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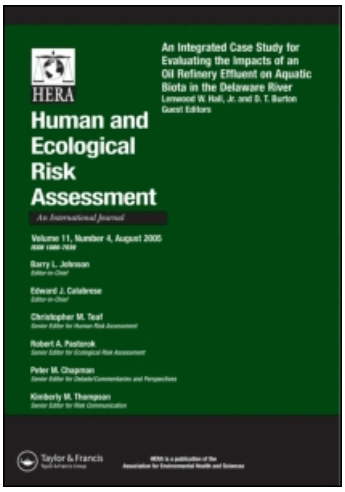

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Bonnie Ransom Stern [a]; Gustavo Lagos [b]
[a] Consulting in Health Sciences and Risk Assessment, BR Stern and Associates, Annandale, VA, USA [b] Mining Centre, Pontificia Universidad Católica de Chile, Santiago, Chile

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SCHOLARLY REVIEW

Are There Health Risks from the Migration of Chemical Substances from Plastic Pipes into Drinking Water? A Review

Bonnie Ransom Stern[1] and Gustavo Lagos[2]
[1]Consulting in Health Sciences and Risk Assessment, BR Stern and Associates, Annandale, VA, USA; [2]Mining Centre, Pontificia Universidad Católica de Chile, Santiago, Chile

ABSTRACT

Plastic pipes used to convey hot and cold drinking water are synthetic polymers containing numerous additives that enhance durability, impact strength, and toughness, and resist material degradation. Although some research studies have been conducted to evaluate the type and levels of chemical substances migrating from polymeric materials into drinking water, the potential adverse health effects associated with these compounds in potable water have not been described. This review evaluates the literature on the occurrence of regulated and unregulated substances in drinking water related to the use of plastic pipes, characterizes potential health hazards, and describes uncertainties associated with human health and exposure in need of further research. Of particular public health concern is the potential for sensitive populations to be exposed to short-term elevations in leachates during critical periods, and for co-occurring leachates targeting the same organ(s) and/or sharing a common mode of toxic action to have additive or synergistic effects. Contaminants are measured in the distribution system, not at the tap where human exposure actually occurs. For increased health protection, it is important to identify compounds that migrate from plastic pipes into drinking water and to better quantify human exposures and health hazards to these substances and their degradates.

Key Words: drinking water, plastic pipes, leachates, occurrence, public health.

INTRODUCTION

During the past two decades, the use of synthetic plastic pipes for conveyance of potable drinking water within the main water distribution system and in premise

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Address correspondence to Dr. Bonnie Ransom Stern, Consulting in Health Sciences and Risk Assessment, BR Stern and Associates, 4533 Pinecrest Heights Drive, Annandale, VA 22003-3535, USA. E-mail: brstern1@aol.com

plumbing[1] has been increasing, due mainly to a combination of corrosion resistance and low cost (Schweitzer 2000). All plastics contain polymeric materials manufactured from fossil fuels, primarily petroleum, and are produced at high temperatures via chemical extrusion processes (Schweitzer 2000). Each polymer tubing material carries the name of the base resin from which it is manufactured. Additives to the base resin aid in the manufacturing process and/or alter the chemical stability and mechanical properties. The specific composition of plastic pipes varies with the manufacturer.

Although thermoplastics have an advantage over metals in resisting corrosion, they have neither the physical strength nor ruggedness of metals (Schweitzer 2000). Therefore, polymeric materials also contain a variety of additives that are incorporated during manufacturing to enhance material durability, impact strength, and toughness and to resist degradation during processing and under field-use conditions (Sadiki *et al.* 1996; Sadiki and Williams 1999; Forsyth and Jay 1997; Schweitzer 2000; Laine and Vartiainen 2003). Organic and inorganic additives include stabilizers, antioxidants, lubricants, softeners, impact processing aids, impact modifiers, fillers, and coloring agents. Special pipe supports are often required and safety considerations may limit allowable temperatures, pressures, and installation locations (Schweitzer 2000). This review evaluates the literature on the occurrence of regulated and unregulated substances in drinking water related to the use of plastic pipes, characterizes potential health hazards, and describes uncertainties associated with human health and exposure in need of further research.

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METHODS

Multiple database sources were searched for data. These included PubMed, ToxNet, IRIS, ATSDR (Agency for Toxic Substances and Disease Register), USEPA (U.S. Environmental Protection Agency), California EPA, WHO (World Health Organization), and the ECB (European Chemicals Bureau). The World Wide Web was searched on Google. Key search terms were: plastic pipes, polymer materials, drinking water, leachates, and chemical occurrence for occurrence data and plastic pipes, polymer materials, leachates, health effects, toxicity, safety, and endocrine disruption for health effects data. A hand search of secondary references in relevant studies was also performed. In addition, several unpublished reports and abstracts of presentations from recent scientific meetings were made available by contacting the authors and requesting copies of these documents.

RESULTS

Polymeric Tubing Materials and Additives

Polymeric plastics used for drinking distribution in homes and buildings include polyethylene (PE), high density polyethylene (HDPE), medium density polyethylene (PEM), low density polyethylene (PEL), cross-linked polyethylene

[1]Service lines from water mains to buildings and drinking water pipes within these dwellings.

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(PEX), polyethylene of raised temperature resistance (PE-RT), aluminum crosslinked polyethylene (Al/PEX), polypropylene (PP), unplasticized polyvinyl chloride (PVC), and chlorinated polyvinyl chloride (CPVC). The use of these materials resins alone or in combination in drinking water systems varies widely among developed and developing countries (Trew *et al.* 1990). There is a trend toward the use of PE in Europe, whereas chlorinated resins are common in the United States (Trew *et al.* 1990; Brocca *et al.* 2002).

Heat stabilizers have included metal mixtures of lead (Pb), calcium (Ca), barium (Ba) and/or cadmium (Cd) (Al Amack *et al.* 2000). Organotins currently dominate the U.S. market for this purpose (Tullo 2000). In Europe today, cadmium/zinc (Cd/Zn) stabilizers are preferred over those of Ba/Zn, Ba/Cd, and organotins; however, lead may still exist in polymeric plumbing systems because of its past uses in the manufacture of plastic pipe (Tullo 2000).

