Journal of Applied Sciences

ISSN 1812-5654

science alert

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 9 (13): 2475-2479, 2009
ISSN 1812-5654

Human Exposure to Perfluorinated Compounds via Smoking and Second-Hand Smoke

Pablo J. Tseng
Department of Chemistry, University of Toronto, 80 St., George Street, Toronto, Ontario, M5S3H6, Canada

Abstract: The current study investigates the potential of human exposure to volatile fluorinated species such as fluorotelomer alcohols and acrylates as well as their non-volatile metabolites from direct or indirect inhalation of cigarette smoke. Using gas chromatography-mass spectrometry, it was observed that, there was no presence of exposure to fluorinated species via indirect inhalation of cigarette smoke, 36±4 ng of 8:2 fluorotelomer alcohol were collected and observed in the analysis of direct consumption of cigarettes. In the liquid chromatography tandem mass spectrometry analysis of the cigarette butt, wrapping paper and tobacco, there were no significant levels above background levels of non-volatile fluorinated compounds. 8:2 fluorotelomer alcohol is a compound that can degrade atmospherically and metabolically into the bioaccumulative and Potentially Toxic Perfluorooctanoic Acid (PFOA) and other metabolites. Direct consumption of cigarettes may be a source of exposure to PFCAs and other metabolites of the 8:2 FTOH.

Key words: Fluorinated compounds, cigarette, environment, health, toxicity

INTRODUCTION

First synthesized in the late 1940s by the electrochemical fluorination (ECF) process (Simons *et al*., 1949), perfluorocarboxylic acids (PFCAs) [$F(CF_2)_nCOO^-$], owing to their chemical stability (Key *et al*., 1997) and surface tension lowering properties (Szajdzinska-Pietek *et al*., 1994), have and continue to have many industrial applications in a variety of consumer products. Despite these favourable applications, however, PFCAs have been under recent scientific scrutiny owing to the discovery of their ubiquitous presence and persistence in the environment (Giesy and Kannan, 2002), accumulation in biological species (Martin *et al*., 2004) and potential toxicity (Lau *et al*., 2007). Direct sources of PFCAs include direct synthesis of PFCAs. Perfluorooctanoic acid for example, is extensively used industrially as an emulsifier for fluoropolymer synthesis. Indirect sources of PFCAs include the degradation of precursor compounds. Scientific endeavours are only beginning to discover the potential consequences of widespread usage of PFCAs and their precursors for the past half century.

The potential toxicity of PFCAs has been previously documented in the literature. Recent investigations of PFCAs in animals (Lau *et al*., 2004) have suggested that exposure to PFCAs, specifically the perfluoro-octanoic, nonanoic and decanoic acids (PFOA, PFNA and PFDA, respectively), is correlated with delayed physical development (Lau *et al*., 2004), depressed ability to gain weight (Butenhoff *et al*., 2004), peroxisome proliferation (Ikeda *et al*., 1985) which would indirectly lead to cancerous growths, as well as cardiac, circulatory and hormonal complications (Langley and Pilcher, 1985). As such, it would be important to investigate potential sources of exposure to these industrial chemicals.

Fluorotelomer Alcohols (FTOHs) are linear chained polyfluorinated alcohols that are employed as manufacturing intermediates for a variety of products (Kissa, 1994). It has been shown that FTOHs undergo atmospheric (Wallington *et al*., 2006), metabolic (Martin *et al*., 2005; Hagen *et al*., 1981) and microbial (Dinglasan *et al*., 2004; Wang *et al*., 2005a) degradation pathways that ultimately lead to their corresponding PFCAs. FTOHs are produced globally at an estimated rate (2000-2002) of 5000 to 6500 metric tons per year, of which an estimated 80% is directed toward polymeric applications (Telomer Research Program, 2002). FTOHs are generally employed as the precursors to the manufacturing of fluorinated compounds (Dinglasan-Panlilio and Mabury, 2006) and with such wide industrial applications it would be appropriate to investigate the incorporation of these compounds in daily consumer products.

The potential ill effects of cigarette smoking have been studied and documented in the literature. The World Health Organization and World Bank estimate that currently there are over one billion people engaged in smoking (World Health Organization, World Bank Group) and with such exposure, it would be of interest to relate exposure to smoking and the potential exposure to the industrial compounds such as PFCAs. This research describes studies that investigated the exposure to volatile precursors of PFCAs from direct and indirect inhalation of smoke and PFCAs present in the cigarette.

