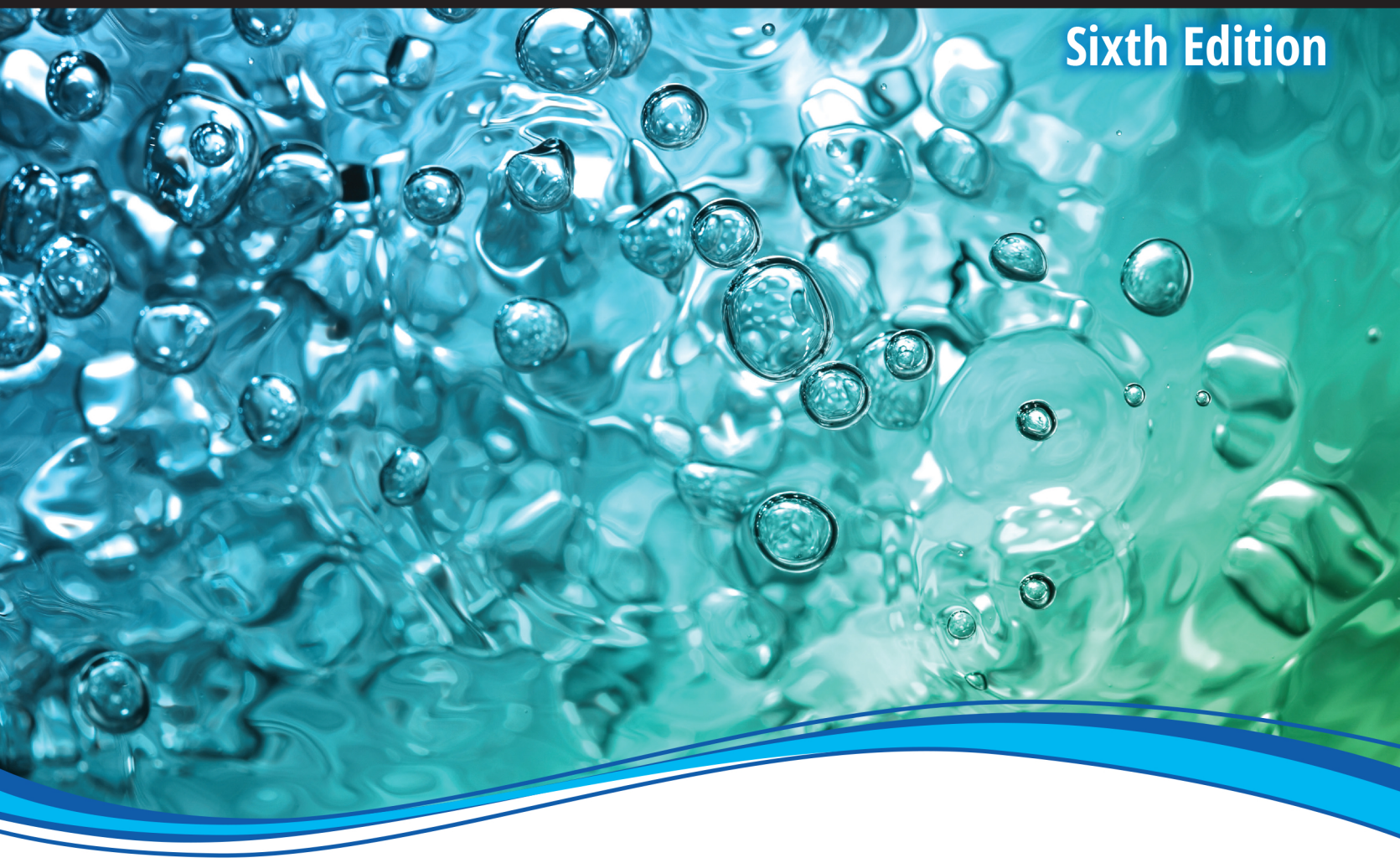
Manual of Water Supply Practices

M4

Water Fluoridation

Principles & Practices

Sixth Edition



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Water Fluoridation Principles & Practices

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Preface

The American Water Works Association has been an active partner in water fluoridation from the original pioneering studies on its implementation and effectiveness from 1945 through 1951, and has supported community water fluoridation since 1951.

In addition, from the 1940s to the 1960s, the US Public Health Service provided national leadership in water fluoridation practice and issued periodic technical advisories on water fluoridation. The US Environmental Protection Agency (USEPA) provided support and guidance on technical practice from 1972 to 1978 until the Centers for Disease Control and Prevention (CDC) assumed responsibility for providing support to state water fluoridation programs in 1978.

These organizations' wealth of knowledge gained through the experiences and management of several thousands of fluoridation process installations can improve future installations and enhance successful continued operations to provide improved health for our communities.

This manual is a resource to assist decision makers planning to use fluoridation treatment, engineers designing and installing these facilities, and water utility personnel managing water operations. The manual presents guidelines and is not intended to take the place of expert advice. Anyone planning or using fluoridation should carefully consider fluoride research, regulations, and methods. State or provincial regulatory requirements should always be the first point of reference for water fluoridation design and practices to improve the health of the citizens.

The first edition of the American Water Works Association M4 *Water Fluoridation Principles & Practices* was prepared from material supplied and previously published by the USEPA. The second edition was updated and revised using additional technical collaboration with the US Centers for Disease Control and Prevention. The third, fourth, and fifth editions were updated and revised incrementally by section. This sixth edition represents a substantial updating and revising of the manual's content to remain consistent with industry practices and to reflect changes in regulatory and public health guidance and the experience of contributing authors.

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Chapter 1

Water Fluoridation

INTRODUCTION

The goal of this manual is to assist with the planning and operation of fluoridation systems by decision makers, design engineers, and water utility personnel. This chapter discusses fluoride occurrence, growth of community water fluoridation, and legal issues surrounding fluoridation. The regulatory requirements of community water fluoridation are also addressed, including both federal regulations and the varying approaches states have used to implement fluoridation programs. Additionally, fluoridation outside of the United States is discussed.

Fluoridation in this manual refers to the addition of fluoride to drinking water to maintain a recommended level to improve oral health. Fluoridation was named as one of the Ten Great Public Health Achievements in the 20th Century by the Centers for Disease Control and Prevention (CDC) along with the use of chlorine for disinfection of public water supplies (CDC Morbidity and Mortality Weekly Report, April 2, 1999). Control of infectious diseases has resulted from clean water and improved sanitation. Infections such as typhoid and cholera transmitted by contaminated water, a major cause of illness and death early in the 20th century, have been reduced dramatically by improved sanitation. Water fluoridation was first implemented in 1945, and in 1951, the National Research Council (NRC) of the National Academy of Sciences (NAS), the US Surgeon General, and professional organizations including the American Water Works Association (AWWA) and the American Dental Association (ADA) recommended that communities implement water fluoridation. The US Public Health Service (USPHS) recommended a range of 0.7 to 1.2 mg/L (based on annual average ambient temperature) as part of the 1962 Drinking Water Standards. In 2011, the US Department of Health and Human Services (USHHS) proposed changing the recommended fluoride level in drinking water to a single value of 0.7 mg/L. According to national health surveillance statistics reported by the USPHS and the CDC, the number of people with access to fluoridated water continues to increase and in 2012, 210.6 million people in the United States had access to fluoridated water.*

* 2012 Water Fluoridation Statistics from the US Centers for Disease Control (CDC).

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OCCURRENCE

Fluorine, a gaseous halogen, is the 13th most abundant element in the earth's crust. Fluorine is also the most electronegative element, so it is not found in its free elemental form in nature. Instead, it exists as a mineral such as fluorosilicates in granites, calcium fluorides in some ores, along with other mineral forms, or as a dissolved reduced ionic form in solution. Fluoride ion solubility varies, but the sodium and potassium salts of fluoride are highly water soluble.

There are both natural and anthropogenic sources of fluoride. Natural sources of fluoride include volcanic and geothermal activity emissions, weathering of certain types of rocks, wind-blown erosion of soils, and marine origin. Commercial ore deposits of fluorspar, fluorapatite, and cryolite are the source for most fluoride products. Anthropogenic releases of fluoride occur predominantly because of the burning of coal for power production and are also caused by manufacturing, steel and aluminum production, and oil refining.

Fluoride is ubiquitous in the environment and therefore likely to be present to some extent in all water sources. Seawater contains approximately 1.2 to 1.5 mg/L of fluoride. The concentration present in source water is often equal to the fluoride in rainfall, which is typically 0.1 to 0.2 mg/L. However, natural levels in proximity to volcanic sources can be significantly higher because volcanic emissions are recognized as a significant environmental source. The naturally occurring concentrations in surface waters are generally lower than those needed to promote good dental health. Fluoride concentrations in groundwater can be more variable than in surface water, with the concentration dependent on the geological setting. In the United States, groundwater levels typically range from nondetectable levels to greater than 4 mg/L. However, elevated levels of naturally occurring fluoride are not common. Based on reported natural fluoride levels in community public water systems, the CDC estimates that less than 0.5% of the US population served by public water systems has natural fluoride levels exceeding 2 mg/L, and less than 0.1% of the population served by public water supplies has naturally occurring fluoride in excess of 4 mg/L. The US Geological Survey (USGS), in a survey of private groundwater wells, estimated that up to 4% of private wells exceed 2 mg/L and up to 1.2% exceed 4 mg/L (Quality of Water from Domestic Wells in the United States, Leslie DeSimone et al. November 2009). Private wells can have a higher incidence of elevated fluoride as many homeowners do not test their wells for contaminants, while public water supplies are required to report on contaminants levels and have worked to identify alternate sources when possible.

HISTORY OF USE (GROWTH OF COMMUNITY WATER FLUORIDATION)

The importance of fluoride as a nutrient for good oral health resulted from environmental observations of communities with naturally occurring fluoride. In the 1920s and 1930s, fluoride was identified as a factor in tooth development. Investigations showed that in communities having naturally fluoridated water, fluorosis (mottled or discolored teeth) occurred when the fluoride content of the water was abnormally high. However, these teeth also showed decreased incidence of tooth decay or dental caries, which was unusual considering the large prevalence of tooth decay in that era. During the 1930s, studies concluded that the beneficial range of fluoride to prohibit dental caries while still minimizing risk of dental fluorosis was 1.0 mg/L to 1.5 mg/L, with an optimum concentration of 1.0 mg/L to achieve the beneficial level while remaining below the higher levels that could stain teeth.

