

Water Fluoridation

Principles and Practices

AWWA MANUAL M4

Fifth Edition



**American Water Works
Association**

Science and Technology

AWWA unites the drinking water community by developing and distributing authoritative scientific and technological knowledge. Through its members, AWWA develops industry standards for products and processes that advance public health and safety. AWWA also provides quality improvement programs for water and wastewater utilities.

MANUAL OF WATER SUPPLY PRACTICES—M4, Fifth Edition
Water Fluoridation Principles and Practices

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Contents

List of Figures, v

List of Tables, vii

Foreword, ix

Acknowledgments, xi

Chapter 1 History, Theory, and Chemicals 1

History and Theory, 1

Chemicals, 9

Bibliography, 13

Chapter 2 Fluoridation System Planning 15

General System Configurations, 16

Chemical Selection Guidelines, 18

Preliminary Calculations, 20

Feed Rate and Dosage Calculations, 22

Example Feed Rate Calculations, 23

Example Calculated Dosage Problems, 26

Simplification of Feed Rate and Dosage Calculations, 27

Preliminary Planning Examples, 31

Bibliography, 31

Chapter 3 Design, Equipment, and Installation 33

Design, 33

Feeders, 37

Auxiliary Equipment, 45

Equipment Installation, 53

Bibliography, 55

Chapter 4 Operation and Maintenance 57

Control Scheme, 57

Troubleshooting, 61

Records, 63

Maintenance, 63

Safety, 66

Bibliography, 71

Chapter 5 Defluoridation 73

Activated Alumina (AA) Treatment Process, 73

Reverse Osmosis Treatment, 79

Bibliography, 80

Additional Sources of Information, 81

Index, 85

AWWA Manuals, 89

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Figures

- 1-1 Dental caries and dental fluorosis in relation to fluoride in public water supplies, 2
- 1-2 The demineralization and remineralization processes lead to remineralized enamel crystals with surfaces rich in fluoride and lower in solubility, 6
- 2-1 Acid feed installation, 16
- 2-2 Solution fluoride saturator, 17
- 2-3 Dry feed installation with volumetric feeder, 17
- 2-4 Dry feed installation with gravimetric feeder, 18
- 2-5 Optimal fluoride levels, 21
- 2-6 Fluoridation nomograph, 29
- 2-7 Fluoridation alignment chart, 30
- 3-1 Fluoride injection point, 35
- 3-2 Positive-displacement solution feeders, 38
- 3-3 Upflow saturator, 40
- 3-4 Downflow saturator, 41
- 3-5 Screw-type volumetric dry feeder, 42
- 3-6 Roll-type volumetric dry feeder, 43
- 3-7 Belt-type gravimetric feeder, 43
- 3-8 Gravimetric feeder—loss-in-weight type, 44
- 3-9 Pacing meter—electronic metering pump, 49
- 3-10 Pacing meter—variable-speed motor control, 50
- 4-1 Simplified process control scheme, 58
- 5-1 Activated alumina with pH adjustment fluoride removal water treatment plant schematic flow diagram, 76
- 5-2 Conventional RO/NF membrane process, 80

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Tables

- 1-1 Number of people and percentage of the population receiving optimally fluoridated water through public water systems (PWS), by state—US, 1992 and 2000, 3
- 1-2 Years when Canadian cities began fluoridation, 5
- 1-3 Characteristics of fluoride compounds, 10
- 2-1 Fluoridation planning checklist, 19
- 2-2 Optimal fluoride levels, 20
- 2-3 Typical values of purity and available fluoride ion (AFI), 22
- 2-4 Fluoride calculation factors, 28
- 3-1 Detention time of sodium fluorosilicate in dissolving tanks, 48
- 4-1 Interfering substances, 60
- 4-2 Emergency treatment for ingested fluoride overdose of fluorosilicic acid H_2SiF_6 , 68
- 4-3 Emergency treatment for ingested fluoride overdose of dry fluoride chemicals NaF and Na_2SiF_6 , 68
- 4-4 Summary of reported fluoride overfeed incidents in public water systems, 69
- 4-5 Recommended fluoride overfeed action, 70

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Foreword

This manual assists decision makers planning fluoridation installations, engineers designing them, and water utility personnel operating them. 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.

The first edition of AWWA Manual M4 was prepared from material supplied and previously published by the US Environmental Protection Agency. This fifth edition updates the following major areas:

- Health effects
- State and federal regulations
- Defluoridation treatment

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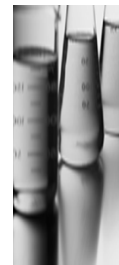
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Chapter 1

History, Theory, and Chemicals

Fluoridation treatment in this manual refers to the addition or removal of fluoride from drinking water to maintain an optimum level to reduce tooth decay. Fluoridation has been practiced for more than 50 years. This chapter discusses the history of fluoridation and the theory of how it reduces tooth decay. The chapter summarizes the results of health effects studies and addresses legal issues. The common chemicals used in fluoridation are also discussed.

HISTORY AND THEORY

Fluoridation History

In 1908, Dr. Frederick McKay, a dentist in Colorado Springs, Colo., became concerned because the teeth of many children in the community were mottled or discolored. Investigations showed that excessive amounts of fluoride in the local water supply caused the mottling. In other towns using naturally fluoridated water, mottled teeth appeared only when, as in Colorado Springs, the fluoride content of the water was abnormally high. This mottling was later termed *dental fluorosis*. Fluorosis occurs only when fluoride is consumed during childhood tooth formation, generally between the ages of 6 months and 3 years.

In the 1920s, the teeth of thousands of children and the water supplies of the communities in which they lived were evaluated. By 1931, the results showed significant relationships between the fluoride concentration in the drinking water and the incidence of tooth decay, technically called *dental caries*. Three distinct relationships were discovered (Figure 1-1).

1. When the fluoride level exceeds approximately 1.5 mg/L, any further increase does not significantly decrease the incidence of decayed, missing, or filled teeth, but higher levels do increase the occurrence and severity of mottling.

