

Identifying New Persistent and Bioaccumulative Organics Among Chemicals in Commerce

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The goal of this study was to identify commercial chemicals that might be persistent and bioaccumulative (P&B) and that were not being considered in current Great Lakes, North American, and Arctic contaminant measurement programs. We combined the Canadian Domestic Substance List (DSL), a list of 3059 substances of “unknown or variable composition complex reaction products and biological materials” (UVCBs), and the U.S. Environmental Protection Agency (U.S. EPA) Toxic Substances Control Act (TSCA) Inventory Update Rule (IUR) database for years 1986, 1990, 1994, 1998, 2002, and 2006 yielding a database of 22263 commercial chemicals. From that list, 610 chemicals were identified by estimates from U.S. EPA EPISuite software and using expert judgment. This study has yielded some interesting and probable P&B chemicals that should be considered for further study. Recent studies, following up our initial reports and presentations on this work, have confirmed the presence of many of these chemicals in the environment.

Introduction

In 2006, we published a paper (1) challenging environmental chemists to start looking for new persistent and bioaccumulative (P&B) chemicals. We also noted that “the vast majority of the approximately 30000 chemical substances in wide commercial use (>907 kg/year) are not measured in environmental media, and their emissions and fate are unknown”. That article was based only on the electronic sorting of the 11317 organic substances in the Canadian Domestic Substances List (DSL) and illustrated potential results with estimated physical–chemical properties. Other approaches have been taken for screening chemicals for persistent and bioaccumulative (P&B) chemicals. Several of these were reviewed in our previous article including the ongoing reviews by the Interagency Testing Committee (ITC) (40000 chemicals) and the DSL categorization (23000 chemicals) as well as several initiatives in Europe, particularly the assessment of the Danish (Q)SAR Database of 166000 substances (2). More recently Brown and Wania (2) used two parallel screening methodologies: one based upon substance properties (either measured or estimated) and the other on structural similarity to known Arctic contaminants to examine 105584 chemicals from the EPISuite software (3) for Arctic

Contamination and Bioaccumulation Potential (AC-BAP). This database of chemicals in the EPISuite includes commercial chemicals, pesticides, pharmaceuticals, food additives, and chemicals detected in the environment. They matched these chemicals against five high production volume (HPV) chemical lists to identify a final list of 120 chemicals.

This ability to screen thousands of chemicals has become possible because of the developments in Quantitative Structure Property Relationships (QSPRs) and the availability of large chemical structural databases. But as was noted in our 2006 article, there still is a need for expert judgment review of the results from QSPR analysis. For example, the available QSPRs generally do not consider functional groups that rapidly degrade (e.g., peroxides, hydrolyzable functional groups). Also, chemicals that are only used as chemical intermediates need to be carefully considered as to whether they will be released to the environment. In addition to the consideration of chemical properties, one needs to consider whether the chemical is produced in commercial quantities (as opposed to a research chemical) and whether there is a reasonable likelihood of it being released to the environment resulting in exposure of humans or wildlife.

Thus, we took the approach that to screen for emerging P&B chemicals, one needs to consider (1) the chemical's properties (both estimated and measured as well as by expert judgment) and (2) the commercial use and environmental releasability of the chemical. We mainly considered P&B characteristics in accord with Mackay et al. (4), that only intensive properties such as degradation half-lives and partition coefficients are meaningfully ranked because they are independent of quantity in the environment. It was concluded this could only be accomplished by expert screening of each individual chemical with some assistance from QSPR estimates. We demonstrate that systematic evaluation of essentially all organic, non-polymer commercial chemicals registered in the United States and Canada yields over 600 chemicals which are potential P&B chemicals, including about 500 that had not been measured in environmental media when this study started in 2006. In addition, we also discuss information on very recent measurements and analyzability of these substances.

Methods

Approach. A variety of databases of commercial chemicals were combined into one substructure searchable database in ISISBase format. In brief, the DSL list totaling 11317 organic compounds was combined with the U.S. Environmental Protection Agency (U.S. EPA) Toxic Substances Control Act (TSCA) Inventory Update Rule (IUR) database (14376 compounds) as well as a list of 3059 substances of commercial “unknown or variable composition complex reaction products and biological materials” (UVCBs). The Chemical Abstracts Service Registry Numbers (CASRN) were cross-compared to remove duplicates, yielding a total of 22043 chemicals. With the release of the IUR production data for 2006, the list was updated with 220 new organic chemicals reported for the first time for a total of 22263 organic chemicals. The combined data set is summarized in Table S1 of the Supporting Information. This was quite a different list of chemicals than the DSL list in our 2006 paper—only 4682 chemicals are in both databases.