Starting in 1945, initial community trials were held to test the theories that fluoride reduced tooth decay formulated over the preceding decades. In each of these trials, one

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city implemented community water fluoridation, while at least one other city acted as the control. The cities had parallel characteristics except for the fluoride content of the water supply. Several of these studies, implemented between 1945 and 1947, are listed here (naturally occurring fluoride levels are given in parentheses):

1. Grand Rapids, Mich. (0.15 mg/L): Adjusted to 1.0 mg/L as part of this study. This city was compared with the control cities of Muskegon, Mich. (0.15 mg/L) and Aurora, Ill. (naturally 1.2 mg/L).
2. Newburgh, N.Y. (0.1 mg/L): Adjusted to 1.1 mg/L as part of this study. The control city for this trial was Kingston, N.Y. (0.1 mg/L).
3. Evanston, Ill.: Adjusted to approximately 1 mg/L as part of this study. This city was compared with the control city of Oak Park, Ill. (negligible amounts of natural fluoride).
4. Brantford, Ont. (0.1 mg/L): Adjusted to 1.0 mg/L as part of the study. This city was compared with the control cities of Sarnia, Ont. (0.1 mg/L), and Stratford, Ont. (naturally 1.2 mg/L).

On Jan. 25, 1945, Grand Rapids, Mich., became the first city to add fluoride to its water supply. In this study, the oral health in Grand Rapids was compared with that of Muskegon, a nearby community consuming water from the same source without fluoride addition. Six years after the study began, surveys indicated that tooth decay levels in six-year-old children (i.e., those born since fluoridation commenced) in Grand Rapids was approximately half that of Muskegon.

At the time of these early community trials, poor oral health and widespread dental decay was common, so favorable results were met with great interest. The analysis of the first results from these community trials was published by the National Research Council (NRC) of the National Academy of Sciences (NAS) in November 1951 and summarized in the January 1952 issue of *Journal AWWA* (Vol. 44, no. 1, 1–8) with the recommendation that all cities with a child population of sufficient size should fluoridate the water supply. Preliminary reports from the NRC in 1951 prompted the US Surgeon General to recommend that cities should fluoridate their water supplies. In July 1951, city officials in Muskegon decided to withdraw from the study and fluoridate the city's water supply. Similar results were observed in the other trials referenced, i.e., significant reduction in dental decay rates was observed in the cities that were fluoridating, with little or no change in the controls. Since that time, the US population receiving optimally fluoridated drinking water has continued to increase (Figure 1-1).

In 1951, major organizations such as the USPHS, NRC, US Surgeon General, and AWWA all endorsed community water fluoridation. In 1962, the USPHS recommended that fluoride in drinking water should be 0.7 to 1.2 mg/L based on ambient annual temperature to reflect the different consumption of water between warmer climates and cooler climates. In 2011, the Department of Health and Human Services proposed changing this range to a single recommended value of 0.7 mg/L to reflect modern exposures and water consumption; this is discussed in further detail in chapter 2.

The AWWA policy statement on fluoridation was adopted by the organization's board of directors on Jan. 25, 1976, reaffirmed on Jan. 31, 1982, and revised on Jan. 20, 2002, Jan. 21, 2007, and Jan. 22, 2012. The official text is as follows:

> The American Water Works Association (AWWA) supports the recommendations of the World Health Organization (WHO), American Medical Association (AMA), Canadian Medical Association (CMA), Centers for Disease Control (CDC), American Dental Association (ADA), Canadian Dental Association (CDA), and other professional organizations in the medical community, for the

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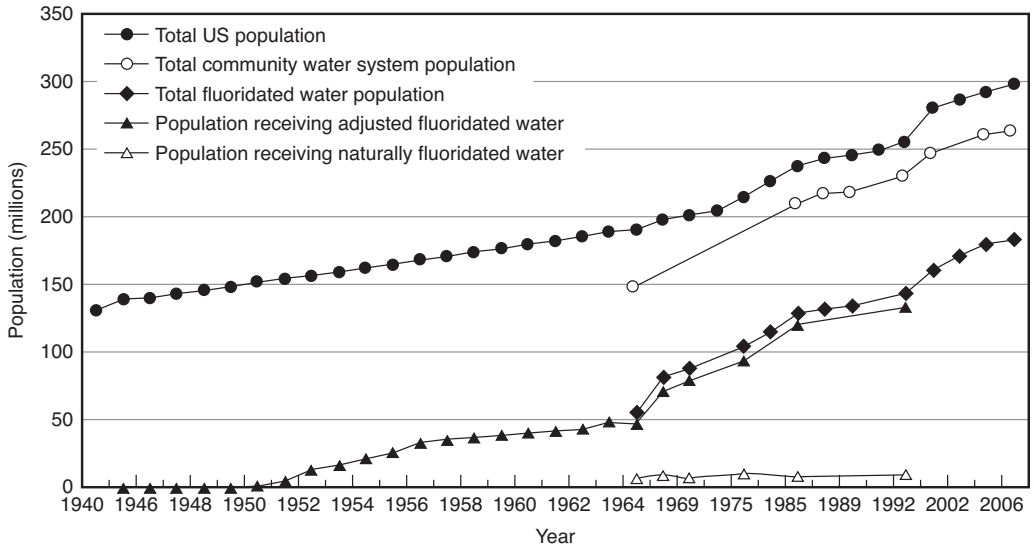

Figure 1-1 Growth of community water fluoridation around the world

Source: CDC - Fluoridation Growth. 2012.

fluoridation of public water supplies as a public health benefit. AWWA supports the application of fluoride in a responsible, effective, and reliable manner that includes monitoring and control of fluoride levels mandated by provincial, state, and/or federal laws and that is subject to community acceptance through applicable local decision-making processes. AWWA is committed to regular reviews of the most current research on fluoride and the positions of the medical and dental communities.

In 1945, Brantford, Ont., became the first Canadian city to add fluoride to its water as part of the community trials referenced previously. Approximately 45 percent of the Canadian population using public water supplies receives fluoridated water.

As the use of drinking water fluoridation increased in the United States and Canada, countries in Europe, South America, Africa, and Asia also began implementing water fluoridation. By the year 2004, water fluoridation was being practiced in more than 60 countries for almost 405 million people. In addition, another 50 million people have water supplies that are considered naturally fluoridated at levels sufficient for good oral health. Fluoridation is practiced extensively in Australia, Brazil, Canada, Chile, Columbia, Ireland, Israel, Malaysia, New Zealand, People's Republic of China, Hong Kong, Singapore, and the United Kingdom. In addition to US organizations such as the American Medical Association (AMA), American Dental Association (ADA), and the CDC, international organizations such as the World Health Organization (WHO) support water fluoridation.

More detailed information about fluoridation in the international community can be found in the American Dental Association's *Fluoridation Facts* document.

Benefits of community water fluoridation. Fluoridation is a cost-effective and practical form of preventing tooth decay. The benefits of community water fluoridation include prevention of dental caries, the ability to provide a consistent and optimized level of fluoride, and an inexpensive mechanism to provide health benefits to all, regardless of age, income, education, or socioeconomic status. Fluoridation has traditionally been justified based on the economics of a 40 to 65 percent reduction in dental caries. The CDC estimates that every $1 invested

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in water fluoridation yields an approximate $38 in savings from dental treatment costs in most cities (Griffin et al. 2001).

Legal Issues

Fluoridation of public water supplies has not been without controversy. Opponents of community water fluoridation have challenged its safety and effectiveness. The legality of fluoridation has been tested in the courts numerous times. Beginning in 1952, injunctions were sought in some communities to prevent the initiation or continuance of fluoridation. These cases were generally based on the following types of arguments:

- Violation of religious freedom
- Abuse of police power (the ability of the state to make laws concerning the health, safety, and welfare of its citizens)
- Infringement of personal choice through mass medication, class legislation (i.e., only children benefit)
- Violation of pure food acts
- An unreasonable or unnecessary measure, wasteful or illegal use of public funds
- An unsafe measure or nuisance
- Availability of alternative
- Breach of contract
- Deprivation of fundamental liberties

In more than 65 years of litigation, fluoridation has withstood challenges based on constitutional objections (related to the First, Ninth, Tenth, Fourteenth, and Fifteenth Amendments). It has withstood legal challenges in more than 25 states and has been upheld in the highest courts in more than a dozen states. The US Supreme Court has denied review several times, generally on the grounds that no substantial federal or constitutional questions were involved. Courts have viewed fluoridation as a proper means of furthering public health and welfare, rejecting the legal argument that fluoridation ordinances are a deprivation of freedoms guaranteed under the Constitution.

More information can be found at www.fluidlaw.org, which is a database maintained by American University's Washington College of Law and the Children's Dental Health Project. FLUID (the Fluoride Legislative User Information Database) is a collection of legal documents related to the fluoridation of water supplies.

REGULATORY

Federal

Fluoridation of public water supplies is not mandated by the US Environmental Protection Agency (USEPA) or any other federal agency in the United States. The 1974 Safe Drinking Water Act (SDWA) specified that no national primary drinking water regulation can require the addition of any substance for preventive health benefits not related to drinking water contamination. This prohibition inherently established fluoridation as a decision to be made by each individual state or local municipality.

The SDWA further required that the USEPA determine the level of contaminants in drinking water at which no adverse health effects are likely to occur, and to apply limits based on possible health risks assuming a lifetime of exposure. These limits (which are nonenforceable) are maximum contaminant levels goals (MCLGs). The enforceable limits

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are maximum contaminant levels (MCLs). Though MCLs are set as close as possible to MCLGs, the enforceable MCLs must also consider cost, the ability to provide a meaningful impact on human health, and the ability of utilities to detect and remove contaminants. MCLs are never lower than MCLGs, but may be higher.

The Interim Regulation for Fluoride was promulgated in 1975 as a National Interim criteria with the MCL varying from 1.4 to 2.4 mg/L based on annual ambient temperature that was double the level recommended by the USPHS. This Interim Standard was challenged in 1981 by South Carolina with a request to delete the MCL but instead implement a Secondary Maximum Contaminant Level (SMCL) for dental fluorosis. In 1986, the USEPA established the current regulatory basis for fluoride in drinking water with a MCL of 4 mg/L and a SMCL of 2 mg/L. The MCLG and MCL for fluoride are both 4 mg/L. This concentration is the level below which a lifetime of exposure is not expected to cause health problems associated with skeletal fluorosis, a crippling disease, and is an enforceable maximum allowable concentration under the SDWA. As of the publication of this manual, USEPA was in the process of reviewing its criteria for fluoride.