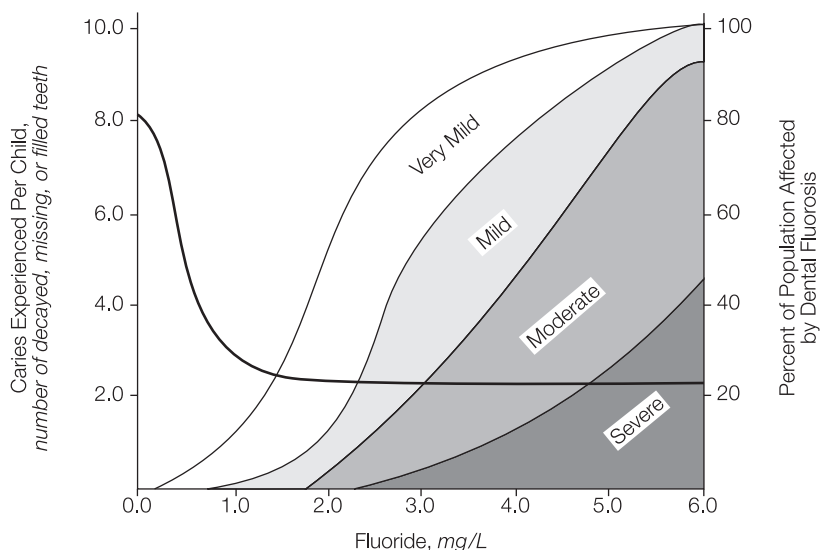


Figure 1-1 Dental caries and dental fluorosis in relation to fluoride in public water supplies

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 diminishes; the drop in benefits is much greater than the drop in fluoride levels. For example, when the fluoride level drops 20 percent over a period of time (from 1.0 mg/L to 0.8 mg/L), there is a 50 percent drop in benefits.

In the 1930s and 1940s, studies determined that fluoride added to drinking water supplies would reduce dental caries. In 1950, the US Public Health Service (USPHS) endorsed fluoridation. In 1962, the USPHS set fluoride levels in drinking water at 0.7 mg/L (in warmer climates) to 1.2 mg/L (in colder climates). The range was recommended because average water consumption varies with average daily air temperature. The range is discussed in more detail in chapter 2 of this manual. The USPHS also recommended that drinking water with natural fluoride levels twice the recommended adjusted level not be used. The agency, however, had no power to force water suppliers to remove excess fluoride.

Although school water fluoridation was widely practiced in several states, the Centers for Disease Control and Prevention (CDC) no longer recommends this practice. At its peak, school water fluoridation had a total of 170,000 children in 13 states with 470 school fluoridation systems. It is no longer recommended because operating and maintaining small fluoridation systems create practical difficulties. These operational problems have occasionally caused higher than recommended fluoride concentrations in school drinking water but no lasting effects among children have been observed.

Since 1974, the US Environmental Protection Agency (USEPA), under the Safe Drinking Water Act, has regulated drinking water. In 1986, USEPA set a maximum contaminant level goal (MCLG) and a maximum contaminant level (MCL) for fluoride of 4 mg/L. An MCLG is a health-related goal, and an MCL is a technologically feasible goal. Although the MCL and the MCLG for a single contaminant in drinking water may be different, in the case of fluoride both levels are

the same. The fluoride regulation applies to community water systems and requires removal of excess fluoride. The MCLG and MCL are intended to protect against adverse health effects, in particular crippling skeletal fluorosis. A secondary MCL was set at 2 mg/L to protect against dental fluorosis. Secondary MCLs are federally unenforceable recommended levels intended to prevent aesthetic health effects. In 1990, the USEPA began the required three-year review of the MCLG and MCL.

The optimal fluoride level is usually established by the appropriate state regulatory agency. USPHS and CDC recommend concentrations and control ranges that can be used as guidelines if state limits have not been established (see chapter 2).

Fluoridation has traditionally been justified based on the economics of a 40 to 65 percent reduction of tooth decay. Water fluoridation has been shown to be the least expensive method of dental caries reduction; the other methods being school water fluoridation, topically applied pastes or gels, and fluoride tablets or drops. However, fluoridation has not been without controversy. Some of the arguments against fluoridation have been the lack of long-term health risk studies and the perception that fluoridation is mass medication, infringing on personal choice.

In the United States during 2000, approximately 162 million people (or about 66 percent of the population served by public water systems) received optimally fluoridated water. This is about 58 percent of the total US population. Table 1-1 lists the population receiving optimally fluoridated water by state and compares the values for 2000 with 1992. Approximately 54 percent of the Canadian population using public water supplies received controlled fluoridated water. (Table 1-2 lists the years when Canadian cities began fluoridation.)

Table 1-1 Number of people and percentage of the population receiving optimally fluoridated water through public water systems (PWS), by state—US, 1992 and 2000

State	2000 Fluoridated Population	2000 Total PWS Population	2000 Percentage Fluoridated	1992 Percentage Fluoridated	Change in Percentage 1992–2000
Alabama*	3,967,059	4,447,100	89.2%	82.6%	6.6
Alaska	270,099	489,371	55.2%	61.2%	–6.0
Arizona	2,700,354	4,869,065	55.5%	49.9%	5.6
Arkansas†	1,455,767	2,431,477	59.9%	58.7%	1.2
California	9,551,961	33,238,057	28.7%	15.7%	13.0
Colorado†	2,852,386	3,708,061	76.9%	81.7%	–4.8
Connecticut	2,398,227	2,701,178	88.8%	85.9%	2.9
Delaware	505,747	624,923	80.9%	67.4%	13.5
District of Columbia	595,000	595,000	100.0%	100.0%	0.0
Florida	9,407,494	15,033,574	62.6%	58.3%	4.3
Georgia	6,161,139	6,634,635	92.9%	92.1%	0.8
Hawaii*	109,147	1,211,537	9.0%	13.0%	–4.0
Idaho	383,720	845,780	45.4%	48.3%	–2.9
Illinois	10,453,837	11,192,286	93.4%	95.2%	–1.8
Indiana	4,232,907	4,441,502	95.3%	98.6%	–3.3
Iowa	2,181,649	2,390,661	91.3%	91.4%	–0.1

* Reported PWS population exceeded total state population; PWS population was set to the 2000 U.S. census of state populations.