MATERIALS AND METHODS

This study was completed between March and June 2008 in Toronto, Ontario, Canada.

Chemicals: Three packs of cigarettes from a popular cigarette brand were purchased from different vendors in the Greater Toronto area. 4:2, 6:2, 8:2 and 10:2 fluorotelomer alcohol (FTOH) standards of >97% purity, perfluorohexanoic acid (PFHxA, 95%) and 2(perfluorooctyl)ethyl acrylate (8:2 fluorotelomer (FT) acrylate, 97%) were acquired from Oakwood Research Chemicals (West Columbia, SC). Perfluoroheptanoic acid (PFHpA, 99%) perfluorooctanoic acid (PFOA, 96%), perfluorononanoic acid (PFNA, 97%), perfluorodecanoic acid (PFDA, 98%) and perfluoro-undecanoic acid (PFUDA, 95%) were purchased from Aldrich Chemical Co. (Milwaukee, WI). The saturated telomer acid (8:2 FTCA) and the unsaturated telomer acids (6:2 and 8:2 FTUCA) were prepared according to Achilefu *et al.* (1995) to a purity of >95%. Sodium perfluoro-1-octane sulfonate (PFOS) and the stable isotope standards of $^{13}C_4$-PFOA, $^{13}C_5$-PFNA, $^{13}C_4$-PFOS, 8:2 $^{13}C_2$-FTUCA were provided by Wellington Laboratories (Guelph, ON). 2H,2H,3H,3H-perfluorodecanoic acid (7:3 telomer acid, 97%) was acquired from Synquest Co. (Alachua, Fl).

Simulation of direct inhalation of smoke: Direct inhalation of cigarette smoke was simulated by vacuum suction of the lit cigarette. The butt of the cigarette sample was connected to an Orbo Amberlite XAD-2 cartridge (100 mg) which, in turn, was connected to an in-house vacuum line at a pressure of -0.84±0.01 bars. The XAD cartridge was present in the set-up to trap target volatile fluorinated species (FTOHs and acrylates) and has been proven to be effective for these compounds in this endeavour (Dinglasan-Panlilio and Mabury, 2006). Each sample was deemed complete when the cigarette had burned to the butt of the cigarette; the vacuum system was turned off at that point in time. Cigarettes were consumed at a rate of 9±1 sec cigarette^{-1}. The rate was governed by the strength of the vacuum and consumed the cigarette evenly.

Simulation of indirect exposure to smoke: A modification of the purge and trap experimental design, as described by Dinglasan-Panlilio and Mabury (2006) was used in this experiment. A Nalgene vessel with a 7 mm diameter hole drilled at the bottom of the vessel to accommodate a cigarette was prepared. Vessel caps were drilled to accommodate an Orbo Amberlite XAD-2 cartridge (100 mg) and a septum needle. The cigarette sample was connected to vacuum suction as previously described, lit, immediately inserted into the hole in the bottom of the vessel until the butt fit snugly in the hole and allowed to burn to the butt. At that point, the vacuum was shut off and in-house carbon filtered air was continuously streamed through the bottle via the needle with escaping air passing through the XAD cartridge for a half an hour after consumption of the cigarette to ensure full air exchange within the bottle. A schematic of the experimental design for volatile compound analysis is show in Fig. 1.

