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PROJECT 09-1190
TECHNICAL REPORT

Usage and Effects of Chlorine Dioxide on PEX Plumbing and Water Distribution Systems in North America

July 12, 2010

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Executive Summary

The purpose of this paper is to examine the usage pattern of chlorine dioxide in North America and to determine the potential impact of chlorine dioxide residuals within the distribution network on crosslinked polyethylene (PEX) piping distribution and plumbing systems. This paper specifically focuses on the usage patterns by public water utilities within the United States. Based on the findings and a review of the available chlorine and chlorine dioxide resistance test data for PEX, an assessment was made of the adequacy of existing standards to ensure minimum performance of PEX piping materials exposed to typical levels of chlorine dioxide in the United States.

Based on the analysis conducted, the following conclusions are made:

- Chlorine dioxide is used in a limited number of potable water systems in North America. In the United States, it is estimated that it is used for oxidation and/or primary disinfection in less than 1% of community water systems (or 600 systems) overall. As a secondary disinfectant, it is estimated that less than 200 systems use chlorine dioxide for the maintenance of residual in the distribution system, primarily in conjunction with chlorine and/or chloramines.

- Typical chlorine dioxide levels in distribution systems in the United States appear to be less than 0.40 mg/L, with two-thirds of systems carrying a chlorine dioxide residual of less than 0.15 mg/L. The actual values are expected to be lower for the bulk of the distribution system due to decay of the residual along the distribution network. The residual level is projected to be even lower in household plumbing systems due to further potential dissipation and decay of the residual in the household hot-water tank.

- There does not currently appear to be a significant trend toward increased chlorine dioxide usage. However, the increased focus on the control and monitoring of disinfection by-products produced by traditional chlorination practices may continue to promote the use of alternative disinfectants such as chlorine dioxide in the future. It is recommended that the industry continue monitoring trends to identify any significant shifts in usage patterns in the future.

- Based on the analysis of available test data, current ASTM F876/F2023 requirements for chlorine resistance of PEX pipe in potable water plumbing applications appear robust enough to ensure minimum performance of both PEX distribution and residential plumbing systems for the vast majority of potential chlorine dioxide exposure levels in North America.

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1.0 Introduction

The majority of water utilities in North America use one or more chemical disinfectants to treat raw water for potable use. The most commonly used disinfectants are chlorine, chloramines, ozone, and chlorine dioxide. Chlorine has traditionally dominated the market. Alternative disinfectants, however, have experienced increased use since the discovery of chlorination disinfection by-products, such as trihalomethanes and haloacetic acids, and the introduction of government regulations to limit their presence in potable water distribution systems. Chlorine dioxide is one of the available alternative disinfectants on the market that can be used effectively to control disinfection by-product formation. A summary of the chemistry and characteristics of chlorine dioxide is provided in Appendix A.

Chlorine dioxide is commonly used in the United States as an oxidant to control taste and odors caused by algae and phenolic contaminants in raw water and to inhibit the growth of algae in flocculation and sedimentation basins[1]. It is also an effective agent in the oxidation of iron and manganese. In addition to its role as an oxidant, chlorine dioxide can also be used as a strong and effective disinfectant as either a primary or secondary disinfectant. The chief goal of primary disinfection is the inactivation of disease-causing pathogens. In contrast, secondary disinfection is primarily used to maintain a residual in the treated water to prevent the re-growth of bacteria in the distribution network prior to its delivery to the consumer. A residual in the distribution network, therefore, is mainly a consequence of secondary disinfection. However, depending on the dosage and the specific disinfection strategies employed, primary disinfection can also lead to the presence of a residual in the distribution network.

A chlorine dioxide residual in the distribution network of a community water system can be carried over to the local pipe distribution and residential plumbing systems. This can lead to the exposure of crosslinked polyethylene (PEX) piping systems to chlorine dioxide which may lead to oxidative degradation of plumbing system components. To ensure a standard level of performance of PEX

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piping materials intended for chlorinated potable water use, performance testing under ASTM F2023 *Standard Test Method for Evaluating the Oxidative Resistance of Crosslinked Polyethylene (PEX) Tubing and Systems to Hot Chlorinated Water* is required for PEX. This standard is based on chlorinated water with the belief that this represents a sufficiently aggressive enough condition to be applicable to the majority of end-use environments. Currently, similar standards do not exist for the evaluation of PEX piping materials exposed to a chlorine dioxide residual.

The PEX piping industry wants to understand the usage rates and levels of chlorine dioxide and verify that the current standards are appropriate for ensuring performance in systems exposed to chlorine dioxide. To this end, this paper examines the usage pattern of chlorine dioxide in North America and determines the potential for chlorine dioxide residuals within the distribution network to pose a significant risk to PEX pipe distribution and plumbing systems according to established minimum performance criteria. The analysis and discussion will primarily center around the United States, focusing on the use of chlorine dioxide as an oxidant and disinfectant in community water systems and the typical residual concentrations that may be encountered in community distribution networks. This paper will also examine the adequacy of existing chlorine resistance standards for PEX to ensure minimum performance of PEX piping materials against exposure to typical levels of chlorine dioxide in the United States.

2.0 Community Water Systems in the United States

The 2008 EPA Drinking Water and Ground Water Statistics Report indicates a total of 51,972 community water systems (CWS) in the United States[a]. Surface and ground water sources supply approximately 65% and 28% of the population, respectively. The remaining 7% is served by non-community water systems that do not operate year-round[b]. Table 1 provides a summary of the distribution of community water systems in the United States by water source.

[a] Community water systems are public water systems that supply water to a population of at least 25 people year-round.

[b] Non-community water systems include non-transient non-community water systems (NTNCWS) that supply water to at least 25 people for a minimum of 6 months of the year. Non-community water systems also include transient non-community water systems (TNCWS) that provide water in temporary locations and stations such as gas stations and campgrounds and are open at least 60 days per year.

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Table 1: Community Water Systems in the United States by Water Source[2]

	Water Source		
	Ground Water	Surface Water	Total
Number of Systems	40,301	11,671	51,972
Population Served	88,039,047	204,094,646	292,133,693
% of Systems	78	22	100
% of Population (CWS)*	30	70	100
% of Population (NAT)^	28	65	93

* Based on a population of 292,300,076 being served by CWS.
^ Based on a national (NAT) population of 311,955,809 being served by any type of water system.

Table 2 provides a summary of the disinfectant use of community water systems in the United States categorized by water source and treatment strategy. According to the 2000 EPA Community Water Systems Survey, approximately 2.2 to 3.0% of surface water systems in the United States rely on chlorine dioxide as a primary disinfectant and 1.1% employ it as a secondary disinfectant. The use of chlorine dioxide by ground water systems is reported by a much smaller number of water systems, accounting for only 0.2% for primary disinfection and 0.1% for secondary disinfection.

Table 2: Chlorine Dioxide Use of Community Water Systems by Water Source and Treatment Strategy[3,4]

Disinfectant	Percentage of Community Water Systems (%)			
	Surface Water		Ground Water	
	Primary	Secondary	Primary	Secondary
Chlorine Dioxide (EPA)*	2.2 – 3.0	1.1	0.2	0.1
Chlorine Dioxide (AWWA)^	9.8	1.5	1.4	0.6

* EPA Survey of 1,246 water systems with 43% consisting of medium to large systems.
^ AWWA Survey of 493 ground water systems and 543 surface water systems with 95% consisting of medium to large systems.

