0010**			
n				**17**			

Notes:
- = not specified
source: a = original paper consulted. e = Fiorenza and Rifai (2003). f = Wilson and Kolhatkar (2002)
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-32. Phenol
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Pensacola FL	Meth	26010	125	0.032	Godsy et al. (1992)	a	
Minimum				**0.032**			
n				**1**			

Notes:
- = not specified
source: a = original paper consulted.
Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-33. Methanol
Degradation Rates from Anaerobic Field Studies

Site Name	Redox Regime	Max. Conc. ug/L	Duration (days)	Rate (days^{-1})	Study Author	Source	Quality
Borden Aquifer, ON	**Anaerobic/Aerobic**	**~5000**	**500**	**0.0028**	**Hubbard et al. (1994)**	**a**	**+**
Minimum				**0.0028**			
n				**1**			

Notes:

- = not specified

source: a = original paper consulted.

Quality: + = High Quality study; ++ = Very High Quality study; "+" and "++" studies highlighted in bold. See text for discussion.

Table B-34. Ethylene Glycol
Degradation Rates from Laboratory Studies

Site Name	Redox Regime	Duration (days)	Rate ($days^{-1}$)	Study Author	Source
Alberta Gas Plant	Aerobic	100	0.0067	Mrklas et al. (2004)	a
Alberta Gas Plant	Aerobic	100	0.02	Mrklas et al. (2004)	a
Site Not Identified	Aerobic		0.029	Howard et al. (1991)	a
Site Not Identified	Aerobic		0.17	Howard et al. (1991)	a
Site Not Identified	Methanogenic	6	1.5	Dwyer and Tiedje (1983)	a
Minimum			**0.0067**		
n			**5**		

Notes:
- = not specified
source: a = original paper consulted.

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