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Filtration and chlorination of small water supplies

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FILTRATION AND CHLORINATION
OF SMALL WATER SUPPLIES

by

Daniel Dean Ludwig

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INTRODUCTION

Sixty years ago, America's municipal water supplies received no chemical treatment for disinfection. In many instances, water was pumped straight from rivers to the city mains. This is a far cry from the rigid control of water quality maintained today by state health departments. Today, most municipal water supplies meet U. S. Public Health Service drinking water standards. However, water is still consumed from individual small water supplies with little or no treatment or disinfection. Some wells on farms or suburban lots yield a bacteriologically safe water, but more and more wells are subject to pollution and are polluted by underground contamination. Seepage from septic tanks or sewer lines may eventually invade the underground water source. Pond water supplies, which are increasing in number and popularity, can never be considered safe without some mode of disinfection regardless of how clear they may appear. Should we continue to uphold decent standards of treatment for our large water supply systems and slip to mediocrity and carelessness with individual systems? We have established a drinking water standard based on municipal treatment practice where control is under the constant supervision of state health departments. In many cases we are satisfied with an even lower standard in small water supplies where we have less control. Are we not at a time when we should study the need for raising the standards and encouraging better disinfection in individual water supplies?

Even though our nation is experiencing a population movement to the cities, a large number of individual water supplies are in existence and more are being installed. Over 700,000 individual small water supplies are installed yearly. Farms, suburban homes, roadside restaurants and bus stops, trailer courts, isolated institutions, camp sites, resorts and motels are typical of situations where small water supplies exist. Many of these supply water for individual families, but in some, from 20 to 50 people may be involved. Contaminated water from small water supplies that serve the public may result in epidemics. Home-processed food and dairy products are subject to food spoilage organisms when contaminated water is used for processing. These organisms materially reduce the permissible food storage time even when frozen. The arguments in favor of adequate disinfection of individual water supplies are numerous.

The public health purpose of disinfection of water supplies is to destroy pathogenic bacteria which may be carried in the water. Chlorine, because of its commercial availability, adequate and continued disinfecting capability, simplicity in application, and ease in control of residuals is the most widely used and accepted water disinfectant. It is customary to maintain a free or combined chlorine residual of 0.2 to 1.0 mg/l and provide a contact period of at least 30 min in municipal water supply practice. In such systems, the source of water may be a large lake, river or series of wells. The physical, chemical and biological history of the source is known from previous records. These data aid in disinfection control. Daily testing indicates the quality of the product. Extended distribution systems and fire storage furnish sufficient contact time of chlorine with the treated water. Such advantageous conditions are not available in small water supply systems that must provide water for long periods with little attention. Rapid changes in the physical and biological character of small water sources occur. Animal excreta and subsequent runoff and precipitation runoff often contribute heavy concentrations of pathogenic and other bacteria. Adequate chlorine contact time is, in most cases, unavailable (2). In view of such conditions, disinfection recommendations applicable for municipal supplies are inadequate for most small water systems.

To provide a factor of safety in systems that normally are not under strict public health supervision, superchlorination is recommended (54). High chlorine residuals will insure destruction of resistant pathogens even under adverse temperature and pH conditions. In small systems, the extra chlorine utilized for superchlorination is not costly. We might apply an old Latin maxim here: "Si vis pacem, para bellum"--"If you want peace, prepare for war".

Superchlorination is not, however, a cure-all in every instance. If adequate chlorine residuals and retention times are not provided, 100 percent kill of organisms cannot be expected. Under certain conditions, the presence of phenols or other organic compounds may impart obnoxious odors. No system can be expected to be entirely perfect, but with proper attention to the characteristics of the water, engineering design can provide a highly satisfactory small water supply.

Purpose of This Study

Since superchlorination with adequate contact time will eliminate bacterial and virus pathogens, its use is advocated for small water supplies. If this practice is to be made attractive to the owners of such systems, we must provide information concerning chlorine residuals required for disinfection and methods for obtaining the necessary contact time. This study, therefore, was directed to:

(1) establishing criteria for the disinfection of small water supplies

(2) establishing recommended chlorine residuals and contact times for small water supplies

(3) recommending methods for obtaining chlorine contact time at critical flow rate conditions

(4) determining some of the factors affecting the critical flow rate

(5) determining whether the use of prechlorination in slow sand filters for obtaining contact time interferes with the efficiency of these filters.

Definition of Terms

Small Water Supply	Any system that furnishes water for human or animal consumption in individual households, farms, or other installations that are isolated from a municipal water supply. This term is used interchangeably with 'Individual Water Supply' in this study.
Slow Sand Filter	A bed of fine sand that is used for filtering water at a rate between 25 and 200 gpd/sq ft.
Superchlorination	The deliberate addition of more chlorine than is normally necessary to disinfect a given contaminated water.
Free Available Chlorine	The concentration of hypochlorous acid and hypochlorite (OCl^-) ions in a chlorinated water at a given time.
FAC residual	The concentration of free available chlorine after the chlorine demand of the water has been satisfied.

ft	foot or feet
gal	gallon(s)
gpm	gallon(s) per minute
gpd	gallons per day
gpd/sq ft	gallon(s) per day per square foot
gpcd	gallons per capita per day
in.	inch(s)
min	minute(s)
mg/l	milligrams per liter
ml	milliliter
ppb	parts per billion

PREVAILING TREATMENT IN SMALL WATER SUPPLIES

Characteristics of Farm Pond and Well Waters

Natural or man-made ponds have become important sources of water for small water supplies in several areas of the country. This has been brought about primarily as a result of droughts during the past 10 years and the deep depths required for wells of sufficient capacity. The expense of deep wells is beyond the financial capability of most owners.

Other advantages that make ponds popular have been described as follows (3):

1. Ponds serve as a source of water for fire protection
2. Ponds serve as a source of water for stock watering
3. Ponds serve as a source of recreation for fishing and swimming
4. Ponds provide added beauty and value to the farm
5. Ponds provide softer and better tasting water
6. Ponds provide water with low iron content.

It might appear from these salient characteristics that well supplies are outmoded. On the contrary, wells have been and continue to provide water. In many cases, ponds are not feasible and wells are the only water source. Where their use is applicable, ponds do provide extra benefits. However, ponds also have certain disadvantages that are inherent to their use as sources of water for human consumption. The following must be considered when designing equipment for the proper treatment of pond water:

1. Turbidity
2. Biological life
3. Algal growths
4. Tastes and odors
5. Nitrates
6. Nitrites
7. Organic matter
8. High pH
9. Color

Ponds may be fed by springs, creeks or, more commonly, by surface runoff. Those fed by surface runoff are apt to be highly turbid especially if the watershed is not grassed. A survey of 47 ponds in central Missouri showed an average of 58 units of turbidity with a high of 144 and a low of 17 units (26). A similar study in Iowa indicated turbidities ranging from 2 to 260 units. Thus, in many cases, filtration is necessary to prepare pond water for consumption. These studies further revealed that the water pH in some Missouri ponds varies from 7.3 to 7.7 (26). One pond water, however, averaged pH 9.1 with a high of 9.4 (27). The pH of water from several ponds in southern Iowa ranged from 7.0 to 7.9. Variations such as this would imply different disinfecting efficiencies for a given chlorine residual. Some pond waters contained nitrates as high as 8.8 mg/1, others had none. Color as high as 1500 mg/1 was recorded in water from a pond with no grass cover (3). Standard plate counts greater than 3000 bacteria per ml were not uncommon. Water from some of the more desirable ponds had high bacteria counts. Moreover, these factors were noted to change from month to month and from season to season (12). Pond water temperatures in Iowa and Ohio varied from 80^{o}F or more in the summer to temperatures approaching freezing in winter (59). It is evident from reports such as these that a wide range of conditions exists in ponds. It follows that sufficient chlorine for disinfection must be applied to provide a factor of safety under changing physical, chemical and biological conditions.

Well water, long used directly from the ground without any treatment, is generally believed to be bacterially safe due to filter action in the soil. We need only refer to the 'Broad Street Pump' incident of 1854 to indicate that wells do become contaminated and harbor pathogenic organisms. In the survey previously mentioned, wells in Iowa were found to be heavily contaminated with chlorine resistant bacteria and coliforms (3). High concentrations of iron and CO_2 in wells may necessitate treatment for their removal. Sand filtration is seldom necessary for most well waters, except possibly for iron removal.

Types and Efficiencies of Treatment Facilities

Surveys have indicated that some owners of small water supplies have made commendable attempts to treat their water; others have done little or nothing (3, 45, 58). Eight different types of treatment facilities were found to be used in Iowa:

1. Natural filtration through soil into existing wells
2. Perforated barrel inlets followed by sand filters
3. Soft brick, beehive filters
4. Floating intakes followed by sand filters
5. Bottom-of-pond filters and underdrain
6. Sand-filled trench filters
7. Slow-sand filters
8. Rapid-sand filters

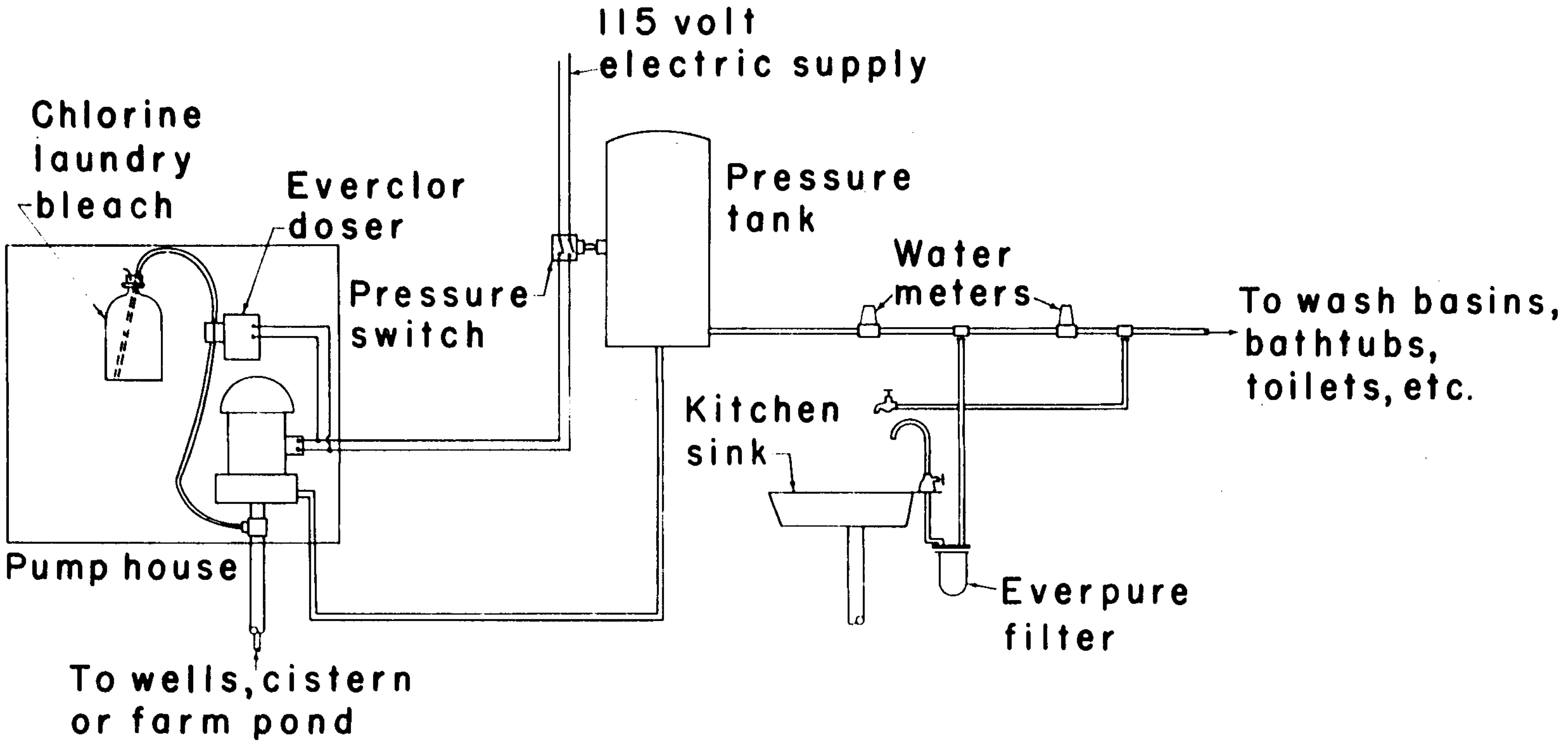
Extensive tests showed that ineffective bacterial treatment resulted with these systems. In some cases where post chlorination was practiced, inadequate disinfection occurred. In an analyses of the effectiveness of 30 horizontal slow sand filters on Missouri ponds, it was discovered that none met the minimum drinking water specifications of the State Board of Health (45).

Well supplies in some cases are filtered through layers of limestone and gravel, the limestone serving to reduce the CO_2 concentration (47). Where chlorination was practiced in well supplies, chlorine was applied at the pump intake during operation of the pump. A schematic diagram of a typical system is shown in Figure 1. Chlorine contact time in this type of setup is available only in the distribution lines and pressure tank. Pressure tanks have been shown to provide negligible retention time for chlorine (2). Pipe systems likewise are ineffective in this respect unless they are of sufficient length. As depicted in this layout, dechlorination is commonly restricted to the kitchen sink outlet. Water for uses other than drinking and culinary purposes is left chlorinated.

Well water and filtered pond water is disinfected in some localities by means of ultraviolet germicidal action (11). These ultraviolet tubes, 15 to 30 watts, are effective in the destruction of coliform organisms as long as the tube does not weaken in strength or become covered with slime. Even though we kill the indicator organisms with this method, there is no assurance that the harmful organisms are inactivated. Much higher wattages are required to destroy pathogenic organisms more resistant than *E. coli*. One major disadvantage of this type of treatment is that continued disinfection in reservoirs and distribution systems is not provided.

Obviously, if the majority of small water supply systems produce imperfectly disinfected water, some standards or recommendations should be proposed to correct the deficiencies.

Figure 1. Diagram of a small water system in which chlorination is practiced


115 volt electric supply
Chlorine laundry bleach
Everclor doser
Pressure switch
Pressure tank
Water meters
To wash basins, bathtubs, toilets, etc.
Kitchen sink
Everpure filter
Pump house
To wells, cistern or farm pond

If owners and designers of small water supply systems are presented with a recommended range of chlorine residuals and contact times that will disinfect specific waters, then we will have a logical approach to the problem. Such recommendations should be based on the two variables that most radically affect the efficiency with which chlorination is accomplished. These factors are water temperature and pH.

Present Criteria for Safe Water

Since the isolation and identification of pathogenic organisms from water is complicated, tedious and expensive, if not impossible, routine examination for bacterial quality requires the use of easily identifiable indicators. The coliform group of bacteria has been used for this purpose for many years. The harmless bacteria, Escherichia coli, which constitutes about 90 percent of the coliforms discharged in fecal matter, are relatively easy to isolate and identify. Since human feces are the principal source of pathogenic organisms, the presence of coliforms in water provides evidence of the potential presence of pathogenic organisms. Coliform organisms found in feces and sewage are numerous; the estimated daily per capita excretion varies from 125 to 150 billion in winter to nearly 400 billion in summer, (14). Thus, the coliform concentration found in a water can be used to indicate the relative degree of pollution.

On the national level, the U. S. Public Health Service prescribes that water supplied to interstate carriers must show less than 2.2 coliforms per 100 ml to be acceptable (43). This is the standard adopted by most municipalities and all State Health Departments. In British practice, the following classification has been suggested for non-chlorinated, piped supplies (49):

		Presumptive coliform count per 100 ml
Class 1	Highly satisfactory	0-1
Class 2	Satisfactory	1-2
Class 3	Suspicious	3-10
Class 4	Unsatisfactory	10

To meet standards similar to these, some state health authorities recommend chlorine residuals between 0.2 to 0.5 mg/l and a contact time of 20 to 30 min. For individual water supply systems, the U. S. Public Health Service recommends a residual between 0.2-1.0 mg/l with a contact period of 30 min (32). One authority avers that the maintenance of 0.4 mg/l residual chlorine is indicative of a safe water (48). The committee report of the Great Lakes-Upper Mississippi River Board of State Sanitary Engineers, the Ten States Standards, on public water supplies recommends a chlorine contact time of at least 30 min (1). This report further recommends that chlorine residuals should provide a finished water that will meet bacteriological requirements of the U. S.

Public Health Service drinking water standards. Thus, it can be seen that we presently classify our treated water, both municipal and individual, solely on the absence or presence in low concentrations of coliform organisms.

OBJECTIVES AND SCOPE OF STUDY

With the aim of providing recommendations for the improvement of disinfection practice in small water supplies, the following were selected as the objectives of the study:

(1) The establishment of recommended criteria for the disinfection of small water supplies

(2) The establishment of recommended chlorine residual and contact times for small water supplies

(3) Analysis of methods for obtaining chlorine contact time at critical flow rate conditions

(4) Determination of some of the factors affecting the critical flow rate in small water supplies

(5) Determination of the effects of prechlorination in the efficiency of slow sand filters when prechlorination is used as a means of obtaining chlorine contact time.

Research concerned with the first two objectives was entirely bibliographic. A review of the available literature covering time-concentration studies in disinfection with chlorine was made to establish the resistivity of various organisms to disinfection. Analysis of these data provided a background for selecting the types of organisms that we should strive to destroy in small water supplies. The establishment of this criteria provided a basis for forwarding recommended combinations of chlorine residuals and contact times that will furnish destruction of the selected types of organisms. Since water temperature and pH greatly affect the efficiency of chlorination, these factors were incorporated into the recommendations.

To analyze properly the efficiency of various vessels and systems in providing chlorine contact time, a study of the expected water usage was first conducted. This study yielded average and maximum usage in typical households and farmsteads. It included per capita usage, over-all household usage, peak rates and volumes and seasonal and daily variations in flow. Data of this type is beneficial in the determination of the critical flow rates for various small water supply systems.

A review of the contact-time efficiencies of various vessels and system components was included. In many instances, chlorine retention efficiency is a function of the rate of flow. A laboratory superchlorination-dechlorination system complete with a chlorine contact tank was constructed to show the application of contact-time efficiencies and for the purpose of conducting further chlorine retention studies. Examples of the procedures to be followed in the design of disinfecting systems for small water supplies were included.

To study the physical, chemical and biological effects of prechlorination on the efficiency of slow sand filters, two slow sand filters were constructed. Four runs were conducted, one filter operating in the normal manner and the other operating as a prechlorinated filter. Analyses were made of the turbidity removal, bacterial reduction, chlorine demand, head loss, and changes in organic matter to determine if prechlorination is an advantageous method of obtaining chlorine contact time. If contact time can be obtained in this manner, small water supplies requiring filtration would not need special chlorine retention vessels.

THEORY OF WATER CHLORINATION

Factors Affecting Disinfection with Chlorine

There are six basic factors that control the efficiency with which disinfection of water with chlorine is accomplished. These are: (1) the type and concentration of organisms; (2) the concentration and form of chlorine; (3) the time of contact; (4) the temperature of the water; (5) the pH of the water; and (6) the nature of the water.

There is a considerable variation in the resistance of different species of organisms to disinfection by chlorine. The pathogenic organisms, those which cause disease in man, are destroyed much more readily than spore forming bacteria. For example, at 20°C and neutral pH, *Staphylococcus dysenteriae* may be killed in three minutes with 0.1 mg/l of free chlorine, while it may take 2.5 mg/l of free chlorine 80 minutes to inactivate *Bacillus globigii* under the same conditions (5, 7). Most spore formers, however, do not cause disease and are thus of less sanitary significance in disinfection. On the other hand, there are other chlorine resistant organisms that are of concern to the sanitary engineer. Specifically, the cysts of *Entamoeba histolytica* require very high residuals of free chlorine if 100 percent kill is required. To inactivate the viruses of poliomyelitis and Coxsackie, high chlorine doses and long contact times are necessary.

Bacteria concentrations become important when the organisms are so numerous that they compete for the chlorine. Under such conditions, the bacteria would soon cause a lowering of the chlorine residual. In addition, there may be some shielding against the disinfectant if the bacteria are grouped together in clumps.

High concentrations of free available chlorine with short contact times are generally more efficient in destroying bacteria than are low chlorine concentrations for longer periods. It is this factor plus the necessity of higher residuals to produce disinfection within reasonable times that superchlorination becomes important in the disinfection of small water systems. The form in which chlorine exists in the water is most important. Free available chlorine is from 25 to 100 times more efficient in disinfecting than combined chlorine in the form of chloramines.

Considerable research has been conducted to determine the length of time necessary to disinfect polluted waters bearing different organisms at various temperatures and hydrogen ion concentrations. Contact time is an essential determination in any chlorination system especially in a small water supply. Sufficiently long contact times are desired to provide insurance of pathogen destruction.

The influence of temperature on chlorination is directly related to the influence of heat on chemical reactions. Higher temperatures result in increased Brownian movement and increased rate of kill. A rise in the pH of the water has the opposite effect. Above neutral hydrogen ion concentration, the rate of disinfection is retarded. Most effective disinfection occurs if the pH is less than 7, however, there is little or no increase in disinfection rate as the pH is lowered below 6.

Most water supplies, surface waters especially, contain suspended and dissolved matter that may react and combine with chlorine. Chlorine, being a powerful oxidizer, reacts with organic matter to produce compounds that are much less effective in disinfecting than free chlorine. Such matter produces a so-called 'chlorine demand'. If this demand is large, all of the original chlorine may be consumed leaving no free available chlorine. A heavy concentration of suspended matter may also affect disinfection efficiency by sheltering bacteria from the chlorine.

The Chemistry of Chlorination

When gaseous chlorine is added to water, the following reaction occurs:

$$Cl_2 + H_2O \longrightarrow HOCl + H^+ + Cl^-$$

This reaction produces both hydrochloric and hypochlorous acid. The hydrochloric acid tends to reduce the water pH and the hypothlorous acid provides the major disinfecting action. The hypochlorous acid dissociates as follows:

$$HOCl \rightleftharpoons H^+ + OCl^-$$

Since it is the hypochlorous acid that provides the disinfection, the concentration of hypochlorous acid should be maintained at a high level. We would like, therefore, to drive the reaction to the left. An increase in the hydrogen ion concentration in the water will produce a high concentration of hypochlorous acid and explains the increased disinfecting potential of chlorine at low pH values.

The ionization constant, K, is a function only of the temperature of the water (13).

$$K = \frac{(H^+)(OCl^-)}{(HOCl)}$$

K varies from 1.5×10^{-8} moles/l at $0^{o}C$ to 2.7×10^{-8} moles/l at $25^{o}C$. Thus, an increase in temperature will raise the molar concentration of HOCl.

In small water supplies, chlorine is generally added in the form of either sodium or calcium hypothlorite rather than as gaseous chlorine. Chlorine in the form of hypochlorites is readily available in commercial form as bleaches, and, in small water supplies, is safer to handle. Hypochlorous acid is similarly produced when hypochlorites are added to water:

$$Ca(OCl)_2 + 2H_2O \longrightarrow 2HOCl + Ca(OH)_2$$

$$NaOCl + H_2O \longrightarrow HOCl + Na(OH)$$

For a given water, the addition of chlorine gas will lower the pH, while a slight increase in pH is noticed upon the addition of hypochlorites due to the formation of hydroxide compounds.

Certain reducing substances such as iron, manganese, nitrites, hydrogen sulfide and organic materials react with hypochlorous acid to produce a chlorine demand. In such reactions, chlorine gains or shares an electron and subsequently becomes either a chloride ion or an organic chloride. When chlorine is combined in this manner, its disinfecting power is lost. Reactions of chlorine with inorganic materials occur rapidly in a stoichiometric fashion. Conversely, reactions of chlorine with organic materials are generally slow.

Small water supplies will contain a wide range of mineral and organic materials depending on whether the source is from the ground or surface water. Ground water will involve concentrations of minerals such as iron, magnesium, manganese, calcium, sodium and potassium. Considerable chlorine demand may result from those materials which are oxidizable. For example, when soluble ferrous and manganous compounds are oxidized to the insoluble hydroxides, about 0.6 and 1.3 mg/l of free chlorine are utilized for each mg/l of iron and manganese removed respectively at pH 7 (37). A similar high demand is exhibited in the conversion of H_2S to sulfate in which 8.5 mg/l of chlorine is required at pH 9 for each mg/l of H_2S removed.

More commonly, a chlorine demand is experienced in the disinfection of water supplies containing ammonia, nitrites and oxidizable substances such as algae. Nitrites are readily oxidized by chlorine to nitrates:

$$NO_2^- + HOCl \longrightarrow NO_3^- + HCl$$

As much as 1.5 mg/l of chlorine may be utilized for each mg/l of nitrate formed. The rate of reaction of chlorine varies with different nitrogen groups (52). In total nitrogen experiments with the three main categories, namely, ammonium ions, amino acids and proteins, it was shown that ammonium ions are normally oxidized within an hour. Amino nitrogen in common amino acids was consumed slowly over an extended period of time, while only negligible changes in protein nitrogen were observed even after extended chlorination periods. From this work it can be seen that the oxidation of nitrogen compounds becomes prolonged as the complexity of the compound increases. Under some conditions, therefore, a constant depletion of free chlorine may exist in a chlorination system.

The reactions with ammonia and hypochlorous acid are significant in the analysis of disinfection. Depending on the pH of the water and the free chlorine dosage, one or more of the following reactions may be in operation at the same time:

$$NH_3 + HOCl \rightleftharpoons HOH + NH_2Cl \text{ (monochloramine)}$$

$$NH_2Cl + HOCl \rightleftharpoons HOH + NHCl_2 \text{ (dichloramine)}$$

$$NHCl_2 + HOCl \rightleftharpoons HOH + NCl_3 \text{ (nitrogen trichloride)}$$

In the combined form of chloramines, chlorine still retains its potential to disinfect. In the presence of bacteria, HOCl will be utilized for the destruction of these organisms. This action will slowly drive the reactions to the left thus producing a steady supply of HOCl. Apparently the reason for the lethargic characteristics of these reactions lies in the difficulty with which the chlorine-amine bonds are cleaved. In waters having pH 8 and over in the presence of excess chlorine, the fairly stable monochloramines predominate and slowly decompose in the following manner (42):

$$2NH_2Cl + HOCl \rightarrow N_2 + 3HCl + H_2O$$

In the intermediate pH range, the unstable dichloramines are continually decomposed to free nitrogen and chlorine in the presence of excess chlorine. Even though the free chlorine hydrolyses to HOCl, a considerable loss in available chlorine is caused by the formation of hydrochloric acid.

$$2NHCl_2 \longrightarrow N_2 + HCl + Cl_2$$

Nitrogen trichloride exists primarily in the low pH range. Its formation is also favored at higher pH values with an increase in applied chlorine. In the breakdown of chloramines to nitrogen, there is also evidence of the formation of small quantities of nitrous oxide, nitrites and nitrates (16, 19). Palin (42) found that, of these, only nitrates could be traced to the ammonia-chlorine reaction. This study further indicated that the amount of nitrate produced is related to the initial ratio of applied chlorine to ammonia nitrogen present. As a possible explanation of this process, Palin speculated on the formation of an intermediate chlorhydroxylamine according to the following side reactions:

$$NHCl_2 + H_2O \longrightarrow NH(OH)Cl + HCl$$

$$NH(OH)Cl + 2\ HOCl \longrightarrow HNO_3 + 3\ HCl$$

When chlorine is first added to water containing ammonia, it may be consumed entirely in the form of chloramines. In the combined state, chlorine still retains its full oxidizing capacity. However, there is a great decrease in its oxidizing potential resulting in a decrease in the intensity with which it enters reactions (44). Continued addition of chlorine forces the breakdown of chloramines until none remain. Beyond this so-called 'breakpoint', only NCl_3 remains and the chlorine residual rises in proportion to the applied dose. During the past twenty years, 'breakpoint chlorination' has been practiced in many municipal water treatment plants with both advantageous and disappointing results. The once high enthusiasm for chlorinating with a residual just past the breakpoint has subsided since difficulty was often encountered due to the complex organic constituents in water supplies.

In surface water supplies on farms, ammonia nitrogen is usually the result of animal excrement. Other chlorine consuming organic matter found in ponds is normally derived from the watershed.