† Complete data were not available from Water Fluoridation Reporting System; additional information was obtained from states.

Table continued next page

Table 1-1 Number of people and percentage of the population receiving optimally fluoridated water through public water systems (PWS), by state—US, 1992 and 2000 (continued)

State	2000 Fluoridated Population	2000 Total PWS Population	2000 Percentage Fluoridated	1992 Percentage Fluoridated	Change in Percentage 1992–2000
Kansas	1,513,306	2,421,274	62.5%	58.4%	4.1
Kentucky	3,235,053	3,367,812	96.1%	100.0%	–3.9
Louisiana*	2,375,702	4,468,976	53.2%	55.7%	–2.5
Maine	466,208	618,033	75.4%	55.8%	19.6
Maryland†	4,124,953	4,547,908	90.7%	85.8%	4.9
Massachusetts†	3,546,099	6,349,097	55.8%	57.0%	–1.2
Michigan	6,568,151	7,242,531	90.7%	88.5%	2.2
Minnesota	3,714,465	3,780,942	98.2%	93.4%	4.8
Mississippi	1,227,268	2,665,075	46.0%	48.4%	–2.4
Missouri*	4,502,722	5,595,211	80.5%	71.4%	9.1
Montana	143,092	645,452	22.2%	25.9%	–3.7
Nebraska†	966,262	1,243,713	77.7%	62.1%	15.6
Nevada†	1,078,479	1,637,105	65.9%	2.1%	63.8
New Hampshire	347,007	807,438	43.0%	24.0%	19.0
New Jersey	1,120,410	7,208,514	15.5%	16.2%	–0.7
New Mexico	1,187,404	1,548,084	76.7%	66.2%	10.5
New York†	12,000,000	17,690,198	67.8%	69.7%	–1.9
North Carolina	4,862,220	5,837,936	83.3%	78.5%	4.8
North Dakota	531,738	557,595	95.4%	96.4%	–1.0
Ohio	8,355,002	9,535,188	87.6%	87.9%	–0.3
Oklahoma†	2,164,330	2,900,000	74.6%	58.0%	16.6
Oregon†	612,485	2,700,000	22.7%	24.8%	–2.1
Pennsylvania	5,825,328	10,750,095	54.2%	50.9%	3.3
Rhode Island	842,797	989,786	85.1%	100.0%	–14.9
South Carolina	3,086,974	3,383,434	91.2%	90.0%	1.2
South Dakota†	553,503	626,221	88.4%	100.0%	–11.6
Tennessee	4,749,493	5,025,998	94.5%	92.0%	2.5
Texas	11,868,046	18,072,680	65.7%	64.0%	1.7
Utah*	43,816	2,233,169	2.0%	3.1%	–1.1
Vermont	240,579	443,901	54.2%	57.4%	–3.2
Virginia	5,677,551	6,085,436	93.3%	72.1%	21.2
Washington†	2,844,893	4,925,540	57.8%	53.2%	4.6
West Virginia†	1,207,000	1,387,000	87.0%	82.1%	4.9
Wisconsin	3,108,738	3,481,285	89.3%	93.0%	–3.7
Wyoming*	149,774	493,782	30.3%	35.7%	–5.4
Total	162,067,341	246,120,616	65.8%	62.1%	3.7

* Reported PWS population exceeded total state population; PWS population was set to the 2000 US census of state populations.

† Complete data were not available from Water Fluoridation Reporting System; additional information was obtained from states.

Source: Centers for Disease Control and Prevention.

Table 1-2 Years when Canadian cities began fluoridation

Belleville	1965	Moose Jaw	1963
Borden	1969	North Bay	1962
Brampton	1968	Oshawa	1953
Brandon	1955	Oakville	1963
Brantford	1945	Ottawa	1965
Burlington	1961	Peterborough	1973
Calgary	1991	Pointe-Claire	1955
Chateauguay	1970	Prince Albert	1960
Cornerbrook	1970	Prince George	1956
Cornwall	1962	Quebec City	1986
Dartmouth	1956	Red Deer	1958
Dorval	1957	Saint John	1992
Dryden	1962	Sarnia	1971
Edmonton	1967	Saskatoon	1955
Estevan	1961	St. Lambert	1971
Glance Bay	1975	St. Thomas	1965
Halifax	1956	Sudbury	1952
Hamilton	1967	Swift Current	1954
Huntsville	1986	Sydney	1968
Kamloops	1966	Toronto	1955
Kindersley	1959	Waterloo	1967
Laval	1958	Welland	1963
Lethbridge	1976	Weyburn	1955
London	1967	Windsor	1962
Mississauga	1961	Winnipeg	1956
Moncton	1970		

Source: Health Canada. 1992. *Canadian Cities with Fluoridation*.

The American Water Works Association policy on fluoridation was adopted by the organization's board of directors on Jan. 25, 1976, and reaffirmed on Jan. 31, 1982, and revised Jan. 20, 2002. The official text follows:

"The American Water Works Association (AWWA) supports fluoridation of water supplies in a safe, effective, and reliable manner that includes adequate monitoring and control of fluoride levels within limits prescribed by health officials subject to community and local decision-making processes."

