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MANUAL for WASTEWATER CHLORINATION and DECHLORINATION PRACTICES

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MANUAL FOR
WASTEWATER CHLORINATION AND DECHLORINATION PRACTICES

Prepared for the State Water Resources Control Board
Under Interagency Agreement
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STATE OF CALIFORNIA

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FOREWORD

This report has been reviewed by the California State Water Resources Control Board and approved for publication. Approval does not signify that the mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

This manual was prepared to provide regulatory agencies, consulting engineers, and treatment plant operators with the urgently needed information on recommended chlorination and dechlorination practices. The principal aim of the manual is to improve wastewater disinfection and reduce residual toxicity associated with chlorination. It is expected that significant savings in chlorine will be realized by following the design and operating practices outlined herein.

The manual has been directed at chlorination systems that meter and control compressed liquid molecular chlorine. The text does not include aspects of hypochlorite or *in situ* chlorination systems. The sections on dechlorination deal primarily with compressed liquid sulfur dioxide as the dechlorinating agent.

Chlorination-dechlorination practices are subject to change and some aspects have received little study. This manual is a revision of an interim manual which was published in 1974 (6). It contains the best information available to date.

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SUMMARY OF RECOMMENDED PRACTICES

The most important considerations in the design and operation of wastewater disinfection systems using chlorine and dechlorination systems using sulfur dioxide are summarized below. This summary applies primarily to the design of new wastewater treatment and/or reclamation plants and to the upgrading of existing ones.

CHLORINATION SYSTEM

Initial Mixing—Rapid initial mixing of the chlorine solution and wastewater is essential for effective disinfection. Mixing must be accomplished within three seconds. This can be achieved by applying chlorine in a turbulent flow regime, or by a mechanical mixer. Mixing must be followed by adequate contact time in a well-designed contact tank.

Contact Time—A minimum chlorine contact time of 30 minutes at peak flow should be provided to achieve highly effective disinfection without excessive chlorine residuals. This should be measured by the first appearance of dye in the effluent from the contact tank.

Contact Tank Design—Chlorine contact tanks should be designed for maximum plug flow (i.e., equal detention for all portions of the flow) and with a minimum of backmixing, dead spaces and short-circuiting. Maximum plug flow will be provided by long, narrow conduits. The best contact tank is a pipeline or a long outfall. Rectangular tanks with longitudinal serpentine baffling are next in the order of preference. The best information currently available indicates that adequate plug flow performance is obtained when the dispersion number is 0.02 or less. This has been achieved with flow length-to-width ratios ranging from 40:1 to 70:1.

Chlorine Control System—At plants using secondary or tertiary treatment, the chlorine control system should be automatically responsive to both flow changes and chlorine demand in order to maintain a constant chlorine residual. This can be accomplished by means of effluent flow pacing and a chlorine residual analyzer. Small treatment plants should provide at least flow proportional control or equivalent.

Chlorine Residual Tests—Accurate control of chlorine residual dictates the use of the indirect (back-titration) iodometric procedure for chlorine residual measurement as outlined in "Standard Methods for the Examination of Water and Wastewater." The amperometric end point should be used in situations where trace residuals are of concern.

DECHLORINATION SYSTEM

Sulfur Dioxide Supply—Special attention must be given to the sulfur dioxide supply system because of its low vapor pressure. This requires the application of heat or the addition of an evaporator.

Sulfur Dioxide Control System—No techniques are available for controlling directly to a zero chlorine residual. There are two alternatives for control: (1) feed-forward, by means of an effluent flow signal and a chlorine residual signal measured at the end of the contact chamber; and (2) feedback residual control, by biasing the dechlorinated sample to the analyzer with an artificial chlorine dosage.

Sulfur Dioxide Monitoring System—No analytical techniques are available for monitoring sulfur dioxide residual. The proposed indirect methods are new and need further field testing. The most common method is to monitor the dechlorinated effluent intermittently on a chlorine residual analyzer.

Equipment—The equipment used for sulfur dioxide dechlorination is identical to that used for chlorination, but should not be used interchangeably with chlorination equipment. However, the control and monitoring analyzers of the same system are interchangeable.

OPERATING PERSONNEL

The performance of the chlorination-dechlorination system is dependent on competent operating personnel who are familiar with the maintenance and calibration of the control equipment. Therefore, special operator training is necessary.

RELIABILITY PROVISIONS

Chlorine Supply—The following provisions are necessary to assure uninterrupted chlorine feed: (1) Adequate reserve chlorine supply; (2) chlorine container scales; (3) a manifolded chlorine header system; (4) automatic chlorine cylinder switchover; and (5) alarm system to alert operating personnel of imminent loss of chlorine supply.

Standby Equipment—The following are necessary to assure reliable disinfection:

1. Provisions for alternate power source.

2. Provisions for a standby chlorination system if (a) only postchlorination is used; or (b) both pre- and postchlorination are used concurrently.

   The prechlorination group can be used as a standby system for postchlorination if not continuously used. The intermediate chlorination group, if used, can function as standby for pre- and postchlorination. Standby equipment should have sufficient capacity to replace the largest unit during shutdowns.

3. The control residual analyzer should be backed up by an effluent monitor analyzer that can be switched over to the control function in the event of failure of the control analyzer.

4. When dechlorination is used, the sample pumps should be arranged in duplicate for the analyzer controlling the sulfonator. One of these pumps can be used to deliver a dechlorinated sample to the analyzer on a programmed basis such as five minutes each hour to demonstrate proof of dechlorination.

Water Supply—Provisions should be made for continuous injector water supply in the event of power failure, either an alternate water supply not dependent on power or a gasoline engine driven injector water supply pump.

Dechlorination System—The reliability provisions indicated above also apply here.

1. INTRODUCTION

1.1 SIGNIFICANCE OF DISINFECTION

Sewage disinfection is defined as the process of destroying pathogenic microorganisms in the waste stream by physical or chemical means. Disinfection is best accomplished by the use of chemical agents such as chlorine, chlorine dioxide, bromine, iodine, or ozone. Present disinfection practices depend almost exclusively on chlorine.

Inasmuch as total sterilization is generally not practical and the specific situation dictates the terms of what is adequate, disinfection means the destruction of most of the pathogenic organisms in the wastewater stream. Disinfection effectiveness is measured by the most probable number (MPN) of the coliform bacteria indicator group which remains after destruction has taken place.

From the viewpoint of health, the disinfection process is the most important stage of treatment. It is the unit process which provides a barrier to the transmission of waterborne disease by destruction of pathogens before release of wastewater to the environment. Consequently, the disinfection process must be effective, dependable, and reliable.

Disinfection is an integral part of the treatment system and, therefore, it must be integrated into the overall process design. Although the principles of effective disinfection are understood, there has been inadequate attention devoted to design which incorporates all of the necessary elements to make it an effective in-plant process.

1.2 WASTEWATER DISINFECTION PRACTICES IN CALIFORNIA

1.21 Establishment of Disinfection Requirements

Under California law, waste discharge requirements are established on a case-by-case basis after hearing by the Regional Water Quality Control Board in whose region the discharge takes place. In almost all cases involving a discharge of sewage effluent to waters of the State or to land where there is public access, it is necessary to establish a disinfection requirement as one of the waste discharge requirements. Bacteriological standards have been established for various situations and in various regions. Some of these are expressed in the Water Quality Control Plans.

The Department of Health Services submits its recommendations for health protection to the regional boards on each discharge for which new or revised requirements are being established and includes a recommended disinfection requirement if one is needed. The Regional Board prepares the discharge requirements and holds a public hearing for discussion and establishment of the final requirements.

1.22 Indicator Organism

Disinfection efficiency is measured by the total coliform bacteria test as outlined in the latest edition of the "Standard Methods" (35). The coliform bacteria group, which is present in the intestines of man and warm-blooded animals, serves as an indicator of human intestinal pathogens, which are extremely difficult to measure (30). With the exception of virus, survival characteristics of most pathogens are similar to those of coliforms. Therefore, the coliform test is a sensitive method of determining disinfection efficiency.

1.23 New Developments in Chlorination

The use of coliform bacteria concentrations as a measure of disinfection has focused a great deal more attention on the design and operation of chlorination systems. In 1961, the first chlorine residual control system for a wastewater effluent was installed at the Napa Sanitary District plant, Napa, California. Since then, most secondary treatment plants in California have installed automatic residual controls.

The pilot plant research work by Collins, et al. (3, 4), and the field investigations by White (43, 44) and Sepp, et al. (31, 32, 33) have revealed the basic design criteria for an optimum chlorination system for the disinfection of wastewater. These criteria are as follows:

1. Complete and rapid initial mixing of chlorine and wastewater;
2. Adequate contact time (at least 30 minutes at peak flow) in a well-designed contact tank or outfall conduit;
3. A well-adjusted and reliable automatic chlorine residual control system; and
4. Competent operating personnel.

In 1979, the California Department of Health Services completed a comprehensive design optimization study (32, 33) on eight secondary and tertiary wastewater treatment plants. The major part of the project consisted of concurrent studies on a mobile optimized chlorination pilot plant and the existing full-scale system at each of the eight study sites. The trailer-mounted pilot plant contained optimum design features, including rapid initial mixing, reliable automatic chlorine residual control, and plug flow type contact tanks providing up to two hours detention time. Disinfection efficiency was measured by total coliform bacteria and iodometric chlorine residual tests. Concurrent fish bioassays on the same effluents were done by the Department of Fish and Game. In addition to the above concurrent studies, special pilot studies were made of initial mixing, residence time distribution, effects of chlorine residual and contact time, and dechlorination.

Table 1 shows the results of six of these concurrent studies. The results of studies 1 and 4 are not shown because these effluents were subject to serious sludge overflows and/or did not practice adequate disinfection, and, consequently, these studies did not yield adequate comparative data. The same plant numbers will be used in subsequent tables. As seen from Table 1, at all locations the pilot plant used significantly less chlorine than the full-scale plant. The average reduction in chlorine dosages achieved by the optimized pilot plant were as follows: 18.6 percent at Plant 2, 56.1 percent at Plant 3, 44.8 percent at Plant 5, 55.7 percent at Plant 6, 30.5 percent at Plant 7, and 54.8 percent at Plant 8. This amounted to an overall average savings in chlorine of 46.7 percent, or 8.9 mg/l. The higher chlorine dosages required by the full-scale plants were due variously to inadequate contact time, unreliable chlorine control system and/or inadequate operation and maintenance. The reduction in chlorine dosages was accompanied by an overall average reduction in effluent chlorine residual of 49.7 percent or 3.3 mg/l, which implies significant savings in sulfur dioxide used for dechlorination.

Table 2 gives the design data for the full-scale plants studied. Table 3 shows the effluent quality for the same plants.

TABLE 1
RESULTS OF COMPARATIVE CHLORINATION STUDIES[1]

TREATMENT PLANT	TOTAL COLIFORM LEVEL, MPN/100	THEORETICAL CONTACT TIME, MINUTES	CHLORINE DOSAGE, MILLIGRAMS PER LITER	CHLORINE RESIDUAL, MILLIGRAMS PER LITER[2]
Plant 2	13 – 64	70 – 78	9.2 – 10.6	1.2 – 2.5
Pilot Plant at No. 2	7 – 20	60	7.9 – 8.8	1.5 – 2.4
Plant 3	2 – 640	45 – 52	27.9 – 47.2	5.5 – 13.6
Pilot Plant at No. 3	<2 – 200	45	7.5 – 27.7	2.5 – 3.7
Plant 5	<2 – 2	79 – 86	9.0 – 13.3	6.7 – 9.1
Pilot Plant at No. 5	<2 – 2	90	3.7 – 7.0	1.4 – 3.6
Plant 6	<2 – 2	89 – 110	7.9 – 16.7	3.8 – 5.4

TABLE 2
TREATMENT PLANT DATA, DESIGN OPTIMIZATION STUDY

TREATMENT PLANT	DISINFECTION STANDARD, COLIFORM MPN/100 ml	TYPE OF WASTE	TREATMENT[1]	CHLORINE CONTROL	MIXER	CHLORINE CONTACT TANK
2	240	Domestic-industrial	A.S. plus nitrification	Compound loop	Hydraulic jump	Rectangular, once-around
3	240	Domestic	A.S.	Compound loop	Turbine	Serpentine
5	100	Domestic	A.S.	Compound loop	Turbine	Circular plus serpentine
6	23	Domestic	A.S. plus filter	Compound loop	Turbine	Serpentine
7	2	Domestic	A.S., nitrification plus filter	Compound loop	Turbine	Rectangular, once-around
8	240	Domestic	Trickling filter	Flow proportional	Hydraulic jump	Rectangular, once-around

[1] Note: A.S. means Activated Sludge.

TABLE 3
EFFLUENT QUALITY, DESIGN OPTIMIZATION STUDY[1]

TREATMENT PLANT	BOD	COD	TSS	$NH_3 - N$	$NO_2 - N$	MEDIAN COLIFORM, MPN/100 ml
2	0.7 – 5.2	35 – 82	2.4 – 15	<0.1	<0.01	$3.3 \times 10^4 - 2.95 \times 10^5$
3	8 – 29	44 – 128	2 – 60	7.7 – 19.6	1.0 – 2.9	$2.4 \times 10^5 - 4.9 \times 10^6$
5	4.7 – 15.5	28 – 70	3 – 11.5	15 – 19	<0.01	$3.3 \times 10^5 - 9.45 \times 10^5$
6	2 – 18	18 – 88	4 – 36	5.8 – 14	0.02 – 2.2	$3.5 \times 10^4 - 2.2 \times 10^6$
7	0.2 – 2.0	20 – 25	0.6 – 10.4	$<0.1 - 0.5$	<0.1	$1.3 \times 10^4 - 6.4 \times 10^4$
8	14 – 26	91 – 132	20 – 49	15 – 27	<0.1	$1.2 \times 10^6 - 4.9 \times 10^6$
1	12 – 29	84 – 109	32 – 140	9.3 – 30.8	<0.01	$4.1 \times 10^6 - 64 \times 10^6$
4	16 – 176	39 – 272	12 – 191	26 – 33	<0.01	$1.1 \times 10^7 - 9.2 \times 10^8$

[1] Values in mg/l except total coliform. Range of daily averages for each three-week study.

1.24 Dechlorination

In the early 1970s, studies of municipal effluents discharged into San Francisco Bay revealed that chlorination increased the toxicity of all treated wastewaters (8). However, dechlorinated effluent was less toxic than either the chlorinated or the unchlorinated effluent.

A study by Stone, et al., (37) concluded that a substantial adverse environmental impact can occur in the receiving water as the result of discharge of wastewater containing chlorine. Chlorine residuals of 0.06 mg/l were damaging to Bay aufwuchs and phytoplankton. After dechlorination with sodium bisulfite, the toxicity attributable to the chlorine residuals was completely removed. The study report expressed hope that improved design and operation of disinfection systems could reduce chlorine residuals to the point where the small effects on organisms in the vicinity of the outfall may be acceptable. However, subsequent studies have proven otherwise.

The Design Optimization Study (32) discussed in Section 1.23 has demonstrated that by optimum design and operation it is possible to reduce the effluent chlorine residuals by as much as 50 percent. The optimized pilot plant effluents were an average of 42.9 percent less toxic to test fish and contained 49.7 percent less chlorine residual than the full-scale effluents. However, the study findings showed that it is not possible to remove all the chlorine-induced toxicity by optimized design alone, and that dechlorination will still be necessary in situations where the toxicity must be removed. The study also indicated that dechlorination with sulfur dioxide removes all chlorine-induced toxicity from the effluents. The excess sulfur dioxide residual apparently was not toxic to fish at the concentrations used.

Dechlorination can be done effectively and inexpensively by the sulfite radical. The use of sulfur dioxide (SO_2) is the most practical method to achieve this whenever the system requires more than five pounds of SO_2 per day. The first wastewater dechlorination system to be put in operation in California was at the City of Burlingame Treatment Plant early in 1973. This was followed by installations at the City of Sacramento's Main Treatment Plant and the North Point Plant of the City of San Francisco, all in 1973. Now most of the treatment plants in San Francisco Bay Area have facilities for dechlorinating their effluents with sulfur dioxide.

When dechlorinating with sulfur dioxide there is usually no need for additional treatment of the dechlorinated effluent by aeration and pH adjustment. Any acid created by the SO_2 is neutralized by the buffering capacity of the wastewater. The reaction of the sulfite ion with dissolved oxygen is quite slow and, except in special situations, the small excess of SO_2 which is left after dechlorination will not significantly depress the dissolved oxygen content in the effluent.

2. CHLORINATION PROCESS AND FACILITY DESIGN

2.1 CHEMISTRY AND KINETICS OF CHLORINE AND WASTEWATER

Several chemical reactions may occur simultaneously when chlorine is added to wastewater. The reactions are affected by ammonia nitrogen concentration, total organic carbon (TOC), temperature, pH, buffering capacity of sewage and the nature of the chlorinating agent.

2.11 Reactions With Water

When chlorine gas is added to water the following reactions occur:

$$Cl_2 + H_2O \rightleftharpoons HOCl + H^+ + Cl^- \qquad (1)$$

or perhaps:

$$Cl_2 + OH^- \rightleftharpoons HOCl + Cl^- \qquad (2)$$

The hydrolysis of chlorine is complete within a few seconds at ordinary water temperature and the ionization of hypochlorous acid (HOCl) is an instantaneous reversible reaction.

Effect of pH—The HOCl molecule ionizes as follows:

$$HOCl \rightleftharpoons H^+ + OCl^- \qquad (3)$$

Thus, chlorine gas tends to lower the pH of the water which, in turn, favors the formation of HOCl. The distributions of HOCl and OCl^- as a function of pH are shown in Table 4. Figure 1 shows the titrable free chlorine, in mg/l, required to produce one mg/l HOCl at varying pH values.

TABLE 4
DISTRIBUTION OF HOCl and OCl^- WITH pH AT 20°C

pH	PERCENTAGE OF TOTAL FREE CHLORINE AS	
	HOCl	OCl^-
6.0	97.45	2.55
7.0	79.29	20.71
7.5	54.77	45.23
8.0	27.69	72.31
9.0	3.69	96.31

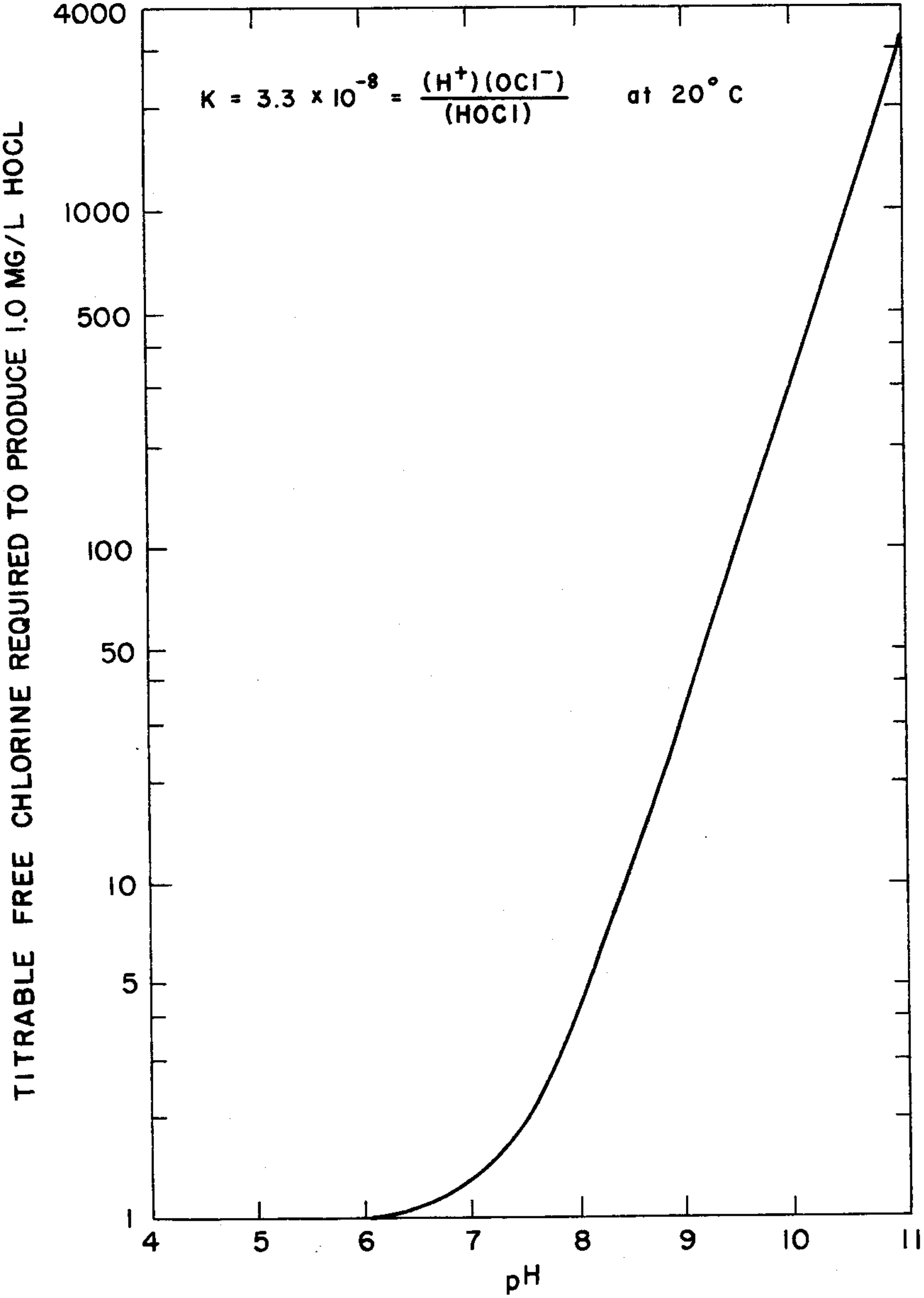


FIGURE I. EFFECT OF pH ON THE DISTRIBUTION OF HYPOCHLOROUS ACID

2.12 Reactions With Wastewater Constituents

There are numerous constituents present in wastewater that immediately react with the HOCl. Consequently, free chlorine (a term referring to HOCl plus OCL^-) is probably not present for more than a fraction of a second after the addition of chlorine in most wastewaters. First, the various inorganic reduced substances (S^{--}, HS^-, SO_3^{--}, NO_2^-, Fe^{++}) will combine with the HOCl and reduce it to the stable chloride ion, which is nonbactericidal. This immediate inorganic chlorine demand will be proportional to the amount of the reduced substances present. The immediate chlorine demand of a "fresh" sewage may only be 5 mg/l; however, it may increase to as much as 100 mg/l as the sewage becomes septic. Second, the HOCl molecule reacts with the nitrogenous matter as is explained below.