Organotins also function as antioxidants; the most common ones are tin mercaptides and tin carboxylate*s* (Schweitzer 2000; Sadiki *et al.* 1996). Processing aids or impact modifiers include acrylic compounds such as methyl methacrylate-butadiene-styrene and acrylonitrile-butadiene and their mixtures (Fayt and Teyssie 1989) and more recently, fatty esters including acid-based derivatives and alcohols (*e.g.*, glycerol) (Tullo 2000). Solvent cements, usually with *a priori* application of primers, are the usual form of joining PVC and CPVC pipe segments due to low cost and ease of use (Schweitzer 2000). Traditional solvents are acetone, methyl ethyl ketone, tetrahydrofuran, and cyclohexanone. More recently reformulated solvent cements include low volatile organic compounds (VOC), such as dimethyl-2-piperidone, N-methyl pyrrolidone, di-methyladipate, alkyl-substituted naphthalene, and cylcopentanone; however, the extent of their use is unknown (Reid 2006).

For PE pipes, additives include higher olefins such as propylene, butylene, 4-methyl-pentene and vinyl acetate, antioxidants such as hindered phenols, butylated hydroxytoluenes (BHT), aromatic amines, phosphates and thioesters (Tullo 2000; Brocca *et al.* 2002); Processing aids include aluminum alkyd complexes, titanium halides, chromium trioxide (Sundberg 2006), lubricants, and waxes. The crosslinking of PE to form PEX involves high-temperature processing such as silane vulcanization, and the co-occurrence of peroxide oxidizing agents, such as di-tert-butylperoxide. Improvements in the density of PEX may occur by the addition of a co-extruded layer of ethylene vinyl alcohol as an antioxidant and/or via welding of a narrow thin strip of aluminum to the extruded plastic (Sundberg 2006). These substances, added during the manufacturing process, are only a subset of the constituents of polymeric materials that may be used, depending on the methods employed to synthesize the polymers.

Leaching and Permeation

All materials in water distribution systems leach substances into drinking water (NAS 2006), resulting in contamination of water with additive residues, degradation products, and transformation by-products that occur via reaction with the substances used to treat drinking water. Processes resulting in migration include corrosion, dissolution, diffusion, and detachment (NAS 2006). Indirect effects on internal water quality may include taste and odor changes, as well as increased chlorine demand

that can reduce residuals in the distribution system and degrade the microbial quality of drinking water (Haas *et al.* 2002).

Permeation by substances external to pipes and nonmetallic joints may compromise the structural integrity of materials and allow contaminant to move from the external environment into drinking water (NAS 2006). Research indicates that permeation, when it occurs, is generally associated with plastic pipes and with chemical solvents such as benzene, toluene, ethylbenzene, and xylene (BTEX) and other hydrocarbons associated with oil and gasoline (*ibid*). These volatile organic compounds (VOC) can readily diffuse through plastic pipe and migrate into water within the pipe. Holsen *et al.* (1991) have reported permeation incidents in connection with plastic piping materials at abandoned industrial sites, near bulk chemical storage tanks and electroplating facilities, as well as at residential sites (*e.g.*, adjacent to or near storage tanks at service stations or dry cleaning operations). If sustained, contact with these VOCs may permanently degrade the integrity of the pipes.

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Occurrence Data

Polyethylene (PE) polymers

Research studies conducted with various types of PE polymer materials have identified the presence of a variety of substances that have leached from the piping under differing experimental conditions. In Skjevrak *et al.* (2003), the study was designed to identify and quantify VOC concentrations leaching into water in unused pipe segments with different base resins and from different manufacturers, prior to potential impacts of use and aging. Three successive tests of 72 h each were performed on each sample (Table 1). The findings demonstrated that organic components of polymerized pipes, including aromatic hydrocarbons, terpenoids, and phenolic derivatives, can migrate into the drinking water, although the nature and concentrations of these leachates varies depending on pipe matrix and additives.

Laine and Vartiainen (2003) collected 1-liter samples from the terminus of a drinking water PE-pipeline. Reference samples were taken from dissolved PE-pipe. The samples were extracted, dried, and re-dissolved. Analysis was made using Liquid Chromatography-Mass Spectrometry (LC-MS) because both methods have been shown to be powerful and reliable tools for characterization of polymer additives (Laine and Vartainen 2003). Only the presence or absence of antioxidants was determined; studies on the concentrations of antioxidants and their degradates are currently in progress. Four different antioxidants were identified in the PE-extract and 3 of them were found in the water samples (Table 2).

Koch (2004) monitored the occurrence of organic compounds in water in a series of PEX, Al/PEX, and PE pipe segments from different manufacturers; concentrations were not measured (Table 3). The presence of MTBE, ETBE, and tert-butanol in water was attributed by the study author to the degradation of the antioxidant di-tert-butylperoxide. Not all compounds were detected in all pipe brands of the same polymeric material, demonstrating the variability associated with polymers synthesized by different manufacturing processes.

Hametner (1999) studied the migration into drinking water of phenolic antioxidants used to stabilize polypropylene (PP) pipe. The low molecular degradation product, 2,4-di-tert-butyl phenol, was detected in aqueous extracts much more

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Table 1. VOCs migrating from HDPE, PEX, PVC pipe segments into water (Skjevrak *et al.* 2003).

Polymer material	Component class	Chemicals	Concentration range (ng/L)	Comments
HDPE (Seven different pipe brands)	Antioxidants/ By-products	2,6 di-tert-butyl- benzoquinone, 2,4-di-tert-butyl phenol; 4-methyl-2-6-di-tert-butyl-phenol	400–5180	Migration of 2,4-di-tert-butyl phenol from pipes to water predominated, ranging from 20–5000 ng/l
	Esters	Butyl, ethyl, hexyl acetates, hexanoates, octanoates; butanoate; ethyl decadienoate; 2,2,4-trimethyl-1, 3-pentanediol diisobutyrate (2,2,4-TPD)	10–710	
	Aldehydes	Nonanal; decanal	40–950	
	Ketones	2-decanone, -undecanone, dodecanone	50–300	
	Terpenoids	Limonene, alpha terpinolene, delta carene	10–80	
	Aromatic hydrocarbons	BTEX, styrene, propyl benzene, trimethyl benzenes, naphthalene,	220–1390	
PEX (Two different pipe brands)		Methyl tertiary butyl ether (MTBE)	33500–47600	
		Tert-butanol	510–580	
		4-butoxy phenol	Not Detected (ND)	
		5-methyl-2-hexanone	660–870	
		Ionol	+	
		Mesityl oxide	ND	
		Tert-butyl isobutyl ether	ND	
		Unidentified VOCs	++	
PVC (Two different pipe brands)	Aldehydes	Hexanol, octanol, nonanol, decanol	Trace amounts of hexanol, octanal; Conc. of nonanol and decanol ranged from ≤170 to ≤289	Quantitative data not shown

Table 2. Occurrence of antioxidant leachates in PE pipeline (Laine and Vartainen 2003).