The majority of water systems that use chlorine dioxide for disinfection are composed of medium to large surface water systems serving a population of greater than 10,000 people[c]. Among these systems, chlorine dioxide is most commonly used as an oxidant and/or primary disinfectant. The usage pattern of chlorine and other alternative disinfectants based on population size can be found in Appendix B. The predominant use of chlorine dioxide in surface water systems reflects its benefit in providing a strong disinfectant capability while limiting the formation of disinfection by-products in organic-rich surface waters such as rivers and lakes.

In addition to the 2000 EPA Community Water Systems Survey, Table 2 also provides a summary of the 1996 AWWA Water Utility Database Survey of mostly medium to large water systems. The results of this survey indicate slightly higher usage rates of chlorine dioxide in general compared to those reported by the EPA survey. For surface water systems, 9.8% of water utilities indicated the use of chlorine dioxide for primary disinfection and 1.5% for secondary disinfection. Among ground water systems, 1.4% of water utilities reported the use of chlorine dioxide for primary

[c] Small systems: Water systems serving a population of 10,000 people or less.
Medium to large systems: Water systems serving a population of more than 10,000 people.

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disinfection and 0.6% for secondary disinfection. These higher percentages compared to the EPA survey results may be explained by the larger number of respondents from the AWWA survey representing medium to large water systems (~95%). Medium to large water utilities represent the majority of chlorine dioxide users among community water systems, and therefore, a greater sampling of these systems in a survey would be expected to increase the average usage rates of chlorine dioxide overall. In terms of water utilities in general, the results of the EPA survey are believed to provide a more accurate representation of chlorine dioxide use by community water systems in the United States.

Table 3: Estimated Number of Community Water Systems Using Chlorine Dioxide in the United States

# of Water Systems			% of Water Systems
Primary	Secondary	Total	
340-430	170	340-600	~1

Based on the EPA survey data provided in Table 2 and the water system statistics data provided in the 2000 EPA Drinking Water and Ground Water Statistics Report, the total number of water systems using chlorine dioxide as an oxidant and/or primary or secondary disinfectant were estimated (Table 3). Due to potential overlap of water systems practicing both primary and secondary disinfection with chlorine dioxide, the total number of systems is presented as a range. Based on this analysis, it is estimated that between 340 and 600 water systems in total use chlorine dioxide as either an oxidant and/or primary or secondary disinfectant. As a secondary disinfectant, it is estimated that less than 200 water systems use chlorine dioxide for the maintenance of a residual in the distribution system.

3.0 Chlorine Dioxide Use by Population Size Served

The results of the 2000 EPA Community Water Systems Survey on treatment practices reveal that chlorine dioxide is most commonly used as an oxidant or disinfectant in medium to large water systems that serve a population of more than 10,000 people. Specifically, chlorine dioxide is most frequently used as an oxidant and/or primary disinfectant in water systems that serve a population of between 50,000 and 100,000 people. For the purpose of secondary disinfection, water systems with a population size ranging from 10,000 to 500,000 are most likely to use chlorine dioxide as a secondary disinfectant to maintain a residual in the distribution network. A limited number of the water systems serving a population of more than 500,000 use chlorine dioxide as a disinfectant. Overall, water systems serving a population of between 10,000 and 500,000 people are most likely to employ chlorine dioxide for oxidation and/or disinfection. As a result, pipe distribution and plumbing systems associated with these larger water systems are most likely to be exposed to a chlorine dioxide residual. In contrast, water systems that deliver water to less than 10,000 people or more than 500,000 people report the lowest incidence of chlorine dioxide use in their treatment strategies.

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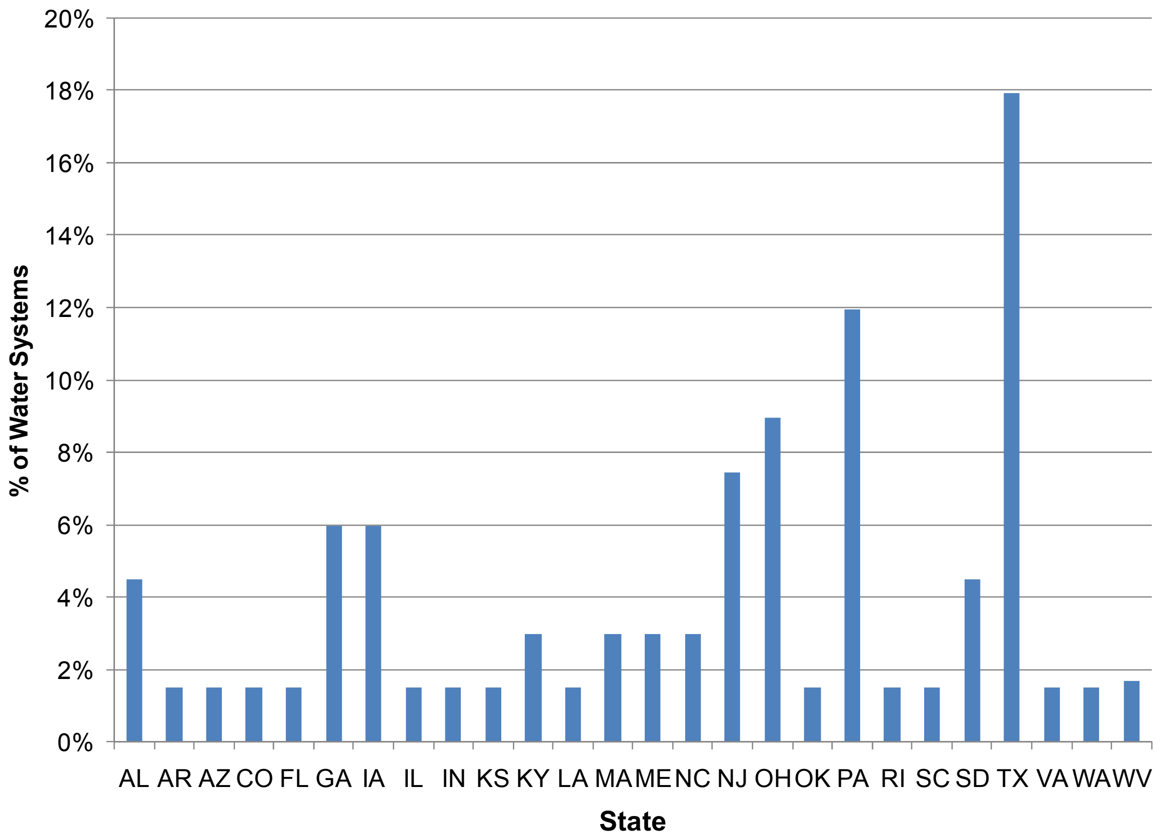
4.0 Geographical Distribution of Chlorine Dioxide Usage in the United States

According to the 1996 AWWA Water Utility Database Survey, chlorine dioxide use is most common in water utilities located in the state of Texas, followed by Pennsylvania, Ohio, and New Jersey. All these states, excluding New Jersey, also reported at least one water system that used chlorine dioxide specifically as a secondary disinfectant. Figure 1 provides a summary of the distribution of water systems using chlorine dioxide categorized by state[4]. Due to the relatively small sample size of this survey compared to the total number of water systems in the United States, the results must be considered with caution and be viewed as directional only.

Figure 1: Distribution by State of Water Systems Using Chlorine Dioxide in the United States[4]



Note: A Total of 67 water systems were reported to be using chlorine dioxide as either a primary or secondary disinfectant.