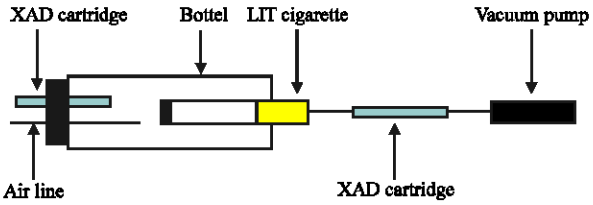

Fig. 1: Schematic diagram of the experimental analysis of volatile compounds

Headspace analysis of consumed cigarette: XAD cartridge contents were extracted twice with 2 mL of ethyl acetate each time. Extracts were combined and then transferred into GC sampling vials. The Hewlett-Packard 6890 gas chromatograph equipped with a 5793 inter mass spectrometer detector was used to analyze volatile analytes. The target analytes 4:2-10:2 FTOH acrylate and 8:2 FTOH were separated using a 30 m Zebron™ ZB-WAX column (0.25 mm i.d., 0.25 μm film thickness). The GC oven temperature was initially held at 60°C from 0-1 min, then ramped at a 5°C min^{-1} rate from 60-75°C, 10°C min^{-1} from 75-130°C and finally 50°C min^{-1} from 130-240°C. Helium was used as the carrier gas at a flow rate of 1 mL min^{-1} with pulsed splitless injection at an initial pressure of 20 psi at 220°C. Analytes were identified under positive chemical ionization mode in single ion monitoring mode. External calibration curves between 10 and 300 pg μL^{-1} for all analytes were used to quantify the concentrations of analytes. Linearity (r^2>0.99) was observed for the calibration curves. The limit of quantification was defined as the lowest standard to yield a signal to noise ratio of ≥10 which corresponded to the 10 pg μL^{-1} (10 parts per billion) standard for the analytes.

Unconsumed cigarette analysis: The cigarette butt, wrapping paper and tobacco of an unlit cigarette sample were analyzed separately. These samples were analyzed for the non-volatile PFCA analytes. The cigarette butts were removed from the rest of the cigarette at the filter and weighed on an analytical weighing balance. They were

then submerged for an hour in a 10 mL Milli-q 18 Ω water solution buffered at pH 9. The sample was then sonicated for 20 min at room temperature. After sonication, the sample was extracted according to the ion-pairing method outlined by Hansen *et al.* (2001). Samples were reconstituted in 50:50 methanol/water mixtures. The analysis of the wrapping paper and tobacco were analyzed in a similar fashion to the cigarette butts.

The Waters Acquity ultra performance liquid chromatography system (UPLC®) coupled to a Quattro micro™ high performance triple quadrapole mass-spectrometer (LC-MS/MS) in negative electrospray mode was used in analyze non-volatile analytes. Injection volumes were 25 µL and the flow rate was 360 µL min^{-1}. Chromatography was done on a Phenomenex Luna 2.5 µm C18(2)-HST column (50 mm in length, 2 mm internal diameter, 2.5 µm particle size) preceded by a C18 guard column (4.0 by 2.0 mm, Phenomenex, Torrance, CA). The mobile phase was a methanol/water mixture and the analytes buffered with 10 mM ammonium acetate and the analytes were separated using gradient conditions. An initial 60:40 methanol/water mixture was increased to 80:20 methanol/water over 6 min followed by a 2 min hold, before reverting to initial conditions. Target analytes in the aqueous analysis included perfluorohexanoate (PFHxA), perfluoroheptanoate (PFHpA), perfluorooctanoate (PFOA), perfluorononanoate (PFNA), perfluorodecanoate (PFDA), perfluoroundecanoate (PFUnA), 8:2 FTCA, 6:2 and 8:2 FTUCA and perfluorooctane sulfonate (PFOS).

Analyte sample concentrations were determined through internal calibration. The final concentration of each internal standard in each sample was 12.5 ng mL^{-1}. $^{13}C_4$-PFOA was used for PFHxA, PFHpA and PFOA, $^{13}C_5$-PFNA was used for PFNA, PFDA and PFUnA, 8:2 $^{13}C_2$-FTUCA was used for 6:2 and 8:2 FTUCA as well as 7:3 and 8:2 FTCA and $^{13}C_4$-PFOS was used for PFOS.

Quality control and assurance: QA/QC data included instrumental blanks, procedural blanks and at least triplicate analysis of sample sets. Recoveries of PFHxA to PFNA were from 86-95% while PFDA, PFUnA, PFOS, 8:2 FTUCA and 8:2 FTCA had recoveries between 60-70%. 8:2 FTOH was spiked into an empty aerated vessel and the system was allowed to purge for 30 min. The recovered percentage of 8:2 FTOH through headspace analysis was 77±3%. Experimental data, however, was unadjusted for recovery values.

RESULTS

Four cigarettes per pack were subjected to headspace analysis, while three cigarettes per pack were subjected to unconsumed cigarette analysis. A summary of the analytes targeted in this experiment and their chemical structure are provided in Table 1.