Trade name	CAS #	PE extract	Water	Preferred name
Irgafos 168	31570-04-4	+	+	Phosphite stabilizer, (tris 2,4-di-tert-butylphenyl)phosphite;
Irganox 1010	6683-19-8	+	+	Hindered phenol, antioxidant (terakis-(3-(4-hydroxy-3,5-di-tert-butylphenyl) propionyloxymethyl) methane)
Irganox 1330	1709-70-2	+	+	Hindered phenol, antioxidant (1,3,5-trimethyl-2,4,6-tris(3,5-di-tert-butyl-4-hydroxybenzyl)benzene)
Naugard xL-1	70331-94-1	+	−	Hindered phenol, antioxidant (2,2′-oxamidobis(ethyl 3(3,5-di-tert-butyl-4-hydroxybenzyl)benzene)

frequently than high molecular phenols. Alkali water extracted greater amounts of phenols whereas acidic drinking water showed no effect. Thermal load (*i.e.*, increasing the water temperature from 23°C to 60°C) also led to a significant increase of extractable phenols, and total organic carbon (TOC).

Polyvinyl chloride (PVC) and chlorinated polyvinyl chloride (CPVC) polymers

Few studies available in the open literature comprehensively characterize the leaching of monomers and/or additives from PVC and CPVC polymer materials. "Early-era"[2] PVC potable water pipes tended to leach vinyl chloride monomer (VCM) into drinking water. Following the scientific evidence demonstrating that this monomer was carcinogenic in both humans and animal models, new guidelines limiting the amount of vinyl chloride residues permitted in PVC pipes were established by the National Sanitation Foundation (NSF) in 1976. As a result, U.S. manufacturing processes were modified to include a process (separate steam-stripping) intended to remove almost all residual monomer. Similarly, the Canadian Standards Association's standard for all plastic pipes was revised in 1990 to include a leaching test for VCM from PVC pipes (Health Canada 2008). The European Union has set standards for the amount of VCM in materials made of PVC that will come into contact with food or drinking water, and a standard test method has been specified to determine the levels of the leachates from plastic pipes used to transport water intended for human consumption (WHO 2006).

However, pipes manufactured prior to the implementation of the new manufacturing process remain in use in many public water systems and may continue to leach VCM into drinking water. Degradation associated with the age of the tubing and/or predisposing environmental conditions such as high temperatures (Al-Malack and Sheikheldin 2001) may increase the degree to which vinyl chloride residues migrate

[2]Manufactured prior to 1977.

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Table 3. Organic compounds detected in PEX, Al/PEX or PE pipes (Koch 2004).

Compound class	Chemical	Polymer material
Ether	2,2,5,5-Tetrahydrofuran	PEX, Al/PEX, PE
	Methyl-*tertiary*-butyl ether (MTBE)	PEX, Al/PEX
	Ethyl *tert*-butyl-ether (ETBE)	PEX, Al/PEX, PE
Alcohol	2-Methyl-2-Propanol (tert-Butanol)	PEX, Al/PEX
Aldehyde/Ketone	2-Propanone (Acetone)	PEX, Al/PEX
Aromatic VOCs	Toluene	PEX, Al/PEX, PE
	Benzene	
Other	Di-*tert*-Butylperoxide	PEX

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into water. For example, the Kansas Department of Health and Environment (KDHE 1998) conducted a systematic survey of 125 rural drinking water distribution systems using PVC pipe manufactured before 1977. Sampling was conducted between June and October (the months expected to have the warmest water temperatures). The results showed that almost 10 percent of the systems had levels of vinyl chloride exceeding the USEPA action level of 2 ppb (KDHE 1998) and attributed to leaching. Al-Malack and Sheikheldin (2001) reported leaching of VCM from locally manufactured PVC pipes (Saudi Arabia) that were exposed to ultraviolet (UV) radiation for up to 30 days. At the end of the exposure period, VCM concentrations also exceeded USEPA's Maximum Contaminant Level (MCL).

VCM is not usually monitored in drinking water because it breaks down into chlorinated by-products such as chloroacetaldehyde and chloroacetic acid via reactions with chlorine already present in the water for disinfection purposes. In developed countries, it is also assumed that VCM is unlikely to be present if the PVC polymer material has been manufactured and tested according to product specification (WHO 2004). Ando and Sayato (1984) have reported that VCM could only be detected by using a special apparatus that prevented the volatilization of VCM and increasing the surface area of the pipe wall in contact with the water. This latter condition is normally high in premise plumbing due to the smaller diameters of pipes in service lines and households as compared with those in central mains. Other predisposing factors for VCM leaching include warmer water temperatures and low or intermittent flow rates, also characteristic of premise plumbing. It should also be noted that measurement of chemical substances in drinking water is rarely conducted in premise plumbing or at the tap unless there are consumer complaints about water quality; otherwise it is usually confined to central water distribution systems (NAS 2006).

Plastic pipe manufactured in less-developed countries, which do not have the comprehensive regulatory environment of developed nations, may contain substances that have been banned in developed countries. Al-Malack (2001) studied the effect of water quality parameters on the leaching of lead and other metal heat stabilizers from PVC drinking water pipes manufactured in Saudi Arabia and aged 27 months (Table 4). For all metals, increasing the duration of exposure with the pipe walls increased metal migration from pipes. Lead and tin exhibited a biphasic response:

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Table 4. Effects of water parameters on leaching of metals in PVC pipe (Al-Malack 2001).