Bone and Tooth Incorporation of Fluoride

The mineral and hard tissue structures of bones, teeth, and other parts of the skeleton contain fluoride. Soft body tissues do not retain fluoride, except as found in calcified deposits. Fluoride enters the teeth either topically or systemically. The topical effect occurs when a portion of the fluoride in drinking water is retained by fluids in the mouth. The fluoride is then incorporated at the surface of the tooth. The

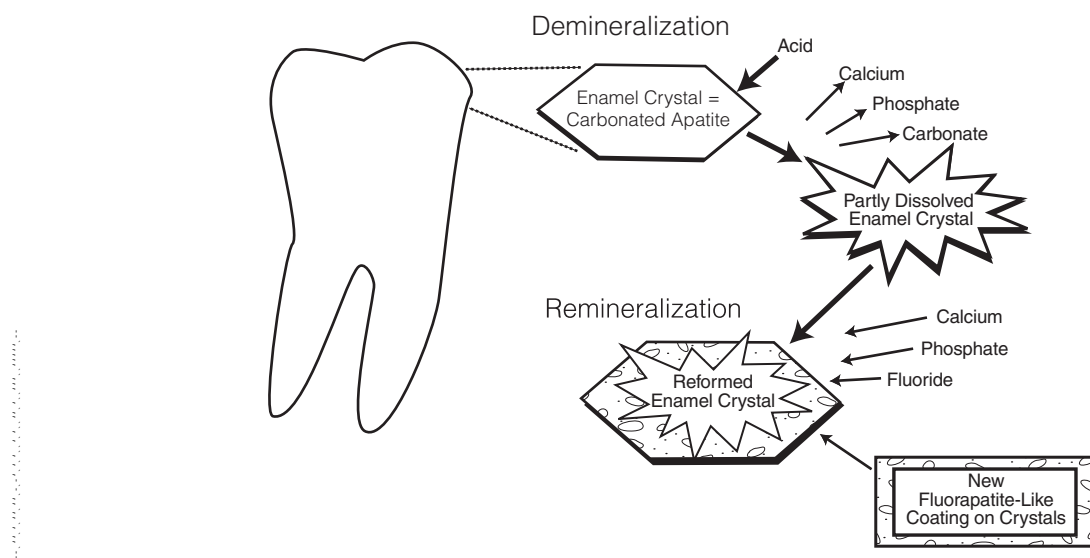
systemic effect occurs when fluoride diffuses through the walls of the stomach and intestines. The fluoride is distributed throughout the body in the blood. The fluoride is then available to all the skeletal structures, including the teeth. Fluoride not deposited in bones and teeth is excreted through the kidneys.

Fluoride incorporation by the teeth is most rapid during the time of a child's formation and growth, roughly from the fourth month of pregnancy to the tenth year. The eighth year generally marks the end of the maximum rate of incorporation of fluoride in the teeth. 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.

Tooth Decay

A tooth is composed of enamel, dentin, pulp, and cementum (Figure 1-2). Tooth decay occurs when acids destroy the tooth structure. These acids are produced by the action of bacteria and enzymes on sugars and carbohydrates in the mouth. This action takes place beneath the plaque, which is an invisible film composed of gummy masses of microorganisms that adhere to the teeth. Oral bacteria alone can convert some of the simple sugars into acids. Bacteria and enzymes acting together convert carbohydrates and more complex sugars into acids. Cavities, or caries, form when the acids dissolve tooth enamel.

Nearly everyone suffers from dental caries, making tooth decay the most prevalent chronic human disease. Before the widespread use of fluorides, more than 98 out of every 100 Americans experienced some tooth decay by the time they reached adulthood. Tooth decay begins in early childhood, reaches a peak in adolescence, and diminishes during adulthood. The highest tooth decay activity is found in school-aged children. In age group 12–17, the average US resident will have 4.09 decayed, missing, or filled teeth.



Source: Adapted from Featherstone, J.D.B. 1999. Prevention and reversal of dental caries: Role of low-level fluoride. *Community Dent Oral Epidemiol* 27:31–40. Reprinted with permission from Munksgaard International Publishers Ltd., Copenhagen, Denmark.

Figure 1-2 The demineralization and remineralization processes lead to remineralized enamel crystals with surfaces rich in fluoride and lower in solubility

Fluoride reduces tooth decay in several ways. Fluoride strengthens the enamel against decay when the enamel layer incorporates fluoride during childhood tooth formation. Another way in which fluoride reduces decay is through constant demineralization and remineralization, which takes place on the surface of the teeth. Acids that form in the mouth cause demineralization through the exchange of ions. Fluoride inhibits the formation of acids, which allows remineralization to occur. Another mechanism that occurs during remineralization is the incorporation of fluoride ions into the enamel, which strengthens it.

Health Effects

High concentrations of fluoride in drinking water have been found to cause adverse health effects.

Skeletal fluorosis. Skeletal fluorosis is an adverse health effect caused by an accumulation of too much fluoride in bone. The stages of skeletal fluorosis range from preclinical (no reported symptoms) to crippling. Symptoms include

- pain in bones and joints
- formation of bone spurs
- osteoporosis in the long bones (loss of bone mass and increase in porosity)
- osteosclerosis (increase in bone density and formation of unusual crystalline structure)
- weakness of extremities
- fused vertebrae

Crippling skeletal fluorosis results from intakes of fluoride of 20 mg/d over periods of 20 years or more. A drinking water fluoride concentration of 10 mg/L, combined with a 2-L/d water consumption rate, would correspond to this value. This is a very rare occurrence in the United States but does occur in other countries, such as India, where some areas have very high fluoride levels.

Severe dental fluorosis. Severe dental fluorosis causes teeth to be stained, pitted, and brittle. USEPA research indicates that at 4 mg/L, 7 percent of the population experience moderate dental fluorosis and 23 percent experience severe dental fluorosis. Doses as low as 2 to 5 mg/L can cause the preclinical and earlier stages. Figure 1-1 indicates the percent of people affected by varying levels of dental fluorosis, from very mild to severe, and the incidence of caries experienced from 0 to 6 mg/L fluoride. As the line indicating the number of caries experienced shows, the optimum benefits from fluoride occur around 1 mg/L fluoride. Recent studies have shown a slight increase in dental fluorosis in communities with nonfluoridated water. The cause may be fluoride in sources other than drinking water. These sources include toothpastes, dietary supplements, mouth rinses, professional applications, and foods and beverages processed with fluoridated water.

Other health effects. Other health effects have been studied, though less extensively than fluorosis. The studied risks include

- kidney disease
- hypersensitivity (allergic reactions)
- gastrointestinal problems
- intelligence

- thyroid (goiter) effects
- substances added during fluoridation
- dietary exposure to metals
- effects on bioavailability or toxicity of toxic metals (aluminum and lead)
- enzyme and mutagenic (gene-altering) effects
- birth defects
- cancer

The evidence of fluoride's part in any of these health risks is largely discounted. The strongest recommendation comes from the National Kidney Foundation, which advises that dialysis patients use mineral-free (fluoride included) water for their treatments.