Ammonia Nitrogen—In wastewater there usually is an appreciable amount (15—30 mg/l) of ammonia nitrogen. The ammonium ion exists in equilibrium with ammonia nitrogen and hydrogen ion as follows:

$$NH_4^+ \rightleftharpoons NH_3 + H^+ \qquad (4)$$

When ammonium ions are present in a water to which chlorine has been added, the following reactions may result:

$$HOCl + NH_4^+ \rightleftharpoons NH_2Cl + H_2O + H^+ \qquad (5)$$

(monochloramine)

$$HOCl + NH_2Cl \rightleftharpoons NHCl_2 + H_2O \qquad (6)$$

(dichloramine)

$$HOCl + NHCl_2 \rightleftharpoons NCl_3 + H_2O \qquad (7)$$

(trichloramine, nitrogen trichloride)

The extent to which the various chloramines are formed depends on the pH, temperature, contact time and concentration of each reacting substance. Monochloramine will predominate at pH 8 and dichloramine at pH 5. Lower pH values and high chlorine dosages favor the formation of trichloramine (NCl_3). The NCl_3 forms only when the ratio of chlorine to $NH_3 - N$ exceeds 12 to 1 by weight.

Organic Nitrogen—In addition to reacting with free ammonia nitrogen in wastewater, chlorine may combine with amino acids, proteinaceous material and many other organic compounds normally occurring in sewage. Very little is known concerning the extent of these reactions, their reversibility or the disinfecting power of the chlorine compounds. Some organic chloramines have little or no germicidal powers at pH values near seven but they titrate as combined chlorine using the iodometric method (see Section 4.1). Therefore, it is generally concluded that ammonia chloramines are far superior to organic chloramines as disinfecting compounds, and that the process

2.13 Germicidal Effectiveness of Chlorine Compounds

and hypothetically,

$$2NHCl_2 + H_2O \rightarrow N_2 + HOCl + 3H^+ + 3Cl^- \qquad (10)$$

where only the species in the form shown enter into the reactions. Thus, all of these reactions must be pH dependent. Other products, ignored here, may include NCl_3, and NO_3^-. A typical breakpoint curve is shown in Figure 2.

It is probably not economically feasible to use this process for disinfection if there is an appreciable amount of ammonia nitrogen in the wastewater since the amount of chlorine to ammonia required to reach breakpoint is approximately 9 to 1 on a weight basis. Wastewaters may contain as much as 10 to 40 mg/l of ammonia nitrogen and the cost of the high chlorine dosage which must be used would be prohibitive in most cases. In addition, the reaction of chlorine with water releases hydrogen ions and the use of the free chlorine residual process in ammonia-laden wastewaters would release enough hydrogen ions to exceed the buffering capacity of most sewages. This would result in significant lowering of the pH in the treated effluent.

The chlorine-ammonia reactions proceed fastest at pH 7–8, and are much slower at either low or high pH values; therefore, where the ammonia nitrogen content is high, it may be necessary to buffer the wastewater to near pH 7 in order to reach breakpoint in relatively short contact times. Factors such as mixing, pH, temperature, ammonia nitrogen concentration, turbidity and amount of chlorine applied will govern the reaction products. For example, low pH values and high chlorine dosages favor the formation of malodorous NCl_3. Therefore, these factors must be known in order to design an effective breakpoint reaction chamber.

The use of free residual chlorination in wastewater treatment is generally confined to the disinfection of nitrified effluents. These situations, especially in California, are always tertiary effluents of high quality where the National Pollutant Discharge Elimination System (NPDES) discharge requirements limit the ammonia nitrogen to 0.01 mg/l.

It has been believed that these effluents can be easily disinfected with much lower chlorine dosages than those encountered in conventional secondary effluents because the residuals are about 90 percent free chlorine. Therefore, the expected chlorine consumption should be much lower. In actual practice, however, the germicidal efficiency of these free residuals has been disappointing. Added to this, the 5-minute chlorine demand of these nitrified effluents appears to be on the order of 10 mg/l. In order to achieve a total coliform MPN of 2.2 per 100 ml in these effluents a chlorine dosage of 20–25 mg/l is often required. This high dosage requirement is unexplainable at this time.

There is much speculation as to why these biologically nitrified effluents behave in this manner. Some plants can achieve the required disinfection with lower residuals than others, but all plants reviewed to date show a high chlorine demand. The only plants that do not behave in this

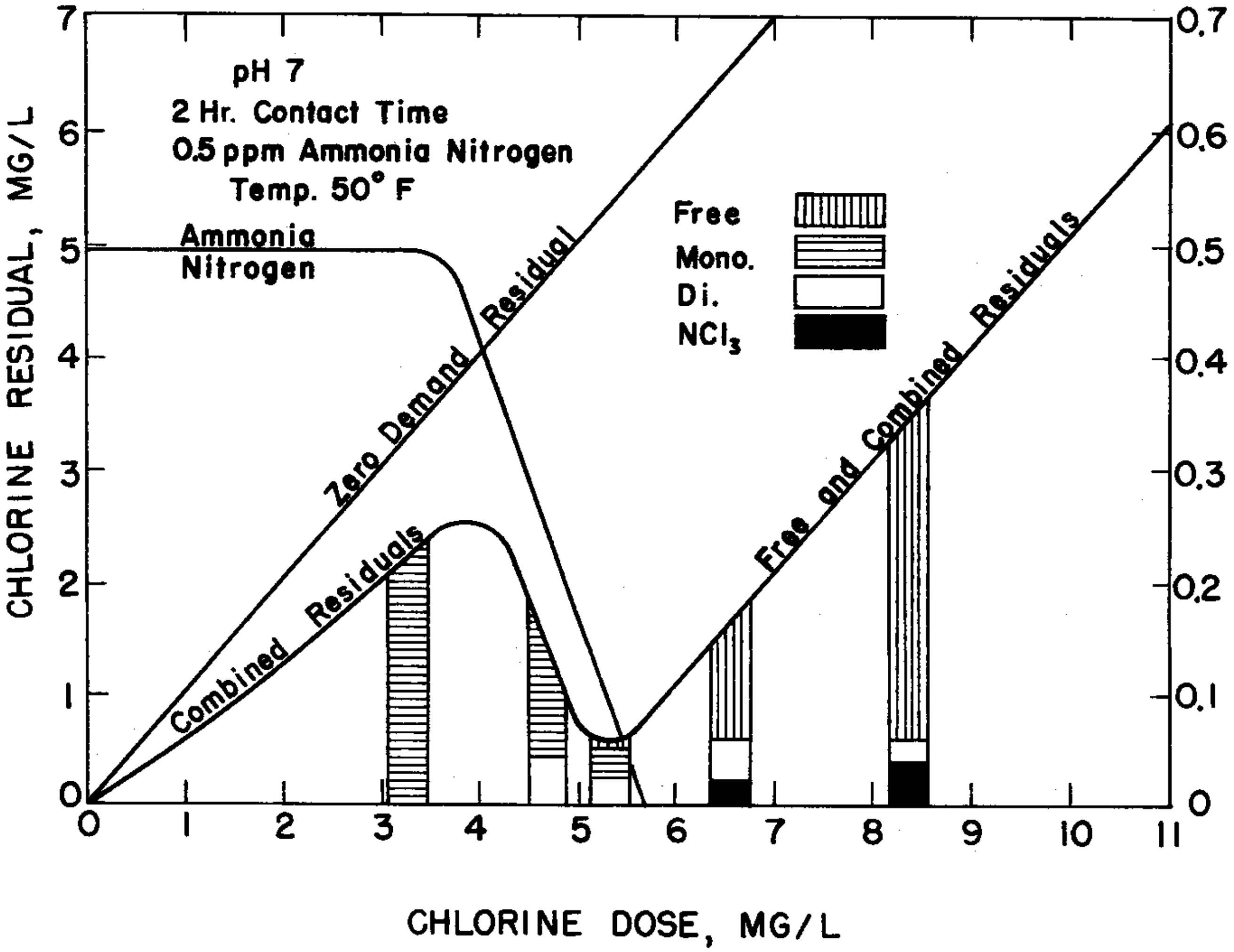


FIGURE 2. REACTIONS BETWEEN FREE CHLORINE AND AMMONIA NITROGEN SHOWING TYPICAL BREAKPOINT.

Another possible explanation for the high chlorine demands in the biologically nitrified effluents is that this process converts many of the organics in the sewage which tends to increase the total organic carbon (TOC). This increases the free chlorine demand. However, if this same nitrified effluent is treated with a small amount of ammonia nitrogen before chlorination (enough to raise the $NH_3 - N$ level up to 1.0 mg/l) so that all the chlorine becomes combined chlorine, the chlorine consumption retreats to a low level and disinfection to MPN 2.2/100 ml is achieved as before with much lower chlorine dosages. Most of the plants under discussion provide 30 minutes or more contact time and have contact tanks providing 70–80 percent plug flow. It appears that free chlorine reacts much faster than does combined chlorine with whatever compounds are formed during biological nitrification. Most of these nitrified effluents are filtered before chlorination and are considered to be tertiary effluents. Whenever tertiary treatment is employed there is a strong implication that substantial virus destruction is obtained. At most plants discussed above the chlorine residuals after 30 minutes contact time are on the order of 8 mg/l. However, in order to assure complete virus removal, treatment by chemical coagulation prior to filtration will be necessary.

2.15 Disinfection Kinetics

The degree of organism destruction in wastewater is a function of the type and concentration of disinfectant, contact time and temperature. Collins and Selleck (3, 4) in studying chlorine disinfection of primary effluent in a pilot plant found that the destruction of both total and fecal coliform bacteria followed the following empirical relationship:

$$Y_2/Y_1 = (Rt/b)^n \qquad (12)$$

where Y_1 = initial bacterial concentration, usually in unchlorinated effluent;

Y_2 = final bacterial concentration at time t, in chlorinated effluent;

R = chlorine residual, in mg/l;

t = contact time, in minutes;

b = the X-intercept when $Y_2/Y_1 = 1.0$, in mg/l x minutes; and

n = slope of the curve.

The above equation plots as a straight line on log-log paper. Collins and Selleck (3, 4) found that the slope n was -3 for ideal plug flow and $-2/3$ for completely mixed flow. The value of the constant b for the particular primary effluent studied was about 4 for total coliform and about 3 for fecal coliform. However, as will be seen below, in practice the constants b and n are different for each effluent. The chlorine residual R can be measured either immediately after mixing or after chlorine contact, each method yielding different results. The reduction of total coliform observed by Collins and Selleck (3, 4) in a stirred batch reactor which simulated plug flow was similar to that shown in Figure 11 (see Section 2.32). The destruction of fecal coliform was considerably faster than that of total coliform. Additional work by the same authors (26) indicated that the germicidal effect of the chlorine residual decreased with time.

The Design Optimization Study (32), which was described in Section 1.23, has shown that in good quality effluents the coliform reduction can be evaluated by means of Equation 12 reasonably well under field conditions. In this study a baffled chlorine contact tank having a dispersion number of 0.02 was used on the pilot plant, and the chlorine residual was automatically controlled by a residual analyzer. Figure 3 shows the regression curves of the coliform survival ratio Y_2/Y_1 versus RT for the pilot plant studies done on each of the 8 effluents. Table 5 shows the constants n and b, and the correlation coefficient r for the same effluents. Except for effluent 4, all the data in Table 5 are statistically significant at 0.01 level. Effluents 2 and 7 are well treated nitrified effluents, and effluent 6 is filtered secondary effluent. The remaining effluents are conventional secondary effluents of variable quality, and the data shown for these exhibit considerable amount of scatter. The scatter is partly due to the great daily variation of the initial coliform levels. The very poor results for effluent 4 are due to sludge overflows. Except for effluent 4 which had extremely high coliform levels, the lower extremity of each curve indicates the point where an MPN level of 2 per 100 ml was reached.

In effluents 5 and 6 it was observed that the germicidal efficiency of the chlorine residual began to decrease with contact times greater than 60 minutes. This may have been due to the conversion of the chlorine residual to poorly bactericidal organic chloramines.

Considering the above evidence, it is recommended that the design of disinfection systems be based on thorough field and laboratory testing.

TABLE 5
SLOPE AND INTERCEPT FOR PILOT PLANT CHLORINATION CURVES, DESIGN OPTIMIZATION STUDY[1]

EFFLUENT NUMBER	INTERCEPT b	SLOPE n	CORRELATION COEFFICIENT r
1	3.7	−3.13	0.69
2	14.6	−4.1	0.93
3	0.3	−1.82	0.68
4	0.1	−1.95	0.30[b]
5	0.1	−1.68	0.78
6	7.76	−3.50	0.81
7	20.7	−3.32	0.88
8	0.004	−1.24	0.55
Mean (signif. values)	6.74	−2.68	—

[1] For the formula $Y_2/Y_1 = (RT/b)^n$, as depicted in Figure 3, where R = chlorine residual after contact, T = theoretical detention time.

[b] Not statistically significant.

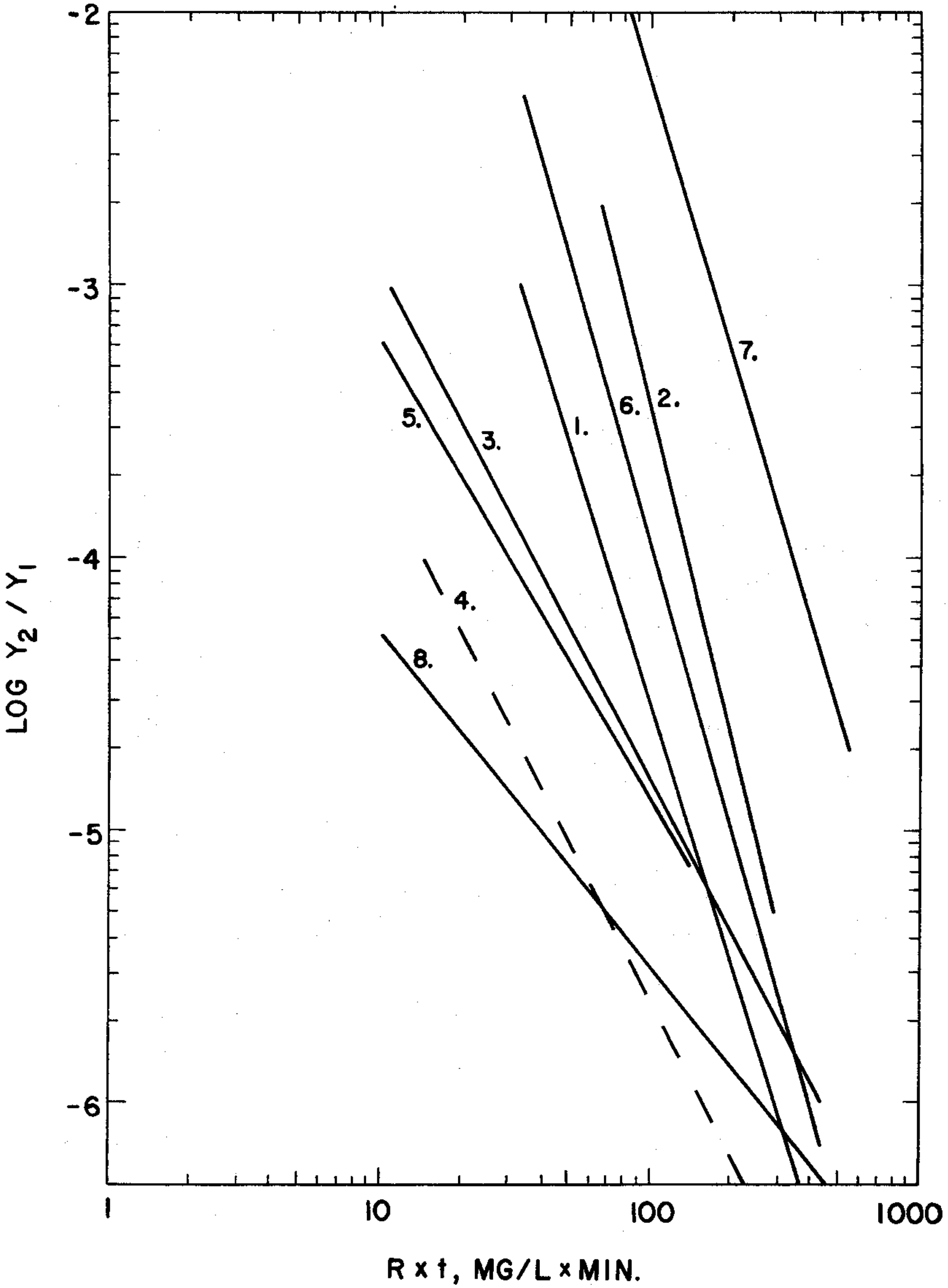


FIGURE 3. REGRESSION CURVES OF PILOT PLANT CHLORINATION DATA FOR DIFFERENT EFFLUENTS

There have been various modifications of Equation 12, one of which is discussed below. White (44) uses the following formula to design chlorine disinfection systems for secondary effluents:

$$Y_2/Y_1 = (1 + 0.23\,R\,t\,)^{-3} \qquad (13)$$

where R is the chlorine residual after contact and other parameters are the same as for Equation 12. This formula was derived by the same authors (3, 4) and is practically identical to Equation 12, except that it uses theoretical values for the constants b and n. (The value of b would be 4.35 in Equation 13.) In Table 5 the constants vary, but the mean b is 6.74 and the mean slope approaches −3. Some of the literature (5, 31) also report −3 slopes in various effluents. Therefore, Equation 13 may be useful for rough estimation of chlorination systems if no other information is available.

2.16 Chlorine Demand

The chlorine demand of the various effluents varies greatly. In the Design Optimization Study (26) it was found that the chlorine dosage required to reduce the coliform MPN to 2 per 100 ml after 60 minutes contact time varied from about 4 mg/l to 22 mg/l in the effluents studied in the pilot plant. These data are shown in Table 6. The quality of these effluents is shown in Table 3. Effluents 1 and 4 contained sludge and appreciable amounts of industrial wastes, and effluents 2 and 7 were completely nitrified. The data in Table 6 is indicative of both the initial and total chlorine demand. Table 7 shows the calculated average chlorine demand which occurred in the pilot contact tank after the immediate demand had been satisfied. These data demonstrate the importance of adequate chlorine demand and chlorine requirement tests.

TABLE 6
CHLORINE REQUIREMENTS OF VARIOUS EFFLUENTS,
DESIGN OPTIMIZATION STUDY

EFFLUENT NUMBER	TOTAL COLIFORM LEVEL IN EFFLUENT,[1] MPN/100 ml	CHLORINE DOSAGE, mg/l	CHLORINE RESIDUAL mg/l	
			(a)	(b)
1	2	22.2	11.5	9.7
2	2	10.7 – 13.0	7.3 – 8.1	4.0 – 4.3
3	2	16.2 – 22.8	4.8	3.7
4	20	12.5	8.5	6.6
5	2	5.0 – 7.0	3.5 – 4.9	2.4 – 3.9
6	2	4.1 – 4.3	2.8 – 3.0	2.2 – 2.7
7	2	11.5 – 12.4	10.0 – 10.9	5.0 – 6.8
8	2	10.6 – 13.5	7.0 – 9.3	5.8 – 7.0

[1] Detention time 60 minutes (Effluent 2, 45 minutes).

[a] Residual immediately after initial mixing (approximately 2-minute detention).
[b] Residual after 60-minute contact.

TABLE 7
CHLORINE RESIDUAL DECAY IN PILOT CONTACT TANK[1]

EFFLUENT NUMBER	RESIDUAL DECAY, mg/l, DURING 60 MINUTES
1	1.6
2	2.6
3	1.1
4	1.8
5	1.0
6	0.7
7	4.6
8	1.3

[1] After satisfaction of the immediate chlorine demand; arithmetic mean values.

2.2 FACTORS AFFECTING PROCESS EFFICIENCY

Several factors will detemine the efficiency of the wastewater chlorination process, in addition to pH, temperature and the concentration of the disinfectant. The factors, which are under the control of the design engineer but have frequently received very little attention, are: (1) initial mixing; (2) chlorine contact time; (3) chlorine control system; and (4) reliability.

