Journal of Power Sources 203 (2012) 222–226

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Short communication

An investigation of mass and brand diversity in a spent battery recycling collection with an emphasis on spent alkaline batteries: Implications for waste management and future policy concerns

Mark P.S. Krekeler [a,*], Heather A. Barrett [b], Robert Davis [c], Chris Burnette [b], Tricia Doran [a], Alyssa Ferraro [b], Amanda Meyer [b]

[a] Department of Geology, Miami University-Hamilton, 1601 University Blvd., Hamilton, OH 45011, USA
[b] Department of Geology, 501 East High St., Miami University, Oxford, OH 45056, USA
[c] Department of Statistics, Miami University-Hamilton, 1601 University Blvd., Hamilton, OH 45011, USA

ARTICLE INFO

Article history:
Received 8 September 2011
Received in revised form
14 November 2011
Accepted 15 November 2011
Available online 25 November 2011

Keywords:
Battery count
Battery recycling
Battery policy
Battery waste management
Battery collection

ABSTRACT

A count of the type and brand of spent alkaline batteries from a collection program operated by Butler County, Ohio was performed to determine the level of brand diversity, to provide estimates of the size of the waste stream, and quantities collected for recycling and for landfilling. The program has a total of 37 school drop off sites at both public and private elementary, middle and high schools. Several additional sites for battery drop include public libraries in the towns of Hamilton, Fairfield, Oxford, two county government administration centers, and two major retail stores in Fairfield and West Chester townships.

A total of 32,866 spent alkaline batteries with a calculated mass of approximately 943.37 kg representing 10–15% of the recycling collection were counted by size and brand type. All five types (AAA, AA, C, D, and 9V) of spent alkaline batteries had approximately 68–76% of the samples concentrated among three or four brands. The number of brands varied among types with AAA (123); AA (228); C (44); D (65); 9V (79). The total annual spent alkaline waste stream mass for Butler County is estimated to be 84,665 kg, and a mass of the spent alkaline battery waste stream collected for Butler County is approximately 7.4% (6289.1 kg) to 11.1% (9433.7 kg). Several other battery types (lead, Ni–Cd, lithium, and button batteries) were observed and comprised 60.2 kg.

Butler County spends $10,000 to collect the batteries each year and the estimated cost for collecting all batteries in the County would be an additional minimum cost of $144,000 to $186,000 per year translating into a per capita cost of approximately $0.39–0.51 per Butler County resident annually. The results of this investigation are useful for recycling program development, developing environmental policies specific to the United States and can be used for comparative purposes with other battery waste streams globally.

1. Introduction

An average of eight disposable alkaline batteries are consumed per person per year in the U.S. according to the USEPA. With a population of approximately 305 million people, this translates into an estimated 2.44 billion batteries used and disposed of per year and the most recent estimate is that 3 billion batteries are purchased in the U.S. (USEPA) [1]. Disposable alkaline batteries consist dominantly of two fundamental modular parts, an anodic region and a cathodic region, which are separated by a permeable membrane. The anodic region is typically a cylindrical body of metallic zinc powder which is surrounded by a concentric cathodic layer which usually consists of MnO_2 (typically ramsdellite) and other manganese oxide or oxyhydroxide compounds including but not limited to Mn_2O_3, MnO and $Mn(OH)_2$ [2,3]. An electrolyte solution that is commonly a KOH solution as well as gelling components and aqueous ionic zinc are common in the liquid phase of the battery [2,3].

These materials are of significant environmental concern globally and are major components of the overall hazardous material waste stream and a major contributor to heavy metals in landfills [4–6]. Details regarding the diversity of brands and mass of spent alkaline batteries turned in for recycling and to landfills are poorly documented at best. Such information is critical for planning recycling efforts and developing policy centering on spent alkaline batteries. In particular the selection of recycling approaches is

* Corresponding author.
E-mail address: krekelmp@muohio.edu (M.P.S. Krekeler).

0378-7753/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2011.11.040

Fig. 1. Photographs of the battery recycling collection count conducted on December 7th, 2009. (A) One of the numerous skids of unsorted batteries staged to be counted. (B) An example of an unsorted collection bucket with a variety of battery types present. (C) An example of separated and counted batteries. (D and E) Examples of counted major brands of AA batteries, the largest component of the waste stream. (F) Examples of Ni–Cd batteries (left) and Pb batteries (right) from the waste stream.

dependent upon the nature of the waste stream and related economic considerations.