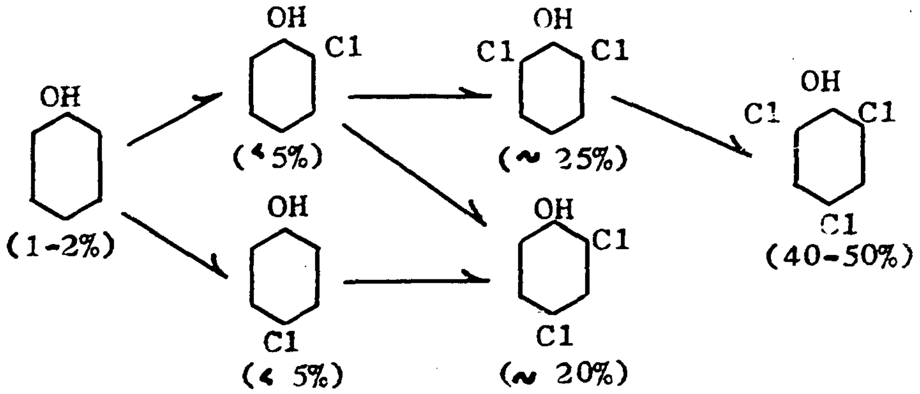
Occasionally small concentrations of phenols are found in ground and surface water supplies. When chlorine is applied to such waters, foul chlorophenolic tastes and odors result. Tests have been conducted to determine why these tastes and odors are present in some instances and absent or delayed at other times (6). It was found that five chlorophenols are formed upon chlorination. The threshold concentrations for taste and odor are summarized in Table 1.

It is evident from these threshold levels that there are three phenol derivatives contributing to provide obnoxious

Table 1. Taste and odor threshold concentrations (6)

Component	Geometric mean threshold ppb	
	Taste	Odor
Phenol	1000	1000
2-chlorophenol	4	2
4-chlorophenol	1000	250
2,4-dichlorophenol	8	2
2,6-dichlorophenol	2	3
2,4,6-trichlorophenol	1000	1000

tastes and odors, namely, 2-CP, 2,4-DCP and 2,6-DCP. Of these, the major contributor is 2,6-DCP. The chlorination of pure phenol, which is in itself relatively tasteless, proceeds through a series of strong tasting complex chlorophenols to a fairly tasteless end product. The following diagram is an example of the course of chlorination of 20 mg/l phenol solution with 40 mg/l chlorine at pH 8 (6).



In the chlorination of phenols, such as the example shown, the number of concurrent and consecutive relationships taking place are functions of concentration, temperature, pH and ammonia. Depending on the character of a given water supply, certain combinations of these factors may prevent or retard the production of chlorophenolic tastes and odors.

Bacteriological Aspects

Among the theories advanced in the past to explain the destruction of bacteria and viruses by chlorine are: oxidation by nascent oxygen and inactivation of bacterial protoplasm by direct action of chlorine. Probably the most logical and reliable explanation, as evidenced from laboratory results, is that forwarded by Green and Stumpf (20). According to them, chlorine disinfects by destroying enzymes in the bacterial cells. With the exception of spore cells, all bacteria are able to oxidize sugar. Twenty different enzymes are essential in the oxidation of sugar. One of these, triosephosphoric dihydrogenase, has been found to be blocked by chlorine. The parallelism between the amount of chlorine needed to destroy bacteria and the amount needed to inhibit bacteria from fermenting glucose was found to be the same in 500 experiments without exception. These experimenters attributed the action of chlorine exclusively to the inactivation of the triosephosphoric enzymes even though chlorine is known to affect other enzymes. Disinfection, then according to the enzyme theory, must proceed in two steps since enzymes are created within the cell plasm: (1) penetration of the cell wall by the disinfectant and (2) reaction of the enzymes with the disinfectant.

The rate of disinfection was shown by Chick in 1908 to be a function of the number of organisms remaining (8).

$$-\frac{dn}{dt} = kn$$

n = number of organisms
k = rate constant

Upon integration between the limits of $t = 0$ at $n = N_o$ and $t = T$ at $n = N$, the relationship becomes

$$N = N_o e^{KT}$$

N = number of organisms at any time
N_o = number of organisms initially present
T = time since disinfectant was applied

Although this law holds in general, departures from it occur frequently.

In time-concentration studies of disinfection, the following empirical formula is applicable in most cases:

$$C^n t = K$$

C = concentration of disinfectant
t = time of exposure for a given percentage of kill
n = a positive number expressing the relationship between C and t
K = a constant for a given organism, pH and temperature

This equation plots as a straight line on log-log paper with a slope of -n. Values of n greater than 1 indicate that the killing time varies sharply with small changes in concentration while values of n less than 1 occur in cases when concentration is much less important than kill time. Typical values of n lie between 0.8 and 2.0.

Enteric vegetative bacteria offer little resistance to chlorination. Under most conditions, they may be killed with less than 1 mg/l of free available chlorine. Considerably more resistance is encountered when chlorine is applied to intestinal protozoa and spore forming bacteria. This difference may be explained by the fact that cysts and spores have walls which are thicker than bacterial membranes. Viruses are also difficult to disinfect in short periods with chlorine. Since little is known of the structure of these minute organisms no explanation can be given for their chlorine resistive characteristics. Table 2 indicates the relative ease with which various types of organisms may be destroyed at room temperature and pH 7.

It should be emphasized that much greater concentrations and contact times are required at lower temperatures and higher pH levels. If the chlorine is in the combined form, disinfection may require as much as 25 to 100 times the concentrations listed. For example, to inactivate polio and Coxsackie viruses at 25°C in thirty minutes, it was necessary to apply a concentration of 9 mg/l of combined chlorine (36).

Table 2. Time and chlorine concentrations required to produce 100 percent kill at 20°-25°C and pH 7

Organism	Disinfection time, min.	Concentration of FAC, mg/l	Reference
E. coli	1	0.036-0.045	Butterfield (7)
E. typhosa*	3	0.056-0.070	Butterfield (7)
S. dysenteriae	3	0.046-0.055	Butterfield (7)
E. histolytica	30	1.6	Fair et al. (15)
Virus of poliomyetitis	30	0.2-0.3	Kelly and Sanderson (35)
Coxsackie virus	3 (27-29°C)	0.44-0.58	Clarke and Kabler (9)
B. anthracis	60	1.0	Brazis et al. (5)
B. globigii	220	1.0	Brazis et al. (5)

*By current terminology Salmonella typhosa

Chlorine has been found useful to destroy algal growths. When free available chlorine residuals were maintained, all types of algae were killed (21). The efficiency with which chlorine destroys algae lies not only in its ability to kill directly but also in the fact that it removes ammonia and nitrite nitrogen which form a large part of the algae food supply. Luxuriant growths of algae may require as much as 4.5 to 5.5 mg/l of free chloride for destruction (17).

Superchlorination

The superchlorination of water involves the deliberate addition of chlorine in excess of normal requirements for disinfection. Application of this principle dates back to 1912 when it was instituted in the treatment of some London well supplies. The first municipal use of superchlorination was in 1922 in New York City (31). In some instances, superchlorination has been found to be the only procedure to insure a satisfactory water (24, 30). Primarily, the advantage of superchlorination lies in its effectiveness in removing taste and odors which would otherwise be present with combined chlorine.

In small water supplies, superchlorination is advocated in preference to lower chlorine residuals to insure destruction of viral and enteric pathogens, to permit the maintenance of a high chlorine residual during marked variations in the quality of input water, and to reduce the required amount of chlorine contact time.

Practice has shown that, in normally alkaline waters, superchlorination results in a slight increase in $CaCl_2$ and $CaSO_4$ hardness and decrease in carbonate hardness (31). Superchlorination in acid waters with hypochlorites is possible since the production of either $Ca(OH)_2$ or $Na(OH)$ would have a neutralizing effect.

Prechlorination

The chlorination of water prior to filtration, commonly known as prechlorination, was first used by Sir John Houston in 1904 in London. In 1908, George A. Johnson achieved tremendous success by adding calcium hypochlorite to the highly polluted influent at the Bubbly Creek filters in Chicago. Due to its inherent advantages, prechlorination has been employed in many filtration works during the past fifty years. A number of advantages have been reported as a result of this process with rapid sand filtration (11, 28, 29, 51, 57).

1. Reduction of the bacterial loading on the filter which improves the factor of safety.
2. Lengthening of filter runs.
3. Cleaner sand beds.
4. Reduction of cracks and mud balls.
5. Coagulation of iron and manganese.
6. Oxidation of organic matter reducing the load on the filter.
7. Increased filtration rates possible.
8. More effective sand washing.

Since there have been relatively few slow sand filters in this country, little has been published to indicate whether prechlorination is as effective in slow sand filtration as it is in the case of rapid sand filtration. Two reports are discussed in the following chapter. Although prechlorination appears to increase significantly the efficiency of filtration, there are many instances in which its employment is inapplicable.

In slow sand filtration, high turbidity and bacteria removal is attributed to mechanical and biological action in the zoogleal film formed on the filter surface. It has been a common belief that the application of chlorine to slow sand filter influents would eliminate the primary features of these filters and obviate their usefulness. Certainly the bacterial activity is destroyed, but biological action is only one of several factors considered in the theory of filtration. If chlorine takes over the function of bacteria removal which is normally attributed to the schmutzdecke, and other factors such as sedimentation and mechanical straining remove turbidity in accordance with present theory, then we should expect equally effective filtration.

Dechlorination

After water has been disinfected by means of superchlorination, it is common practice to either lower the residual or remove the chlorine entirely if the water is to be used for human consumption. Although high chlorine residuals have been observed to be harmless to the body, residuals greater than 1 to 2 mg/l often possess a chlorinous odor that many people find obnoxious. Aeration will remove chlorine, hypochlorous acid, dichloramines and nitrogen trichloride. When large volumes are treated, dechlorination is most economically accomplished with chemicals such as sodium bisulfite, $NaHSO_3$; sulfur dioxide, SO_2; or sodium sulfite, Na_2SO_3. When each of the above reagents reacts with chlorine, hydrochloric acid is produced and neutralization may be necessitated. The following reactions indicate the removal of free available chlorine with sulfur dioxide.

$$H_2O + SO_2 \longrightarrow H_2SO_3$$
$$HOCl + H_2SO_3 \longrightarrow HCl + H_2SO_4$$

Highly porous granular activated carbon is very effective in removing chlorine from water. It is especially useful in the form of precoat carbon filters in the superchlorination-dechlorination of small water supplies. Chlorine is absorbed in the pores where it oxidizes carbon to carbon dioxide (14). The theoretical reactions are hypothesized as follows:

$$C + 2HOCl \longrightarrow CO_2 + 2H^+ + 2Cl^-$$
$$C + NH_2Cl + 2H_2O \longrightarrow CO_2 + NH_3 + H^+ + Cl^- + H_2$$
$$C + NHCl_2 + 2H_2O \longrightarrow CO_2 + NH_3 + 2H^+ + 2\ Cl^-$$
$$C + NCl_3 + 2H_2O \longrightarrow CO_2 + NH_3 + H^+ + Cl^- + Cl_2$$

In addition to dechlorination, carbon filters may serve also to remove turbidity, odor, color and cysts of E. histolytica. When chlorine residuals fall below that required for destruction of certain bacteria, carbon filters may provide conditions satisfactory for the growth of these bacteria (25).

The life of carbon filters in the removal of chlorine residuals is a function of the applied chlorine residual, the time of operation, the on-off cycle of use, the rate of flow, and the amount of carbon in the precoat. Longer service life has been found to result with intermittent operation rather than with continuous operation. This effect, which allows recovery of the filter between uses, may be the result of removal of the CO_2 which may form a barrier between chlorine compounds and the carbon grains. When filters were operated with a two-minute on and four-minute off cycle, Guillaume (22) found filter life to follow the following equation:

$$T = \frac{G - 2}{11} (10)^{1.8E} \quad \text{hours}$$

G = grams of carbon per rate of flow in gpm
E = effluent chlorine concentration, mg/l

PREVIOUS INVESTIGATIONS IN THE PRECHLORINATION OF SLOW SAND FILTERS

Two previous studies of the effects of prechlorinating slow sand filters have been reported. One concerned the application of chlorine to municipal filters that had been in operation for 43 years. The other involved the investigation of prechlorination on a small water supply slow sand filter.

In 1947, experiments were conducted at one of the few slow sand filtration plants remaining in this country to determine if adequate increases in filter runs could be accomplished with prechlorination (33). The Whitney Filter Plant at New Haven, Connecticut, treated lake water with the following average characteristics:

pH	7.3
Alkalinity	33 mg/1, as $CaCO_3$
Hardness	49 mg/1, as $CaCO_3$
Turbidity	8 units
Color	20 mg/1

Two adjacent beds were cleaned. To one, chlorine was applied at the rate of two mg/1 and gradually the chlorine was increased to six mg/1. The other filter was operated in the normal manner. The run ended when both filters had reached a terminal head loss of 50 inches. Figure 2 shows that the head loss increased twice as fast in the unchlorinated filter. The unchlorinated filter reached 50 inches of head after 49 days,

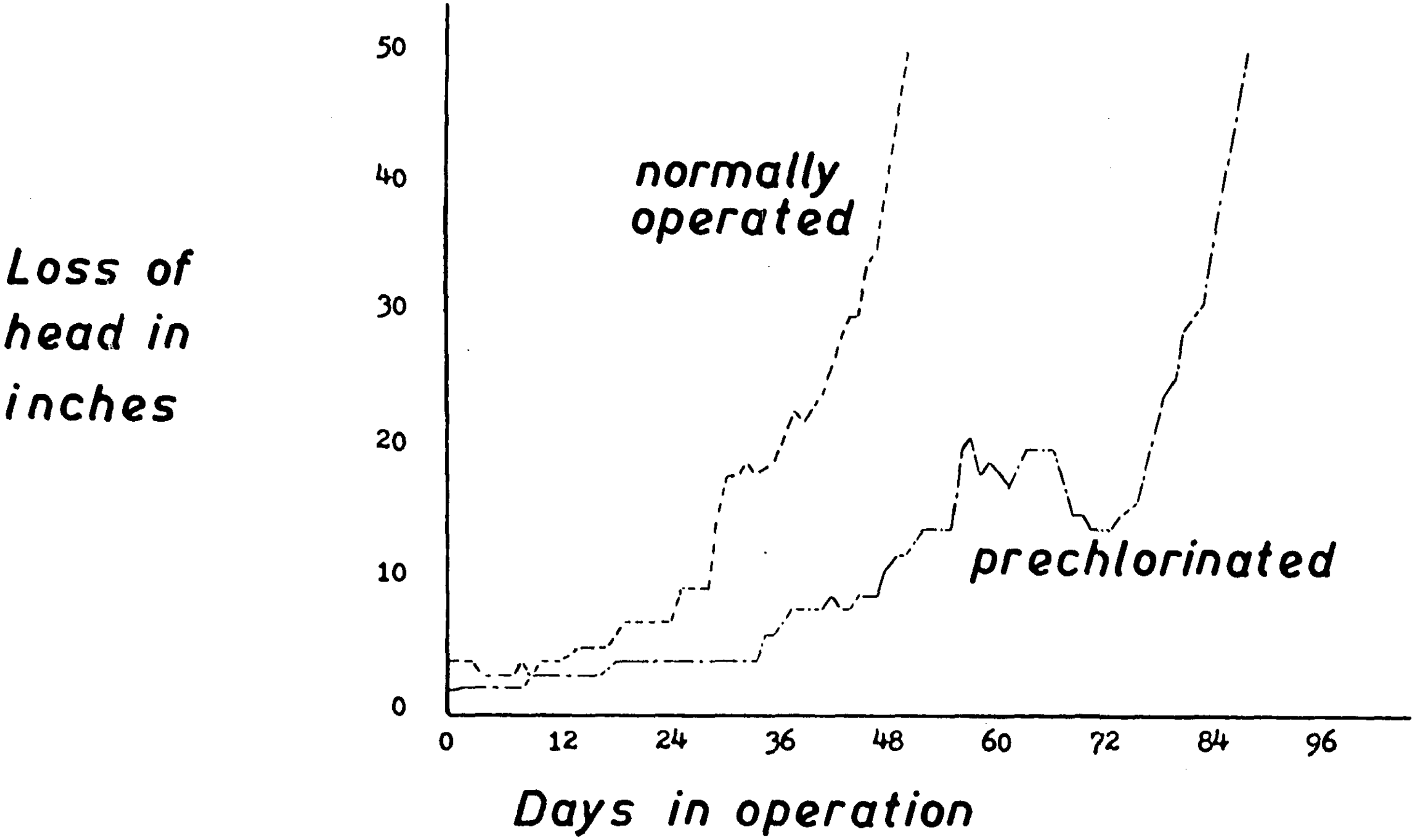


Figure 2. Comparison of head loss through prechlorinated and normally operated slow sand filters

while the prechlorinated filter was able to operate for 85 days. The resulting total volume of filtrate represented an increased yield of 72 percent. When the chlorine dosage rate was increased after the 54th day, the rate of head loss declined. A corresponding increase in the ammonia nitrogen was recorded at this time also. During this run, no change in color or turbidity was evident with prechlorination in comparison with the normally operated filter. On occasions when the flow was low, a slight 'mud-flat' odor was noticed.

A second run was conducted to determine the effect of heavily chlorinating a partially clogged slow sand filter. A filter that had been in operation for 44 days and had reached a head loss of 28 inches was steadily dosed with 15 mg/1 of chlorine. An initial increase in head loss developed which later began to recede. This increase was attributed to the dying and settling of various organisms. By the eighth day, the loss in head reached a minimum of 11 inches. During the run, drastic changes were observed in the effluent water. Color increased from 5 to 30 mg/1 during the first 34 days after prechlorination. A slight earthy odor turned objectionable after a few days until curing of the filter was complete. After 54 days of prechlorination, the effluent was considered acceptable for consumption and turned into the distribution system.

During this test, which lasted 184 days, chlorine residuals of the effluent were recorded. Figure 3 reveals the comparison of the effluent free and combined chlorine residuals with the applied dosage. During the first 34 days of operation with 15 mg/l of applied chlorine, a fairly low residual was observed in the filter effluent. Thereafter, a sharp increase was noted until a total chlorine residual peak of 2.2 mg/l was recorded on the 43rd day. Subsequently, the applied chlorine dosage was varied in an unsuccessful attempt to maintain an effluent residual of 0.1 mg/l free chlorine. After the 84th day, when ammonia nitrogen ceased to appear in the effluent, there appeared to be a small degree of correlation between the applied chlorine and the effluent residual. A comparison of Figures 3 and 4 indicates that the effluent chlorine residuals are, in general, a function of the nitrogenous material in the filter.

A final test was conducted to determine if the curing effects experienced in the previous runs could be avoided by heavily dosing a clean filter. The applied dose was 10 mg/l of free chlorine. The effluent exhibited an earthy taste and odor. Color increased from 12 to 22 in three days, remaining above normal for nearly a month. The odor subsided after 21 days only to be followed by a chlorinous odor. During the first few days of prechlorination, small white particles were sloughed off of the filter. On one occasion the flow rate was decreased to 0.6 mg when the applied chlorine level was

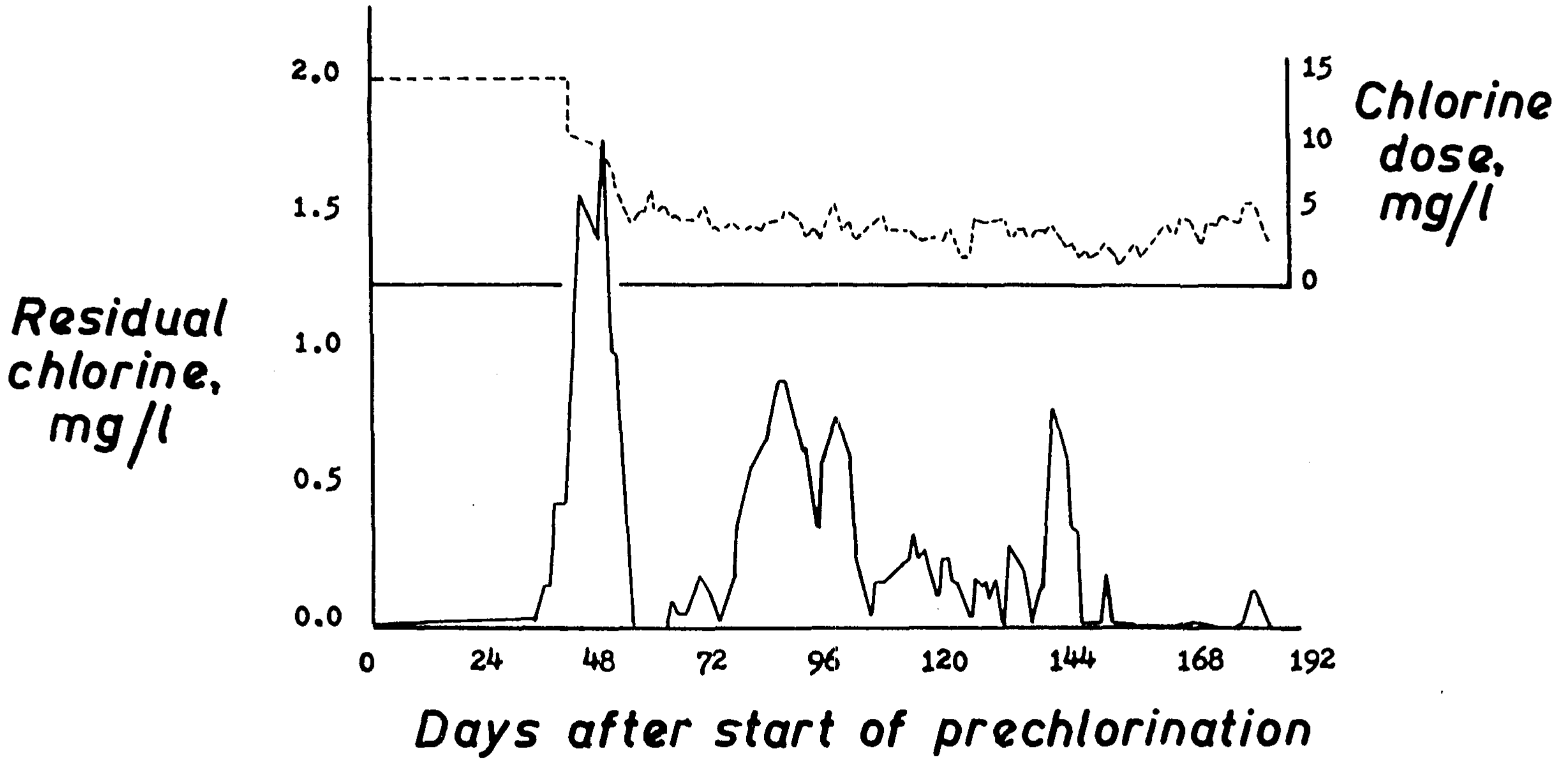


Figure 3. Chlorine dosage and chlorine residuals in the effluent of a prechlorinated slow sand filter

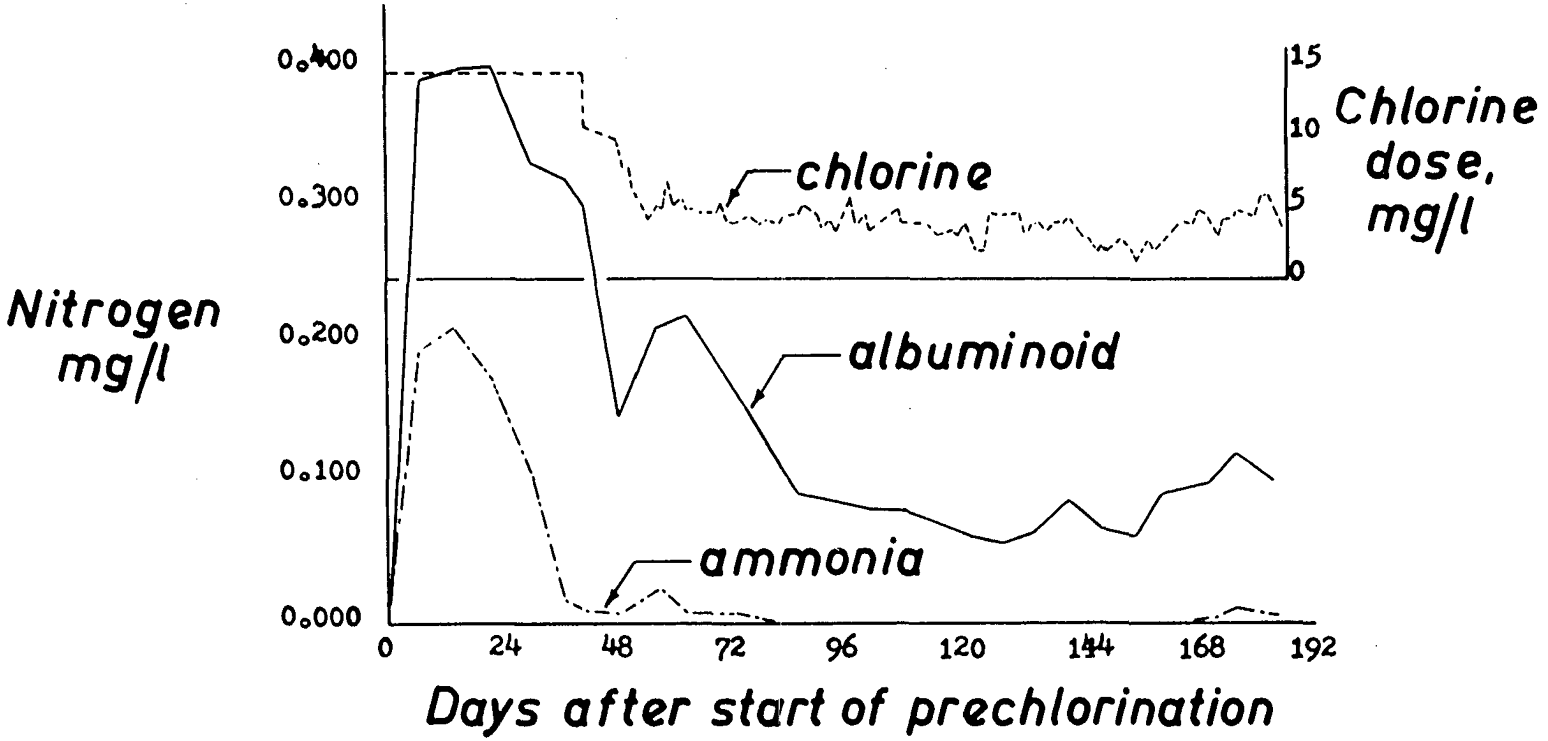


Figure 4. Effect of prechlorination on albuminoid and ammonia nitrogen in the effluent of a prechlorinated slow sand filter

increased to 42 mg/l. Considerable frothing was noticed in the filter. Subsequently, a haze developed at the plant which caused irritation of the eyes.

As a result of these three tests, the authors forwarded the following conclusions concerning prechlorination of slow sand filters:

1. Prechlorination increased filtering capacity. The increase depends on the condition of the raw water and the chlorine dosage rates. The use of moderate dosage rates increased the output of a filter 72 percent without disturbing the physical characteristics of the water.

2. The use of higher dosage rates resulted in more rapid curing of previously unchlorinated filters, but the unpalatable effluent had to be wasted for about two months.

3. During the removal of organic matter, which had been deposited in the filter during normal operation, the liberated ammonia was at a maximum when the effluent chlorine residual was negligible. Correspondingly, the disappearance of ammonia was followed by maximum chlorine residuals.

Hale, in 1959, while experimenting with a slow sand filter to be used in small water supplies, applied chlorine prior to filtration (23). The entire system was designed to provide for the flow of water through each of the following appurtenances in the order listed: influent pump, settling tank, slow sand filter, storage tank, service pump and pressure tank. Chlorine was injected into the system by means of a positive displacement chlorine injector at the settling tank whenever the influent pump was in operation. The total chlorine residual on the filter varied between 0.1 and 0.3 mg/l. Post chlorination was not employed.

Operation of this system indicated a reduction in color from 145 mg/l in the raw water to 42 mg/l in the filter effluent. Turbidity reduction was from 32 to 6 units. In each of the weekly effluent samples, coliform concentration was less than 3 per 100 ml as determined by the presumptive MPN coliform test. In comparison with operation of the system using post chlorination only, the author concluded that there was no apparent advantage in the use of prechlorination.

EXPERIMENTAL APPARATUS AND PROCEDURES

Water Usage Recorders

Water usage data was collected in several homes to obtain values of the rates, volumes and flow durations that can be expected in small water supply systems. These data provide estimates of critical flow conditions for the design of adequate disinfecting facilities in such supplies.

Daily records of the total water consumption were made in five residences from the household water meter. To obtain data concerning the rates at which water is used in households, continuous recording meters were installed in six homes. Two types of recording meters were used. The first type was a Chart-A-Meter, Model B, manufactured by the H. E. Anderson Co., Muskogee, Oklahoma. These spring-wound, chart-recording meters mounted directly on the household meters. Data available on the circular charts, which covered a 24-hour period, included: time of use, volume, rate, time between uses and number of uses. Rates were computed by determining the time elapsed during the flow of each usage. A transparent grid was utilized to estimate the time for usages of short duration. In two homes, these recorders were installed to record usage at the kitchen sink only as shown in Figure 5.