2.21 Initial Mixing

Rapid initial mixing of the chlorine solution and wastewater is essential for effective disinfection. A rapid initial mix followed by a plug flow contact chamber will provide maximum process efficiency (4). Initial mixing of the chlorine solution and the wastewater prior to the contact period must not be confused with mixing in the contact tank. Longitudinal mixing in the contact tank should be avoided, because it results in short circuiting in the tank and unreliable disinfection. The initial mix should be accomplished in three seconds. This can be done most effectively by either applying chlorine in a turbulent flow regime, or by employing a mechanical mixer immediately downstream from chlorine application point. Diffusers are necessary in all applications. Mixers and diffusers are discussed in Sections 2.31 and 2.35, respectively.

In the past practice it has been common for the chlorine solution to be applied directly to chlorine contact tanks or to open channels, often without a diffuser. Flows in those tanks and in many open channels are usually highly stratified, resulting in very little dispersion of the chlorine. Heukelekian and Day (10) demonstrated conclusively in 1951 that the distribution of chlorine in contact tanks will not be uniform unless special mixing compartments are provided. Without special mixing, the greater portion of the chlorine may pass along the bottom of the tank resulting in poor overall bacterial removals in spite of a reasonably high chlorine residual in the effluent.

In a recent study (14) it was reported that substantial viral and bacterial reduction occurred during high energy mixing. Both virus and coliform destruction were directly proportional to chlorine residual and contact time in the plug flow mixers used. At the higher chlorine residuals, organism destruction was also directly proportional to mean velocity gradient (G) within the range of 10^2 to 10^5 sec^{-1}. The Prandtl eddy frequency had an effect similar to the mean velocity gradient. The Reynolds Number had the least effect.

In the Design Optimization Study (32), two tubular plug flow mixers were used on the pilot plant. The 1.5-inch mixer had a G value of 875 sec^{-1} and the 3-inch mixer had a G value of 115 sec^{-1}. However, when all the subsequent piping was accounted for, the overall G values probably did not differ much. The G value is the mean velocity gradient in a shearing fluid, and is defined as $G = \sqrt{P/\mu}$, where P is the power input per unit volume and μ is the absolute viscosity of the fluid. The results (regression curves) of the pilot mixing study are shown on Figure 4. The contact time in both mixers was 20 seconds. It is quite apparent that the coliform destruction is directly proportional to the total chlorine residual measured. As different effluents were used for each mixer, the different location of the curves may be due to differences in effluent quality.

In the same Design Optimization Study (32), greater than 99 percent coliform reduction was observed in all the full-scale mixers studied. Four of these were turbine mixers and two utilized the hydraulic jump for mixing. The mixers had G values ranging from 250 to 850 sec^{-1}. White (44) has recommended G values of 500–1000 sec^{-1} for chlorine mixers. and this appears to be an appro-

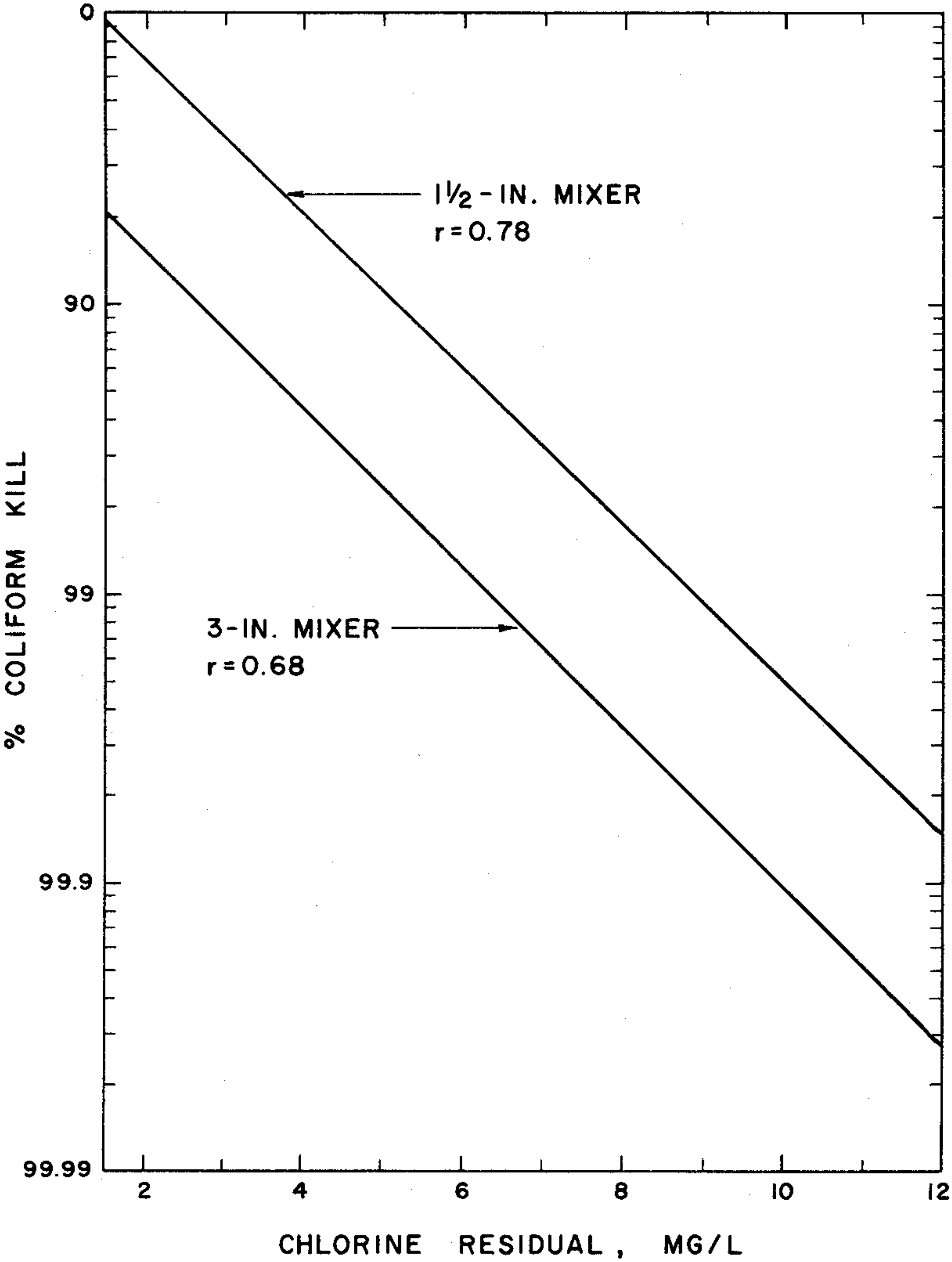


FIGURE 4. COLIFORM KILL IN TUBULAR MIXERS

2.23 Chlorine Control Systems

Thirty or more years ago it was considered adequate to have a manually controlled chlorinator in operable condition which could produce a 0.75 mg/l orthotolidine (OT) residual at the end of 30 minutes contact time at average dry weather flow. This was supposed to achieve adequate disinfection. Owing to the variations in diurnal flow patterns, it was soon recognized by the design engineers that the additional cost for flow paced chlorinators was readily justified by savings in chlorine. Later when discharges were required to achieve a specified coliform concentration in the plant discharge, continuous monitoring of the chlorine residual was deemed necessary. This refinement in the chlorination process revealed rapid and large unpredictable chlorine demand changes. The next step was to convert the chlorine residual measurement into a control signal so that the chlorinator would respond automatically to both flow and chlorine demand changes. Investigations of current practices have shown that systems using chlorine residual control provide much improved cost-effective performance over those that rely solely on flow pacing with manual adjustment of chlorine dosage (42, 43, 44). However, even these systems may be wasteful of chlorine, if they are not properly designed and operated (32).

Control systems based on chlorine residual can be either direct residual control where the analyzer provides signals for either the change in chlorine demand alone or for a combination of the flow rate and chlorine demand; or compound loop control where the control apparatus receives two separate and independent signals—one from the effluent flow meter and the other from the residual analyzer. Direct residual control is not applicable where dechlorination is required. An effluent flow meter is mandatory for dechlorination.

The compound loop system is generally preferred because it can better deal with sudden changes in flow and chlorine demand. A compound loop system is illustrated in Figure 5. Using conventional chlorination equipment, the flow measuring device sends a control signal direct to (or via a ratio station) the chlorine metering orifice controller, while the chorine residual analyzer sends a separate signal to the vacuum regulator valve which controls the vacuum differential across the chlorine metering orifice. Therefore, when applying the flow formula $Q = CA\sqrt{2gh}$, the flow of chlorine is controlled by changing the opening of the orifice by the flow signal and by the changing of the differential across the orifice by the analyzer signal. Such a control system is made up of readily available and proven equipment. Details of this system are described in Section 2.34 under the heading "Methods of Control."

The second analyzer shown on Figure 5 is used to monitor the chlorine residual after the prescribed contact time. This unit can also be equipped with control features allowing it to adjust the "set point" of the control analyzer, which results in maximum disinfection efficiency. Where dechlorination is required, the second analyzer is used to control the dechlorination process (see "Methods of Control" and "Monitoring Equipment" in Section 2.34; and Section 3.33).

2.24 Cleaning and Reliability

Experience has shown that all chlorine contact tanks should have provisions for cleaning. For reasons not fully understood, chlorination results in additional solids removal; the chlorine residual in a contact tank may effect the removal of as much as 50 percent of the remaining suspended solids from an activated sludge effluent which will accumulate on the bottom of the tank (40). These solids will start decomposing and may recontaminate the effluent, thus reducing the disinfection efficiency. Therefore, these solids must be removed.

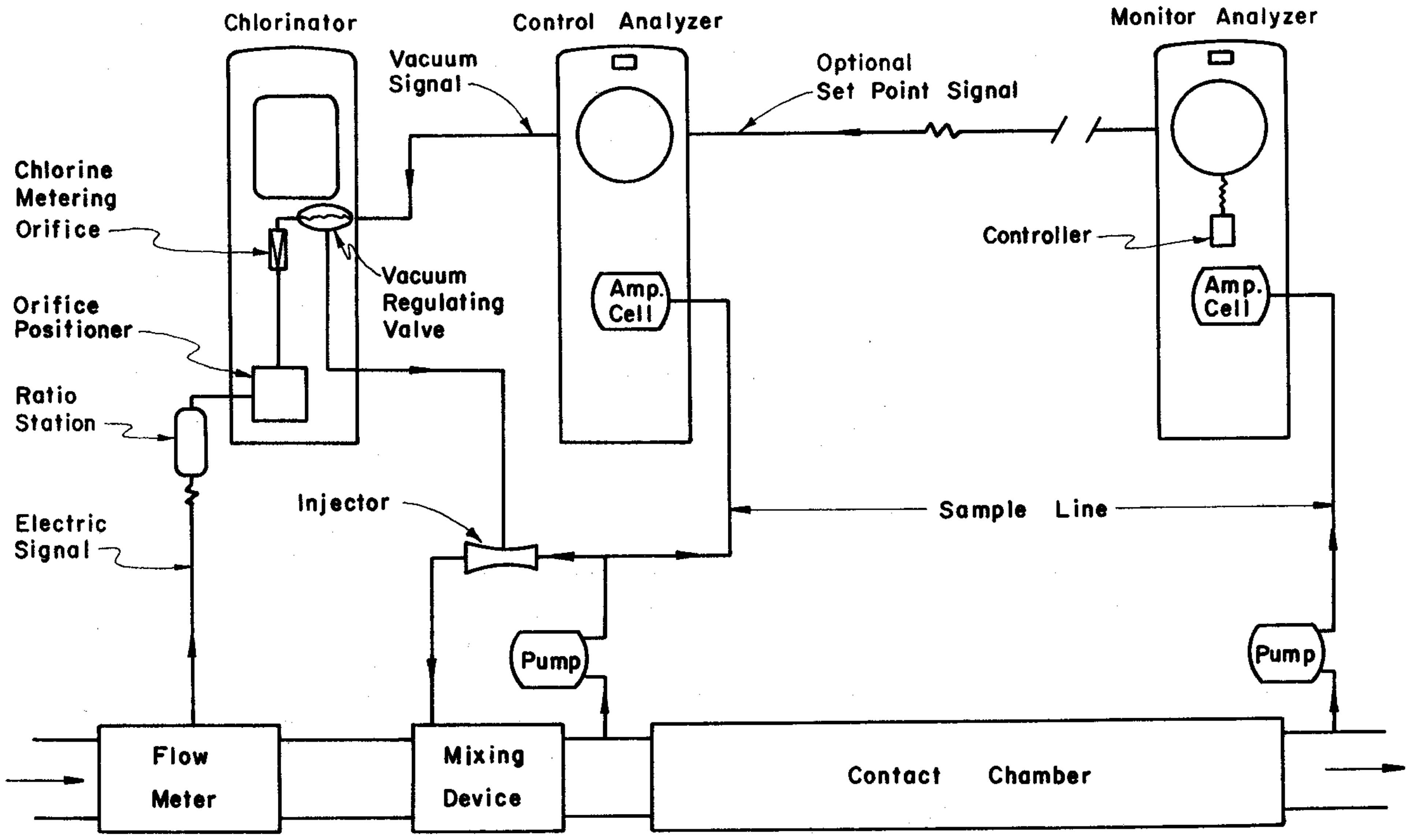


FIGURE 5. COMPOUND LOOP CHLORINE CONTROL SYSTEM

Cleaning must be done in a manner which does not interrupt the disinfection process. One method is to provide mechanical sludge removal by scrapers which, however, is difficult to do for well-baffled tanks. A dredging apparatus, which vacuums the sludge off the bottom, may be more suitable.

Another method would be to provide two contact tanks so that one could be cleaned while the other remains in service. Adequate disinfection may be provided with increased chlorine dosage during the relatively short cleaning period. Dual tanks have an added advantage in that they can be connected in series to double the chlorine contact time and enable adequate disinfection with a lower chlorine residual and lower toxicity.

A two-tank effect can also be obtained by providing a removable wall and inlet-outlet gates at the mid-point of a contact tank, allowing either half of the tank to be taken out of service for cleaning.

A third alternative would be to provide a retention tank or pond of adequate capacity to hold

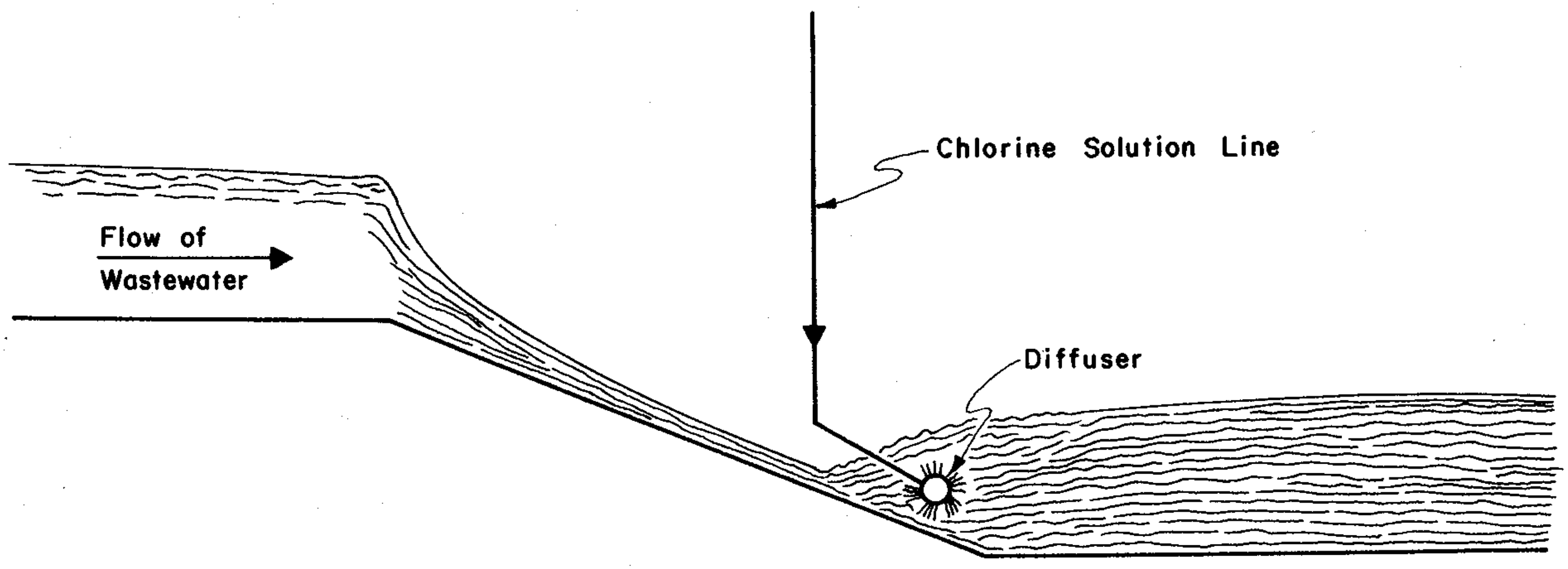


FIGURE 6. HYDRAULIC JUMP AS AN INSTANTANEOUS MIXING DEVICE FOR CHLORINE AT THE POINT OF APPLICATION

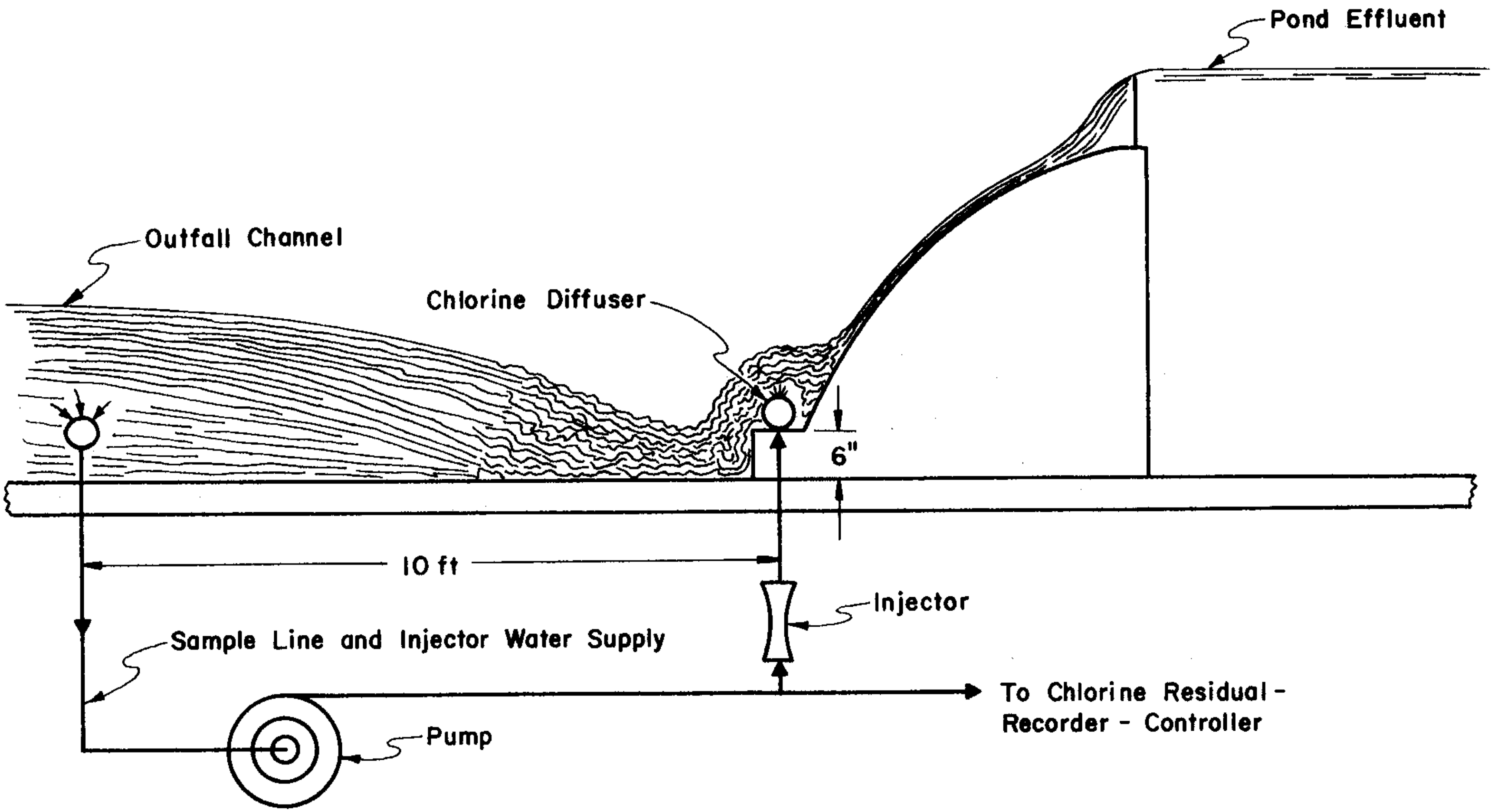


FIGURE 7. A HYDRAULIC CHLORINE MIXING DEVICE

The designer should use caution in locating the diffuser in a hydraulic jump because the turbulent zone moves upstream and downstream with the variations of flow. The diffuser should be placed so that it never has less than six inches of water cover and that it lies in a turbulent zone.

