November 1, 2004

**Lecture 4: Polybrominated Biphenyl Ethers (PBDEs)**

I. **Chemical Nature, Production, Use, Emissions**

A. PBDEs are widely used as flame retardants in end use products like textiles, electronic equipment and insulation materials.
   1. Use of brominated fire retardants is relatively new, having risen steadily over the last 30 years.
      a. In 1999, present production was estimated to be about 132,000 tons/yr, but the consumption was steadily increasing (cited in Palm et al. 2002)
   2. Their ubiquity in all kinds of end use products (consumer and industrial), their similarity to PCBs in physicochemical properties and possibly toxicological properties, and findings of ubiquitous and increasing levels of residues in the environment and tissues (including human milk and blood) has raised concern and brought intense scientific study over the last 5-10 years.

B. **Chemical Nature**

1. The general chemical formula of a PBDE is C\(_{12}\)H\(_{(9-0)}\)Br\(_{1-10}\)O, with the sum of H and Br atoms always equal to 10
   a. The theoretical number of possible congeners is 209 when considering all possible placements of Br substituents to make a unique compound.
   b. The congeners are classified into 10 groups, ranging from monobromodiphenyl ethers (1 Br substituent) to decabromodiphenyl ethers (10 Br substituents)
      1. Compounds with less than four Br atoms are generally not found in commercial PBDE products.
      2. Unlike the variation and distribution of PCBs in Aroclors, the number of PBDE congeners used in commercial products is comparatively small.

2. **Nomenclature**

   a. A sequential numbering system designated by International Union of Pure and Applied Chemistry is used to designate the congeners similarly to the system of naming PCBs.

   ![Diagram of PBDE structure](image)

   Br\(_x\)

   Br\(_y\)

   3. Commercial PBDEs are synthesized by bromination of diphenyl ethers under conditions resulting in mixtures of brominated diphenyl ethers
a. Commercial products predominantly consist of penta-, hepta-, octa-, and decabromodiphenyl ethers.

C. Flame Retardant Properties of PBDEs
   1. The rationale for using brominated compounds as flame retardants is based on the ability of halogen atoms, generated from the thermal decomposition of the bromoorganic compound, to chemically reduce and retard the development of fire (Darnerud et al. 2002).
      a. Factors favoring PBDE use
         1. High bromine content (=good flame retardant properties)
         2. Thermal stability
         3. Comparatively low cost

D. Use of PBDEs
   1. PBDEs are placed in various products either as additives or as reactives.
      a. When used as a reactive, the compound is chemically incorporated into the polymer and is unlikely to be emitted from the product.
         1. Unreacted PBDEs concentrations are negligible when used as a reactive compound (Palm et al. 2002)
      b. When used as an additive, the product is more likely to be emitted.
         1. BFR (brominated flame retardant) emissions are mainly from their use as additives.
         2. Estimates from Denmark indicate additives are ~56% of total BFR use, and PBDEs specifically account for 21% of the additive consumption (estimates made circa 1997; cited in Palm et al. 2002).
            a. Note that other brominated compounds besides PBDEs are used as flame retardants. Thus, the term BFR is used to refer to all compounds with bromine that have flame retardant capability.
         c. When used as additives, PBDEs are used at concentrations of 5-30% in many different polymers, resins, common plastics (including acrylonitrile butadiene styrene and high impact polystyrene).
   2. Examples of products containing BFRs, especially PBDEs
      a. Components of electronic devices (e.g., cabinets and circuit boards in personal computers and TV sets and various other products like electrical cables, switches and capacitors)
      b. Building materials
      c. Textiles
      d. Polyurethane foams used in upholstered furniture
         1. Flammability is reduced by adding PBDEs to 10-30 weight %
3. In 1994, the annual world production of flame retardants was estimated to be 600,000 metric tons (cited in Darnerud et al. 2002)
   a. 60,000 tons are chlorinated
   b. 150,000 tones are brominated
      1. 1/3 contain tetrabromobisphenol A (TBBP-A) and derivatives
      2. 1/3 contain various bromines, including polychlorinated biphenyls (PCBs)
      3. ~1/3 contain PBDEs

4. More recent estimates (circa 2003) indicate about 70,000 t (metric tons) of PBDEs are annually sold worldwide (statistic cited in Hites 2004)

E. Types of PBDEs used commercially
1. Three types of PBDE products, characterized by their congener profile, are currently used in the world: pentabrominated diphenyl ethers (pentaBDE); octaBDE, and decaBDE.
   a. A fourth product, tetraBDE is no longer used.