A possible reason for the higher frequency of chlorine dioxide use in Texas may be the higher reliance of its water utilities on surface water sources which are high in organic content and chemical precursors, such as bromide, that can lead to the formation of disinfection by-products[5]. In cases of water sources with high bromide contamination, chlorine dioxide can be used as a strong disinfectant that ensures the adequate inactivation of pathogens while at the same time keeping the formation of disinfection by-products, such as bromate, to levels under regulatory

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limits. Texas is also the second most populous state in the United States, where more than 71% of its population receives water treated from a surface water source[2]. As discussed in Section 2, chlorine dioxide usage is highest for water systems that draw upon surface water sources.

A review of the water quality reports (EPA Consumer Confidence Reports) of 42 randomly selected water systems using chlorine dioxide in the United States also appears to confirm that the majority of water systems using chlorine dioxide are located in the state of Texas. Further details on the distribution of water systems by state from this review of water quality reports can be found in Appendix C. Due to the relatively small sample size in this review, the distribution trend observed should be viewed with caution and be considered as directional only.

5.0 Chlorine Dioxide Treatment Strategies

Of the 67 water systems found to employ chlorine dioxide as an oxidant and/or disinfectant from the 1996 AWWA Water Utility Database Survey, only one surface water system and one ground water system were reported to use chlorine dioxide as the sole chemical oxidant and/or disinfectant. The majority of water systems using chlorine dioxide also practiced chlorination, primarily for the purpose of secondary disinfection. A smaller percentage of water systems also used chlorine dioxide with chloramines or in combination with both chlorine and chloramines. Table 4 provides a summary of the various treatment strategies involving the three main disinfectants for those systems reported to be using chlorine dioxide as an oxidant and/or disinfectant[4].

Table 4: Water Systems Using Chlorine Dioxide in Combination with Other Disinfectants by Water Source[4]

Disinfectants	Percentage of Water Systems Using Chlorine Dioxide (%) (# of Water Systems)	
	Surface Water	Ground Water
Chlorine Dioxide Only	2 (1)	12 (1)
Chlorine Dioxide and Chlorine	66 (39)	75 (6)
Chlorine Dioxide and Chloramines	17 (10)	0 (0)
Chlorine Dioxide, Chlorine and Chloramines	15 (9)	12 (1)
Total	100 (59)	100 (8)

Overall, the results of this survey indicate that chlorine dioxide is often used in conjunction with other disinfectants such as chlorine or chloramines when employed as an alternative disinfectant. The most common multi-disinfectant treatment strategy appears to be the use of chlorine dioxide as an oxidant and/or primary disinfectant and the use of chlorine as a secondary disinfectant to maintain a residual within the distribution network. This strategy takes advantage both of the ability of chlorine dioxide to oxidize and disinfect while minimizing by-product formation and the ability of chlorine to maintain a stable residual within the distribution network.

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The use of heavily contaminated water sources can also necessitate a multi-disinfectant treatment strategy. In these cases, chlorine dioxide may be unable to achieve the necessary oxidation and/or disinfection targets without the use of other disinfectants or treatment strategies due to the limitation imposed on its dose by the formation of chlorite, a regulated by-product of chlorine dioxide oxidation and disinfection (See Section 7.1).

The results of the 1996 AWWA Water Utility Database Survey also suggest that the relatively uncommon practice of secondary disinfection with chlorine dioxide also occurs primarily in conjunction with either chlorine and/or chloramines. Based on the difficulty of maintaining a stable chlorine dioxide residual in a distribution network due to rapid decay to very low levels, the prevention of bacterial re-growth in a distribution system may be achieved primarily by chlorine and/or chloramines when chlorine dioxide is applied in combination with these other secondary disinfectants. Section 7.2 provides the details of several studies that show the tendency of chlorine dioxide residuals for rapid decay along the distribution system.

6.0 Trends in Chlorine Dioxide Use in the United States

The first limited use of chlorine dioxide began during the 1940s after the discovery of chlorophenols which were found to cause taste and odor issues associated with the chlorination of heavily contaminated water sources. Chlorine dioxide was capable of effectively oxidizing these phenolic compounds and was applied primarily for its role as an oxidant in conjunction with chlorine. However, the use of chlorine dioxide decreased during the 1960s and 1970s due to high chemical costs, inefficiencies and poor conversion yields which sometimes caused taste and odor issues along with equipment failures related to the corrosive nature of sodium chlorite.[6]

Since the 1970s, the discovery and increasing concern over disinfection by-products and regulations aimed at limiting their presence in the distribution system have renewed the interest in chlorine dioxide as an alternative disinfectant. Although chloramines have traditionally been the most popular alternative disinfectant, there is growing interest and use of chlorine dioxide primarily for its function as an oxidant and primary disinfectant in conjunction with the use of chlorine and/or chloramines. As a secondary disinfectant, however, chlorine dioxide use has been limited due to concerns over taste and odor issues and the difficulty of maintaining a stable residual in large distribution networks[1]. In Canada, the 2008 Chlorite and Chlorate Guideline Technical Document by Health Canada recommends that chlorine dioxide be used only as a primary disinfectant, citing its inability to maintain a stable residual in the distribution system due to its rapid degradation to by-products such as chlorite and chlorate and the high rate of dissipation along the distribution network[7].

The 2007 AWWA Disinfection Survey of 312 community water systems indicates a general increasing trend in the use of chlorine alternatives such as chlorine dioxide, ozone, and chloramines

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since a similar survey was conducted in 1998 (Table 5). However, comparing the percentages of disinfectant use among only medium to large water systems from the 1998 survey, the values are relatively comparable to the percentages from the 2007 survey for the three alternative disinfectants. This comparison is expected to provide a better representation of the change in alternative disinfectant use since the respondents from the 2007 survey consisted mostly of medium to large water systems. The majority of respondents from the 1998 survey, however, consisted of small water systems. On this basis, there does not appear to have been a significant increase in chlorine dioxide usage for the period between 1998 and 2007.

Table 5: Summary of Disinfectant Use as Reported from the 1998 and 2007 AWWA Disinfection Surveys[8]

Disinfectant	1998 AWWA Survey % Water Systems		2007 AWWA Survey
	All Systems	Medium to Large Systems Only	% Water Systems
Chlorine (Gas)	70	84	63
Chlorine (Hypochlorite Bulk Liquid)	22	20	31
Chloramines	11	29	30
Chlorine Dioxide	4	8	8
Ozone	2	6	9

Due to the limited sample size, the trends observed from the 1998 and 2007 AWWA Disinfection Surveys may not be truly representative of community water systems in general. The data presented in Table 5 should be viewed with caution and considered as directional only.

A more accurate indication of the trend in disinfectant use in the field is provided by the EPA Community Water Systems Surveys conducted in 1995 and 2000, both of which sampled a significantly greater number of water systems. Based on these surveys, an overall decrease in the use of chlorine dioxide for surface water is observed from a maximum of 8% overall to 4% between 1995 and 2000. Chlorine dioxide disinfection of ground water also appears to have decreased from a maximum of 0.7% to 0.3% during the same time period.

Table 6: Summary of Chlorine Dioxide Use as Reported from the 1995 and 2000 EPA Community Water Systems Surveys[1,3]

Disinfectant	Percentage of Community Water Systems (%)			
	Surface Water		Ground Water	
	Primary	Secondary	Primary	Secondary
Chlorine Dioxide (2000)*	2.2 – 3.0	1.1	0.2	0.1
Chlorine Dioxide (1995)^	6.3	1.6	0.3	0.4

* Approximately 1,246 water systems surveyed.
^ More than 1,998 water systems surveyed.