A National Toxicology Program study released in 1990 indicates equivocal (uncertain) evidence of carcinogenicity in rats fed sodium fluoride. This evidence is based on a small number of bone tumors. As a result of the equivocal evidence ruling, the USPHS conducted a comprehensive review of the benefits and risks of fluoridation. Its 1991 report recommends the use of fluoride to reduce dental caries and supports optimal fluoridation of drinking water.

A National Research Council panel, in a report issued Aug. 17, 1993, found that there was no credible evidence that fluoridation causes cancer, kidney disease, or birth defects. The panel found some studies that suggested long-term exposure to fluoride increases hip or vertebra fractures in people after age 80. However, the evidence was uncertain. The National Institutes of Health is organizing a long-term study to see whether these fractures are related to fluoridation.

The Medical Research Council (MRC) issued a report in September 2002 that reviewed the current status of fluoridation and health. The report based its conclusions on a review conducted in 2000 by the University of York, United Kingdom, and many other relevant studies. The beneficial effect of water fluoridation on dental caries was confirmed. However, the MRC identified some areas of uncertainty regarding the benefits and risks of water fluoridation. Some of the conclusions included in the MRC report follow:

- The public needs additional information to make informed decisions regarding fluoridation.
- Further work is warranted on the impact of fluoridation on caries that includes an understanding of combined impact of fluoride from all sources (e.g., toothpaste).
- The available evidence suggests no effect on the risk of hip fracture.
- The available evidence suggests no link between water fluoridation and cancer.
- There is no evidence for any significant health effects on the immune system, on the kidney and gastrointestinal tract, or for reproductive and developmental defects.
- There is no evidence for any significant health effects caused by chemicals added during the fluoridation process or for indirect effects, such as increased leaching of lead from pipes and aluminum from cooking utensils, although these areas should be kept under review.

Legal Issues

The legality of fluoridation has been tested in the courts several times. Beginning in 1952, injunctions were sought in some communities to prevent the initiation or continuance of fluoridation. These cases were generally based on several of the following types of arguments: violation of religious freedom, violation of pure food acts, abuse of municipal authority, an unreasonable or unnecessary measure, wasteful or illegal use of public funds, an unsafe measure or nuisance, availability of alternatives, breach of contract, class legislation (i.e., only children benefit), and deprivation of fundamental liberties.

In all cases, fluoridation has prevailed. During 30 years of litigation, fluoridation has withstood challenges under constitutional objections (related to the First, Tenth, and Fifteenth Amendments); it has been upheld in the highest courts in more than a dozen states; and it has withstood legal challenges in more than 25 states. At least eight times the US Supreme Court has denied review, generally on the grounds that no constitutional question was involved.

Even though the basic issues involved in fluoridation litigation were resolved more than a decade ago, cases based on the same issues occasionally appear. A few of these suits have been successful in obtaining injunctions. Some referendums to prohibit or discontinue fluoridation have been successful. In the last few years referendums have been used to authorize about 50 percent of the new fluoridated water systems.

CHEMICALS

In theory, any compound that forms fluoride ions in water can be used for fluoridation. However, several practical considerations are involved in the selection of which compounds to use.

- The compound must be sufficiently soluble to permit its use in routine water treatment plant practice.
- The cation (positively charged ion) to which the fluoride ion is attached must not have any undesirable characteristics.
- The material should be relatively inexpensive and readily available in grades of a size and purity that are suitable for the intended use.

The three most commonly used fluoride compounds are sodium fluoride, fluorosilicic acid, and sodium fluorosilicate. Before 1992, fluorosilicic acid was known as hydrofluosilicic acid, and sodium fluorosilicate was called sodium silicofluoride. The AWWA standards that address fluoride compounds are

- AWWA Standard B701, Sodium Fluoride
- AWWA Standard B702, Sodium Fluorosilicate
- AWWA Standard B703, Fluorosilicic Acid

The chemical, physical, and other characteristics of these three compounds are summarized in Table 1-3. Other compounds have also occasionally been used for fluoridation, as discussed later in this section.

Table 1-3 Characteristics of fluoride compounds

Item	Sodium Fluoride (NaF)	Sodium Fluorosilicate (Na ₂ SiF ₆)	Fluorosilicic Acid (H ₂ SiF ₆)
Form	Powder or crystal	Powder or very fine crystal	Liquid
Molecular weight	42.00	188.05	144.08
Available fluoride ion—percent (100% pure material)	45.25	60.7	79.2
Pounds required per million gallons (grams required per cubic meter) for 1.10 mg/L F ⁻ at indicated purity	1.8 (2.225) (98%)	14.0 (1.678) (98.5%)	46 (5.512) (23%)
pH of saturated solution	7.6	3.5	1.2 (23% solution)
Sodium ion contributed at 1.0 mg/L F ⁻	1.17	0.40	0.00
F ⁻ ion storage space— ft ³ /100 lb (m ³ /kg)	22–34 (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	0.762	Infinite
Weight—lb/ft ³ (kg/m ³)	65–90 (1,000–1,400)	55–72 (880–1,150)	10.5 lb/gal (30%) (1.26 kg/L)
Typical commercial purity—percent	97–99	98–99	20–30
Shipping containers	50-lb bags 100-lb bags 125- to 400-lb Fiber drums, bulk	50-lb bags 100-lb bags 124- to 140-lb Fiber drums, bulk	13-gal carboys 55-gal drums Tanks cars, bulk

Sodium Fluoride

The first fluoride compound used in adjusted fluoridation was sodium fluoride. It was selected not only on the basis of the criteria just specified but also because its toxicity and physiological effects had been studied thoroughly. Once fluoridation became an established practice, other compounds came into use.