Many battery technologies have well-established recycling processes [7–14] and methods exist for recycling spent alkaline batteries [15–19,2]. These approaches are largely batch processes, which require minimal sorting and produce raw materials. However, these approaches are very energy or material intensive and often do not produce high value products and are not profitable.

Although recycling of alkaline batteries does occur at modest levels compared to the entire waste stream volume there is significant room for improvement in generating more environmentally benign processes and more profitable products. Production of high value materials may require sorting of spent components which may target specific brands, sizes or types of spent alkaline batteries. Little detail is known regarding the composition of spent alkaline battery waste streams. Information is lacking regarding costs of battery collections and this is very important for municipalities and other organizations considering implementing a battery collection program. We report the first detailed count of a battery collection as a tool for recycling planning and decision making.

2. Materials and methods

Access was granted to a battery collection at the LeSourdsville facility Butler County Recycling & Sewer and Water Department. A total of 41 undergraduate student helpers were trained to identify different battery types and sizes. Students were organized into groups that progressively sorted, counted and recorded batteries while Butler County staff transported batteries (Fig. 1). Krekeler and Barrett provided oversight. Interviews with student participants and random recounts suggest a total count error of ± 350 batteries total.

During March 2006, the Butler County Recycling & Sewer and Water Department initiated a new battery collection program by installing household battery collection tubes. The program accepts

Table 1
Summary of count data for each type of spent alkaline battery with major brands (>2.5% by mass) being delineated. Mass estimates for each brand grouping were calculated using the mass specified. The percentages of each grouping is based on mass.

AAA = 10.8 g	No.	Mass (kg)	Percent*	AA = 22.7 g	No.	Mass (kg)	Percent*	C = 65.8 g	No.	Mass (kg)	Percent*
Duracell	1080	11.66	41.87	Duracell	5462	123.99	20.32	Duracell	217	14.28	28.26
Energizer	513	5.54	19.89	Duracell Procell	3300	74.91	12.28	Duracell Procell	38	2.50	4.95
Rayovac	95	1.03	3.68	Energizer	8402	190.73	31.26	Energizer	268	17.63	34.90
GP	101	1.09	3.92	Rayovac	1512	34.32	5.63	Rayovac	62	4.08	8.07
Others	791	8.54	30.65	Others	8202	186.19	30.52	Other	183	12.04	23.83
Subtotal	2580	27.86		Subtotal	26878	610.13		Subtotal	768	50.53	
D = 133.5 g	**No.**	**Mass (kg)**	**Percent***	**9V = 45.9 g**	**No.**	**Mass (kg)**	**Percent***	**Size**	**No.**	**Mass (kg)**	**Percent***
Duracell	528	70.488	34.60	Duracell	428	19.65	38.42	AAA	2580	27.86	2.95
Duracell Procell	106	14.151	6.95	Energizer	301	13.82	27.02	AA	26878	610.13	64.68
Energizer	331	44.1885	21.69	Rayovac	85	3.90	7.63	C	768	50.53	5.36
Rayovac	79	10.5465	5.18	Other	300	13.77	26.93	D	1526	203.72	21.59
Other	482	64.347	31.59					9V	1114	51.13	5.42
Subtotal	1526	203.72		Subtotal	1114	51.13		Total	32866	943.37	

alkaline, nickel–cadmium, Ni-metal hydride, lithium, button, lead (excluding automotive) and other household batteries. Over the past 4 years the program has expanded to include a total of 37 school drop off sites in addition to several other sites at libraries, government buildings and businesses throughout the county. Butler County estimates that approximately $10,000 is spent annually on the program. These costs include labor, equipment, and fees for battery processing. Butler County employs a recycling technician who is responsible for the collection and transport of batteries. Butler County contracts with a private firm Environmental Enterprises, Inc., to manage the battery material. Interviews with Butler County Recycling & Solid Waste District indicate that there are several motives for the project. The County believes that the program helps educate consumers, creates value for reuse and remanufacturing and prevents pollution.

3. Results

3.1. Spent alkaline battery population

A waste stream sample consisting of a total of 32,866 spent alkaline batteries with a calculated mass of approximately 943.37 kg was counted by size and brand type (Table 1). By visual estimation this portion of the waste stream represents approximately 10–15% of the total onsite collection. The distributions of all five types of alkaline batteries had one striking similarity; approximately 68–76% of all batteries of each type were concentrated among three or four brands (Table 2). An exponential relationship between the number of spent alkaline batteries per type and the number of brands occurs with an $R^2 = 0.9869$ (Fig. 2).