### Commercial PBDE Products and Congener Group Composition (as weight %) (Darnerud et al. 2002)

<table>
<thead>
<tr>
<th>Congener Group</th>
<th>TetraBDE (%)</th>
<th>PentaBDE (%)</th>
<th>OctaBDE (%)</th>
<th>DecaBDE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td>7.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TriBDE</td>
<td></td>
<td>0-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TetraBDE</td>
<td>41-41.7</td>
<td>24-38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PentaBDE</td>
<td>44.4-45</td>
<td>50-62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HexaBDE</td>
<td>6-7</td>
<td>4-8</td>
<td>10-12</td>
<td></td>
</tr>
<tr>
<td>HeptaBDE</td>
<td></td>
<td></td>
<td>43-44</td>
<td></td>
</tr>
<tr>
<td>OctaBDE</td>
<td></td>
<td></td>
<td>31-35</td>
<td></td>
</tr>
<tr>
<td>NonaBDE</td>
<td>9-11</td>
<td>0.3-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DecaBDE</td>
<td>0-1</td>
<td>97-98</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Proportional commercial sales of PBDE products in 2001 (from Hites 2004)

<table>
<thead>
<tr>
<th>Product</th>
<th>Americas</th>
<th>%</th>
<th>Europe</th>
<th>%</th>
<th>Asia</th>
<th>%</th>
<th>Rest of World</th>
<th>%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>pentaBDE</td>
<td>7,100</td>
<td>95</td>
<td>150</td>
<td>2</td>
<td>150</td>
<td>2</td>
<td>100</td>
<td>1</td>
<td>7,500</td>
</tr>
<tr>
<td>octaBDE</td>
<td>1,500</td>
<td>40</td>
<td>610</td>
<td>16</td>
<td>1,500</td>
<td>40</td>
<td>180</td>
<td>5</td>
<td>3,790</td>
</tr>
<tr>
<td>decaBDE</td>
<td>24,500</td>
<td>44</td>
<td>7,600</td>
<td>14</td>
<td>23,000</td>
<td>41</td>
<td>1,050</td>
<td>2</td>
<td>56,150</td>
</tr>
<tr>
<td>Total</td>
<td>33,100</td>
<td>49</td>
<td>8,360</td>
<td>12</td>
<td>24,650</td>
<td>37</td>
<td>1,330</td>
<td>2</td>
<td>67,440</td>
</tr>
</tbody>
</table>

2. Congener constituents of commercial products
   a. PentaDBE (five major constituents in a ratio of 9:12:2:1:1)
      1. 2,2’,4,4’-tetrabromodiphenyl ether (BDE-47)

      ![2,2’,4,4’-tetrabromodiphenyl ether](image1)

      2. 2,2’,4,4’,5-pentabromodiphenyl ether (BDE-99)

      ![2,2’,4,4’,5-pentabromodiphenyl ether](image2)

      3. 2,2’,4,4’,6-pentabromodiphenyl ether (BDE-100)

      ![2,2’,4,4’,6-pentabromodiphenyl ether](image3)

      4. 2,2’,4,4’,5,5’-hexabromodiphenyl ether (BDE-153)

      ![2,2’,4,4’,5,5’-hexabromodiphenyl ether](image4)
5. 2,2’,4,4’,5,5’-hexabromodiphenyl ether (BDE-154)

b. OctaBDE
   1. Several hexa- to nona-brominated congeners

c. DecaBDE
   1. Almost entirely composed of decabromodiphenyl ether (BDE-209)
      a. 2,2’,3,3’,4,4’,5,5’,6,6’-decabromodiphenyl ether