Metal/Water quality parameter	Duration of exposure to pipe (0 to 48 h)	Water pH (5–9)	Water temp. (25°C and 45°C)	Total dissolved solids (TDS) (2–2670 mg/L)	Exposure to Ultraviolet (UV) radiation (12 h to 14 d)
Lead (Pb)	↑Leaching, 0.43 at 10 h to 0.78 mg Pb/L at 48 h	↑Leaching at pH = 5, no change at pH 7 to 9	No change	↑Leaching (0.5 to 1.2 mg Pb/L)[1]	↑Leaching with ↑ duration (0.12 to 0.8 mg Pb/L)
Tin (Sn)	↑Leaching, 0.2 at 10 h to 0.31 mg Sn/L at 48 h	↑Leaching at pH = 5, little change at pH 7 to 9	↑Leaching, + 42% change	↑Leaching (0.4 to 2.6 mg Sn/L)[1]	↑Leaching, (0.08 to 0.11 mg Sn/L)
Cadmium (Cd)	↑Leaching, <0.05 at 8 h to 0.3 mg Cd/L at 48 h	↑Leaching with ↓ pH at pH 6 to 9	No change	↑Leaching. (0.07 to 0.124 mg Cd/L)	↑Leaching, (0.002 to 0.01 mg Cd/L)
Barium (Ba)	↑Leaching, 0.11 at 8 h to 0.42 mg Ba/L at 48 h	↑Leaching with ↓ pH at pH 5 to 9	↑Leaching, + 85% change	↑Leaching ,(0.067 to 0.224 mg Ba/L	↑Leaching, (0.001 to 0.01 mg Ba/L)
Calcium (Ca)	↑Leaching, 45 at 8 h to 49 mg Ca/L at 48 h	↑Leaching, with ↓ pH at pH 5 to 9	↑Leaching, + 29% change	↑Leaching, (56 to 4881 mg Ca/L)	↑Leaching, (1.1 to 1.7 mg Ca/L)

Concentrations extrapolated from Figure 3 of Al-Malack (2001); all other values given in the text.

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the diffusion rate at the start of the study, attributed to surface migration, was greater than that at the end of the study, attributed to leaching from the pipe matrix. Decreasing pH was associated with an increase in migration for all five metals (barium cadmium, calcium, lead, tin) studied. Elevating the water temperature from 35°C to 45°C increased tin, barium, and calcium concentrations but had no effect on water levels of lead or cadmium. A positive association for all metals was also seen with an increase in total dissolved solids (TDS). Increasing duration of exposure to ultraviolet (UV) radiation over a 14-day period demonstrated that UV penetration to about 50% of the pipe thickness occurred at some locations and levels of metals in water increased over time. The effect of UV-radiation was attributed to combined effects of both heat and light. Overall, the magnitude of the changes was greatest for lead and observed concentrations in water were significantly greater than the Action Level. Significant increases were also observed with tin, and to a lesser extent, with cadmium and barium. Calcium concentrations were only affected by the level of TDS.

Several studies have investigated the leaching into drinking water of organotins used as antioxidants in PVC and CPVC pipes. Sadiki *et al.* (1996) tested raw and treated water samples and tap water samples for analysis of organotin compounds in recently installed PVC pipe. Methyltin and dimethyltin at concentrations ranging from 0.5 to 257 ng tin (Sn)/L and 0.5 to 6.5 ng Sn/L, respectively, were detected in approximately 45% of the homes tested. In a follow up study, organotin compounds, primarily methyltins and butyltins, at concentrations up to 22 ng Sn/L and 43.6 ng Sn/L, respectively, were detected in water samples from six Canadian water distribution systems. Water samples from PVC pipe segments containing organotin compounds were analyzed in the laboratory and the results were consistent with the organotin patterns found in the distribution system samples (Sadiki *et al.* 1996). The study authors concluded that their findings confirm the presence of both methyl- and butyltins as stabilizing agents in drinking water PVC pipes used in Canada.

Forsyth *et al.* (1993) examined the extraction of butyltins in PVC rigid pipe. Concentrations of butyltin ranging from 0.9 to 5985 μg/g were detected in potable water pipe samples. Forsyth and Jay (1997) performed a similar study with CPVC pipe, with water temperatures at either 24°C or 65°C. In samples collected under high-temperature conditions, monobutyltin and dibutyltin concentrations reached 19.8 and 197 μg Sn/g pipe, respectively. Repetitive extraction experiments demonstrated that organotin levels initially decreased rapidly and then much more slowly, suggesting that long-term leaching from new CPVC delivery systems was likely to occur. The study authors concluded that long-term studies in residential housing were needed to examine the time decay of organotins with increasing age of CPVC tubing (Forsyth and Jay 1997). Considerable variability in leachate levels occurred among CPVC pipes obtained from different manufacturers.

Health Hazards of Chemicals Known to Leach from Plastic Pipes

Existing information on the known health hazards associated with exposure to drinking water leachates from plastic pipes are summarized in Table 5. Although some data are available from human studies or case reports, the majority of information comes from studies in animal models such as rats and mice. This review is

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Table 5. Summary of health effects of chemicals known to leach from polymeric pipes.

Chemical group/ Chemical of concern	Target organ of systemic toxicity	Reproductive/ Developmental toxicity	Genotoxicity/ Carcinogenicity	References/ Comments
Aromatics				
Benzene	CNS, hematopoietic (↓ RBC; anemia, bone marrow); immune system (humans, rodents)	Fetotoxicity: ↓ growth; ↑ skeletal variants; abnormal blood system development (rodents)	Genotoxic (humans, rodents)	USEPA (2002); ATSDR (2005a) IARC (1987)
			Known human carcinogen (IARC, USEPA)	
Toluene	CNS (humans, rodents); kidney and liver (rodents)	Reproduction: ↑ spontaneous abortions; Fetotoxicity: ↓ growth; neurodevelopment (rodents)	Not genotoxic Clastogenic	USEPA (2005); ATSDR (2000); IARC (1999)
			Insufficient data to assess human carcinogenicity (IARC, USEPA)	
Ethylbenzene	CNS (humans, rodents); kidney and liver (rodents)	Fetotoxicity: neurodevelopment (rodents)	Not genotoxic	USEPA (2000); ATSDR (1999b); IARC (2000)
			Possible human carcinogen (IARC) Insufficient data to assess human carcinogenicity (USEPA)	
Xylenes	CNS (humans, rodents); kidney and liver (rodents)	Fetotoxicity: ↑ fetal deaths, ↓ growth, ↑ skeletal abnormalities; Development neurobehavioral effects (rodents)	Not genotoxic	USEPA (2002c); ATSDR (2005e), IARC (1999)
			Insufficient data to assess human carcinogenicity (IARC, USEPA)	