Table 1: Summary of the experimental target analytes

Headspace (indirect and direct inhalation) analysis	
4:2 fluorotelomer alcohol	$CF_3(CF_2)_3CH_2CH_2OH$
6:2 fluorotelomer alcohol	$CF_3(CF_2)_5CH_2CH_2OH$
8:2 fluorotelomer alcohol	$CF_3(CF_2)_7CH_2CH_2OH$
10:2 fluorotelomer alcohol	$CF_3(CF_2)_9CH_2CH_2OH$
2(perfluorooctyl)ethyl acrylate (8:2 acrylate)	$CF_3(CF_2)_7CH_2CH_2OC(O)CHCH_2$
Non-volatile analyte (unconsumed cigarette) analysis	
C_6 to C_{11} PFCA	$CF_3(CF_2)_{(4-9)}COOH$
8:2 fluorotelomer unsaturated acid (FTUCA)	$CF_3(CF_2)_6CFCHCOOH$
8:2 fluorotelomer saturated acid (FTCA)	$CF_3(CF_2)_6CF_2CH_2COOH$
6:2 fluorotelomer unsaturated acid (FTUCA)	$CF_3(CF_2)_4CFCHCOOH$
Perfluorooctananesulfonic acid (PFOS)	$CF_3(CF_2)_6CF_2SO_3H$

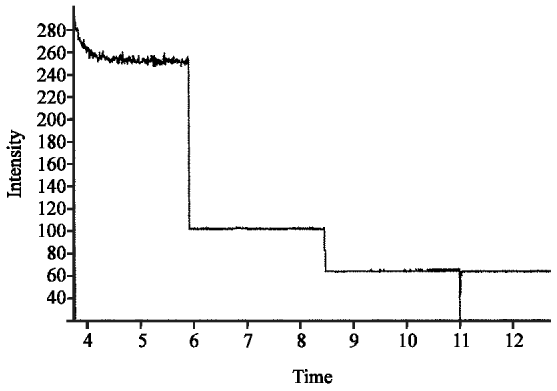

Fig. 2: Chromatogram of indirect inhalation sample (sample 1 of 4 of pack 1)

Indirect and direct exposure via inhalation: The indirect and direct inhalation exposure was determined based on the analysis of XAD cartridge beads that have been proven to be a suitable partitioning layer for fluorinated species (Dinglasan-Panlilio and Mabury, 2006). The analytes that were monitored in these analysis included 4:2, 6:2, 8:2 and 10:2 FTOH, as well as 8:2 FT acrylate. In the analysis of simulated indirect inhalation of cigarette smoke, there was no evidence of exposure to any of the monitored fluorinated species in the experiment (Fig. 2).

In the analysis simulated direct inhalation of cigarette smoke, there was evidence of the presence of 8:2 FTOH in all of the analyzed samples (Fig. 3). None of the other monitored volatile fluorinated species were detected.

The retention time of 6.75 min was the expected retention time of 8:2 FTOH for the employed GC method. The specific mass to charge ratio corresponding to 8:2 FTOH, 465, was then extracted to provide further evidence that the signal observed in the original chromatogram was that of a species with m/z of 465. A sample chromatogram

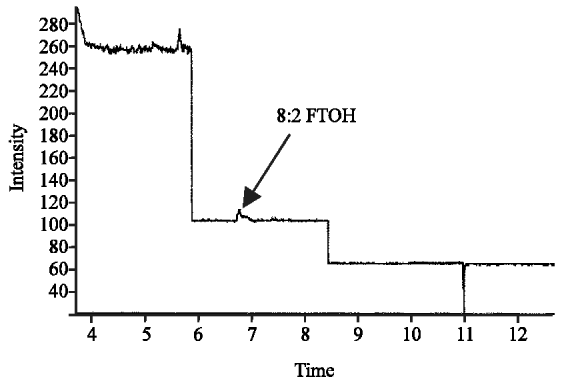

Fig. 3: Chromatogram of direct inhalation sample (sample 1 of 4 of pack 1)

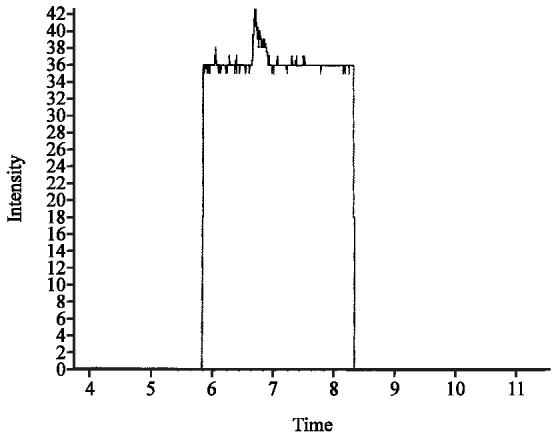

Fig. 4: Chromatogram of extracted ion 465-8:2 FTOH

is provided in Fig. 4. Quantification of the samples showed that 36±4 ng of 8:2 FTOHs were detected per cigarette.