Sodium fluoride is a white, odorless material available either as a powder or as crystals of various sizes. Its formula weight is 42.00. Its solubility is practically constant at 4 g/100 mL of water at temperatures generally encountered in water treatment. When added to water, sodium fluoride dissociates into sodium and fluoride ions:



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 to more than 98 percent. Impurities consist of water, free acid or alkali, sodium fluorosilicate, sulfites, and iron, plus traces of other substances.

Powdered sodium fluoride is produced in different densities; the light grade weighs less than 65 lb/ft³ (1,000 kg/m³), and the heavy grade weighs about 90 lb/ft³

(1,400 kg/m³). A typical sieve analysis of powdered sodium fluoride passes 99 percent through a 200-mesh sieve and 97 percent through a 325-mesh sieve.

Crystalline sodium fluoride is produced in various size ranges, usually designated as coarse, fine, and extra fine; however, some manufacturers can provide lots in specific mesh sizes. The crystalline type is preferred for utilities using manual handling because it results in a minimum of dust. 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 3.

Fluorosilicic Acid

Fluorosilicic acid is available as a 20 to 35 percent aqueous solution of H₂SiF₆; it has a formula weight of 144.08. The most common concentration used in water treatment is 23–25 percent. When pure, it is a colorless, transparent, fuming, corrosive liquid having a pungent odor and an irritating action on the skin. On vaporizing, the acid decomposes to form hydrofluoric acid (HF) and silicon tetrafluoride (SiF₄). Under conditions where an equilibrium between the fluorosilicic acid and its decomposition products exists, such as at the surface of strong solutions, etching of glass can occur.

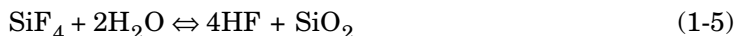
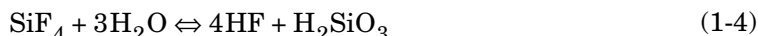
Fluorosilicic acid dissociates virtually 100 percent in solution, releasing hydrofluoric acid and silicon tetrafluoride:



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



Silicon tetrafluoride is a gas that easily volatilizes out of solution if present in high concentrations. It also reacts quickly with water to form silicic acid (H₂SiO₃) or silicon dioxide (SiO₂):



All solutions of fluorosilicic acid exhibit a low pH (approximately 1.2). Even at a concentration low enough to produce 1 mg/L of fluoride ion, the pH of poorly buffered waters can be lowered. For example, in water containing 30 mg/L of total dissolved solids with a pH of 6.5, after H₂SiF₆ is added to produce 1 mg/L F[−], the pH drops to 6.2.

Fluorosilicic acid is manufactured as a by-product of phosphate fertilizer; it is relatively impure and seldom exceeds 30 percent strength. 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. Some suppliers of by-product fluorosilicic acid sell a fortified form that has a small amount of

hydrofluoric acid added to prevent the formation of precipitate. Acid prepared from hydrofluoric acid and silica does not normally form a precipitate when it is diluted.

Because fluorosilicic acid contains a high proportion of water, shipping large quantities can be expensive. 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, who usually package it in drums or polyethylene carboys. Rather than attempt to adjust the acid strength 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.

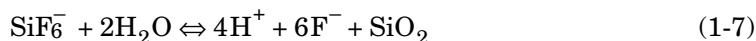
Attempts to dilute the acid are subject to errors in measuring both the acid and the diluting water. The acid should be used undiluted as it comes from the shipping containers. If the acid is too concentrated for the solution feeder to handle, then a smaller sized feeder should be used or a weaker solution of other, less expensive compounds should be used, such as saturated solutions of sodium fluoride. (Very small metering pumps are available.)

Sodium Fluorosilicate

Fluorosilicic acid can readily be converted into various salts, one of which, sodium fluorosilicate, is widely used in fluoridation. Sodium fluorosilicate is one of the least expensive compounds currently in use. The conversion of fluorosilicic acid, essentially a low-cost by-product containing too much water to permit economical shipping, to a dry material containing a high percentage of available fluoride results in a compound having most of the advantages of the acid with few of its disadvantages. Sodium fluorosilicate is a white, odorless, crystalline powder. Its molecular weight is 188.06. Its solubility 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 rapidly:



Silicofluoride ions, SiF_6^- , may react in two ways. The most common reaction is hydrolysis of SiF_6^- , releasing fluoride ions and silica. Silica, the main ingredient in glass, is very soluble in water.



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



Silicon tetrafluoride reacts as described in Eq 1-4 and Eq 1-5. 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, and silica.

Sodium fluorosilicate is sold in two commercial forms: regular and fluffy. The regular form has a density of about 85 lb/ft³ (1,400 kg/m³), the fluffy form about 65 lb/ft³ (1,000 kg/m³). A typical sieve analysis of the regular grade allows more than 99 percent through a 200-mesh sieve and more than 10 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.

Considerable quantities of sodium fluorosilicate are imported. Sodium fluorosilicate is normally packed in bags and drums similar to those used for sodium fluoride. As with sodium fluoride, sodium fluorosilicate must be made into a solution in a dissolving chamber before being fed into the water supply.

Other Fluoride Compounds

Ammonium silicofluoride, magnesium silicofluoride, potassium fluoride, calcium fluoride (fluorspar), and hydrofluoric acid have also been used for fluoridation. Each has particular properties that make the material desirable in a specific application, but none of them has widespread application in the United States. Fluorspar is used occasionally in South America, particularly in Brazil.

Ammonium silicofluoride has the advantage of supplying all or part of the ammonium ion necessary for the production of chloramines, when this form of disinfectant is used.

Magnesium silicofluoride and potassium fluoride have the advantage of extremely high solubility, which is of particular importance in applications, such as school fluoridation, where infrequent refills of the solution container are desired. In addition, potassium fluoride is quite compatible with potassium hypochlorite; a mixture of the two can be used for simultaneous fluoridation and chlorination.

Calcium fluoride (fluorspar) is the least expensive of the compounds used for fluoridation and also the least soluble. One feed technique is to first dissolve it in alum solution and then use the resultant solution to supply both the alum needed for coagulation and the fluoride ion. However, this method of operation is wasteful because of fluoride loss during alum coagulation and filtration (see chapter 4).