Hydraulic mixing structures require considerable headlosses and are often not available or practical in existing installations. For these situations mechanical mixing must be employed. Mechanical mixers, if designed properly, can effect a complete mix of chlorine solution with the wastewater in less than three seconds (44). The mixer should be located at or immediately downstream from chlorine application point and the mixing chamber should be small so that the streams blend quickly. Figure A–1 in the Appendix illustrates a mechanical mixer in a pipeline. Figures A–2 and A–3 illustrate mechanical mixers applied in open channel flow. Additional details are provided in Chapter 3 of Reference (44).

Mixing can also be accomplished by introducing the chlorine solution into the center of a pipe carrying turbulent flow. It has been reported that adequate mixing will occur within a length of ten pipe diameters, provided that the Reynolds Number is greater than 2000 (41, 42).

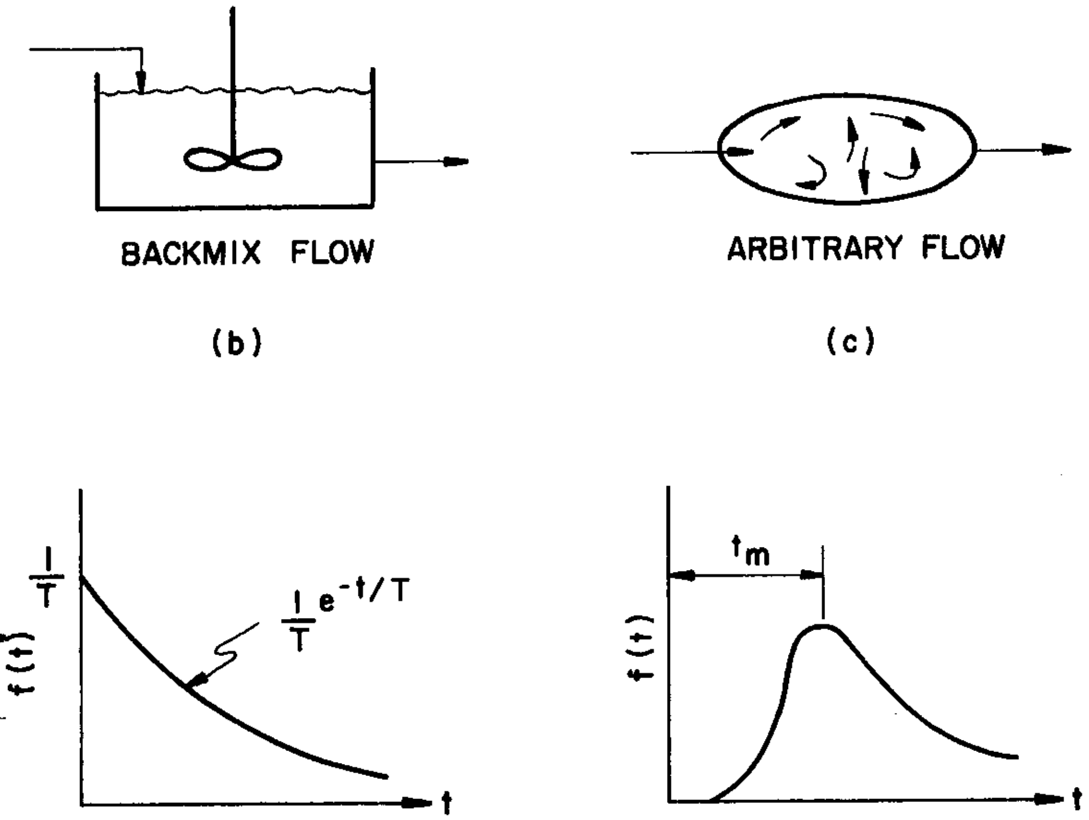
2.32 Chlorine Contact Tanks

Distribution of Residence Times—The importance of contact time in the chlorination of wastewater is well known. Unfortunately, many contact tanks currently in operation were designed solely on a volumetric basis and, consequently, are classified as rectangular, circular, or plant outfall conduits (34).

The chlorine contact tank can be described as a chemical reactor where the chlorine residual reacts with the microorganisms. The residence time distribution discussed herein, which refers to the hydraulic residence of a fluid, is identical to the contact time distribution. The distribution of residence times may differ appreciably in reactors of different geometrical configuration, even if the reactor volumes and flow rates are identical (4). The distribution of residence times for ideal plug flow, completely backmixed flow and for an arbitrary flow are depicted in Figure 8. In ideal plug flow, the flow through the reactor is uniform with no longitudinal mixing along the flow path. The residence times in this reactor is the same for all elements of fluid. In completely backmixed flow, the contents of the reactor are well mixed and uniform in composition throughout. The exit stream from this reactor has the same composition as the fluid within the reactor. A backmixed reactor should not be confused with a batch reactor. In a batch reactor, all the reactants added to the vessel are mixed and held for a predetermined time so that chemical reaction can proceed. The composition of the batch reactor contents changes with time. An example of a batch reactor is a laboratory beaker used for performing chlorine requirement tests. However, the residence time distribution in a batch reactor is identical to that of an ideal plug flow reactor.

Examination of the residence time distribution functions f(t) depicted in Figure 8 reveals that a large portion of flow passes through the backmixed tank in a very short time (15). It follows that chlorine contact tanks should be designed to approach plug flow reactors and that backmixed flow situations should be avoided. (The f(t) function is an equation which mathematically describes the residence time distribution curves.)

In practice, the residence time distribution of continuous flow tanks may vary between the extreme limits of ideal plug flow and completely backmixed flow conditions. Ideal plug flow can never be achieved in a real contact tank; it is always accompanied by some backmixing and some dead spaces. Consequently, the distribution of residence times in real tanks will be of an intermediate character as indicated in Figure 8 (c). The exception to this is when an outfall pipe is used as a contact tank. Flow characteristics in an outfall approach ideal plug flow conditions.



LEGEND

$T=\frac{V}{Q}$ = mean residence time

$f(t)$ = residence time distribution function

E TIME DISTRIBUTION FOR VARIOUS KINDS OF FLOW

Typical results from tracer tests conducted on real chlorine contact tanks are shown in Figures 9 and 10. The first one is for a longitudinally baffled tank, the second one is for a circular tank. Note in Figure 9 that the well-designed tank has a modal value approaching the nominal contact time T, and that the curve is fairly narrow. That is, the well-designed tank provides a distribution of residence times approaching that of a plug flow reactor. On the other hand, the distribution of residence times provided by the unbaffled tank in Figure 10 is similar to that provided by a backmixed reactor.

Ignoring initial mixing effects, the batch reactor produces results similar to the plug flow reactor. The effects of the residence time distribution on process efficiency are illustrated in Figure 11, which compares the reduction of total coliform bacteria, Y_2/Y_1, provided by a stirred batch reactor with that provided by a continuous flow backmixed reactor (4). The amperometric chlorine residuals were approximately equal in the two reactors studied. In the batch reactor study the chlorine solution was applied instantaneously; replicate samples were then withdrawn at selected intervals of time for bacteriological analysis. In the continuous flow backmixed reactor study, the chlorine was applied continuously to the reactor and replicate samples were collected for bacteriological analysis when the reactor reached steady state.

Figure 11 clearly demonstrates the overall effect of residence time distribution provided by different chlorine contact tanks on coliform reduction, and also demonstrates that a gross design criterion of volume/flow rate, if used alone, is meaningless. For example, there exists a difference of four orders of magnitude in the coliform reduction effected in the two reactors for a theoretical detention time, T, of 37 minutes.

Tracer Tests and Dispersion Parameters—The hydraulic performance of chlorine contact tanks can best be evaluated by means of a tracer, such as salt or organic dye. The usual tracer test consists of injecting a measured slug of tracer instantaneously into the entrance of the tank and measuring the tracer concentrations at the effluent weir. The tracer concentrations or fluorometer readings are then plotted against time on graph paper which produces the well-known residence time distribution curve. The most convenient way to conduct a tracer test is to use Rhodamine WT dye and a recording flow-through fluorometer.

The tracer curve indicates both the actual contact time and the dispersion characteristics. The smaller the dispersion, the more closely a tank approaches plug flow. The most important hydraulic efficiency and dispersion parameters are:

T = V/Q = theoretical detention time (nominal residence time) where V = tank volume, and Q = flow rate;

t_i = time to initial appearance of the tracer in tank effluent, the minimum contact time;

t_{10} = time for 10 percent of the tracer to pass;

t_{90} = time for 90 percent of the tracer to pass;

t_m = modal time; i.e., time to the peak of the curve;

t_a = average contact time; i.e., time to the centroid of the curve;

t_{90}/t_{10} = Morrill Index, which measures the spread of the curve; and

d = reactor dispersion number.

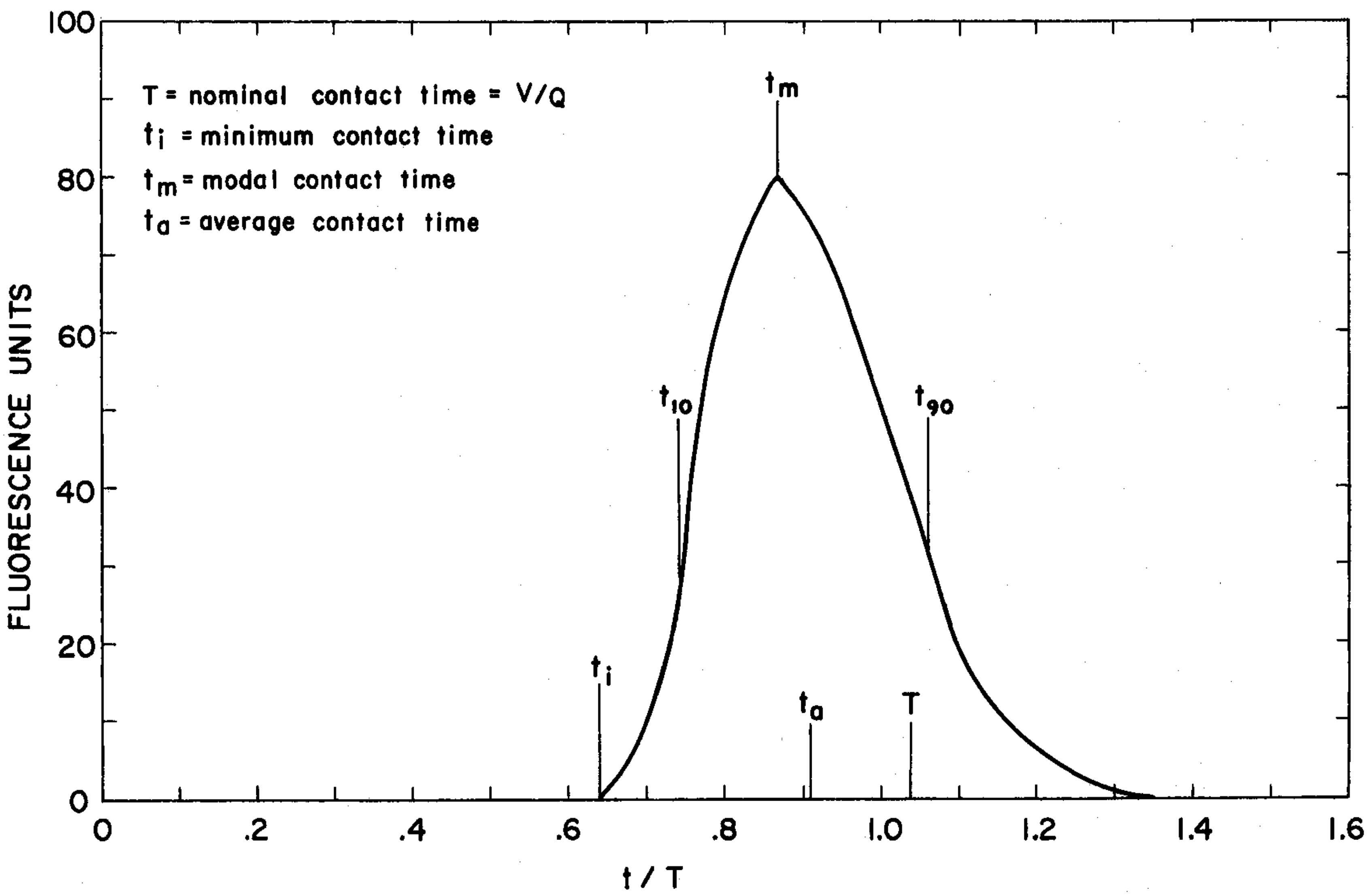


FIGURE 9. DISTRIBUTION OF RESIDENCE TIMES IN A WELL BAFFLED CONTACT TANK

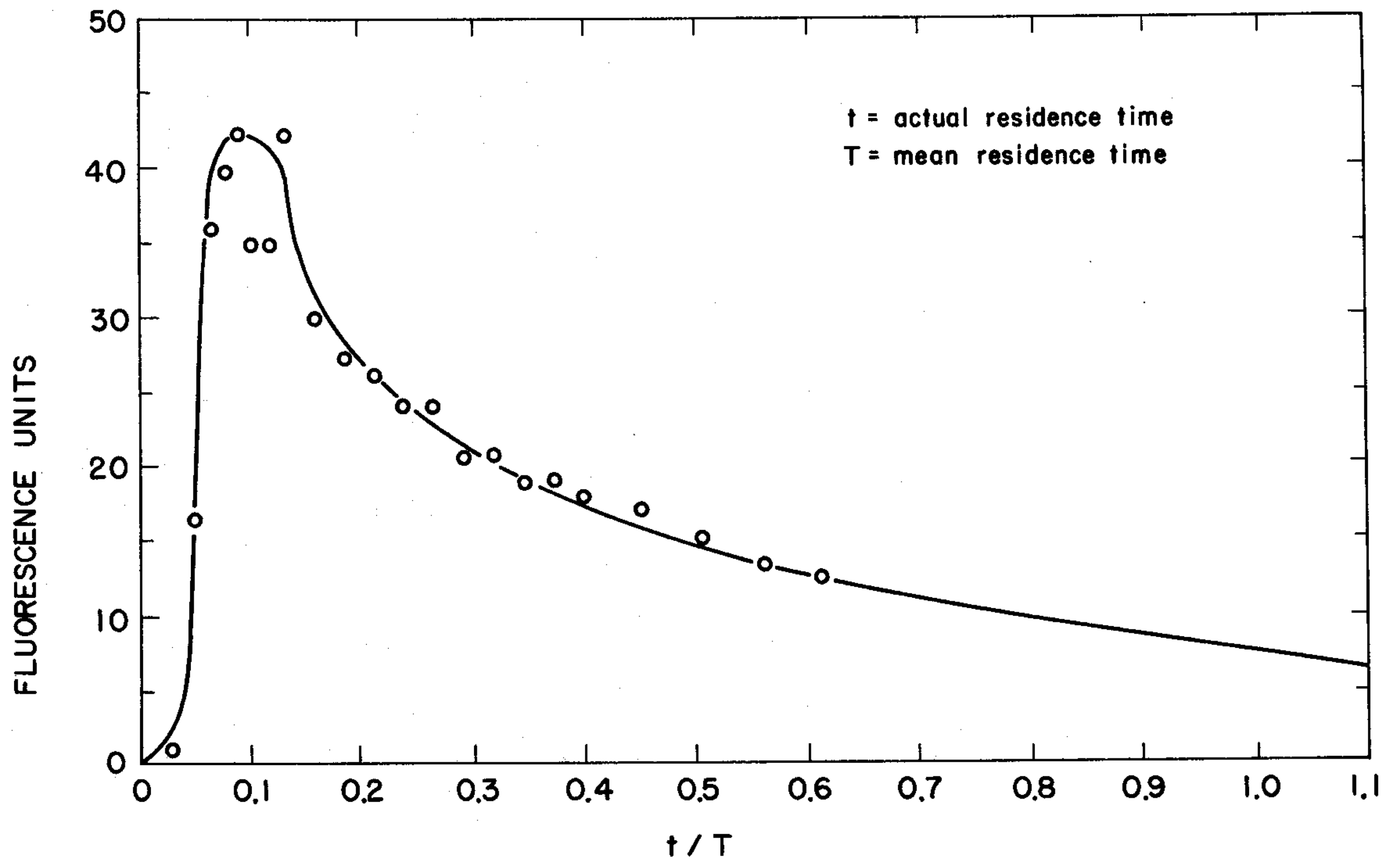


FIGURE 10. DISTRIBUTION OF RESIDENCE TIME IN AN UNBAFFLED CHLORINE CONTACT TANK

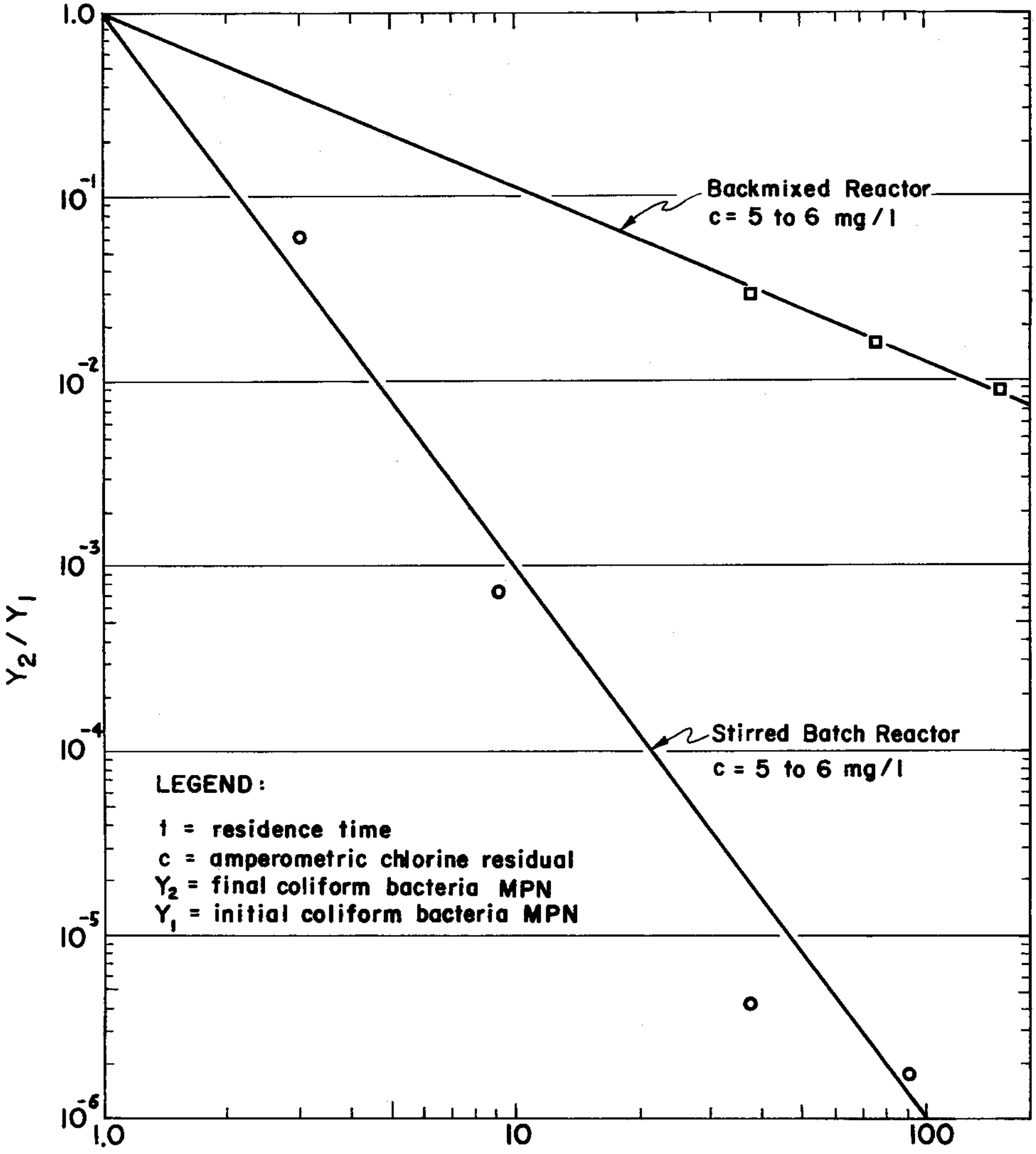


FIGURE 11. COMPARISON OF REACTOR PERFORMANCE

Some of these parameters are illustrated on Figure 9. The initial dye breakthrough time, t_i, is important because it indicates the minimum contact time in the tank. Hydraulic efficiency is further evaluated by means of time ratios to theoretical detention time; i.e., t_i/T, t_{10}/T, t_m/T and t_a/T. The ratio of t_a/T is an indication of dead or inactive space. In the absence of such inactive space $t_a/T = 1.0$. Tracer curves often exhibit a long tail which is due primarily to recycling of tracer from the inactive space. In this case the t_a/T value may exceed 1.0. Rebhuhn and Argaman (22) have presented another method for estimating percent of dead space and plug flow for sedimentation tanks.

The use of the reactor dispersion number, d, is recommended for evaluating contact tank performance (15, 31, 44). The value of d approaches zero for ideal plug flow, and infinity for completely mixed flow. Trussell and Chao (39), on the basis of a mathematical analysis, concluded that a dispersion number of 0.01 was low enough for chlorine contact tanks. However, in the Design Optimization Study (32) it was found that for practical purposes a dispersion number of 0.02 should be adequate.