Table 2
"Total Brands" refers to the total number of different brands that were noted among the batteries. In most cases, a given brand would only show up a few times in our sampling. For each different type of alkaline battery, there were three or four brands that made up a large majority of the total distribution; we have referred to these as "Dominant Brands." The "Dominant Brand" and "Cumulative Percent" columns in the table above refer to the number of brands that could be considered fairly common in our battery samples and the percent of the given type of battery that they comprise, respectively. Finally, the "Next Most Common" column states how frequently the most common non-dominant brand showed up in our sampling.

Type	Number of cells	Total brands	Dominant brands	Cumulative percentage	Next most common
AA	26878	228	4	69.5	1.5
AAA	2580	123	4	69.3	1.7
C	768	44	4	76.2	2.5
D	1526	65	4	68.4	3.2
9V	1114	79	3	69.6	2.8

The waste stream investigated represents 6 months of collection; our sample of the waste stream represents 10–15% of this collection. A mass estimate of the total recycling collection per year therefore is approximately 9433.7 kg to 6289.1 kg year^{-1}. By using the total mass determination (943.37 kg) and the number of batteries collected (32,866) and average mass per battery value of 0.0287 kg battery^{-1} is obtained. According the U.S. 2010 census Butler County has a population of 368,130 people. Combined these values can be used to estimate other factors of battery waste. Using the USEPA [1] value of 8 batteries consumed or used per person per year approximately 2.95 million batteries per year are used in Butler County with an associated mass of 84,665 kg. Accordingly approximately 7.4% (6289.1 kg) to 11.1% (9433.7 kg) of spent alkaline batteries are recycled in Butler County and approximately 92.6% (78375.9 kg) to 89.1% (75231.3 kg) are estimated to be landfilled from the county.

3.2. Comments on other battery types

Several other battery types (lead, Ni–Cd, lithium, and button batteries) were observed in the waste stream mixed with the spent alkaline batteries and the mass of this sub-waste comprised 60.2 kg. Brand information for these battery types were not counted owing to lack of labels and ambiguities in labeling. Lead batteries comprise approximately 36.5 kg of the waste stream or 60.6% of the other battery type population. Approximately 80% of lead batteries were from lighting apparatuses, 10% were from children's driving toys (Power Wheels) and 10% were odd-shaped batteries with an

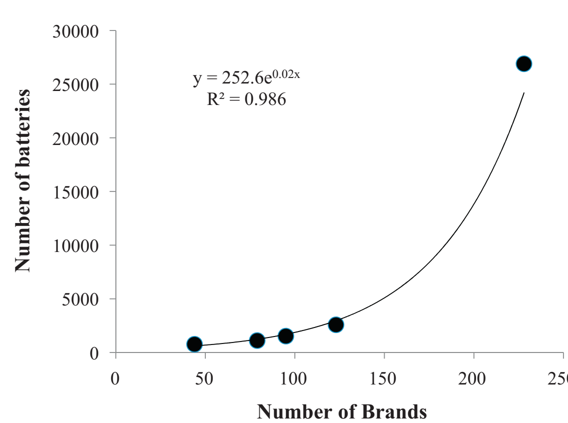

Fig. 2. A strong exponential relationship exists between the number of batteries in each type and the number of brands. This relationship is interpreted to be a function of minimum efficient scale.

unclear origin or use. Nickel containing batteries (Ni–Cd batteries and Ni Metal hydride) comprise 16.5 kg of the waste stream or approximately 27.4% of the other battery type population. Approximately 50% of Ni–Cd batteries were not labeled; common Ni–Cd batteries were from Dewalt tools. The lithium battery waste stream comprised 5.4 kg or 8.9% of the other battery type population and consisted largely of a variety of cell phone batteries (∼10%), laptop computer batteries (∼50%), and AA size batteries (∼40%). Button batteries comprise 1.8 kg or approximately 3.1% of the waste stream and consisted of a variety of shapes and sizes. Approximately 70% of the button batteries were unlabeled.