The USEPA has established the secondary drinking water regulations with associated SMCLs, which are nonenforceable guidelines. The secondary contaminant list is based on aesthetic (taste, odor, staining of clothes or materials) or cosmetic effects (skin or tooth discoloration). Fluoride is the only contaminant other than copper that has both a primary and secondary standard. The SMCL for fluoride is 2 mg/L and is meant to prevent discoloration or pitting of teeth in children exposed during their formative years to water with high naturally occurring levels of fluoride. The SMCL seeks to balance the beneficial effects of fluoridation (protection against dental caries) with the undesirable cosmetic effects caused by excessive exposure. A state may choose to adopt a secondary standard (or any level lower than the federal MCL) as its enforceable standard.

The SDWA requires that water utilities notify customers in their annual Consumer Confidence Report when any regulated contaminant exceeds the regulatory limit in its treated water, regardless of whether the contaminant is naturally occurring or added as part of the treatment process. Any public water system that exceeds the primary or secondary MCL for fluoride should consult with its primary drinking water administrator to clarify the specific requirements for public notification. In general, an exceedance of the 4 mg/L MCL must meet the Tier 2 public notification requirements. An exceedance of the 2 mg/L SMCL must meet the Tier 3 public notification requirements. Because some states use the SMCL as the enforceable standard, the public notification requirements may differ from state to state. Any water utility serving a community considering fluoridation should have a firm understanding of the notification requirements in its state prior to initiating fluoridation.

State and Local

States have used different strategies to implement community water fluoridation programs, including legislation, administrative regulation, and public referenda at the state or local level. Thirteen states require fluoridation of public water systems that do not naturally contain optimal levels (Table 1-1). The specific requirements of these laws vary from state to state. Some have population thresholds, such that only systems serving a minimum number of customers are required to add fluoride, while others allow individual communities to opt out.

Ohio and Kentucky provide a good example of the variation between states. Ohio's state fluoridation statute requires all community water systems serving more than 10,000 customers to adjust fluoride to optimal levels. In contrast, Kentucky's regulation is an administrative code that imposes different requirements based on the population size of the community served.

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Table 1-1 States requiring fluoridation of public water supplies

State	Year of mandate
Connecticut	1965
Kentucky	1966
Illinois	1967
Minnesota	1967
Ohio	1969
South Dakota	1969
Georgia	1973
Nebraska	1973, 2008
California	1995
Delaware	1998
Nevada	1999
Louisiana	2008
Arkansas	2011

Source: CDC, www.fluidlaw.org

In addition to the states listed in Table 1-1, Washington, D.C., and Puerto Rico have fluoridation mandates. The US Army Corps of Engineers Washington Aqueduct (the wholesale water supplier to the District of Columbia Water and Sewer Authority; Arlington County, Va.; and the City of Falls Church, Va.) has been adding fluoride since 1952.

Puerto Rico enacted legislation in 1998 requiring water fluoridation as needed to bring the fluoride concentration to an optimal level. The standards are governed by the Department of Health and operational compliance is overseen by the Aqueduct and Sewer Authority. Although Puerto Rico requires community water fluoridation, it is not widely practiced primarily due to infrastructure issues.

Although only 13 states have a fluoridation mandate, no state prohibits fluoridation. In most states, the decision is made at a local (regional or municipal) level. The decision at a local level can arise and be implemented in several ways. As an example, a local municipal health agency may make the recommendation to a city's governing body (i.e., mayor, city council, etc.). The local legislature may put the recommendation to referendum as a ballot question during a future election. Some municipalities have local ordinances requiring fluoridation. A local ordinance may be instituted if the legislature grants the recommending health agency the authority to require fluoridation without a referendum. The issue can become more complex when a public water supplier serves more than one municipality, such as in consecutive systems.

In most cases, the water supplier is not the entity that authorizes fluoridation, although it is tasked with implementation. The mandate to fluoridate can be the result of a legislative act or a directive from a state or local health agency. Regardless of the mechanism by which fluoridation was instituted, the water supplier is responsible for working with its primary regulatory drinking water administrator to ensure compliance with relevant permit requirements, such as design and maintenance of the fluoride chemical feed system, monitoring of fluoride levels in water samples, reporting data, and public notification.

The obligation a utility may have under fluoridation requirements is likely to be different in different communities. It is imperative that the water utility in any community considering fluoridation consult with its state drinking water administrator throughout the process of consideration and implementation of fluoridation.

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Regulations in Other Countries

Similar to the SDWA in the US, the European Water Quality Directive (1980) provides maximum allowable concentrations of substances in water, and European countries use this directive as the framework for establishing their own water quality regulations. Currently, the WHO's guideline for fluoride is 1.5 mg/L. The directive neither mandates nor prohibits fluoridation. In the UK, the decision to fluoridate is made at a local level. The fluoridating utility works to a Code of Practice for fluoridation, which provides standards for the water industry. Compliance with the standards is monitored by the Drinking Water Inspectorate (the regulator for drinking water quality). Most recently, the European Parliament on May 16, 2006, voted 526 in favor and 126 against to maintain fluorides on the approved list of additives.

As in the United States, the fluoridation of public water supplies in Canada is not mandated nationally. Health Canada is the agency that oversees drinking water quality and works with the provincial and territorial governments to review, maintain, and periodically revise the Guidelines for Canadian Drinking Water Quality. Canada's maximum acceptable concentration (MAC) of fluoride in drinking water is 1.5 mg/L. As with organizations in the United States, Health Canada has recently revised its recommendation that the optimal level of fluoride in drinking water (for protection against dental caries) be decreased from a range (0.8 to 1.0 mg/L) to the single value of 0.7 mg/L. The decision to fluoridate is made by municipalities in collaboration with their provincial or territorial authority, and may include input from residents. Health Canada, the Canadian Public Health Association, the Canadian Dental Association, and the Canadian Medical Association all endorse the use of fluoride for the prevention of dental cavities. More information on water fluoridation in Canada can be found in *Fluoride and Human Health*, Health Canada, October 2010.

REFERENCES

Susan Griffin, K. Jones, and S.L. Tomar. 2001. An Economic Evaluation of Community Water Fluoridation. *Journal of Public Health Dentistry* 61(2):7886. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-7325.2001.tb03370.x/pdf.

DeSimone, L.A. 2009. *Quality of Water from Domestic Wells in Principle Aquifers of the United States*. Reston, VA: US Geologic Survey.

Center for Disease Control. 2012. *Fluoridation Growth*. Atlanta, GA: CDC.

Health Canada. 2010. Fluoride and Human Health. Ottawa, ONT; Health Canada.

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Chapter 2

Health and the Human Body

This chapter focuses on the health effects of fluoride and, in particular, the role of fluoride in preventing tooth decay.

FLUORIDE IN THE HUMAN BODY

The mineral and hard tissue structure of bones, teeth, and other parts of the skeleton contain fluoride. Soft body tissues do not retain fluoride, except as found in calcified deposits. Bones and teeth are predominantly composed of a crystalline matrix of calcium, magnesium, phosphorus, hydroxide, and fluoride. Since the fluoride ion and hydroxide have roughly the same atomic diameter, they can interchange on the mineral crystal. As the relative amount of fluoride increases and hydroxide decreases, bone density increases and tooth enamel has increasing resistance to decay. Fluoride acts on teeth both topically and systemically, although the topical mode of action is considered more important for reduction of dental caries. The topical effect can occur either through direct contact of fluoridated water with teeth or as a result of slightly elevated background fluoride concentrations in the saliva; the fluoride is then available to be incorporated at the tooth surface. The systemic effect occurs when fluoride diffuses through the walls of the stomach and intestines. The fluoride level in the blood is then available to all the skeletal structures, including the teeth, and in saliva. Fluoride not deposited in bones and teeth is excreted through the kidneys.

Fluoride incorporation by the teeth systemically occurs during the time of a child's formation and growth as the teeth are forming in the gum, pre-eruption. Teeth differ from other parts of the skeleton in that once they are formed, with the exception of the inner part of the tooth and the root, there is very little cellular activity. Maximum reduction in caries is achieved when fluoride is available both via the blood supply for incorporation during tooth formation and after the tooth erupts topically at the tooth surface over the lifetime of the individual.

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The surface of the tooth is always exposed to a demineralization and remineralization cycle. Food and bacteria can result in a demineralization of the tooth surface, but fluoride in saliva and plaque promotes a remineralization of the tooth surface with a competent crystal. Although the systemic exposure allows the tooth enamel to form as a decay-resistant crystal, topical exposure allows a repair of tooth surface demineralization and therefore benefits all people of all ages.

The skeleton is the fluoride reservoir. When fluoride is ingested, roughly half of the fluoride is incorporated in the skeleton and roughly half is expelled principally by filtering in the kidneys, which quite efficiently removes fluoride from the blood. The bones experience a demineralization and remineralization throughout a person's lifetime. That process allows fluoride to be incorporated into the bone, but it also allows release of fluoride when ingested fluoride exposure reduces. This results in replenishment of fluoride in the bloodstream if fluoride exposure is less than it was at an earlier point. Although benefits of fluoride for the skeleton structure is not fully understood, the 2006 National Research Council (NRC) review of fluoride in drinking water cited some studies that suggest that the fluoride level for good oral health may be beneficial for bones in that there appears to be a relationship with lower bone breakage when the water is optimally fluoridated (National Research Council 2006).

DISCOVERY OF THE BENEFITS OF FLUORIDE

The modern study of the impacts of fluoride on the human body had its beginnings in the late 19th century with independent observations of mottled enamel by Stefano Chiaie in Italy and C. Kuhns in Mexico. As early as 1901, J.M. Eager documented his findings of discolored teeth in Naples, Italy, and postulated that the etiology may be connected to either something in the air or drinking water (although the source was believed to be volcanic fumes or the "emanations of subterranean fires"). Also in 1901, a young dentist named Frederick McKay relocated from Philadelphia to Colorado Springs, Colo. spent the next several decades researching mottled enamel, fluoridation, and the prevalence of dental caries.

Upon arrival in Colorado Springs, McKay noticed that many of his patients had significant brown staining, or mottling of the teeth, an enamel appearance he had not previously observed. This mottling was later termed *dental fluorosis*. A study by the Colorado Springs dental society completed at the time indicated that up to 90 percent of the city's locally born children had this condition, which McKay termed "Colorado brown stain." In 1908, McKay began conducting epidemiological studies into the cause of the staining in collaboration with G.V. Black, dean of the Northwestern University Dental School. They determined that the mottled enamel was caused by developmental imperfections in the children's teeth. McKay later concluded that these teeth were surprisingly resistant to decay.

