Review

Decontamination of chemical agents from drinking water infrastructure: A literature review and summary

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ABSTRACT

This report summarizes the current state of knowledge on the persistence of chemical contamination on drinking water infrastructure (such as pipes) along with information on decontamination should persistence occur. Decontamination options for drinking water infrastructure have been explored for some chemical contaminants, but important data gaps remain. In general, data on chemical persistence on drinking water infrastructure is available for inorganics such as arsenic and mercury, as well as select organics such as petroleum products, pesticides and rodenticides. Data specific to chemical warfare agents and pharmaceuticals was not found and data on toxins is scant. Future research suggestions focus on expanding the available chemical persistence data to other common drinking water infrastructure materials. Decontaminating agents that successfully removed persistent contamination from one infrastructure material should be used in further studies. Methods for sampling or extracting chemical agents from water infrastructure surfaces are needed.

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Contents

1. Introduction

Chemical, biological, or radiological (CBR) contamination events or attacks on drinking water infrastructure could have significant public

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health, economic, and social impacts. The intentional introduction of harmful contaminants into drinking water distribution systems, for example, has the potential to contaminate the water over a relatively large geographical area, along with storage tanks, pipes and pumps used to convey the water, service connections to buildings, and water-consuming appliances, such as water heaters. Complicating the situation is the propensity of some contaminants to adhere to corroded pipes or biofilms on the pipe walls, potentially prolonging the impact of the contamination by desorption, leaching, or otherwise detaching from the surface and into the water over time after the incident. Contamination incidents could also impact drinking water treatment plants, wastewater treatment facilities, and storm and sewer systems. The focus of this article is summarizing available data on the propensity of representative target chemical contaminants to adhere to wetted drinking water infrastructure surfaces, such as pipes, and techniques for decontamination of persistent contaminants. Persistence and decontamination data included in this report pertain to the most common types of water pipe used in North America, including cast/ductile iron, cementitious material like cement-mortar lined ductile iron, and plastics like PVC (AWWA, 2012; Folkman et al., 2012).

Research on chemical persistence on drinking water infrastructure has often focused on the adherence of inorganic contaminants (Gerke et al., 2008; Lytle and Schock, 2000; Lytle et al., 2004; Schock et al., 2005). There are, however, many other chemical classes of concern, including organics, pharmaceuticals, chemical warfare agents, and toxins. Historically, research into drinking water treatment of chemicals has focused on regulated inorganic contaminants, such as heavy metals, disinfection byproducts, and organics such as pesticides, herbicides, and chemical discharges from industrial processes. Many of these chemical agents make their way into water systems through discharge or agricultural runoff into ground or surface water. Drinking water treatment plants are designed to remove these contaminants from water before they enter the distribution system. However, data on persistence of many chemical agents that could potentially be used to contaminate a drinking water distribution system is very limited. This article summarizes available adherence and decontamination data for common classes of chemical contaminants in regard to water distribution system infrastructure, identifies contaminant classes for which little data currently exists, and discusses which of these may be suitable for future research.

2. Inorganics

2.1. Arsenic

In drinking water, arsenic will be found in its oxidized forms as arsenic (III) (arsenite) or arsenic (V) (arsenate). In a drinking water contamination scenario, arsenate would be more pertinent since arsenite will be oxidized in drinking water when it reacts with disinfectant residuals (free chlorine or chloramines or oxidants in the drinking water process). Common arsenate and arsenite compounds are soluble in water, but solubility depends on the compound. Sodium arsenate, for example, has a solubility of 61 g/100 ml water at 15 °C (Budavari, 1996).

Association of arsenic with infrastructure surfaces, especially in drinking water, is well documented. Numerous studies have directly collected corrosion/scale samples from drinking water distribution systems, analyzed those samples for sorbed arsenic through inductively coupled plasma mass-spectrometry (ICP-MS), and included inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and X-ray diffraction (XRD). All have shown the presence of sorbed arsenic (Jain et al., 1999; Lytle et al., 2004, 2010; Schock et al., 2008). In general, arsenite (As(III)) is considered more soluble and mobile, and arsenate (As(V)) is considered more likely to associate with solid surfaces. One study found that arsenic can incorporate into calcite (Bardelli et al., 2011). Calcite can be present on iron or cement-mortar pipe interiors, depending on water quality conditions.