Unconsumed cigarette analysis: The cigarette butt, wrapping paper and tobacco had an average mass of 0.043±0.005, 0.056±0.007 and 0.25±0.01 g, respectively. In the analysis of these parts of the cigarette, there was no evidence beyond those of background levels of non-volatile perfluorinated compounds present in these various parts of the cigarette.

DISCUSSION

Given the ubiquitous presence of fluorinated compounds in the environment and their wide applications in industry and consumer products, it was of interest to determine whether direct and indirect smoke exposure were sources of human exposure to volatile and non-volatile fluorinated compounds.

In the analysis of exposure to volatile fluorinated compounds, it was observed that there was no evidence of exposure via the evolution of the smoke from a burning cigarette. In the experimental set-up, cigarette smoke evolved in a highly contained (250 mL) vessel that was thoroughly purged with incoming air after the cigarette had been consumed. The only location of air removal from the vessel was through the XAD cartridge which would have trapped the targeted fluorinated compounds if any were present. Given that no detection of fluorinated species was made even within the small volume of the experimental set-up (Fig. 2), the risk of exposure to the monitored fluorinated compounds in this scenario would be insignificant. However, it was shown that exposure to 8:2 FTOH is possible from direct consumption of cigarettes, making indirect inhalation a possible route of 8:2 FTOH exposure upon breathing in the smoke released from smoker expiration. The detection of 8:2 FTOH is not surprising considering its widespread synthesis and industrial applications. The degradation of 8:2 FTOH to its metabolites such as 8:2 FTUCA and PFOA have been previously documented by Dinglasan *et al.* (2004) and Wang *et al.* (2005a, b). Given the proven metabolic degradation of 8:2 FTOH, it is possible that direct and indirect inhalation of cigarette smoke may be a source of exposure to these fluorinated compounds.

The degradation of 8:2 FTOH to PFOA other fluorinated metabolites is of concern considering the toxicological effects of PFOA on mammal systems. Liver enlargements, tumour induction and altered cycles in cell cycle control and apotosis in animal models (Lau *et al.*, 2007) have been documented. Effects on developmental and immuno-toxicology and hormonal and biochemical effects have also been observed and reported by Lau *et al.* (2007). The results of non-volatile fluorinated compounds present in the various components of a cigarette suggest that there is no significant exposure in comparison to background (ambient) levels. However, indirect exposure to these bioaccumulative, non-volatile fluorinated compounds (such as PFOA) can results from the biotransformation of 8:2 FTOH and their precursor compounds to the resulting PFCAs.

In conclusion, direct consumption of cigarettes is a potential exposure route to 8:2 FTOH, which has been shown and suggested to degrade into other more potentially toxic and bioaccumulative metabolites such as PFOA and other PFCAs. Indirect exposure to 8:2 FTOH from cigarette smoke is potentially experienced when inhaling the expired smoke of a smoker and not necessarily from the inhalation of smoke originating from a burning cigarette. Furthermore, exposure to the monitored non-volatile fluorinated compounds from the

cigarette butt, wrapping paper and tobacco does not exceed those of background concentrations and would not be a significant source of fluorinated compound exposure.

ACKNOWLEDGMENTS

The funds were drawn from the Gordon Fellowship, an academic scholarship awarded to the author. The author would like to thank the reviewers for constructive feedback.

REFERENCES

Achilefu, S., L. Mansuy, C. Selve and S. Thiebault, 1995. Synthesis of 2H, 2H-perfluoroalkyl and 2H-perfluoroalkenyl carboxylic acids and amides. J. Fluor. Chem., 70: 19-26.

Butenhoff, J.L., G.L. Kennedy, S.R. Frame, J.C. O'Connor and R.G. York, 2004. The reproductive toxicology of ammonium perfluorooctanoate (APFO) in the rat. Toxicology, 196: 95-116.