After years of field investigations, McKay began to believe that the etiologic agent responsible for the mottled enamel was something in the water supply. In 1923, McKay recommended to the residents of Oakley, Idaho, that they change their water source due to the elevated levels of fluorosis observed in the town's children. Within a few years of the change, the younger children of Oakley were not exhibiting mottled enamel. A similar scenario occurred in Bauxite, Ark. In both cases, the water supply was analyzed but nothing unusual was observed. In 1931, McKay's theory was validated when he sent water samples to H.V. Churchill, a chemist with Aluminum Company of America. Churchill was using a new method of spectrographic analysis that could evaluate the concentration of a variety of analytes (including fluoride) down to much lower concentrations than the method previously employed by McKay. All of the samples McKay submitted were from areas where mottled enamel was endemic, and results of all samples showed elevated levels of fluoride (2 to 12 mg/L).

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Once the agent causing fluorosis had been identified, research into the occurrence and dose-response relationships could commence. In the 1930s, H. Trendley Dean, the head of the Dental Hygiene Unit of the US Public Health Service (PHS), and McKay collaborated to better understand the adverse health effects of fluoride in drinking water. As the investigations continued with few adverse effects but increasing evidence of the benefits, their research continued to determine optimal fluoride concentrations in drinking water to balance the benefits of fluoride with the adverse effects. Dean identified locations around the United States with naturally occurring levels of fluoride, establishing a community fluorosis index. This led to further studies that quantified the dose-response relationship between fluoride, mottling, and the reduction of dental caries. The 21 Cities study in 1942 by Dean used environmental observations to establish a basis for an optimal level of fluoride for oral health benefits. From this research stemmed an optimal level of fluoride that both maximized caries reduction in a community while minimizing adverse health effects. Three distinct relationships were recognized:

1. At fluoride levels up to 1.5 mg/L, a reduction in tooth decay was observed. Fluoride levels greater than 1.5 mg/L did not significantly decrease the incidence of decayed, missing, or filled teeth. However, levels greater than 2.0 mg/L could increase the occurrence and severity of mottling.
2. At a fluoride level of approximately 1.0 mg/L, the optimal condition exists: maximum reduction in caries with no aesthetically significant mottling.
3. At fluoride levels below 1.0 mg/L, caries reduction diminished; at levels less than 0.5mg/L, approximately four times higher occurrence of caries was noted than in children exposed to levels greater than 0.5 mg/L.

Community water fluoridation studies in the 1940s were initiated to test the hypothesis that dental caries could be prevented by adjusting the fluoride level of community water supplies from negligible levels up to 1.0 to 1.2 mg/L. Studies were conducted in four pairs of cities in the United States and Canada, and caries were reduced 50 percent to 70 percent among children in communities with fluoridated water. These studies established fluoridation as a practical and effective public health measure.

In 1962, the USPHS set the recommended range of fluoride in drinking water from 0.7 mg/L (in warmer climates) to 1.2 mg/L (in colder climates). A range was recommended because average water consumption was believed to vary with average daily air temperature with an increased consumption of water in warmer locations. In January 2011, the US Department of Health and Human Services proposed as the recommended level of fluoride for community water systems a single value of 0.7 mg/L, which is the lowest level of the accepted beneficial range. The basis for setting the recommended value near the lowest recognized beneficial fluoride level is twofold: (1) Multiple sources of fluoride contribute to modern exposure levels, and (2) studies conducted since the recommended range was first introduced indicate that water consumption is not dependent on ambient air temperature as was once believed.

Dental Health

Dental caries, or tooth decay, is a largely preventable bacterial disease. Nearly everyone suffers from dental caries, making tooth decay the most prevalent chronic human disease. Before the widespread use of fluoride, more than 98 out of every 100 Americans experienced tooth decay by the time they reached adulthood. Tooth decay begins in early childhood and reaches a peak in adolescence, with the highest incidence of tooth decay being found in school-aged children. In the United States, tooth decay is experienced by more than 40 percent in the primary teeth of children ages two to 11 years, more than 60 percent

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in the permanent teeth of adolescents 12 to 19 years, and 91 percent of adults 20 to 64 (Dye et al. 2007). In the age group of 12- to 19-year-olds, the average US resident will have 2.55 decayed, missing, or filled teeth (Dye et al. 2007).

Tooth decay is a function of the presence of sugar as a substrate and certain bacteria combined with dental hygiene and fluoride. Cavities, or caries, form when acids dissolve the tooth enamel, thus destroying the tooth structure. These acids are produced as a metabolic by-product of certain bacteria, in particular *Strepotococcus mutans* and *Lactobacilli*. Cariogenic bacteria (i.e., bacteria that cause dental caries) reside in dental plaque, an organic matrix of bacteria, food debris, and salivary components that adhere to tooth enamel. Although plaque serves as a substrate for cariogenic bacteria, it is also the mouth's fluoride reservoir. As food is ingested, the bacteria in plaque consume the sugars, and this produces organic acids that lower the pH in the mouth. When this occurs, plaque releases fluoride onto the tooth surface. The presence of fluoride augments the remineralization process, which is discussed in greater detail in the subsequent paragraphs.

A cycle of demineralization and remineralization is constantly taking place in the mouth (Figure 2-1). Demineralization involves the loss of calcium, phosphate, and carbonate from the tooth's enamel structure; if it is not halted or reversed, it will eventually result in the formation of a cavity. Remineralization is the reversal of this process; it occurs when calcium and phosphate in the saliva are deposited back into the enamel. Fluoride enhances remineralization by adsorbing to the tooth surface and attracting both calcium and phosphate ions. Fluoride also acts to bring the calcium and phosphate ions together and is included in the chemical reaction that takes place, producing a crystal surface that is much less soluble in acid and more resistant to decay than the original tooth material. Demineralization and remineralization are constantly taking place on the surface of the teeth throughout a person's life.

Fluoride from topical sources also inhibits the cariogenic bacteria themselves. Cariogenic bacteria take up fluoride when they produce acid, and once inside the cells, fluoride interferes with bacterial enzyme activity and ultimately their intracellular pH control. This reduces bacterial metabolism and acid production, which directly reduces the dissolution rate of tooth mineral.

Adverse Health Effects

The USEPA's MCL for fluoride (4 mg/L) is meant to be protective of human health and is much higher than the dose considered optimal for prevention of dental caries (0.7 mg/L). The weight of evidence from all currently available research does not support a link between exposure to fluoride in drinking water at 0.7 mg/L and any significant adverse health effects, including those related to cancer, immunotoxicity, reproductive/developmental toxicity, genotoxicity, and/or neurotoxicity (National Research Council 2006). However, elevated fluoride concentrations have been linked to adverse health effects, some of which are discussed further in the following sections.

Dental Fluorosis. Dental fluorosis is caused by a hypo-mineralization in enamel formation. It is a permanent condition that results from exposure to increased levels of fluoride during tooth development. Because dental fluorosis is a condition that occurs when teeth are forming pre-eruption in the gums, only children age eight years old or younger are at risk; children older than eight years, adolescents, and adults are not susceptible to dental fluorosis.

Dental fluorosis becomes apparent upon eruption of the teeth. It ranges from very mild symmetrical whitish areas on teeth (very mild dental fluorosis) to pitting of the enamel and brownish discoloration (severe dental fluorosis). The very mild and mild forms are barely detectable even by experienced dental professionals and have no effect on tooth function. Moderate and severe forms of dental fluorosis, which the USEPA has

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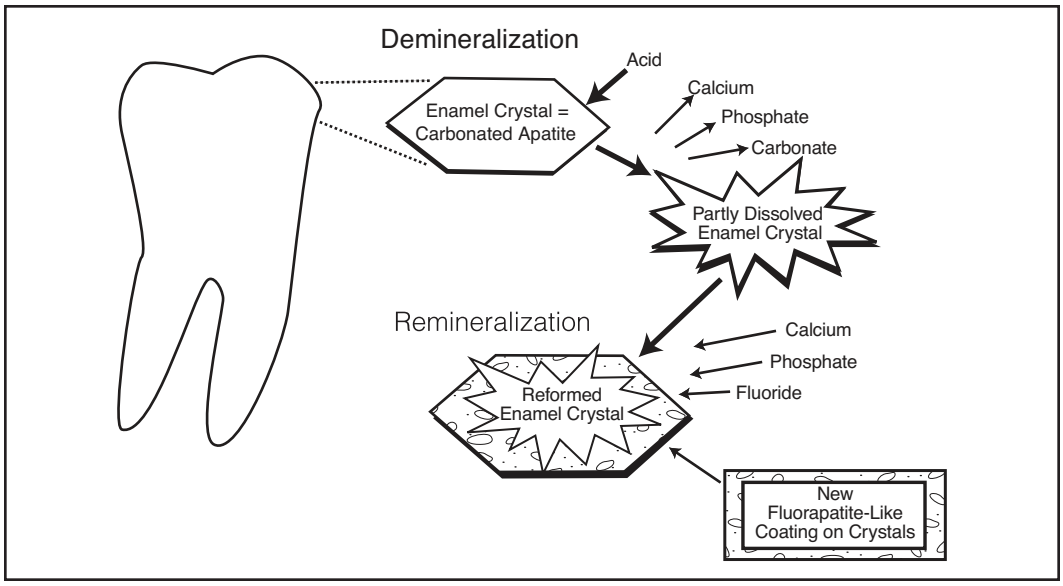

Figure 2-1 The demineralization and remineralization process

Source: Adapted from Featherstone, J.D.B. 1999.

considered a cosmetic issue, represent less than 3.5 percent of the cases of fluorosis nationally based on the National Health and Nutrition Examination Survey (Beltran-Aguilar et al. 2010). Figure 2-2 illustrates that a small percentage of the population is affected by very mild and mild fluorosis at 1 mg/L fluoride, which corresponds to the concentration at which the optimal benefit from dental caries reduction is achieved. Recent studies have shown a slight increase in dental fluorosis in communities with nonfluoridated water. This may be the result of other sources of fluoride, including toothpastes, dietary supplements, mouth rinses, professional applications, and foods and beverages processed with fluoridated water.

Young children and dental fluorosis. The principal cause of moderate and severe dental fluorosis is from children swallowing fluoride toothpaste. For children who use toothpaste, there is an increased chance of dental fluorosis among those younger than six years, and especially for those younger than two years, because they are more likely to swallow the toothpaste than older children as their spitting reflex has not yet developed. To prevent fluorosis, the CDC recommends that health-care professionals provide direct individual advice on the use of fluoride toothpaste by young children, especially those younger than two years, depending on individual assessment of diet, availability of dental health care, fluoride levels in the community water, and other risk factors for dental decay. Universally, dental health professionals should advise parents to supervise children while brushing teeth and to use only a smear or pea-size quantity of fluoride-containing toothpaste until age six.