The dispersion number is computed from the variance of the tracer curve, which for equidistant time intervals is:

$$s_t^2 = \frac{\Sigma\, t^2 C}{\Sigma C} - \left[\frac{\Sigma tC}{\Sigma C}\right]^2, \qquad (14)$$

where s_t^2 = variance of time-concentration curve;

C = tracer concentration at time t; and

t = time, minutes.

The term Δt must be introduced in both nominator and denominator if discrete time intervals are used. This method does not require a knowledge of actual tracer concentrations and can be used with qualitative data, such as fluorometer readings. The variance, s_t, is easy to calculate on a pocket calculator.

Note that $\frac{\Sigma tC}{\Sigma C} = t_a$, the average contact time.

In order to find the dispersion number, the calculated time-variance must be first reduced to dimensionless variance, s^2, as follows:

$$s^2 = s_t^2/t_a^2 \qquad (15)$$

For small amounts of reduced variance, say $s^2 < 0.10$, the second term can be neglected and the dispersion number is:

$$d = 1/2\ s^2. \qquad (17)$$

An example calculation of the dispersion number is shown in the Appendix.

The dispersion number of a pipe can be estimated from the following empirical equation (5, 39):

$$d = 89{,}500\ f^{3.6}\ (D/L)^{0.859} \qquad (18)$$

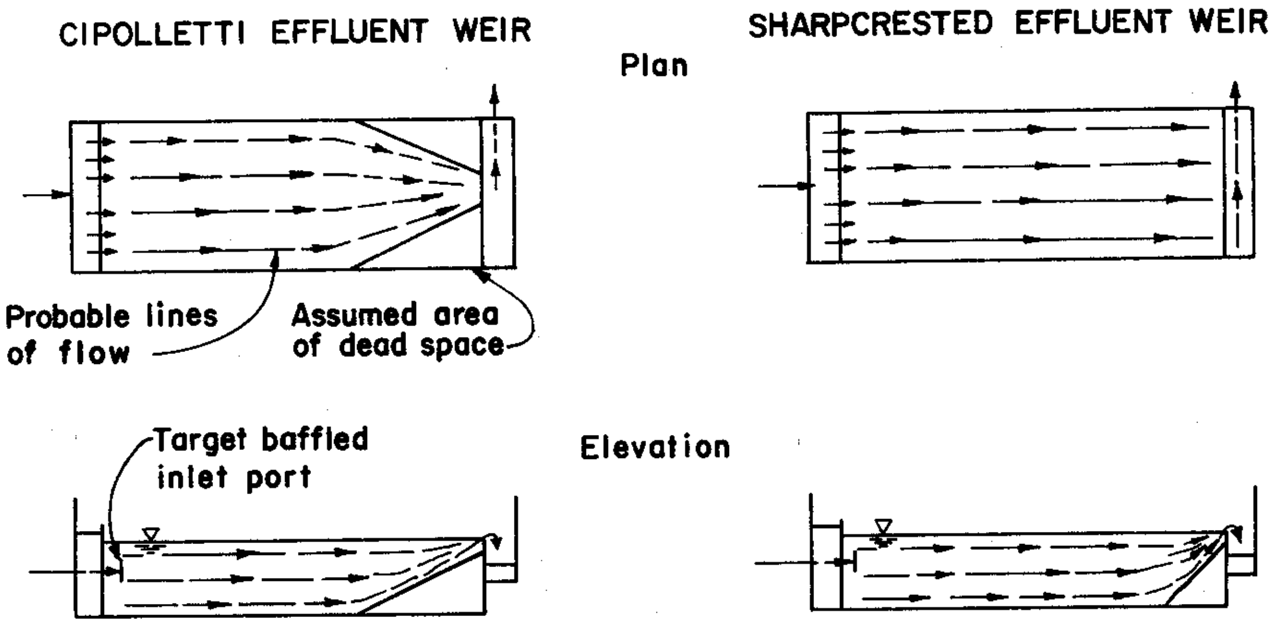
Where D is the pipe diameter, L the pipe length, and f the Darcy–Weisbach friction factor. Equation 18 is reported to be accurate for Reynolds numbers greater than 10,000.

One advantage of using the dispersion number is that it can be used in mathematical models to predict both hydraulic performance and disinfection efficiency. In contrast to the other dispersion parameters which only consider one or two points of the tracer curve, the dispersion number represents an expression of the entire shape of the tracer curve. It should be noted, however, that the dispersion number by itself does not indicate the minimum contact time or the extent of dead space.

Physical Characteristics Affecting Contact Time—Marske and Boyle (17), in a field investigation of chlorine contact tank design, studied the following physical characteristics that are considered in the design of a contact tank: (1) the depth of tank as it relates to the effect of surface wind; (2) the effect of the outlet weir configuration; (3) the effect of serpentine baffling configuration; and (4) the effect of length-to-width ratio. The effects of these physical characteristics are discussed below.

Two tracer tests conducted on a very long, narrow channel approximately three feet deep, indicated that wind may cause surface currents and concomitant short-circuiting. In the tests, a downstream wind resulted in a relative time ratio, t_i/T of 0.36 whereas an upstream wind resulted in a t_i/T of 0.54. Consequently, due to wind effects, a unidirectional, shallow tank or channel may not provide the plug flow distribution of residence times that would be expected from geometrical configuration alone. However, the designer may compensate for these wind-induced surface currents and their concomitant effects on process efficiency as follows: (1) By providing grid type cross baffles at frequent intervals that extend across the entire flow path and about six inches below the water surface; or (2) by providing extra time so that the t_i is adequate to effect disinfection even with strong downstream winds.

Tracer tests, performed on a 3.5 feet wide Cipolleti Weir and on an 18-foot wide sharp-crested weir indicated that all hydraulic performance parameters were improved when the sharp-crested weir was employed. The value of t_i/T increased from 0.19 to 0.27 and the percentage of plug flow in the basin increased from 38 percent to 58 percent. The expected flow patterns for the two weirs studied and the probable lines of flow are shown in Figure 12. The observed hydraulic performance parameters are also included. The data indicate that high weir overflow rates are undesirable. Consequently, it is recommended that in short tanks the weirs extend across the entire width of the final channel of the contact tank. In long channels the effect of weirs probably is minimal.



Performance Parameters

% Plug flow = 38

% Dead space = 21

t_i/T = 0.19

Performance Parameters

% Plug flow = 58

% Dead space = 13

t_i/T = 0.27

(For definition of parameters, see Reference 17)

FIGURE 12. INFLUENCE OF EFFLUENT WEIR CONFIGURATION ON HYDRAULIC EFFICIENCY

A tank designed with a very high length-to-width (L/W) ratio would, of course, begin to approach a pipeline. Site limitations will often make a long pipeline for a chlorine contact tank impractical. Consequently, design engineers frequently use rectangular tanks with special inlet configurations and serpentine baffles to prevent short-circuiting. The length, L, discussed herein is the total length of the flowpath, not necessarily the physical length of the tank.

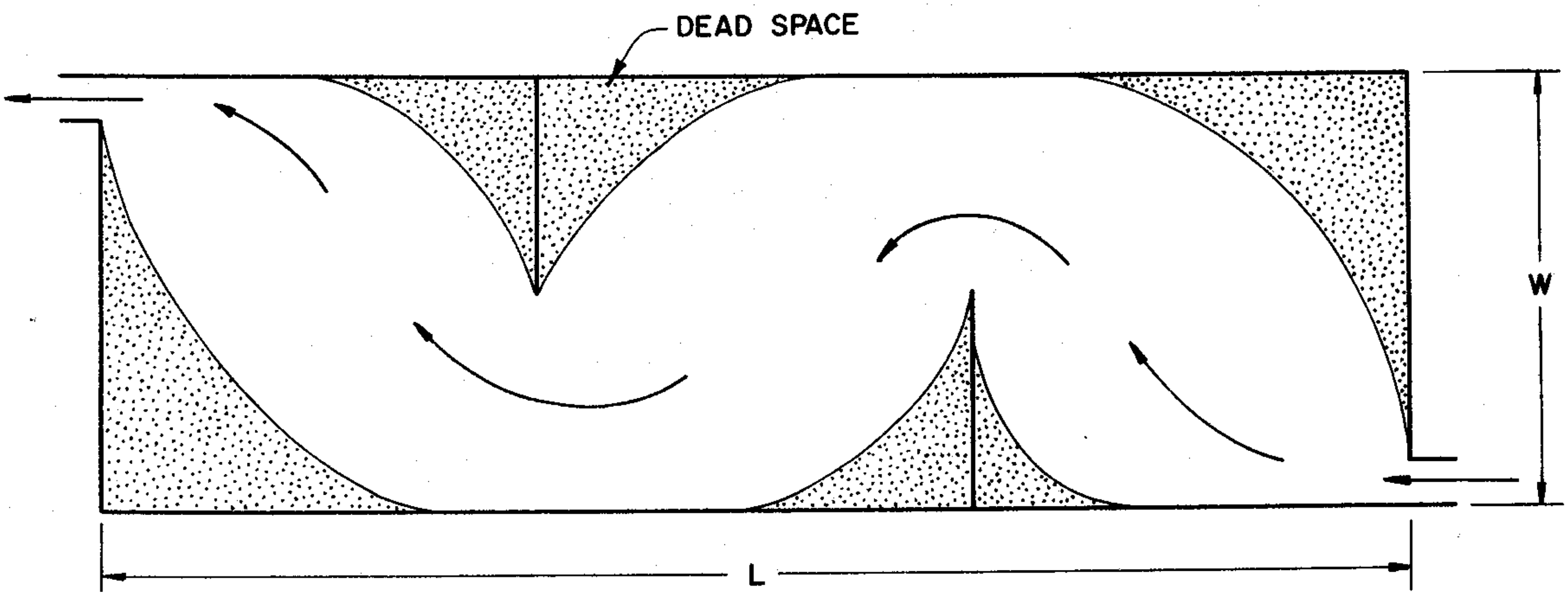
In the past it has been common to install tanks with L/W ratios of 2:1 or less. The tanks have been frequently constructed with only 2 or 3 cross baffles which may only extend to the longitudinal centerline. Such a design will not markedly reduce short-circuiting, nor provide plug flow conditions. A poorly baffled tank of this type is depicted in Figure 13. Increasing the number of cross baffles and extending their length would be an improvement. However, longitudinal baffles give much better results.

By placing the baffles parallel to the longitudinal axis, a much higher L/W ratio can be obtained with the same number of baffles. Figure 14 shows a well-baffled serpentine tank having an effective L/W ratio of 72. The tank functions essentially as a long, narrow channel and is able to provide flow conditions approaching plug flow. Marske and Boyle (17) have indicated that a minimum L/W ratio of 40:1 is necessary to achieve adequate plug flow performance. As the length of the tank increases, the effect of other geometric configurations decreases. Another field study (25) revealed that a dispersion number of 0.015 has been achieved with L/W ratios ranging from 30:1 to 70:1. At the present state of knowledge it is not known why good plug flow is achieved with a relatively small L/W ratio in some tanks and with a large L/W ratio in others.

Field investigations (31) have shown that dead or inactive space may amount to 20—40 percent of total space in some of the existing chlorine contact tanks. The dead space significantly reduces the overall hydraulic performance of a tank and is one of the principal causes for bringing about inadequate contact time. The contamination caused by these dead spaces must also be considered. The dead spaces contain wastewater with chlorine residuals of greatly diminished germicidal efficiency which may allow significant regrowth of coliforms. Therefore, the designer should strive to reduce the amount of dead space to 10 percent or less of the tank volume. Air spargers have been used with varying success in contact tanks to reduce dead space. Rounding off the corners at turns will eliminate most of the dead space in the tank shown on Figure 14. Tracer studies on model tanks may indicate the most desirable configuration for a practical situation.

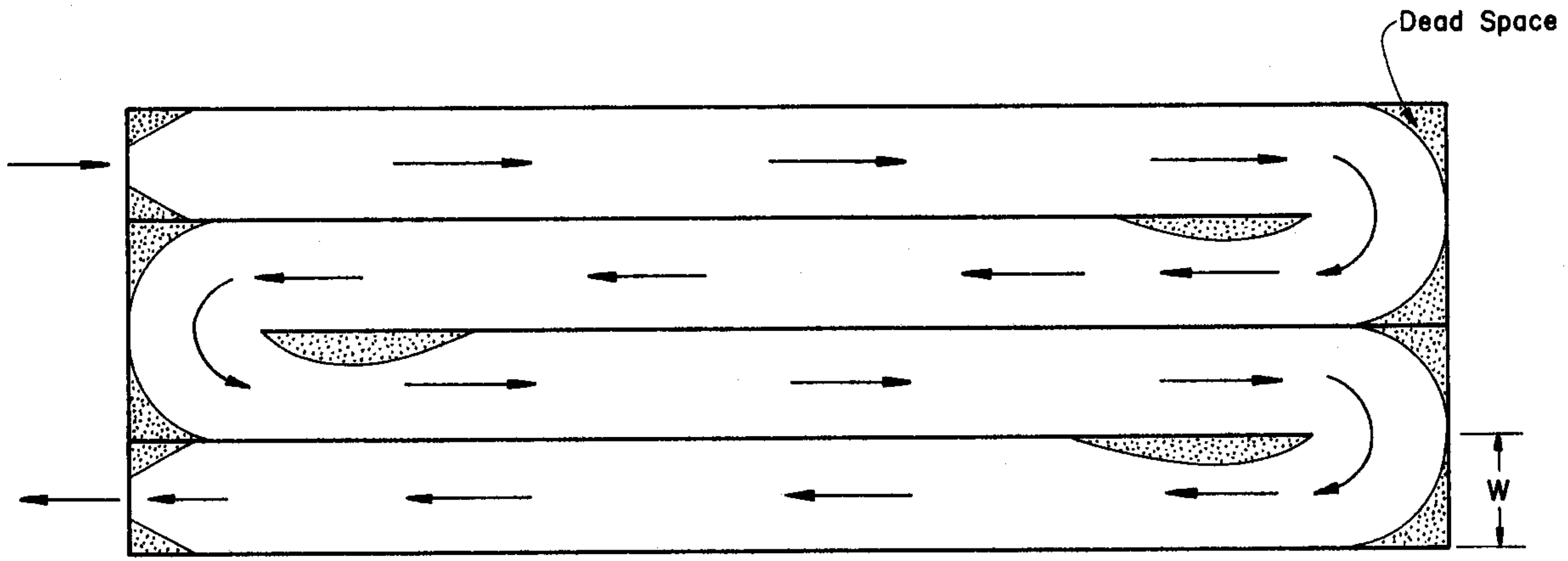
Figure 15 depicts another well-designed chlorine contact tank with longitudinal serpentine baffling. This tank approaches ideal plug flow characteristics and its tracer curve is similar to that shown on Figure 9. The good dispersion characteristics in this tank may be due to the unusually high cross-sectional flow velocity of 0.31 ft/sec (9.5 cm/sec) which, by creating lateral turbulence, practically eliminated all dead spaces.

Trussell and Chao (39), using mathematical analysis, have shown that a dispersion number of 0.01 provides adequate plug flow for chlorine contact tanks. The comprehensive Design Optimization Study (32) has indicated that a dispersion number of 0.02 may be adequate, provided that an adequate t_i is also present. Dye studies on contact tanks (31, 32) have shown that the dispersion number generally decreases with increasing L/W ratios, although the correlation is poor. Figure 16 shows the combined results of these two tracer studies done on 19 different baffled tanks. It is apparent that it would be difficult, but not impossible to design a contact tank which has a dispersion number of 0.01. Figure 16 also shows that a dispersion number of 0.02 can be achieved in most tanks with an L/W ratio of 40:1.



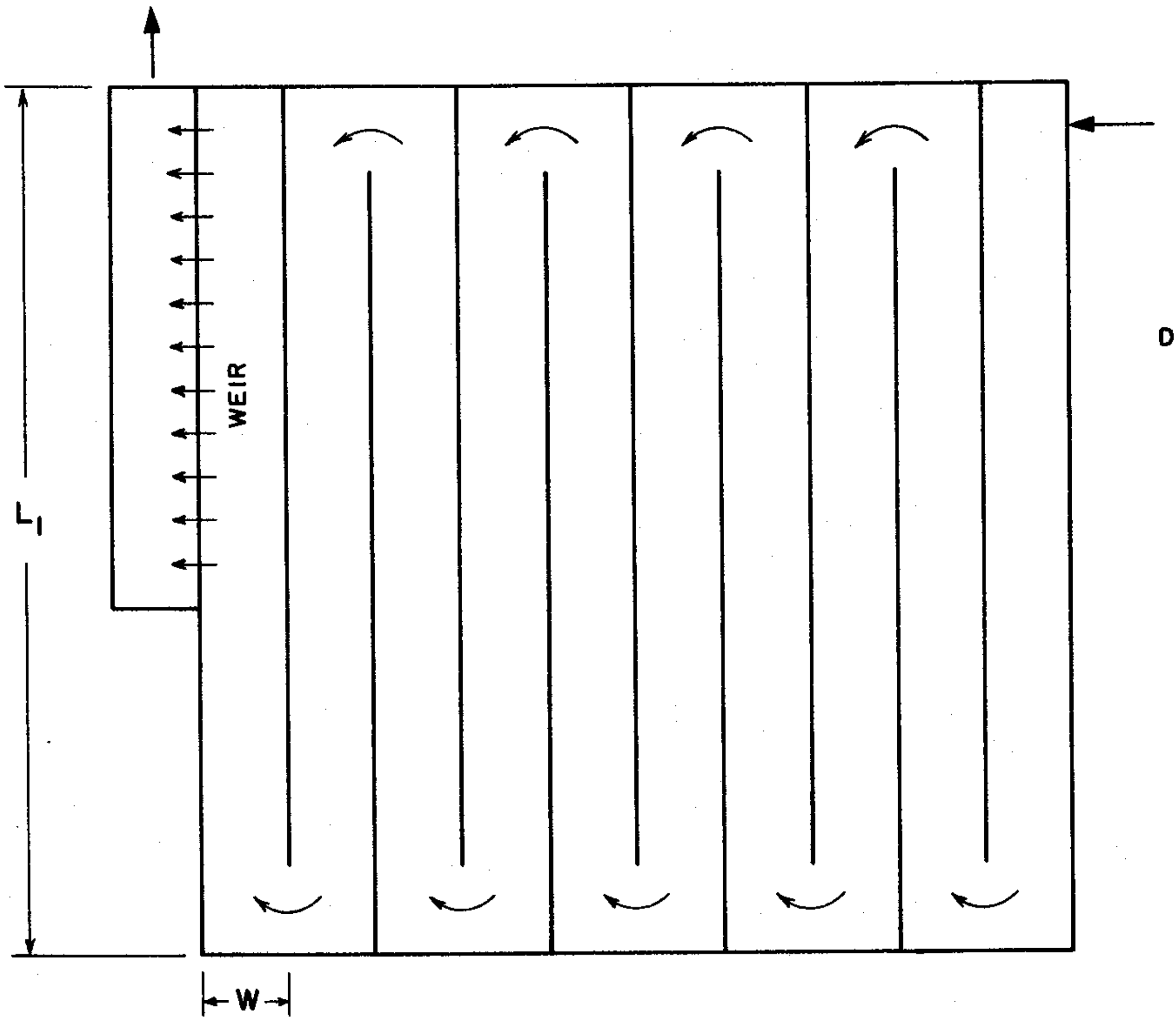
L:W = 3:1

FIGURE 13. A POORLY BAFFLED CONTACT TANK



Flow L : W Ratio = 72 : 1
t_m / T = 0.70
% Plug Flow = 95

FIGURE 14. A WELL DESIGNED CONTACT TANK WITH LONGITUDINAL BAFFLING



DISPERSION VALUES:

$L = 10\,L_1$

$L/W = 100$

$H/W = 1.0$

$d = 0.0054$

$t_i/T = 0.70$

$t_m/T = 0.95$

FIGURE 15. A WELL DESIGNED CONTACT TANK WITH SERPENTINE BAFFLING

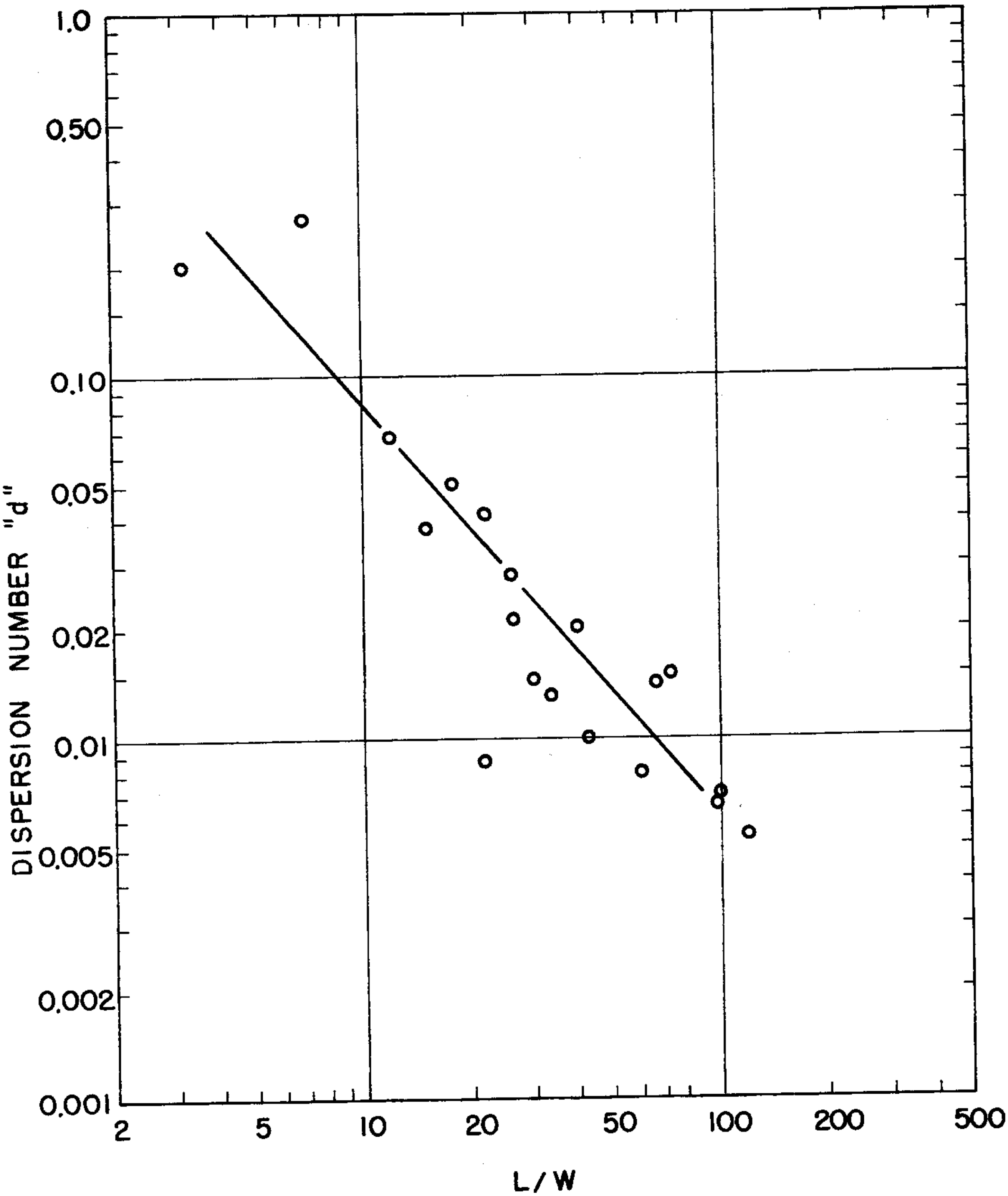


FIGURE 16. CORRELATION OF L/W WITH DISPERSION NUMBER

One of the tanks studied (32), which provided excellent plug flow (d = 0.0085) with a relatively short L/W ratio of 22:1, had a grid type cross baffle at the inlet and a good turning baffle at the 180° turn. The unusually good performance of this tank may have been due to the good baffling. It should be noted, however, that turning baffles, if not properly designed, may actually decrease hydraulic performance by increasing the dead space. The Design Optimization Study (32) has revealed that the use of L/W ratios alone is not sufficient in contact tank design and that the expected t_i value, extent of dead space, and the depth-to-width ratio (H/W ratio) must also be considered. In order to reduce side drag and density currents the H/W ratio should be 1.0 or less. A grid type cross baffle placed near the inlet is beneficial by distributing the flow and reducing short-circuiting. A high flow velocity may help to keep the solids in suspension and will reduce the undesirable dead space.

2.33 Chlorine Supply System

100 and 150 Pound Cylinders—Although most packagers make it available, the 100-pound cylinder is seldom used. The most popular size is the 150-pound cylinder. The gross weight of a full 150-pound cylinder varies from 250 to 285 pounds and the cylinders are best handled by a special two-wheeled hand truck. Each cylinder has a single outlet valve equipped with a fusible plug that will melt at about 158°F.

Weighing scales should always be provided for 100- and 150-pound cylinders. This is the only way that the operator can determine the status of the chlorine supply. For installations which require only one cylinder to be in use, it is desirable to have both the in-use cylinder and the stand-by cylinder installed on separate reading scales. Two-cylinder scales with separate read-out dials are specifically made for such situations. If the withdrawal rate requires more than two cylinders to be in use at a time, there are portable beam scales available that will accommodate a maximum of six 150-pound cylinders.

There are five important design considerations:

1. Direct sunlight must never reach the cylinder.
2. The maximum withdrawal rate should be limited to 40 pounds per day per cylinder.
3. Minimum allowable room temperature is 50°F.
4. Heat must never be applied directly to the cylinder.
5. Sufficient space should be allowed in the supply area for at least one spare cylinder for each one in service.

In general, the chlorine supply area should be kept cooler than the chlorinator. This reduces the possibility of reliquefaction. Installations using 150-pound cylinders are more often than not subject to low withdrawal rates which makes them susceptible to reliquefaction in the piping

Filters and traps ahead of all chlorinator control apparatus are highly desirable. Most small chlorinators have built-in filters which should be preceded by a trap. The latter is an accessory that should be specified.

Ton Containers—Unlike the 150-pound cylinders, either gas or liquid may be withdrawn from ton containers. Consequently, each container has two outlet valves. Also unlike the small cylinders, the ton containers have six fusible plugs—three in each of the two dished heads.

Ton containers are transported by truck or multiple unit tank cars (TMU). A truck can carry a maximum of fourteen containers; a TMU, fifteen.

The gross weight of these containers (3500 pounds) dictates that proper handling equipment be used. The container is designed for use in the horizontal position, and must be positioned before connecting to the supply header so that the two outlet valves line up vertically, one over the other. In this position, the eductor tube connected to the top valve is in the gas withdrawal position, and the eductor tube connected to the bottom valve is in the liquid withdrawal position.

Proper handling equipment includes the following:

1. Two-ton capacity electric hoist.
2. Cylinder lifting bar.
3. Cylinder trunnions.
4. Monorail for hoist.

The trunnions are used primarily to easily position the cylinder outlet valves. In addition, the trunnions provide support and proper spacing for the cylinders.

One of the critical design dimensions is the height of the monorail above the floor. The primary criterion is that the monorail be high enough to pick up a cylinder off the truck and have sufficient clearance to lift one cylinder over another that is connected to the header.

At room temperature the allowable continuous withdrawal rate from a ton cylinder is 400 pounds per day. Theoretically, gas withdrawal can be used up to any capacity if enough cylinders are connected to the supply header. However, when the system withdrawal rate reaches 1500 pounds per day, it is logical to change over to liquid withdrawal which requires the use of an evaporator.

For gas withdrawal rates up to 1500 pounds per day, cylinder space should be provided for four cylinders in service, four standby cylinders, and four empty spaces for the next delivery. A further consideration for providing storage space is the cost reduction for quantity delivery of containers.

Gas withdrawal systems using ton containers require the same considerations as those for smaller cylinders. Never let the sun shine directly on the cylinders and never apply heat directly to the cylinders. If it is not possible to keep the cylinders cooler than the chlorinators, then it is highly desirable to install an external pressure reducing valve immediately downstream from the last cylinder. Just upstream from this valve a combination filter and sediment trap should also be installed.

Liquid withdrawal systems are not affected by temperature variations or temperature conditions as gas withdrawal systems are. For example, all that is required for a liquid system is a carport type of structure that will prevent the sun from shining on the cylinders. This precaution prevents stressing the fusible plugs in the cylinders. However, a gas withdrawal system should be completely contained in a building and should include the ancillary devices described above.

A liquid system should be designed to take care of inadvertent trapping of the liquid between the containers and the evaporators. This is accomplished by expansion tanks. These expansion tanks are imperative if the liquid chlorine storage area is remote from the chlorinator room. They are highly desirable on any liquid withdrawal system. The Chlorine Institute approved arrangement is shown in Figure 17. It utilizes a frangible disc which ruptures at about 450 psi. This allows liquid to go into the tank which activates the pressure alarm switch. This device is necessary to protect the system against the condition where an operator might close both the cylinder outlet valve (or auxiliary header valve) and the liquid inlet valve on the evaporator. Any subsequent ambient temperature rise would result in a pressure increase in the liquid chlorine sufficient to rupture the header piping.

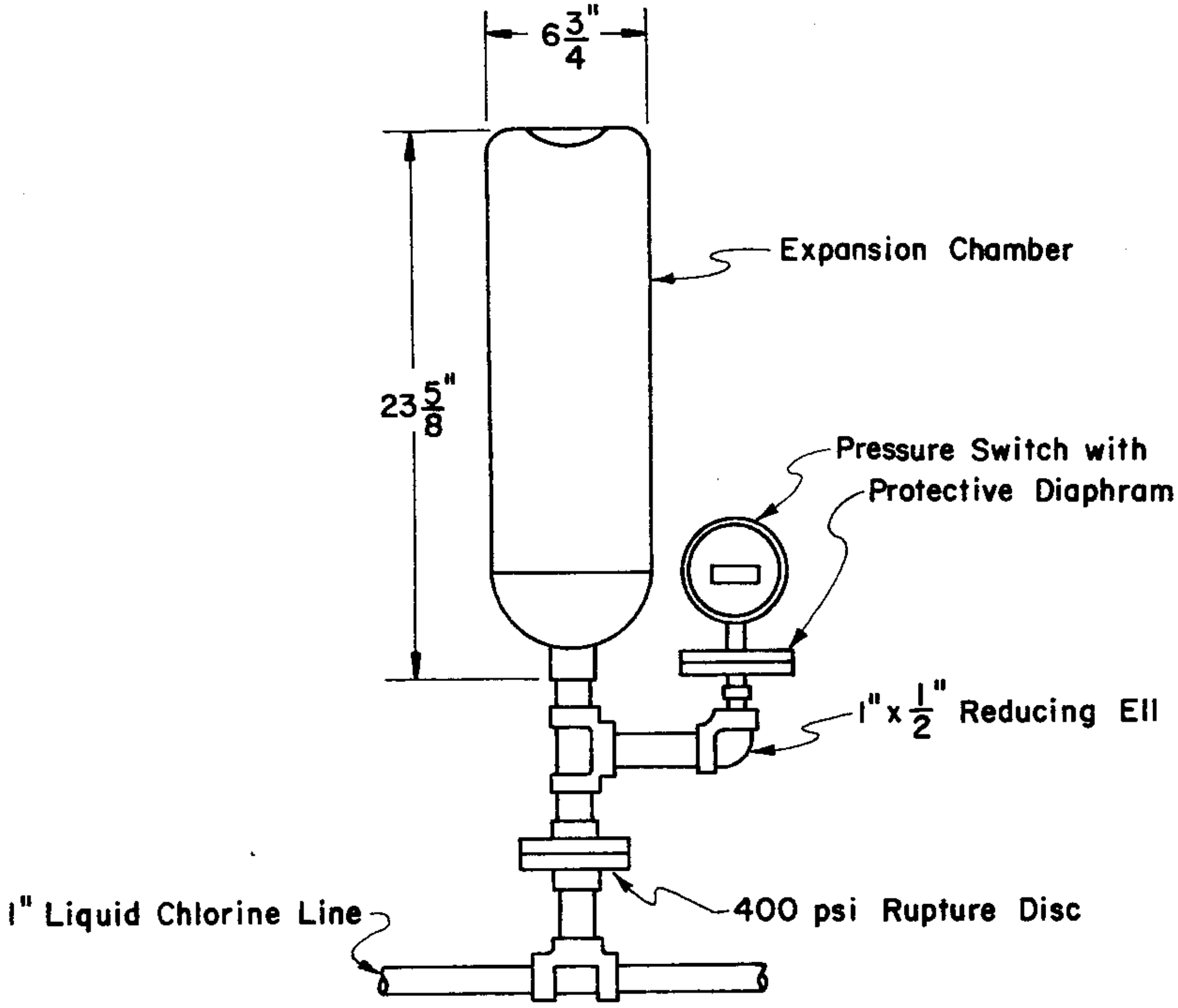
There is no need to install filters or reducing valves on the liquid lines. Liquid chlorine cannot be filtered nor can it be reduced in pressure. Even though there are subtle differences between gas and liquid systems and while a gas system can be easily modified to accommodate liquid chlorine the system should be designed for one or the other, not both.

A note of caution about manifolding ton containers withdrawing liquid: Always be certain that the temperature of the cylinders to be manifolded is about the same; never connect "hot" cylinders to the manifold simultaneously with cylinders already in use. The danger here is that the hot cylinder could easily overfill one in use which is cooler and therefore is at a lower pressure. Overfilling a container leads directly to vessel rupture.

However, the manifolding of containers withdrawing gas is a totally different situation. A hot cylinder connected along with cool cylinders will take over the entire chore of gas withdrawal until its pressure is reduced to that of the cool cylinders; then all cylinders connected will share equally the withdrawal rate. This is the principle upon which the automatic switch-over system operates.

It is not only desirable but should be imperative that both liquid and gas withdrawal supply systems incorporate the use of duplicate headers for two very good reasons: (1) These headers when used for gas withdrawal must be cleaned frequently; about once a year or 75 tons of chlorine—whichever is sooner. A liquid system should be cleaned about once per year or 250 tons of chlorine—whichever is sooner. (2) The second header can be used to divert a leaking container or evaporator to the chlorine absorption tank thus avoiding a dangerous chlorine spill.

Pressure gages, switches, and alarms are desirable in the chlorine supply system. A gas with-



Notes : <u>Connection is to liquid phase only</u> !

All fittings 2000# C.W.P. Forged Steel

All piping seamless Carbon Steel Sch 80

Use Teflon Tape at all threaded joints

From Chlorine Institute Dwg. 136

FIGURE 17. LIQUID CHLORINE EXPANSION CHAMBER

Every installation using ton containers should be equipped with a Chlorine Institute Ton Container Emergency Kit. This kit is designed to seal off a ton container that develops a leaking fusible plug or outlet valve as well as any small leak in the container shell. (See "Safety Equipment" in Section 2.34.)

Evaporators—When the rate of chlorine withdrawal exceeds 1500 pounds per day an evaporator should be used. This changes the supply system to liquid withdrawal which has different characteristics than gas withdrawal systems as described above.

Evaporators are available in sizes from 4000 pounds/day to 8000 pounds/day. Since liquid withdrawal rates from a single ton container can easily satisfy the needs of one 8000 pounds/day evaporator it follows that evaporators can be used to conserve space necessary for cylinder storage. The optimum storage requirements should be based on the quantity-discount price break offered by the local supplier. This usually occurs at a quantity of five. This dictates storage space for fifteen cylinders, five in service, five empties and a vacant space for five incoming cylinders.

The most widely used evaporator is the electric heater type. These units are equipped with G. E. Calrod heating elements. A well-designed evaporator must have a wide margin of safety to allow for the accumulation of sludge which is inherent in handling of liquid chlorine. Therefore, to provide a sufficient safety factor, ,the vaporized chlorine gas must demonstrate at least 20°F of superheat to prevent carryover of liquid chlorine into the chlorinators. The result of this gas withdrawal which is beyond the reserve capacity of the evaporator would be devastating to the chlorinator.

Other types of evaporators are the recirculated hot water type and the low pressure steam injection system.

Integral with the evaporator is the electrically interlocked chlorine pressure reducing and shutoff valve. Normally the water bath temperature is maintained between 160°F and 180°F. When the water bath temperature falls to 150°F this valve is closed on the assumption that the heat to the water bath has somehow failed. This protects the chlorinator from severe damage.

All evaporators should be equipped with a cathodic protection system that protects both the water bath tank and the outside of the chlorine container vessel from aggressive water corrosion. The outside of the water bath should be insulated.

Accessories that are consistent with good practice but are still considered optional are: a gas temperature gage and an automatic water level control of the water bath.

The electric heater type requires a 3-wire 240 or 480 V circuit for the heater elements in the water bath. The load requirement is 12 KW for 6000 pounds/day and 18 KW for 8000 pounds/day. A two-wire 120 V circuit is needed for the chlorine shutoff valve, the high and low temperature alarms, solenoid valve on water bath make-up line, water level pressure switch, and alarms for these functions.

As of December 1975 all evaporators must be equipped with a pressure relief device. This development is described in detail in Reference 44, pages 86–89. Current practice is for the evaporator manufacturer to provide as optional equipment a pressure relief system for all types of evaporators. This is done to satisfy the legal requirements of unfired pressure vessels. The basic requirement of this relief system is to relieve the pressure on the gas phase (evaporator discharge) side through a frangible disc and a spring loaded relief valve. The frangible disc protects the relief valve from the corrosive chlorine or sulfur dioxide gas during the long periods of inactivity. During

Single-Unit Tank Cars—Chlorine is available in five sizes of single unit cars: 16, 30, 55, 85, and 90 tons. Each car is equipped with an outlet dome that is made identical for all tank cars approved by the Chlorine Institute. This dome contains two liquid outlet valves that are in line with the longitudinal axis of the car and two gas outlet valves on an axis at right angles to the liquid valves. In the very center of the dome is a safety relief valve that will expel gas to atmosphere under overpressure conditions. In each liquid outlet line, there is installed a safety check valve described as an excess flow valve. In case the car is in an accident and the valves are sheared off, the check valves will jam in a shut tight position due to the momentary velocity of the liquid exiting through the sheared off valve. This is why any tank car withdrawal system should be equipped with a rotameter to see that the unloading rate is less than that which will cause the check valve to jam closed. This rate varies from 7,000 pounds per hour for 30 ton cars up to 15,000 pounds per hour for 90 ton car.

For the layout of a single-unit car unloading site, the designer should consult the latest edition of the Chlorine Institute Manual (2) which includes recommended unloading facilities, precautions, and federal regulations.

The usual chlorine tank car system includes one car as the supply unit and one as the standby unit. Therefore, two separate liquid chlorine headers should be provided (one for each car) between the tank car platform and the chlorination equipment. One additional line should also be furnished. This one is for chlorine gas flow but can also be a standby for either of the above-described liquid lines. This gas withdrawal line can also be used as the connection for the air padding system if called for. One of the most important functions of this "separate" gas line is to remove excess air padding in the tank car and to reduce its vapor pressure in the event of a leak.

Air padding systems are sometimes imperative for tank car unloading operations. While not always necessary, whenever it is used the system should include an air drying system capable of providing dry air with a dewpoint of −40°F. This system should also include a humidity alarm switch.

Gages should be provided in both headers just downstream from the flexible connections to the car and on the loading platform. An expansion tank with a pressure alarm switch, as illustrated in Figure 17, should be provided on the liquid header piping.

Weighing scales for the tank cars are the only accurate method of determining the status of the car contents and these track scales are extremely expensive.

Weighing Scales—The subject of scales has been discussed for the separate types of chlorine containers. The appropriate type of weighing equipment is an essential feature of each chlorination installation. It is not possible to measure and record the flow of liquid chlorine in conventional measuring devices with any accuracy due to the characteristics of liquid chlorine. As the liquid flows past a point of slight pressure drop as in a rotameter, the liquid flashes to gas causing a great change in density. This makes calibration of a flow meter practically impossible. A magnetic meter will not respond to liquid chlorine. An alternative is to equip each chlorinator with a chlorine gas flow recorder. A record of the amount used will give the operator a good idea of how much is left but here again, the accuracy of these devices is far from that provided by a weighing scale.

There is one additional way to alert operating personnel to imminent loss of chlorine supply in a tank car. This is to install a recording thermometer with an alarm switch on the liquid line adjacent to the tank car connection. As the car runs out of liquid chlorine, the temperature drops dramatically. This condition will sound an alarm. After the liquid has been exhausted, a 55 ton car will still be able to provide about 650 pounds of gaseous chlorine at 70°F before the pressure drops below 30 psi.

Materials of Construction—The chlorine supply system should consist of steel and cast iron products. The supply system is defined as that part of the system that begins at the chlorine containers and terminates at the inlet to the chlorinator. From the chlorinator and beyond, the materials of construction are entirely different and are discussed elsewhere (see Section 2.35).

The supply system piping must be Schedule 80 black seamless steel and fittings must be 2,000-pound forged steel. Do not use bushings (they cannot meet the 2,000-pound criterion). Use reducing fittings instead.

All unions should be ammonia type with a lead gasket joint. Never use a ground joint union. Filter bodies and reducing valve bodies are usually cast iron. Expansion tanks should be of welded steel construction, but can be a standard 100- or 150-pound chlorine cylinder. Valves for the chlorine supply system should be Chlorine Institute approved. Two types of valves are used, one is for main line shutoff purposes and the other for isolating cylinders (header valves). Header valves are identical to the outlet valves of ton containers: bronze bodies with monel seat and stem. Main line valves can be either the ball type or rising stem type. The ball type is more popular because it utilizes a lever which not only indicates at a glance the position of the valve, but also makes it easier to operate the valve.

All gages on the supply system must be equipped with a protector diaphragm. The diaphragm should be of silver and the diaphragm housing can be either Hastelloy "C" or silver cladded steel. Shutoff valves should not be used ahead of gages. Gages require a minimum of maintenance so that when they need to be replaced, the entire supply line should be drained of pressure before replacing or removing the gage. The value of a shutoff valve for this purpose is lost, because a valve in a chlorine supply system loses it reliability if it is not operated on a frequent basis.