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Styrene	CNS, PNS, hearing loss (humans, rodents); liver (rodents)	Reproduction: Neuroendocrine (humans, rodents)	Genotoxic Possible human carcinogen (IARC); not Classified by USEPA	ATSDR (1992); IARC (2002); Luderer *et al.* (2004)
Trimethyl Benzenes	CNS (humans, rodents); kidney and liver (rodents)	Not known	Genotoxicity not known Not classified for carcinogenicity	USEPA (1995)
Vinyl Chloride	CNS, immune, liver (humans, rodents);	Reproduction: sperm, testes effects (rodents)	Genotoxic Known human carcinogen (IARC, USEPA)	USEPA (2000a); ATSDR (2006b); IARC (1979)
PAH				
Naphthalene	Blood system (hemolytic anemia); eyes (cataracts) (humans, rodents);	Blood system (hemolytic anemia) (humans);	Not genotoxic Possible human carcinogen (IARC), under review by USEPA	USEPA (2002); ATSDR (2005d); IARC (2002)
Ethers/Alcohols				
2,2,5,5-Tetrahydrofuran	Kidney and liver (rodents)	Not likely	Not genotoxic Not classified for Carcinogenicity	USEPA (1995)
Methyl-tert-butyl ether (MTBE)	CNS (humans, rodents) kidney, liver (rodents)	Not likely	Not genotoxic Not classifiable (IARC, USEPA)	USEPA (2007c); ATSDR (1996); IARC (1999)

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Table 5. Summary of health effects of chemicals known to leach from polymeric pipes. *(Continued)*

Chemical group/ Chemical of concern	Target organ of systemic toxicity	Reproductive/ Developmental toxicity	Genotoxicity/ Carcinogenicity	References/ Comments
Ethyl tert-butyl-ether (ETBE)	CNS (humans, rodents) kidney and liver (rodents)	Not likely	Based on structure-activity, Not likely to be genotoxic	ATSDR (1996)
2-Methyl-2-Propanol (Tert-Butanol)	CNS (humans, rodents); kidney and liver (rodents);	Not known	Not genotoxic Insufficient data to assess human carcinogenicity (USEPA)	USEPA (2007a,b)
Cyclo-hexanone	CNS, kidney, and liver (rodents)	Not known	Not mutagenic Insufficient data to assess human carcinogenicity (USEPA)	USEPA (1993)
Ketones				
Acetone	CNS (humans); kidney and liver (rodents)	Not known	Not genotoxic Insufficient data to assess human carcinogenicity (USEPA)	USEPA (2003)
Anti-Oxidants/ Alkylphenols				
2,6 di-tert-butyl-benzoquinone	—	—	—	Alkyphenyl derivative No data located in the literature
2,4-di-tert-butyl phenol;	—	—	—	Alkylphenol No data located in the literature

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4-methyl-2-6-di-tert-butyl-phenol	Kidney, liver, blood system (↓ clotting, ↑ hemorrhage) (rodents)	Development: neurobehavioral (rodents)	Not genotoxic	USEPA (1986); IARC (1986)
			Not classified for Carcinogenicity	
Phenol,2.4-bis(dimethyl ethyl)phos-phite	—	—	—	Alkyphenyl derivative; no data located in the literature
Benzene propanoic acid,	—	—	—	No data located in the literature
Phenol	CNS (humans, rodents); blood system (anemia, bone marrow, methemoglobinemia), kidney and liver (rodents)	Fetotoxicity: ↓ growth, ↓ wts of some reproductive organs; altered skeletal development (rodents)	Positive and negative genotoxicity	USEPA (2002); ATSDR (2006a); IARC (1999)
			Insufficient data to assess human carcinogenicity (IARC, USEPA)	
Metals				
Lead	CNS, PNS, hearing and vision damage, hypertension (humans, rodents);	Reproduction: ↓ sperm count, ↑ spontaneous abortion (humans); Development: brain damage, cognitive dysfunction, delayed development, neurobehavioral effects, hearing loss, blood effects; delayed sexual maturity; liver, kidney, (humans, rodents),	Genotoxic	USEPA (2005); ATSDR (2005c); IARC (2006)
			Inorganic lead: probable/likely human carcinogen (IARC, USEPA)	

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Table 5. Summary of health effects of chemicals known to leach from polymeric pipes. *(Continued)*

Chemical group/ Chemical of concern	Target organ of systemic toxicity	Reproductive/ Developmental toxicity	Genotoxicity/ Carcinogenicity	References/ Comments
Cadmium	Kidney, lung (humans, rodents); central nervous system (rodents)	Reproduction: ↓ fertility; Fetotoxicity	Mixed genotoxicity	USEPA (2007); ATSDR (1999a); IARC (1996)
		Effects on some male reproductive organs, ↓ birth wt., skeletal malformations; Development: neurobehavioral (rodents)	Probable/likely human carcinogen (IARC, USEPA)	
Barium	Kidney, blood (hypertension), lung (humans, rodents)	Reproduction: ↓ litter size (rodents); Development: ↓ birth wt. (rodents)	Not genotoxic	USEPA (2005); ATSDR (2005b)
			Not likely to be an oral human carcinogen (USEPA)	

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Organotins				
Tributyltins (TBT)	CNS, blood, endocrine, liver, kidney (rodents)	Reproduction: ↑ spontaneous abortions, maternal hormonal changes; Fetotoxicity: ↑ fetal & postnatal deaths, ↓ birth wts, external/skeletal malformations; changes in wt/structure of some male reproductive organs, Development: ↓ sperm counts/motility; neurotoxicity, endocrine effects, developmental delays, cognitive deficits, neurobehavioral, immunotoxicity (rodents)	Positive and negative genotoxicity, limited data	ATSDR (2005c);
			Insufficient data to assess human carcinogenicity (IARC, USEPA)	
Dibutyltins (DBT)	Liver, kidney, blood, endocrine (rodents)	Reproduction: ↑ spontaneous abortions; Fetotoxicity: external/skeletal malformations, Development: neurotoxicity, immunotoxicity (rodents)	Not known	ATSDR (2005c); Nielson and Rasmussen (2004)
Monobutyltins (MBT)	Liver (rodents)	Not known (limited data)	Not known	ATSDR 2005c,

intended to characterize potential health hazards and identify target organs of toxicity. No exposure-effects assessment has been conducted, due to the limited data on the drinking water occurrence of polymeric tubing leachates.