4. Discussion

4.1. Comments on error

Estimating the error in such an investigation of this type has several challenges. To execute the count an estimated total of 270 person hours were required and a total of 150 h were required to enter, check, and process the tabulated data. Student assistants counting batteries were trained for a total of approximately 90 min. This training consisted of teaching students battery recognition, organization and counting techniques. Students were offered extra credit as a means to motivate good performance. Krekeler examined approximately 20 count sheets by students recording numbers and spot checked them for accuracy. A single report of inadequate counting by a single student was identified after the count. After much discussion with the students observing the problem a count error of 200 batteries (by type) were attributed to this student. Combining this and general errors occasionally found on count sheets we estimate that the error in the total count is approximately ±350 batteries. Using the average mass/battery ratio of 0.0287 kg battery^{-1} this translates to approximately 10 kg or approximately 1% of the mass. Additionally, zinc–carbon batteries were not always culled from the count as labeling was ambiguous. This battery type constitutes approximately 2% of sales in the U.S. and thus we attribute a 2% estimated error to this factor and our total estimated error is approximately 3% or 30 kg. Error for other battery types are less certain as these constituted a small percentage of the total recycled stream and not all materials were available for line of sight inspection.

4.2. The nature of spent alkaline battery waste stream and recycling

The very strong exponential correlation between the number of batteries per type and the number of brands observed can be explained by the economic principle of minimum efficient scale. Fundamentally minimum efficient scale is a concept where a larger market size can support more manufacturers or firms supplying a given product [20–24]. In an open or competitive market the number of firms (n) will be determined by the relationship:

$$n = \frac{Q}{q^*}$$

where Q is the total market sales such as the total number of a battery type, and q^* is the quantity that minimizes the typical firms cost per unit manufactured or produced. As Q becomes larger, n also increases. The distribution observed is expected for a large market. Although ample papers exist with respect to minimum efficient scale in manufacturing in general, no papers specific to batteries of any type could be found.

Although this is a viable interpretation of the observed data, it should be noted that when the sample size is small, poorly represented brands may be missed totally. For example if a minor brand represented only 0.01% of the general population then counting the 1526 D cells of this study would unlikely show a single cell of this brand. Although out of the scope of this paper, we suggest a more rigorous analysis of minimum efficient scale of batteries is warranted and may be a quantitative tool to evaluate battery waste streams globally. Larger sample sizes would be required to address sampling bias.

Owing to the abundance of Duracell, Energizer, Rayovac, and GP brands in the waste stream it may be feasible to sort the dominant battery types using automation and focus specific recycling efforts on these battery types. Developing high value materials from spent alkaline batteries is a fundamental step in developing economically feasible approaches and brand specific preliminary studies focused on developing high value recycled materials have been carried out on Duracell spent alkaline batteries [25,26]. Similar studies on Energizer, Rayovac and GP brands should be carried out based on their abundance in the waste stream observed. If suitable manganese oxide and zincite products could be produced from these brands a driver would be established to further research high value materials recycled directly from spent alkaline battery waste streams. By mass the AA waste stream is the largest and the three dominant brands are Duracell, Duracell Procell and Energizer. Accordingly specific recycling approaches to this fraction of the waste stream may be the most prudent.

With this data in mind, we suggest a common recycling approach for all five battery types. Based on the number of brands, it is not feasible to perform brand-specific recovery and recycling for most brands. We suggest that brand-specific recovery and high value material recycling approaches should be investigated for the dominant brands given for each type of battery. All other alkaline batteries of a given type should be thrown into a common pool for which non-brand-specific recovery and recycling could be performed such as those outlined in references [2,3,15–19].

4.3. The nature of other components of battery waste stream

Other battery types (lead, Ni–Cd, lithium, and button batteries) present in the waste stream comprised a relatively minor fraction of the overall mass of the waste stream but are of profound environmental concern because of the metals contained in them. Heavy metals are very well recognized as being toxins [27,28]. Lead is well recognized as having toxic effects in the environment and for humans [29–33]. Both nickel [34–36] and cadmium [37–39] are well recognized as being toxic in the environment. Button batteries are well known to have significant mercury content as well as silver content. Mercury in the environment is a well recognized global pollution problem [40–43] and silver is of environmental concern as well [44,45]. The lack of labels for most button batteries prevents any cursory assessment of feasibility for recycling. The current relative high prices of mercury and silver warrant a more thorough investigation of the button battery waste stream.

4.4. General economic and policy implications

Butler County allocates approximately $10,000 towards the recycling program and using this as a proportion for the waste stream cost, plus the cost of an additional mid-level manager ($60,000) for oversight, the estimated cost for collecting the total waste stream annually is approximately $144,000–186,000. This would translate to a per capita cost of approximately $0.39–0.51 per Butler County resident.

The Butler County program indicates that battery collection programs can be operated at an estimated cost of approximately $0.39–0.51 per capita for economic settings similar to that of Butler County. Analogous settings would be counties of similar population sizes and tax bases. Presumably costs would be similar in areas of higher populations; however, rural regions may not have sufficient infrastructure to support collections.