Dinglasan, M.J.A., Y. Ye, E.A. Edwards and S.A. Mabury, 2004. Fluorotelomer alcohol biodegradation yields poly-and perfluorinated acids. Environ. Sci. Technol., 38: 2857-2864.

Dinglasan-Panlilio, M.J.A. and S.A. Mabury, 2006. Significant residual fluorinated alcohols present in various fluorinated materials. Environ. Sci. Technol., 40: 1447-1453.

Giesy, J.P. and K. Kannan, 2002. Perfluorochemical surfactants in the environment. Environ. Sci. Technol., 36: 146A-152A.

Hagen, D.F., J. Belisle, J.D. Johnson and P. Venkateswarlu, 1981. Characterization of fluorinated metabolites by a gas chromatographic-helium microwave plasma detector-the biotransformation of 1H, 1H, 2H, 2H-perfluorodecanol to perfluorooctanoate. Anal. Biochem., 118: 336-343.

Hansen, K.J., L.A. Clemen, M.E. Ellefson and H.O. Johnson, 2001. Compound-specific, quantitative characterization of organic fluorochemicals in biological matrices. Environ. Sci. Technol., 35: 766-770.

Ikeda, T., K. Aiba, K. Fukuda and M. Tanaka, 1985. The induction of peroxisome proliferation in rat-liver by perfluorinated fatty acids, metabolically inert derivatives of fatty acids. J. Biochem., 98: 475-482.

Key, B.D., R.D. Howell and C.S. Criddle, 1997. Fluorinated organics in the biosphere. Environ. Sci. Technol., 31: 2445-2454.

Kissa, E., 1994. Fluorinated Surfactants: Synthesis, Properties, Applications. Marcel Dekker, Inc., New York.

Langley, A.E. and G.D. Pilcher, 1985. Thyroid, bradycardic and hypothermic effects of perfluoro-N-decanoic acid in rats. J. Toxicol. Environ. Health, 15: 485-491.

Lau, C., J.L. Butenhoff and J.M. Rogers, 2004. The developmental toxicity of perfluoroalkyl acids and their derivatives. Toxicol. Applied Pharmacol., 198: 231-241.

Lau, C., K. Anitole, C. Hodes, D. Lai, A. Pfahles-Hutchens and A. Seed, 2007. Perfluoroalkyl acids: A review of monitoring and toxicological findings. Toxicol. Sci., 99: 366-394.

Martin, J., D.M. Whittle, D.C.G. Muir and S.A. Mabury, 2004. Perfluoroalkyl contaminants in a food web from Lake Ontario. Environ. Sci. Technol., 38: 5379-5385.

Martin, J.W., S.A. Mabury and P.J. O'Brien, 2005. Metabolic products and pathways of fluorotelomer alcohols in isolated rat hepatocytes. Chem. Biol. Interact., 155: 165-180.

Simons, J.H., H.T. Francis and J.A. Hogg, 1949. The electrochemical process for the production of fluorocarbons. 2. The electrolysis of solutions of organic substances in liquid hydrogen fluoride. J. Electrochem. Soc., 95: 53-55.

Szajdzinska-Pietek E., S. Schlick and A. Plonka, 1994. Self-assembling of perfluorinated polymeric surfactants in water-electron-spin-resonance spectra of nitroxide spin probes in nafion solutions and swollen membranes. Langmuir, 10: 2188-2196.

Wallington, T.J., H.D. Hurley, J. Xia, D.J. Wuebbles and S. Sillman *et al*., 2006. Formation of $C_7F_{15}COOH$ (PFOA) and other perfluorocarboxylic acids during the atmospheric oxidation of 8:2 fluorotelomer alcohols. Environ. Sci. Technol., 40: 924-930.

Wang, N., B. Szostek, P.W. Folsom, L.M. Sulecki and V. Capka *et al*., 2005a. Aerobic transformation of C-14-labeled 8-2 telomer B alcohol by activated sludge from a domestic sewage treatment plant. Environ. Sci. Technol., 39: 531-538.

Wang, N., B. Szostek, R.C. Buck, P.W. Folsom and L.M. Sulecki *et al*., 2005b. Fluorotelomer alcohol biodegradation-direct evidence that perfluorinated carbon chains breakdown. Environ. Sci. Technol., 39: 7516-7528.