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DISINFECTION PRACTICES AND THE CHALLENGES OF BYPRODUCTS IN DRINKING WATER

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Abstract: Disinfection of drinking water in treatment plants is typically performed to inactivate pathogens. Common disinfectants used in drinking water treatment plants are chlorine, chloramines, chlorine dioxide, UV and ozone. However, chemical disinfectants also react with the naturally occurring organic carbon and nitrogen compounds to form disinfection byproducts (DBPs) both in the treatment plant and within the distribution system. Many of these DBPs are potential carcinogens at low concentrations and are widely considered as a growing health concern for consumers. For this reason, regulatory agencies such as US Environmental Protection Agency (US EPA) and Health Canada have promulgated standards or guidelines for common DBPs. This paper discusses various challenges related to disinfection practices and identifies DBPs of emerging concern. In particular, the concerns related to nitrosodimethylamine in drinking water are discussed. The importance of a comprehensive approach to controlling DBP exposure is addressed. Current research at the Centre for Sustainable Infrastructure Research in Regina evaluates the interactions between distribution pipe materials and various disinfectants, and subsequent formation of DBPs.
Keywords: Disinfection, Disinfection byproducts, Nitrosodimethylamine, Distribution Infrastructure

Introduction

Disinfection is a process used in drinking water treatment to inactivate pathogenic microorganisms. Depending on its application within the system, disinfection is classified as either primary or secondary disinfection. Primary disinfection is aimed at inactivation of microorganisms and is done at the water treatment plant. Secondary disinfection is aimed at protecting water in the distribution system from microbiological regrowth and contamination. Disinfection byproducts and deterioration of the distribution system pipe network are among the primary concerns for disinfection process.

Disinfectants typically react with dissolved organic and inorganic matter to form various types of disinfection byproducts (DBPs). The formation of byproducts is dependent on the chemical composition of the water and the disinfectant used during the treatment process. Historically, chlorine is the most common disinfectant used in drinking water treatment. However, chlorine is also highly reactive with the organic matter in the water and forms disinfection byproducts such as trihalomethanes (THMs) and haloacetic acids (HAAs). The two reactants (chlorine and organic content) are present in the drinking water throughout its transit to the consumers tap. Therefore, the reactions leading to the formation of DBPs are present throughout the distribution system.

The high reactivity of chlorine, in conjunction with the regulatory pressure on maintaining the levels of DBPs in drinking water, has forced water utilities to look for alternative disinfectants. Many utilities in the US have switched to chloramine disinfection and a number of municipalities in Canada (Cities of Regina, Moose Jaw and Winnipeg) are planning on contemplating switching from chlorine to chloramines.

Alternative disinfectants (e.g. chloramine, chlorine dioxide or ozone) have their own associated DBPs. For instance, THMs and HAAs for chloramines, chlorite for chlorine dioxide and bromate, aldehyde, ketone and carboxylic acid for ozone.

Chloramines are known to cause lower concentrations of THMs than chlorine (Sung *et al.*, 2005). For this reason, many water treatment utilities have switched in recent years to chloramines as an alternative disinfectant (Connell *et al.*, 2000). However, chloramination also had some deleterious effects on the distribution system and on water quality. High concentration of N-nitrosodimethylamine (NDMA) in chloraminated water is one such type of water quality change (Mitch *et al.*, 2003). NDMA is a much more potent carcinogen than other types of conventional byproducts and is persistent in the natural environment (Tate and Alexander, 1975). Though there is no direct evidence of human health effects from NDMA exposure, it is considered as a toxic pollutant by the Agency for Toxic Substances and Disease Registry in the US (ATSDR,1989). Therefore, it became essential to understand the behavior of residual disinfectants and both conventional and emerging disinfection byproducts in a distribution system for optimizing the decision-making processes used in providing consumers with safe drinking water.

The distribution system transports treated water to the consumer's tap. Therefore, it may provide long residence time for disinfectants to form byproducts. Source water chemistry, incompatible treatment and un-optimized disinfection can heighten the problem. The use of disinfectants may also increase the structural deterioration of the distribution system. Complying with regulatory requirements while reducing chronic effects of DBPs is an ongoing challenge for most utilities. The formation of DBPs in the distribution system adds to the complexity of the existing challenges of corrosion control and microbial inactivation (Figure 1). All three elements are interlinked. Therefore, finding an optimized solution became a challenge for many water utilities. The discovery of new DBPs is bringing further complexity to this interaction.

The objective of this paper is to discuss the challenges of disinfection byproducts in distribution system. The paper analyzes the ways to control emerging byproducts. Nitrosodimethylamine (NDMA), one of the emerging byproducts of disinfection is discussed in this paper. This paper also discusses current research at the NRC Centre for Sustainable Infrastructure Research.