In assembling the piping system, either welded or threaded construction can be used. Welded is preferable. If threaded construction is used, the contractor must be cautioned to use sharp dies and all threaded pipe must be cleaned with solvent before assembly. Pipe dope should not be allowed. Do not use solvents containing hydrocarbons or alcohol. A suitable thread lubricant should be carefully applied to each joint. Teflon tape is satisfactory for threaded pipes up to one inch in diameter. It is a rarity for chlorine supply lines to be larger than one inch. Other lubricants can be: John Crane Plastic Lead Seal No. 2; a mixture of linseed oil and graphite; a mixture of linseed oil and white lead; or a mixture of litharge and glycerine. The latter must be prepared as a heavy syrup-like consistency from litharge powder and glycerine. (See page 173, Reference 44).

2.34 Chlorine Control Systems

Capacity—The first step in the design of a chlorination facility is to determine the maximum chlorine dosage needed for the given situation, including prechlorination, intermediate and postchlorination applications. While this manual is specific for disinfection (postchlorination), total capacity must include the requirements for the other purposes stated above. Chlorinators should be divided into two groups: one group for prechlorination and intermediate point of application; the other group for postchlorination (disinfection). Equipment should be arranged so that the first group can provide standby service for the disinfection equipment. A third group may be desirable if both pre- and postchlorination is to be continuous. The third group should be arranged for both intermediate chlorination and standby for either pre- or postchlorination.

Chlorinator capacity is a function of flow signal and chlorine demand of the wastewater. Attention is called here to the term "flow signal." Since it is imperative that chlorine feed rate be controlled in proportion to flow, the chlorinator capacity must be sized to the capacity of the plant flow meter. While it is true that chlorinators have overriding dosage control, this feature must be reserved for variations in chlorine demand of the wastewater. For example: at a proposed plant, the flow meter that is to be used for plant flow measurement has a range of 0 to 10 mgd, which is the ultimate design capacity of the facility. Furthermore, the chlorine demand is to be a maximum of 150 pounds per million gallons. The chlorinator capacity for that plant must be 10 x 150 = 1,500

Effluents that are treated to a free chlorine residual require about 9 parts of chlorine for each part of ammonia nitrogen.

If industrial wastes are present to the extent of 10 to 25 percent of the total wastewater flow, it may be necessary to increase the chlorine requirement for primary effluents by a factor of two and perhaps more depending on the nature of the wastes. This may apply to secondary effluents as well, depending on how effectively the treatment process can cope with the industrial waste. The more uncertain the factor of industrial waste, the more uncertain becomes the needed quantity of chlorine for disinfection. In this case, laboratory estimation of chlorine demand will be necessary.

Methods of Control—Chlorinators for both pre- and postchlorination should be provided with flow proportional control. The prechlorinator should be controlled from the plant influent flow meter and the postchlorinator from an effluent flow meter. Never attempt to control the postchlorinator from the influent flow meter or vice-versa; it will not work because of the lag time between the two measuring points. As discussed previously, the flow proportional signal should be used to control the chlorine metering orifice in the chlorinator. This can be done either pneumatically or electrically. If it is to be pneumatic, the signal must be linear (3—15 psi). If it is to be done electrically, there are a variety of linear signals. The one most preferred is the analog milliamp signal with outputs of 1—5; 4—20; and 10—50 milliamps. The most common is 4—20 ma.

gage calibrated from 0—100 inches of H_2O. However, it should be noted that this type of system is not compatible with dechlorination requirements. Therefore, any system needing sulfur dioxide dechlorination cannot operate solely on chlorine residual signal.

A critical factor in the success of the feedback residual control systems described above is loop time. This should be kept as short as possible (less than 3—4 minutes). Assuming proper mixing at the point of application, a representative sample for the analyzer should be taken downstream from the chlorine mixing device within 45 seconds after the application of chlorine at average flow. At peak flow this time would be reduced to about 20 seconds. However, it will take the sample another 45 to 60 seconds to reach the cell since it has to pass through a filter and internal piping within the analyzer; therefore, the earliest time the sample can reach the measuring cell is about 1½ to 2 minutes after the chlorine has been mixed with the wastewater. If the chlorine has been well mixed, the control residual will lie on the flat part of the residual die away curve shown in Figure 18. Another mandatory requirement of a well-designed system is to utilize the remote injector concept by installing the injector as close to the point of application as is physically possible. The average loop time should be on the order of 2 minutes with a maximum not to exceed 5 minutes.

Where dechlorination is used, a second analyzer is required at the end of the chlorine contact tank to control the sulfonator feed rate which provides the necessary dechlorination. This unit also provides the operator with the information necessary to operate the disinfection process because he is concerned with the chlorine residual at the end of the contact time. This residual is the crucial parameter for determining the effectiveness of disinfection by chlorine.

Sample Lines—All sample lines to the various analyzers should be designed so that they can be easily purged of slime layers and other organic debris. Biofouling of sample lines introduces significant errors in the analyzer system by creating a false chlorine demand due to dechlorination in the line. The sample lines carrying a dechlorinated effluent are particularly vulnerable to biofouling.

Sample lines should be designed to provide velocities up to 10 feet per second. This acts to decrease dead time in the control loop and produces some scouring action thereby inhibiting buildup of slime layers in the piping.

A most important consideration is the sampling point for coliform bacteria determination. It is best to use the sample line to the chlorine residual analyzer monitoring the residual at the end of the contact tank for this purpose. Under no circumstance should the coliform sample be taken closer than 5 feet upstream from the SO_2 diffuser. If the effluent discharge is to waters where tides can affect this area, special provisions have to be made for sampling, such as sampling at low tide.

Effluent Flow Meter—As indicated before, the postchlorinator should be controlled from the effluent flow meter. However, the location of the flow meter in relation to the treatment units is important. In some cases the effluent flow may be subject to frequent fluctuations which make the adjustment of the chlorine dosage difficult, resulting in the waste of chlorine. This happens where the sewage flow is subject to frequent pumping. It also occurs in plants using filtration during the filter backwash cycle. The effluent flow meter should be placed in a location where the fluctuations in flow are the least, such as at the end of the chlorine contact tank. Where filters are used, it may be better to locate the flow meter ahead of the filtration unit in order to prevent the disruption of flow signal by the backwash cycle.

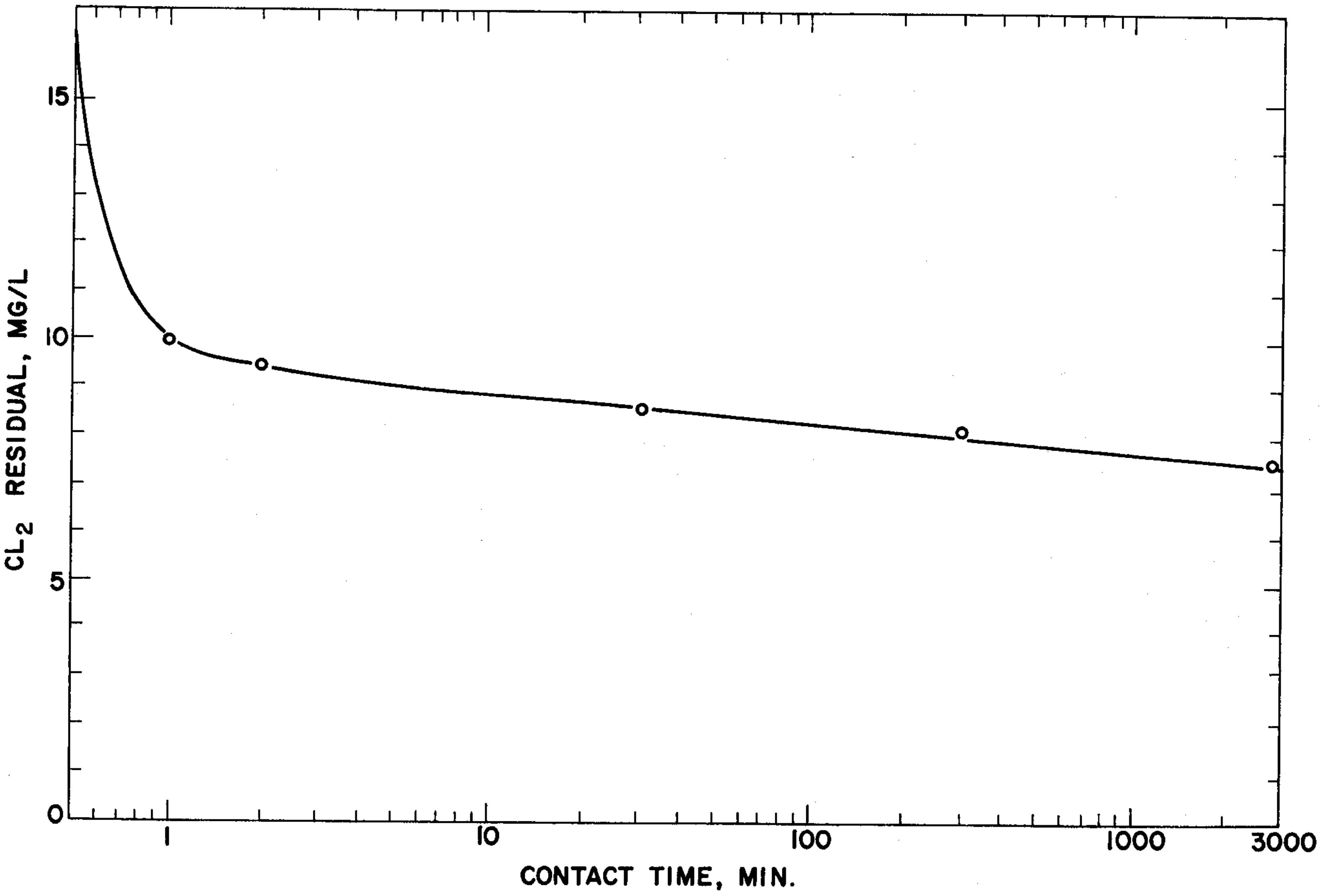


FIGURE 18. A CHLORINE RESIDUAL DIE-AWAY CURVE

Alarms—Every chlorination facility should have an alarm system that adequately alerts the operators in the event of deficiencies, malfunction, or hazardous situations related to chlorine supply, chlorine metering equipment, chlorine leaks, and chlorine residual.

The chlorine supply system should be monitored for chlorine leaks and low pressure which indicates loss of supply. High pressure alarms are only appropriate for liquid withdrawal systems. Pressure alarms are triggered by high and low pressure switches. Chlorine leaks in the supply and control area should be monitored by a permanent chlorine leak detector and alarm that meets OSHA requirements. The detector should be capable of sensing atmospheric chlorine concentrations as low as one ppm (by volume).

The chlorinators should be equipped with high and low vacuum sensing devices. Low vacuum signifies failure of the injector system and high vacuum signifies loss of chlorine supply. Either of these is indicated by a vacuum switch.

Installations using evaporators require alarms for warning of high and low water bath temperature and low water bath level.

Chlorine residual control analyzers should be equipped with adjustable high and low residual alarms.

Systems using tank cars, storage tanks, or tank trucks that involve air padding system should have a high humidity alarm on the dried compressed air supply.

Monitoring Equipment—In addition to the chlorine leak detector previously described, two categories of monitoring equipment may be utilized. One is for monitoring chlorine residual at the end of the contact chamber, and the other is for recording of chlorine flow through the chlorinator.

It is desirable to install an amperometric chlorine residual analyzer/recorder to record the chlorine residual in the effluent from the contact chamber. This unit will be in addition to the analyzer used in the chlorine control system. (See Figure 5.) The effluent monitor will insure against the loss of residual in the chlorine contact tank and thus help to prevent improper disinfection and the proliferation of slime growths in the contact tank. Where dechlorination is required the analyzer at the end of the contact tank is necessary for automatic control of the sulfonator.

The effluent monitor residual recorder and the control residual recorder should both be furnished with identical capabilities so that one can be a standby for the other.

Continuous recording of the amount of chlorine applied by each chlorinator provides valuable information, particularly for trouble-shooting the residual control process. Malfunctions in the system are readily identified when the chlorine feed rate can be compared with the chlorine residual chart at any given moment. Facilities utilizing chlorine residual control should have each chlorinator equipped with individual chlorine flow recorders.

Recorders should also be provided for the plant effluent flow meters so that the flow for any given moment can be compared with chlorine residual and chlorine dosage.

Safety Equipment—Certain items of safety equipment should be provided for the operators. This equipment consists of, but is not limited to, the following:

1. Breathing apparatus.
2. Chlorine absorption tank.
3. Emergency chlorine container repair kits.
4. Chlorine leak detector.
5. Expansion tanks.

There are two types of breathing apparatus—the canister-type gas mask and the oxygen or air-type breathing unit. The canister-type gas mask is limited in effectiveness to changing chlorine cylinders or normal maintenance work. It is not satisfactory for use in repairing a leak. Therefore, either of the following type equipment, or equivalent, should be furnished: the air-tank type breathing unit with thirty minutes air supply as manufactured by MSA or Scott Aviation Company; or the oxygen-breathing apparatus as manufactured by MSA (Mine Safety Appliance Company). The latter is similar to a canister type. When the seal on the unit is broken, the unit manufactures its own oxygen which lasts for forty-five minutes. These canisters must be discarded after the seal is once broken.

Emergency chlorine container repair kits are available for 100- and 150-pound cylinders, ton containers, tank cars, and storage tanks. These are identified as Chlorine Institute Emergency Container Kits. It is imperative that the appropriate kit be provided for installations using ton containers, tank cars, or storage tanks. Should an operation involve the storage of four or more 150-pound cylinders, it would also be advisable to have an emergency container kit available.

A suitable continuous chlorine leak detector should be furnished for every chlorination station, regardless of the size of containers. This is not only desirable from a safety viewpoint but is necessary to meet the OSHA personnel safety requirements. Leak detectors are equipped with circuitry to actuate external alarms. Leak detectors have been described under "Alarms."

The use of expansion tanks with frangible discs is described in the section on chlorine supply. These devices are used only on liquid supply systems when it might be possible to trap liquid chlorine in a section of pipe or in the evaporator. (See Figure 17.)

2.35 Injector System

Description—The injector system is the heart of the entire chlorination facility. If this system is inoperable, no other part of the system can function. The injector puts the chlorine gas into solution and carries it to the point of application. The various parts of this system include: the operating water supply to the injector; the injector; the injector vacuum line from the chlorinator; the injector discharge system described as the chlorine solution line; and the diffuser at the point of application.

Water Supply—The injector must pull a specified vacuum in order to move the chlorine from the supply system through the chlorinator, dissolve it into the injector water supply, and carry it to the point of application. This requires a specified amount of water—about 40 gallons of water per day per pound of chlorine, more or less depending on the conditions. The amount of water must be enough to maintain a chlorine solution strength not to exceed 3500 mg/l. Therefore, the amount of water is a function of the amount of chlorine being fed to the system. A second factor is the pressure at the point of application of the chlorine. This is known as injector back pressure. Higher back pressure requires high injector inlet pressures and more operating water to make the injector function properly. The injector also has minimum operating water requirements. Chlorination equipment manufacturers use injector operating curves that specify how much water at what pressure is required for a given amount of chlorine to be applied against a given back pressure. It is the designer's responsibility to make a hydraulic analysis of the chlorine solution line between the injector and the point of application to establish the amount of back pressure to be expected. With this information and the maximum chlorine feed rate desired, the chlorinator manufacturer can advise regarding the necessary water supply inlet pressure at the injector and the optimum injector operating water quantity. The back pressure should never be allowed to fall below four feet at the injector discharge. (See the section on Diffusers.) A negative head in the chlorine solution line causes release of molecular chlorine at the point of application.

Injector Pumps—In most systems, injector water supply pumps must be furnished. The choice of pump is between a turbine type or a centrifugal type. These two types of pumps have widely

The following features should be included in all remote injector installations. The vacuum line between the chlorinator and the injector should be sized so that the total pressure drop in this line is not more than one and one-half inches Hg regardless of vacuum line length. A shutoff valve should be provided at each end of this vacuum line. A vacuum gage should be installed adjacent to, but downstream from, the shutoff valve at the injector end. The injector should always be installed in a horizontal position to achieve a low profile (better hydraulics) and to allow easy disassembly of the injector. Additional details of injector design and performance are given by White (Chapter 3 of Reference 44).

Flow Meters—Large chlorinator installations that use either the three- or four-inch adjustable injectors should be provided with some type of flow meter on the water inlet to each injector. Propeller meters with rate indication are quite satisfactory. This allows the operator to make the proper adjustment to the injector to insure maximum efficiency, proper chlorine solution strength and adequate back pressure.

Gages and Alarms—Gages should be provided to show the injector operating water pressure for each injector in the system. Chlorinators cannot operate without sufficient injector water pressure. Each injector should be provided with a chlorine solution pressure gage mounted immediately downstream from injector discharge. These must be compound gages reading to 30 inches Hg vacuum and to 30 psi pressure and equipped with a silver diaphragm protector. These gages are necessary for proper evaluation of injector operating efficiency. They provide the operator with the back pressure readings for various quantities of water passing through the injector. In some situations this is critical information that cannot be obtained in any other way. It also constitutes proof of proper or improper diffuser design and/or chlorine solution line design.

Every installation should be provided with a loss of water pressure alarm to indicate failure of the water supply. Overpressure switches are not necessary for the injector system.

Chlorine Solution Lines—The piping downstream from the injector is the chlorine solution line. It is permissible to manifold the injector discharge from two or more chlorinators into one point of application, provided that there is one diffuser for each injector, valved so that the diffuser can be shut down when an injector is shut down. However, a solution line to the point of disinfection should not be manifolded to any other point of application. The most desirable arrangement is for each injector (in a multiple injector system) to have its own solution line and diffuser. For pipe materials see "Materials of Construction."

Chlorine solution flow proportioning systems are not worth the expense and most end in failure. Some waters release a tremendous amount of carbon dioxide and other gases when used to carry chlorine solution. The bubbles of gas in the solution passing through the rotameter can cause sufficient vibration so as to severely limit the accuracy of the reading. Glass tube rotameters should not be used because the vibration just described can cause the rotameter float to shatter the glass tube. The only rotameters that can be used on chlorine solution are the "straight through" metal (Hastelloy "C") or PVC tube type with dial indication.

Diffusers—A properly designed diffuser is one of the most important elements of a successful chlorination facility. There are two basic types: one for discharging chlorine solution into a pipeline flowing full, the other for discharging into an open channel.

Pipeline diffusers are of two general types. One type discharges all the solution into the center of the pipe; this type is satisfactory for pipe sizes up to 30 inches in diameter. The other discharges the solution through perforations over the middle half of the diameter. These arrangements give the best possible dispersion of the chlorine solution. To insure rapid mix the diffuser should be either located in a highly turbulent flow regime, or immediately followed by a mechanical mixer. (See Section 2.31.)

For the open channel there are two general diffuser types: one a series of nozzles suspended from flexible hose; the other a perforated pipe across the channel. Open channel diffusers require much more care in location selection than do pipeline diffusers because of the poor mixing characteristics of open channel flow. Perforated pipe across the channel is the preferred type. These diffusers should be placed directly in an area of maximum turbulence with a minimum water cover of 6—9 inches. The location of the diffuser in a hydraulic jump is illustrated in Figure 6.

If a Parshall flume is used as a mixing device, the diffuser must be located upstream of the flume throat and as close as possible to the throat without affecting the head versus flow characteristics. The time of travel from the diffuser to the turbulent zone should be 5 seconds or less at 75 percent of average flow.

An open channel diffuser can be a great nuisance and even a hazard if the perforations do not provide the proper hydraulics for the chlorine solution line. Anytime a negative head exists in the chlorine solution line, molecular chlorine will break out of the chlorine solution and cause serious chlorine gas emission at the diffuser. Therefore, if the wastewater level at the diffuser is below the injector throat, the hydraulic gradient from the injector to the diffuser must be calculated based on an assumed back pressure of 5 feet at the discharge of the injector. The friction loss through the diffuser holes plus the line losses minus the difference in elevation between wastewater level and injector throat must equal approximately five feet of head. This is one of the reasons for having a compound gage on the solution line at the discharge of each injector. The minimum recommended size of diffuser holes is 3/8 inch. The minimum recommended velocity through the holes is 10—12 feet per second. All open channel diffusers should be constructed for easy removal. They may become plugged or the hole configuration might have to be changed. This requires a flanged connection so that the entire diffuser can be lifted bodily from the channel. Diffusers are available with projecting pins that fit into slotted wall brackets.

Design considerations and additional details pertaining to diffusers can be found in Chapter 2 of *Handbook of Chlorination* (42), and White (44).

Materials of Construction—The materials used for the injector system are those employed in good water works practice for the water system up to the inlet of the injector assembly. From this point forward, a corrosive chlorine solution will be encountered which requires special materials. The chlorine solution lines can be Schedule 80 PVC, rubber-lined steel, saran-lined steel, or certain types of fiber cast pipe.

Valves on solution lines can be either diaphragm or ball type. The ball type PVC valve is preferable up to 2½-inch size, although the ball-type valve is available in much larger sizes. The diaphragm type should be considered for sizes 3-inch and larger. Diaphragm types are usually flanged, rubber-lined, or PVC-lined cast iron Saunders-type valves.

The injector vacuum line between the chlorinator and the injector is the most controversial as to material selection of all the piping used for the chlorination facility. This line carries moist

Space Requirements—Modern chlorination equipment is available in modules so that the chlorinators and accessory equipment can be arranged in a panel-like array. There should be about four feet between the front of a module and the nearest wall and about two feet on the sides and rear. *Handbook of Chlorination*, Figure 2–12 (42) illustrates space requirements for chlorinator-evaporator installations and Figure 2–15 illustrates space requirements for a ton container supply area.