Leachates that are potential endocrine-disrupting compounds are presented in Table 6. Endocrine disruptors are exogenous substances that alter the functions of the endocrine system by mimicking, enhancing, or inhibiting the actions of hormones in the body. Endocrine disruption is not considered a toxicological endpoint *per se* but a functional change that may lead to adverse health outcomes by interfering with metabolic, reproductive, developmental, homeostatic, or other essential biological processes (USEPA 1997; EC 2000). Endocrine-active compounds are a priority public health concern for national and international regulatory agencies and public health organizations.

All identified substances presented in Table 5 have the potential to cause acute ocular, dermal, respiratory, and/or gastrointestinal irritation (HSDB 2008). A large number of compounds are classified as liver, kidney, and nervous system toxicants and are known or suspected to cause reproductive and/or developmental abnormalities. Although the data are insufficient to assess the potential human carcinogenicity of most leachates, benzene and vinyl chloride are classified as known human carcinogens and ethylbenzene, styrene, lead, and cadmium are considered to be likely or probable human carcinogens (Table 5).

In EU countries, drinking water monitoring is required for six leachates with known or suspected evidence of endocrine-disrupting activity (Table 6), including tributyl tin. Mammalian studies have demonstrated that tributyl tins are rapidly metabolized *in vivo* to dibutyl and monobutyl tins (ATSDR 2006c). Therefore, the potential endocrine-disrupting effects of tributyl tins may be due to the biological activities of these metabolites, which are also the organotin species used as stabilizers in polymeric materials. Organotin chlorides are also formed *in vivo* via gastric hydrolysis when the stabilizers are ingested (Farr and Murphy 2005). At present, there is no requirement in the United States for drinking-water monitoring of either tributyl tins or its substituted forms.

Taste and Odor

Taste and odor have historically been considered organoleptic properties of potable water indicative of aesthetic or secondary characteristics of drinking water quality (USEPA 1991). More recent drinking water recommendations for protection of public health include evaluation of taste, odor, turbidity, color, total organic carbon (TOC), and chlorine demand (European Communities 2000). These assessments have been recommended because of concerns that alterations in secondary drinking water characteristics are indicative of the presence of chemical or biological substances associated with human health effects (NAS 2006). In a study of drinking water odor and taste complaints in the United Kingdom, Rogers *et al.* (2004) noted that components of plastic plumbing pipes that leach chemicals having the potential to affect taste and odor included the following: antioxidants used for PVC, PE, and PP fittings, reaction products formed from the interaction of chlorine with residues or constituents of the tubing, and monomers, adhesives and sealants used for membrane systems containing plastics. These compounds included amines, styrene,

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Table 6. Known or suspected endocrine-disrupting activity of some leachates from plastic pipes.

Compound	Known or suspected endocrine disrupting activity/ Biological system	Classification	References
Styrene	Neuroendocrine/reproduction	Evidence of disruption, EC Priority List Classification; EU monitoring required	EC (2000), Annex 13; EU Directive 2000/60/EC
Phenol	Estrogens/reproduction	Evidence of potential disruption, EC Priority List Classification; EU monitoring required	EC (2000), Annex 13; EU Directive 2000/60/EC
Alkyphenols/ phenol Derivatives	Estrogens/reproduction	Evidence of potential disruption, EC Priority List Classification; EU monitoring required for some compounds	EC (2000), Annex 13; EU Directive 2000/60/EC
MTBE	Estrogens, androgens/male reproduction	Potential candidate, monitoring not required	EC (2000), Annex 1; de Payster *et al.* (2003)
Lead	Neuroendocrine/central nervous system, reproduction, Development	Evidence of disruption, EC Priority List Classification; EU monitoring required; Listed by Health Canada	EC (2000), Annex 13; EU Directive 2000/60/EC; Health Canada (2000)
Cadmium	Estrogens, progesterone/reproduction	Evidence of potential disruption; EC Priority List Classification; EU monitoring required. Listed by Health Canada	EC (2000), Annex 13; EU Directive 2000/60/EC; Health Canada (2000); Hensen and Chedrese (2004); Stoica *et al.* (2000)
Organotins	Androgens, estrogens, progesterone, thyroid, gonadotrophins/reproduction, development, central nervous system	Evidence of potential disruption, EC Priority List Classification; EU monitoring required for TBT species	EU (2000), Annex 13; EU Directive 2000/60/EC;

solvents, lubricants, and other organic compounds that are classified as hazardous substances.

DISCUSSION

Toxicological and some human clinical studies on individual chemicals from polymer materials that can leach into drinking water have shown a variety of adverse effects on a range of target organs/systems, including liver, kidney, central nervous system, and immune, reproductive, developmental, and endocrine endpoints. Additional concerns for human health include: (1) combined exposures to multiple chemical constituents of drinking water that target the same organ or biological system; (2) multi-route exposures to the same chemical or chemical mixtures; and (3) the impact of short-term exposures on sensitive or susceptible populations.

A number of drinking water leachates from polymer pipe materials affect common organs/systems or induce similar effects on the endocrine system. Doses inducing these effects may vary considerably among chemicals. Regulatory concerns about the combined effects of multiple substances targeting the same organs/systems have led to the development of a framework for assessing the effects of chemical mixtures (USEPA 1986, 2000b). Simultaneous exposure to these leachates, considered as a chemical mixture in drinking water, may result in combined human exposure levels that are likely to increase potential human health risks as compared with exposure to only a single compound. For example, organotins have been considered by USEPA's Office of Water as a possible candidate for regulatory determination, due in part to the potential for additive or synergistic adverse health effects associated with co-occurring species in drinking water (Lipscomb and Hertzberg 2005). The USEPA is developing a chemical mixtures risk assessment for these organotins (Lipscomb and Hertzberg 2005). Similarly, based on a common target system and mode of toxic action, ATSDR (2004) has evaluated the interaction profile of mixtures of BTEX in order to recommend approaches for exposure-based assessment of the potential hazards to human health. The results of modeling simulation and experimental exposure analysis suggest that the neurotoxic effects of individual chemical compounds will be additive over a range of doses.