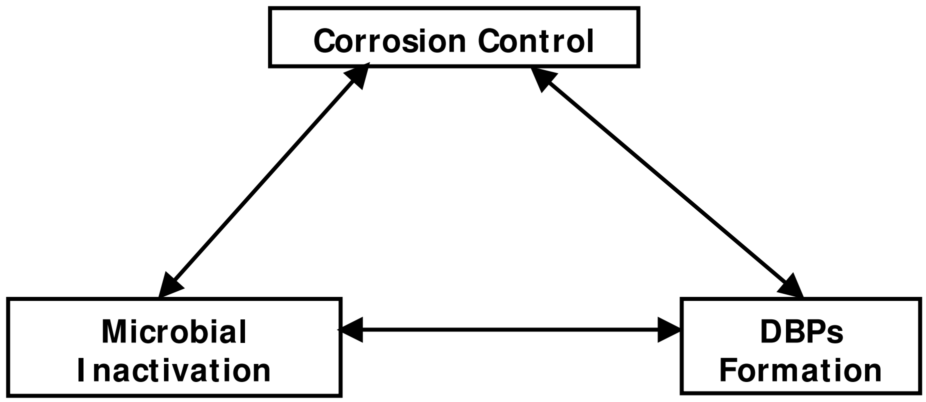

Figure 1. Interactions between various components disinfection in distribution system

Emerging DBPs

Chlorine disinfection typically forms THMs and HAAs. For that reason, USEPA suggested using alternative disinfectants (USEPA, 2006). It brought a focus from the research community to investigate alternative disinfectants and the health effect of their byproducts as many of these new DBPs are found to be toxic. Variation in source water characteristics, environmental and treatment conditions cause differences in reaction kinetics that affect the type and concentrations of DBPs formed. With the adoption of alternative disinfectants, water quality data from full-scale treatment facilities become available and it brought the concerns regarding many of these emerging DBPs. Nitrosamines and hydrazine are two examples of emerging DBPs that are carcinogenic.

Nitrosodimethylamine (NDMA)

Occurrence of NDMA in water

Groundwater contamination was due to disposal, spillage or leakage of rocket fuel containing NDMA. In the San Gabriel Valley (California) groundwater NDMA concentrations were found up to 3000 ng/L (DHS, 2002). Other sources of NDMA in groundwater were antioxidants, additives to lubricants and softeners of copolymers (Gui *et al.*, 2000). NDMA is also found during drinking water and wastewater treatment processes (Najm and Trussell, 2001). It appears in both groundwater and disinfected water in a water treatment plant (Sen *et al.*, 1994). Both chlorine and chloramines were found to generate NDMA in water (Choi *et al.*, 2002). There has also been contribution of polymer used during water treatment on the formation of NDMA (Wilczak *et al.*, 2003a). However, it also requires the presence of certain precursor in the source water. The common precursors are nitrite, nitrous oxide and dimethylamine (Mills and Alexander, 1976).

NDMA was first noticed in Canada from one drinking water treatment plant in Ontario as a result of industrial contamination (Andrews and Taguchi, 2000). Subsequent investigations revealed the contribution of the disinfection process during drinking water treatment to the NDMA formation. Once discovered as a treatment byproduct, province-wide regular sampling was conducted and many occurrences of NDMA were observed

(Jobb *et al.*, 1993). Though there is potential for NDMA presence all over Canada, it has not been investigated beyond Ontario (Environment Canada, 2001).

NDMA as disinfection byproduct in distribution system

Studies conducted on the presence of NDMA during water treatment processes were mostly focused on the contribution of disinfection to the formation of NDMA. However, there had been very little evidence on the effect of distribution system components on the NDMA growth and decay. In the state of California, NDMA was observed in several distribution systems (Wilczak *et al.*, 2003b). There had also been evidence of polymer usage during treatment process affecting NDMA formation. Though nitrification is known to occur in the distribution system for chloraminated water, it does not contribute to the formation of NDMA. In the state of California, monitoring results from various surface water treatment plants indicated higher NDMA concentrations in chloraminated than in chlorinated water (DHS, 2002). However, localized and limited monitoring in distribution systems does not provide sufficient information on the kinetics of NDMA formation. Therefore, there is a growing need for research on the formation of NDMA and its eventual effect on the decisions concerning conversion to alternative disinfection.