Quantitative Structure Property/Activity Relationships (QSPRs/QSARs). QSPRs and QSARs were used in the screening of thousands of chemicals and for the identification of chemicals of high priority for further assessment. Selected

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physical and chemical property values estimated with the QSPRs in the EPISuite software (3) included octanol–water partition coefficient ($\log K_{ow}$) (KOWWIN), bioconcentration factor (BCF) (BCFWIN), Henry's Law constant (HENRYWIN), octanol–air partition coefficient ($\log K_{oa}$), vapor pressure (MPBPWIN), and atmospheric oxidation half-life ($AO_{1/2}$) (AOPWIN). The potential P&B criteria that could be used for screening are listed in Table S2 of the Supporting Information.

QSARs, ECOSAR, and OncoLogic were used to predict toxicity to aquatic organisms and cancer potential, respectively (3, 5). Additionally, the analog identification methodology (AIM) tool was used to identify close analogs that have measured data (6). Further details on these QSARs and toxicity estimates are provided in Tables S3 and S4 of the Supporting Information, but these estimates were not considered during the selection of P&B chemicals.

Selection of Potential P&B Chemicals. To make sure that the chemicals selected were commercially important, only IUR chemicals were considered. Initially, HPV chemicals were individually screened using expert judgment for persistence, persistence of potential metabolites, and bioconcentration/bioaccumulation factors (BCF/BAF) of the parent and potential metabolites. In addition, all non-HPV chemicals in the IUR database during the six reporting years were individually reviewed. This focus on chemicals produced in quantities less than 453592 kg/yr was thought to be necessary when a preliminary analysis of fragrances indicated that of the six fragrances detected in the environment (7, 8), five out of six of the chemicals with production data in the IUR database were produced in the ~4535–226796 kg/yr range. The final overall assessment amounted to expert judgment review of approximately 14000 chemicals.

Some of these criteria are more conservative than the international criteria used for selecting P&B chemicals as illustrated in Table S2 of the Supporting Information. Also, about 2000 compounds that had $\log K_{ow}$ (~2–5) and $\log K_{oa}$ (5–12) were selected because some substances with lower $\log K_{ow}$ and high $\log K_{oa}$ may bioaccumulate in air-breathing organisms (9, 10). These 2000 chemicals needed to be further screened for persistence as indicated below.

Generally, a chemical was considered potentially bioaccumulative if the $\log K_{ow}$ value was greater than 3 (greater than 2, if $\log K_{oa}$ was between 5 and 12). Chemicals that had high $\log K_{ow}$ values (above 8) were still considered to be potential bioaccumulative chemicals unless they had very high molecular weights, even though many QSARs suggest that BCF decreases after $\log K_{ow}$ is greater than 6. A more detailed discussion of BCF/BAF criteria is provided by Gobas and co-workers (11).

Many chemicals that were identified as potentially persistent were partially or totally ionic. For partially ionic compounds the undissociated $\log K_{ow}$ value was used; for the totally ionic compounds, the $\log K_{ow}$ value of the ionic form was used.

Expert judgment criteria for biodegradability was based upon the "rules of thumb" that have been available for many years (12) (e.g., persistent: highly halogenated, highly branched, nitroaromatic; biodegradable: straight aliphatic chains, esters, acids, hydroxyl functional groups). If part of the molecule had persistent functional groups, it was considered as a potential P&B chemical, especially if the estimated $\log K_{ow}$ of the potential metabolite would suggest that it would be bioaccumulative. The majority of these rules of thumb are programmed into the BIOWIN programs in EPISuite (3), but the persistence of many chemicals that are chemically oxidized or hydrolyzed are not predicted by the software. Therefore, the QSPR estimates for persistence were used for the expert assessment but required adjustments for many chemicals. For example, peroxide chemicals (R–O–O–R, 63 chemicals in the 22262 chemical database) are not

predicted to biodegrade with the BIOWIN program. However, peroxides are very chemically reactive under environmental conditions, so one needs to consider the persistence of the breakdown products. There are 10 peroxides in Table S3 of the Supporting Information that are highly branched, and peroxide degradation products are predicted to be nonbio-degradable by the BIOWIN programs.

Results and Discussion

Priority Identification. Characteristics of the 22263 chemicals in the DSL/IUR database are summarized in Table S2 of the Supporting Information, along with an indication of the regulation, guidance document, or publication that provided the screening criteria. A significant proportion of the chemicals could be bioaccumulative (e.g., $\log K_{ow} > 5$; 19%), persistent in the atmosphere ($AO_{1/2} > 2$ days; 10%), and potentially susceptible to long-range transport ($\log K_{aw} > -5$ and < -1 ; 32%) when sorted by individual criteria.

Initially, 105 chemicals were selected electronically using three characteristics based on $\log K_{ow} > 3$, $AO_{1/2} > 1$ day, and $\log K_{aw} > -5$ and < -1 . Of the 2000 chemicals that are potentially biomagnified in air breathing organisms, 95 were selected as P&B chemicals after a persistence assessment. These 95 were added to the other selected P&B chemicals from the 14000 IUR chemicals for a total of 505 chemicals. Of the combined list of 610 chemicals, 62% were halogenated (181 fluorinated, 116 chlorinated, 80 brominated, and 10 iodinated) and 7.9% were siloxanes, reflecting the generally higher P&B characteristics of these classes of compounds. The full list of 610 substances is provided in Table S3 of the Supporting Information.