Occurrences of leachates from plastic pipes into drinking water are not the only potential sources of human exposure to these compounds. The USEPA (1992, 2007) and WHO (2000) have stressed the need to estimate combined health hazards from chemical substances with multiple human exposure pathways (tap water, diet and beverages, indoor and ambient air, soil) as well as multiple exposure routes (ingestion, inhalation, dermal contact). The relative source contribution of exposure from drinking water may or may not contribute significantly to total human environmental exposures, as leachates in potable water are rarely measured at the tap.

Although traditional assessment of the potential health hazards and risks of environmental chemicals has focused on acute and chronic exposures and effects in adults, the impact of chemical exposures on sensitive or susceptible subpopulations is a current priority public health concern. The developing young, from conception to adolescence, have different susceptibilities during early life stages than adults, due to dynamic growth and developmental processes as well as physiological, metabolic

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and behavioral differences, and have been identified as the most sensitive human subgroups (IPCS 1996, 2001b; Faustman *et al.* 2000).

Developmental processes can be disrupted by exposures to chemicals (IPCS 2001b; WHO 2005). Minor perturbations in the timing and pattern of these processes, especially during critical periods of pregnancy, the neonatal/postnatal developmental stages and puberty, can induce irreversible health effects and long-term downstream consequences. The nature and magnitude of chemically induced outcomes depend on the timing of exposure, the type of toxic insult and the dose of the chemical. For example, depending on the timing and nature of neurotoxicity from contaminants such as lead, behavioral deviations in the young can range from mild (*e.g.*, learning disabilities) to severe (*e.g.*, mental retardation) (WHO 2005).

The developing nervous, reproductive, endocrine, and other systems are also much more vulnerable to the disrupting effects of toxic chemicals than the comparable adult organ systems (IPCS 2001a; WHO 2005). Levels and durations of exposure that produce few or no obvious effects on mature systems in adults may pose serious risks to the developing young (Faustman *et al.* 2000). Low-level exposure to environmental chemicals such as lead, organotins, or volatile organic compounds can result in physical malformations. However, they are more likely to produce cellular and molecular changes that are expressed as neurobehavioral/cognitive deficits, impairment of immune system competence or altered structural/functional integrity of cells and tissues. These changes often result in no observable effects at birth but manifest later in life as reproductive dysfunction, behavioral or intellectual abnormalities, and/or earlier onset of neurodegenerative diseases or cancer (WHO 2005). For example, there is increasing evidence from human and animal studies suggesting that exposure to benzene *in utero*, and/or maternal and paternal exposures prior to conception, induce changes in the maturation of the fetal blood system that are associated with an increased likelihood of the development of childhood leukemia (Snyder *et al.* 1993; USEPA 2002a).

Infants and children differ from adults in that they consume more water per kg body weight per day (USEPA 2001) and thus would be exposed to a greater chemical dose per kg than adults. Further, the microenvironment of the young is more restricted than that of adults. Infants and young children spend more time indoors at home or in day care. Therefore, the relative source contribution of residential and community drinking water supplies in these age groups may comprise a substantial proportion of the total environmental exposure for leachate chemicals. Acute or short-term exposures to chemical substances in drinking water by the pregnant woman can have a significant effect on the development of her fetus (WHO 2007; Longnecker and Rogan 2001). In the young infant ingesting powdered milk formula reconstituted with tap water, reconstituted fruit juices and tap water during the first year of life, the primary exposure pathway to leachates from polymeric materials is likely to be via drinking water. Many of these chemical compounds are also transferred from the nursing mother to her infant via breast milk (WHO 2005). Therefore, short-term elevations of leachates can have significant health impacts on the most sensitive human subpopulations during critical developmental stages (IPCS 1996, 2001a,b; WHO 2005).

Higher exposures typically occur in occupational populations or result from acute accidental releases/spills and long-term leaks (*e.g.*, underground gasoline storage

tanks). Workers or homeowners using highly volatile solvents to join plastic pipe segments, especially in confined spaces, are vulnerable to excessive exposures from the vapors of adhesives and cements unless they utilize appropriate protective equipment and clothing. Failure to apply specific solvents and primers that are compatible with the type of polymeric pipe material in the system, in strict compliance with manufacturers' instructions, and to follow specified procedures during installation and/or repair can lead to improper joining and solvent cementing of plastic pipes and fittings. This can result in chemical leaching into drinking water, as well as subsequent pipe degradation or failure and costly repairs (NAS 2006).

Other home maintenance activities may also degrade premise plumbing comprised of polymer materials. For example, vinyl piping materials (PVC and CPVC) can be severely damaged by direct contact with fungicides on surrounding drywall and wood framing inside residences, applied to prevent the growth of mold and mildew in areas near the pipes (NAS 2006), unless precise procedures for protecting the pipes are followed as per manufacturers instructions. Termiticides and other insecticides can cause similar damage if injected into the indoor annular spaces close to the pipe wall for pest control and the pipes must be shielded or removed from pesticide exposures during application. Lack of compliance with these methods can alter the structural integrity of these polymers, resulting in increased chemical leaching into drinking water, as well as pipe leaks and the consequent growth of indoor mold (NAS 2006).

Spills or leaks of petroleum distillates, VOCs and solvents into soils surrounding underground polymeric pipes may lead to permeation of these substances into drinking water, and result in human exposure. Relative to the main distribution system, service lines have higher pipe surface area to water volume ratios, longer water stagnation times and intermittent flow rates, and a decreased potential for dilution, all of which can increase the potential severity of permeation in premise plumbing (NAS 2006).

In studies of HDPE and CPVC pipes, Heim and Dietrich (2007) observed that increased water residence time resulted in significantly increased leaching of organic compounds as compared with glass controls; chlorine demands of the leachate were also increased. Haas *et al.* (2002) has noted that increased chlorine demand by plastic pipes can decrease the residual disinfectant in potable water and hence degrade its microbial quality. In studies on the interactions between TOC, chlorinated drinking water and pipe materials, Camper *et al.* (2004) and Chan *et al.* (2002) showed that increasing levels of humic substances in the presence of free chlorine and monochloramine increased the biofilm growth on PVC pipe surfaces. These findings suggest that humic substances can serve as carbon and energy sources for bacterial growth in an otherwise low nutrient environment. The health impacts associated with these secondary characteristics are not well documented.