Hydrofluoric acid, although low in cost, presents too much of a safety and corrosion hazard to be acceptable for general water fluoridation. It has, however, been used in a specially designed installation.

Other fluoride compounds have been suggested for use in water fluoridation, among them ammonium bifluoride and sodium bifluoride. These materials have the advantages of high solubility and low cost, but their potential corrosiveness has made them generally unacceptable.

The manufacturers or suppliers of the various fluoride compounds can provide technical data and specification sheets that will assist the prospective purchaser in selecting the appropriate grade of chemical for the type of feeder used.

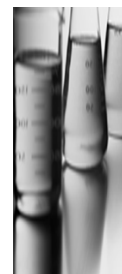
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Chapter 2

Fluoridation System Planning

This chapter introduces general types of fluoridation systems. It also presents guidelines for planning fluoridation systems. Included are chemical selection guidelines, feed rate and dosage calculations, example feed rate problems, and examples of preliminary planning.

Fluoridation systems are usually 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 final approval of systems. Among the considerations in choosing the right fluoridation system for a particular situation are

- optimal fluoride level
- population served or water usage
- water system characteristics (such as source of supply, treatment, storage, distribution, personnel)
- chemical availability
- cost

Although no type of fluoridation system is solely applicable to a specific situation, some general limitations are imposed by the size and type of water facility. For example, the manager of a large metropolitan water plant usually should not consider a fluoridation system involving the manual preparation of batches of solution, and the manager of a small facility consisting of several unattended wells should not consider a large dry feed system.

GENERAL SYSTEM CONFIGURATIONS

This section introduces the general configurations of fluoridation systems. Specific information on fluoridation equipment is found in chapter 3.

The simplest fluoridation system (Figure 2-1) is one based on the use of fluorosilicic acid. The acid is supplied in carboys or drums, mounted on a platform scale. A solution feed pump, mounted on a shelf above the carboy, injects the acid into a water main in proportion to the water flow. The feed pump should not be mounted more than 4 ft (1.2 m) above the top of the carboy. An antisiphon valve is usually part of the feeder, and auxiliary equipment, such as a loss-of-weight recorder, can be added.

A sodium fluoride saturator system is almost as simple. This system requires slightly more space and piping than a straight acid feed system (Figure 2-2). Many of the same comments made regarding acid feed systems apply to the saturator systems. The metering pump should be located not more than 4 ft (1.2 m) above the low saturated water line in the saturator. The suction line should be as short as possible. The metering pump should be equipped with an antisiphon valve. There should also be an antisiphon valve at the fluoride injection point if the fluoride solution is injected into a water main. Once the solution has been adjusted, the only operator attention required is the occasional replenishing of chemical (without weighing) and the cleaning of the saturator.

The fluoride saturator does not need to be sealed as tightly as the acid carboy. Saturator systems should have a water meter and, if necessary, a water softener. The feedwater line should contain a Y-strainer and sufficient unions to allow easy removal of piping. When mounting a metering pump on a shelf or platform above the saturator, it is advisable to offset it sufficiently to permit access to the container for filling and cleaning. Mounting the metering pump on the lid of the saturator is not recommended. A saturator should never be pushed to its design capacity limit for any length of time. When a saturator's capacity is approached, another method of fluoridation should be considered, such as the use of fluorosilicic acid.

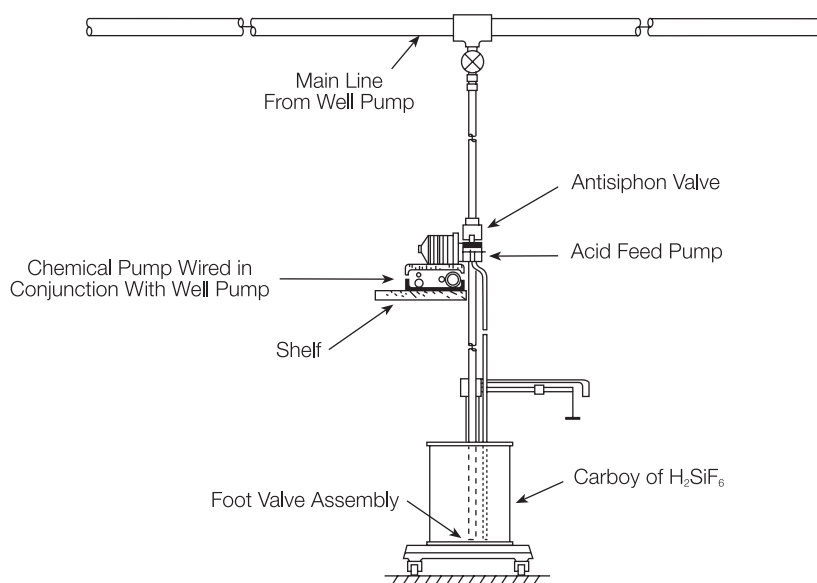


Figure 2-1 Acid feed installation

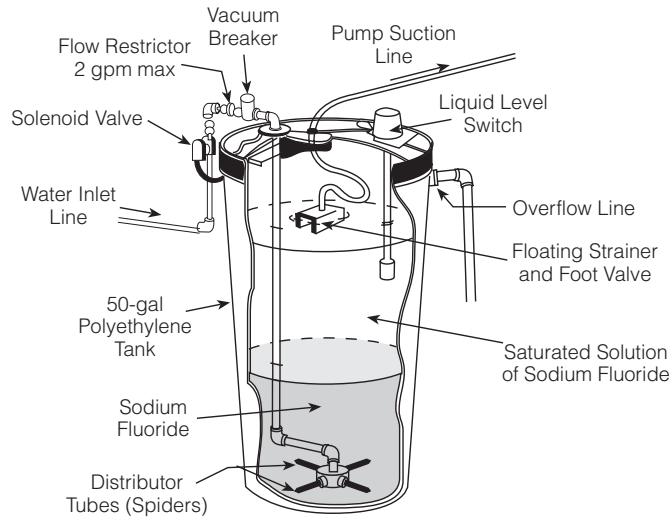


Figure 2-2 Solution fluoride saturator

Dry feeding of sodium fluorosilicate or sodium fluoride is limited to water plants large enough to accommodate a volumetric or gravimetric feeder. Volumetric dry feeders (Figure 2-3) are capable of feeding at very low rates, and some of the smallest disk types, such as those used for pilot-plant installations, are able to handle water rates as low as 25 gpm (95 L/min). If an open channel for feeding by gravity from the dissolving tank is not available, an eductor or centrifugal feed pump can be used for injecting fluoride solution into a main. The roll-type and screw-type volumetric dry feeders are capable of handling flow rates from less than 100 gpm to several million gallons per day (400 L/min to several megaliters per day). Gravimetric dry feeders can treat flows from about 2 mgd (7.6 ML/d) up to the greatest water usages encountered (Figure 2-4).