Overall, both the EPA and AWWA surveys indicate that there has not been a significant trend toward increased chlorine dioxide use as an alternative disinfectant in the recent past. The EPA survey results between 1995 and 2000 actually appear to indicate a decrease in chlorine dioxide use during this time period. A more recent survey conducted by AWWA appears to indicate that there may only have been a very minor increase in chlorine dioxide usage by community water systems since 2000.

In order to assess the possible change in disinfection practices in the future, data from two AWWA surveys were reviewed which provided information on the planned addition of various alternative disinfectants for the water systems surveyed[4,8]. A summary of these results is provided in Table 7.

Table 7: Percentage of Water Systems Planning to Add Various Alternative Disinfection Practices[4,8]

Disinfectant Planned for Addition	Percentage of Water Systems (%)				
	1996 AWWA Water Stats Survey				2007 AWWA Survey
	Surface Water		Ground Water		
	Primary	Secondary	Primary	Secondary	
Chlorine	0.6	1.5	1.2	1.0	N/A
Chloramines	4.8	7.7	2.2	2.2	10
Chlorine Dioxide	2.6	0.7	0.2	0.0	4
Ozone	7.6	2.8	0.8	0.4	7

N/A: Not Applicable

The planned addition of chlorine dioxide as a future disinfection strategy was reported by the smallest percentage of water systems in both 1996 and 2007. Based on the 1996 survey results, fewer than 3% of water systems planned to add chlorine dioxide as an oxidant and/or primary disinfectant for surface water treatment and only 0.7% planned for its use as a secondary disinfectant. An insignificant proportion of water systems reported the intention to use chlorine dioxide for ground water disinfection as either an oxidant and/or primary disinfectant and none for its use as a secondary disinfectant. In contrast, chloramines and ozone were reported by the greatest percentage of water systems as potential alternative disinfectants for addition to their current treatment regimes. For surface water systems, ozone was most frequently selected as an oxidant and/or primary disinfectant (7.6%) and chloramines as a secondary disinfectant (7.7%). For ground water systems, the majority of water systems planning the addition of alternative disinfectants reported their preference for the use of chloramines as either an oxidant and/or disinfectant.

Similar to the results of the 1996 survey, the 2007 AWWA Disinfection Survey found that chloramines were the most favored disinfectant for inclusion in future treatment strategies, followed by ozone and chlorine dioxide. The results of these surveys indicate that chloramines continue to be the alternative disinfectant of choice for treatment plant operators compared to disinfectants such as chlorine dioxide and ozone.

Due to the limited sample size of the two AWWA surveys, the results presented in Table 7 must be considered with caution and be viewed as directional only. Furthermore, these survey results do not necessarily reflect the future trend in the use of the alternative disinfectants since the planned additions may not necessarily translate into actual additions in practice. Moreover, there may be

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elimination of already existing disinfection strategies in conjunction with these additions that may offset any gains made by a particular alternative disinfectant.

Overall, there does not appear to be a significant trend toward increased chlorine dioxide use compared to chloramines and ozone. Chlorine dioxide also appears to be the least preferred alternative disinfectant in shaping future treatment strategies, particularly as a secondary disinfectant for the maintenance of a residual. However, chlorine dioxide use may increase in the future considering the steady increase of medium to large water systems in the United States, the increasing focus on the control of disinfection by-products and the continuing trend toward disinfection for systems currently delivering untreated water. The promulgation of more stringent regulations[d] that aim to tighten the control over disinfection by-products and residuals in the distribution system may also further encourage the addition of alternative disinfectants, such as chloramines, ozone and chlorine dioxide, to existing treatment practices for water utilities in the United States. It is recommended that the industry continue to monitor chlorine dioxide usage to identify any significant shifts in usage patterns in the future.

7.0 Chlorine Dioxide Residual in the Distribution System

Although chlorine dioxide use in North America is significantly below that of chlorine and chloramines, there remains a small fraction of distribution piping and residential plumbing systems that can potentially be exposed to a chlorine dioxide residual. This section will examine the typical levels of chlorine dioxide residuals that may be encountered in the field in order to assess the potential risk the residuals may pose to the integrity of PEX piping systems.

The residual chlorine dioxide concentration within a distribution network of a water system is dependent upon several factors: raw water quality, temperature, dose at the treatment plant, the specific disinfection and water treatment strategy employed, and the design and size of the distribution network. During oxidation and primary disinfection, the oxidant demand of the raw water at the various stages of treatment will reduce the chlorine dioxide concentration below that of the initial dose. As the water moves through the treatment plant, any chlorine dioxide not consumed in the oxidation and disinfection process will enter the distribution network as a residual. If chlorine dioxide is not re-dosed as a secondary disinfectant prior to the water entering the distribution network, the residual can quickly dissipate and degrade to near negligible levels[7,9]. The presence of organic material, elevated water temperature and an increase in the water retention time will all accelerate the rate of chlorine dioxide decay along the distribution network. Several studies of community water systems in the United States and Canada have demonstrated the tendency of chlorine dioxide residuals to dissipate rapidly to very low levels along the distribution system. The

[d] Stage 2 Disinfection and Disinfection By-Products (D/DBP) Rule, 2006

following discussion will examine the details of these studies to better understand the behavior of chlorine dioxide residuals through the distribution piping and plumbing systems.

7.1 Primary Water Treatment with Chlorine Dioxide

The typical chlorine dioxide dosage for oxidation and primary disinfection can range from 0.07 to 2.0 mg/L depending on the raw water quality and the specific treatment strategy of the water system[1]. Practically, however, the dose is restricted by the tendency of chlorine dioxide to degrade into chlorite, a regulated by-product of chlorine dioxide disinfection, which is limited to a concentration of 1.0 mg/L in the finished water in the United States and Canada[1,7]. Because up to 70% of chlorine dioxide may eventually be converted into chlorite, if the oxidant demand of the raw water is greater than 1.4 mg/L, chlorine dioxide dosages exceeding 1.4 mg/L become prohibitory due to the accumulation of chlorite above regulatory limits[1,10]. A study of 17 community water systems by the 2008 AWWA Disinfection Survey reported a mean chlorine dioxide dose of 1.18 mg/L at the treatment plant for oxidation and/or primary disinfection[8]. This practical limit in chlorine dioxide dose as imposed by subsequent chlorite formation also limits, in turn, the concentration of the chlorine dioxide residual that ultimately ends up in the distribution network. Under certain circumstances, however, chlorine dioxide dosages exceeding 1.4 mg/L may be applied to raw water high in oxidant demand provided that additional physical or chemical methods are used to lower the oxidant demand prior to the injection of chlorine dioxide. The use of chlorine and/or chloramines in conjunction with chlorine dioxide in a multi-disinfectant approach to water treatment is a common strategy used by water utilities to achieve adequate disinfection and oxidation of heavily contaminated raw water, while at the same time preventing the production of chlorite above regulatory limits (See Sections 5 and 7.3).

7.2 Fate of the Chlorine Dioxide Residual in the Distribution System

Following injection of chlorine dioxide at the treatment plant, any residual that is not consumed by disinfection and oxidation processes enters the distribution system. The results of two studies investigating the fate of the chlorine dioxide residual in distribution networks of community water systems are presented in Tables 8 and 9.