The lack of data in the open literature on PVC and CPVC polymers and their additives in potable water plumbing is problematic. Most of the publicly available literature on individual products states that the PVC or CPVC pipe has met ANSI/NSF Standard 61 criteria for lack of adverse human health effects in plumbing pipes and fittings. No data are provided on the amounts or types of leachate identified due, in part, to proprietary formulations. Annex A of Standard 61 (NSF 2005) defines the toxicological review and assessment procedures for evaluation of substances

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imparted to drinking water through contact with drinking water system components and Annex B the testing conditions that are used to certify the product under the anticipated use conditions.

There is a hierarchy of approaches that are acceptable for risk estimation for potential chemicals of concern (COC), depending on the quantity and quality of available toxicity data for the COC: (1) a conservative threshold of evaluation (TOE), used when the toxicity data required (by NSF Standard 61) to perform a qualitative or quantitative risk assessment are unavailable; (2) a qualitative risk assessment to clear a substance to a default Total Allowable Concentration (TAC) and Specific Product Allowable Concentration (SPAC), used when a minimum toxicity data set is available; (3) a quantitative risk assessment to develop chemical- and product-specific TACs and SPACs when the COC is regulated and/or has sufficient toxicity data for quantitative evaluation; and (4) a chemical class-based evaluation when the data are inadequate to perform a chemical-specific risk assessment; this evaluation uses a surrogate approach based on toxicity data from structurally similar chemical substances.

Further, NSF/ANSI 61 specifies in detail the test protocols to be used for analyzing levels of potential COCs under anticipated conditions of product uses (NSF 2005). However, different certification organizations utilize different minimum reporting limits or limits of detection (LOD) and/or dilution strengths; thus, a determination of potential human health risks (or lack thereof) for specific leachates may vary, depending on the LOD of the analytical method used or the degree of sample dilution. Second, different certification agencies may interpret the data differently. Third, considerable uncertainty and variability in the toxicity evaluations of leachates exists, depending on the amount of available data and the specific approach used for assessment of health effects. Further, these tests are intended only for adult exposures. Elevated short-term or acute exposures may have severe effects on the developing young if they occur during critical windows of development; transient effects on normal developmental pathways may impact development and have immediate and/or long-term downstream consequences (USEPA 2007). In response to these concerns, the European Union is currently revising its testing protocols and action levels and expanding its monitoring requirements for unregulated drinking water substances that are reported to leach from plastic pipes and are known or suspected endocrine-active compounds (WHO 2004). Regulatory actions by relevant authorities would have a stronger scientific basis if it were possible to obtain and independently review the data for plastic pipes and their components that are certified using the hierarchy of NSF/ANSI certification practices.

SUMMARY AND CONCLUSIONS

There are numerous chemical substances that can be released from polymeric materials into drinking water over time. When plastic pipes are used for residential plumbing and/or in the distribution humans may be exposed to a variety of chemical leachates. The health effects of the leachate chemicals that have been evaluated toxicologically are significant, ranging from liver and kidney effects to adverse health outcomes on the reproductive, developmental, immune and nervous systems,

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endocrine disruption, and/or carcinogenicity. Many of these substances target the same organs/systems, leading to concerns that leachates whose drinking water concentrations are individually below a chemical-specific SPAC may have additive and synergistic effects when considered as a chemical mixture; some effects might be antagonistic.

A major uncertainty is the frequency and magnitude of elevated short-term exposure levels over time and under varying environmental conditions. The polymeric material matrix is a synthetic system, and degradation, release of chemical substances within the matrix and their interaction with disinfection by-products and other compounds in drinking water over time is not well characterized. Short-term exposures may have a significant impact on susceptible populations such as the pregnant woman and her fetus, the infant, and the young child. Such exposures may interfere with developmental processes occurring during critical periods and can have long-term and sometimes irreversible health consequences.

Monitoring for regulated chemicals is conducted at the entrance to or in the distribution system except for lead and copper, which are monitored at-the-tap. Therefore, little information on chemical exposures and water quality characteristics is available for water actually ingested by consumers. The U.S. National Academy of Sciences (NAS) (2006) has noted that the unique characteristics of premise plumbing can magnify the potential public health risks relative to the main distribution system and complicate development of coherent strategies to deal with premise plumbing concerns. Changes in taste and odors, and other secondary properties of drinking water such as TOC, turbidity, and chlorine demand, may also be indicative of the presence of substances that can pose a human health hazard.

When choosing drinking water distribution system materials for both the central system and premise plumbing, the NAS (2006) recommends that the following factors be considered: (1) health effects of the materials when in contact with drinking water; (2) hazards and safety in working with the materials; (3) structural capabilities of the material; (4) water quality impacts of the material; (5) cost and availability of the material; (6) compatibility of the material with other substances in the system and with the conveyed water, water disinfection process, and surrounding soils; (7) environmental effects of the material; (8) certification of the materials; and (9) future changes that could impact on the above. However, not all factors are given equal weight and economic considerations and the availability of the material often dominate the choice of the material.

Based on available data, this review has shown that numerous chemical substances in polymeric tubing have the potential to migrate from the pipe into drinking water. Migration may vary significantly among pipes, depending on the materials/resins used in manufacturing and extrusion, differing location/environmental conditions and usage patterns. The possible health effects of some leachates have been studied in animals and/or humans. The majority of constituents or additives in plastic pipes have not been monitored and/or evaluated toxicologically. Chemical compounds are not routinely measured at the tap and the potential for additive or synergistic adverse health effects *in situ* is not well characterized. Health and water authorities may not even be aware of the potential risks, especially to sensitive subpopulations.

Other health concerns include worker exposures; identification and characterization of new chemicals used in the manufacture of polymeric tubing; interactions

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between the physical and chemical properties of drinking water conveyed in polymeric materials and their effects on disinfectant residuals and biogrowth promotion; and the effects of varying flow rates and residence time of water in premise plumbing plastic pipes. For protection of public health, it is important to characterize human exposures to both regulated and unregulated chemical substances that are constituents of polymeric pipes and have the potential to migrate into drinking water, and to better assess the human health effects of these compounds when ingested in water.

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