There are many stakeholders in the alkaline battery industry. Disposable alkaline batteries have numerous manufacturers in the U.S. and internationally as well as and numerous consumers, all at a range of scales. Providing constraints on the spent alkaline battery waste stream is very important for understanding the overall number and diversity of manufacturers contributing to the waste stream. The data can be used by government agencies, manufacturers, environmental NGOs, and consumers as a starting point for discussions regarding the waste stream. The data of this investigation provide a preliminary tool to assess possible fees or taxation relating to the waste stream.

If regulations are to be put in place that link disposal in some way with manufacturing source, it arguably should be done based on the nature of waste stream. One complicating factor is that brands of international origin occur in the waste stream. However in our count it was not feasible to determine the country of origin for each battery type. Discussion with Duracell indicates that they know of counterfeit batteries that are manufactured internationally as well. These batteries are of lower quality and known (in some cases) or are suspected of containing mercury which has been eliminated in U.S. production since the implementation of the *Mercury-containing and Rechargeable Battery Management Act of 1996*. Identifying batteries containing mercury in the U.S. waste streams is of great environmental concern and is problematic. Detailed investigations of brand type, country of origin, and pollutant metals should be undertaken for multiple waste streams. More stringent import monitoring of batteries should be done to ensure environmental equity for manufacturers and consumers.

The data of this investigation offer a means for comparative analysis with other waste streams globally. One waste stream in one region of the U.S. may not be the same as that of another owing to a variety of market factors. Similarly, the data offer a means of comparison to battery waste streams in countries and regions aside from the United States which have differing market structures. Such investigations may be critical in developing environmental policy in such regions.

5. Concluding comments

To our knowledge this is the first detailed investigation of its kind for a battery waste stream. Such investigations are feasible elsewhere and require only a moderate amount of student or participant training. The investigation provides constraints for developing recycling strategies, developing environmental policies, and enabling economic decisions for municipalities and NGOs for implementation of battery collection programs.

Acknowledgements

We thank the very helpful comments of two anonymous reviewers on this manuscript. This study would not have been possible without the many Miami University-Hamilton student volunteers: M. Beane, D. Bedell, J. Chafin, D. Chance, J. Childs, R. Connaughton, S. Craft, J. Crawford, J. Dreske, H. Ellinghausen, J. Field, M. Field, B. Fusco, S. Girdler, A. Goins, G. Grollmus, M. Hargrave, H. Higbee, M. Hollister, C. Kinsey, B. Lafary, N. Marengo, K. McCarthy, T. Michel, J. Minhas, K. Monroe, B. Munsey, E. Nimis-Pateman, H. Patrick, R. Peery, N. Pitheckhoff, D. Prichard, J. Stevison, J. Stitzel, J. Taylor, T. Walker, M. Weiler, J. Whipple, J. White, and D. Yowler. We thank Dr. George Davis, Dr. Bill Even, and Dr. James Brock of the Miami University Department of Economics for helpful discussion. We thank Anne Fiehrer-Flaig, Utah Bailey, and Arnold Fugate of Butler County for access to the collection and county information. We thank Duracell Corporation for helpful discussion. This work was supported in part by a start-up grant to Krekeler by Miami University-Hamilton.