II. Physicochemical Properties
   A. Summary Properties for Congener Group
Selected Physicochemical Properties of Commercial PBDE products

<table>
<thead>
<tr>
<th>Property</th>
<th>PentaBDE</th>
<th>OctaBDE</th>
<th>DecaBDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight</td>
<td>801.5 (proportioned)</td>
<td>Decabromodiphenyl ether: 959.22</td>
<td></td>
</tr>
<tr>
<td>Form</td>
<td>Solid</td>
<td>Solid</td>
<td>Solid</td>
</tr>
<tr>
<td>Vapor Pressure (Pa)</td>
<td>4.69 x 10^{-5}</td>
<td>6.59 x 10^{-6}</td>
<td>4.3 x 10^{-6} (@21°C)</td>
</tr>
<tr>
<td>Water Solubility (µg/L)</td>
<td>13.3</td>
<td>&lt;1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Solvent solubility (wt%)</td>
<td></td>
<td></td>
<td>Acetone: 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Benzene: 0.48</td>
</tr>
<tr>
<td>Log Kow</td>
<td>6.58</td>
<td>6.29</td>
<td>6.27</td>
</tr>
<tr>
<td>K_H</td>
<td></td>
<td></td>
<td>1.93 x 10^{-8}</td>
</tr>
<tr>
<td>Log Koc</td>
<td></td>
<td></td>
<td>6.25</td>
</tr>
</tbody>
</table>

B. Specific congener properties
1. As will be seen, PBDE-47 and PBDE-99 residues account for the greatest percentage of residue found in the environment and tissues; thus, it is useful to know their important physicochemical properties (reported by Palm et al. 2002)
2. PBDE-47 (2,2',4,4'-tetrabromodiphenyl ether)
   a. Mol. Wt.: 485.8
   b. Melting point: 78.75 °C - 82.25 °C
   c. Vapor Pressure: 1.86 x 10^{-4} Pa – 3.19 x 10^{-4} Pa
   d. Water Solub: 10.9 µg/L – 15.3 µg/L
   e. Log Kow: 6.01 – 6.19
3. PBDE-99 (2,2',4,4',5-pentabromodiphenyl ether)
   a. Mol. Wt.: 565.7
   b. Melting point: 92.3 °C
   c. Vapor Pressure: 1.76 x 10^{-5} Pa – 6.82 x 10^{-5} Pa
   d. Water Solub: 2.4 µg/L
   e. Log Kow: 6.53 – 6.71

III. Environmental Attenuation & Distribution
A. Little research has been conducted on PBDEs with regard to environmental attenuation, including process of photodegradation (under real or simulated real environmental conditions), chemical/biological degradation, or mass transfer.
B. Most work has concentrated on monitoring residues in various environmental media (mostly sediments) and tissues (human blood and milk, fish, various kinds of food).
C. Distribution and approximate half-lives or persistence in environmental compartments has been estimated by modeling based on fugacity concepts and physicochemical properties (Palm et al. 2002)
Modeled half-lives (hrs) of diphenyl ether and three prevalent PBDE congeners (Palm et al. 2002). Half-lives were estimated using EPIWIN estimation software (http://esc.syrres.com/interkow/epi.htm)

<table>
<thead>
<tr>
<th>Estimated Half-life (hours)</th>
<th>Diphenyl ether</th>
<th>BDE-47</th>
<th>BDE-99</th>
<th>BDE-209</th>
</tr>
</thead>
<tbody>
<tr>
<td>In air</td>
<td>26.7</td>
<td>256</td>
<td>467</td>
<td>7620</td>
</tr>
<tr>
<td>In water</td>
<td>360</td>
<td>3600</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>In soil</td>
<td>360</td>
<td>3600</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>In sediment</td>
<td>1440</td>
<td>14400</td>
<td>14400</td>
<td>14400</td>
</tr>
</tbody>
</table>

Modeled distribution and persistence of 1000 kg/h/yr emissions of diphenyl ether and decabromodiphenyl ether (BDE-209) (Palm et al. 2002)

