Aerobic and Anaerobic PCB Biodegradation in the Environment

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Studies have identified two distinct biological processes capable of biotransforming polychlorinated biphenyls (PCBs): aerobic oxidative processes and anaerobic reductive processes. It is now known that these two complementary activities are occurring naturally in the environment. Anaerobic PCB dechlorination, responsible for the conversion of highly chlorinated PCBs to lightly chlorinated *ortho*-enriched congeners, has been documented extensively in the Hudson River and has been observed at many other sites throughout the world. The products from this anaerobic process are readily degradable by a wide range of aerobic bacteria, and it has now been shown that this process is occurring in surficial sediments in the Hudson River. The widespread anaerobic dechlorination of PCBs that has been observed in many river and marine sediments results in reduction of both the potential risk from and potential exposure to PCBs. The reductions in potential risk include reduced dioxinlike toxicity and reduced carcinogenicity. The reduced PCB exposure realized upon dechlorination is manifested by reduced bioaccumulation in the food chain and by the increased anaerobic degradability of these products. — Environ Health Perspect 103(Suppl 5):97–99 (1995)

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Introduction

Polychlorinated biphenyls (PCBs) are a family of 209 related chemical compounds that were manufactured and sold as complex mixtures differing in their average chlorination level. The individual PCB isomers, or PCB congeners, are described according to the position of the chlorine substitution, e.g., 2,3,4,3′,4′-pentachlorobiphenyl (the shorthand 234-34-CB will be used in this article).

The desirable physical and chemical properties of PCBs (excellent dielectric and flame resistance properties, chemical and thermal stability) led to their extensive industrial use as heat transfer fluids, hydraulic fluids, solvent extenders, plasticizers, flame retardants, organic diluents, and dielectric fluids (*1*). Extensive application of these chemically and thermally stable compounds has resulted in widespread contamination (*2–4*); it is estimated that several hundred million pounds have been released to the environment (*5*). The high octanol/water partition coefficient (K_{ow}) of some PCB congeners results in their accumulation in fatty tissues and their biomagnification in the food chain (*6*).

PCB Biodegradation

These compounds have been shown to undergo biodegradation under a variety of conditions in the laboratory and in the environment (*7–10*). Two distinct biological systems capable of biodegrading PCBs have been identified: aerobic oxidative processes and anaerobic reductive processes.

The aerobic bacterial biodegradation of PCBs is widely known and has been well studied (*7–10*). Several microorganisms have been isolated that can aerobically degrade PCBs, preferentially degrading the more lightly chlorinated congeners. These organisms attack PCBs via the well-known 2,3-dioxygenase pathway, converting PCB congeners to the corresponding chlorobenzoic acids. These chlorobenzoic acids can then be degraded by indigenous bacteria, resulting in the production of carbon dioxide, water, chloride, and biomass.

Anaerobic bacteria attack more highly chlorinated PCB congeners through reductive dechlorination. In general, this microbial process effects the preferential removal of *meta* and *para* chlorines, resulting in a depletion of highly chlorinated PCB congeners with corresponding increases in lower chlorinated, *ortho*-substituted PCB congeners. The altered congener distribution of residual PCB contamination observed in several aquatic sediments was the earliest evidence of the anaerobic dechlorination of PCBs (*11–13*). This same activity has been observed in the laboratory (*14–16*), where the selective removal of *meta* and *para* chlorines was also noted.

The widespread dechlorination of PCBs in aquatic sediments has now been documented for several river systems (*17–19*). These surveys demonstrate that PCB dechlorination is prevalent in aquatic sediments. Extensive PCB dechlorination has been observed in sediments of the upper Hudson River (Figure 1). This survey of approximately 1000 sampling locations in a 6-mile stretch of the river (mile point 194.5 to 188.5) indicates that microbial dechlorination is widespread throughout these sediments. Extensive changes had occurred in sediments exhibiting a broad range of PCB concentrations, even as low as 5 ppm (*17*).