Monitored or Analyzable? We estimate that 101 of the 610 chemicals have been measured in environmental media (as parent compound or degradation products) and about 47 (legacy organochlorines, polybrominated diphenyl ethers [PBDEs], perfluorinated alkyl acid, alkyl phenols, and synthetic and aromatic musks) are on routine monitoring lists. Our search for measured chemicals included environmental databases (e.g., Scopus, this journal, as well as Google, using CASRNs, for reports and proceedings) but does not include occupational exposure or unpublished measurements.

A number of compounds among the 610 were produced in the 1980s and 1990s but are no longer in commercial production in the United States (e.g., polybrominated biphenyls [PBBs], PBDEs, polychlorinated biphenyls [PCBs], organochlorine pesticides [OCP], perfluorooctanesulfonate [PFOS] related compounds); nevertheless, there are major reservoirs of "in use" end-use products (e.g., PBDEs, PFOS) or in the environment (e.g., PBBs, OCPs).

Given our focus on P&B chemicals, it was not surprising that more than half were neutral organics. We concluded, after review of vapor pressure and structure of individual compounds, that 404 were amenable to extraction using conventional analytical methodology for persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs), and current use pesticides (i.e., neutral and moderately polar organics) and by gas chromatography–mass spectrometry (GC-MS) analysis. By this we mean extraction and isolation steps in methods such as U.S. EPA 1613 or 1668 for PCBs/dioxins (13, 14) and/or U.S. Geological Survey (USGS) methodology for pesticides and personal care products in water (15). Another 33 chemicals (including some alcohols, siloxanes, and pigments/dyes) may be analyzable. However, there is a lot of uncertainty particularly for siloxane-related compounds, for which there is as yet no consensus on analytical methodology for environmental samples (16). We assume that 35 of 48 silicone-based products would be amenable to GC-MS analysis on the basis of similar physical chemical properties to the cyclic siloxanes (D3–D6) for which some environmental measurements have been made (17).

Another subset of chemicals were analyzable by liquid chromatography–mass spectrometry (LC-MS) with tandem MS applied (LC-MS/MS). These were mainly the perfluoroalkyl acids (e.g., perfluoroalkane sulfonates [PFSA] and perfluorocarboxylates [PFCAs]) for which LC-MS methodology is now relatively well-established (18). Ten other carboxylates were included in this list as “maybes”.

We assessed each of the 610 for possible degradation products focusing mainly on hydrolysis products (i.e., esters, amides, PFSA/PFCAs). The latter group comprised 133 of the 193 compounds for which we identified possible analyzable degradation products. We did not attempt to identify any analyzable degradation products of siloxanes because of lack of information. Silanols are known atmospheric oxidation degradation products of siloxanes (19), but determining whether they are likely to be significant environmental contaminants was a very challenging question and beyond the scope of the study. A summary of the assessment of the measurement and analyzability of the 610 parent chemicals and degradation products are presented in Table S5 of the Supporting Information.

Priority Chemicals. To reduce the list of 610 so that a more manageable number could be identified, we determined priorities from each chemical group (i.e., brominated, chlorinated, fluorinated, silicone, and other); these are identified in Table S3 of the Supporting Information. Table 1 provides a few examples of priority chemicals from each chemical class along with estimated properties, information on analyzability, and on quantity in commerce for years 1998, 2002, and 2006. Table S3 of the Supporting Information presents additional information on these chemicals, including their predicted toxicity. Besides the priority chemical examples in Table 1, Table S3 of the Supporting Information also contains 30 additional chemicals that are identified as priorities. The fluoro siloxanes (two compounds) were assigned to the fluorinated group and chloro/bromos (one compound) to the brominated group. The major criteria used to select the top priority chemicals were production volume, BCF, and persistence (e.g., $AO_{1/2}$). We omitted most chemicals for which there were already a relatively large number of environmental measurements (e.g., PBDEs, synthetic musks, triaryl phosphates, haloalkyl phosphates).

Brominated. All of the six brominated chemicals in Table 1 are brominated flame retardants (BFR), except for tetrabromopyrene, and they may be replacements for important BFR classes of compounds that are experiencing regulatory action such as penta-, octa-, and deca-bromodiphenyl ether (deca-BDE). The first chemical, tetrabromobisphenol A (TBBPA), is the largest BFR in use today with extremely large production (45359237–226796185 kg in 2006) and is one of the few BFRs that can function as an additive (not chemically bound) and reactive (chemically bound) flame retardant (20). In addition, TBBPA is used as a raw material to manufacture other flame retardants (20), several of which are potential P&B chemicals (Table S3 of the Supporting Information). The additive applications of TBBPA are primarily in acrylonitrile butadiene styrene (ABS) (20), and because TBBPA is not chemically bound, it may be released to the environment.