The other recording device used in this study was fabri-

Figure 5. Water usage recorder mounted at kitchen sink

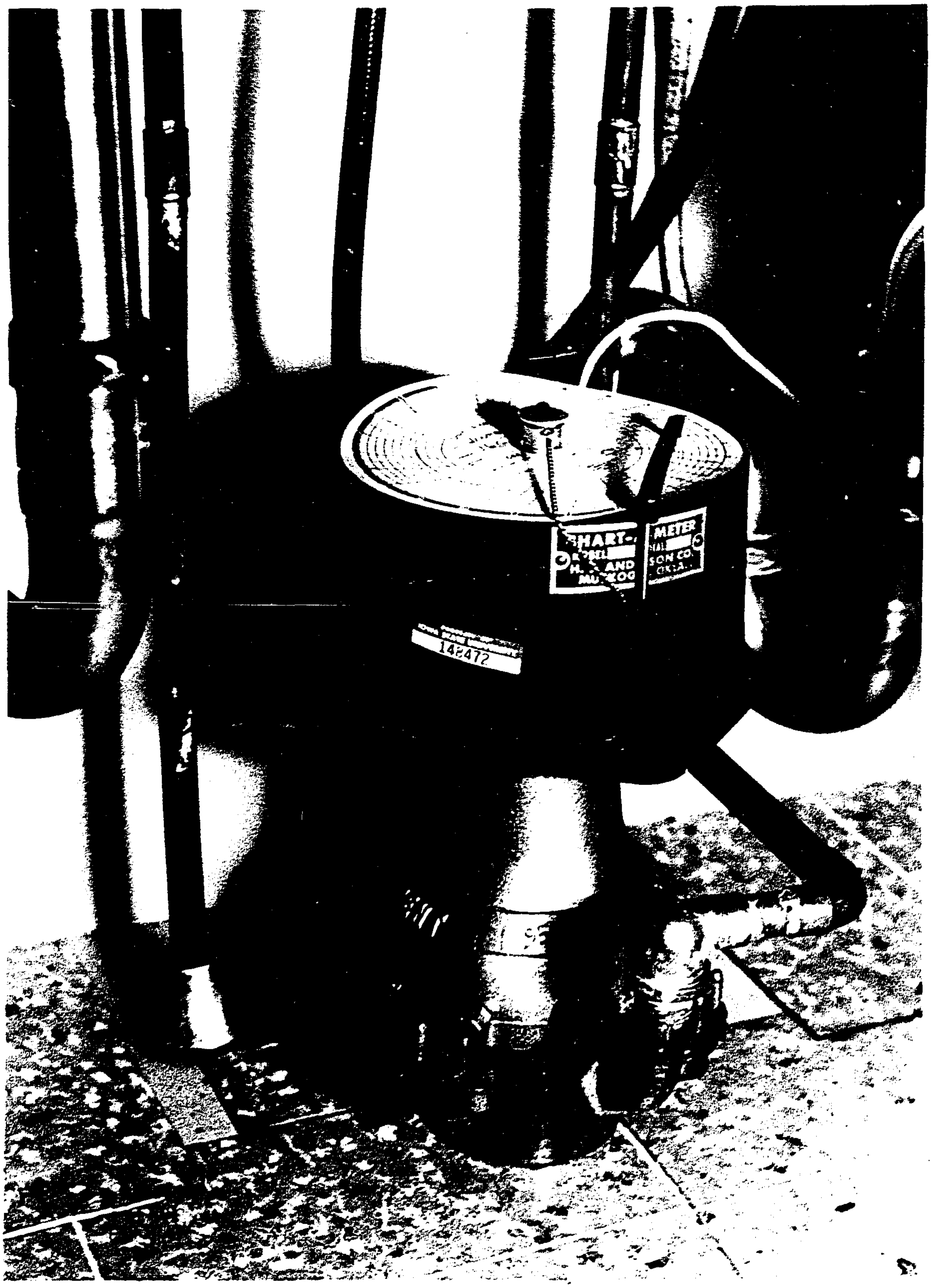


CHART-
AND
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cated at the City of Ames water plant. It consisted of an electric clock motor and an electromagnet activated stylus. The motor served to pull an 11/16-in. wax coated tape under the stylus at a constant rate. After each gallon of flow, the water meter completed a circuit which in turn caused the stylus to mark the tape. Analyses of the tapes yielded essentially the same data that was provided with the Chart-A-Meters. The number of marks per unit length of tape provided an indication of the rate at which water was drawn. Although this device did not record some uses of short duration, it did yield comparable overall data.

Pilot Superchlorination-Dechlorination System

A complete laboratory superchlorination-dechlorination system was assembled for the purpose of conducting chlorine retention studies. Typical small water supplies in which well water is superchlorinated will normally contain a pump, chlorinator, pressure tank, and a carbon filter for dechlorination. This system (Figure 6) includes, in addition, a chlorine retention tank. Other apparatus was installed for laboratory test control.

Tap water from the university supply was filtered through a precoat carbon filter to remove any chlorine residual that might exist. This supply entered an open tank used to simulate a well source. Bacteria tracers were fed into the tank through an automatic doser when the pump was in operation. A similar doser was used to apply chlorine solution at the pump intake. Water flowing from the detention tank was split into two open circuits--one of which simulated the critical flow rate of the system, and the other represented low rate usage at the kitchen sink. In the latter circuit, a solenoid valve operated by an intermittent timer allowed the dechlorinated water to flow only for short periods of time.

Two types of detention tanks were used in these tests. One was a 42-gal gravel filled storage tank (D, Figure 7), the other was a 115-gal shell-in-shell tank (F, Figure 8). Both had previously been tested for retention efficiency with the use of organic dye tracers (39). In these tests, runs were made to determine the chlorine retention efficiency of the complete system with bacteria tracers. The first appearance of bacteria in the effluent indicated the effective retention time.

Prior to the start of a run, the entire system was decontaminated with high dosages of chlorine. Sodium thiosulfate was used to reduce the chlorine residual to zero. With the flow rate set at the desired level, a test was started by adding a 1-liter solution of bacteria tracer to the simulated well supply. This solution consisted of 2-ml of nutrient broth culture diluted in 1-liter of chlorine-free water. During the test, additional bacteria solution was gravity fed from a carboy. No

Figure 6. Laboratory setup of a small water supply superchlorination-dechlorination system

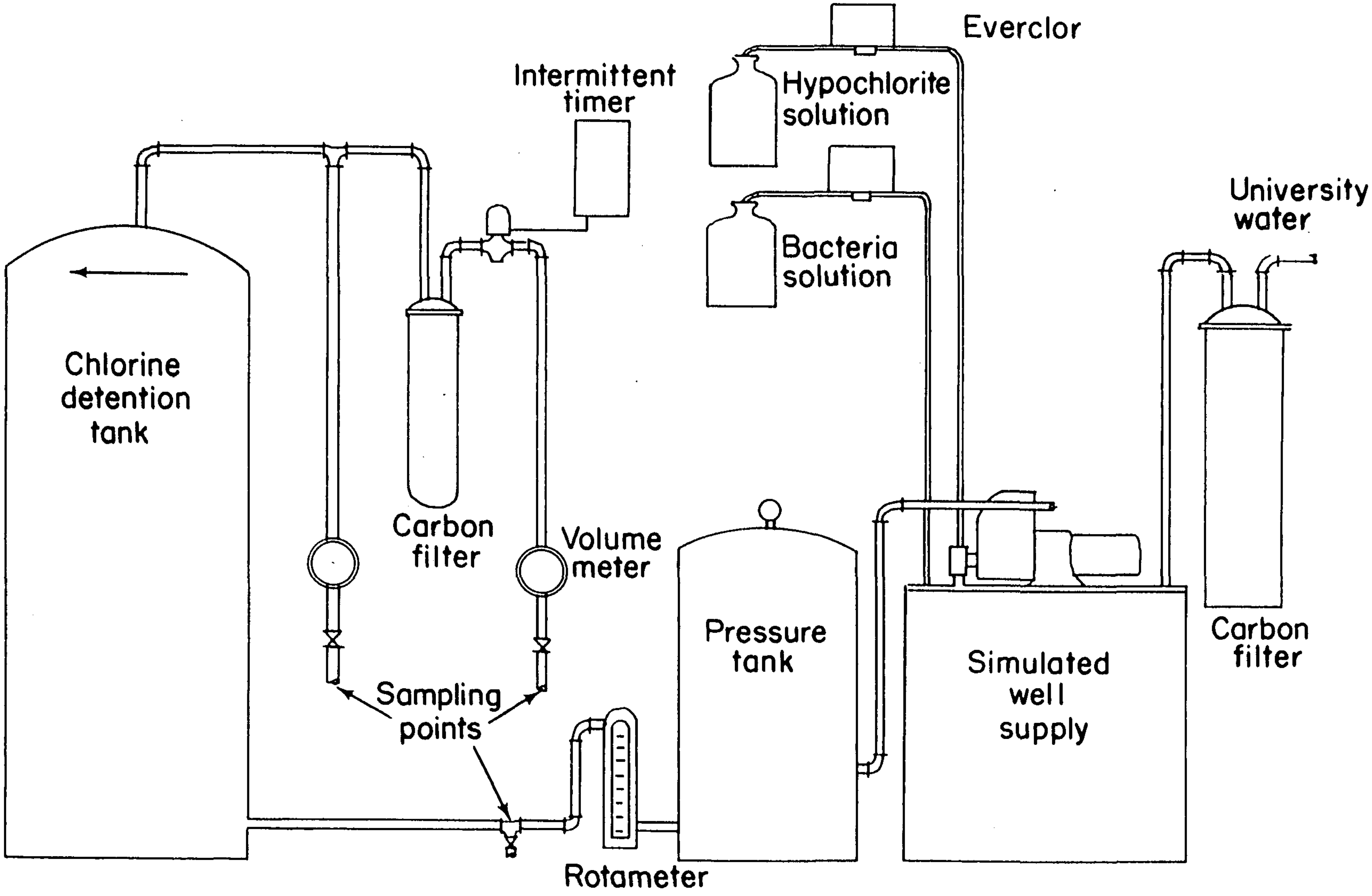
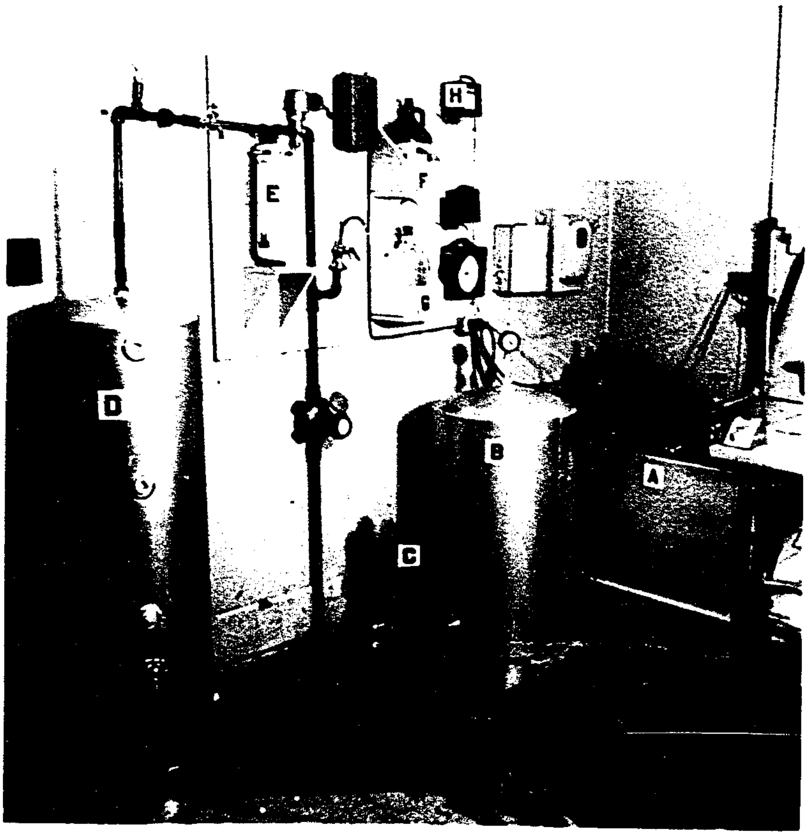
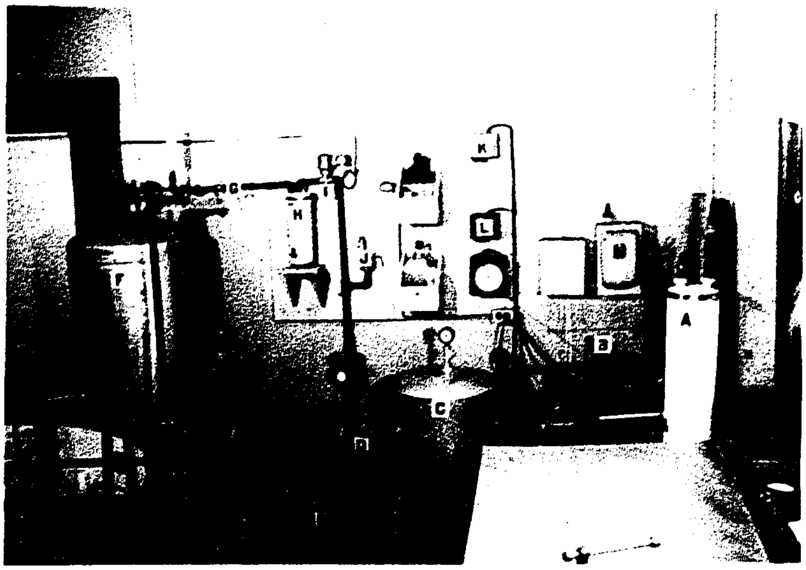

Everclor
Intermittent timer
Hypochlorite solution
Bacteria solution
University water
Chlorine detention tank
Carbon filter
Volume meter
Pressure tank
Simulated well supply
Carbon filter
Sampling points
Rotameter

Figure 7. Laboratory superchlorination-dechlorination system with 42-gal gravel filled chlorine contact tank (A - Tank used to simulate well source, B - pressure tank, C - rotameter, D - gravel filled chlorine contact tank, E - precoat carbon filter, F - chlorine supply, G - bacteria supply, H - chlorine doser)

Figure 8. Laboratory superchlorination-dechlorination system with shell-in-shell chlorine contact tank (A - precoat carbon filter for dechlorinating tap water, B - centrifugal pump, C - pressure tank, D - rotameter, E - sampling point, F - chlorine contact tank, G - sampling point, H - precoat carbon filter, I - solenoid valve actuated by intermittent timer, J - sampling point, K - chlorine doser, L - bacteria solution doser)


H
E
F
G
D
B
A
C


K
H
J
L
F
A
B
C

chlorine was added in the tests with bacteria tracers. Sampling was conducted at selected intervals at the points shown in Figure 6.

The following bacteria were used as tracer organisms: S. albus, S. aureus, B. cereus, B. megatherium, B. subtilis, and Serratia marcescens. All bacteria counts were made by innoculating nutrient agar plates and incubating at 35°C for 24 hrs.

Runs were also conducted with this system to test the efficiency with which it would destroy several of the tracer organisms. In these runs, the FAC residual was maintained at 5 mg/l. The flow was set at a rate which would be typical of the critical rate in many small water supply systems. A final run was made to determine the time required to bring the systems from zero FAC to equilibrium at 5 mg/l FAC.

Slow Sand Filters

Two identical slow sand filters were constructed to provide a means for comparison of the operating results of a prechlorinated filter with a normally operated filter. Each filter consisted of a housing, water collecting system, sand, head loss piezometer and control valves. The filter housing was made by removing both ends of a 55-gal oil drum and welding it to another drum from which one end has been removed. Each filter had an effective filtering area of 2.64 sq ft. The filtered water collecting systems or underdrains consisted of ½-in. manifolds with three 3/8-in. laterals on each side. Each lateral had two rows of 1/8-in. holes spaced on 2-in. centers to permit filtered water to enter the collecting system at an angle of 30 degrees from the vertical.

The filtering medium consisted of a fine, uniformly graded, white sand marketed by the Clayton Silica Company, Cedar Rapids, Iowa. A sieve analysis (Figure 9) of the sand indicated an effective size of 0.28 mm and a uniformity coefficient of 2. Both values lie within their respective accepted limits of 0.2 to 0.3 and 1.5 to 2.5 for slow sand filters. As shown in Figure 10, 30 in. of this sand were laid over 6 in. of pea gravel.

Each filter was equipped with a piezometer (Figure 11) on the effluent line for the determination of head loss. A constant head of 30 in. of water was maintained above the sand with float valves. The flow rate was controlled manually with ½-in. needle valves at the filter effluents. Sampling faucets were installed at the sand surface and at the 6, 12, 18, and 24 in. sand depths in the prechlorinated filter.

Filtered water flowed into storage reservoirs, also fabricated from 55-gal. drums. The reservoirs were used to store the filtered water to enable daily observation of the clarity and odor of the filter effluents. Water from the reservoir in the prechlorinated system was pumped through a dechlorinating

Figure 9. Sieve analysis of sand used in slow sand filters

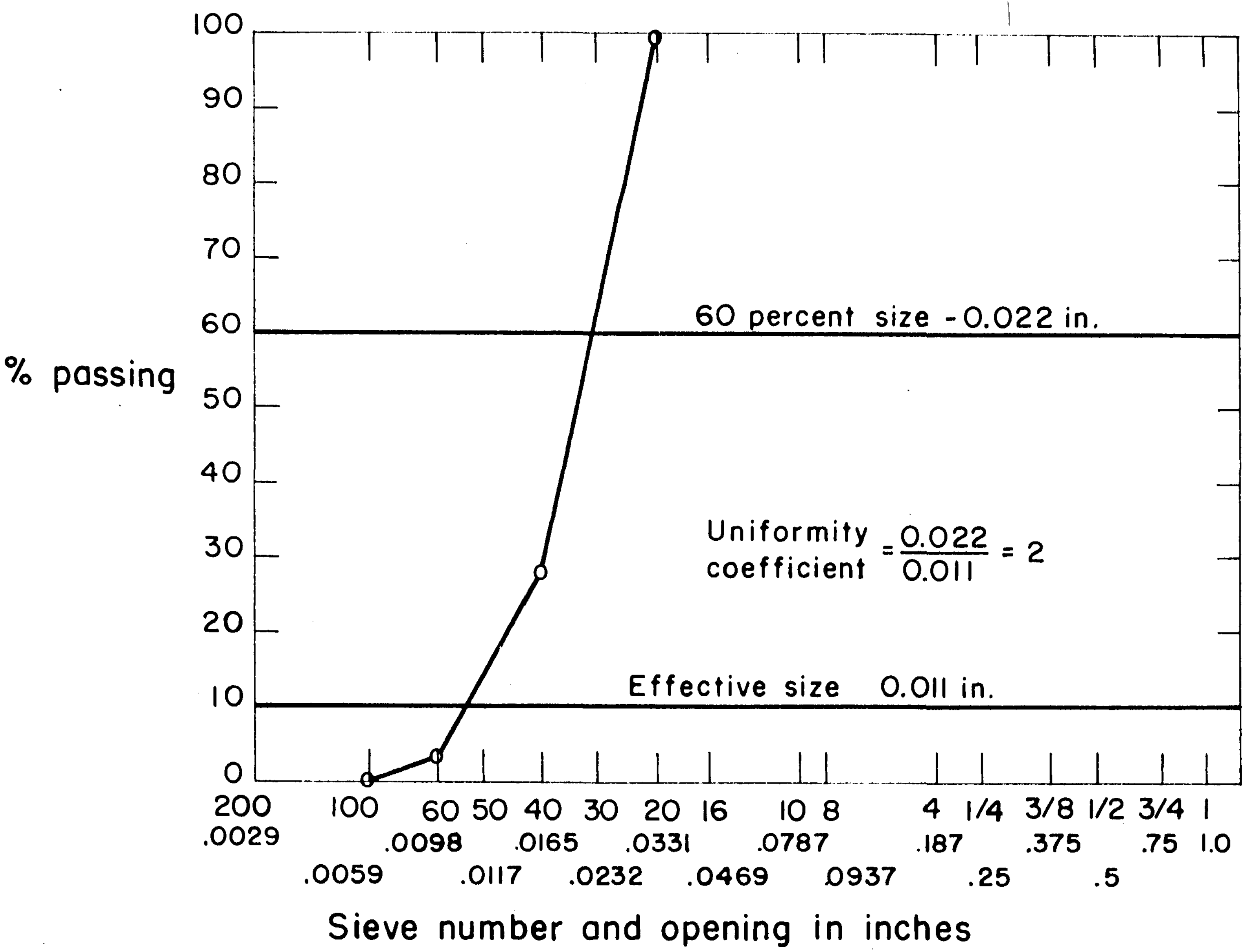
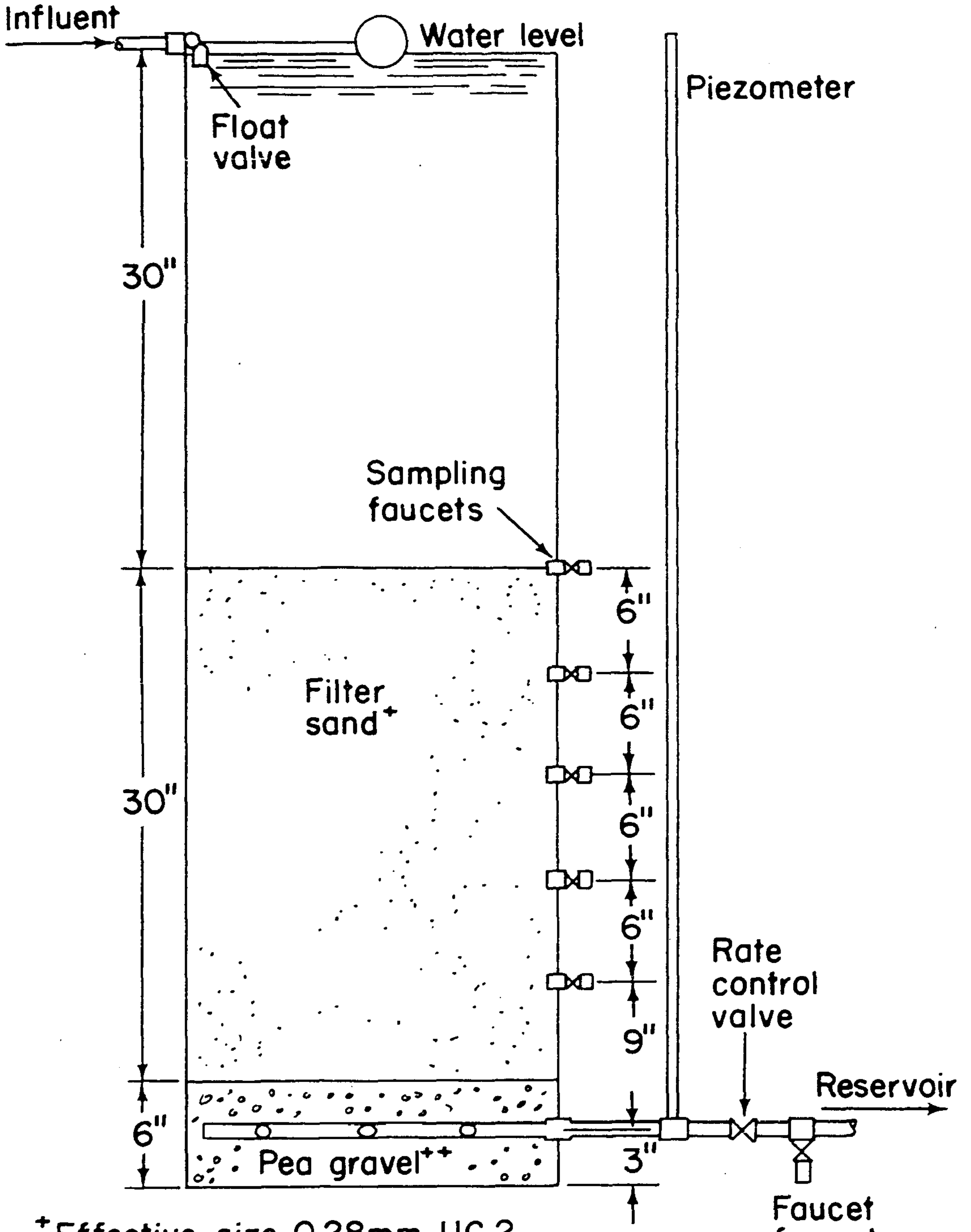

100
90
80
70
60
50
40
30
20
10
0
% passing
60 percent size - 0.022 in.
Uniformity coefficient = 0.022 / 0.011 = 2
Effective size 0.011 in.
200 .0029
100 .0059
60 .0098
50 .0117
40 .0165
30 .0232
20 .0331
16 .0469
10 .0787
8 .0937
4 .187
1/4 .25
3/8 .375
1/2 .5
3/4 .75
1 1.0
Sieve number and opening in inches

Figure 10. Cross section of slow sand filter

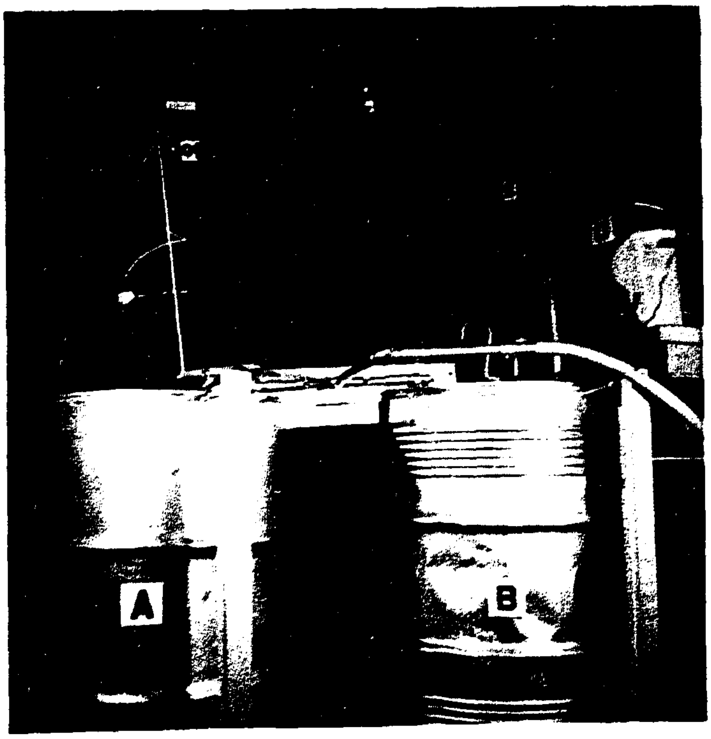


+Effective size 0.28mm, UC 2
++Passed 1/4" sieve retained on 3/8" sieve

Figure 11. Slow sand filter apparatus
(A - prechlorinated filter, B - standard filter,
C - piezometer, D - chlorine solution carboy,
E - roughing filter)

Figure 12. Slow sand filter apparatus


A


A
B

precoat carbon filter during sampling, otherwise both reservoirs emptied to waste.

Chlorine was applied in all runs at the water surface in the prechlorinated filter influent. Initially, prechlorination was accomplished by feeding chlorine solution from a carboy through a capillary tube. This solution was mixed by adding sufficient distilled water to one gallon of 5.25 percent NaOCl to give a 6,000 mg/1 FAC residual. During the first three runs, occasional build up of crystals, believed to be NaCl, occurred in the capillary and interfered with chlorine feed. In the final run, chlorine was fed through an Everclor automatic dosing device (Figure 12). With this method, a 1,250 mg/1 chlorine solution was used. A uniform chlorine residual could not be maintained on the filter during any run due to variation in the chlorine demand of the water and changes in the air and water temperature.