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Emission Medium</th>
<th>Amount in Air (kg)</th>
<th>Amount in Water (kg)</th>
<th>Amount in Soil (kg)</th>
<th>Amount in Sediment (kg)</th>
<th>Total Amount (kg)</th>
<th>Persistence (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphenyl ether</td>
<td>Air</td>
<td>27,464 (85.3%)</td>
<td>3552 (11.0%)</td>
<td>1075 (3.3%)</td>
<td>124 (0.39%)</td>
<td>32,215</td>
<td>32.2</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>3142 (1.0%)</td>
<td>301,000 (95.6%)</td>
<td>123 (0.04%)</td>
<td>10,541 (3.3%)</td>
<td>315,000</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>Soil</td>
<td>75.5 (0.01%)</td>
<td>827 (0.16%)</td>
<td>517,000 (99.8%)</td>
<td>28.9 (0.006%)</td>
<td>518,000</td>
<td>518</td>
</tr>
<tr>
<td></td>
<td>All Three</td>
<td>30,682 (3.55%)</td>
<td>306,000 (35.3%)</td>
<td>518,000 (59.9%)</td>
<td>10,695 (1.24%)</td>
<td>865,000</td>
<td>288</td>
</tr>
<tr>
<td>BDE209</td>
<td>Air</td>
<td>24,948 (0.57%)</td>
<td>15,770 (0.36%)</td>
<td>3,500,000 (80.1%)</td>
<td>827,000 (19%)</td>
<td>4,360,000</td>
<td>4365</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>0.019 (0.00000002%)</td>
<td>210,000 (1.9%)</td>
<td>2.71 (0.000024%)</td>
<td>11,000,000 (98.1%)</td>
<td>11,200,000</td>
<td>11,217</td>
</tr>
<tr>
<td></td>
<td>Soil</td>
<td>296,000 (0.0000000006%)</td>
<td>109 (0.002%)</td>
<td>5,190,000 (99.9%)</td>
<td>5,715 (0.1%)</td>
<td>5,200,000</td>
<td>5198</td>
</tr>
<tr>
<td></td>
<td>All Three</td>
<td>24,948 (0.12%)</td>
<td>226,000 (1.09%)</td>
<td>8,690,000 (41.8%)</td>
<td>11,800,000 (57%)</td>
<td>22,080,000</td>
<td>6926</td>
</tr>
</tbody>
</table>

IV. Environmental Residues
A. All researchers agree that concentrations of PBDEs have risen over the last 30+ years and seem to be continuing on an upward slope.
B. Recently, Hites (2004) has critically reviewed all environmental and tissue residue information, and he has conducted a meta-analysis to define trends.
   1. Hites focused on the best available residue data and distilled the information for six PBDE congeners that were the most prevalent and had the highest data quality: congeners BDE-47, -99, -100, -153, -154, and –209. The next series of graphs from Hites (2004) papers show definitive increasing trends in residues.

Distribution of PBDEs in human tissues by tissue types and place. Note that Sweden has instituted controls on use of PBDEs that include banning of certain products. The horizontal lines of the box plots represent the 90th, 75th, 50th (median), 25th and 10th percentile
distributions. The dots represent outliers, or percentiles above 90 and below 10%. “Neonates” and “maternal” indicate blood samples. “Milk” refers to mother’s milk.

Trends in total PBDE residues in human blood sera (Hites 2004)

Darnerud et al. (2001) redrew data from Noren & Meironyte (1998) to show increasing levels of PBDEs in mother’s milk in Sweden over the past 30 years.
Trends of PBDEs in marine animals. The doubling time represents the time (years) it takes for residues to increase in concentration by 2-fold (i.e., double in concentration). (Hites 2004)

Trends in PBDE residues in bird eggs. Note that the doubling time for eggs collected from the Great Lakes region (for herring gull eggs, *Larus argentatus*) is less than for eggs (guillemot eggs, *Uria aalge*) collected in Sweden. (Hites 2004), but the Swedish data does not include congeners BDE-153 and –154.
Ratio of congeners BDE-47+99+100 to BDE-153+154 in herring gull eggs samples from the Great Lakes (Hites 2004). The congener distribution over time seems to be favoring the lower brominated diphenyl ethers, but the reason is not really known at this time. However, the distribution is similar to that of human tissues, indicating similar sources of exposure.