Skeletal fluorosis and bone fractures. Fluoride is readily incorporated into the crystalline structure of bone and will accumulate over time. A small exposure of fluoride, as associated with water fluoridation, is generally considered beneficial for bones, but excessive exposure at levels above the recommended level for good oral health can result in adverse effects. Skeletal fluorosis is an adverse health effect caused by an accumulation of excessive fluoride in bone. This is the result of excessive chronic fluoride exposure.

Skeletal fluorosis is extremely rare in the United States with only seven reported cases by the Centers for Disease Control (CDC). However, fluorosis does occur in countries with areas of very high levels of naturally occurring fluoride, such as India and China.*

* Other confounding factors, such as inhalation of fluoride fumes from burning coal indoors, are often also present, thus increasing exposure levels.

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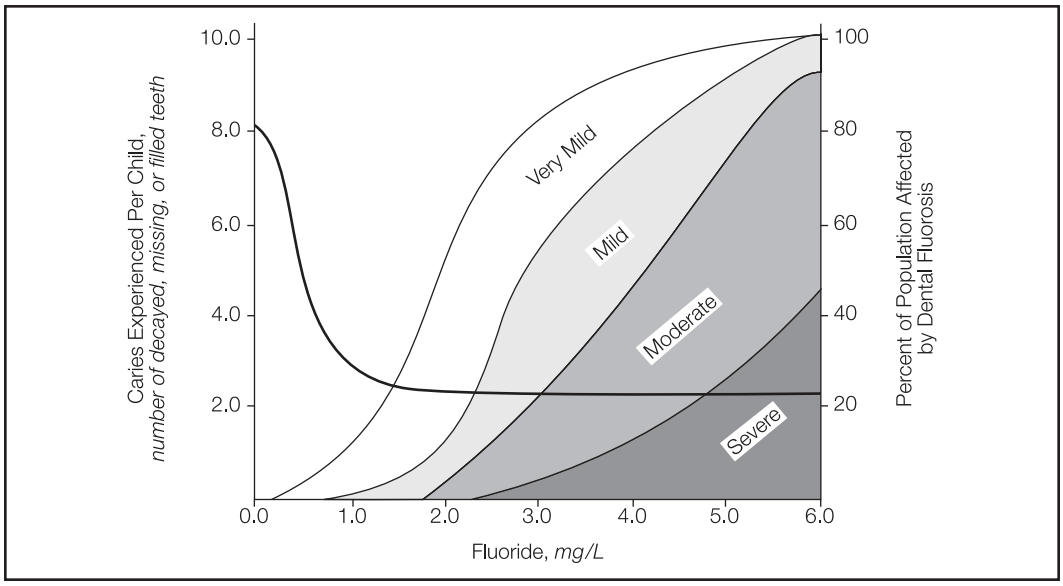

Figure 2-2 Dental caries and dental fluorosis in relation to fluoride in public water supplies

Source: Water Fluoridation: A Manual for Engineers and Technicians *(US Department of Health and Human Services, Centers for Disease Control and Prevention, September 1986).*

The Institute of Medicine (IOM) established recommendations for the tolerable upper intake level for fluoride to safeguard against skeletal fluorosis. This value is 10 mg/day for 10 or more years. This corresponds to a drinking water fluoride concentration of 5 mg/L, assuming a 2-L/day rate of water consumption. Fluoride increases bone density but can increase brittleness in long slender bones. Fluoride has been shown to affect bone calcification, and some studies have linked chronic elevated doses to bone fractures.

Cancer

Numerous human epidemiological studies on the potential carcinogenic effects of fluoride in drinking water have been conducted. The general consensus among the reviews completed to date is that no evidence exists linking water fluoridation and cancer.

According to a 2006 NRC review of fluoride in drinking water, the studies that had been completed to date regarding fluoride exposure and osteosarcoma risk were inconclusive and tentative. The NRC study went on to state that the multiyear Harvard-based hospital study that was in progress at the time would be an important assessment of the potential relationship between osteosarcoma and fluoride. The results from the full study did not find a significant association between bone fluoride levels and osteosarcoma risk (Kim et al. 2011).

In 2011, California's Office of Environmental Health Hazard Assessment published a report on the carcinogenicity of fluoride and its salts. This report concluded that the current body of epidemiological evidence on the carcinogenicity of fluoride is inconclusive, suggesting that fluoride is not a recognized causative agent for cancer.

Other Health Effects

Myriad other possible health effects related to fluoride have been studied, including its potential impact on kidney disease, hypersensitivity (allergic reactions), gastrointestinal

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problems, intelligence, thyroid (goiter) effects, effects on bioavailability or toxicity of toxic metals (aluminum and lead), enzyme and mutagenic (gene-altering) effects, and birth defects. Overall, evidence suggests no risk to people consuming optimally fluoridated water in the United States.

FLUORIDE DELIVERY

Recommended Water Fluoride Content

For water utilities, the recommended fluoride level is usually established by the appropriate state regulatory or health agency. The US Department of Health and Human Services (USHHS) recommended level of 0.7 mg/L can be used as a guideline if state limits have not been established. The 0.7 mg/L level was based on the evidence that in our modern society, water consumption does not significantly vary by region or climate, and that the lowest level in the recognized optimum range was sufficient protection for most persons.

Alternative Methods of Fluoride Delivery

While community water fluoridation is one of the most cost-effective mechanisms for dental caries reduction, other sources of fluoride also reduce tooth decay. At an individual level, people may receive fluoride for tooth decay prevention through fluoridated toothpaste and mouth rinses, professional fluoride treatments, fluoride dietary supplements, and beverages and food processed in fluoridated areas. Water fluoridation continues to be effective in reducing dental decay by 20 percent to 40 percent despite the availability and use of these other fluoride sources. Community fluoridated water also reduces the disparity in dental decay that may be seen among populations with low socioeconomic status, especially those with limited access to dentifrices, supplements, and routine dental care. Other forms of community fluoridation include salt and milk fluoridation.

REFERENCES

Beltrán-Aguilar E.D., L. Barker, B.A. Dye. 2010. Prevalence and Severity of Dental Fluorosis in the United States, 1999–2004. NCHS data brief 53. Hyattsville, MD: National Center for Health Statistics.

Dye, B.A., S. Tan, V. Smith, B.G. Lewis, L.K. Barker, G. Thornton-Evans, et al. 2007. Trends in Oral Health Status: United States, 1988–1994 and 1999–2004. National Center for Health Statistics. Vital Health Stat 11(248).

Featherstone, J.D.B. 1999. Prevention and reversal of dental caries: Role of low-level fluoride. *Community Dent Oral Epidemiol* 27:31–40.

Kim, H.Y., G. Chung, H.J. Jo, Y.S. Kim, Y.C. Bae, S.J. Jung, J-S Kim, S. Bo. Oh. 2011. Characterization of Dental Nociceptive Neruons. *Journ. of Dental Research* 90(6): 771–776.

National Research Council, U.S. Committee on Fluoride in Drinking Water, National Academies. 2006. Fluoride in Drinking Water: A Scientific Review of EPA's Standards.

US Department of Health and Human Services, Centers for Disease Control and Prevention. September 1996. Water Fluoridation: A Manual for Engineers and Technicians.

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Chapter 3

Fluoride Products

This chapter provides an overview of the fluoride products used to adjust fluoride content in drinking water, presents their characteristics and sources, and introduces standards and regulations to ensure quality.

CHEMICAL CHARACTERISTICS

Historically, several products were used for water fluoridation during the first decades of water fluoridation. As water fluoridation practice evolved, now only three products are approved for adjusting fluoride:

- Sodium fluoride: a granular salt dissolved into a solution
- Sodium fluorosilicate: a granular salt dissolved into a solution
- Fluorosilicic acid: a liquid acid normally added without dilution

Over time, the trend has been a shift from dry products mixed into solutions to the predominant use of fluorosilicic acid. This trend for fluoride products mirrors the change in other additive products used for water treatment because the water treatment industry often has been willing to pay more for a premixed additive solution to minimize the handling of chemicals at a water treatment facility. The CDC has reported trends in use of products (Table 3-1).

This section provides background information about the manufacturing processes, aquatic chemistry dissociation of the fluoride ionic form(s), and physical and chemical characteristics.

Sodium Fluoride

The first fluoride compound used to adjust fluoride in drinking water was sodium fluoride. It was selected because (1) it is a readily available product and (2) its toxicity and physiological effects had been studied. Once fluoridation became an established practice, other compounds came into use.

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Table 3-1 Trends in the use of fluoride products over time

	Population receiving adjusted fluoridated water	Percent of population receiving adjusted fluoridated water	Systems	Percent of systems
1960				
Fluorosilicic acid	10,285,630	25%		
Sodium fluorosilicate	24,588,937	60%		
Sodium fluoride	5,186,351	13%		
Ammonium silicate calcium fluoride	73,000	0.2%		
1993				
Fluorosilicic acid	80,019,175	63%	5,876	59%
Sodium fluorosilicate	36,084,896	28%	1,635	16%
Sodium fluoride	11,701,979	9%	2,491	25%
2010				
Fluorosilicic acid	152,501,133	81%	9,125	75%
Sodium fluorosilicate	24,224,615	13%	1,208	10%
Sodium fluoride	12,815,339	7%	1,825	15%

Source:

1. 1960 US Public Health Service Fluoridation Census
2. 1993 CDC Fluoridation Census
3. 2010 CDC Water Fluoridation Reporting System

Sodium fluoride is a white, odorless product available either as a powder or as crystals of various sizes. It is most commonly produced by neutralizing fluorosilicic acid with caustic soda (NaOH). It is also produced by neutralizing hydrogen fluoride with caustic soda. It is the most expensive of the fluoride additives because of the high processing effort and large amount of caustic soda required to produce it. As a result of the high cost of production, production sources are currently located outside the United States (CDC 2012).

Crystalline sodium fluoride is produced in various size ranges, usually designated as coarse or fine. The crystalline type is preferred for utilities practicing manual handling because it minimizes dusting when emptying a bag into a saturator. The AWWA product specification on sieve analysis of sodium fluoride specifies passing 98 percent through a US Standard Sieve Series mesh No. 20 and 50 percent through a No. 100 mesh sieve. Different manufacturers have different gradations, so some consumers request limits on allowable fines. Customer-specified limitations have often been to limit fines of less than 5 percent passing through a No. 325 mesh and less than 20 percent passing through a No. 100 mesh to minimize dusting of the product during handling. Sodium fluoride is commercially available in both 50- and 100-lb (23- and 45-kg) bags.