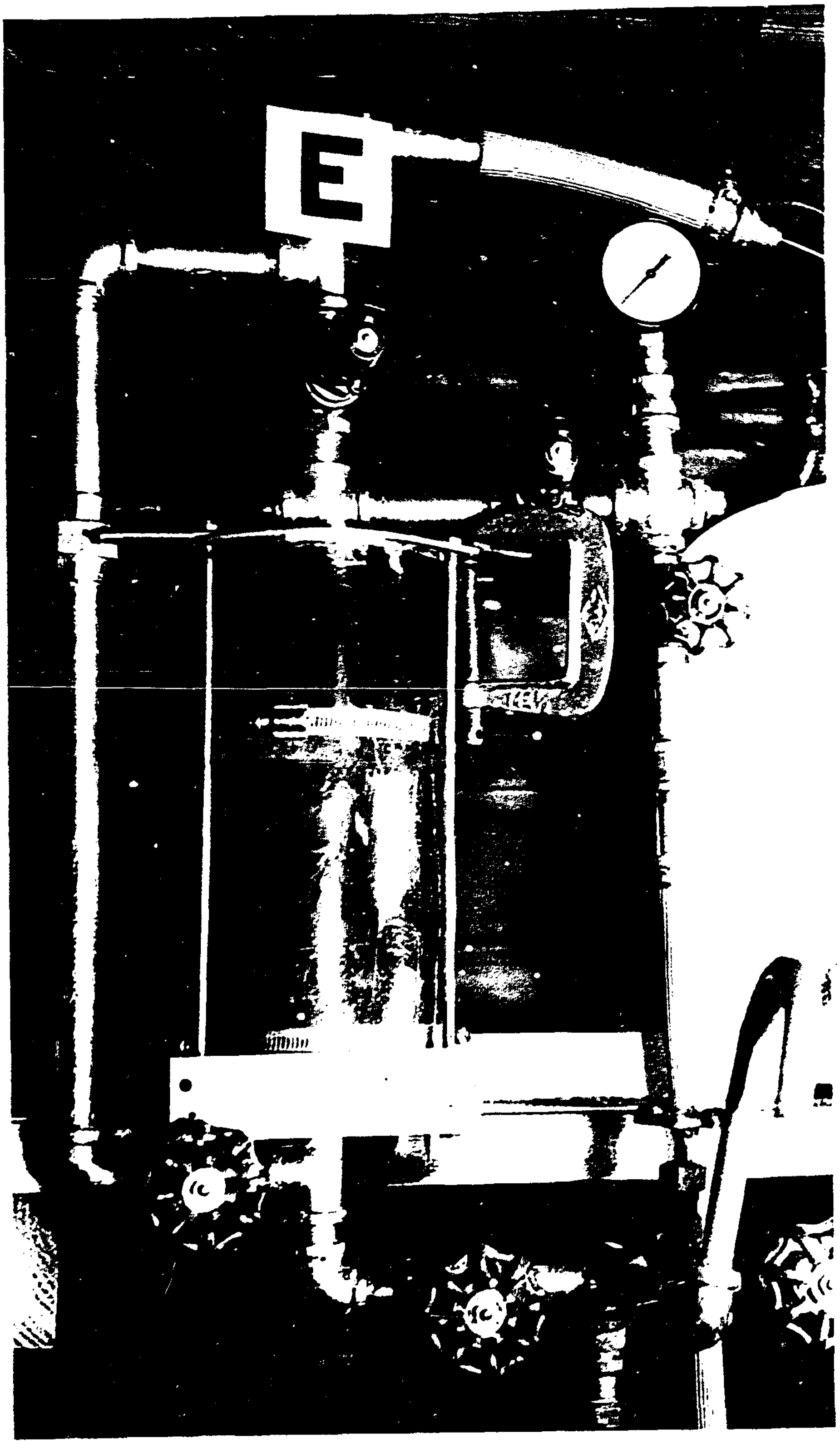
Raw water was pumped from Squaw Creek to the filter installation. This creek was normally heavily contaminated with wastes apparently from an upstream trailer court. It provided an excellent source for bacteriological studies. On occasions livestock were seen wallowing in this stream.

The turbidity of the creek water during most runs was above the recommended level of 20-25 units for slow sand filters. To provide a more uniform turbidity in the influent water, a roughing filter, shown in Figure 13, was constructed using a 14-in. piece of 6-in. plastic tubing. The underdrainage system for this filter was covered with approximately one inch of pea gravel. Two inches of sand having an effective size of 0.6 mm served as the filtering medium. Backwash water was supplied either from the raw water line or pumped from the reservoirs. Since sufficiently high pressure was not available from either source for proper backwashing, the sand depth had to be kept at a minimum. The rate of flow through the roughing filter was 1.96 gpm/sq ft.

Daily samples were taken during the runs for physical, chemical and bacterial analysis. After the flow rate in each filter was checked by volumetric measurement and adjusted, head loss measurements were made. The roughing filter was backwashed daily for approximately five minutes. With the carbon filter pump in operation, samples were taken at the following locations shown in Figure 14: (A) influent raw water, (B) roughing filter effluent, (C) prechlorinated filter influent, (D) prechlorinated filter effluent, (E) carbon filter effluent, and (F) control filter effluent. Flaming of the faucets was practiced when samples for bacteriological examination were taken. Daily mean water temperature was determined on each filter from a recording thermometer.

At a rate of 100 gpd/sq ft, each filter was able to treat

Figure 13. Roughing filter used in tests with slow sand filters


E

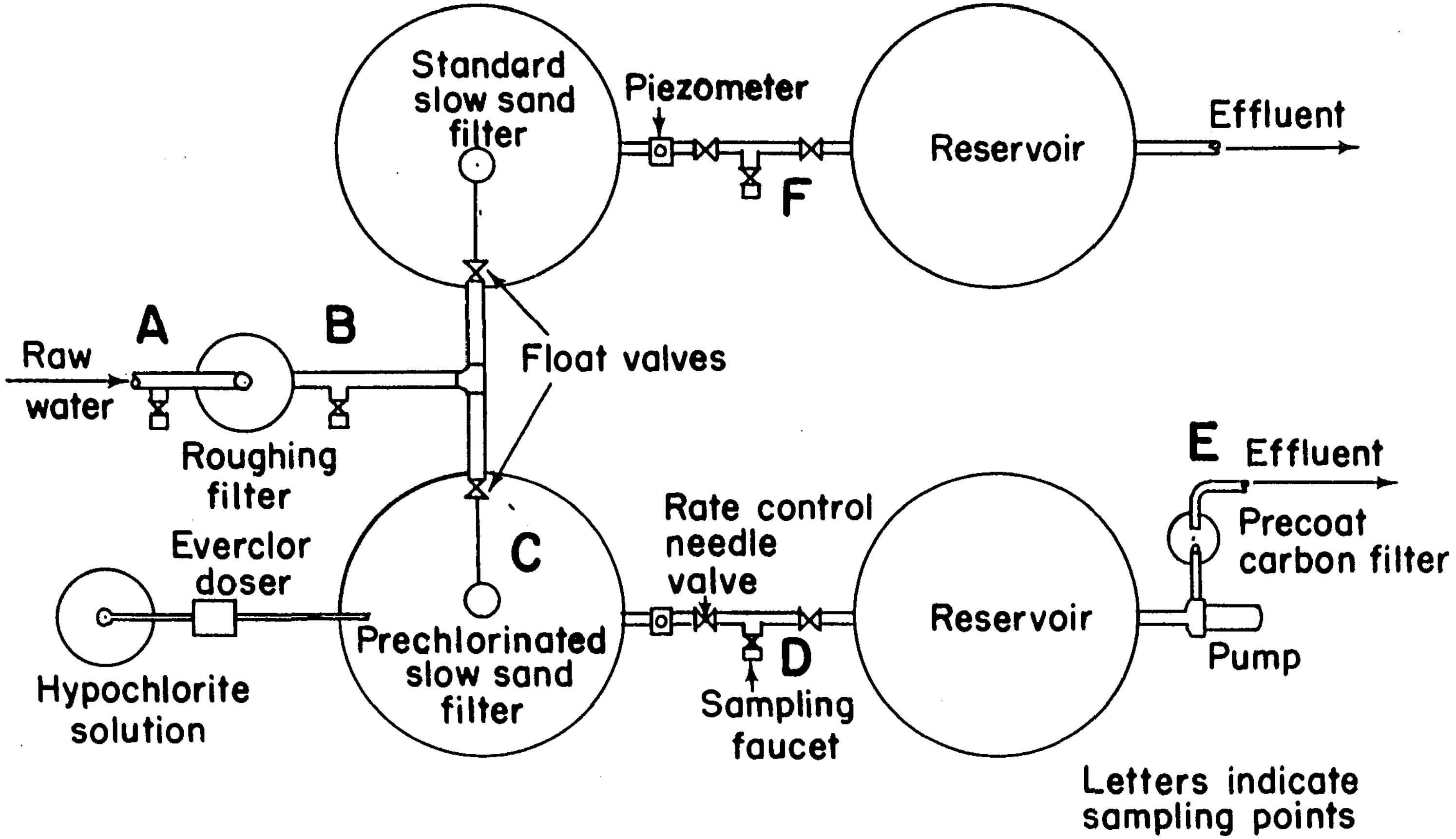


Figure 14. Flow diagram for slow sand filters

264 gallons per day. The theoretical retention time in the filter was computed to be 3.37 hours. Based on a tank detention time efficiency of 75 percent (39), these filters provided a probable retention time of 2.5 hours for chlorination. Physical, chemical, and bacteriological analyses were conducted on samples taken from the slow filters in accordance with procedures outlined as follows:

Determination	Method
Free available chlorine residual (FAC)	Orthotolidine flash test
Turbidity	Hellige turbidimeter
Standard Plate count	Nutrient agar
E. coli	MPN Millipore filter
pH	pH meter
Kjeldahl nitrogen	Kjeldahl distillation and titration
Nitrite nitrogen	Colorimetric
Nitrate nitrogen	Colorimetric
Ammonia nitrogen	Direct nesslerization
Total solids	Gravimetric
Volatile solids	Gravimetric
BOD	Azide modification of Winkler method

All tests were conducted in accordance with procedures outlined in Standard Methods (50) except the nitrite and nitrate nitrogen tests (55). Due to the many time consuming tests, all of the determinations could not be made during any single run. Consequently, four runs were made: Run I, head loss determination --16 days; Run II, head loss, bacteriological tests, chlorine residuals, and turbidity--25 days; Run III, bacteriological tests, chlorine residuals--37 days; Run IV, organic tests, chlorine residuals, sand samples, turbidity, solids and BOD--11 days.

EXPERIMENTAL OBSERVATIONS AND ANALYSES

Analysis of Time-Concentration Data for Disinfection with Free Available Chlorine

Criteria for destruction of pathogenic organisms

Our present standards for a safely disinfected water are based on the absence, or presence in low concentrations, of coliform organisms. Following this standard, we normally apply sufficient chlorine to eliminate coliforms from treated water and to insure a small chlorine residual in the distribution system. This practice is logical for a number of reasons. First, research has shown that, in general, *Esch. coli* are as resistant to disinfection as most pathogenic bacteria. Secondly, coliforms are an excellent indicator of the possible presence of enteric type bacteria due to the ease with which they may be isolated and identified. Thirdly, the use of coliforms as an index of bacteriological quality has resulted in the consistent production of acceptable water in all of our approved municipal water supply systems.

The U. S. Public Health Service recommendations specify that, "Of all of the standard ten milliliter (10 ml) portions examined per month in accordance with the specified procedure, not more than ten (10) percent shall show the presence of organisms of the coliform group" (43). In using this standard, we do not exclude the possibility of some pathogenic bacteria being present in treated waters. *Salmonella typhosa* (*Eberthella* typhosa), for example, has in some tests been found to have almost the identical resistance to chlorine that is exhibited by E. coli (34). If we allow as many as one coliform per 100 ml of water, then we cannot rule out the presence of S. typhosa even though the probability is slight. In fact, at pH values up to and including 7.8, and with FAC residuals up to and including 0.03 mg/1, we can expect S. typhosa to be more resistant than E. coli. It is not the purpose of this study to degrade the use of the coliform test in water treatment, but to show that more stringent disinfection standards are needed for individual water supplies. This expedient has served us ably since about 1910. It has proven especially valuable in municipal water treatment where trained operators can observe the bacteriological quality and adequate chlorine contact is available.

In individual water supplies, equipment and personnel for making lactose broth innoculations are virtually nonexistent. Likewise, sufficient chlorine contact time is normally not provided. To overcome the absence of bacteriological tests in systems in which the characteristics of the water will vary, superchlorination is recommended. Snow has very aptly stated, "The adoption and maintenance of minimum chlorine residuals should not minimize and can never replace bacteriological analyses as the true measure of potability" (46). In small water supplies, however, there is no other recourse. On the other hand, superchlorination is not necessarily the maintenance of a minimum residual. By definition, superchlorination is the deliberate addition of more chlorine than is normally necessary to disinfect a given contaminated water.

In a study of the available literature, Varma and Baumann reviewed the chlorine residuals and contact times needed to kill vegetative bacteria, viruses and cysts (54). They in turn recommended that, under the adverse conditions of 0°C and pH 8.5, small water supplies be superchlorinated with a FAC residual of 5 to 6 mg/l for a contact time of about 7 min.

Adoption of this recommendation would provide both bactericidal and virucidal disinfection. Cysts of E. histolytica which would survive this treatment could be removed by precoat-carbon dechlorinating filters. Five mg/l FAC is roughly 25 times the amount of chlorine recommended for the disinfection of most water supplies. Chlorination at this level would certainly produce a satisfactory water under the stated adverse conditions if the recommended contact time was provided. It must be considered however, that there are pond and well waters that do not approach 0°C and pH of 8.5. In addition, superchlorinating at this level will normally require dechlorination.

In a report concerning recommended chlorine residuals for military water supplies, Snow (46) recommended two separate residuals; (1) a low residual that would be sufficient for bactericidal purposes and (2) a high residual for cysticidal purposes. In localities where only waterborne bacteria are likely to be present, the lower residual of 0.2 mg/l with contact time of 30 min would suffice. Where evidence of non-bacterial waterborne diseases such as amoebic dysentery or infectious hepatitis exists, a higher residual should be applied. The 0.2 mg/l FAC residual would be effective over the normal pH range of natural waters. Military water treatment systems in most cases maintain chlorine residuals which are much higher than the lower residual of 0.2 mg/l. For example, the U. S. Eighth Army in Korea requires that water points maintain 5 mg/l and 10 mg/l in the summer and winter respectively. These residuals are recommended also by the Committee on Sanitary Engineering and Environment, National Research Council for areas where resistant pathogens are present.[1]

It is felt that more specific recommendations can be made for the disinfection of small water supplies. If superchlorination is to be practical and economical, then owners or operators of such systems should be supplied with recommended chlorine levels and contact times that are applicable to the raw water supply that they are treating. Some of the available data on time-concentration studies was plotted to present a graphical picture of the problem. Four classes of organisms are shown in Figure 15; (1) vegetative bacteria (E. coli),

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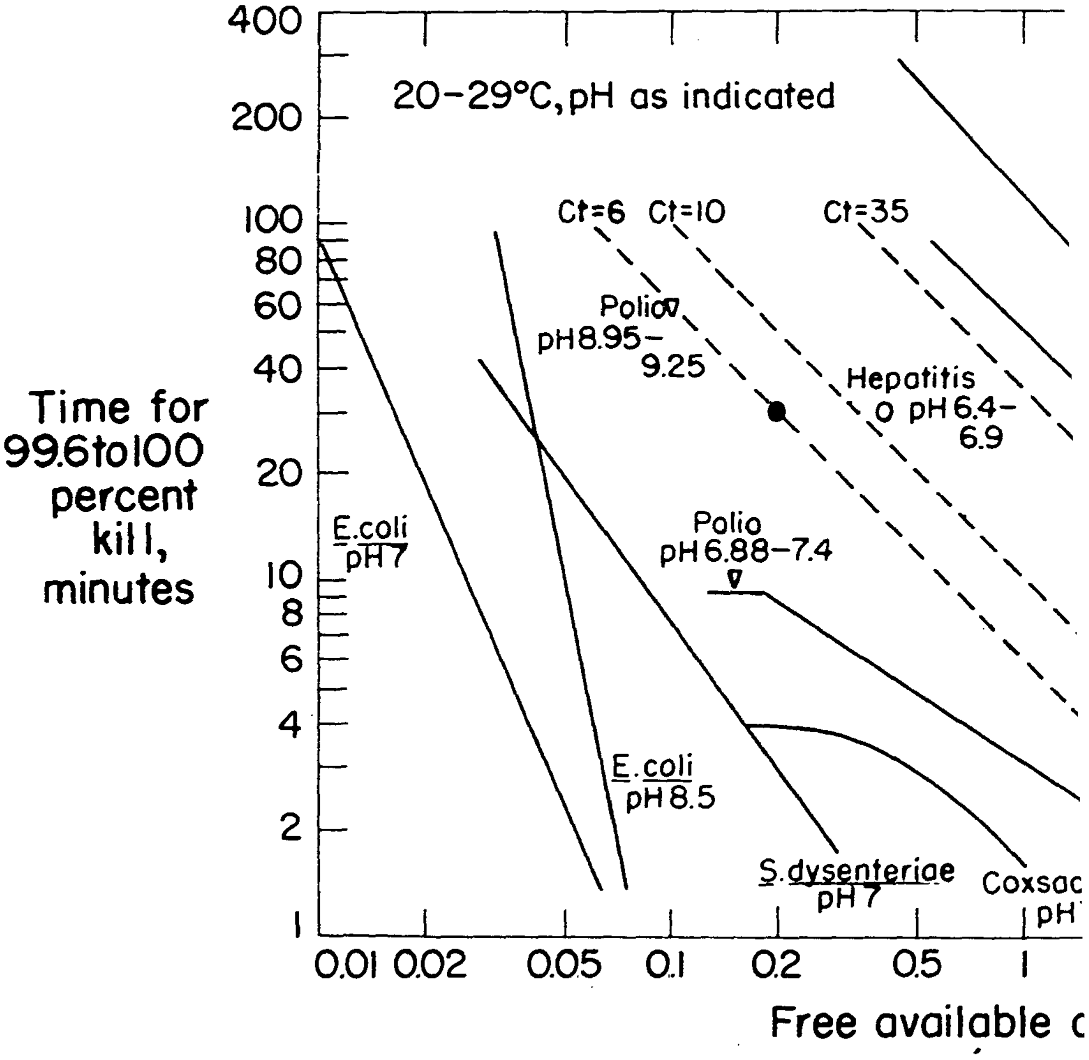
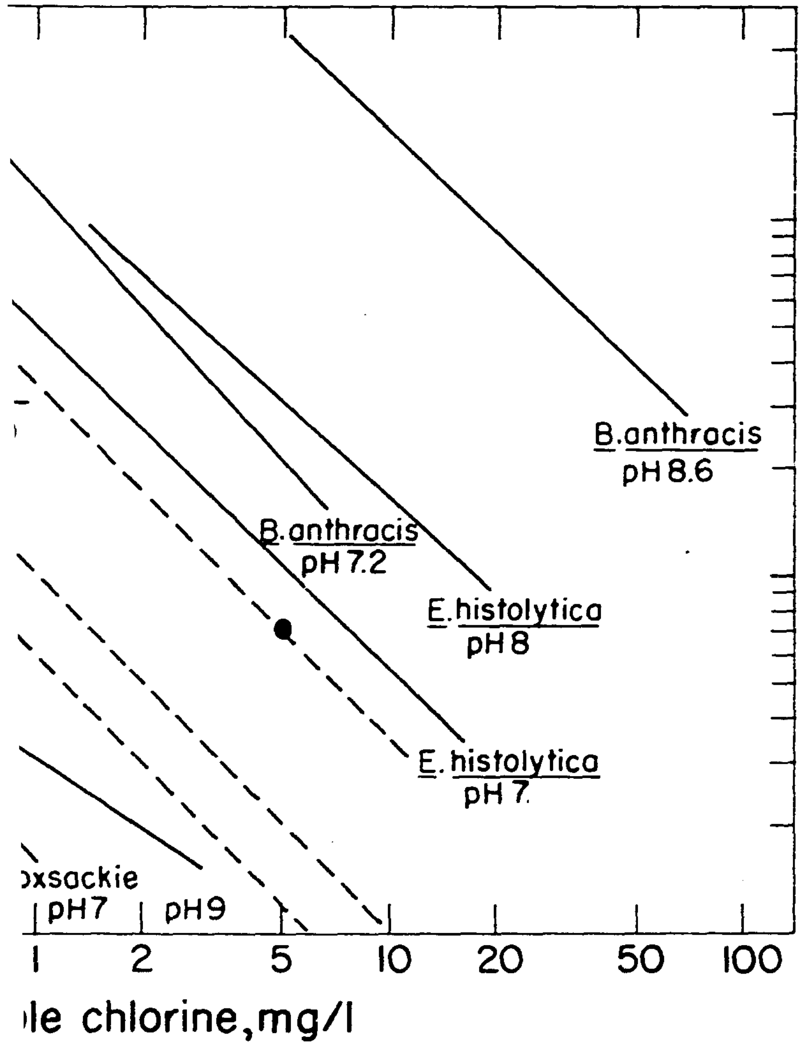
[1] McCall, Robert G., Lt. Col. Med. Service Corps. Office of the Surgeon General, Washington, D. C. Memorandum for the record. Private communication. 1961

Figure 15. Free available chlorine *versus* time for 99.6 to 100 percent kill of various organisms in temperature range 20° to 29°C and pH as indicated


20–29°C, pH as indicated
Time for 99.6 to 100 percent kill, minutes
400
200
100
80
60
40
20
10
8
6
4
2
1
0.01
0.02
0.05
0.1
0.2
0.5
1
Free available c
Ct=6
Ct=10
Ct=35
Polio pH 8.95–9.25
Hepatitis pH 6.4–6.9
E.coli pH 7
E.coli pH 8.5
Polio pH 6.88–7.4
S.dysenteriae pH 7
Coxsac
pH


B.anthracis
pH 8.6
B.anthracis
pH 7.2
E.histolytica
pH 8
E.histolytica
pH 7
ɔxsackie
pH7
pH9
1
2
5
10
20
50
100
le chlorine,mg/l

(2) viruses (poliomyelitis and Coxsackie), (3) cysts (E. histolytica), and (4) spores (B. anthracis). The plotted data were taken from sources considered the most up-to-date and reliable. Data from other investigators may vary slightly due to variation in organism strains. It should further be mentioned that all of the data do not cover the entire temperature range of 20° to 29°. Sources of data are given in Table 3.

An inspection of this plot of kill time versus FAC reveals the increasing resistance to chlorination for these organisms in the order listed above. It is also evident that the majority of the curves have slopes approaching -1. Straight lines on this type of plot follow the general equation:

Where: $C^n t = K$

C = concentration of FAC, mg/l
t = time of contact for the indicated percentage of kill, min
n = a positive number expressing the relationship between C and t
K = a constant for a given organism, pH and temperature.

The slope is expressed as $-n$. In cases where the slope is equal to -1, the general equation becomes $Ct = K$.

The dotted line passing through the coordinates 0.2 mg/l and 30 min with a -1 slope follows the equation $Ct = 6$. If we extend the recommendation given by Snow to include other combinations of chlorine concentration and contact time, both bactericidal and virucidal disinfection can be accomplished in the temperature range given. Using the envelope $Ct = 10$,

Table 3. List of sources of data for time-concentration studies

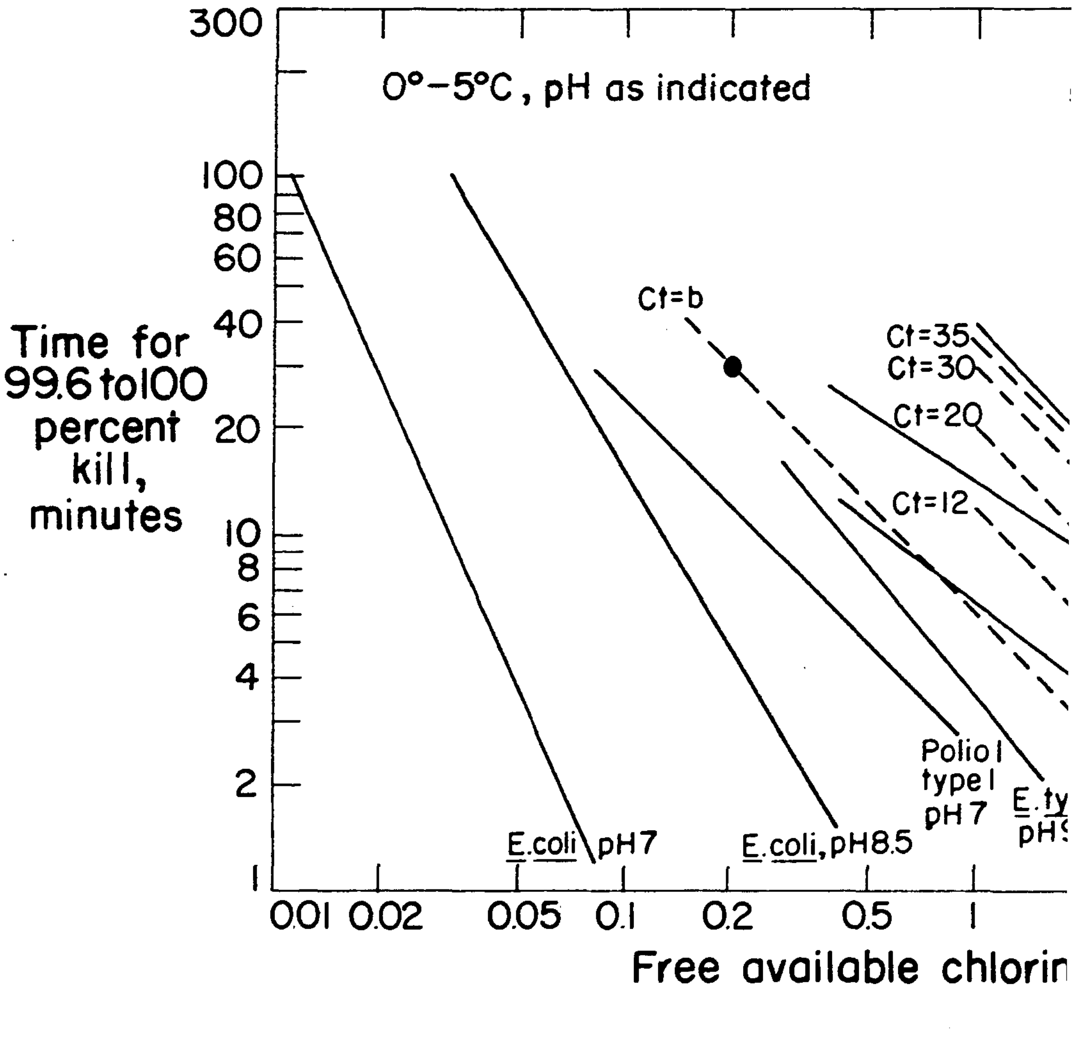
Organism	Temperature range	pH	Source
_E_. _coli_	2°-5°C	7,8.5	Butterfield (7)
_E_. _typhosa_	2°-5°C	9.8	Butterfield (7)
_S_. _dysenteriae_	20°-25°C	7.0	Butterfield (7)
Poliomyelitis	0°C	7,8.5	Weidenkopf (56)
Poliomyelitis	20°-30°C	6.85-9.25 6.5-7.4	Lensen _et_ _al_. (38)
Coxsackie	3-6°C	7,9	Clarke and Kabler (9)
_E_. _histolitica_	3°C	7,8	Fair _et_ _al_. (15)
_E_. _histolitica_	20°C-25°C	7,8	Snow (46)
_B_. _anthracis_	4°C	7.2,8.6	Brazis, _et_ _al_. (5)
_B_. _anthracis_	22°C	7.2,8.6	Brazis, _et_ _al_. (5)
_P_. _tularensis_	15.5-18.5°	7,3	Foote, _et_ _al_. (18)
Hepatitis	room	6.4-6.9	Neefe, _et_ _al_. (41)

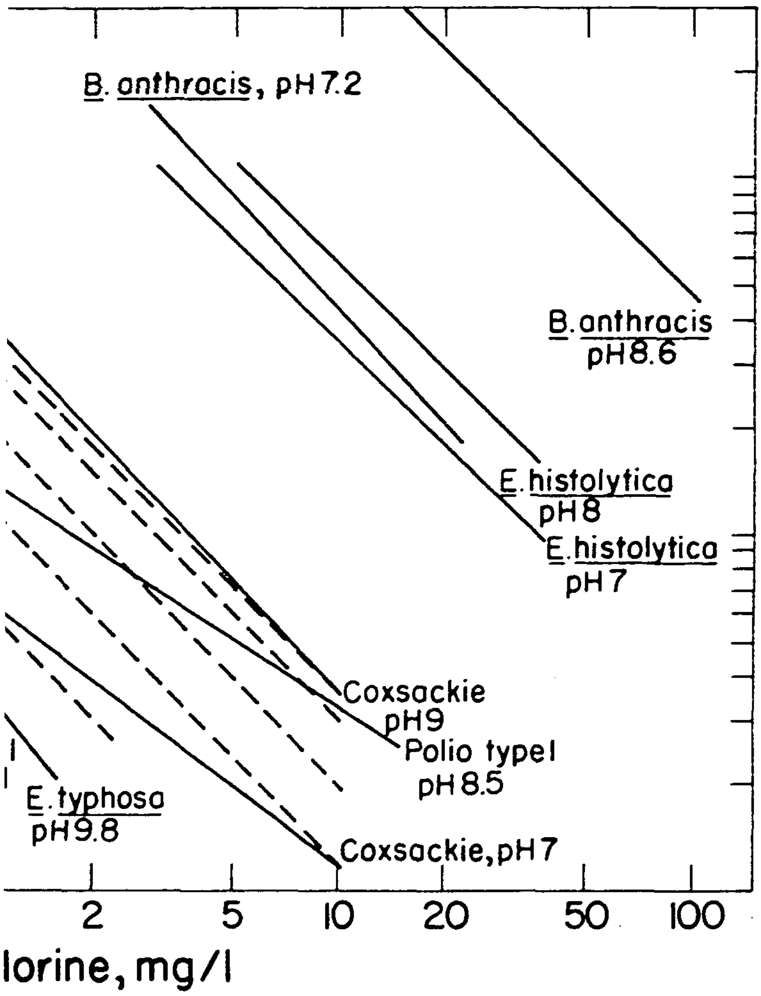
we could possibly expect the destruction of hepatitis also. If a similar line is drawn through the recommendation given by Baumann, 5 mg/l for 7 min, the equation becomes Ct = 35. Chlorinating with various FAC residuals and contact times along this line would provide a large margin of safety for disinfecting the viruses shown as well as all vegetative bacteria. Whether viruses more resistant than polio type 1 or Coxsackie exist is unknown to the author. Even with superchlorination in this range, we would not be able to destroy cysts of E. histolylica or spores of B. Anthracis.