Likely penta- and octa-BDE replacements in the list are tetrabromophthalic acid ester (TBDEHP, CASRN 26040–51–7) and ethylene bis(tetrabromophthalimide) (EBTBP, CASRN 32588-76-4). Both TBDEHP and EBTBP are on the European Union list of P&B substances (21), but EBTBP has recently been delisted according to the manufacturer (22). These two are representative of a much larger group (Table S3 of the Supporting Information) that are all esters. They have low predicted BCFs due to a combination of high $\log K_{ow}$ (7.6–12) and potential for ester hydrolysis. Many chemical esters were filtered out because they biodegrade fast. However, these

compounds have very low water solubility, which could make hydrolysis very slow, and the degradation products appear to be persistent.

Two highly brominated compounds were included in the priority list (Table S3 of the Supporting Information): CASRNs 155613-93-7, an octabromoindane, and 84852-53-9, decabromodiphenyl ethane (DBDPE). Both are possible replacements for deca-BDE. As highly brominated compounds, they are likely to have relatively low bioavailability but high persistence and, therefore, would be good candidates for survey of sediment. They could also debrominate to more bioavailable compounds. DBDPE is listed as a low production volume chemical in Europe but is not listed on TSCA IUR or Canada's DSL, yet it has been increasing in Great Lakes herring gull eggs over the past decade (23).

Finally, CASRN 128-63-2, a tetrabromopyrene, is not a flame retardant but apparently has been used as a chemical intermediate for production of monomers used in electroluminescent displays (24), which may be used to replace liquid crystal displays. It is unclear if it would be released during use, but relatively high use (~226796–453592 kg in 2002; ~13607–226796 kg in 2006) and disposal similar to what occurs with LCDs could result in release. It had a somewhat higher predicted BCF than most of the other brominated compounds, although not above the BCF criteria for POPs of 5000 (25).

Chlorinated. The four example high-priority chlorinated chemicals in Table 1 (from a total of 116 chlorinated compounds in Table S3 of the Supporting Information) reflects mainly $AO_{1/2}$ and production criteria. Three out of four compounds have $AO_{1/2}$ values quite a bit higher than greater than 2 days, a POPs long-range transport (LRT) criteria (25). We included Declorane Plus (DP) because of its large production volume and predicted persistence, which appears to have been confirmed by measurements in Great Lakes sediments (26). However, it has a low predicted BCF due to a high $\log K_{ow}$ value (and molecular size). Similarly, bis(4-chlorophenyl)sulfone (BCPS, CASRN 80-07-9), an HPV chemical that is used in production of thermostable plastics (27) is included despite a relatively low predicted BCF because of detection in Great Lakes herring gull eggs (27) and presence of high levels in guillemot eggs in the Baltic Sea (28). The microbicide triclocarban (CASRN 101-20-2) was included because of its large production (although lower in 2006 than in previous years) and relatively high predicted BCF (1187), although there is some evidence that triclocarban will biodegrade slowly in sewage and activated sludge (29). Several other microbicides are also found in Table S3 of the Supporting Information (e.g., triclosan [CASRN 3380-34-5], tribromosalan [87-10-5], and tetrachlorosalicylanilide [1154-59-2]), although their production is much lower than that of triclocarban as of 2006. Triclosan can be considered a well-monitored chemical and therefore was not included.

Along with DP, six other cyclopentane-based compounds are listed in Table S3 of the Supporting Information. Hexachlorocyclopentadiene (HCCPD; CASRN 77-47-4) has previously been used as a key intermediate in the production of chlorinated cyclodiene pesticides, but only one of these pesticides, endosulfan, is currently registered in the United States (30). Presently, it is mainly used as a reactive intermediate and in the manufacture of DP as well as the preparation of chlorendic anhydride (20). HCCPD has been detected in the atmosphere above the Great Lakes (31). The chlorinated cyclopentanes are all chemical intermediates probably used in the production of HCCPD (32).