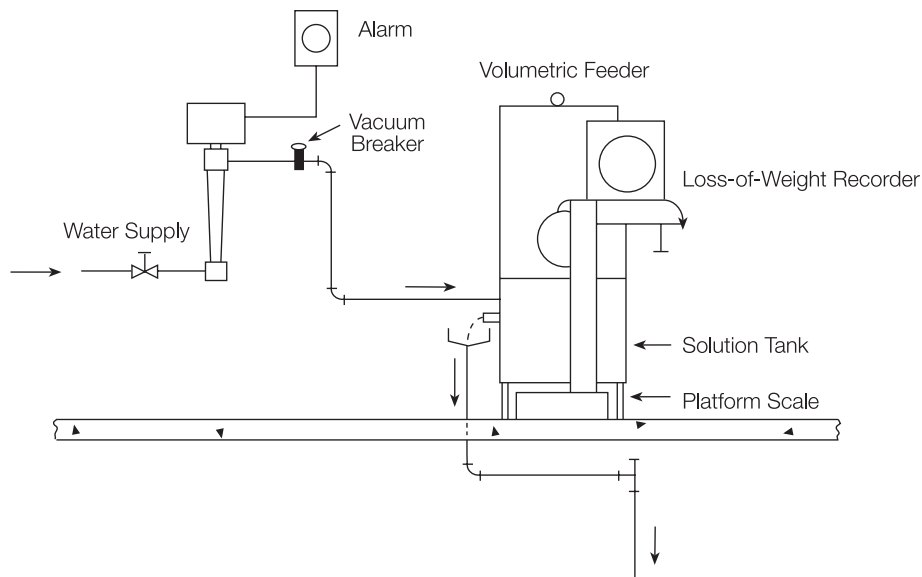


Figure 2-3 Dry feed installation with volumetric feeder

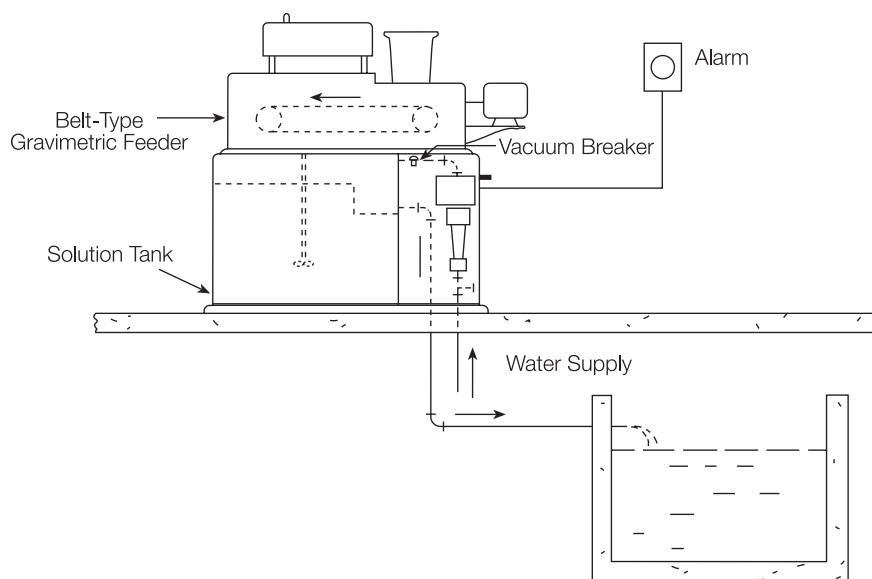


Figure 2-4 Dry feed installation with gravimetric feeder

The fluoridation system with the lowest equipment cost feeds a fluoride solution into a water flow in a pipeline. The only requirements are to prepare a fluoride solution of known concentration and to pump it into the water so that the necessary fluoride concentration in the water is achieved. Of the most commonly used fluoride compounds, sodium fluoride and fluorosilicic acid are of sufficient solubility to make up solutions of fixed strength that can then be fed with a metering pump. Fluorosilicic acid, normally purchased as a solution, can be fed either directly from the shipping container or from an intermediate storage tank (day tank).

For small water plants, some type of solution feed is usually selected. There is almost no lower limit to the ranges of the smallest metering pumps. In addition, if the feed rate for solution feed is impractically low, a more dilute solution can be fed (although this is not preferred). Conversely, there is almost no upper limit to the capacity of gravimetric dry feeders or pumps. Large water plants can select either dry feed using sodium fluorosilicate or direct feed using fluorosilicic acid. All other water plants have a choice, modified by individual circumstances. Assistance can be obtained from state health department engineers, manufacturers' representatives, and consultants.

CHEMICAL SELECTION GUIDELINES

For small water plants, the amount of chemical used is small enough that the cost per pound is not a major factor. Therefore, sodium fluoride or fluorosilicic acid, even though relatively expensive in small lots, can be used. The decision to use fluorosilicic acid, a manually prepared sodium fluoride solution, or a saturator depends on the quantities to be fed, the skill of the operator, and the availability and desirability of acid. Table 2-1 is a checklist, based mainly on water pumping rates, that can be used as a rough guide in differentiating between the various types of fluoridation installations. The population divisions in this table are general guidelines and will overlap.