Decontamination information is limited, but useful information has been presented by two studies. One study showed that sodium arsenite injected into chlorinated water does adhere and persist on cement-lined iron coupons (small pieces of material used for sampling) cut from pipe sections ((USEPA), 2008). The coupons were conditioned in Cincinnati, Ohio, tap water and had an established biofilm. Persistence of arsenic was not influenced by flow rate. Decontamination with flushing did not consistently remove arsenic from the coupons, and flushing with low pH (pH = 4) did not increase the removal of sorbed As. Maximum removal observed with flushing (using normal tap water pH of 8.5 and low pH water) was 51%. Flushing with a phosphate buffer did not result in the removal of any additional arsenic. Acidified potassium permanganate consistently removed 54–61% of adhered arsenic. Implementation of National Sanitation Foundation (NSF) Standard 60 Pipe Cleaning Aid Products Flushing (NW-310/NW-400 flushing, Floran Biogrowth Remover/Catalyst, and Floran Top Ultra/Catalyst) resulted in 46–67% removal. Copeland et al. (2007) show that arsenic desorbs from iron scale over time with increasing pH (testing between pH 6 and 9) (Copeland et al., 2007). Increasing pH above 9 may be an effective way of removing adsorbed arsenic (Pierce and Moore, 1982).

2.2. Mercury

Mercuric compounds (Hg(II)) are soluble and have, therefore, been the subject of much more study in ambient and drinking water matrices than mercurous compounds. Oxidized mercury compounds of interest are mercuric chloride, mercuric sulfate, and mercuric nitrate. Mercuric chloride is more soluble than other compounds, with a solubility of 7.4 g/100 ml at 20 °C (3.6 g/100 ml at 0 °C) (Budavari, 1996). In drinking water, it is often assumed that mercury would effectively be in an oxidized, soluble state due to the oxic nature of drinking water with disinfectant. In some aquatic systems, mercury can be transformed by microorganisms to methylmercury, which is highly toxic (Najera et al., 2005).

Mercury persistence on drinking water infrastructure has not been studied in detail, but persistence on biofilm has been observed. One study showed that mercury (Hg(II), introduced as HgCl₂) sorbed to biofilms, but found that planktonic cells were more susceptible to the toxic effects of mercury than biofilm organisms (Najera et al., 2005). This was explained by the fact that diffusion may prevent all of the dissolved mercury from reaching the biofilm, but also that EPS material in the biofilm may sequester mercury and prevent it from impacting the biofilm organisms. Other work observed that the biofilms grown on glass slides did sorb Hg(II) and methylmercury (Hintelmann et al., 1993). After an initial spike, the amount of mercury detected in the biofilms decreased. This could be due to desorption, but the authors believe that de-methylation of the mercury followed by volatilization of elemental mercury could explain the disappearance. Finally, a study focused on wastewater showed that a mercury-resistant strain of bacteria does uptake and reduce soluble mercury in wastewater (von Canstein et al., 1999). A bench-scale study found less than 1% attachment of mercury when introduced at 100 mg/L on pipes made of iron, galvanized iron, PVC, cement-mortar and polyethylene, epoxy and copper, some with biofilm (Welter et al., 2009).

Like persistence data, little information on decontamination was found. One study that focused on drinking water found that mercury injected as mercuric chloride did persist on cement-lined iron with an established biofilm ((USEPA), 2008). Decontamination results were mixed. Flushing results were variable with more adhered mercury found post-flushing in some experiments and 19–51% removal in others. Low pH (pH 4) consistently showed 21–23% removal. Acidified permanganate removed 72–96% of the adhered mercury. Mercury was injected as Hg(II) which is the fully oxidized state, so oxidation was not the mechanism for removal. It was speculated that the low pH of the permanganate solution dissolved adhered mercury and removed it from the pipe surface.