All of the priority chlorinated compounds in Table S3 of the Supporting Information should be readily analyzable by gas chromatography and be amenable to extraction by conventional techniques that are used for other chlorinated organics such as PCBs and chlorobenzenes. Thus, this group

TABLE 1. Examples of High Priority Chemicals with Persistence and Bioaccumulation Potential^a (See Table S3 of the Supporting Information for Additional Compounds)

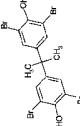
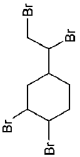
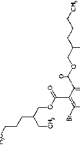
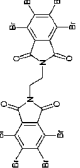
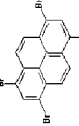
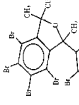
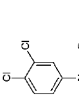
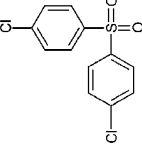
Common Name/ Acronym	CASRN (without hyphens)	Class ^b	Molstructure	VP ^c	AO ^{d,2}	Log K _{ow} ^e	Log K _{ow} ^f	Log K _{oa} ^g	BCP ^h	Chemical Intermediate	Currently Analyzed in Moni- toring or Research Programs	Analyzable Using Existing Methods for Neutral POPs or Other Neutrals ⁱ	Analyzable Degradation Product ^j	Production Range (kg) 1998	Production Range (kg) 2002	Production Range (kg) 2006
TBBPA ^k	79947	Br		1.15E-09	3.61	-11.02	7.20	18.22	4.13	N	Y?	Y	Y	500	500	500
TBECH ^l	3322938	Br		1.40E-02	2.20	-2.77	5.24	8.01	2153	N	Y	Y	?	0.5	0.5	-
TBDEHP ^m	26040517	Br		2.28E-09	0.49	-4.91	11.95	16.86	3	N	N	Y	Y	10	10	10
EBTBP ⁿ	32588764	Br		3.39E-20	0.27	-18.83	9.80	28.63	10	N	N	Y	Y	50	10	10
TBPyr ^o	128632	Br		5.41E-08	6.57	-5.07	8.49	13.56	2424	Y	N	Y	?	-	1	0.5
OBTMPJ ^p	155613937	Br		1.64E-10	6.20	-6.91	11.80	18.71	1	N	N	Y	?	10	0.5	-
Triclo- carban	101202	Cl		4.81E-07	0.50	-8.73	4.90	13.63	1187	N	N	Y	?	1	10	0.5
BCPS ^q	80079	Cl		1.08E-04	219	-5.25	3.9	5.76	199.5	Y	N	Y	?	50	50	50

TABLE 1. Continued

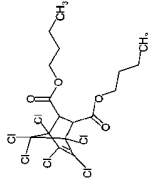
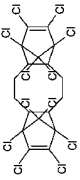
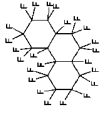
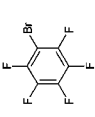

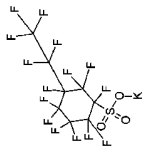
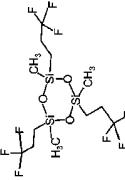
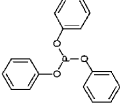
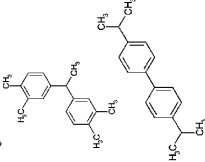
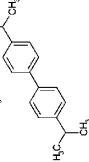
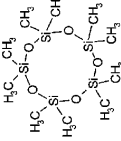
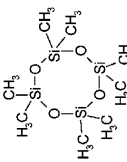
Common Name/ Acronym	CASRN (without hyphens)	Class ^a	Moisture	VP ^b	AO _{1/2} ^c	Log K _{ow} ^e	Log K _{ow} ^f	Log K _{oa} ^g	BCF ^h	Chemical Intermediate	Currently Analyzed in Moni- toring or Research Programs	Analyzable Using Existing Methods for Neutral POPs or Other Neutrals ⁱ	Analyzable Degradation Product ^j	Production Range (kg) 1998	Production Range (kg) 2002	Production Range (kg) 2006
DBDC ^r	1770805	Cl		1.63E-05	320	6.28	7.25	0.97	29340	Y	N	Y	?	0.5	0.5	-
DP ^s	13560899	Cl		9.41E-08	160	-3.52	11.27	14.79	1	N	Y	Y	Y	10	10	10
PFTHP ^t	306912	F		42.8	Very long	8.78	9.58	-2.60	19	N	N	Y	?	0.5	-	-
BPFB ^u	344047	F		972	1026	-0.72	3.88	1.21	196	Y	N	Y	?	0.5	-	-
C8PFPA ^v	68412680	F		6.95E-02	38.2	-3.36	6.48	9.84	19510	N	N	N	N	0.5	0.5	-
PFECHS ^w	67584423	F		2.09E-07	Very long	-9.83	0.47	10.30	3	N	N	N	N	-	0.5	-
TFPD3 ^x	2374143	F		40.4	2.39	3.84	8.66	4.82	343	N	N	Y	?	10	10	0.5