References

[1] www.epa.gov/wastes/conserve/materials/battery.
[2] N. Vatistas, M. Bartolozzi, S. Arras, J. Power Sources 101 (2001) 182.
[3] N. Vatistas, M. Bartolozzi, J. Power Sources 79 (1999) 199.
[4] R.J. Slack, J. Gronow, N. Voulvoulis, Sci. Total Environ. 337 (2005) 119.
[5] S. Panero, C. Romoli, M. Achilli, E. Cardarelli, J. Power Sources 57 (1995) 9.
[6] J. Avraamides, G. Senanayake, R. Clegg, J. Power Sources 159 (2006) 1488.
[7] D.P. Mantuano, G. Dorella, R.C.A. Elias, M.B. Mansur, J. Power Sources 159 (2006) 1510.
[8] H. Roberts, J. Power Sources 116 (2003) 23.
[9] A. Zabaniotou, E. Kouskoumvekaki, D. Sanopoulos, Resour. Conserv. Recy. 25 (1999) 301, 1999.
[10] A.G. Morachevskii, Russ. J. Appl. Chem. 70 (1997) 1.
[11] G. Diaz, D. Andrews, J. Miner. Metal. Mater. Soc. 48 (1996) 29.
[12] P. Ammann, J. Power Sources 57 (1995) 41.
[13] S. Frohlich, D. Sewing, J. Power Sources 57 (1995) 27.
[14] C. Sancilio, J. Power Sources 57 (1995).
[15] G.X. Xi, L. Yang, M.X. Lu, Mater. Lett. 60 (2006) 3582.
[16] J.M. Nan, D.M. Han, M. Cui, M.J. Yang, L.M. Pan, J. Hazard Mater. 133 (2006) 257.
[17] M.B.J.G. Freitas, M.K. de Pietre, J. Power Sources 143 (2005) 270.
[18] Y.Q. Xia, G.J. Li, Waste Manage. 24 (2004) 359.
[19] A.L. Salgado, A.M.O. Veloso, D.D. Pereira, G.S. Gontijo, A. Salum, M.B. Mansur, J. Power Sources 115 (2003) 367.
[20] M. Bhattacharya, J-R. Chen, Appl. Econ. 41 (2009) 2169.
[21] D. Caton, M. Perloff, Modern Ind. Org. (2005).
[22] W.D.S. Reekie, Afr. J. Econ. 52 (1984) 223.
[23] M.A. Fuss, Eur. Econ. Rev. 15 (1981) 123.
[24] D.G. Rhys, J. Ind. Econ. 25 (1977) 313.
[25] H.A. Barrett, O. Borkiewicz, M.P.S. Krekeler, J. Power Sources 196 (2011) 508.
[26] M.P.S. Krekeler, Waste Manage. 28 (2008) 2061.
[27] M. Valko, H. Morris, M.T.D. Cronin, Curr. Med. Chem. 12 (2005) 1161.
[28] S.J. Stohs, D. Baggi, Free Radical Bio. Med. 18 (1995) 321.
[29] B.P. Lanphear, R. Horung, J. Khoury, K. Yolton, P. Baghurstl, D.C. Bellinger, R.L. Canfield, K.N. Dietrich, R. Bornschein, T. Greene, S.J. Rothenberg, H.L. Needleman, L. Schnaas, G. Wasserman, J. Graziano, R. Roberts, Environ. Health Persp. 113 (2005) 894.
[30] J.L. Pirkle, R.B. Kaufman, D.J. Brody, T. Hickman, E. Gunter, D.C. Paschal, Environ. Health Persp. 106 (1998) 745.
[31] B.P. Lanphear, T.D. Matte, J. Rogers, R.P. Clickner, B. Dietz, R.L. Bornschein, P. Succop, K.R. Mahaffey, S. Dixon, W. Galke, M. Rabinowitz, M. Farfel, C. Rohde, J. Schwartz, P. Ashley, D.E. Jacobs, Environ. Res. 79 (1998) 51.
[32] L.M. Conroy, R.M. Menezes-Lindsay, P.M. Sullivan, S. Cali, L. Forst, Arch. Environ. Health 51 (1996) 95.
[33] R.A. Goyer, Environ. Health Persp. 100 (1993) 177.
[34] L. Maderova, J.J.C. Dawson, G.I. Paton, Water Air Soil Poll. 210 (2010) 63.
[35] E. Denkhaus, K. Salnikow, Crit. Rev. Oncol. 42 (2002) 35.
[36] T.P. Coogan, D.M. Latta, E.T. Snow, M. Costa, CRC Crit. Rev. Toxicol. 19 (1989) 341.
[37] D.J. Spry, J.G. Wiener, Environ. Poll. 71 (1991) 243.
[38] D.M. Ditoro, J.D. Mahony, D.J. Hansen, K.J. Scott, M.B. Hicks, S.M. Mayr, M.S. Redmond, Environ. Toxicol. Chem. 9 (1990) 1487.
[39] A.M. Scheuhammer, Environ. Poll. 46 (1987) 263.
[40] N.E. Selin, Annu. Rev. Environ. Resour. 34 (2009) 43.
[41] D.W. Boening, Chemosphere 40 (2000) 1335.
[42] M.F. Wolfe, S. Schwarzbach, R.A. Suliaman, Environ. Toxicol. Chem. 17 (1998) 146.
[43] F. Slemr, E. Langer, Nature 355 (1992) 434.
[44] H.T. Ratte, Environ. Toxicol. Chem. 18 (1999) 89.
[45] I.J. Morgan, R.P. Henry, C.M. Wood, Aquat. Toxicol. 38 (1997) 145.