PBDEs residues in dated sediment cores showing a similarity in doubling times over 20 years (Hites 2004). However, note that the doubling time for cores taken in Norway seem to show a leveling off of PBDE accumulation.
An earlier critical review of all aspects of PBDEs by Darnerud et al. (2001) agrees with Hites (2004) observations of data showing an increasing trend in environmental loading of PBDEs as determined from sediment core dating and residue analysis. Note that Darnerud reported individual congeners, and BDE-47 and BDE-99 dominated, suggesting a contamination source from the penta-brominated diphenyl ether product.

Hites (2004) analyzed the PBDE congener profile data with a statistical technique called principal components. The technique groups similar data to determine any unique and/or similar relationships between different class variable. For example, the class variable,
Canadian Arctic Seals seems to be very different than the group Columbia River white fish. However, a lot of overlap in congener profiles occurs among humans and fish and marine mammals, suggesting similar congener profiles and thus similarity in sources.

V. Ecotoxicological Aspects
A. Fish LC50 to commercial BDE: >500 mg/L; Daphnia LC50’s exceed compound water solubility (Hardy 2002)
B. Darnerud et al. (2001) have critically analyzed the PBDE literature prior to 2000. In their review they have noted some trends that show the following.
   1. A relationship exists between fish age and the level of PBDE residue found in tissues.
      a. The older the fish, the greater the residue concentrations as shown in the following graph.

2. Darnerud et al. (2001) plotted the BDE-47 congener concentrations in marine animal tissues representative of several trophic levels. Although Darnerud et al. describe the phenomenon as biomagnification, it may just represent bioaccumulation to different levels owing to differences in organismal fat content, body size, specific food sources, or metabolic rate.
VI. Potential for Exposure (Humans): Residues in Food

A. Food is thought to be the number one pathway for human exposure to PBDEs
   1. However, studies of potential inhalation exposure have not been reported
      a. Darnerud et al. 2001 reported an experiment in which PBDEs were detected in air
         drawn form a warm TV.
         1. However, their own experiments showed no correlation between frequency of
            computer usage and PBDE levels in mother’s milk.
         2. On the other hand, workers at a Swedish dismantling plant had significantly
            higher serum levels of PBDE congeners compared to both hospital cleaners
            and office clerks using computers.
            a. It was concluded that daily computer work in an office does not seem to
               increase serum PBDE levels.

B. Schecter et al. (2004) have recently published a monitoring study of PBDE residues in
   different foodstuffs. The results are shown in the following graphs; note that the PBDE
   congeners are summed to give a total PBDE residue concentration (ng/kg wet weight of
   food).
   1. Fish had the highest levels (although variable among types of seafood), followed by
      meat and dairy products.
VII. Toxicity
A. Acute toxicity (Darnerud et al. 2001)
   1. Deca-BDE: acute oral rat LD50, >2000 mg/kg; acute dermal rabbit, >2000 mg/kg
   2. Octa-BDE: acute oral rat LD50 >28,000 mg/kg; acute dermal rabbit, >2000 mg/kg
   3. Penta-BDE: acute oral rat, 500-5000 mg/kg; acute dermal LD50, >2000 mg/kg
B. Subchronic toxicity (90-day dietary exposure) (Hardy 2002)
   1. Deca-BDE: NOAEL @ 5000 mg/kg/day
   2. Octa-BDE: NOAEL @ 500 mg/kg/day
   3. Penta-BDE: NOAEL < 2 mg/kg/day (effects was hepatocytomegally)
C. Mutagenicity: all studies for deca-BDE, octa-BDE, and penta-BDE were negative (Darnerud et al. 2001)
D. Research on toxicological effects and dose-response relationships (presuming endpoints are well characterized) are really in their infancy. However, three endpoints have been tagged as potential concerns: thyroxine antagonist (i.e., disruption of thyroid hormone functioning); neurodevelopmental deficits; carcinogenicity.
E. Effects on the Thyroid
   1. The structures of PBDEs and methoxy- and hydroxy- metabolites are similar (3-dimensionally) to thyroxine hormone T4 (McDonald 2002).
      ![Thyroxine (T4)]
      ![2,2',4,4',6-pentaBDE]
      ![methoxy-PBDE]
      ![hydroxy-PBDE]
      a. Both methoxy-PBDEs and hydroxy-PBDEs have been found in salmon blood plasma, suggesting possible exposure routes for humans.
      2. In *in vitro* studies, hydroxylated metabolites of PBDEs bound with high affinity to thyroid hormone transport protein (i.e., transthyretin) (Meerts et al. 2000) and also bound to thyroid hormone receptors.
         a. The binding to receptors, however, indicated low affinity for the receptor compared to the thyroxine hormones.
b. Although all PBDEs can bind to thyroid hormone transport protein, the affinity of decaBDE for the protein is very low. (reported by McDonald 2002)