Since disinfection with chlorine is greatly affected by temperature, a similar plot was made for the temperature range 0°C to 5°C. In Figure 16, the line Ct = 6 does not include the viruses of poliomyelitis or Coxsackie at high values of pH. It still offers a valid margin of safety for the destruction of pathogenic bacteria as evidenced by its location with respect to E. coli. On the other hand, the envelope Ct = 35 corresponds almost identically with the time-concentration curve for Coxsackie at pH 9. Superchlorinating with various residuals and contact times providing Ct = 35 would assure disinfection of the viruses shown in the temperature range 0° to 5°C.

The use of envelopes such as these would prove beneficial in the design of disinfecting system for small water supplies. If the worst possible expected conditions, coldest water temperature and maximum pH, are known, the designer could utilize any combination of FAC and contact time that would assure adequate disinfection. In order to construct recommended envelopes of the equation Ct = K, a decision had to be made concerning the types of organisms that we are striving to eliminate. Snow's second recommendation applied to residuals sufficient

Figure 16. Free available chlorine *versus* time for 99.6 to 100 percent kill of various organisms in temperature range 0° to 5°C and pH as indicated


0°–5°C, pH as indicated
Time for 99.6 to 100 percent kill, minutes
300
100
80
60
40
20
10
8
6
4
2
1
Ct=b
Ct=35
Ct=30
Ct=20
Ct=12
E. coli pH7
E. coli, pH8.5
Polio I type I pH 7
E. ty
pH
0.01
0.02
0.05
0.1
0.2
0.5
1
Free available chlorin


B. anthracis, pH 7.2
B. anthracis pH 8.6
E. histolytica pH 8
E. histolytica pH 7
Coxsackie pH 9
Polio type I pH 8.5
E. typhosa pH 9.8
Coxsackie, pH 7
2
5
10
20
50
100
lorine, mg/l

to destroy cysts of _E_. _histolytica._ There appears to be no need to chlorinate at levels (Ct = 650) sufficient to kill these organisms, since their removal in small water supplies can be accomplished with precoat carbon filters. Similarly, to be assured of killing the spore forming _B_. _anthracis_, which causes anthrax, uneconomically high residuals would be necessary (Ct = 4500). Man and animals can be afflicted with anthrax by consuming water carrying _B_. _anthracis_, however, this is not its normal mode of transmission. Little is known of the chlorine death points of other pathogens that may be more resistant than the viruses. Apparently, however, some food spoilage organisms are in this category. In tests with _S_. _aureus_, it was found that this organism is more resistant to chlorination than the virus Coxsackie (Table 11). This bacterium causes food poisoning and is usually found in contaminated milk products.

For several reasons, it was decided to select the virus Coxsackie as the upper limit of resistant pathogens that we should strive to destroy in small water supplies. (1) Accurate data for chlorine residual and times of contact for disinfection are available; (2) Coxsackie virus can be destroyed with FAC residuals less than 10 mg/l and relatively short chlorine contact times; (3) Little is known of the chlorine resistance of organisms more resistant than Coxsackie; (4) It is not necessary to attempt disinfection of cysts of

E. histolytica; (5) FAC residuals and contact times for destroying the pathogenic spore former *B. anthracis* are too high for routine disinfection; (6) By superchlorinating to destroy Coxsackie, we include destruction of poliomyelitis and hepatitis viruses and pathogenic vegetative bacteria. It should be emphasized that the selection of Coxsackie as an upper limit of the chlorine resistant organisms is only a recommended criterion for disinfection in small water supplies. We cannot economically provide sufficient chlorination that will yield a sterile water in all cases.

Recommended combinations of FAC residuals and contact times

Once the upper pathogen limit had been established, envelopes were drawn which would provide combinations of FAC residuals and contact time for disinfection at this level (Figure 16). For waters with maximum pH value of 9, the previously mentioned line, Ct = 35, is shown. For waters with a maximum pH value equal to 7, the envelope is Ct = 12. Intermediate envelopes of Ct = 20 and Ct = 30 were constructed by interpolation. This interpolation was based on the available HOCl concentration at the respective values of pH. All of these lines were drawn in the FAC range from 1 to 10 mg/l for use in small water supply installations. They could have been extended into the range 0.1 to 1 mg/l, but chlorine retention times would increase. One of the major advantages of superchlorination in small water supplies is that chlorine contact time is minimized. For this reason, the FAC range from 1 to 10 mg/l is recommended. Table 4 summarizes the recommended envelopes to be used for water having an expected low temperature of 0° to 5°C and a given maximum pH.

Table 4. Recommended time-concentration envelopes for the superchlorination of individual water supplies having a minimum expected temperature between 0°C and 5°C

Maximum expected pH	Value of K, $Ct = K$
6.5-7.5	12
7.5-8.0	20
8.0-8.5	30
8.5-9.5	35

In some localities the minimum water temperature may not fall as low as 5°C; therefore, different envelopes are recommended for a higher minimum temperature. Ten degrees Centigrade, or 50°F, was considered to be applicable in this case. Since time-concentration laboratory studies are normally conducted at either room temperature or in the range 0°-5°C, no data were available for making a plot for 10°C. A transposition from the plots at 20°-29°C and 0°-5°C was accomplished using the van't Hoff-Arrhenius reaction rate equation:

$$\ln \frac{t_1}{t_2} = \frac{E(T_2 - T_1)}{R\, T_1\, T_2}$$

where:

T_1, T_2 = upper and lower temperatures between which reaction rates are compared

t_1, t_2 = times required for equal percentages of kill to be effected at temperatures T_1 and T_2 at a fixed concentration of disinfectant, min

E = activation energy, calories

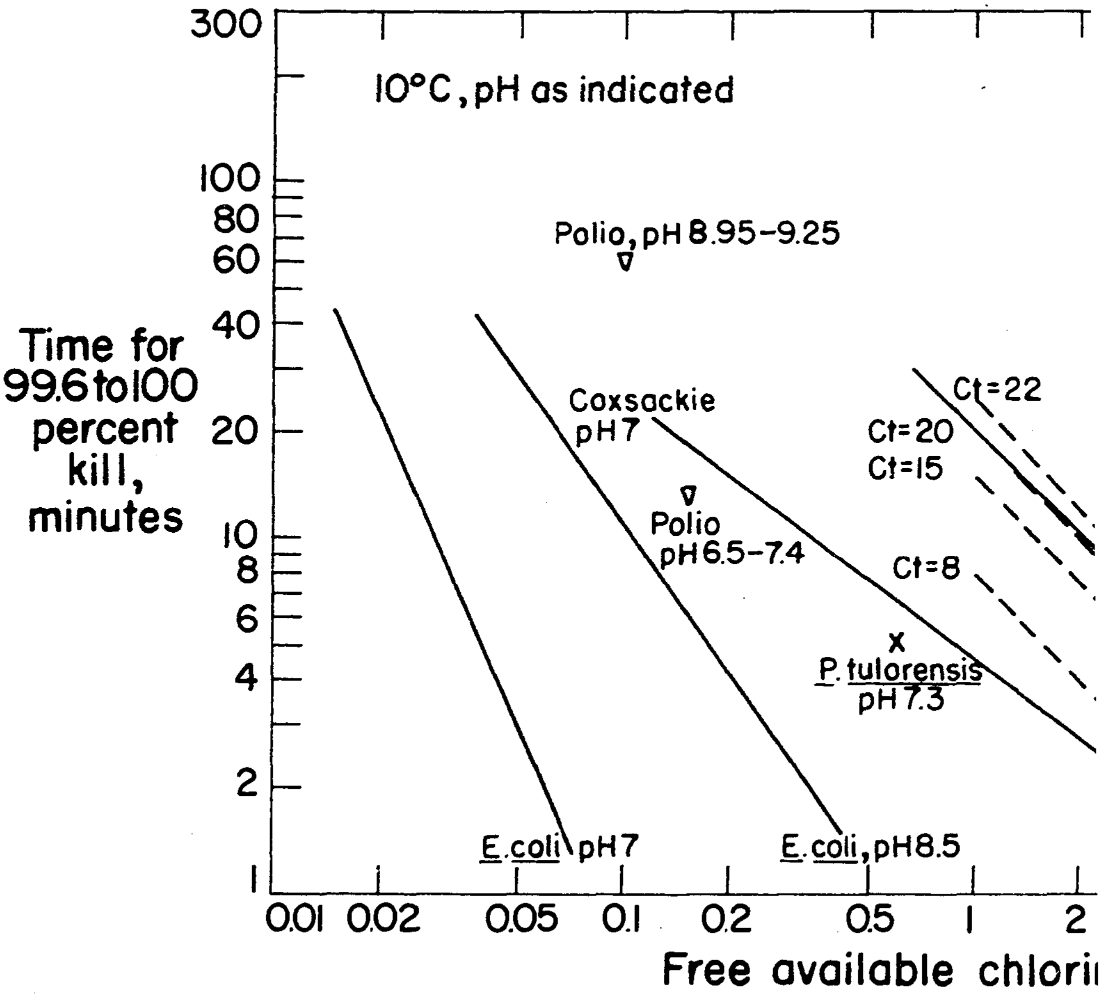
R = gas constant, 1.99 cal/°K .

To accomplish this transposition, values of T_1, T_2 and t_1, t_2 for a specific organism pH were taken from the respective graphs for 0°-5°C and 20°-29°C at a specific FAC concentration. Substitution of these values into the equation yielded the activation energy, E. Once E was determined, contact times, t_2, were computed using the same values of T_1 and t_1, and substituting 10°C (283°K) for T_2. One or more similar computations were made at different FAC concentrations to provide sufficient points for plotting the line for each organism.

Figure 17 shows the recommended envelopes. Using Coxsackie at pH 9 and 7 for the maximum and minimum, the line $Ct = 22$ and $Ct = 8$ were drawn. Interpolation yielded the equations for the intermediate pH ranges. Table 5 shows the recommended envelopes for superchlorination with a minimum expected temperature of 10°C.

One advantage of using these recommended combinations of FAC residuals and contact times is that superchlorination

Figure 17. Free available chlorine versus time for 99.6 to 100 percent kill of various organisms at 10°C and pH as indicated


10°C, pH as indicated
Time for 99.6 to 100 percent kill, minutes
300
100
80
60
40
20
10
8
6
4
2
1
Polio, pH 8.95–9.25
Coxsackie pH 7
Polio pH 6.5–7.4
Ct=22
Ct=20
Ct=15
Ct=8
P. tulorensis pH 7.3
E. coli pH 7
E. coli, pH 8.5
0.01
0.02
0.05
0.1
0.2
0.5
1
2
Free available chlori

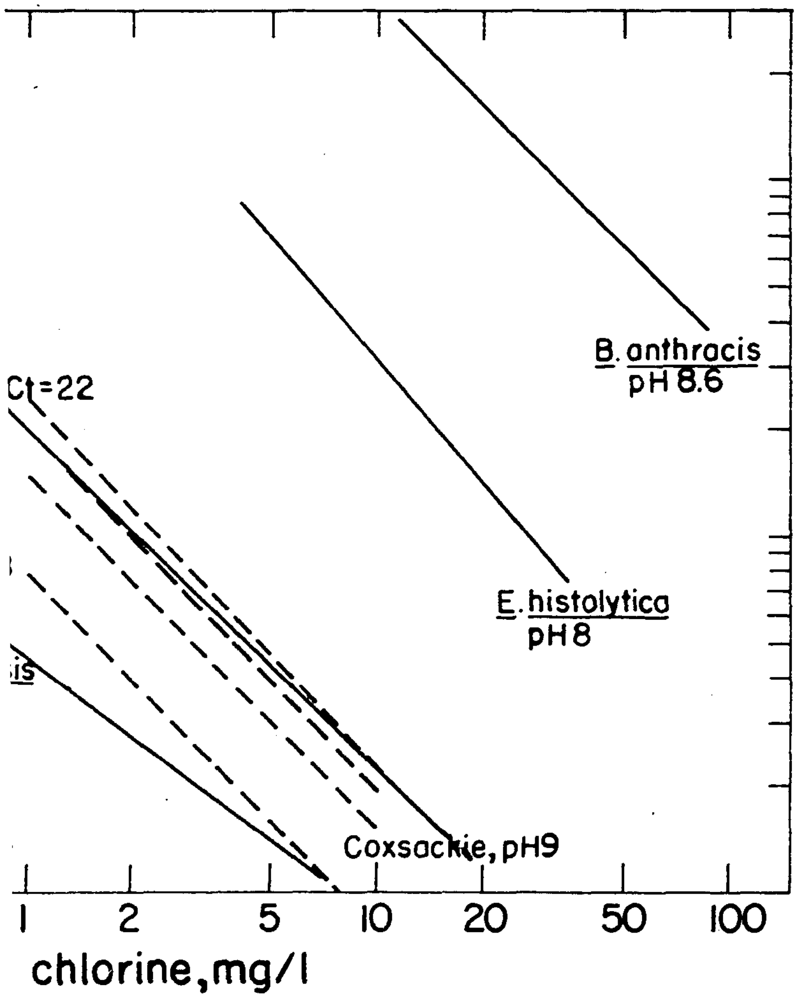

Ct=22
B. anthracis
pH 8.6
E. histolytica
pH 8
is
Coxsackie, pH9
1
2
5
10
20
50
100
chlorine, mg/l

Table 5. Recommended time-concentration envelopes for the superchlorination of individual water supplies having a minimum expected temperature of 10°C

Maximum expected pH	Values of K Ct = K
6.5-7.5	8
7.5-8.0	15
8.0-8.5	20
8.5-9.5	22

need not be conducted at higher residuals than are necessary for a given water supply. If the pH is never expected to rise above 7.5, then the lowest set of combinations is adequate. An equally important advantage lies in the design of chlorine contact vessels. At higher residuals for a given envelope, the contact times are shorter. Hence, a smaller contact tank can be provided.

In order to apply these recommendations in small water supplies, three factors should be determined first: (1) The minimum expected water temperature; (2) The maximum expected pH; and (3) The critical flow rate. The first two factors will indicate the equation that should be utilized. For example, with a shallow well with a minimum expected temperature of 10°C and a maximum pH of 7.7, the equation Ct = 15 would apply. Combinations such as 5 mg/1 FAC for 3 min, 3 mg/1 FAC for 5 min, 1.5 mg/1 for 10 min or 1 mg/1 for 15 min could be used. The selection of a particular combination would depend on the critical flow rate. If this rate is not high, eg.; 4 gpm, less chlorine and a longer contact time could be used. At 8 to 10 gpm the size of chlorine retention tank needed would necessitate the use of higher residuals.

Let us assume that an owner has available a 50-gal chlorine contact tank with a 70 percent contact efficiency. The available contact time for various flow rates through the tank would be as follows:

5 gpm	7 min
7 gpm	5 min
10 gpm	3.5 min

Now, if the critical flow rate in this installation were 7 gpm, the owner would have to maintain a residual that would provide destruction of pathogens in 5 min. For the water assumed, this required residual would be 3 mg/1. If the flow rate were 10 gpm, the required FAC residual would be 15/3.5 or 4.3 mg/1.

Chlorine Retention Studies

Typical rates and demands

An evaluation of the means of obtaining chlorine retention in a small water system necessarily embodies knowledge of expected rates and volumes of water flow. A safe chlorine retention system should be designed to provide adequate contact time at the critical rate of flow for an indefinite period of time. On a farmstead, for example, the maximum expected rate might occur at a fire hose outlet at a flow depending on the pump capacity. The maximum rate might also occur when all fixtures in the system were opened simultaneously. Since a dairy farm or motel may use 3,000 to 5,000 gal daily at rates from 10 to 15 gpm compared with households using only 100 to 300 gal at much lower rates, it is necessary to know the critical expected flow for each system for safe and economical design. Studies were conducted to obtain typical data of this nature. Recording devices were placed in typical family residences, monthly usage was collected from the city water works and published data were analyzed.

The data shown in Table 6 were obtained from recording charts placed in the homes of staff members and graduate students in the city of Ames. Five of the residences were occupied by two adults and two children, and one was occupied by two adults and three children. For the 57 days of records indicated, these families used an average of 41.8 gallons per person per day.

Table 6 also reveals that rates of flow greater than 10 gpm occurred in only about 1 percent of the uses. The most

Table 6. Average household water uses for six residences in Ames, Iowa

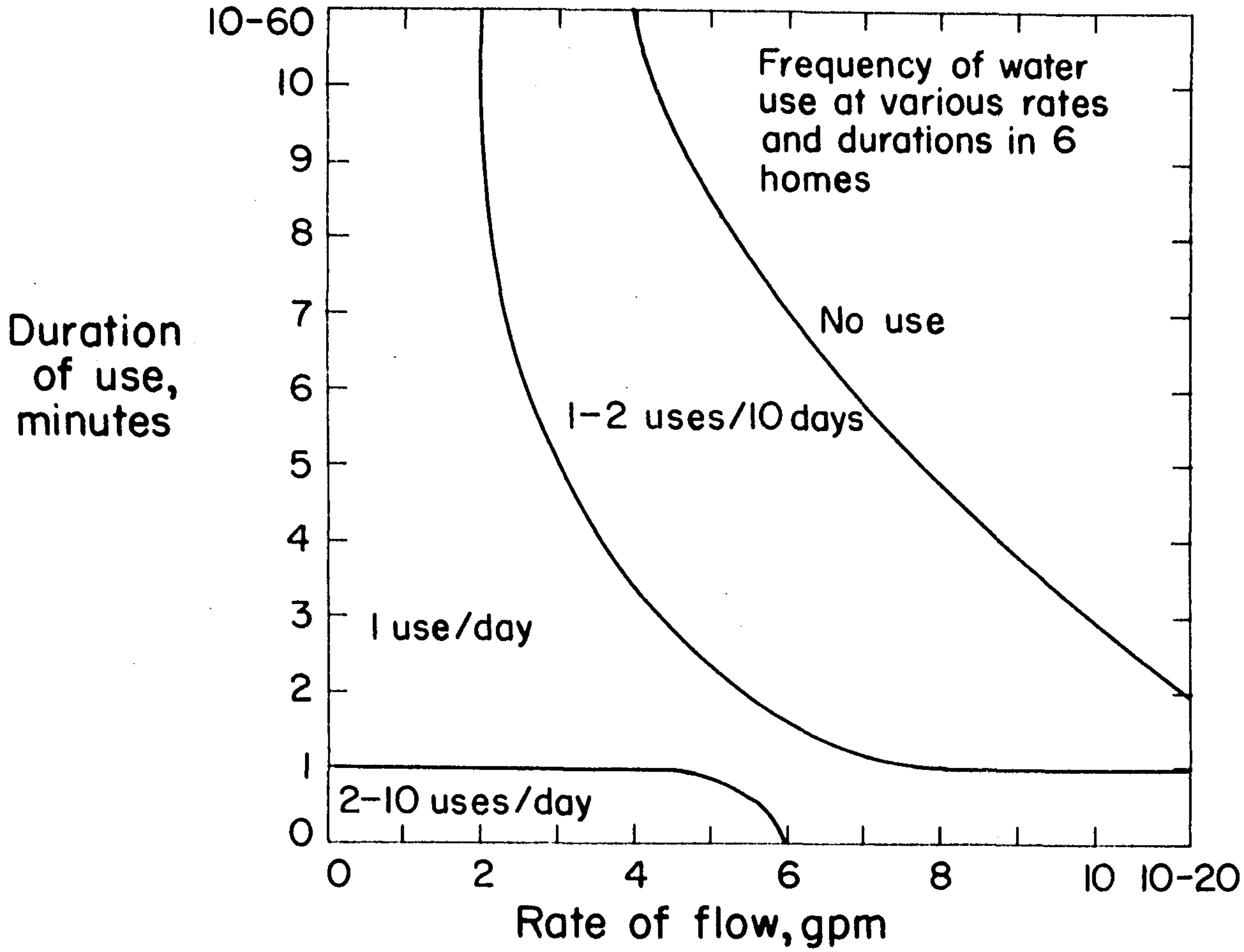
Residence	No. in family	Days of record	Av. water use, gpcd	Property class[a]	No. daily uses at given rate (means) Rate of water use, gpm 0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	over
1	4	14	56.9	1	25.6	6.7	2.9	5.3	4.5	2.4	1.5	0.5	0	0.8	0.8
2	4	7	34.8	3	22.9	7.9	2.6	0.4	0.9	0.1	0.3	0.1	0.7	0.6	0
3	4	7	39.0	4	18.9	6.1	3.9	0.7	0.6	0.1	0.1	0	0.1	0.1	0.6
4	5	13	40.7	3	14.5	9.7	3.2	1.6	1.5	0.7	0.6	0.8	0.7	0.8	0.5
5	4	8	45.5	1	20.7	6.4	10.3	3.5	5.1	2.0	0.7	0.4	0.6	0.3	0.1
6	4	8	33.9	4	16.1	2.6	3.0	3.3	8.1	3.1	3.0	1.5	0.4	2.1	0.4
Mean values			41.8		19.9	6.6	4.3	2.3	3.5	1.4	1.0	0.6	0.4	0.8	0.4
Percent average daily uses at given rate					48.0	15.9	10.4	6.0	8.4	4.3	2.6	1.4	1.0	1.9	1.0

[a] Property class value: 1--$25-30,000
2--$20-25,000
3--$15-20,000
4--under $15,000

frequent uses occurred at flows less than 3 gpm with approximately 48 percent of the daily water uses being at rates of 1 gpm or less. To make use of these data in the design of chlorine retention systems, an analyses of rates _versus_ duration of use was in order. Tabulated frequency-rate-duration data for the 57 days of records yielded the plot shown in Figure 18. This figure indicates that the most frequent rates used are generally less than one minute in duration. Examples of this usage might be: hand and face washing, teeth brushing, toilet flushing, drinking and cooking water, etc. Although the actual maximum rates for these residences were not determined, this plot can provide the expected critical water usages. At a flow rate of 4 gpm for 60 min, the volume of water used would be 240 gal. Although neither of these conditions occurred during these studies, they are indicative of the critical conditions on which chlorine retention computations may be based.

Critical flow conditions such as those just given are typical of what might be expected in an average residential home. They are not, however, representative of all residences with families of four people. Most farm or suburban dwellings having an individual water supply have pumps with about a 10 gpm capacity. This would indicate that the critical flow could be based on the maximum pumping rate for an indefinite

Figure 18. Frequency at which water was used at various rates and durations in 6 homes


Frequency of water use at various rates and durations in 6 homes
No use
1-2 uses/10 days
1 use/day
2-10 uses/day
Duration of use, minutes
Rate of flow, gpm
10-60
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
10-20

period of time. On the other hand, some individual water supplies may have high capacity pumps which supply pressure for both consumptive and non-consumptive uses. An example would be a farm with an irrigation system. Only the water used for consumptive or household use would need be disinfected. To determine the critical flow rate for disinfection purposes, an estimate of the total fixture demand could be used. Table 7 lists the flows of various fixtures that were determined in a survey of 8 farmsteads (60).

Table 7. Average and maximum flow rates for individual fixtures and water using appliances

Fixture or appliance	Average demand, gpm	Maximum demand, gpm
Kitchen sink	2.8	4.8
Lavoratory	2.6	5.5
Toilet	3.1	4.8
Tub	3.2	5.7
Shower	2.6	5.0
Automatic washer	3.6	4.6
Washer	2.3	3.3
Hydrant	5.2	13.0
Sill cock	3.8	5.0
Automatic livestock waterer	1.7	3.1

The worst possible flow condition would be the sum of the maximum rates of all fixtures and appliances provided they did not exceed the pump capacity.

It is common on many farmsteads to superchlorinate all water entering the distribution system and dechlorinate only water that is used for drinking and culinary purposes at the kitchen sink. Even if this procedure is practiced, adequate chlorine contact time should be provided to insure disinfection of all water utilized. There are some small water supplies that would not exceed rates of flow greater than 3 to 4 gpm, e.g.; a source of drinking water on an isolated Army firing range. To illustrate water usage in a small water supply having a single outlet, records of the flow at the kitchen sinks of two residences were analyzed. These data were taken from Chart-A-Meter recorders installed in the cold water lines to the kitchen sinks. Table 8 indicates the averages and ranges of certain use characteristics which were determined from 30 days records at each residence. It is evident from the wide range in values, that water use of this type is not consistent from day to day. The maximum values of flow rate and duration would apply in the design of a chlorine contact vessel for similar systems of this type.

It should be pointed out that, in the design of chlorination systems for individual water supplies, demand cannot be

Table 8. Summary of cold water sink usage for two residences

Item	Average	Range
Daily uses	34	10-76
Maximum usage rate	3.8 gpm	1.4-5.25 gpm
Gpcd	3.52 gal	1.3-9.4 gal
Largest daily use	2.47 gal	0.45-13.2 gal
Gal per use	0.39 gal	0.07-13.2 gal
Duration of each use	0.9 min	0.1-15 min

considered constant. Daily, monthly and seasonal variations are evident. Per capita usage for eight residences was obtained from daily water meter readings. These data are summarized in Table 9. These figures indicate that heavy uses occur on different days of the week for the eight residences. Some families apparently wash on Mondays; others wash more than once each week. In some cases, the heaviest uses occurred on the weekends. Such demand may result from car washing, lawn watering and general cleaning. In the design of small water supplies, daily consumption is directly associated with the size of the storage reservoir. If the reservoir is also to serve as a chlorine contact tank, the retention efficiency must be compatable with the critical rate of flow. Specifically, if the storage tank is to hold a given percentage of the average daily flow, it must be designed so

Table 9. Daily per capita water usage for eight residences

Residence	Number of people		Weeks of records	Day of week							Weekly mean
	Adults	Children		Sun	Mon	Tues	Wed	Thurs	Fri	Sat	
1	2	2	8	65.2	62.5	43.8	66.9	55.6	62.0	59.6	59.5
2	2	2	6	24.3	43.4	40.3	32.6	29.1	40.3	42.9	36.1
3	2	2	1	33.7	35.5	21.0	42.0	39.2	69.2	35.5	39.5
4	2	3	2	55.0	33.3	39.2	38.3	36.0	51.2	40.8	42.0
5	2	2	6	39.6	38.6	40.3	41.7	48.3	35.1	48.3	41.3
6	2	2	1	46.1	19.5	30.0	--	22.2	41.2	33.0	27.4
7	12	2	2	31.0	37.0	37.6	33.8	39.3	39.4	33.7	36.7
8	5	0	2	37.0	58.0	24.8	37.6	35.0	34.3	52.1	41.4
Mean values				41.3	41.0	35.9	42.4	33.7	46.6	43.2	40.5

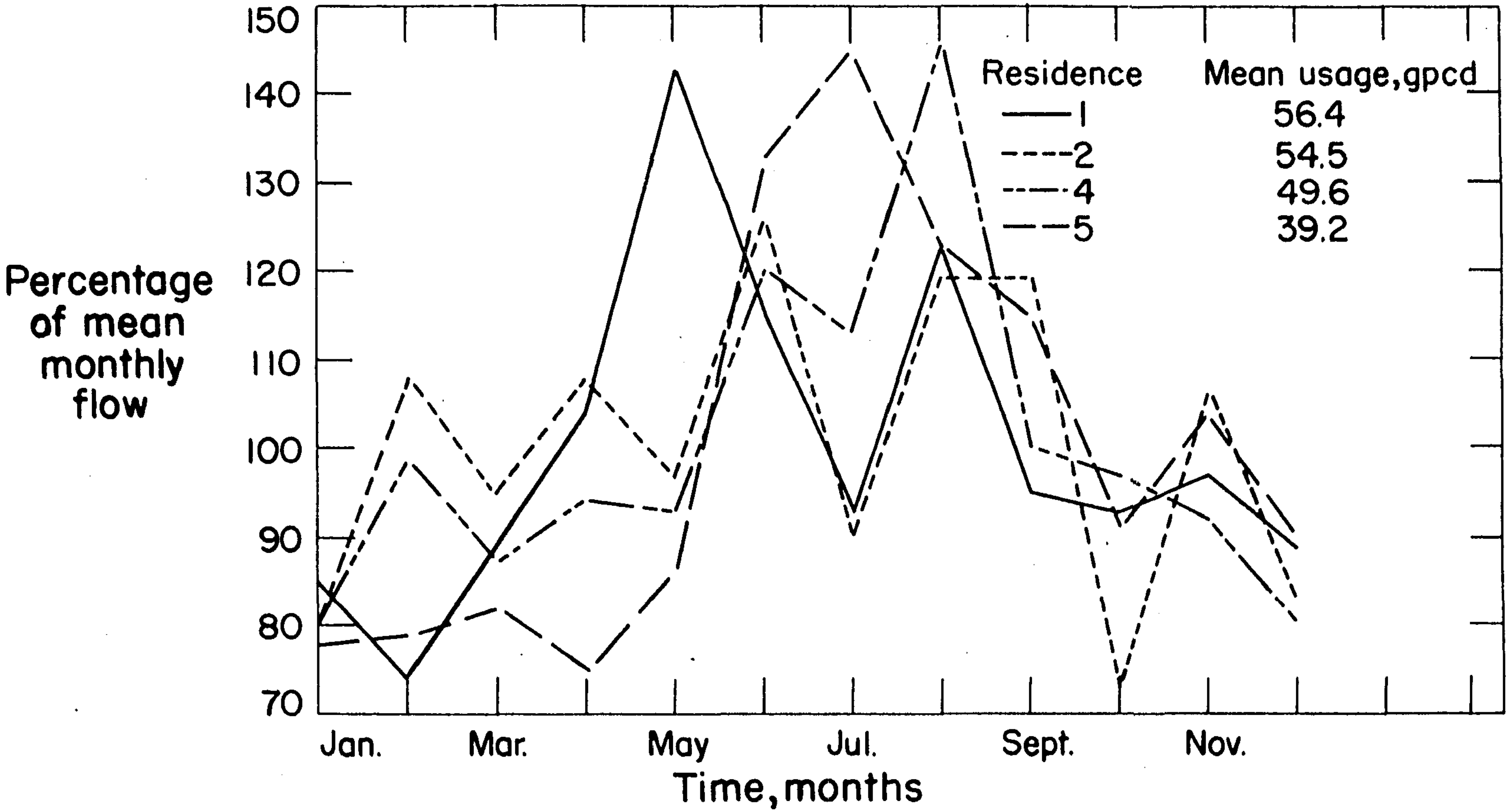
that under continuous heavy flows, all of the water receives adequate time of contact with chlorine.