Challenges of NDMA

There have been many challenges researchers faced with analysis of NDMA in water. The development of analytical methods is required for very low-level concentrations. Accurate and reliable methods are needed for measurement of NDMA at parts per trillion levels. For regular monitoring purposes, these methods have to be cost effective. There has also been uncertainty in modeling the kinetics of formation of dissipation of NDMA. Regulatory monitoring and compliance for individual utilities would be a major challenge, as the municipalities would incur additional costs for compliance of NDMA

Controlling DBPs

There are continuing efforts to reduce exposure to harmful DBPs. The formation and distribution of DBPs to consumer's taps can be controlled in a comprehensive way (Figure 2). As part of the already existing source water protection, many contaminants are typically managed in the source water so that they do not enter the drinking water distribution system. The DBP precursors can be reduced as part of the source water protection plan. Sometimes the precursors can make their way to the treatment process. In those circumstances, these organic precursors can be removed before the disinfection process to reduce the formation of DBPs. If these DBPs are formed during the treatment process adsorption has been used in many utilities to remove THMs and HAAs. However, it is not found to be effective for removing NDMA. UV is found to be effective in treating NDMA.

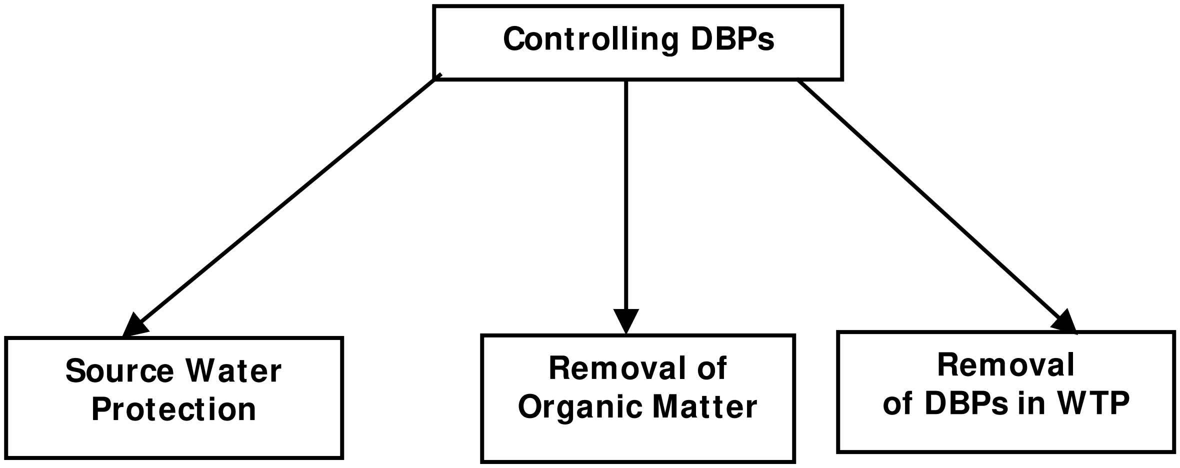

Figure 2. Three types of measures to control DBPs

Distribution Infrastructure and Disinfection

Iron, lead and copper components

Corrosion byproducts attached to pipe surfaces or accumulated as sediments in the distribution systems can shield pathogenic microorganisms from disinfectants (Butterfield *et al.* 2002;). Release of corrosion byproducts, identified in the form of increased turbidity, may provide safe havens for pathogens (Morin *et al.* 1999). Another consequence is the loss of disinfectant residual and subsequent biofilm formation in the distribution system (Frateur *et al.* 1999). Frateur *et al.* (1999) concluded that free chlorine is not electrochemically consumed at the metal surface, though it is more easily reducible than oxygen. Therefore, the corrosion of cast iron pipes induces only a chemical decay of chlorine corresponding to its reaction with ferrous ions released by iron dissolution and the total consumption rate is obtained from the corrosion current density. Vikesland and Valentine (2002) identified similar mechanisms for the consumption of monochloramine by ferrous ions. Decreased microbiological disinfection efficiency can promote the growth of biofilms and subsequent microbiolgically induced corrosion (MIC) problems (Bremer, Webster, and Wells 2001).

Lehtola *et al.* (2004) concluded that new copper pipes inhibit microbial activities, based on their observation that the heterotrophic plate count (HPC) in waters was consistently below that of similar Polyethylene (PE) pipes for the first 200 days. Lehtola *et al.* (2005) subsequently reported that copper pipes depleted chlorine residual faster than PE pipes, with the result that more chlorine had to be added to water flowing through copper pipes to achieve similar microbial quality to PE pipes.

Edwards and Dudi (2004) reported a case in Washington, D.C., where a switch of disinfectants from chlorine to chloramines released excessive lead from lead service lines, lead solder and brass plumbing material. Bench-scale testing found that chlorine reacts with soluble lead to rapidly precipitate a stable lead solid that did not form in the presence of chloramine.