A current list of sites where PCB-dechlorinating microorganisms have been found is shown in Table 1. Note that these organisms can be detected in a number of PCB-free (uncontaminated) environments upon the addition of PCBs in the laboratory. This suggests that PCB-dechlorinating activity may be the result of a common reductive pathway present in many different anaerobic microorganisms located throughout the environment. Support for this hypothesis comes from recent efforts demonstrating that several iron and cobalt heme cofactor systems are capable of reductively dechlorinating a wide variety of chlorinated organic compounds (*20,21*), including PCBs (*22*). In general, environmental dechlorination is more extensive at higher PCB concentrations, consistent

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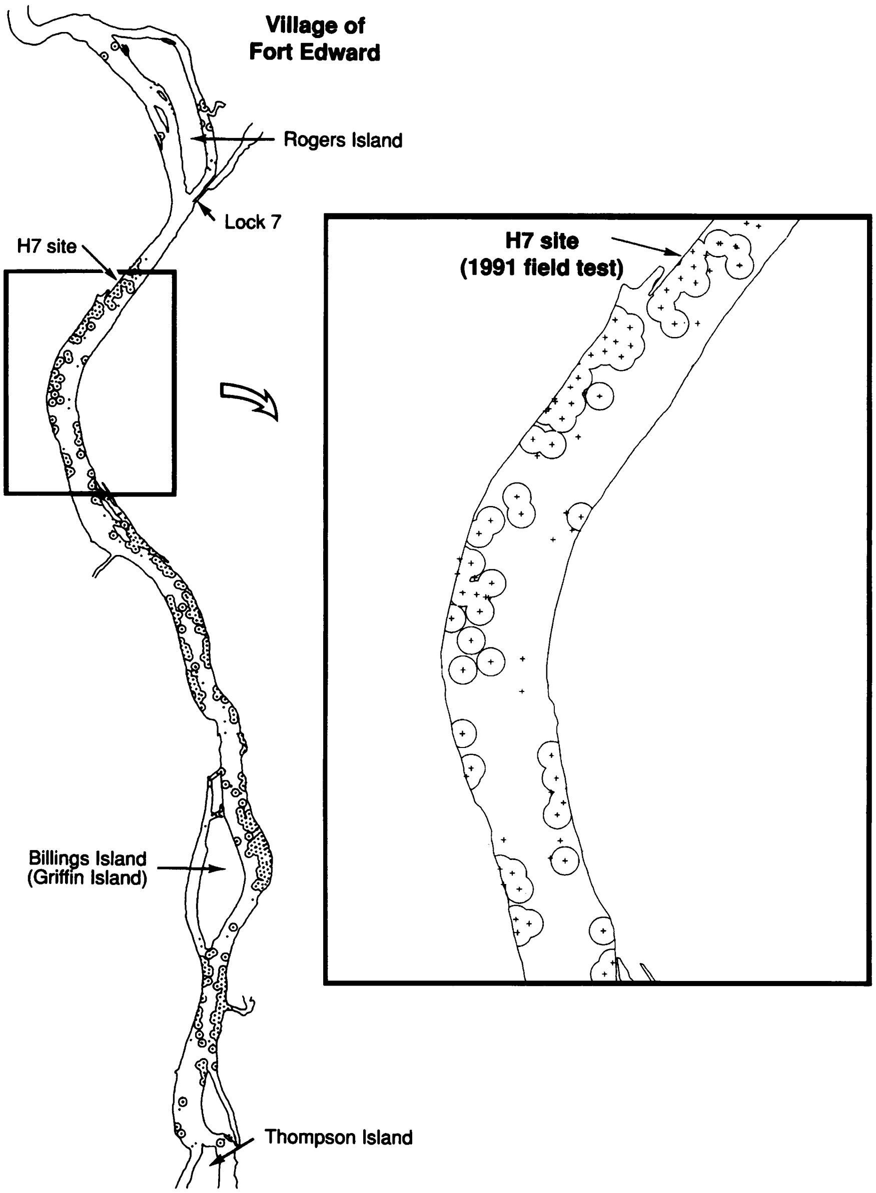

Figure 1. Locations of sediment PCB accumulations in the upper Hudson River, based on reanalysis of the 1984 New York State survey of the Thompson Island Pool. (+) Samples containing ≥10 ppm PCB; (○) samples displaying extensive dechlorination (peak 70/peak 47 ≤1).