3. PentaBDE fed to mice via the diet, showed decreased T4 hormone after 14 days.
   a. A single oral exposure of 0.8 mg/kg caused lowering of T4 hormone levels 8 days later. (reported by McDonald 2002)

4. The dose causing 20% reduction of serum T4 was about 7 mg/kg for the penta-BDE (technical material) and 5 mg/kg for the octa-BDE technical material (Reported by McDonald 2002)

5. Fetal rats exposed via gestation had reduced T4 levels when the dose was 10 mg/kg (to the dam or mother rat).
   a. The NOAEL seemed to be 1 mg/kg, and the LOAEL was 10 mg/kg (McDonald 2002)

F. Neurodevelopmental Effects

1. Studies in mice exposed as newborns indicate that PBDEs, like PCBs, cause learning and motor deficits that worsen as the animals grow older (literature reviewed by McDonald 2002)
   a. Note, however, that the effects were seen at single dose levels of 0.2-20 mg/kg; these doses are extremely high compared to the levels possible if food is a major source of exposure.

2. At least three possible mechanisms by which PBDEs may adversely affect brain development:
   a. Thyroid hormone disruption;
   b. Disruption of second messenger communications;
   c. Alteration of neurotransmitter systems.

3. All three mechanism my be operative for PBDEs (McDonald 2002).
   a. Thyroid hormones control proliferation of neuronal and glial cells, regulate neuronal migration and differentiation, and regulate neuronal connectivity and myelination. They also control normal cytoskeletal assembly and stability, which is essential for proper neuronal migration and outgrowth. Thyroid hormones also regulate the development of cholinergic and dopaminergic systems serving the cerebral cortex and hippocampus.

G. Carcinogenicity

1. Evidence suggests the deca-BDE is an animal carcinogen

2. “Dose-related increases in liver neoplastic nodules (adenomas) were clearly related to deca-BDE treatment in both male and female rats. Acinar cell adenoma of the pancreas also were increased among high-dose male rats. Statistically significant increases in hepatocellular adenomas and carcinomas (combined) were observed in male mice relative to controls, but the increases were within the range of historical controls. Marginal increases in thyroid gland follicular cell adenomas or carcinomas (combined) were observed for male and female mice.”

VIII. Toxicokinetics (Darnerud et al. 2002; McDonald 2002)

A. Deca-BDE given orally to rats resulted in fecal excretion of >90% in two days.
   1. Elimination in urine was <1% of the administered dose over a period of 16 days.
   2. Thus, absorption by the GI tract was minimal (~0.3%)
3. For all dose levels of radiolabelled deca-BDE (250-50,000 mg/kg), more than 99% of the radiolabel was eliminated in the feces within 72 h.

B. In a 2-year accumulation study, rats were maintained on diets providing ~1 mg technical deca BDE/kg bw/day.
   1. Little deca-BDE was found in most tissues (~background levels), but adipose tissue contained bromine levels about 3 times the control levels.

C. Feeding of rats with a single oral dose of 300 mg/kg penta-BDE technical product resulted in half-lives of 50 and 105 days for two hexa-BDEs and 42 and 25 days for two different penta congeners.
   1. The half-life for tetra-BDE was 19-30 days.