Vasquez *et al.* (2006) investigated total lead release in the presence of free chlorine and chloramine residuals in drinking waters produced from ground, surface, desalinated, and blended water sources. The authors observed that for both desalinated and blended finished waters, more total lead was released in the presence of chloramines than in the presence of free chlorine.

Polymeric components (PVC, PE etc.)
Based on depth profiling of the deterioration of polymeric material in contact with chlorinated water, many researchers concluded that the chemical species responsible for anti-oxidant loss was highly soluble in the material matrix, while the species responsible for polymer degradation was insoluble since only the immediate surface in contact was degraded (Hassinen *et al.* 2004). This implies that while the structural strength of the polymer is immediately affected (loss of anti-oxidants leads to increased brittle-failure of polymers), the surface itself may not exhibit extensive signs of deterioration (Fischer *et al.* 1993). Lundback *et al.* (2005) reported that even low concentration of residual chlorine (< 0.5 ppm) could decrease the lifetime of polymeric pipes by a factor of 10. Higher temperatures, such as those in hot water household plumbing exacerbated the deterioration of polymeric components due to more rapid loss of anti-oxidants (Gill *et al.* 1999). Bonds (2004) evaluated the effects of chloramines on degradation of various elastomers used in distribution system fittings. A year-long study by the author concluded that joint gaskets and fittings (with lower exposed surface area) exhibited negligible deterioration compared to sheets of the same material exposed to similar environments.

Effect of change in disinfectants on infrastructure
Changes in the disinfectant process, to reduce or eliminate any contaminant of concern, invariably leads to changes in the final water quality. When this changed water quality is introduced into the distribution system it will result in a series of changes, in which the distribution system as well as the final water quality are likely to be impacted (Imran *et al.* 2005). For instance, one way of maintaining simultaneous compliance with different regulations is to change the secondary disinfectant from chlorine to chloramine. Chloramine is more stable in the distribution system and can therefore maintain a residual longer than chlorine. An added benefit to utilities is that DBP formation by chloramine is significantly lower than that for chlorine.

However, there are some specific problems associated with chloramine such as lower potency for microbial inactivation compared to chlorine, nitrification (Liu *et al.* 2005) and increased potential for lead release (Vasquez *et al.* 2006). Therefore, a change in disinfectant to comply with the Stage 2 DBP rule and LT 2 Enhanced Surface Water Treatment Rule (ESWTR) could lead to a potential violation of the Lead and Copper Rule (LCR), the Total Coliform Rule (TCR) or the maximum concentration level (MCL) for nitrates and nitrites (USEPA 1999).

The corresponding effect on the distribution system would be increased service line leaks due to corrosion of lead service lines or dissolution of lead from solders and alloys. Recent research also points to the deterioration of elastomers (gaskets) in distribution fittings (Bonds 2004). Therefore, it is necessary that while evaluating different compliance strategies, the effects on the existing distribution infrastructure are given due consideration. However, the historical focus of compliance has been on the water quality at the point of entry to the distribution system and the effect of water quality on the distribution system has largely been ignored.

Current DBPs Research at CSIR

The NRC Centre for Sustainable Infrastructure Research in Regina is currently working on a project involving NDMA in the water distribution system. This project involves developing laboratory capabilities for measuring different types of water quality parameters including DBPs, particularly NDMA. Currently CSIR is developing analytical methods for NDMA measurement at a very low level in collaboration with the University of Regina. Once the analytical method is developed, a survey will be conducted on the presence of NDMA in different utilities across Canada. It will cover most regions in Canada. It is also expected that the project would evaluate the seasonal variations of NDMA at different utilities. The project would investigate the kinetics of NDMA and the interactions with distribution system components.

Summary

Disinfection is an important process in water treatment to inactivate microorganisms. Chlorine disinfection is used in most water treatment facilities. However, disinfection practices have faced many challenges in recent years, including deterioration of pipes and appurtenances with the changes in usage of disinfectants. Different DBPs are formed with the use of alternative disinfectants. Many of these emerging DBPs are carcinogenic in nature. NDMA is one such DBP. It is toxic at a very low level. Studies related to NDMA have faced many challenges, including accurate, reliable and cost-effective analytical methods to quantify NDMA at parts per trillion levels. The changes of DBPs can also change water chemistry and eventually affect the water distribution system infrastructure itself. The NRC Centre for Sustainable Infrastructure Research is currently developing analytical methods for measuring NDMA and planning to conduct NDMA occurrence surveys, including seasonal variation and the effect of distribution system interaction.

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