Sodium fluoride must be made into a solution before being added to water supplies. The chemical can be dissolved in a mixing tank, a saturator, or a dissolving chamber. (Equipment requirements are discussed in detail in chapter 5.) Its formula weight is 42.0 (fluoride is 19 and sodium is 23) and results in an available fluoride content of 45 percent. Its solubility is practically constant at near 4 g/100 mL of water at temperatures generally encountered in water supplies. It is the ideal additive for use with saturators for small systems because of its relatively constant solubility. It also dissolves readily and can achieve a saturated solution within five minutes. When added to water, sodium fluoride dissociates into sodium and fluoride ions:

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$$NaF \Leftrightarrow Na^{+} + F^{-} \tag{3-1}$$

Solution pH varies with the type and amount of impurities, but solutions prepared from the usual grades of sodium fluoride exhibit a pH near neutral (approximately 7.6). Sodium fluoride is available in purities ranging from 90 percent to more than 98 percent. Impurities consist of water, free acid or alkali, sodium fluorosilicate, sulfites, and iron, plus traces of other substances.

Fluorosilicic Acid

Fluorosilicic acid is principally collected as a by-product of phosphate fertilizer. A small quantity, less than 5 percent of the market availability, is derived from gas separation columns from the production of hydrogen fluoride derived from calcium fluoride ore, and less than 1 percent of the market is derived from quartz etching of silicon chips. Fluorosilicic acid produced from calcium phosphate ore and apatite ores is created by adding the ores to sulfuric acid to form a phosphoric acid–gypsum slurry. The phosphoric acid is separated from the gypsum and desiccated to pellets for use in fertilizers. The fluoride remains dissolved in the phosphoric acid–gypsum slurry as a silica tetrafluoride gas. It can be removed from the slurry using vacuum extraction, then partitioned from the phosphate in gas separation columns with collection in a water bath. The collected acid is then concentrated to between 20 percent and 30 percent strength, with 23 percent being the reference concentration.

Acid prepared from phosphate rock (as part of fertilizer manufacture) contains colloidal silica in varying amounts. Although this is of little consequence when the acid is used as received, dilution results in the formation of a visible precipitate of the silica. Rather than attempt to adjust the acid strength with water dilution to some uniform figure, producers sell the acid as it is produced and adjust the price to compensate for acid strength greater or less than the quoted figure. Suppliers usually provide assay reports of the acid strength of each lot.

With a reference concentration of 23 percent, fluorosilicic acid contains a high proportion of water (typically 72 percent to 78 percent water content), and shipping large quantities can be expensive. It is normally collected during manufacturing in 20,000-gallon railcars that are then used to transport the product to regional depots for distribution to users. Large users can purchase the acid directly from the manufacturer in bulk lots (tank cars or tank trucks), but small users must obtain the acid from distributors, which usually package it in drums or polyethylene carboys. Some locations may have a regional distributor that uses a mini-bulk delivery of chemicals. Mini-bulk uses 500-gallon tanks on a truck that can then act as a nurse-truck delivery to top off on-site storage tanks of smaller facilities.

Fluorosilicic acid is not a pure substance but a mixture of various oligimers and crown-ether silico-fluoride complexes with an average formula of H_2SiF_6 and a formula weight of 144.0. This results in an available fluoride ion content of 79 percent. The most common concentration used in drinking water is 23 percent to 25 percent but the concentration may be higher or lower as delivered. Fluorosilicic acid is a transparent, fuming, corrosive liquid having a pungent odor and an irritating action on the skin; but based on impurities, it can vary from a water-white to a straw-colored appearance. On vaporizing, the acid decomposes to form hydrofluoric acid (HF) and silicon tetrafluoride (SiF_4). Under conditions where equilibrium between the fluorosilicic acid and its decomposition products exists, such as at the surface of strong solutions, etching of glass can occur as a result of the volatile hydrogen fluoride. At normal room temperature, hydrogen fluoride will volatilize from the surface of the solution. Due to the small percentage of fluoride in the form of hydrogen fluoride and the relatively small exposure of the surface to the bulk contents of a storage tank, hydrogen

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fluoride in fluorosilicic acid has a slow release rate. However, the corrosive character of hydrogen fluoride results in a nuisance etching and corrosion to glass, metals, and electrical products if tanks are not property sealed and vented.

When fluorosilicic acid is dissolved in water, the dissociation of hydrofluoric acid and silicon tetrafluoride is pH dependent. At the pH and concentration used for water fluoridation, the presumed dissociation results in hydrofluoric acid and silicon tetrafluoride:

$$H_2SiF_6 \leftrightarrow 2HF + SiF_4 \tag{3-2}$$

Hydrofluoric acid strongly dissociates, lowering the pH of the solution:

$$HF \leftrightarrow H^+ + F^- \tag{3-3}$$

Silicon tetrafluoride is a gas that volatilizes if present in high concentrations. It also reacts quickly with water to form silicic acid (H_2SiO_3) or silicon dioxide (SiO_2):

$$SiF_4 + 3H_2O \leftrightarrow 4HF + H_2SiO_3 \tag{3-4}$$

$$SiF_4 + 2H_2O \leftrightarrow 4HF + SiO_2 \tag{3-5}$$

Concentrated solutions of fluorosilicic acid exhibit a low pH (approximately 1.2). The alkalinity consumption as mg/L of calcium carbonate ($CaCO_3$) per mg/L of fluoride is 2.08, so the buffering capacity of the water should be considered when adding fluoride to poorly buffered waters.

Attempts to dilute the acid are subject to errors in measuring both the acid and the diluting water. The acid should be used undiluted as it comes from the shipping containers. The most unstable range for dilution is a mix of 10:1 to 20:1 when the silica can readily precipitate into a nuisance scale.

Fluorosilicic acid has a higher density than water, and one of the two approved AWWA verification tests is hydrogen titration or gravimetric measurement of density to determine the concentration of fluorosilicic acid. Hydrogen titration is the more accurate method as it differentiates other acids from fluorosilicic acid in solution. Fluorosilicic acid can be delivered at a concentration between 20 percent and 30 percent, but is invoiced at a 23 percent basis, so it is important for an operator to measure the concentration of the solution in order to correctly establish the precise dosage. At a concentration of 25 percent, the density of the solution is 10.1 pounds per gallon (Figure 3-1).

Sodium Fluorosilicate

Fluorosilicic acid can readily be converted into various salts, one of which, sodium fluorosilicate, is a partially neutralized form of the acid. The most common process is to add sodium chloride to fluorosilicic acid, resulting in a hydrochloric acid–sodium fluorosilicate solution. Sodium fluorosilicate can also be formed by mixing fluorosilicic acid with sodium chloride or caustic soda. The sodium fluorosilicate is precipitated into crystals and then desiccated. In some cases, sodium fluorosilicate tends to be the least expensive product in use because the transport is a major factor in the cost of any additive product. Because sodium fluorosilicate does not have the large dilution water associated with fluorosilicic acid, it costs less to transport. The conversion of aqueous fluorosilicic acid to a dry product containing a high percentage of available fluoride results in a compound having

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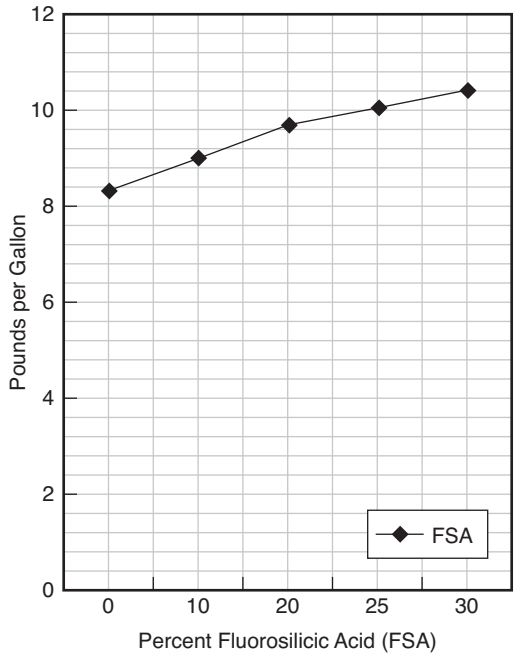

Figure 3-1 Density of fluorosilicic acid vs. percentage based on data provided by The Mosaic Company, 2006.

Source: CDC

most of the advantages of the acid with few of its disadvantages. It is also a weak acid in comparison to fluorosilicic acid, which is a strong acid.

The sodium fluorosilicate used in the United States is produced domestically and imported. Sodium fluorosilicate is normally packed in bags and drums similar to those used for sodium fluoride, but is also available in 2,000-pound supersacks for ease of handling. As with sodium fluoride, sodium fluorosilicate must be made into a solution in a dissolving chamber before being fed into the water supply.

Sodium fluorosilicate is sold with a density of about 85 lb/ft^3 (1,400 kg/m^3). A typical sieve analysis of the regular grade allows more than 98 percent through a US Standard Sieve mesh No. 40 and at least 25 percent through a 325-mesh sieve. Depending on feeding characteristics, other size specifications can be selected. Experience shows that a low moisture content plus a relatively narrow size distribution results in a material that is handled better by dry feeders.

Sodium fluorosilicate is a white, odorless, crystalline powder. Its molecular weight is 188 (two sodium at 46, six fluoride at 114, and one silica at 28) resulting in an available fluoride ion content of 60 percent. Its solubility is temperature dependent and varies from 0.44 g/100 mL of water at 32°F (0°C) to 2.45 g/100 mL of water at 212°F (100°C). When sodium fluorosilicate is dissolved in water, virtually 100 percent dissociation occurs within several minutes:

$$Na_2SiF_6 \leftrightarrow 2Na^+ + SiF_6^- \tag{3-6}$$

Silicofluoride ions, SiF_6^-, may react in two ways. The more common reaction is hydrolysis of SiF_6^-, releasing fluoride ions and silica.