TABLE 1. Continued

Common Name/ Acronym	CASRN (without hyphens)	Class ^b	Molstructure	VP ^d	AO _{1/2} ^d	Log K _{ow} ^e	Log K _{ow} ^f	Log K _{ow} ^g	BCF ^h	Chemical Intermediate	Currently Analyzed in Moni- toring or Research Programs	Analyzable Using Existing Methods for Neutral POPs or Other Neutrals ⁱ	Analyzable Degradation Product	Production Range (kg) 1998 ^j	Production Range (kg) 2002	Production Range (kg) 2006
TPP ^v	101020	Other		1.02E-02	0.99	-4.66	6.62	11.28	25170	Y	N	Y	Y	50	50	50
BDNPE ^z	1742149	Other		9.67E-03	0.33	-1.41	6.34	7.75	15170	N	N	Y	?	10	10	-
DIPBP ^{aa}	69009901	Other		9.80E-03	0.84	-1.20	6.67	7.87	27240	N	N	Y	?	10	10	10
DS ^{bb}	541026	Si		2.91E+01	7.15	0.69	5.71	5.02	2014	N	Y	Y	?	100	500	100
D4 ^{cc}	556672	Si		1.57E+02	8.94	0.55	5.09	4.54	1687	N	Y	Y	?	500	500	500

^a All physical-chemical property estimations using EPIsuite version 3.12. ^b Br = brominated, Cl = chlorinated, F = fluorinated, Si = silicon. ^c VP = vapor pressure, estimate (Pa). ^d AO_{1/2} = atmospheric oxidation half-life (days, 12 h day at 1.5 × 10⁶ OH/cm³). ^e K_{aw} = atmosphere-water partition coefficient. ^f K_{ow} = octanol-water partition coefficient. ^g K_{oa} = octanol-air partition coefficient. ^h BCF = bioconcentration factor. ⁱ Analyzable by conventional published methods. ^j “?” indicates that degradation products are unknown and thus extending the methods to degradation products is uncertain. ^k Production values from TSCA IUR for the reporting years to 2006. Values refer to range of kg: 0.5 = 4535-226796; 1 = 226796-453592; 10 = 453592-22679618; 100 = 22679618-45359237; 500 = 45359237-226796185; 1000 = 226796185-453592370 kg for the reporting year. ^l TBBPA = tetrabromobisphenol A. ^m TBDEHP = 1,2-dibromo-4-(1,2-dibromoethyl) cyclohexane. ⁿ TBDEHP = tetrabromophthalic acid di-2-ethylhexyl ester. ^o EBTPB = ethylene bis(tetrabromophthalimide). ^p TBTPyr = tetrabromopyrene. ^q OBTPMI = octabromo-1,1,3-trimethyl-3-phenylindane. ^r BCPS = bis (4-chlorophenyl) sulfone. ^s DBDC = dibutyl chloredate. ^t DP = Declorane Plus. ^u PFTHP = perfluoroperhydrophenanthrene. ^v BPFB = bromopentafluorobenzene. ^w C8PFPA = phosphonic acid, perfluoro-C₆-C₁₂-alkyl derivatives. ^x PFCEHS = decafluoro(pentafluoroethyl)-cyclohexanesulfonate. ^y TFDP3 = tris-trifluoropropyltrimethylcyclotrioxane. ^z TPP = triphenyl phosphite. ^{aa} BDNPE = 1,1-bis[3,4-dimethylphenyl] ethane. ^{ab} DIPBP = diisopropylbiphenyl. ^{bb} D5 = decamethylcyclopentasiloxane. ^{cc} D4 = octamethylcyclotetrasiloxane.

could possibly be retrospectively analyzed in existing extracts. However, a search of analytical standards suppliers (Sigma-Aldrich, Supelco, Accustandard) and using the CASRN in a Google search revealed no suppliers for the cyclopentane/enes, possibly because they are chemical intermediates and have not been synthesized for other uses.

Fluorinated. The selection of fluorinated compounds was challenging because a large number on the list were actually chemical intermediates (e.g., telomer iodides, sulfonyl fluorides) used in production of fluoropolymers containing fluorotelomer or fluoroalkylsulfonate moieties. Also the phase out of the PFOS-related products may make many chemicals (33) on the list a lower priority. Thus, our selection (Table S3 of the Supporting Information) includes chemicals that we believe are currently in use and actually replacements in some cases (e.g., fluorotelomer acrylates [CASRNs 17527-29-6 and 2144-53-8] and perfluorobutane sulfonamides [CASRNs 34449-89-3, 67584-55-8, 67584-59-2]). These compounds are likely to yield PFCAs and perfluorobutane sulfonates (PFBS) in the atmosphere (34, 35) and in sewage treatment plants (36, 37). Overall about 73% of the 181 fluorinated compounds likely give rise to PFCA or PFSA. Also included in the high-priority fluorinated chemicals in Table S3 of the Supporting Information are several trifluoromethyl-substituted compounds (CASRNs 328-84-7, 393-75-9, 50594-77-9), which have relatively long $AO_{1/2}$ and significant production (~453592–4535,923 kg for 2 of 3 in 2002; ~226796–453592 kg in 2006). However, none of the three meet the POPs $\log K_{ow} = 5$ criteria and may therefore not be very bioaccumulative. They could, however, fit into the class of chemicals with relatively high predicted biomagnification in air-breathing animals because of the intermediate $\log K_{ow}$ and relatively high $\log K_{oa}$ (10) and therefore deserve further study.