Table 1. Known sites containing microorganisms capable of anaerobic PCB dechlorination.

PCB-contaminated sites	
Escambia Bay	Florida
Fox River/Green Bay	Wisconsin
Grass River	New York
Hoosic River	Massachusetts
Housatonic River	Massachusetts
Hudson River	New York
Kalamazoo River	Michigan
Lake Hartwell	South Carolina
Lake Ketelmeer	The Netherlands
Lake Shinjii	Japan
Moreau Drag Strip	New York
New Bedford Harbor	Massachusetts
Otonabee River/Rice Lake	Canada
Rhine River	Germany
Rhine River	The Netherlands
Sheboygan River	Wisconsin
Silver Lake	Massachusetts
St. Lawrence River	New York
Waukegan Harbor	Illinois
Woods Pond	Massachusetts
Uncontaminated sites	
Adirondack Marsh	New York
Center Pond	Massachusetts
Hudson River	New York
Puget Sound	Washington
Red Cedar River	Michigan
Saline River	Michigan
St. Lawrence River	New York

with the faster dechlorination rates observed at higher PCB concentrations in the laboratory (*23*).

Benefits of Anaerobic PCB Dechlorination

The benefits of anaerobic PCB dechlorination involve reductions in both the potential risk from and potential exposure to PCBs. These reductions in the potential risk from PCBs include reduced dioxinlike toxicity and reduced carcinogenicity. The preferential loss of *meta* and *para* chlorines catalyzed by anaerobic dechlorination results in dramatic reductions in the levels of coplanar, dioxinlike PCB congeners in the mixture (*24*). These reductions in concentrations correlate with reductions in ethoxyresorufin-*O*-deethylase (EROD) induction potency and toxic equivalency factors for the mixture. Most importantly, these same extensive reductions are occurring in the environment (*24*). The reduced carcinogenicity as a result of dechlorination is supported by the recent reanalysis of the original rat cancer studies (*25*). In these studies, only the most highly chlorinated PCB mixture (Aroclor 1260, average 6.4 chlorines per biphenyl) resulted in observable cancer potencies. Aroclor 1254 (average 5.1 chlorines per biphenyl) and Clophen A30 did not demonstrate any tumorigenic effect (*25*). Clophen A30 is similar in composition to Aroclor 1242, with an average 3.3 chlorines per biphenyl. Decreasing PCB chlorination levels and microbial anaerobic PCB dechlorination therefore reduce carcinogenic potential.

Additional reductions in risk associated with PCB-contaminated sediments are realized via reduced PCB exposure upon dechlorination. This reduced exposure is manifested in two ways. First, the lightly chlorinated PCB congeners produced upon dechlorination are more readily degraded by indigenous aerobic bacteria (*26*). Moreover, new evidence indicates that the aerobic process is occurring naturally in undisturbed Hudson River sediments (*27*). Second, dechlorination significantly reduces the bioaccumulation potential of the PCB mixture through conversion to congeners that do not significantly bioaccumulate in the food chain. The lightly chlorinated PCB congeners resulting from dechlorination (e.g., 2-CB and 2-2-CB) display an approximate 450-fold reduction in their tendency to accumulate in fish, as compared to the more highly chlorinated tri- and tetra-chlorinated PCBs present in the original Aroclor 1242 mixture. Thus, natural anaerobic PCB dechlorination reduces the potential risk associated with PCBs via direct reductions in carcinogenic potency, dioxinlike toxicity, and exposure.

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