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Table 8: Average Residual Levels of Chlorine Dioxide, Chlorine and Chloramines at Different Points in the Distribution System for Water Systems in the United States[9]

Disinfectant	Average Concentration (mg/L) (Range)		
	Entry Point	Average Retention Time Site	Maximum Retention Time Site
Chlorine Dioxide*	0.03 (0.00 – 0.16)	0.00 (0.00 – 0.00)	0.00 (0.00 – 0.01)
Free Chlorine	1.00 (0.00 – 3.90)	0.88 (0.00 – 3.00)	0.63 (0.00 – 2.20)
Chloramines	2.00 (0.00 – 4.00)	1.57 (0.00 – 3.40)	0.92 (0.00 – 2.50)
Total Chlorine	2.20 (0.00 – 5.50)	1.85 (0.00 – 3.90)	1.39 (0.00 – 3.40)

* The chlorine dioxide data represents approximately 8% of the water systems surveyed from a total of 312 water systems.

Table 9: Average Chlorine Dioxide Residual Levels at Different Points in the Distribution System for 8 Different Water Systems in Quebec, Canada[7]

Season	Average Concentration (mg/L) (Range)			
	Treatment Plant Outlet	D1*	D2	D3
Winter	0.22 (0.01 – 0.53)	0.09 (<0.01 – 0.21)	0.09 (<0.01 – 0.22)	0.03 (<0.01 – 0.06)
Summer	0.32 (<0.01 – 0.63)	NM	NM	NM

* D1, D2 and D3: Three different sampling locations along the distribution system (D1 is closest to the treatment plant outlet and D3 is farthest).
NM: Not measured

The chlorine dioxide residual from both studies is observed to deplete rapidly as the water travels from the treatment plant to the end of the distribution system. From an initial residual level of up to 0.16 mg/L among the water systems surveyed in the United States, the residual concentration is observed to decay completely at approximately the middle of the distribution network. Considering the relatively low initial concentration, the rapid depletion of the chlorine dioxide residual is not unexpected. In the Canadian study during the winter season, the initial chlorine dioxide residual is higher near the entry point of the distribution system, with an average concentration of 0.22 mg/L. This residual is observed to decrease by approximately 60% at the first sampling location to a level of 0.09 mg/L. At the final sampling location, located furthest downstream of the distribution network, the residual concentration drops further by approximately 86% to 0.03 mg/L.

The concentrations of chlorine and chloramines for water systems in the United States also experience a significant depletion along the distribution system by approximately 40 to 50% at the maximum retention time sites. The higher initial concentrations of these disinfectants, however, ensure that a significant proportion of the residual remains preserved until the end of the distribution system.

The study of chlorine dioxide residuals presented in Tables 8 and 9 highlights the relatively low concentration of chlorine dioxide that initially enters the distribution system after primary treatment and/or oxidation and its rapid dissipation along the distribution network. Assuming the results of these studies are typical of distribution networks of medium to large water systems in North America that use chlorine dioxide as a primary disinfectant and/or oxidant, the majority of people receiving water treated with chlorine dioxide may be exposed to near negligible levels of chlorine dioxide within their local pipe distribution and plumbing systems. The studies also show that the greater the retention time of the water within the distribution network, the greater the degree of depletion of the chlorine dioxide residual. Because medium to large water systems represent the majority of chlorine dioxide users, significant depletion of residuals as shown in Tables 8 and 9 may be typical of water systems employing chlorine dioxide as a primary disinfectant and/or oxidant, assuming similar initial concentrations at the entry point.

7.3 Review of Chlorine Dioxide Residuals in the Field

The maximum concentration limit of chlorine dioxide in finished water, as specified by the EPA[e] in the United States, is 0.8 mg/L[1]. Canada currently has not established a maximum concentration limit for chlorine dioxide but requires its disinfection by-products, chlorite and chlorate, to be present at levels below 1.0 mg/L in drinking water[7]. Health Canada believes that the high dissipation rate and reactivity of chlorine dioxide justifies this guideline strategy. Despite the absence of a maximum concentration limit, Health Canada recommends a maximum chlorine dioxide dose of 1.2 mg/L at the treatment plant to ensure chlorite and chlorate levels remain below the regulated limit[7].

The maximum concentration in the United States and the effective maximum concentration in Canada for chlorine dioxide are relatively high compared to several countries in Europe, such as Austria, Switzerland, Belgium and Germany, all of which limit the concentration of chlorine dioxide residuals at less than 0.25 mg/L in the drinking water[11,12]. Although the theoretical upper limit set by regulation is comparatively high, the practical residual level in the field for water systems in North America is expected to be less than 0.4 mg/L. Above this concentration, taste and odor issues may arise, rendering the water unpalatable for the consumer[7]. Therefore, a practical upper chlorine dioxide residual limit of 0.4 mg/L may be established.

The concentration of chlorine dioxide residuals that may actually be encountered in the field was determined by a review of the annual water quality reports of 42 randomly selected water systems reported to be using chlorine dioxide for oxidation and/or disinfection. These water systems are believed to represent approximately 7 to 12% of the total number of community water systems using chlorine dioxide in the United States. Due to the limited sample size, the results of the analysis based on this selected group of water utilities should be considered with caution and be viewed as directional only.

Conservative estimates of the average residual levels at the entry point to the distribution system for chlorine, chloramines, and chlorine dioxide were calculated based on maximum average reported residuals for each water system. Table 10 provides a summary of the calculated average residuals for

[e] Stage 1 Disinfection and Disinfection By-Products (D/DBP) Rule, 1998

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the three major disinfectants. A detailed summary of the residual concentrations for each water system can be found in Appendix C.

Table 10: Average* Residuals in the Distribution System of 42 Water Systems Using Chlorine Dioxide as a Disinfectant and/or Oxidant

	Disinfectant		
	Chlorine	Chloramines	Chlorine Dioxide
Average* Residual (mg/L)	1.6	2.6	0.15
% of Systems Reporting Residual Concentration	79	29	81

* The averages were calculated based on the maximum average values of each water system.

An average chlorine dioxide residual of 0.15 mg/L, well below the maximum regulatory limit of 0.8 mg/L, was calculated for the water systems examined. As expected, the residual averages for chlorine and chloramines were significantly higher at 1.6 mg/L and 2.6 mg/L, respectively. The majority of water systems were observed to use chlorine dioxide in conjunction with chlorine and less frequently with chloramines. This provides further confirmation of the prevalence of multi-disinfectant treatment strategies for chlorine dioxide water systems as indicated by the 1996 AWWA Water Utility Database Survey (See Section 5).

Table 11 lists the number of water systems that reported a chlorine dioxide residual. The majority of the water systems reported chlorine dioxide residuals of less than 0.15 mg/L and approximately half of the systems indicated residual levels at or below 0.05 mg/L. An appreciable number of water systems, representing 35% of the sampled systems, also reported residual levels greater than 0.15 mg/L. The average residual of these systems was 0.33 mg/L, which is below the practical limit of 0.40 mg/L to be expected in the field from taste and odor considerations. Only two systems reported residual concentrations just slightly greater than 0.40 mg/L and one system reported a maximum average residual of 0.79 mg/L. The residual concentration of 0.15 mg/L is used as a dividing marker for the impact analysis to be discussed in Section 10.

Table 11: Distribution of Chlorine Dioxide Water Systems According to Residual Concentration.

Chlorine Dioxide Residual Range (mg/L)	Number of Systems	% of Systems
≤ 0.05	17	50
0.06 – 0.10	4	12
0.11 – 0.15	1	3
>0.15	12	35

Assuming that the data presented in Tables 10 and 11 are representative of water systems using chlorine dioxide as a disinfectant and/or oxidant in the United States, it is estimated that, of the water systems using chlorine dioxide (1% of all systems), only a small fraction may be susceptible to a chlorine dioxide residual above 0.15 mg/L. The majority of the chlorine dioxide water systems are estimated to carry a chlorine dioxide residual at levels below 0.15 mg/L, with the majority of these systems having residuals less than 0.05 mg/L at the entry point to the distribution system. The actual level is expected to be lower due to decay along the distribution network, which has been shown to be potentially significant in several studies as discussed in Section 7.2. Furthermore, water systems that use chlorine dioxide are typically medium to large in size, which allows for a longer average retention time and consequently, further opportunity for residual decay.