The fluorinated alkyl phosphonate (PFPA, CASRN 68412-68-0) (Table 1) was included because of the high predicted BCF (19510) for the monosubstituted compound along with high $AO_{1/2}$. Several other related phosphates with perfluorinated substituents are also found in Table S3 of the Supporting Information (CASRNs 2965-52-8, 67939-97-3, 67969-69-1, 68412-69-1, 74499-44-8, 148240-85-1, 148240-87-3, 148240-89-5). The phosphates are amenable to LC-MS/MS analysis as with other perfluoroalkyl acids (18) and the first measurements of C_6 -, C_8 -, and C_{10} -PFPA in the Great Lakes region have recently been made (38).

Several relatively volatile compounds are included in Table 1 and Table S3 of the Supporting Information. The trifluoropropyl substituted cyclic siloxane, TFPD3 (CASRN 2374-14-3), is very interesting because it combines relatively high $AO_{1/2}$ with large production volumes (~453592–4535923 kg in 2002; ~226796–453592 kg in 2006). Because of relatively high $\log K_{ow}$ (8.66), this compound has low predicted BCF (343). Nevertheless, other siloxanes have high predicted (and in some cases measured) BCFs as discussed below. Perfluoroperhydrophenanthrene (PFTHP, CASRN 306-91-2) represents a class of perfluorinated cyclics (see CASRN 306-91-2 in Table S3 of the Supporting Information), which are likely very persistent, but have low predicted bioaccumulation due to their very high $\log K_{ow}$. These compounds have many applications in the electronics industry, including as a fluid for vapor phase soldering, condensation inert heating, and for testing and direct contact cooling (39). They are most likely emitted directly to the atmosphere given their volatility. Unlike the chlorinated and brominated compounds, the 10 priority fluorinated compounds in Table S3 of the Supporting Information are more of a challenge to analyze by existing methodology. The trifluoromethyl-substituted compounds (CASRNs 328-84-7, 393-75-9, 50594-77-9) and PFTHP appear to be amenable to analysis by GC-MS using conventional techniques for extraction and isolation of PCB/chloroben-

zenes, although methods would need modification to avoid volatilization losses due to high volatility. Most others are more likely analyzed by LC-tandem MS as degradation products (i.e., perfluoroalkyl acids or directly in the case of PFPA).

Other Chemicals. The selection of chemicals from this large group (totaling 185 in Table S3 of the Supporting Information) was based mainly on predicted BCF and production volume. All 10 priority chemicals were produced in the range of ~453592–4535923 kg to up to ~22679618–45359237 kg in 2002 and most continue to be HPV chemicals in 2006 (see the three examples in Table 1). $AO_{1/2}$ values for these 10 priority chemicals and indeed most other chemical compounds were less than 2 days, reflecting much greater reactivity with the hydroxyl radical, especially for aromatic hydrocarbons. Triphenyl phosphate (CASRN 101-02-0) was included because of its high predicted BCF (25170). Several related phosphates, tri(*t*-butylphenyl) phosphate (CASRN 31570-04-4), trihaloalkyl phosphates [e.g., tris(2-chloropropyl)phosphate, CASRN 6145-73-9] and triphenyl phosphine (CASRN 603-35-0) are also in the list of 610 compounds but were not included in the priority list because of low predicted BCFs. Nevertheless, there is evidence for environmental contamination by some of these compounds in the Great Lakes (40, 41). Some tris-(chloroalkyl) phosphates may be replacements for penta-BDEs (42), so we foresee increased use. Several other nonhalogenated compounds in Table S3 of the Supporting Information have high predicted BCF including CASRNs 25973-55-1 (10350), 1742-14-9 (15170) (Table 1), 69009-90-1 (27240) (Table 1), and 1222-05-5 (13200), the synthetic musk, galoxide. All are characterized by $\log K_{ow}$ s (6–7) which give large BCFs and substitution on aromatic rings in the *para*-position, which may limit biodegradation. There are generally no experimental BCFs to confirm these predictions. All 10 priority “other” compounds in Table S3 of the Supporting Information appear to be amenable to analysis by GC-MS using conventional techniques for extraction and isolation.