Seasonal variations in consumption should also be considered in small water supplies. Peak demands for most homes will occur during the warmer months. In warmer climates, the variation may be negligible. Figure 19 shows the variations in monthly flow in four residences in Ames, Iowa. The data for this plot were obtained from the city records. In these homes, peak consumption occurs between May and August. It would be during periods such as this that maximum daily flow also occurs. During the summer months when the flow is greatest, the bacteria concentration in the raw water is apt to be high. This may not be the case with some underground supplies in which there is little annual change in water temperature.

Methods of obtaining chlorine contact time

The efficiency with which a tank or vessel provides chlorine contact time may be defined as the ratio of the actual or observed retention time divided by the theoretical retention time. Previous studies have been conducted to determine the chlorine retention efficiency of various components of small water systems and specially designed contact tanks (2, 4, 39). This research, in which organic dye and coliform tracers were used, produced reliable retention efficiencies that may be

Figure 19. Variation in mean monthly water usage for four homes in Ames, Iowa, 1954-1960


Percentage of mean monthly flow
150
140
130
120
110
100
90
80
70
Jan.
Mar.
May
Jul.
Sept.
Nov.
Time, months
Residence
Mean usage, gpcd
1 56.4
2 54.5
4 49.6
5 39.2

applied to the design of disinfecting systems for individual water supplies. It was shown that chlorine contact time efficiency in pressure tanks and unmodified, full-flowing storage tanks is negligible. In pressure tanks, immediate thorough mixing occurred; while short circuiting in the unmodified storage tanks resulted in ineffective chlorine retention time. High efficiencies 75 to 85 percent, can be obtained in distribution pipes. However, due to the limited amount of pipe in most individual water supplies, only short retention times are available even with low flow rates.

Four types of systems were found to be able to provide adequate chlorine contact time: (1) coiled pipes, (2) gravel-filled storage tanks, (3) shell-in-shell storage tanks, and (4) prechlorinated sand filters. First probable trace efficiencies for these systems are listed in Table 10. These efficiencies are based on the first probable occurrence of an organism in the contact vessel effluent. They were determined from statistical computations of the results of tests using dye as a tracer. The use of first probable trace efficiencies provides a more conservative value than can be achieved using bacteria tracers. To compute the minimum chlorine contact time in a vessel at a specific rate of flow, the first probable trace efficiency is multiplied by the theoretical retention time.

Table 10. Typical first probable trace efficiencies in four types of chlorine contact systems (4)

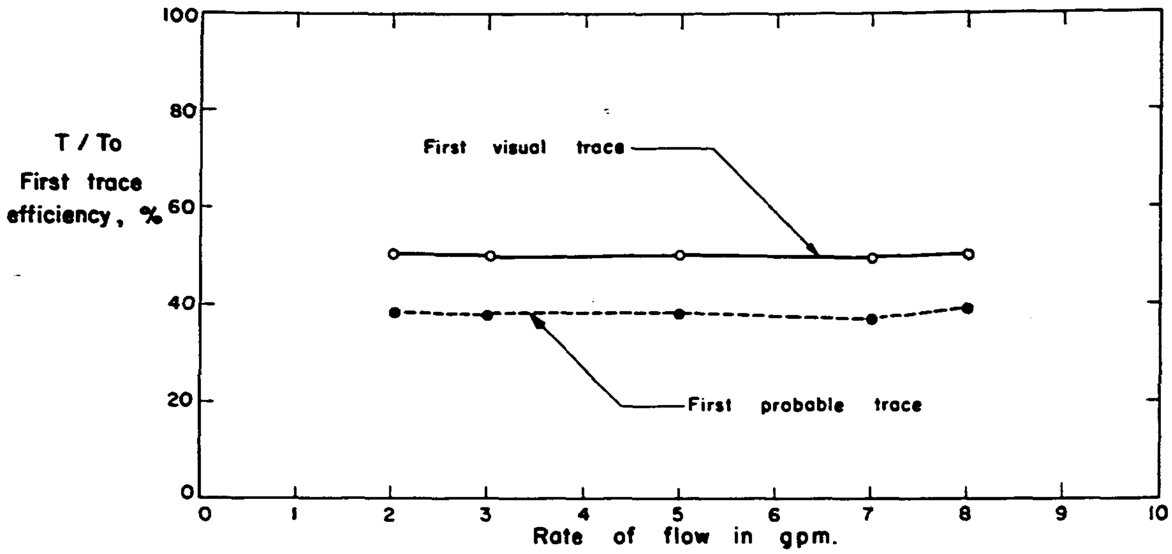
Type of system	Rate of flow	First probable trace efficiency, percent
Coiled pipe .75-2.00 in. dia.	8 gpm	75
Gravel-filled storage tank porosity 0.45, effective size 0.2 in.	8 gpm	38
Shell-in-shell	8 gpm	43
Prechlorinated slow sand filter	2 gpm/sq ft	70

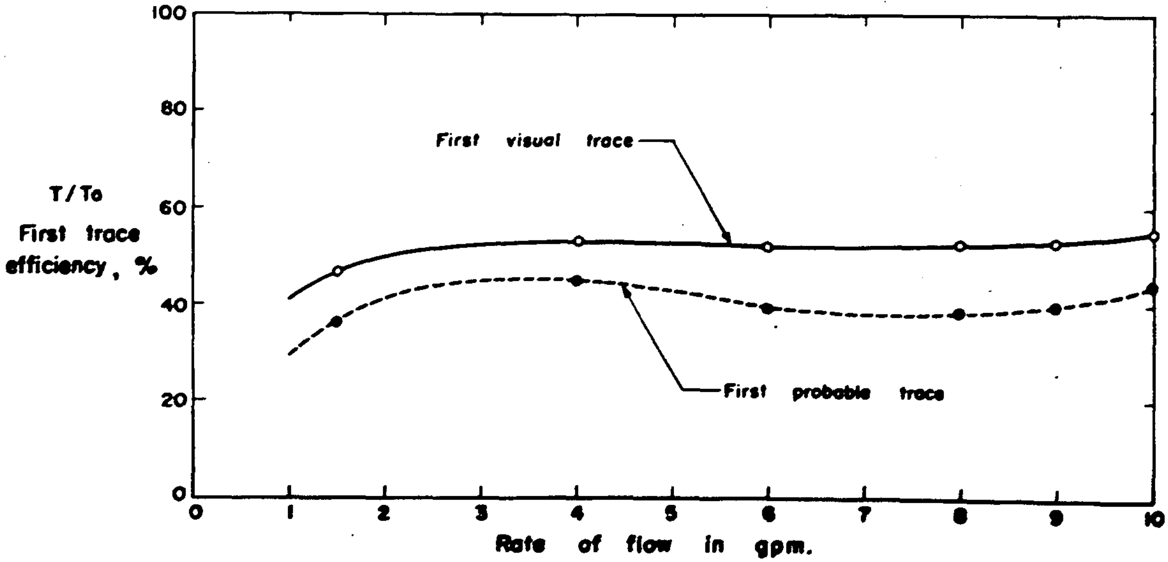
Detention-time efficiencies vary with the rate of flow. Depending on the type of system, the efficiency may either increase or decrease at lower flow rates. Figures 20 and 21 indicate first trace efficiencies for an 82-gal gravel-filled tank and a 115-gal shell-in-shell tank. In the range from 2 to 8 gpm, the gravel filled tank exhibits a fairly consistent first probable trace efficiency of approximately 38 percent. With the shell-in-shell tank, the efficiency increases to a maximum at 4 gpm and then falls to a minimum at 7 gpm. For this reason, a chlorine retention tank should be tested at several rates of flow to rate its efficiency.

In this study, chlorine retention tests were conducted with a 42-gal gravel filled tank using bacteria tracers. The

Figure 20. First trace efficiencies with 82-gal gravel filled chlorine contact tank

Figure 21. First trace efficiencies with 115 gal shell-in-shell chlorine contact tank

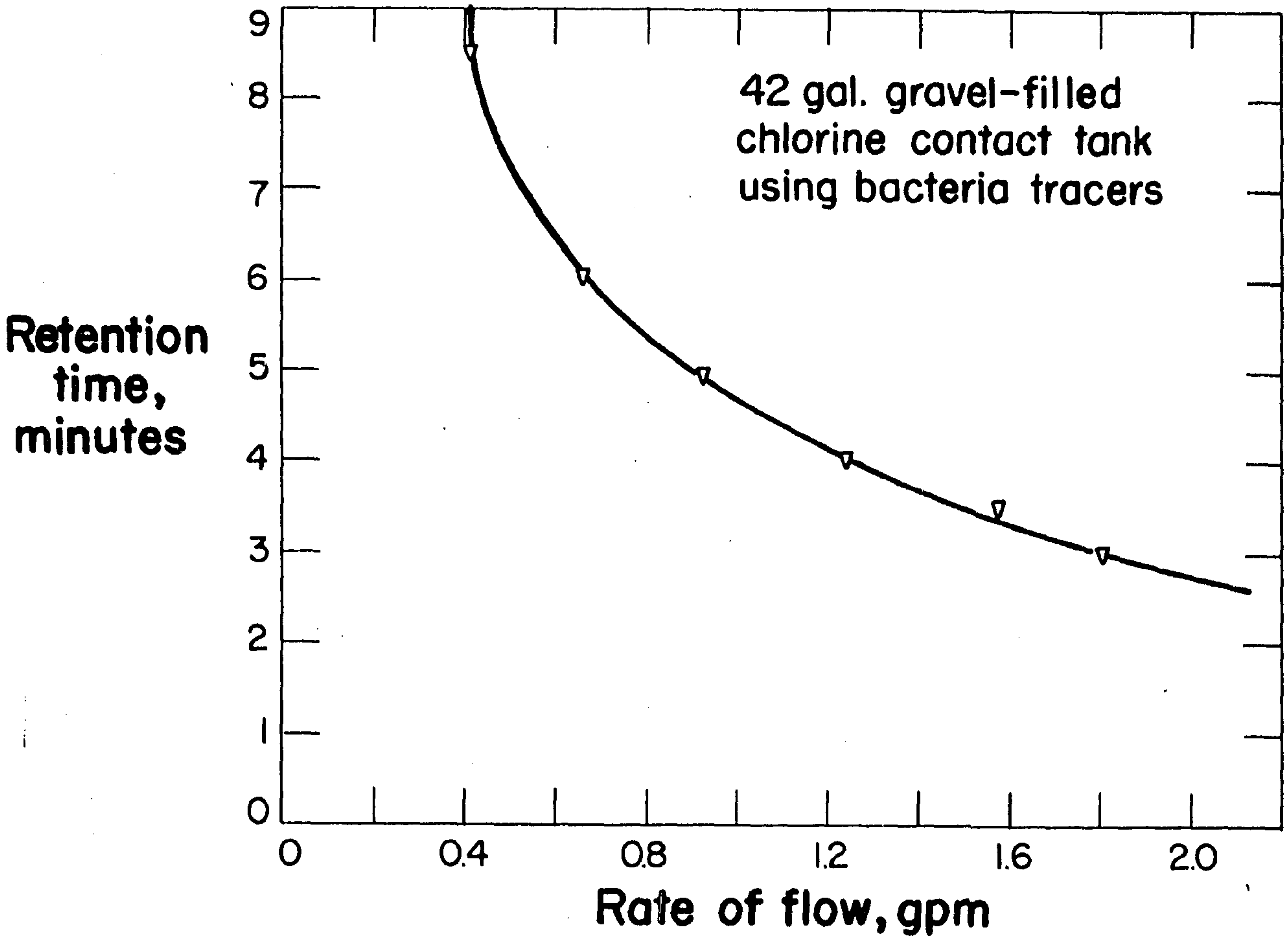

T / To
First trace
efficiency, %
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
Rate of flow in gpm.
First visual trace
First probable trace


T / To
First trace
efficiency, %
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
Rate of flow in gpm.
First visual trace
First probable trace

gravel had a porosity of 0.425 and an effective size of 0.1 in. The first trace time was determined by the first sample to show the presence of the tracer organism on nutrient agar. A plot of the effective retention time versus rate of flow is shown in Figure 22. With this tank it is apparent that the retention time decreases as the flow rate increases in the interval from 0.4 to 2.0 gpm. The tank efficiency increases, however, with increase in flow rate. At a continuous flow rate of 1 gpm, the effective retention time would be about 4.5 min. At 2 gpm, this time would be reduced to 2.7 min. It is evident that a tank of this size would only be able to furnish adequate contact times in systems with low flow rates. Examples of the system in which it might prove applicable would be an isolated continuous flowing drinking fountain, cattle waterer or any individual water supply system having a pump capacity of 2 gpm or less.

The superchlorination-dechlorination system was tested to determine its efficiency in destroying certain bacteria at a chlorine residual of 5 mg/1 and 7 min contact time. In this test the shell-in-shell tank was used to provide retention time. With dye tests, this tank was found to have a first probable trace retention time of 6.0 min at a flow rate of 8.33 gpm. Using bacteria tracers, the first trace was at 7 min. The flow rate of 8.33 gpm is the pump capacity recommended by the National Fire Protection Association for new

Figure 22. Flow rate *versus* retention time in 42-gal gravel filled chlorine contact tank using bacteria tracers


42 gal. gravel-filled chlorine contact tank using bacteria tracers
Retention time, minutes
0
1
2
3
4
5
6
7
8
9
0
0.4
0.8
1.2
1.6
2.0
Rate of flow, gpm

systems (40). This was selected as a typical critical flow rate in individual water supply systems. The combination of 5 mg/l FAC and 7 min contact time falls on the uppermost envelope Ct = 35 in Figure 16. It was desired to see if several of the tracer organisms were more resistant to chlorine than the viruses upon which the equation Ct = 35 is based.

With the system flowing at the critical rate and the chlorine residual at 5 mg/l, bacteria solution was injected into the simulated well at the pump intake (A, Figure 7). Samples were taken at the contact tank and carbon filter effluent after 7 min. Table 11 indicates that the three organisms tested were all resistant to disinfection with chlorine and could not be completely killed in 7 min at 5 mg/l FAC. The pH and water temperature during these tests varied from 7.3 to 7.4 and 11.5 to 12°C respectively. These results serve to show that even using the recommended chlorine residuals and contact time given in Tables 4 and 5, a sterile product does not result. These represent the more resistant bacteria that we do not attempt to destroy.

A test run was conducted with the superchlorination-dechlorination system to determine the amount of time required to bring the system to the desired FAC residual. With the system operating at a flow rate of 8.25 gpm and zero chlorine residual, the chlorine doser was allowed to begin feeding.

Table 11. Results of tests with superchlorination-dechlorination system using chlorine resistant bacteria

Organism	Bacteria/ml in simulated well at T = 0 min	Bacteria/ml in detention tank effluent at T = 7 min	Bacteria/ml in carbon filter effluent at T = 7 min
S. aureus	390	8	0
S. albus	108	2	1
B. megatherium	465	34	0

Periodic examinations of the contact tank effluent indicated that the equilibrium residual of 5 mg/l was not reached until 30 min after the beginning of chlorine injection. This means that the chlorine contact tank should be brought to the desired FAC residual before water is consumed from the system. During actual operation, the chlorine supply could become exhausted without the owner's knowledge. Upon the addition of a new chlorine supply, sufficient water should be run to waste to insure that a FAC residual exists in the effluent.

The following are examples of how small water supply systems may be designed using the FAC residuals and contact times recommended in this study: Consider a shallow well source in which it is planned to install a pump having a capacity of 6 gpm. The ground water is not expected to become colder than 4°C at any time. The pH of the water varies from 7.3 to 7.8

Using the equation Ct = 20 from Table 4 for pH 7.5 to 8 and 0^{o} to $5^{o}C$, any combination of FAC and contact time that is equal to 20 may be used. If it is desired to maintain a FAC residual of 10 mg/l, then a contact time of 2 min should be provided. A gravel filled tank should be able to provide this time. Using the value of 38 percent first probable trace efficiency for the 82-gal tank (Figure 20), the contact time would be computed as follows:

$$\frac{82 \text{ gal} \times 0.43 \text{ (porosity)}}{6 \text{ gpm (critical rate)}} \times 0.38 = 2.24 \text{ min}$$

Therefore, this tank would be satisfactory.

If a FAC residual of 2 mg/l is desired, then a larger or more efficient retention tank would be needed to furnish the necessary 10 min contact time. A shell-in-shell tank may be applicable. At 6 gpm, a first probable trace efficiency of 40 percent is given for the shell-in-shell tank used in this study (Figure 21). The contact time provided would be:

$$\frac{115 \text{ gal} \times .40}{6 \text{ gpm}} = 7.65 \text{ min}$$

Thus, this tank would not provide 10 min chlorine retention time at the critical rate of 6 gpm. Raising the chlorine residual to 3 mg/l would require 6.67 min contact time and the shell-in-shell tank would suffice.

If the water source is a farm pond, a sand filter may be required for turbidity removal. Consider a pond water which has an expected low temperature of 10°C and a maximum expected pH of 9. The equation Ct = 22 from Table 5 could be applied in this case. If prechlorination of the sand filter influent was practiced, chlorine contact time could be obtained during filtration. In slow sand filters long contact times would be available. At 100 gpd/sq ft, water flowing through a sand bed of 24 in. depth, the contact time would be about 56 min.

Porosity = 0.375

Chlorine retention efficiency = 0.7

100 gpd/sq ft = 0.0695 gpm/sq ft

$$\frac{\text{Volume}}{\text{rate}} = \frac{1\text{ sq ft} \times 2\text{ ft} \times 0.375 \times 7.48\text{ gal/cu ft} \times 0.7}{0.0695} = 56.4\text{ min}$$

Therefore, with long detention time available, a lower residual may be utilized in this example. Substituting 56 min in the equation Ct = 22, results in a residual of 0.4 mg/l FAC.

A rapid sand filter will afford less chlorine contact time. At 2 gpm/sq ft with a predicted retention efficiency of 0.7, the effective contact time in a rapid sand filter 30 in. deep would be about 2.5 min.

$$\frac{1\text{ sq ft} \times 2.5\text{ ft} \times 0.375 \times 7.48 \times 0.7}{2\text{ gpm}} = 2.45\text{ min}$$

With this filter, a residual of 9 mg/l would be necessary.

Slow Sand Filter Runs with Prechlorinated Water

In all tests conducted with the slow sand filters, the rate of flow was maintained at 100 gpd/sq ft. This rate corresponds to 4.356 mgad which is double that used on most municipal slow sand filters. This rate was selected since there is a current trend to operate at higher filter rates, and to save time, it was desired to reduce the lengths of filter runs.

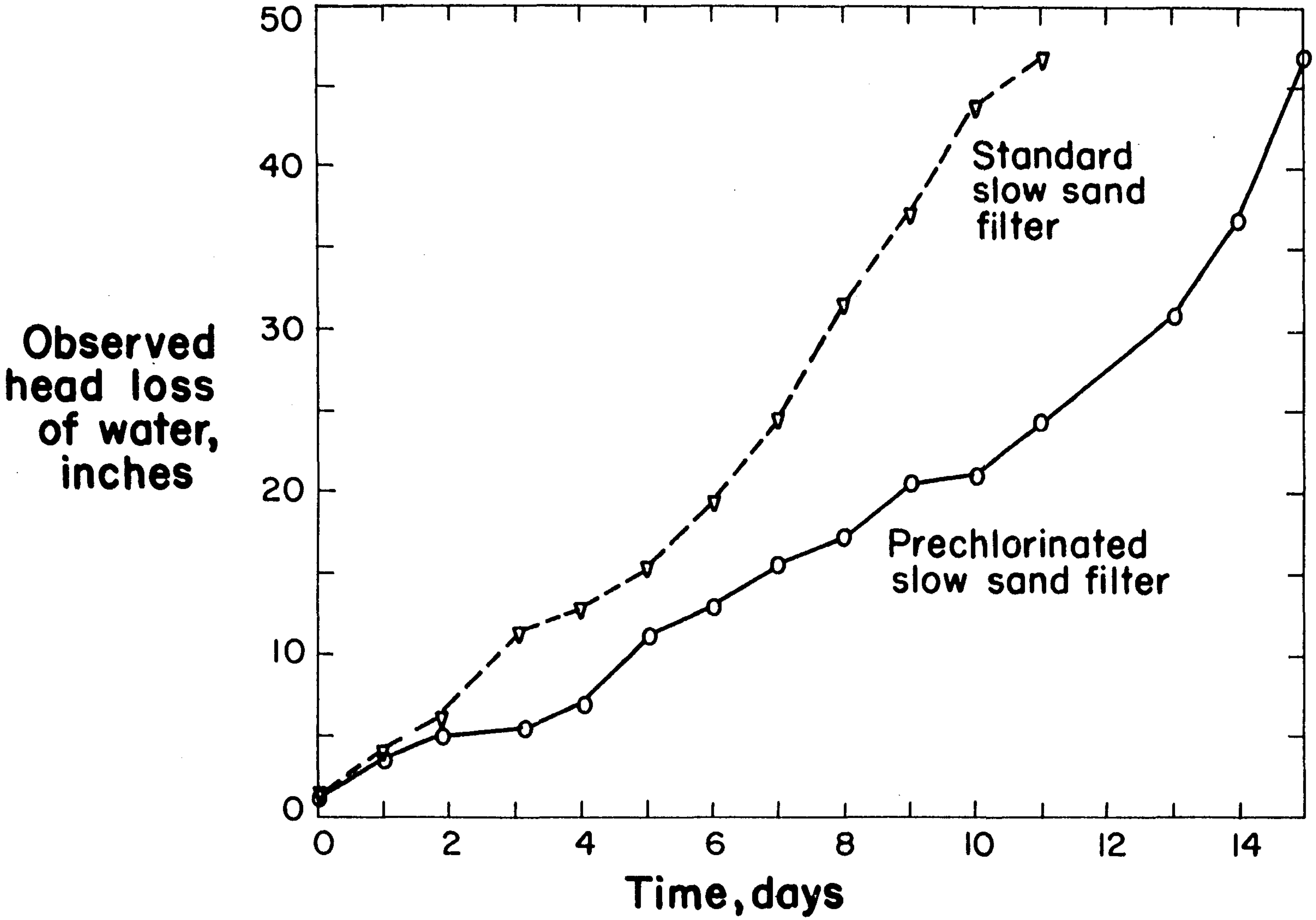
Head loss

During Run I, raw creek water was fed directly to both slow sand filters. Chlorine solution was fed to one filter to provide a FAC residual of 10 mg/l. During the run, the creek turbidity was at a level of 35 units or more, and consequently a rapid buildup in head loss resulted. Water temperature varied from 67°F to 97°F. FAC on the test filter averaged 8.8 mg/l with a low and high of 6 and 12 mg/l respectively.

Both filters were operated to a terminal head loss of 47 inches. As shown in Figure 23, the prechlorinated unit filtered for 15 days as compared with 11 days for the standard slow sand filter. For this run, the use of prechlorination provided an increase in length of run and volume of filtrate per run of 36.4 percent.

As a consequence of the short run with the turbid raw water, all succeeding runs were conducted using water pretreated with the roughing filter. During Run II, with an average

Figure 23. Head loss *versus* time in operation for prechlorinated and standard slow sand filters, Run I

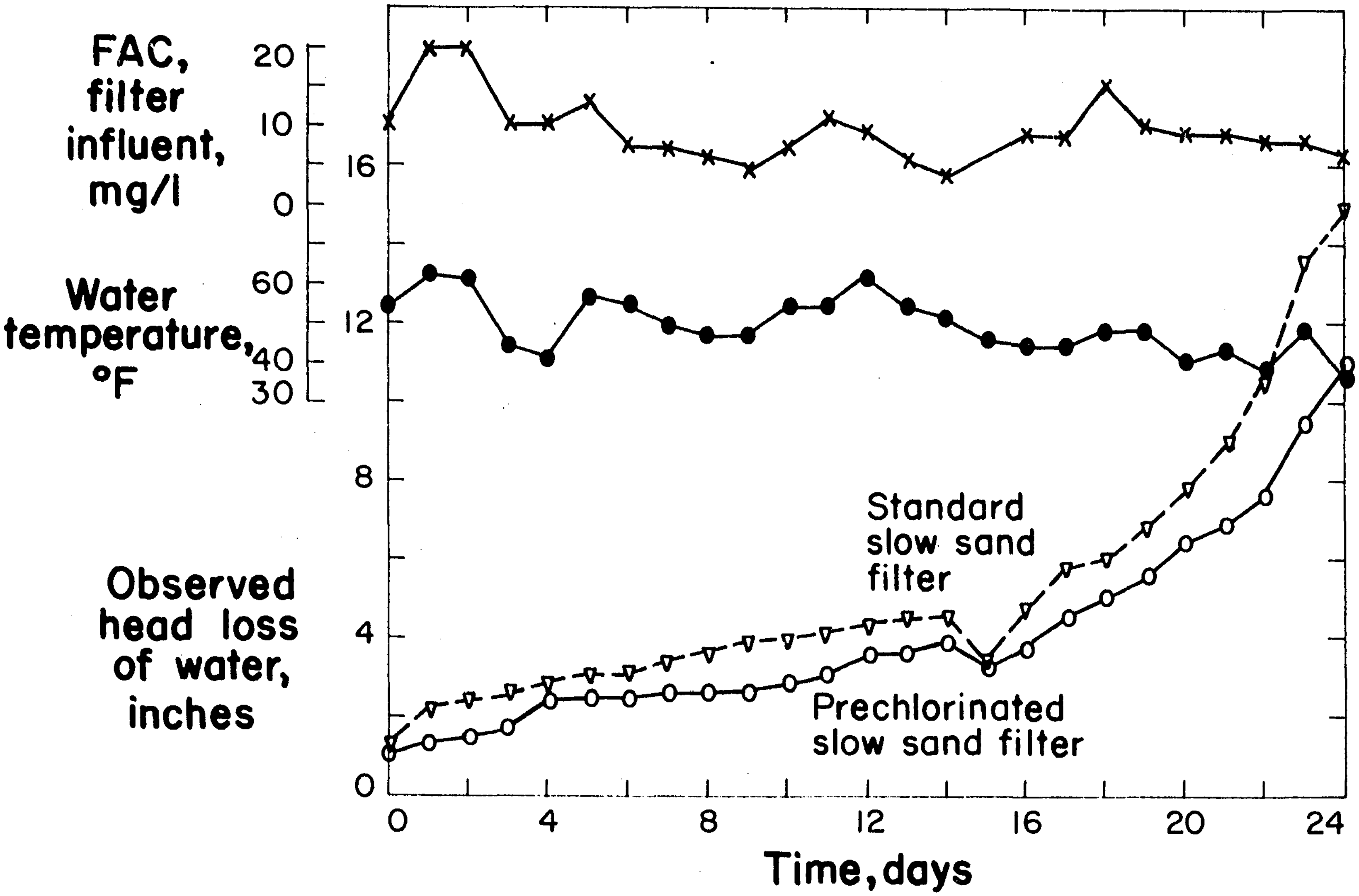


Observed head loss of water, inches
0
10
20
30
40
50
0
2
4
6
8
10
12
14
Time, days
Standard slow sand filter
Prechlorinated slow sand filter

turbidity of 20.5 units fed to the filters, much slower rates of head loss increase resulted. Figure 24 reveals only a slight difference in the rate of buildup of head loss for the two filters. At the end of the run, the prechlorinated filter registered a head loss of 10.9 inches while the standard filter had reached 14.9 inches. The filter run had to be terminated after 24 days when the creek intake became clogged during a storm. At this point, only about one-fourth of the total available head loss had developed. A comparison of the plot of head loss versus time for Run II, Figure 24, with a similar plot in Figure 2, shows that Run II compares favorably with the early stages of head loss buildup on a prechlorinated municipal slow sand filter.