For PEX materials used in distribution network piping systems, the exposure potential to chlorine dioxide for the bulk of the piping system is expected to be on average lower than 0.15 mg/L due to decay within the distribution network. However, there is still a small potential for chlorine dioxide exposure at levels between 0.15 and 0.8 mg/L, particularly for portions of the piping system closer to the entry point of the distribution system where the dissipation and degradation processes have had the least opportunity to lower the residual.

For PEX materials in residential plumbing systems, the exposure potential is estimated to be significantly less than 0.15 mg/L due to dissipation of the residual both within the distribution network and within the home. The residual is first subject to decay within the distribution network. After the water reaches the home of the consumer, there is a further chance of decay as the water is stored in the elevated temperature environment of a hot-water tank. Specific studies of residual consumption in the hot-water tank were not available to characterize this explicitly. However, several studies of water systems in hospitals have shown that chlorine dioxide residual in hot water is significantly lower than in cold water[13]. The results of one study indicate a decrease of the chlorine dioxide residual of more than 70% in hot water compared to the residual measured in cold water[14].

8.0 Chlorine Dioxide Use in Europe

Similar to North America, chlorine is the principal primary disinfectant and oxidant used by water systems in Europe. However, the use of chlorine dioxide is generally more prevalent in Europe, especially in countries such as France, Italy, Belgium, Germany and Switzerland[12,15]. In particular, the use of chlorine dioxide for secondary disinfection to maintain a residual in the distribution system is a widespread practice in Europe compared to North America[15]. As a result, there is a greater potential for pipe distribution and plumbing systems in Europe for exposure to a chlorine dioxide residual. In contrast, North American water systems rarely apply chlorine dioxide as a secondary disinfectant, relying instead on chlorine or chloramines for maintaining a residual in the distribution network. Although primary treatment can also lead to the presence of a residual, without rigorous optimization and monitoring programs in place to carefully control the residual level along the entire distribution network, the residual may be subject to significant decay before the water reaches the piping and plumbing systems of the consumer. Possible differences in average water retention times, a focus away from high-dose chemical disinfection practices[f] and greater attention toward multi-barrier approaches and organic reduction strategies may be some of the reasons why European water utilities achieve better success in maintaining a stable chlorine dioxide residual throughout the distribution network[6]. It has been reported that water pre-treated with granular activated carbon systems experience lower levels of chlorine dioxide consumption[16].

Typical chlorine dioxide residuals in Europe can range from less than 0.05 mg/L to greater than 0.25 mg/L depending on the raw water quality, specific disinfection practices and strategies, and the condition and size of the distribution network[12,15]. Legislated maximum chlorine dioxide residuals for a selected number of European nations are presented in Table 12.

Table 12: Legislated Maximum Chlorine Dioxide Residual Concentrations for Three European Countries[17]

Country	Chlorine Dioxide Residual (mg/L)
Belgium	0.25
Switzerland	0.15
Germany	0.20

Overall, the prevalence of chlorine dioxide use as a secondary disinfectant in Europe does not reflect the usage pattern of water systems in North America, which continue to rely predominantly on chloramines as the preferred secondary disinfectant for preventing bacterial re-growth within the distribution system. As a result, pipe distribution and plumbing systems in Europe are much more likely to be exposed to higher levels of chlorine dioxide overall due to its prevalent use as a residual, particularly in countries such as Italy[g], which is the most frequent user of chlorine dioxide in Europe[12].

9.0 Summary of Chlorine Dioxide Use in North America

Chlorine dioxide accounts for a very small fraction of total disinfectant use by community water systems in North America. In the United States, it is most often used as a primary disinfectant and/or oxidant in medium to large water systems that draw on surface water sources such as rivers and lakes. This accounts for less than 2.2 to 3.0% of community water systems. In total, it is estimated that less than 600 community water systems in the United States deliver water treated with chlorine dioxide, representing approximately 1% of all community water systems in the United States. Among those systems that use chlorine dioxide, it is estimated that less than one third apply it as a secondary disinfectant, predominantly in conjunction with other disinfectants such as chlorine and chloramines. When multiple disinfectants are used, the principle residuals relied upon

[f] European Drinking Water Directive (98/83/EC), which European nations use as a guiding principle for the implementation and regulation of disinfection practices, does not require the use of chemical disinfectants or residuals.

[g] 70% of drinking water in Italy is obtained from river water high in organic matter[11].

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for ensuring the potability of the finished water may largely be provided by chlorine and/or chloramines due to the rapid decay of chlorine dioxide along the distribution network to very low levels.

Surveys conducted by EPA and AWWA on community water systems suggest that chloramines has been the most preferred alternative disinfectant to chlorine in the past and continues to be the most popular secondary disinfectant alongside chlorine. Chlorine dioxide and ozone appear to be the least preferred alternative disinfectants for primary disinfection and oxidation and especially for secondary disinfection. Overall, there does not appear to be a significant trend toward increased chlorine dioxide use for the near future. However, increased focus on the control and monitoring of disinfection by-products and residuals in the distribution system, the general increase in medium to large water systems, and the continuing reliance on chemical disinfection practices may all contribute to the growth in chlorine dioxide use in the future. It is recommended that the industry continue to monitor chlorine dioxide usage to identify any significant shifts in usage patterns in the future.

The chlorine dioxide residual has been shown in several studies to dissipate significantly along the distribution network, with near complete depletion of the residual prior to the water reaching the consumer. Several factors can contribute to an increase in the residual consumption within the distribution network: higher average residence times which are typically associated with larger water systems, higher residual oxidant demand of the finished water, and lower initial doses at the treatment plant. Since chlorine dioxide use is most common as a primary disinfectant and/or oxidant in medium to large water systems, it is expected that decay along the distribution system would play a significant factor in determining the residual level to which piping and plumbing systems will be exposed. Specifically for residential plumbing systems, there is a further potential for residual decay during storage of the water in a hot-water tank.

Based on a review of the water quality reports of 42 water systems using chlorine dioxide as a disinfectant and/or oxidant, it was observed that the majority of water systems reported a residual concentration of less than 0.15 mg/L near the entry point to the distribution system. Nearly half were found to have levels below 0.05 mg/L. A moderate percentage of systems (35%) reported a chlorine dioxide residual greater than 0.15 mg/L, with an average maximum residual of 0.33 mg/L. Assuming that the water systems investigated are representative of those using chlorine dioxide in the United States, it is estimated that the majority of these water systems carry chlorine dioxide residuals at levels below 0.15 mg/L in the distribution network. However, higher residual levels may be encountered in the field for a very small fraction of water systems, accounting for approximately 0.3% of all water systems (or 200 utilities).

Based on the data presented in Section 7.3, PEX piping materials used for distribution network piping systems are expected to be exposed to residual levels less than 0.15 mg/L under the majority of situations in the field. A third of chlorine dioxide systems, however, are estimated to have

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exposure levels greater than 0.15 mg/L. The potential for chlorine dioxide exposure at levels greater than 0.4 mg/L appears to be extremely low. For PEX piping materials in residential plumbing systems, the exposure potential is expected to be even less than that of PEX materials used in the main distribution network because dissipation and degradation of the chlorine dioxide residual may occur both within the distribution network and in the hot-water tank within the home of the consumer.