Silicone Related Compounds. Selection of the top 10 from this group (totaling 48 in Table S3 of the Supporting Information) was based on high predicted BCFs (8 of 10 are greater than 5000) and $AO_{1/2}$ (9 of 10 are greater than 2 days) as well as high production volume (D4 and D5 examples in Table 1; ~45359237–226796185 kg/yr). Dimethyl cyclic siloxanes with 4 to 6 siloxane groups appear to be particularly bioaccumulative, and recent laboratory measurements confirm this (43). Environmental measurements in Scandinavia show that the cyclic siloxanes are the major siloxanes found in environmental media despite wide use of linear and cyclic products (17). Unlike the other groups, the analytical methodology for determining siloxanes is not well-established (16). Nevertheless, all 10 compounds listed as priorities in Table S3 of the Supporting Information are likely to be amenable to extraction and isolation methods similar to those currently used for the cyclic siloxanes (17). They probably cannot be determined, however, in existing extracts developed for analysis of halogenated organics or PAH/hydrocarbons because of background contamination issues. The wide use of linear and cyclic siloxanes, including their use in personal care products, combined with high volatility (most have vapor pressures greater than 1 Pa) means that they are widespread contaminants in laboratories. Also they may contaminate laboratory reagents. Thus, minimizing contamination during sample collection and storage as well as during analysis is a major challenge. Several laboratories are currently developing methods to analyze siloxanes (44), but it may be several years before the full picture of whether predicted BCFs and long persistence of these compounds is confirmed.

This study has yielded some interesting probable P&B substances that should be considered for further study and measurement. True success of a predictive study like this is that one identifies potential chemicals and then analytical chemists develop a method for detection and are successful in finding them in the environment. Most of the 610 chemicals we identified are not currently analyzed, yet most are in commerce on the basis of 2002 and 2006 IUR information. Several chemicals that we identified in initial reports on this project (45) have recently been detected: 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) and 2-ethylhexyl 2,3,4,5-tetrabromobenzoate (TBPH) in house dust (46); 1,2-dibromo-4-(1,2-dibromoethyl) cyclohexane (TBECH) in arctic beluga whales (47); the above as well as hexabromobenzene (HBB) in herring gull eggs (48); pentabromotoluene (PBT_o), pentabromoethylbenzene (PBEB), and HBB in Great Lakes air (49); BTBPE in Great Lakes air (31), and decafluoro(pentafluoroethyl)-cyclohexanesulfonate (PFECHS) and C₈-PFPA in wastewater effluents and water throughout Canada (38, 50). We hope that in a small way we helped point some of these investigators into studying these chemicals.

We have been flexible with the definition of P&B chemicals rather than strictly using guidelines or threshold values. However, most assessments of P&B characteristics have faced a similar challenge. Indeed, a report prepared for the POPs Review Committee of the Stockholm Convention noted that 5 of 10 substances proposed for addition to the POPs list were concluded to fulfill the screening criteria for classification as POPs despite their low BCF (<5000) (51). Other assessments of the 610, or the 22263, could take a different approach, for example, simply identifying the priority chemicals without categorizing them first as halogenated or other, and this might yield a quite different priority list.

Brown and Wania (2) identified 120 chemicals as potential Arctic contaminants on the basis of persistence, long-range transport, bioaccumulation potential, and structural similarity. Comparing lists, 110 of these are in our 22000 chemical DSL/IUR database. The other 10 are pesticides (e.g., endosulfan, chlorothalonil, picloram, etc.). Current-use pesticides were not included in the present study because they are not reported in the IUR database. Altogether, there are 86 chemicals in their 110 industrial chemicals that are in our 610 chemical list, indicating good agreement between studies.

Previous experience from contaminant measurements in the Great Lakes, Arctic, and Baltic indicates that some chemicals become concerns because of widespread detection, biomagnification, increasing trends, and high persistence (e.g., penta-BDEs, decabromodiphenyl ether, toxaphene) and not because much is known about toxicity. We subscribe to this view and have selected priority chemicals with this in mind, particularly for the halogenated compounds. However, for the other chemicals and siloxanes-related substances, we relied mainly on POPs criteria for BCF and AO_{1/2} as well as production volume.

Further work should be done with the list of 610 chemicals and with the larger list of 22263 chemicals in commerce. Information on uses and releases is critical to proper assessment and prioritization, and some available information has been added in the comment field in Table S3 of the Supporting Information. Some compounds may have very high release potential, for example, plasticizers, hydraulic fluids, or solvents, fire-fighting surfactants and other defoaming agents, fragrances, auto wax products, and soil repellants. Others are degraded during use (e.g., antioxidants, vulcanizing agents, ultraviolet [UV] stabilizers, polymer initiators) and may not be released into the environment.

In selecting the 610 chemicals that are potential P&B chemicals, focus was placed on chemicals whose whole structure or part of the structure would be persistent. For chemicals for which only part of the structure appears to be

persistent by the “rules of thumb” (12), it may be desirable to use computer-aided software to predict the degradation pathways and examine the transformation products for P&B properties as has recently been done by Kern et al. (52) for a number of pesticides and pharmaceuticals.

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Supporting Information Available

Tables provide sources of the chemicals in the database (S1), P&B characterization of the database (S2), property and toxicity data on the 610 chemicals selected as potential P&B chemicals (S3), characterization of toxicity estimates for the 610 chemicals (S4), and analyzability of the chemicals (S5). This information is available free of charge via the Internet at <http://pubs.acs.org>.

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