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Table 3-2 Characteristics of fluoride products

Item	Sodium fluoride (NaF)	Sodium fluorosilicate (Na_2SiF_6)	Fluorosilicic acid (H_2SiF_6)
Form	Dry crystals	Dry crystals	Aqueous liquid
Molecular weight	42.00	188.05	144.08
Pounds required per million gallons (grams required per cubic meter) for 0.7 mg/L F^- at indicated purity	11.5 (14.2) (98%)	11.7 (1.07) (98.5%)	29.3 (3.5) (23%)
Sodium ion contributed at 0.7 mg/:L F^-	0.82	0.28	0.0
F^- ion storage space, ft^3/100 pounds (m^3/kg)	22–33 (0.0137–0.0212)	23–30 (0.0143–0.0187)	54–73 0.0337–0.0455)
Solubility at 25°C, g/100 mL water	4.05	0.568 at 10°C 0.632 at 15°C 0.696 at 20°C 0.762 at 25°C	Greater than 40,000
pH of saturated solution	7.6	3.5	1.2 (23% solution)
Alkalinity consumed, mg as $CaCO_3$ per mg F^-	0.0	1.06	2.08
Weight lb/ft^3	65–90 (1,000–1,400)	85–90 (1,320–1,400)	10.1 lb/gal at 25% 10.5 lb/gal at 30% (1.26 kg/L at 25%) (1.31 kg/L at 30%)
Shipping containers	50-lb bags 25-kg bags 125- to 400-lb fiber drums	50-lb bags 25-kg bags 124- to 140-lb fiber drums	20,000-gal railcar 4,000- to 5,000-gal truck 500-gal mini-bulk deliveries 300-gal tote tanks 55-gal drums 13-gal carboys
Typical commercial purity, percent	97–99	98–99	20–30

Source: ANSI/AWWA B701, B702, B703; AWWA Fluoride Standards Committee

$$SiF_6^- + 2H_2O \leftrightarrow 4H^+ + 6F^- + SiO_2 \tag{3-7}$$

Alternatively, SiF_6^- dissociates very slowly, releasing fluoride ions and silicon tetrafluoride:

$$SiF_6^- \leftrightarrow 2F^- + SiF_4 \tag{3-8}$$

Silicon tetrafluoride reacts as described in Eq 3-4 and Eq 3-5. The pH values of the solutions are acidic (generally about 3.6). Sodium fluorosilicate is available in purities of 98 percent or greater, with the principal impurities being water, chlorides, silica, and carbonates. The alkalinity consumption as mg/L of $CaCO_3$ per mg/L of sodium fluorosilicate is 1.06, so the buffering capacity of the water should be considered when adding fluoride to poorly buffered waters.

Table 3-2 presents the characteristics of fluoride products.

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Product Standards

Two entities publish standards that are generally accepted by the water treatment industry: AWWA and the National Sanitation Foundation (NSF) International. Both publish in conjunction with the American National Standards Institute (ANSI). AWWA prepares standards for the manufacturing, quality, and verification of the fluoride additives for use in drinking water. The AWWA standards set the physical, chemical, and impurities standards for each product, including information on verification of the standard requirements and requirements for delivery. AWWA publishes the following standards for individual fluoridation products:

- ANSI/AWWA B701 Sodium Fluoride
- ANSI/AWWA B702 Sodium Fluorosilicate
- ANSI/AWWA B703 Fluorosilicic Acid

NSF International prepares standards that cover impurities of drinking water treatment additives from their production and through their distribution to user and includes documentation of the purity of additives. Standard NSF/ANSI 60 Drinking Water Treatment Chemicals – Health Effects provides for product purity and safety assurance that aims to prevent adding harmful levels of contaminants from chemicals and water treatment additives. Standard 60 sets the requirements for certification of individual drinking water treatment chemicals for compliance with MCL concentrations set by the USEPA; it also sets standards for chemical handling to ensure product quality is maintained. Verification testing by independent certification entities including NSF International and Underwriters Laboratories (UL), documents that the actual purity exceeds the standards. The NSF/ANSI Standards 60 and 61 (Drinking Water System Components – Health Effects) were developed by a consortium of associations, including NSF International, AWWA, ANSI, the Association of State Drinking Water Administrators (ASDWA), and the Conference of State Health and Environmental Managers to replace the previous additives overview effort by the USEPA.

In the United States, authority to regulate products for use in drinking water rests with individual states. NSF, in cooperation with the ASDWA, conducts a biennial survey to determine which states and Canadian provinces/territories require (by legislation, regulations, or policies) that drinking water additives be evaluated by NSF/ANSI 60. In 2013, an ASDWA survey found that 47 states and nine provinces/territories had adopted NSF/ANSI 60.

NSF/ANSI Standard 60 specifies the product quality for use in drinking water treatment, and various independent certification entities provide the validation for the products. Those third-party entities certify products in accordance with NSF/ANSI Standard 223. Standard 223 covers minimum requirements to be used by conformity assessment organizations when testing and certifying products to Standard 60.

Other Standards

US Pharmacopeia (USP) prepares standards for products used in pharmaceuticals. Some water facility operators may hear from concerned citizens that USP would provide a more rigorous quality standard. In fact, USP grade sodium fluoride provides less protection for drinking water because it is tested for nonspecific heavy metals, and it has no criteria for arsenic content or radiological exposure. Most importantly, USP does not provide certification of quality by an independent third-party credentialing entity to established quality verification. USP also does not have a standard for fluorosilicic acid or sodium fluorosilicate.

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REFERENCE

Center for Disease Control. 2012. Water Fluoridation Principles and Practices. Atlanta, GA: CDC.

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Chapter 4

System Planning

This chapter introduces the types of fluoridation systems. It also presents guidelines for system planning, including chemical selection, preliminary planning, dosage calculations, and system considerations.

Fluoridation systems, as is the case with other drinking water processes, are normally planned in coordination with the state or provincial agencies responsible for drinking water regulations. The regulations may address fluoride levels, recommended systems, monitoring requirements, and record keeping. The agencies may have the final approval of the system and design.

Among considerations in choosing the right fluoridation system for a particular situation are:

- Type of fluoridation system
- Water system characteristics (such as source of supply, single or multiple points of supply, treatment, storage, distribution, personnel)
- Chemical availability
- Cost

DECIDING WHETHER TO FLUORIDATE

The decision to fluoridate may be established on the state level, regional level, or local level, depending on the state and community. Water fluoridation is managed by a state or provincial program, but each program has different requirements with respect to the requirements for fluoridation. Currently, 13 states have a mandatory fluoridation requirement, although there may be caveats such as population thresholds, the stipulation that a public water system will implement fluoridation if another entity provides the funding, or if directed by the state to implement.

The first step in deciding to fluoridate is working with the state on requirements for a particular water system, including new startups and terminations. The next level of consideration is potential regional implications. In some cases, a water system may require concurrence of all other water systems with a connection in order to agree to the

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decision on fluoridation, so a regional coordination may be necessary. The local water system might have a directive to fluoridate by a public health board, by a local community governance board (if different than the water utility), or by a public vote.

If there are no state requirements for fluoridation, then it becomes a community decision. The question is strictly related to the health of the community. Communities with fluoridated water have significantly improved oral health than communities without fluoridated water, and that benefit extends to all people of all ages and socioeconomic demographics.

Choice of System

There are three basic types of fluoridation systems:

- Using saturated solutions of sodium fluoride
- Using unsaturated solutions of sodium fluorosilicate
- Feeding aqueous fluorosillic acid

Using Sodium Fluoride. Sodium fluoride is normally fed as a saturated solution. A saturator is a tank that allows the salt to dissolve to an aqueous saturated solution. Using a dry feeder instead of a saturator is uncommon based on reported systems by states to the CDC Water Fluoridation Reporting System, and this may be due to the higher relative cost of sodium fluoride and the suitability of sodium fluorosilicate in dry feeders.

With a nearly uniform saturation concentration across those temperatures at which most water is treated, sodium fluoride and the associated sodium fluoride saturator require minimal operator input to yield a consistent concentration of fluoride from the saturator. The process involves dissolving the salt into a saturated solution and then feeding that solution at a measured rate to the facility product flow. The cost for the equipment and installation is the least expensive configuration, it is easy to maintain, and operation is simpler than other systems. The downsides include the cost of the sodium fluoride, which is more expensive than the other fluoride products due to the greater processing to derive the product, and its limitations when using a high-hardness feedwater. The use of sodium fluoride in locations with high natural water hardness is a limitation as the high calcium in the water can suppress the saturated solution and result in increased nuisance scaling. For many small water systems, a saturator system may be an appropriate choice.

Using Sodium Fluorosilicate. Sodium fluorosilicate is a crystalline salt that must be dissolved to an unsaturated solution prior to feeding. An unsaturated solution is necessary because the salt achieves a saturated solution only after a lengthy mixing period. It also has a temperature-dependent concentration so the concentration of the unsaturated solution is indeterminate. Consequently, it cannot be used in a saturator but must instead be metered by a dry feeder into a solution tank where the unsaturated solution is formed. It is a weak acid, so there are fewer negative effects such as material attack on concrete metals, glass, and other surfaces. It has fewer personnel safety concerns and is easy to handle.

Sodium fluorosilicate can be the least expensive of the products depending on the cost of energy (fuel) and location because the logistical transport cost can be a significant portion of the cost of fluoridation products. As a weak acid, it can be more suitable in locations with high water hardness as it is not subject to the scaling and reduced solubility of sodium fluoride. Both sodium fluorosilicate and sodium fluoride have lower quantities of contaminants due to processing of fluorosilicic acid to derive the dry products, which tends to retain impurities in the reject slurry.

Feeding Aqueous Fluorosilicic Acid. Fluorosilicic acid is the most commonly used product. The handling characteristics of an aqueous product ready for direct addition can minimize operator involvement, and this is consistent with a general tendency in the

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water treatment industry to use liquid products not requiring mixing in water treatment. It is easy to simply have a storage tank that receives the delivered product and pump a metered acid feed to the application point. However, fluorosilicic acid is a strong acid and has an aggressive character with a propensity to attack many materials and surfaces. It also has the greatest potential for overfeeds and consequently requires more safety and regulators in the feed system.

FLUORIDE APPLICATION POINT

In systems that supplement naturally occurring fluoride, it may be necessary to fluoridate at each entry point to the distribution system. The configuration of the water system will be the major consideration on the type of feed arrangement that will be necessary.

If the water wholesaler does not already fluoridate, fluoridation application points may be required at all interconnections in regular use (i.e., not emergency connections). Once these categories of application points have been identified, the specific configuration of each application point can be determined.

The location of the fluoridation application point ahead of each entry point should be at a choke point, or bottleneck, through which all water entering the entry point will pass. In a water treatment plant, this location may be a channel where other water treatment chemicals are added, a pipe coming from the filters, or the clearwell. In a well–pump system, this may be the discharge line of the pump if there is only one. If there is more than one pump, the point may be the manifold line leading to the distribution system or storage facility.