During Run III, the prechlorinated filter reached a head loss of 27.6 inches after 37 days of operation. In this run, the chlorine dosage rate was set in an attempt to maintain a FAC residual of 5 mg/1 on the filter. Based upon the head loss buildup for runs II and III, it is estimated that this filter could have been operated for 60 to 90 days of filtration at a rate of 100 gpd/sq ft before reaching the limiting head loss of 50 inches. The exact length of run would, of course, be dependent on variations in temperature, organic concentration in the influent and turbidity. Under actual conditions in small water supplies, slow sand filters such as this would operate intermittantly, and runs from four to six

Figure 24. Head loss *versus* time in operation for prechlorinated and standard slow sand filters, Run II


FAC, filter influent, mg/l
20
10
0
Water temperature, °F
60
40
30
Observed head loss of water, inches
16
12
8
4
0
Standard slow sand filter
Prechlorinated slow sand filter
0
4
8
12
16
20
24
Time, days

months could be expected.

Inspection of the variations in the FAC residual and water temperature in Figure 24 indicates that the chlorine residual is, in general, a function of the water temperature. This correlation must be considered as being due to the dependence of chlorine flow through the capillary feeder on temperature in the filter building. Higher temperatures caused increased pressure in the carboy and thus increased the rate of flow. A variation in temperature would affect the degree of ionization, but it would have no effect on the amount of FAC. Since a uniform chlorine residual could not be maintained on the filter throughout these tests, it is concluded that in the prechlorination of slow sand filters in small water supplies, capillary feeding is not reliable. With intermittent operation, addition of chlorine should be made when water is being drawn.

In tests on municipal filters (33), a decrease in head loss was noted when the chlorine dose was significantly increased. During Run III, this condition was shown to result on the small slow sand filters. A heavy dose of chlorine was applied to the filter on two occasions for 24 hours. After six days of operation, (Table 12) a FAC residual of 68 mg/l caused a reduction in head loss from 2.9 to 2.0 inches. Likewise, a decrease from 20.5 to 9.5 inches was observed when

Table 12. The effect on head loss of heavily increasing the dose of chlorine on a prechlorinated slow sand filter, Run III

Days in operation	FAC residual on filter, mg/l	Head loss, inches
1	7.2	3.4
2	3.9	3.45
3	1.0	3.5
4	0.7	3.0
5	--	2.9
6	68	2.0
7	7.4	3.25
9	4.0	3.6
10	2.5	4.0
17	6.7	6.1
20	4.7	7.0
24	--	17.0
27	9.2	20.5
31	>25	9.5
32	--	12.5
37	4.2	27.6

the residual was increased to greater than 25 mg/l after 31 days operation. This phenomenon is probably the result of either one or both of two causes. First, a significant increase in the HOCl concentration may have resulted in more rapid oxidation of normally slowly reacting organic compounds that had been previously deposited in the filter and surface cake. If this action occurred, reduction in the size of the particles would have enlarged the pores and permitted the water to flow more freely. Secondly, reduction in head loss may have been the result of electrokinetic effects (53).

One theory proposes that chlorine causes a change in the negative charge believed to be characteristic of bacteria. Dead bacteria cells held in the interstices by electrostatic attraction would then be released and washed through the filter. Although such action may take place, it would probably have little significance since the accumulation of other matter in the filter is neglected. With respect to the deliberate addition of excess chlorine to the filter in this experiment, it is believed that an increase in the oxidation rate of organic matter is most effective in decreasing the head loss, while electrokinetic effects may play a less important role.

Turbidity removal

Measurements of the turbidities of the influent and effluent water from both slow sand filters were made during Run II (Table 13). The raw water turbidities on each filter were similar. This is to be expected since the samples were taken near the surface where the raw water entered. Undoubtedly, if

Table 13. Comparison of influent and effluent turbidity measurements on prechlorinated and standard slow sand filters, Run II (Units of turbidity)

Days in operation	Prechlorinated filter Influent	Prechlorinated filter Effluent	Standard filter Influent	Standard filter Effluent
1	32	4	32	4
2	22	5.1	22	9.5
3	12	2.0	12	2.0
4	20	2.1	20	2.75
5	13	1.0	55	1.5
6	16	1.25	16	2.0
7	26	2.0	26	4.0
8	15	1.75	15	3.5
9	15	1.2	15	1.75
10	50	2.7	43	3.5
11	12	---	14	---
12	10.5	1.25	10	1.4
13	11	1.8	11	1.5
14	11	2.0	10	1.5
15	73	2.75	73	2.5
16	21	2.3	30	2.3
17	14	3.0	14	2.5
18	11	1.75	11	1.75
19	14	1.0	14	1.2
20	9.9	1.1	11.5	1.2
21	15.0	1.5	15	1.5
22	13.6	1.25	13.6	1.25
23	13.5	1.75	9.0	1.75
24	11.0	1.5	11.0	1.5
25	8.5	2.75	8.5	1.5
Average	18.8	2.04	20.5	2.41

the samples had been taken at lower depths, lower turbidities on the prechlorinated filter would have been evident due to the oxidizing and coagulating effects of the chlorine. Even though the roughing filter was in operation during this run, the data indicates that on the 15th day the raw water turbidity on both filters rose to a level of 73 units. On this day the creek became very muddy during a heavy rain and the roughing filter could not filter at approximately 2 gpm/sq ft for 24 hours without passing a large amount of turbidity.

The average effluent turbidity from the prechlorinated filter was 2.04 units compared with 2.41 units from the control filter. For this run, prechlorination reduced the effluent turbidity by 15.4 percent. Although excellent turbidity removal was obtained from the standard slow sand filter, prechlorination was effective in producing an even clearer water.

During Run IV the turbidity removal efficiency of the roughing filter was studied. This unit, though designed only to reduce the turbidity load to the slow sand filters for these tests, showed that its use would be applicable to small water supply systems for a similar purpose. Turbidity measurements on the roughing filter were recorded on only 7 days during the run; however, they are sufficient to indicate the general range of turbidity reduction. Table 14 shows that the average influent and effluent turbidities were 33.6 and 19.4 units respectively. This corresponds to an average reduction of 42.3 percent. A similar filter with a greater depth of sand would probably be able to maintain an influent to slow sand filters of between 10 and 20 units of turbidity. More adequate backwashing, which was not possible with the pumps used in these tests, would increase the efficiency of such a unit.

Table 14. Turbidity reduction with roughing filter, Run IV (Units of turbidity)

Days in operation	Influent	Effluent	Reduction, percent
1	55	35	36.4
2	20	13.5	32.5
5	32	14	56.3
6	25	12	52
7	32	18	43.8
9	33	22	33.3
10	42	25	40.5
11	30	16	46.6
Average	33.6	19.4	42.3

Analyses of the solids removed in both the roughing filter and the prechlorinated slow sand filter were made during Run IV (Tables 15 and 16).

In the roughing filter, the fixed and volatile solids reductions averaged 9.9 and 3.3 percent respectively. The average total solids reduction was 7.9 percent. Since only suspended solids were removed in this filter, these data indicate that about 25 percent of the suspended solids were comprised of organic matter. The roughing filter, therefore, aided in lowering the organic load on the slow sand filter. A device of this type would be effective in reducing the chlorine demand in a prechlorinated filter which treats polluted water such as was used in these tests.

With the prechlorinated slow sand filter (Table 16), the average total solids reduction was 4.1 percent. Since nearly all of the turbidity was removed in the filtering process, the reduction consisted primarily of suspended solids. With no biological life present in the filter to utilize organic matter, the volatile dissolved solids apparently combined with chlorine and passed with the effluent. Although insufficient data were taken with the standard filter to show that biological life will materially reduce the dissolved organic matter, it is believed that this is the case. Bacteria in a slow sand filter utilize suspended and dissolved organic solids for

Table 15. Solids reduction with roughing filter, Run IV

Days in operation	Total solids mg/l Infl.	Total solids mg/l Effl.	Total solids mg/l Percent reduction	Fixed solids, mg/l Infl.	Fixed solids, mg/l Effl.	Fixed solids, mg/l Percent reduction	Volatile solids, mg/l Infl.	Volatile solids, mg/l Effl.	Volatile solids, mg/l Percent reduction
2	504	441	12.5	346	289	16.5	158	152	3.8
3	534	472	11.6	298	283	5.0	236	189	19.9
4	506	472	4.2	313	275	12.1	193	210	-8.8
6	479	462	3.6	368	352	4.4	111	110	1.0
7	589	518	12.0	340	280	17.7	249	238	4.4
9	597	555	7.0	405	373	7.9	192	182	5.2
10	577	485	16.0	402	307	23.6	175	178	-1.7
11	496	477	3.8	263	258	1.9	233	219	6.0
Average	476	433	7.9	304	269	9.9	172	164	3.3

Table 16. Solids reduction with prechlorinated slow sand filter, Run IV

Days in operation	Total solids, mg/l Infl.	Effl.	Percent reduction	Fixed solids, mg/l Infl.	Effl.	Percent reduction	Volatile solids, mg/l Infl.	Effl.	Percent reduction
2	441	452	-2.0	289	291	-0.7	152	161	-5.9
3	472	457	3.2	283	263	7.1	189	194	-2.6
4	485	459	5.4	275	256	6.9	210	203	3.3
5	471	471	0.0	307	334	-8.8	164	137	16.5
6	462	449	2.8	352	343	2.6	110	106	3.6
7	518	471	9.1	280	266	5.0	238	205	13.9
9	555	489	16.9	373	301	19.3	182	188	-3.3
10	485	487	-4.4	307	308	-3.3	178	179	-0.6
11	477	445	6.7	258	238	7.8	219	207	5.5
Average	485	464	4.1	303	289	4.3	182	176	3.4

nourishment and reproduction. With prechlorination, the only dissolved organic reduction that can be expected depends on the rate at which oxidation by the chlorine takes place. During the estimated 2 hours duration of the filtration process, it is doubtful that chlorine has sufficient time to cause a significant amount of oxidation. From the solids data obtained from this run, it is concluded that there is negligible reduction of dissolved organic matter in a prechlorinated slow sand filter. In small water supplies, a filter of this type would not run continuously as was the case in this run. Intermittent operation and overnight rest periods would possibly result in a larger reduction of organic solids.

Bacteria reduction

Slow sand filters generally are considered to provide a reduction in bacteria of about 98 to 99 percent. This high bacterial removal efficiency is attributed primarily to the formation of a zoogleal layer on the sand surface. During the first few days of a run with a cleaned filter, these high efficiencies do not result. Once this film is formed, it is believed that bacteria and other organic matter are utilized for food by the organisms comprising the film. Multiplication of the zoogleal organisms renders the film slimy or sticky and thus increases its straining capability.

When a disinfectant such as chlorine is added to the influent to a slow sand filter, saprophytic bacteria are unable to survive, and the film or mat of living organisms cannot exist. If the bacteria removal efficiency of a slow sand filter is based on the presence of coliforms in the effluent of slow sand filters operating at a rate of 50 gpd/sq ft, then we could expect 100 percent kill under the same conditions if prechlorination is practiced. During Run II with the slow sand filter, samples were taken for bacteriological analysis to permit a comparison of the operation of prechlorinated and normally operated slow sand filters with regard to bacteria removal efficiency. In addition to the standard coliform tests, a comparison was also made on the basis of total bacteria by means of the standard plate count. Since the rate of flow was maintained at twice the normal slow sand filter rate, lower than normal bacteria removal with the control filter was expected.

Coliform densities, as determined by the presumptive test using 3-tubes for each of 3 dilutions, are tabulated in Table 17. If all three dilutions gave negative results, a coliform concentration of less than 3 per 100 ml was recorded and 100 percent removal assumed. It is noted that this was the case for the prechlorinated filter effluent on all but 3 of the 25 days of the run. Chlorine concentration (FAC) on the filter on the first day was 20 mg/1, and on the 21st day a FAC residual of 9 mg/1 was recorded. It is highly improbable that coliforms could survive these concentrations. Confirmation and completion tests were not conducted. It can only be assumed, therefore, that the positive readings on these two days is attributed to the presence of spore forming bacteria which are capable of causing the fermentation of lactose broth. On the 16th day, the chlorine doser plugged and no chlorine residual existed on the filter. The low reading of 3 organisms per 100 ml indicates that an effective filter cake must have been built up to provide such a high removal. The average reduction for the prechlorinated filter was 99.98 percent compared with only 84.6 percent for the standard slow sand filter. This indicates that a heavily contaminated source, such as was used in these tests, can be treated with a prechlorinated slow sand filter to produce a water which is bacteriologically safe in accordance with the U. S. Public Health Service standard of less than 2.2 coliforms per 100 ml.

The coliform density of samples taken in Run II were also measured using the membrane filter technique. With this method, the average coliform reduction with the prechlorinated filter was 99.72 percent. For the control filter, the average reduction was 86.05 percent. Both of these averages compare closely with the MPN test results.

Table 17. Coliform removal with prechlorinated and normally operated slow sand filters, MPN method, Run II

Day	Raw water	Control filter		Prechlorinated filter		FAC residual on filter
	E. coli per 100 ml	*E. coli* per 100 ml	Percent removed	*E. coli* per 100 ml	Percent removed	
1	4300	2900	32.50	3	99.93	20.0
2	2300	1500	34.80	<3	100.00	20.0
3	2300	230	90.00	<3	100.00	10.0
4	4300	750	82.60	<3	100.00	10.0
5	4300	230	94.65	<3	100.00	13.0
6	9300	91	99.02	<3	100.00	13.0
7	360	2400	--	<3	100.00	7.7
8	2300	72	96.85	<3	100.00	7.0
9	9300	91	99.02	<3	100.00	6.0
10	>100,000	91	99.91	<3	100.00	4.6
11	9300	91	99.02	<3	100.00	7.3
12	360	91	74.70	<3	100.00	11.0
13	1500	930	38.00	<3	100.00	9.5
14	4300	2900	32.50	<3	100.00	5.7
15	$>1.1\times10^6$	230	99.98	<3	100.00	3.9
16	46,000	150	99.67	3	99.99	--
17	43,000	230	94.65	<3	100.00	9.0
18	46,000	230	99.50	<3	100.00	8.8
19	2300	430	81.30	<3	100.00	15.4
20	2000	73	96.35	<3	100.00	10.0
21	910	110	87.90	3	99.67	9.0
22	4300	3	100.00	<3	100.00	9.1
23	15,000	73	99.51	<3	100.00	8.2
24	1500	73	95.13	<3	100.00	8.0
25	7500	3	100.00	<3	100.00	6.7
Average removal			84.6		99.98	

Even with the maintenance of high chlorine residuals on the filter during this run, many bacteria were found to survive the disinfecting treatment. Standard plate counts using nutrient agar indicated an average bacterial removal of 98.85 percent for the prechlorinated filter (Table 18). Those bacteria surviving were identified from growths on the agar plates as belonging to the order Actinomycetaleae and the family Bacillaceae. Since organisms such as these survive superchlorination residuals between 4 and 20 mg/l with a contact time of 2 hours, it is evident that even if we establish a very stringent level of chlorination, a sterile water will not result.

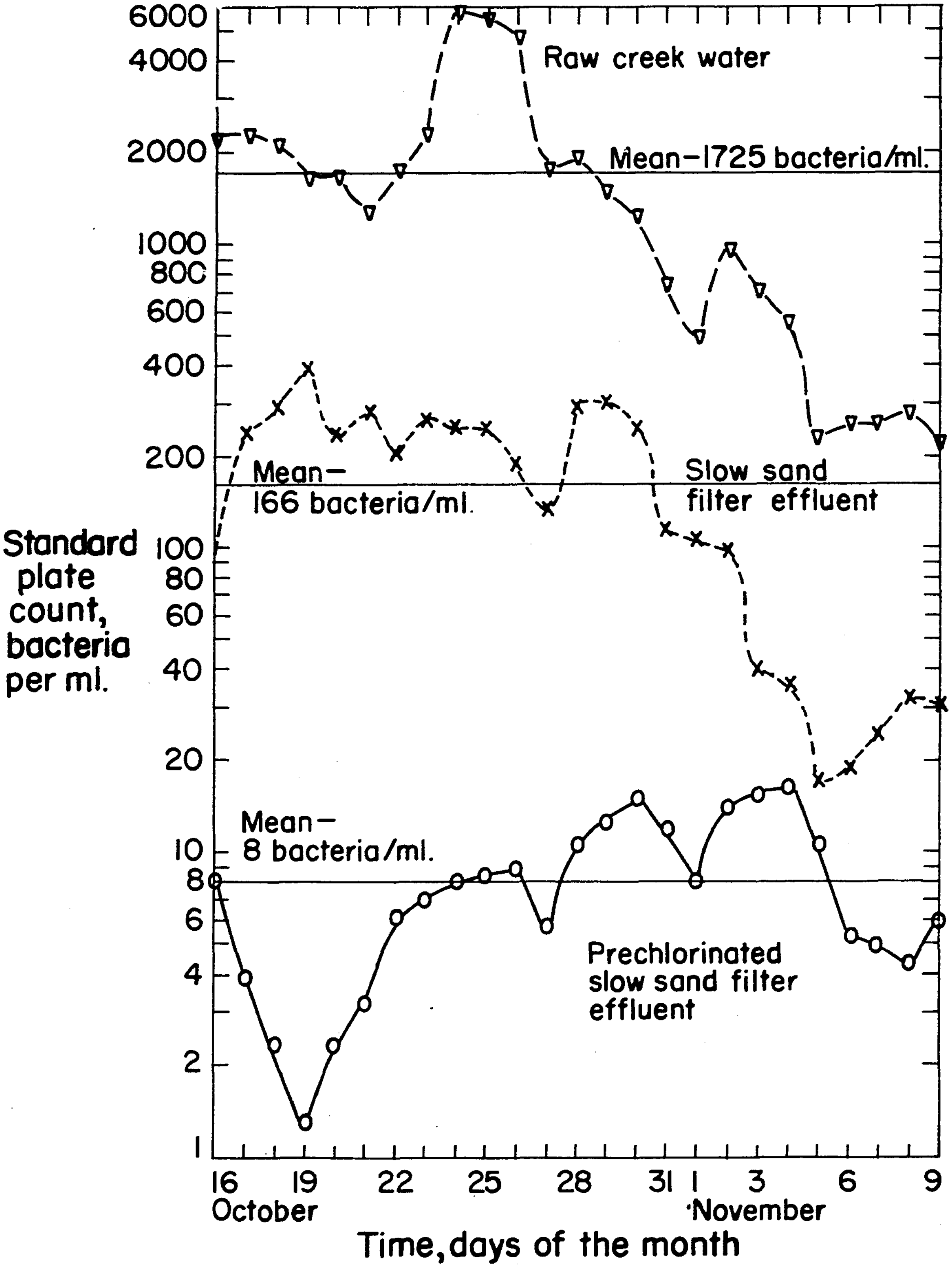
The data in Table 18 are plotted in Figure 25 to give a graphical picture of the bacterial removal efficiency of the two filters. These points were plotted using 3-day moving average bacteria counts. The mean count of 166 bacteria per ml for the standard slow sand filter effluent is about twenty times that for the prechlorinated filter. Post chlorination of this water would probably reduce this level to that obtained in the prechlorinated system effluent. However, this would require a reservoir that would provide contact time of about two hr. Small storage reservoirs have been shown to be ineffective in this respect (2).

Further bacteriological studies with the prechlorinated slow sand filter were made during Run III. In these tests,

Table 18. Bacterial removal with prechlorinated and normally operated slow sand filters, standard plate count, Run II

Day	Raw water bacteria/ml	Control filter		Prechlorinated filter	
		Bacteria/ml	Percent removal	bacteria/ml	Percent removal
1	2200	88	99.6	8	99.67
2	3060	148	93.15	3	99.02
3	1565	480	96.93	1	99.93
4	1725	238	86.20	3	99.83
5	1780	420	76.40	0	100.00
6	1580	34	97.85	4	99.75
7	470	375	20.20	-	---
8	3295	194	94.12	8	99.76
9	3275	217	93.37	7	99.79
10	10,800	330	96.94	9	99.91
11	2060	189	90.82	9	99.56
12	1800	32	98.22	8	99.56
13	1470	178	87.90	0	100.00
14	2405	654	82.80	24	99.00
15	570	65	88.60	14	97.54
16	610	74	87.90	6	99.01
17	1010	200	80.20	15	98.52
18	850	41	95.17	3	99.65
19	1030	50	95.14	24	99.67
20	180	26	85.55	19	89.50
21	390	16	95.90	7	98.20
22	100	10	90.00	-	--
23	280	30	89.30	4	98.57
24	420	36	91.42	6	98.57
25	210	30	85.17	3	98.57
Average	1725	166	84.21	8	98.85

Figure 25. Comparison of bacteria removal in prechlorinated and normally operated slow sand filters, Run II


Standard plate count, bacteria per ml.
6000
4000
2000
1000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
Raw creek water
Mean–1725 bacteria/ml.
Mean–
166 bacteria/ml.
Slow sand filter effluent
Mean–
8 bacteria/ml.
Prechlorinated slow sand filter effluent
16
19
22
25
28
31
1
3
6
9
October
November
Time, days of the month

the filter effluent was dechlorinated with a precoat carbon filter. The water temperature during this run varied from 34 to 47°F, and much lower bacterial concentrations were recorced. Table 19 shows that on several occasions higher bacterial concentrations occurred in the carbon filter effluent than in the sand filter effluent. Since the carbon filter used in this run was sterilized in an autoclave prior to use, multiplication of the chlorine resistant bacteria must have occurred in the carbon filter.

This explanation appears likely since the carbon medium having very fine pores could collect some of the bacteria. Highly resistant bacteria, such as bacillus, could possibly multiply in such an environment. If highly resistant bacteria can multiply in chlorine concentrations as shown in Table 19, then moderately resistant organisms would be likely to reproduce in the presence of lower chlorine residuals. This factor makes it appear that in small water supplies treating surface waters that normally contain a multitude of organisms, superchlorination is a necessity.

Chlorine reduction through a slow sand filter

In the construction of the prechlorinated slow sand filter, sampling faucets were installed at equidistant intervals from the sand surface to the underdrainage. Sampling at these points

Table 19. Concentration of bacteria at various stages of treatment in a small water supply system using a prechlorinated slow sand filter and dechlorination, standard plate count, Run III

Day	Raw water bacteria/ml	Prechlorination filter effluent bacteria/ml	Carbon filter effluent bacteria/ml	Infl. FAC* mg/l	Effl. FAC** mg/l
1	120	2	0.5	7.2	5.2
2	94	5	5	3.9	1.7
3	74	1	0.5	1.0	0.5
4	44	6	9	0.65	0.3
5	57	0	4	1.2	0.7
6	82	0	3	68.0	110.0
7	21	0.5	11	7.4	5.7
9	21	1	3	4.0	2.4
10	66	2	0	2.5	2.4
20	51	1	1	4.7	5.7
24	30	1	17	--	4.1
27	27	2	4	9.2	8.4
32	44	3	0.5	25	--
37	50	0	2	4.2	2.3
Average	70	1.8	4.3		

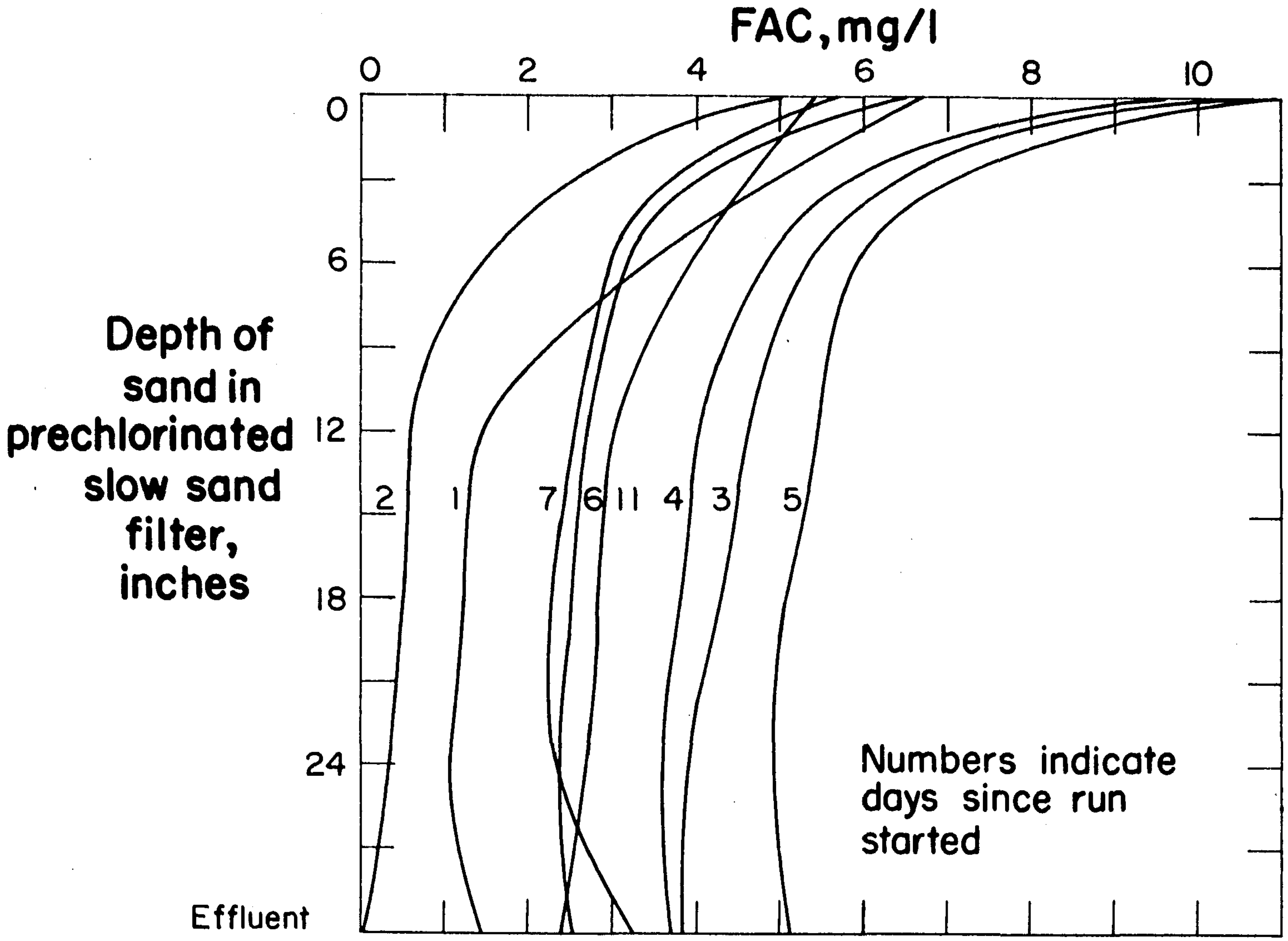
*Chlorine residual in sand filter influent

**Chlorine residual in sand filter effluent provided data concerning the chlorine concentration throughout the filtering process. During Run II, it was noticed that the filter effluent FAC concentration would vary from 23 to 100 percent of the concentration at top of the filter. Obviously oxidation occurs during the theoretical 120 min that it takes for the chlorinated water to flow through the 30 in. of sand. The chlorine demand is expected to result principally from matter embedded in the upper reaches of the sand. The correlation between this demand and depth of filter bed is shown in Figure 26. From this plot, it can be seen that the greatest demand is in the first 12 in. below the sand surface. In most cases, the major reduction occurred between the surface and the 6-in. level. Below the 12-in. level, all of the curves appear to approach a uniform slope of small chlorine demand.

Although sampling was not possible in the first 6 in. of the sand, it is apparent from the shape of the curves, that the highest demand occurs in the surface cake and in the first few inches. This is to be expected since the majority of the matter and bacteria will settle on the surface and only the smaller particles will penetrate below. Chlorine demand through the remainder of the sand bed would result from the oxidation of dissolved or colloidal organic matter.