10.0 Impact of Chlorine Dioxide on PEX Piping Systems

This section considers the potential impact of chlorine dioxide on PEX piping systems based on anticipated exposure levels and projected material response to exposures at those levels.

Based on the available data for PEX pipe, an estimate of PEX performance in chlorine dioxide treated water at typical end-use water quality conditions is made. The failure time of a PEX piping material tested in accordance with ASTM F2023 at 115°C/60 psig was found to approximately double when the chlorine dioxide concentration was decreased from 4.3 mg/L to 0.8 mg/L. Assuming a linear relationship between chlorine dioxide concentration and failure time, the extrapolated failure time for PEX at a chlorine dioxide concentration of 0.15 mg/L is generally comparable to the failure time for chlorine at 4.3 mg/L[h]. Therefore, ASTM F2023 appears to be robust enough to account for chlorine dioxide usage at levels below 0.15 mg/L. Given that approximately two-thirds of chlorine dioxide systems have residuals less than 0.15 mg/L at the entry point to the distribution system and that these residuals appear to dissipate rapidly along the distribution system and are anticipated to dissipate further in the hot-water tank, the potential for exposure in hot-water plumbing systems to chlorine dioxide residuals greater than 0.15 mg/L would appear to be very low. It appears, therefore, that ASTM F2023 testing is aggressive enough to ensure minimum performance of residential plumbing systems for the current chlorine dioxide usage in the vast majority of applications in North America. The generally conservative nature of the ASTM F2023 test methodology in terms of its temperature and stress components further ensures the robustness of ASTM F2023 in accounting for the most prevalent chlorine dioxide usage levels.

For PEX materials used in distribution system piping, there appears to be the potential for exposure to water qualities more aggressive than outlined in ASTM F2023. However, given that distribution systems operate at low water temperatures and that PEX pipe performance is validated for hot potable water applications, the current requirements of ASTM F876 appear robust enough to ensure minimum performance of distribution system piping for essentially all potential chlorine dioxide exposure levels.

[h] The failure time for PEX exposed to chlorine at 4.3 mg/L is observed to be 16% higher than the extrapolated failure time for chlorine dioxide at 0.15 mg/L. The difference in the failure times is generally within the ±15% tolerance expected between replicates specimens.

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The above analysis must be taken as directional only based on several considerations. First, the results of the ASTM F2023 testing used in the above analysis is based on testing of one PEX material at a single test condition only and does not represent a performance extrapolation of the PEX material. Furthermore, the data necessary to specifically characterize the potential decay of the chlorine dioxide residual in residential hot-water tanks is not available and, therefore, an estimate of the potential decay in this system cannot be quantified. Information on the typical residual levels of chlorine dioxide water systems was also determined from a review of a limited number of water systems and therefore may not be representative of all water systems in the United States. Lastly, it was observed that most water systems use chlorine dioxide in conjunction with other disinfectants such as chlorine and chloramines. The potential impact of multiple disinfectant residuals on PEX piping systems has not been considered.

11.0 Conclusions

Based on the review of the current usage patterns of chlorine dioxide, the following conclusions are made:

- Chlorine dioxide is used in a limited number of potable water systems in North America. In the United States, it is estimated that it is used for oxidation and/or primary disinfection in less than 1% of community water systems (or 600 systems) overall. As a secondary disinfectant, it is estimated that less than 200 systems use chlorine dioxide for the maintenance of residual in the distribution system, primarily in conjunction with chlorine and/or chloramines.

- Typical chlorine dioxide levels in distribution systems in the United States appear to be less than 0.40 mg/L, with two-thirds of systems carrying a chlorine dioxide residual of less than 0.15 mg/L. The actual values are expected to be lower for the bulk of the distribution system due to decay of the residual along the distribution network. The residual level is projected to be even lower in household plumbing systems due to further potential dissipation and decay of the residual in the household hot-water tank.

- There does not currently appear to be a significant trend toward increased chlorine dioxide usage. However, the increased focus on the control and monitoring of disinfection by-products produced by traditional chlorination practices may continue to promote the use of alternative disinfectants such as chlorine dioxide in the future. It is recommended that the industry continue monitoring trends to identify any significant shifts in usage patterns in the future.

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- Based on the analysis of available test data, current ASTM F876/F2023 requirements for chlorine resistance of PEX pipe in potable water plumbing applications appear robust enough to ensure minimum performance of both PEX distribution and residential plumbing systems for the vast majority of potential chlorine dioxide exposure levels in North America.

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Appendix A

Chlorine Dioxide Chemistry

Chlorine dioxide is a highly volatile and energetic molecule that reacts violently with reducing agents at high concentrations. It is dark amber in color and extremely unstable under pressure and at ambient temperatures. In the gaseous phase, it can be explosive under conditions in which the chlorine dioxide concentration exceeds 10% by volume in air. Although highly reactive as a pure solution, it can be stored under chemically stable conditions as a dilute aqueous solution provided that build-up of pressure, high temperatures, and exposure to light are avoided. Due to its instability, chlorine dioxide is always produced on-site through various chemical reactions. Common generator reactions that are employed by most generators use sodium chlorite ($NaClO_2$) with either hypochlorous acid (HOCl) or hydrochloric acid (HCl). The mass-balance reactions are provided below.[6,19]

$$2\ NaClO_2 + HOCl \rightarrow NaCl + NaOH + 2\ ClO_2(g)$$

$$5\ NaClO_2 + 4\ HCl \rightarrow 4\ ClO_2(g) + 2\ H_2O + 5\ NaCl$$

$$2NaClO_2 + Cl_2(g) \rightarrow 2\ ClO_2(g) + 2\ NaCl$$

The third reaction involving sodium chlorite and chlorine gas has the advantage of producing a neutral end product. Extreme pH conditions, whether acidic or basic, can disrupt the formation of chlorine dioxide and facilitate less efficient chlorate-forming reactions. Depending on the type of generator system used, therefore, pH control is an essential element in the process flow in order to minimize production of inorganic by-products such as chlorates and chlorides, and optimize the production of chlorine dioxide.[1]

Chlorine dioxide is a strong and selective oxidant that reacts by accepting a single electron and forming chlorite (ClO_2^-) as a by-product. Chlorite, in turn, is ultimately reduced to chloride (Cl^-) involving the transfer of four additional electrons.[1]

$$ClO_2 + e^- \rightarrow ClO_2^- \qquad 0.95\ V$$

$$ClO_2^- + 2\ H_2O + 4\ e^- \rightarrow Cl^- + 4\ OH^- \qquad 0.76\ V$$

The total oxidation capacity of chlorine dioxide is represented by the five electrons involved in the above two reactions. Table A1 provides a comparison of the oxidation capacity of aqueous chlorine dioxide versus free chlorine. Chlorine dioxide is capable of more than double the oxidation capacity of free chlorine. The high oxidation capacity of chlorine dioxide coupled with its ability to

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selectively target phenols while avoiding reactions with organic matter such as humic and fulvic acids allows it to be an effective oxidant in the control of taste and odors in water treatment without the production of disinfection by-products such as trihalomethanes[6,19,20].