When other chemicals are being fed, chemical compatibility must be considered. Although fluoride is nonreactive with most other chemicals used at a treatment facility, whenever possible, fluoride should be added after treatment in an effluent finishing location. Products containing aluminum, calcium, and phosphates can produce negative impacts when associated with fluoride. Chemical solutions containing calcium, including lime, have the potential to form a calcium fluoride scale. Therefore, the fluoride injection point should be as far downstream as possible from the addition point of those chemicals to allow adequate time for complete dissolution of the calcium before the fluoride is added. Facilities using aluminum sulfate (alum) can experience some fluoride loss if fluoride is added prior to the alum addition: at an alum dosage rate of 100 mg/L, fluoride loss can be up to 30 percent. Adding fluoride too early in the lime–soda ash process can also result in a reduction in concentration. When possible, fluoride addition prior to phosphate addition for pipeline corrosion control is preferable for analytical verification because phosphate and other acids have a potential to interfere in the measurement of fluoride in some colorimetric testing procedures. If this situation cannot be avoided, then the facility should use the ion-specific electrode method of analytical measurement instead of the colorimetric method.

In most facilities, fluoride is added in a finishing step after other treatment processes. This is the preferred location so that nothing else will be added to affect the fluoride concentration. Less than 10 percent of facilities add fluoride earlier in the process flow, including the pretreatment process. In those cases, some chemical additions such as products containing calcium or aluminum have the potential to reduce the fluoride content. If this is the case, the facility should measure the fluoride in the water as it enters the distribution system to document the proper residuals.

Another factor in selecting the addition point is the desirability of having the feeder as close to the addition point as possible when dry fluoride is used and mixed into a solution. The discharge line from the feeder should be as short and straight as possible, although circumstances sometimes require a long discharge line. When this is the case, sharp curves or loops in the line should be avoided because they provide sites for

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precipitation buildup and subsequent blockage. Not infrequently, the addition of a separate unit process at an application point requires a new structure. The fluoride storage and feed equipment should have a designated room, and chemical storage should not be shared with different chemicals.

PROJECT PERMITTING AND PLANNING

Once the decision to proceed with water fluoridation is established, then the steps include identifying funding, preparing a design, obtaining all necessary permits, construction, and final implementation. Funding for implementation is often by the community or water system, but in some cases may be provided by another party.

Next, plans and specifications are prepared by the design engineer, which is usually a private professional design engineering firm retained by the water provider or, in a few cases, engineering staff of the water provider itself. In a few states, the state hires the engineer to provide design services for fluoridation systems to improve the consistency and quality of the installation. After approval by the permitting agency, the engineering plans and specifications become contract documents for a construction project that is bid and awarded to a qualified contractor. Some water providers may elect to purchase and install the fluoridation equipment using in-house staff and equipment.

Once the contract documents are in place, the fluoridated water system startup generally proceeds as follows:

- During construction, the design engineer often conducts field visits to observe construction procedures, answer contractor questions, and provide other engineering support to the contractor to ensure that the system is constructed according to the contract documents.
- As construction approaches completion, the water provider's operators receive training on fluoridation system equipment operation and maintenance from the design engineer and equipment vendors, or in some states, by state technical staff.
- The completed installation is inspected by the permitting agency for compliance with contract documents.
- The water provider prepares a fluoride monitoring and reporting plan for submittal to the permitting agency, and it notifies the public of the upcoming fluoridation implementation.
- The fluoridation system is ready to start up once the following happens: The permitting agency approves the installation and the monitoring and report plan, and the water provider completes a successful public notification.

Normal water fluoridation structures require a series of permits. Due to the presence of a hazardous chemical, these permits will be more extensive. The local building and safety department is likely to require:

- Building permits
- HVAC permits
- Plumbing permits
- Fire protection permits
- Electrical permits

In an effort to reduce the exposure of personnel to combustion products, the local fire department may require additional permits, including:

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- Corrosive chemical storage facility permits
- Hazardous materials disclosure
- Sprinkler activation notification through a central data processing facility
- Tests of the activation notification

The successful construction of a fluoridation system is the result of efforts by and coordination among various entities, most notably regulatory and permitting agencies, the water provider, the fluoridation system design engineer, and the construction contractor.

Fluoridation implementation is heavily driven by regulatory requirements stipulated by permitting agencies, such as the state drinking water program and/or state health department, the local fire department, and others. The following permitting requirements are common in most jurisdictions that regulate fluoridation:

1. A permit from the state/regional/local regulatory agency is almost always required before the community can fluoridate.
2. Design drawings and specifications must be prepared (in many states by a licensed engineer) and submitted to the permitting agency for approval prior to construction.
3. Safety devices are required. These vary greatly among jurisdictions, but they generally include day tanks, overfeed controls, vacuum breakers, anti-siphon devices, and eyewashes and safety showers.
4. In many jurisdictions, a fluoridation system requires inspection and approval by the permitting agency's drinking water program staff before operation can commence. In some jurisdictions, the operators are also required to have some formal training prior to startup.
5. Most jurisdictions require personal safety gear for the safety of the facility operator, such as long gauntlet gloves, chemical aprons, respirators, goggles, showers, eyewash facilities.
6. All jurisdictions require the correct operator certification (appropriate for the size and complexity of the water system) prior to the operation of the fluoridation system.
7. Almost all jurisdictions require daily sampling for fluoride levels in the finished water. Many jurisdictions require daily sampling from each individual source (well and treatment plant). Water providers should understand the applicable sampling and reporting requirements. Some split sampling verification is generally required.
8. Water providers should check with the appropriate permitting agencies on requirements for records to be maintained, such as daily fluoride sample results at source, daily weights of fluoride chemical added, and, in some jurisdictions, calculation of fluoride levels.
9. Emergency response procedures should be specified for each facility.

PROCESS OF IMPLEMENTING FLUORIDATION

Designing a new system or evaluating an existing facility will require preparation of calculations. The following sections provide the basis for calculations for different types of facilities.

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Process Calculations

Historically, deciding on the correct dosage for a particular location involved some consideration of ambient average temperature. Currently, that has been substantially simplified with the recommended level being established as a uniform 0.7 mg/L. Considering the natural fluoride in the source water, the dosage required to achieve a finished fluoride level of 0.7 mg/L can be calculated. The first step in planning is to determine the natural fluoride in the supply, and then that establishes the dosage required to achieve a finished fluoride level of 0.7 mg/L. Then, based on the system pumping rates, chemical purity, and available fluoride ions, the quantity of chemical needed daily can be determined.

Some treatment facilities will have a simple design, such as a groundwater well with a pump that either is on or off. Other facilities may have more complex and variable flows that accommodate different design considerations, including:

- Peak day flow
- Maximum month flow
- Annual average flow (this might be different based on current day flows at initial operations with a higher value at a future time when the facility is operating at design capacity with community growth)
- Minimum day flow
- Minimum hour flow (not common for water treatment, but could be a consideration in some cases)

An average flow rate determined from recent monthly data for three years should be used as a basis for current flows, along with the ultimate design capacity of the facility. Seasonal changes in water supply must be taken into account to determine the changes in water demand and average background water fluoride concentration. These inputs determine the fluoride dose, feed rates, chemical usage, and chemical storage. The CDC recommends that the water utility maintain a three-month supply on hand to guard against fluoride chemical shortages; the Canadian authority makes a similar recommendation.

Naturally occurring fluoride levels fluctuate for a variety of reasons, such as local geology, runoff, and so on. Therefore, the natural fluoride should be verified seasonally as it might change. For example, a wetter season (with rain dominating the flow) may result in a lower fluoride concentration, while a drier season (with groundwater springs dominating the flow) might result in a higher fluoride concentration. Most wells produce relatively uniform fluoride concentrations because the rate of fluoride leaching from the underlying geology tends to be consistent. Four to 10 data points per well should be sufficient, depending on the availability of data from the well. Many wells are not sampled more frequently than every three years, so older records may need to be accessed. When cluster wells are grouped, the combined fluoride concentration must be determined by a mass balance using the operating well flow rates under normal operational scenarios and conditions, not the maximum rated outputs.

Calculation of the chemical feed rate is necessary for proper adjustment of the fluoride feeder. To calculate the chemical feed rate, the following must be known:

- Desired fluoride dosage
- Plant rate or pumping rate
- Commercial purity and fluoride concentration of the fluoride chemical being fed (available fluoride ion)

The dosage is the amount of fluoride chemical needed to obtain the optimal fluoride level in the drinking water. The dosage, expressed as milligrams per liter (mg/L) or parts

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Table 4-1 Typical values of purity and available fluoride ion (AFI)

Chemical purity	%	AFI	Available F %
Sodium fluoride	98	0.452	44
Sodium fluorosilicate	98.5	0.607	60
Fluorosilicic acid	23	0.792	18

per million (ppm), is obtained by subtracting the naturally occurring fluoride level from the desired fluoride level. For example, if the desired fluoride level is 0.7 mg/L and the natural fluoride level is 0.2 mg/L, the dosage is 0.5 mg/L (0.7 – 0.2 = 0.5).

Only a portion of the bulk quantity of chemical additive contributes to the optimal fluoride level. The fluoride products as delivered are not 100 percent pure, and the fluoride ions may be bound to other elements. Table 4-1 lists examples of purity and available fluoride ion (AFI) for the fluoride products discussed in chapter 3. The percent available fluoride is the purity multiplied by the AFI.

The feed rate can then be calculated using the dosage, process water flow, purity, and available fluoride ion for the fluoride product that will be used. With these data, the chemical feed rate (in pounds per day) can be calculated for the various methods of feeding fluorides by the following relationship:

$$\text{Chemical feed rate (lb/day)} = \frac{D \times Q(\text{mgd}) \times (8.34)}{\text{AFI} \times P}$$

Where:

D = Dosage in mg/L
Q = Facility flow rate in mgd
AFI = Available fluoride ion, decimal fraction
P = Fluoride product purity, decimal fraction

The 8.34 conversion factor allows milligrams per liter and million gallons per day to equal pounds.

Example Feed Calculations

Sodium Fluorosilicate. The recommended fluoride level is 0.7 mg/L with a natural fluoride level of 0.2 mg/L. The chemical supplier has indicated that the commercial purity of the sodium fluorosilicate supplied is 98 percent and that a cubic foot of the supplied material weighs 65 pounds. If the plant rate is 2,000 gpm, determine the chemical feed rate in pounds per minute, cubic feet per hour, and grams per minute.

Given:

Recommended fluoride level = 0.7 mg/L
Natural fluoride level = 0.2 mg/L
Chemical purity = 98 percent
Pumping rate = 2,000 gpm or 2.8 mgd
Chemical weight = 65 lb/cubic foot

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