In an attempt to correlate the chlorine demand through the prechlorinated filter with the other factors involved, such

Figure 26. Free available chlorine versus depth in a prechlorinated slow sand filter, Run IV


FAC, mg/l
0
2
4
6
8
10
Depth of sand in prechlorinated slow sand filter, inches
0
6
12
18
24
Effluent
2
1
7
6
11
4
3
5
Numbers indicate days since run started

variables as nitrate, nitrite and ammonia nitrogen, volatile and fixed solids, turbidity and BOD were compared. None of these showed sufficient correlation to explain the daily variation in demand through the filter. From the plot in Figure 27, it is apparent that aging of the filter has some effect on the amount of chlorine removed. Curves 34 and 37 were plotted from data in Run III. As the length of the filter run increases, less chlorine was removed in the filter. During the early stage of a run, chlorine demand occurred deeper in the filter bed due to the penetration of solid matter. With the building of a surface cake, less and less suspended matter penetrated below the 6-in. level. This indicates that a shallower sand bed, perhaps 18 to 24 in., could be utilized. Apparently the decrease in chlorine demand with time results from the increased concentration of oxidizable material at the filter surface due to the buildup of a surface mat. At the start of a run, there is some chlorine demand in the sand bed itself. Once this demand has been satisfied and a filter cake is formed, oxidation is confined to the surface where higher FAC residuals exist.

Table 20 summarizes the average chlorine reduction between the surface and filter effluent for the four runs with the prechlorinated slow sand filter.

Figure 27. Percentage of free available chlorine on top of filter *versus* depth in a prechlorinated slow sand filter, Runs III and IV

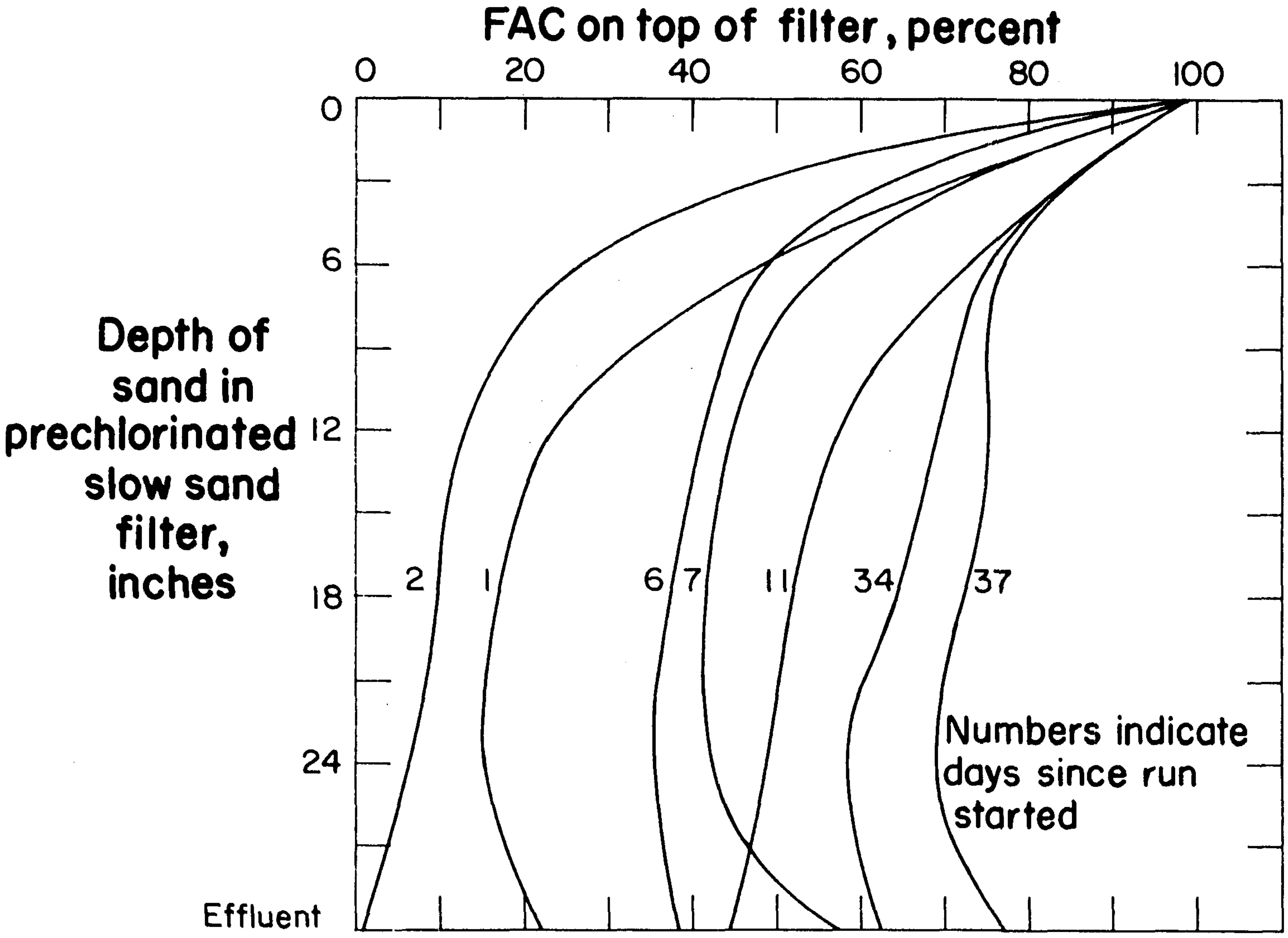

FAC on top of filter, percent
0
20
40
60
80
100
0
6
12
18
24
Effluent
Depth of sand in prechlorinated slow sand filter, inches
2
1
6
7
11
34
37
Numbers indicate days since run started

Table 20. Average chlorine reduction through prechlorinated slow sand filter, Runs I-IV

Run	Length days	Average chlorine reduction, percent
I	17	44.7
II	25	34.2
III	37	30.8
IV	11	51.7

Since these runs were much shorter than would be expected in actual operation with this type of filter, extrapolation is not in order. However, even with long runs, the effluent chlorine concentration should not approach that of the influent as long as there is chlorine demand in the water. In summary, it can be concluded that in these runs, as the length of filter run increased, the percentage of initial influent chlorine residual in the effluent also increased. Thus, the system becomes safer since we are more assured of continued disinfection in the storage tank and distribution system.

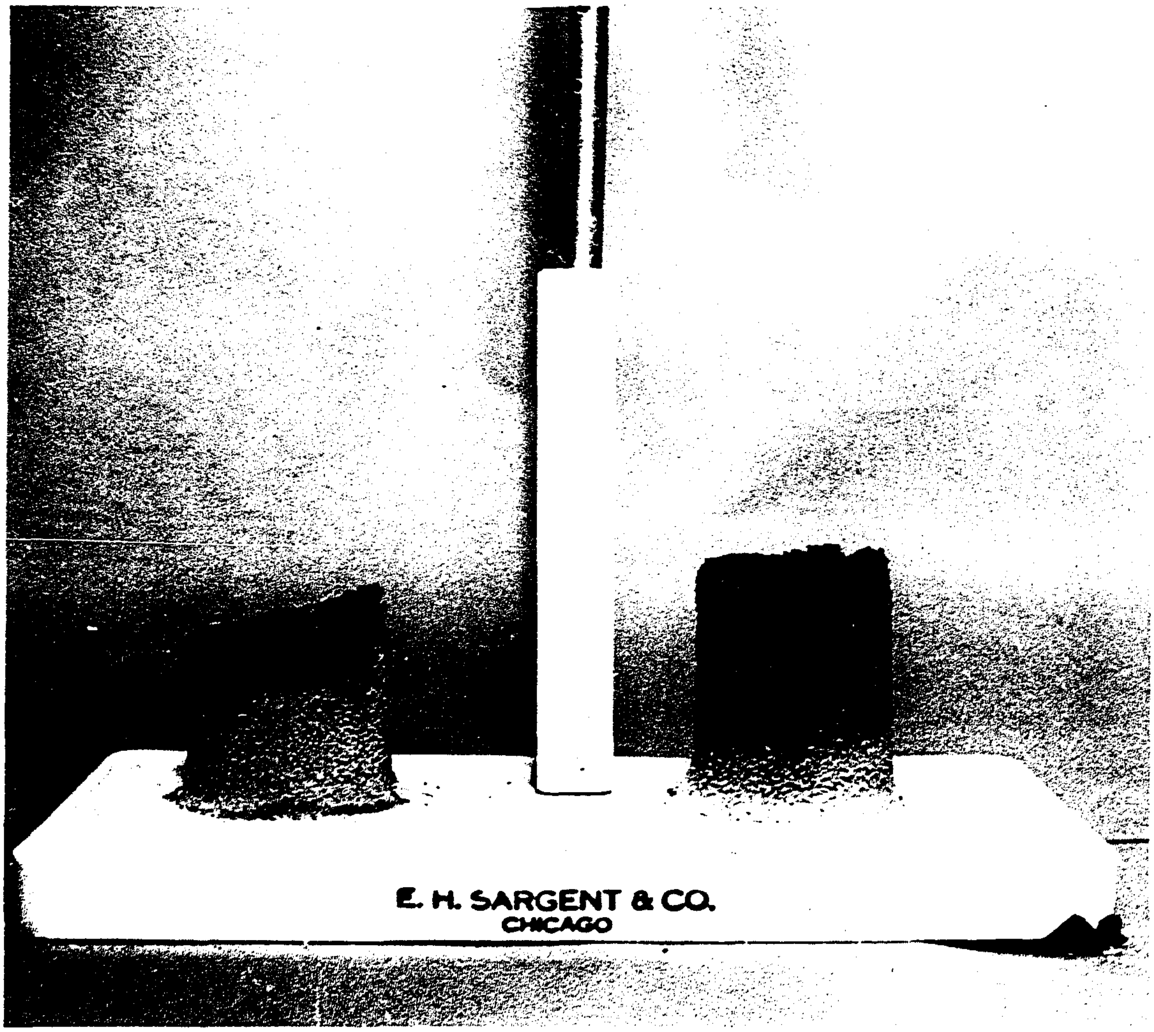
Filter cake and penetration of suspended solids into sand

After each of the four runs with the slow sand filters, samples of the upper 3 in. of sand were compared. The muddy cakes on both the prechlorinated and standard slow sand filter appeared identical upon visual inspection. The thickness of these chocolate brown cakes varied from 1/16 to 1/8 of an in.

depending on the length of a run. Underneath, the dark brown color faded as the depth increased. With the standard slow sand filter, penetration extended usually to a depth of 2 to $2\frac{1}{2}$ inches where the sand turned tan in color. Occasional probing of the sand during scraping indicated that this tan color existed as far down as 1 ft below the surface before the sand showed its original whiteness. Samples from the prechlorinated filter showed the penetration of brown matter only as deep as $\frac{1}{2}$ to 1 in. below the filter cake. Below this level there existed a rapid color transition to clear white sand. These results were comparable to those obtained with prechlorinated municipal sand filters after long runs (33). Since short runs at double the normal rate of filtration were conducted in these experiments, it is expected that deeper penetration on both filters would occur with long filter runs. A comparison of the depth of penetration between two samples from the prechlorinated sand filter are shown in Figure 28. The sample on the right indicates the penetration of silty matter after the filter had been in operation for 11 days during a period when the creek was turbid. The sample on the left was taken under similar conditions after only two days of filtering.

Scrapings from the filter cakes were diluted in a drop of distilled water and examined with a microscope. Different conditions were observed to exist on the surfaces of the two filters. The standard slow sand filter cake contained motile

Figure 28. Sand samples taken from the surface of prechlorinated slow sand filter (Sample on left shows filter cake and depth of penetration of solid matter after 2 days of filtering. Sample on right, taken after 12 days of filtration, indicates penetration of 2 in.)


E. H. SARGENT & CO.
CHICAGO

plankton entwined in a dark fibrous surrounding. Large portions of the sand particle surfaces were coated with a dark brown to black mucus. A completely different picture existed with samples from the prechlorinated filter. No living organism were visible. Numerous dead diatoms lay among sharply defined particles of various shades of black and brown. The sand particles were particularly clean. These observations indicate that the expected high degree of oxidation of biological life occurred in the filter cake of the prechlorinated filter, whereas biological action aided filtration in the standard filter.

The explanation for longer filter runs with prechlorinated slow sand filters can be attributed largely to the filter cake. Filtration theory explains that filters with porous compressible surface mats results in an increasing rate of head loss with time. This condition exists with both prechlorinated and normally operated slow sand filter as is exhibited in Figures 2, 20 and 21. Therefore, if the filter cake controls the rate of head loss increase, we must attribute the increase in run length to oxidation by chlorine of organic matter in this porous mat. With higher rates of oxidation, slower build up of head loss will result.

Five samples of the filter cake on each filter were analyzed for organic composition during Run IV. Table 21 reveals that the prechlorinated filter cake contained an average of

10.86 percent volatile solids compared with 14.18 percent for the standard filter. The difference of 3.32 percent represents a 23.2 percent decrease in organic matter in the prechlorinated filter for this run. In actual operation, the difference will vary in accordance with the type and growth of organic matter in the raw water, the chlorine residual and the rate of flow. These data are significant in that they reveal that all organic matter is not completely oxidized on the surface on the prechlorinated filter, but that continued oxidation of slowly reacting proteinacous material may be taking place.

Table 21. Percentage of fixed and volatile solids in the filter cake of prechlorinated and normally operated slow sand filters, Run IV

	Prechlorinated filter		Standard filter	
Sample no.	Fixed solids percent	Volatile solids percent	Fixed solids percent	Volatile solids percent
1	88.85	11.45	85.96	14.04
2	89.05	10.95	85.90	14.10
3	89.20	10.80	85.60	14.32
4	88.93	11.07	85.69	14.31
5	89.68	10.32	85.85	14.15
Average	89.14	10.86	85.82	14.18

Changes in organic matter

In the process of filtering superchlorinated water, changes in some of the organic constituents can be expected. During Run IV, examinations of total, nitrate, nitrite and ammonia nitrogen were conducted with the prechlorinated filter to determine if these changes could be of significance in actual systems.

A decrease in the total nitrogen content is to be expected due to the formation of organic chloro additives and substitution products. The percentage reduction will vary from day to day as a function of the raw water. This variation is exhibited in the Kjeldahl nitrogen data in Table 22.

Table 22. Results of Kjeldahl nitrogen tests with prechlorinated slow sand filter, Run IV, mg/l

Day	Top of filter	Filter effluent	Carbon filter effluent
1	0.56	0.63	0.0
5	1.54	1.41	0.99
6	0.56	0.56	0.42
7	1.22	0.94	0.24
9	0.7	0.28	0.28
10	0.63	0.35	0.0
11	1.83	0.85	0.57
Average	1.01	0.72	0.36

Only small changes are noted during the beginning of the run. This may be the result of organic matter left on the filter bed from a previous run. After the 6th day, reduction is significant. It is apparent also from this data that the carbon filter is efficient in reducing the organic nitrogen content during dechlorination.

Nitrites and nitrates often pose problems in small water supplies. Natural nitrification or contamination by drainage from cultivated fields can raise the concentration of these two compounds to the toxic level. Nitrites, 10 to 15 times as toxic as nitrates, may be converted to nitrates in the presence of chlorine. Nitrates are unaffected. Whether prechlorinated slow sand filtration would be effective in reducing either nitrites or nitrates would depend on whether nitrates would be removed in the process. This is doubtful.

Table 23 shows the nitrate and nitrite nitrogen levels during Run IV. The nitrate concentrations were fairly high, but only trace amounts of nitrite nitrogen were found in the creek water. The absence of nitrite nitrogen in all of the filter effluent samples certainly indicates that oxidation was complete in the time that it took the water to flow through the filter. A comparison of the averages indicates an increase of about 12 percent between the filter influent and effluent. The small quantities of nitrites that were lost would

Table 23. Results of nitrite and nitrate tests with prechlorinated slow sand filter, Run IV

		Nitrite Nitrogen (mg/l)			
Day	Raw water	Prechlorinated influent	Filter effluent	Carbon filtered	Standard filter effluent
1	0.05	0.0	0.0	0.0	0.0
2	0.0	0.02	0.0	0.02	0.04
3	0.04	0.02	0.0	--	0.04
4	0.05	0.04	0.0	0.0	0.02
5	0.02	0.0	0.0	0.0	0.0
6	0.08	0.03	0.0	0.0	0.09
7	0.07	0.0	0.0	0.0	0.07
9	0.04	0.04	0.0	0.0	0.01
10	0.01	0.06	0.0	0.02	--
11	0.09	0.0	0.0	0.0	--
Mean	0.05	0.2	0.0	0.004	0.03
		Nitrate nitrogen (mg/l)			
1	6.2	5.85	5.85	6.0	6.3
2	9.5	4.45	8.95	9.5	5.6
3	12.6	16.2	13.7	15.5	14.8
4	8.5	9.5	9.5	10.0	5.4
5	8.5	8.95	9.0	10.0	9.0
6	7.4	6.1	9.5	5.4	8.5
8	4.45	4.7	6.1	4.1	3.75
9	4.3	4.45	3.35	3.75	3.15
10	7.75	8.5	10.0	9.5	--
11	6.85	7.75	8.95	5.85	--
Mean	7.61	7.63	8.49	7.96	7.06
Percent of raw	100	100.3	111.9	104.5	92.8

not have produced an increase such as this. It is apparent from these data, that in general, nitrate nitrogen was not reduced with the prechlorinated filter. On the other hand, the average nitrate nitrogen in the control filter effluent was lower than that of the raw water. In view of these results, a prechlorinated slow sand filter cannot be expected to cause a reduction in nitrates. There is, however, a production of nitrates during the process of filtration from the conversion of nitrites and from the oxidation of chloramines.

Ammonia nitrogen reacts quickly with chlorine to form chloramine and nitrogen trichloride. Whether monochloramine, dichloramine, nitrogen trichloride or a combination of these forms exists will depend on the pH of the water and the chlorine concentration. Over a period of time, all of these combined forms of chlorine can be expected to decompose yielding nitrogen gas. Thus, during the process of filtration in a prechlorinated slow sand filter, we might expect a reduction in the initial ammonia concentration. During Run IV, the raw water pH varied from 7.2 to 8.2 with the majority of the readings near 8. Free residual chlorine ranged from 5.0 to 10.5 mg/l. Table 24 indicates the ammonia nitrogen concentrations at separate stages of the chlorination-filtration-dechlorination process.

It will be noted that radical changes exist between the raw water and end product ammonia concentration. This may be attributed to one of two possible causes. Between the time water enters the filter and the time it flows from the reservoir a minimum of 2 hours elapse. If the ammonia nitrogen concentrate in the creek varied sufficiently during the day, the filter influent and effluent concentration may also be expected to fluctuate. In addition, samples at the carbon filter were taken after pumping from the reservoir at 1 gpm for 5 min. At this rate of flow, higher or lower ammonia concentrations may have come from dead spots in the reservoir. This data, therefore, does not indicate whether ammonia nitrogen is reduced in the process of filtration.

Table 24. Results of ammonia nitrogen tests with prechlorinated slow sand filter, Run IV

Day	Raw water, mg/l	Filter effluent, mg/l	Carbon filter effluent, mg/l
2	0.0	0.0	0.23
3	0.24	0.05	0.0
4	0.25	0.08	0.32
7	0.2	0.0	0.2
9	0.02	0.0	0.0
10	0.23	0.0	0.8
11	0.08	0.05	0.14
Average	0.11	0.03	0.24

The ammonia nitrogen content in the prechlorinated slow sand filter effluent was nearly zero in all tests. This should be so since ammonia does not remain uncombined in the presence of excess chlorine. The three results that did indicate the presence of ammonia were attributed to the interference of chloramines with the Nessler's reagents used in the test.

Upon dechlorination, combined chlorine is removed from organic compounds resulting in the formation of CO_2 and NH_3. This supports the hypothesized reactions previously discussed in the section on the chemistry of water chlorination. Considering the high FAC residuals maintained in these tests, it is presumed that all of the ammonia detected in the carbon filter effluent resulted from the reduction of nitrogen trichloride. It is apparent that in superchlorination-dechlorination systems treating water with a high ammonia nitrogen content that ammonia odors may be present in the dechlorinated product.

Tastes and odors

Samples of the filtered effluents in the reservoir were checked daily for tastes and odors. At no time during 90 days of operation did any of the prechlorinated slow sand filtered water appear to be other than satisfactory. The treated water was sparkling clear and had a natural taste. Only the slight chlorinous odor was perceptible.

On the other hand, water treated with the standard slow sand filter was unfit for consumption on many occasions. A grayish, bubbly film covered the surface in the reservoir and fishy or earthy odors prevailed. During Runs II and III a gasoline or oil slick remained on the surfaces of this filter and its reservoir.

SUMMARY

For many years we have been classifying waters as potable or non-potable on the basis of the presumptive coliform test. In so doing, we consider that a water is safe for consumption if coliforms and organism of similar, or less, resistance to disinfection are destroyed. This standard has sufficed for the treatment of large volumes of water in municipal water supplies. Adequate chlorine contact time and state health department bacteriological control are available in these large systems to insure a finished water that will meet the U. S. Public Health Service drinking water standard of less than 2.2 coliforms per 100 ml.

Most individual water supplies, on the other hand, cannot provide the necessary contact time for chlorine disinfection, nor are they periodically inspected for the presence of coliform organisms. Consequently, few individual water supplies meet the recommended drinking water standard. In view of the fact that farm ponds and wells have wide annual variations in temperature and pH, superchlorination of small water treatment systems has been recommended. Superchlorination with adequate contact time will eliminate vegetative bacterial pathogens and more resistant virus pathogens. To properly apply the practice of superchlorination in small water supplies, recommendations concerning the chlorine levels to be maintained are necessary.

Before superchlorination residuals can be recommended for specific small water supplies, we must first establish a criterion concerning the types of organisms that we desire to destroy. Bibliographical and graphical analyses show that the virus of highest known chlorine resistance is Coxsackie. Superchlorinating to destroy Coxsackie will provide destruction of all pathogenic vegetative bacteria and all of the viruses of known chlorine resistance (hepatitis and poliomyelitis). It will not, however, afford cysticidal or sporicidal disinfection. Since cysts of E. histolytica can be removed with precoat carbon filters, and most spore forming bacteria are of little sanitary significance, there is no need to apply sufficient chlorination for their destruction. The adoption of Coxsackie as the upper pathogen limit for disinfection with superchlorination was therefore recommended. In including viruses in the organisms that we desire to destroy, we are applying a factor of safety in disinfection, and we are attempting to raise the standards for a potable water in small water supplies.

With FAC time-concentration plots of various chlorine resistant organisms, lines of the equation $Ct = K$ were drawn for different ranges of temperature and pH. (C = FAC residual, t = chlorine contact time, K = a constant depending on water temperature and pH). Each of these envelope equations furnishes a combination of FAC residuals and chlorine contact times to provide for the destruction of Coxsackie virus and lesser chlorine resistant pathogenic bacteria. From the minimum expected water temperature and maximum expected pH, superchlorination based on the recommended criterion can be accomplished in any small water supply. In addition to the economic advantage of superchlorinating at a level consistent with the raw water characteristics, a choice in the length of chlorine contact time is afforded with the use of these equations.

The design of disinfection systems for small water supplies necessarily includes a determination of critical flow rates and retention efficiencies of a chlorine contact vessel. Records of the water usage in several homes were taken to furnish examples of maximum and average flow rates and volumes. A review of previous work with chlorine detention vessels was incorporated with similar tests in this study in which bacterial tracers were used. Examples were given of the procedures that may be followed in selecting a means of obtaining chlorine contact time for a specific water at a given critical flow rate.

An investigation was conducted to determine if prechlorination of slow sand filters, as a means of obtaining chlorine contact time will affect filtration efficiency. Analyses of influent and effluent turbidities, solids, chlorine residuals, nitrogen compounds and bacterial concentrations of both prechlorination and normally operated slow sand filters indicated that in most cases, prechlorination of a slow sand filter is beneficial. Little reduction in dissolved organic matter was noticed, and increases in nitrates occurred. Excellent bacteria and turbidity reductions were evidenced in the sparkling clear potable finished product. Filtering a prechlorinated water through a slow sand filter in these tests at a rate of 100 gpd/sq ft indicated that this procedure is an excellent method of treating and disinfecting a turbid well or pond water.

CONCLUSIONS

The following conclusions are drawn as a result of this study:

1. Current standards for a safely disinfected water, based on the presumptive coliform test, are inadequate for the disinfection of small water supplies.

2. We cannot economically provide sufficient chlorination in small water supplies that will yield a sterile water in all cases.

3. By superchlorinating to provide for the destruction of Coxsackie virus, we can destroy all of the viruses of known chlorine resistance and all pathogenic vegetative bacteria. It is recommended that this level of superchlorination be adopted for the disinfection of small water supplies.

4. With the use of FAC time-concentration envelope equations, $Ct = K$, superchlorination to destroy Coxsackie virus can be accomplished in any small water supply. The constant, K, is a function of the minimum water temperature and the maximum pH. These equations provide a range of FAC residuals and contact times for the design of a small water supply disinfection system. It is recommended that FAC residuals between 1 and 10 mg/1 be used.

5. Critical flow rates in small water supplies, determined with the use of recording devices, from the maximum pump

capacity, or from the maximum demand of fixtures in the system, are necessary for proper design of small water supply disinfecting systems.

6. Per capita water consumption in typical residences of families of four was found to vary between 34 and 60 gpcd. An average of 3.5 gpcd was drawn from the cold water tap in the kitchen sink.

7. Per capita water consumption varied widely from day to day in the eight homes from which data were collected. Peak monthly consumption occurred between the months of May and August for these Iowa homes.

8. Four systems were found to be able to provide adequate chlorine contact time in small water supplies: (1) coiled pipe, (2) gravel filled storage tanks, (3) shell-in-shell storage tanks, and (4) prechlorinated slow sand filters. The efficiency with which these systems provides chlorine contact time is, in general, a function of the flow rate.

9. Prechlorination of slow sand filters in small water supplies will yield longer filter runs in comparison with normally operated slow sand filters. This slower buildup of head loss is attributed to intense oxidation of organic matter on the surface of the prechlorinated filter.

10. In tests with a prechlorinated and a normally operated slow sand filter, both operating continuously at 100 gpd/sq ft, the average effluent turbidities were 2.04 and 2.41 units respectively. Prechlorination reduced the effluent turbidity

by 15.4 percent.

11. A 1.96 gpm/sq ft roughing filter, used to reduce the turbidity load on the slow sand filters in these tests, provided an average reduction in the raw water turbidity of 42 percent.

12. With continuous operation of the prechlorinated slow sand filter in these tests, negligible reduction of dissolved organic matter occurred.

13. At a flow rate of 100 gpd/sq ft, bacteria reduction, as measured by the standard plate count, averaged 98.85 and 84.21 percent for the prechlorinated and normally operated slow sand filter respectively.

14. In the early stages of a run, chlorine demand due to suspended matter extended to about 12 in. below the surface of the filter. As the length of the run increased, this demand became confined to the upper 6 in. of sand with the majority of the demand in the surface cake. Overall chlorine demand decreased with increase in run length due to the concentration of oxidizable organic matter at the sand surface.

15. Deeper penetration of suspended solids into the sand occurred with the standard slow sand filter than in the prechlorinated slow sand filter. In short runs, solids penetration in the prechlorinated filter extended only about 1 in. below the filter cake. At a filtration rate of 100 gpd/sq ft, as much as 2 to 2½ in. of sand may have to be removed during cleaning of a prechlorinated filter.

16. Approximately 10.9 percent of the solids in the surface cake of the prechlorinated filter were found to be volatile compared with 14.2 percent in the standard filter. This indicates that all organic matter is not completely oxidized on the surface of the prechlorinated filter, but that continued oxidation of slowly reacting proteinaceous material may be taking place.

17. Reduction in Kjeldahl nitrogen in the prechlorinated slow sand filter increased with age of the run.

18. In these runs, prechlorination of a slow sand filter resulted in the removal of all nitrites in the filter effluent. Small quantities of nitrites in the raw water were apparently converted to nitrates.

19. Nitrate concentration in the effluent of the prechlorinated slow sand filter showed an average increase of 12 percent. This increase is attributed to conversion on nitrites and to the oxidation of chloramines in the water.

20. Raw water ammonia nitrogen completely combined with chlorine in the prechlorinated slow sand filter to form chloramines. Upon dechlorination, ammonia nitrogen reappeared in the carbon filter effluent. This observation tends to support the equations hypothesized for dechlorination of water by precoat carbon filters.

21. During all runs conducted with the prechlorinated slow sand filter, an excellent product resulted. The treated water was sparkling clear and had a natural taste in spite of

the grossly contaminated influent water which, at times, contained phenol wastes.

22. A prechlorinated slow sand filter is an excellent method of treating turbid surface or underground water for consumption. Chlorine contact time is provided for adequate disinfection thus eliminating the necessity of a special chlorine contact vessel.

RECOMMENDATIONS

1. In the disinfection of small water supplies, we should raise our current standards and strive to destroy both vegetative pathogenic bacteria and viruses. The use of the chlorine resistance of Coxsackie virus as the design basis is recommended.

2. Superchlorination of small water supplies should be accomplished using FAC time-concentration equations of the form $Ct = K$ with FAC residuals in the range 1 to 10 mg/l.

3. Studies should be conducted to determine the resistance to chlorination of food and milk spoilage organisms which may cause contamination in small water supplies.

4. In individual water supply systems having slow sand filters for the treatment of turbid water, prechlorination should be utilized to obtain chlorine contact time.

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