Table A1: Oxidation Capacity of Chlorine Dioxide and Chlorine[19]

Disinfectant	Oxidation Capacity
Chlorine Dioxide	$5e^-$
Free Chlorine	$2e^-$

Appendix B

Additional Water System Disinfectant Usage Data

Table B1: Chlorine Dioxide Use for Surface Water Systems[3]

Pre-disinfection/Oxidation Prior to Sedimentation	≤100	101 – 500	501 – 3,300	3,301 – 10,000	10,001 – 50,000	50,001 – 100,000	100,001 – 500,000	Over 500,000	All Sizes
Chlorine	18.6	2.9	37.6	50.9	51.7	45.8	52.2	45.4	34.5
Chlorine Dioxide	**0.0**	**0.0**	**0.0**	**3.0**	**3.9**	**11.4**	**7.4**	**4.3**	**2.2**
Chloramines	0.0	0.0	0.0	1.0	8.3	0.0	10.0	11.1	2.4
Ozone	0.5	0.9	0.0	1.0	0.0	5.3	3.9	6.0	1.0
Potassium Permanganate	0.0	1.1	24.9	29.4	37.1	29.2	27.8	26.6	20.3
Other Pre-disinfection	0.0	0.0	4.8	1.0	0.0	0.0	1.7	0.0	1.3
Pre-disinfection/Oxidation Prior to Filtration									
Chlorine	7.4	11.9	24.2	24.3	35.4	38.3	31.5	37.7	23.0
Chlorine Dioxide	**0.0**	**2.0**	**0.0**	**0.0**	**1.1**	**2.0**	**2.8**	**0.0**	**0.8**
Chloramines	0.0	0.0	0.0	0.0	4.6	1.3	6.9	7.7	1.4
Ozone	0.0	15.3	0.0	0.0	1.1	2.3	4.1	6.0	3.5
Potassium Permanganate	0.0	1.2	6.9	10.1	5.5	7.8	3.9	2.6	5.0
Other Pre-disinfection	0.0	0.0	4.4	0.0	0.0	2.0	0.0	0.0	1.0
Post-Disinfection After Filters									
Chlorine	27.8	58.3	77.4	85.3	83.7	75.3	74.5	53.9	68.7
Chlorine Dioxide	**0.0**	**0.0**	**0.0**	**1.0**	**5.0**	**1.5**	**0.6**	**0.0**	**1.1**
Chloramines	0.0	0.0	0.0	4.1	22.5	18.9	23.6	21.3	7.1
Ozone	0.0	0.7	0.0	0.0	0.0	5.3	0.0	1.7	0.4
UV	11.7	0.0	0.0	0.0	0.0	0.0	0.6	0.0	1.6
Other Post-disinfection	0.0	0.0	7.9	0.0	2.1	1.0	1.1	0.0	2.1

Note: The percentages in each column may not necessarily add up to 100%. A single water system may report the use of multiple disinfectants.

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Table B2: Chlorine Dioxide Use for Ground Water Systems[3]

Pre-disinfection/Oxidation Prior to Sedimentation	≤100	101 – 500	501 – 3,300	3,301 – 10,000	10,001 – 50,000	50,001 – 100,000	100,001 – 500,000	Over 500,000	All Sizes
Chlorine	0.0	7.5	9.4	10.6	11.3	5.9	9.5	0.0	7.2
Chlorine Dioxide	**0.0**	**0.0**	**0.0**	**0.0**	**0.7**	**10.5**	**0.4**	**0.0**	**0.2**
Chloramines	0.0	0.0	0.0	0.0	0.0	0.6	4.5	0.0	0.1
Ozone	0.5	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.1
Potassium Permanganate	0.0	3.7	3.2	4.4	0.7	1.2	0.4	0.0	2.6
Other Pre-disinfection	1.3	0.0	0.0	0.0	0.7	0.0	4.9	0.0	0.4
Pre-disinfection/Oxidation Prior to Filtration									
Chlorine	1.5	7.1	10.0	7.5	10.8	1.2	3.0	2.5	6.9
Chlorine Dioxide	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.4**	**0.0**	**0.0**	**0.0**
Chloramines	0.0	0.0	0.0	0.0	0.0	1.2	0.4	0.0	0.0
Ozone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Potassium Permanganate	1.0	1.4	5.0	2.4	4.0	0.0	0.4	0.0	2.6
Other Pre-disinfection	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Post-disinfection After Filters									
Chlorine	8.5	7.8	15.3	21.0	19.9	3.3	11.5	2.7	12.3
Chlorine Dioxide	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**6.6**	**0.0**	**0.1**
Chloramines	0.0	0.0	0.0	0.8	1.4	1.8	3.4	0.0	0.3
Ozone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other Post-disinfection	0.0	0.0	1.4	0.0	0.0	5.8	0.0	0.0	0.5

Note: The percentages in each column may not necessarily add up to 100%. A single water system may report the use of multiple disinfectants.

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Appendix C

Distribution System Water Quality Data of Community Water Systems

Table C1: Maximum Average Chlorine, Chloramine and Chlorine Dioxide Residual Concentrations near the Distribution System Entry Point of 42 Community Water Systems using Chlorine Dioxide

Water Utility	State	Chlorine (mg/L)	Chloramines (mg/L)	Chlorine Dioxide (mg/L)	Year Reported
Mobile Area Water and Sewer System	AL	2.0	NR	0.15	2008
City of Mesa	AZ	1.0	NR	0.01	2007
City of Grover Beach	CA	2.1	NR	0.16	2008
City of Greeley	CO	1.1	NR	0.16	2009
Fort Collins	CO	0.5	NR	0.00	2008
Groton Utilities	CT	1.9	NR	NR	2008
Tampa Water Department	FL	NR	3.5	0.43	2008
City of Oldsmar Public Water System	FL	3.5	NR	NR	2008
Clayton County Water Authority	GA	2.2	NR	0.01	2008
Macon Water Authority	GA	2.0	NR	0.79	2008
Fayette County Water System	GA	1.4	NR	0.01	2008
City of Decatur	IL	0.7	1.3	0.05	2009
Paducah Water	KY	1.0	NR	0.38	2009
Madisonville Water Filtration Plant	KY	1.6	NR	0.28	2008
Town of Tewksbury	MA	NR	NR	NR	2006
City of Smithville	MO	NR	NR	NR	2007
Union County Public Works	NC	1.2	2.9	0.03	2009
Town of Holden Beach	NC	2.0	2.6	0.02	2008
Harnett County Regional WTP	NC	1.4	2.9	0.10	2008
New Jersey American Water	NJ	2.0	NR	0.16	2007
Water Commissioners of Town of Waterford	NY	0.8	NR	0.01	2008
Village of Albion Water System	NY	2.2	NR	0.39	2008
Village of Colonie	NY	1.2	NR	0.05	2008
Village of Waterloo	NY	NR	2.6	0.43	2008
Binghamton Water Bureau	NY	1.4	NR	0.04	2008
City of Troy	NY	0.8	NR	0.01	2008
Akron Public Utilities	OH	1.4	NR	0.32	2008
Village of Archbold	OH	1.2	NR	0.10	2008
City of Alliance	OH	1.2	NR	0.18	2008
City of Tulsa	OK	1.8	NR	NR	2008
Kiawah Island Utility	SC	NR	2.5	0.10	2007
Charleston Water System	SC	NR	2.2	0.10	2008
Winchester Utilities	TN	2.4	NR	0.02	2008
Texas City	TX	NR	2.2	NR	2008
McAllen Public Utility	TX	2.2	NR	0.31	2007
El Paso Water Utilities	TX	2.6	NR	0.04	2008
City of Terrell	TX	0.6	2.7	0.04	2008
City of Sachse	TX	NR	2.6	0.04	2008
City of Allen	TX	2.6	NR	0.04	2009
Benbrook Water Authority	TX	1.3	NR	NR	2007
City of Waxahachie	TX	NR	2.9	0.01	2008
Western Virginia Water Authority	VA	1.3	NR	NR	2009

NR: Not Reported

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