The smallest area used for the installation of a chlorinator, weighing scales, and a spare cylinder of chlorine should not be less than six feet by six feet.

There should be adequate room provided to allow ready access to all equipment for maintenance and repair. There should be sufficient clearance to allow safe handling of equipment containers. Absolute minimum clearance around and in back of equipment is two feet.

Some general minimum space guidelines are as follows:

1. Plants with one chlorinator feeding less than 200 pounds per day should have at least 64 square feet.
2. Plants using two chlorinators with a total feed rate of up to 400 pounds per day should have at least 160 square feet.
3. For each chlorinator-evaporator unit, 160 square feet should be provided.

Ventilation—Adequate forced air ventilation is required for all chlorine equipment rooms. An exception to this would be small chlorinator installations (<100 pounds per day) located in separate buildings if the windows and doors can provide the proper cross-criculation. For a small building, windows in opposite walls, a door with a louver near the floor, and a rotating-type vent in the ceiling usually provide the necessary cross-ventilation.

Factors to be considered in the design of a ventilation system are: air turnover rate, exhaust system type and location, intake location and type, electrical controls, and temperature control.

A forced air system should be capable of providing one complete air change in two to five minutes. Since chlorine gas is 2½ times heavier than air, it is logical to provide air inlet openings for ventilation fans at or near floor level. For small installations it is common to employ an exterior exhaust fan with the intake duct extending to the chlorine room floor. A wall-type exhaust fan is an acceptable alternative. The exhaust system should be completely separate from any other ventilation system. For larger installations a blower-type fan is needed. The use of free-moving, gravity-operated louvers may be advantageous in colder climates for conserving room heat when the blowers are not in operation; however, venting systems should not have covers. The fan discharge should be located so as to not contaminate the air supply of any other room or nearby habitations. It is mandatory that the ventilation discharge be located at a high enough elevation to assure atmospheric dilution; i.e., at the roof of a single story building.

Air inlets should be so located as to provide cross-ventilation. To prevent a fan from developing a vacuum in the room and thereby making it difficult to open the doors, louvers should be provided above the entrance door and opposite the fan suction. In some cases, it may be necessary to provide temperature control on the air supply so that the chlorination system is not adversely affected. A signal light indicating fan operation should be provided at each entrance when the fan can be controlled from more than one point.

Wind Socks—All installations should locate at least one wind sock on the chlorine supply structure. This is very valuable in the event of a leak.

Doors—Exit doors from the chlorination room should be equipped with emergency hardware and open outward. Some design guides recommend two means of exit from each room or building in which chlorine is stored, handled, or used; however, this would not appear to be essential in most cases.

Inspection Window—A means should be provided which permits viewing of the chlorinator and other equipment in the chlorination room without entering the room. A clear glass, gas-tight window which is installed in an exterior door or interior wall of the room is recommended. Door windows appear to be a logical provision even with a separate wall inspection window.

Heating—The chlorinator room should be provided with a means for heating and controlling room air temperatures above 55°F. A minimum room temperature of 60°F has been recommended as a good practice. Ideally, the heating system should be able to reliably maintain a uniform moderate temperature throughout the chlorination room.

Hot water heating is generally preferred because of safety considerations and the uniformity of temperature which this method of heating provides without the extremes which might be experienced with failure of a steam heating system. Electric heating is suitable and forced air heating would be appropriate if an independent system is provided for the chlorination room or building. Central hot air heating is not acceptable since gas could escape through the heating system.

Chlorine vapor leaving a container will condense if the piping temperature is significantly lower than the temperature of the container. Design should provide a higher temperature in the chlorinator room than in the container room. This applies to systems using the gas phase from the containers. Elimination of unnecessary windows may aid in maintaining uniform building temperatures.

If container storage and chlorination equipment are in separate rooms, the temperature of the chlorine containers should not be allowed to drop below 50°F if evaporators are not used.

Drains—It is generally desirable to keep the plant floor drain system separate from that of the chlorinator. Drainage from a chlorinator drain relief valve may contain chlorine. Consequently, hose, plastic pipe, or tile drain are recommended. The discharge should be delivered to a point beyond a water sealed trap or disposed of separately where there is ample dilution.

Scale pits are generally designed with floor drains having a water seal trap. In actual practice, most traps probably do not contain ample water to form a seal and it would be preferable to provide a straight pipe drain outside to grade.

Vents—Chlorinators and external chlorine pressure reducing and shutoff valves have vents. Chlorinators have a pressure vacuum relief system which should be carried to the outside atmosphere without traps to a safe area, with one vent for each chlorinator. In the case of a malfunction, the operator can easily determine which chlorinator is malfunctioning if the vents are separate. The ends of the vent lines should point down, be covered with copper wire screen to exclude insects, and should not be more than twenty-five feet above the chlorinator. The line should have a slight downward pitch from the high point (directly above the chlorinator) to drain any condensate away from the chlorinator. It is acceptable to run the vent vertically (but no more than twenty-five feet) above the chlorinator to the roof, with a 180° return bend at the exit.

External chlorine pressure reducing and shutoff valves should be checked for vents. When supplied, these vents should drain away from the valves. In other words, these valves should be located high enough so that the individual drains will have a continuous downgrade to the outside atmosphere.

Evaporators have water bath vapor vents which can be manifolded together and discharged to the atmosphere without traps.

Electrical—Controls for fans and lights should operate automatically when the door is opened and there should be provisions to activate these manually from outside the room. Switches for fans and lights should be outside of the room at the entrance. A signal light indicating fan operation should be provided at each entrance when the fan can be controlled from more than one point.

2.37 Reliability Provisions

The need for continuous and dependable disinfection has been stressed. The chlorination system can fail due to a number of causes and, therefore, the design of the system must include the necessary provisions to either prevent failures or allow immediate corrective action to be taken. Although assured reliability is essential, design provisions for this are often slighted.

Chlorine Supply—As a chemical feed process, one of the most frequent interruptions in treatment is caused by the exhaustion of the chlorine supply. Five features are essential to maintain continuous chlorine feed and are discussed elsewhere in this text. These are: (1) an adequate reserve supply of chlorine sufficient to meet normal needs and bridge delivery delays and other possible contingencies; (2) chlorine container scales; (3) a manifolded chlorine header system; (4) an automatic device for switching to a full chlorine container when the one in use becomes empty; and (5) an alarm system to alert operating personnel of imminent loss of chlorine supply. Without these five features it is not possible to assure uninterrupted chlorine feed even with full-time operator attendance and no equipment breakdowns.

The chlorine header system is needed both to provide a connected on-line chlorine supply which is adequate to assure uninterrupted flow of feed for whatever period that the system may be unattended and to allow switchover to a full cylinder without interruption of feed.

Power Failure—Power outage usually results in water supply failure which in turn automatically shuts down the chlorination system. A range of special provisions can be employed to assure reliability of power and water supply depending on the particular situation. As discussed previously, these may be in the form of a standby power source and pumps.

Standby Equipment—The design of the chlorine feed system should provide for continued operation in cases of equipment failure. Where both pre- and postchlorination are to be practiced, separate chlorination systems should be provided for each plus a standby system. If prechlorination is not to be continuously used, it may be possible to use this system as the standby system for disinfection. The units, piping, and accessories should be designed with this application in mind. If

Water Supply—As mentioned above, during a power failure the injector water system will be shut down unless there is an alternate supply that does not require power, such as an elevated tank. Standby equipment to provide injector water in the event of a power failure would consist of an engine driven injector supply pump. Every injector water supply system should have such a standby pumping unit. There is no way to operate the chlorination system without an adequate water supply.

Chlorine Residual Analyzers—Every system using an analyzer for chlorination control should be backed up by an effluent monitor analyzer that can be switched over to the control function in the event of control analyzer failure. Provisions should also be made for standby sample pumps.

3. DECHLORINATION PROCESS AND SYSTEM DESIGN

3.1 CHEMISTRY OF DECHLORINATION

Dechlorination may be required for chlorinated wastewater discharges to remove chlorine residual from the effluent. The least expensive and most effective way to dechlorinate is by the use of sulfur dioxide. For small flows (less than 1 mgd) sodium bisulfite should be considered.

3.11 Sulfur Dioxide

Sulfur dioxide in water rapidly forms sulfurous acid:

$$SO_2 + H_2O \rightarrow H_2SO_3 \qquad (19)$$

The sulfite radical thus formed reacts rapidly with both free and combined chlorine as follows:

(Free Chlorine)

$$H_2SO_3 + HOCl \rightarrow H_2SO_4 + HCl \qquad (20)$$

(Combined Chlorine)

$$NH_2Cl + H_2SO_3 + H_2O \rightarrow NH_4HSO_4 + HCl \qquad (21)$$

The above reactions produce small amounts of acid; however, these would be neutralized by the buffering capacity of the wastewater. The reactions are complete in about 1.5 minutes at pH 7.5 and 18°C. Aeration of the effluent and pH adjustment are not necessary in dechlorination.

The control of the addition of sulfur dioxide can be accomplished by the use of a chlorine residual analyzer at the discharge from the chlorine contact chamber or similar suitable location.

It requires approximately one mg/l of SO_2 to dechlorinate one mg/l chlorine residual (free or combined). Chlorine residual levels for usual disinfection needs are in the 5 to 8 mg/l (iodometric-amperometric end point) range. The sulfur dioxide equipment should have the capacity to reduce the chlorine residual to less than 0.1 mg/l.

3.12 Activated Carbon

In some cases granular activated carbon can also be used for dechlorination. The process of chlorine removal by activated carbon is not a pure adsorption process. It also involves a chemical reaction between the chlorine and the water where the carbon acts as the catalyst (11, 13, 16, 20).

Activated carbon is believed to react with chlorine residual as follows (12, 24, 36, 38):

With free chlorine residual

$$C + HOCl \rightarrow C(O) + HCl \qquad (22)$$

With monochloramine (two parallel reactions)

$$NH_2Cl + H_2O + C \rightarrow NH_3 + HCl + C(O) \qquad (23)$$

$$2NH_2C1 + C(O) \rightarrow N_2 + 2HC1 + H_2O + C \qquad (24)$$

With dichloramine

$$2NHCl_2 + H_2O + C \rightarrow N_2 + 4HCl + C(O) \qquad (25)$$

where C is the carbon surface and C(O) is the surface oxide. Some of the surface oxide may be released as CO_2.

Equations 23–25 have also been used to describe a proposed nitrogen removal process where the dichloramine reaction is particularly efficient (12, 24, 36). The reaction with monochloramine proceeds best at pH 8.3, and that with dichloramine at pH 4.2. Complete removal of chlorine residual has been achieved with a 10-minute carbon contact (36). However, another study has reported that 16-minute carbon contact was necessary for completion of the monochloramine reaction (24). Regular backwashing of carbon beds is necessary to restore dechlorination efficiency (13). The surface oxide which builds up on the carbon may cause "fatigue" or long term reduction of dechlorination efficiency. Loss of efficiency is also caused by the presence of organic matter. Spent carbon can be regenerated by heating in a closed vessel at 500–700°C. Dechlorination efficiency is further affected by pore size, pH, and temperature. Increase in temperature or decrease in pH increases the efficiency, and vice versa.

3.13 Other Chemicals

Installations not large enough to warrant the use of sulfur dioxide in cylinders, or large installations wishing to eliminate any possible hazard from sulfur dioxide gas should use liquid sodium bisulfite ($NaHSO_3$).

Sodium metabisulfite ($Na_2S_2O_5$) is the anhydride of the bisulfite. It is a creamy white powder that is hygroscopic. It cakes while in storage. When it is dissolved in water it dissociates to sodium bisulfite. It may give off SO_2 upon dissolving, so that great care must be exercised during this procedure. The same is true for the handling of granular sodium sulfite (Na_2SO_3).

In view of the difficulties that can be encountered in the handling of either the metabisulfite or the sulfite, the best choice by far is the liquid sodium bisulfite. It reacts with chlorine as follows:

$$NaHSO_3 + Cl_2 + H_2O = H_2SO_4 + NaCl + HCl \qquad (26)$$

The above reaction requires 1.46 lb of sodium bisulfite to dechlorinate 1 lb chlorine. This chemical is usually shipped as 38 percent $NaHSO_3$ which is equivalent to approximately 23 percent by weight of SO_2, so that at a specific weight of 11 lb per gallon there will be 2.53 lb equivalent SO_2 per gallon for dechlorinating purposes.

Sodium thiosulfate, which is used as a dechlorinating agent in the laboratory, reacts as follows:

$$2Na_2S_2O_3 + Cl_2 = Na_2S_4O_6 + 2NaCl \qquad (27)$$

Sodium thiosulfate as a dechlorinating agent is not recommended for field use because of its high cost and its tendency to react in steps which create a time factor.

Although not considered as a dechlorinating agent, any ferrous salt in solution will react with free chlorine, monochloramine, and more slowly with dichloramine to form a ferric salt that eventually hydrolizes to form ferric hydroxide. On a weight basis, 8 parts of $FeSO_4 \cdot 7H_2O$ (ferrous sulfate) will be required to dechlorinate one part of chlorine.

3.2 DECHLORINATION PRACTICES

3.21 Sulfur Dioxide

Dechlorination of heavily chlorinated potable water by sulfur dioxide has been practiced since 1922 when it was first used in the Toronto water supply. The use of free residual chlorination followed by dechlorination with sulfur dioxide to control the residual of potable water entering a distribution system is now an accepted modern water treatment process (41).

Sulfur dioxide is the most popular dechlorinating agent because chlorination equipment can be used without modification to handle this gas. It is relatively inexpensive ($0.15 per lb in 1980), easy

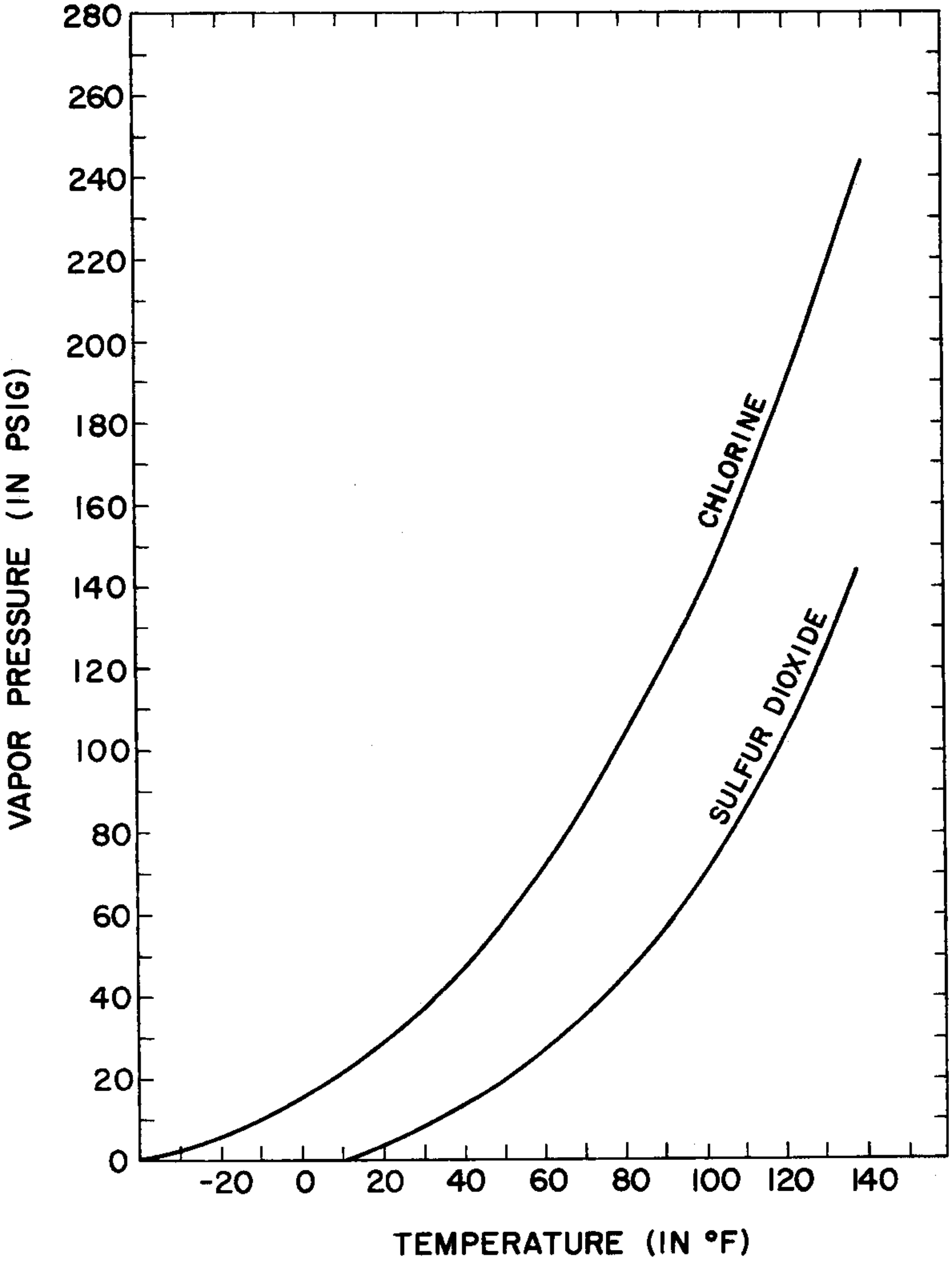


FIGURE 19. VAPOR PRESSURE CURVE OF SULFUR DIOXIDE AND CHLORINE

At one wastewater reclamation plant in California where advanced treatment is employed to prepare effluent for groundwater recharge, the tertiary treated effluent containing approximately 20 mg/l COD is chlorinated with a dose of 5–8 mg/l just prior to mixed media and carbon filtration. The carbon filters, which have a throughput rate of 5 gpm/sq ft and contact time of 34 minutes, remove all the chlorine along with most of the organics. Since the suspended solids have already been removed, the carbon filters need to be backwashed at a frequency of once a week or less. The carbon is regenerated about every 60 days by heating to 1700°F. The dechlorination achieved at this plant is more or less incidental to organics removed.

Another wastewater treatment plant, which employs physical-chemical treatment, uses a dual media filter consisting of sand and activated carbon for dechlorination. The application rate is 4.6 gpm/sq ft but the contact time is very short. This unit just recently went into operation; therefore, there hasn't been enough time to evaluate its adequacy.

Activated carbon has been little used to dechlorinate wastewater on a field scale. This method is more expensive than the use of sulfur dioxide, and does not have the control flexibility of the latter process. Therefore, its use probably will be limited to special cases of advanced waste ponds. Little information is available on the time required to dechlorinate wastewater by this method. Recent laboratory work (7, 25) indicates that chlorine residual tends to disappear in accord with a zero order reaction; i.e., linearly with time. Under field conditions, however, environmental factors such as wind velocity, temperature and sunlight may change the overall reaction.

3.3 FACTORS AFFECTING EFFICIENCY OF SULFONATION PROCESS

3.31 Mixing

The application of sulfur dioxide to wastewater differs considerably from the application of chlorine. The reaction is inorganic in nature. The SO_3^{--} ion reacts with the chlorine residual to convert the active chlorine to chloride and the sulfite ion (SO_3^{--}) to sulfate ion (SO_4^{--}). This reaction takes precedence over any side reaction due to organics that might be encountered in wastewater. The reaction of the surplus sulfite ion (after the reaction with chlorine) with dissolved oxygen is very slow at the pH and temperatures usually encountered. Therefore, mixing of the sulfur dioxide solution is not as critical as with the application of chlorine. What is needed is simple but rapid dispersion of the sulfur dioxide. This should occur within 45 to 60 seconds. Since sulfur dioxide is much more soluble in water than is chlorine it disperses more rapidly. Therefore, it is rarely necessary to use mechanical mixers at the point of application.

3.32 Contact Time

The chemical reaction between the sulfur dioxide solution and the chlorine residual is practically instantaneous at the pH and temperature usually encountered in wastewater; therefore, contact chambers are not required. A mixing chamber which provides complete dispersion of the sulfur dioxide solution is all that is necessary.

3.33 Control System

Due to the lack of appropriate analytical instrumentation for monitoring sulfur dioxide, the control system must be based on chlorine residual measurement. The most logical system is feed-forward. This system requires an effluent flow signal and a chlorine residual signal measured at the end of the contact chamber. The two signals are combined to generate a control signal for the sulfur dioxide metering equipment. This scheme is illustrated by Figure 20.

Other systems have also been devised and have a good measure of success. The basic problem with dechlorination control arises from the usual National Pollutant Discharge Elimination System (NPDES) requirement that the wastewater discharge should not contain more than 0.02 mg/l total chlorine residual. From a practitioners standpoint this is zero residual. Amperometric analyzers cannot maintain calibration if they do not "see" a chlorine residual at frequent intervals.

To overcome this problem, a biased sample control has been devised which is remarkably reliable. This system is described on page 150 and in Figure 3—31 of Reference 44. In this system the dechlorinated sample to the sulfonator control analyzer is biased with a constant artificial chlorine dosage which results in 2 mg/l residual in the biased sample when there is zero residual in the dechlorinated sample. Any deviation from this will be corrected by the control system. This arrangement is similar to that depicted in Figure 21 with the control function added. It utilizes compound loop feed forward control to achieve zero chlorine residual in the effluent.

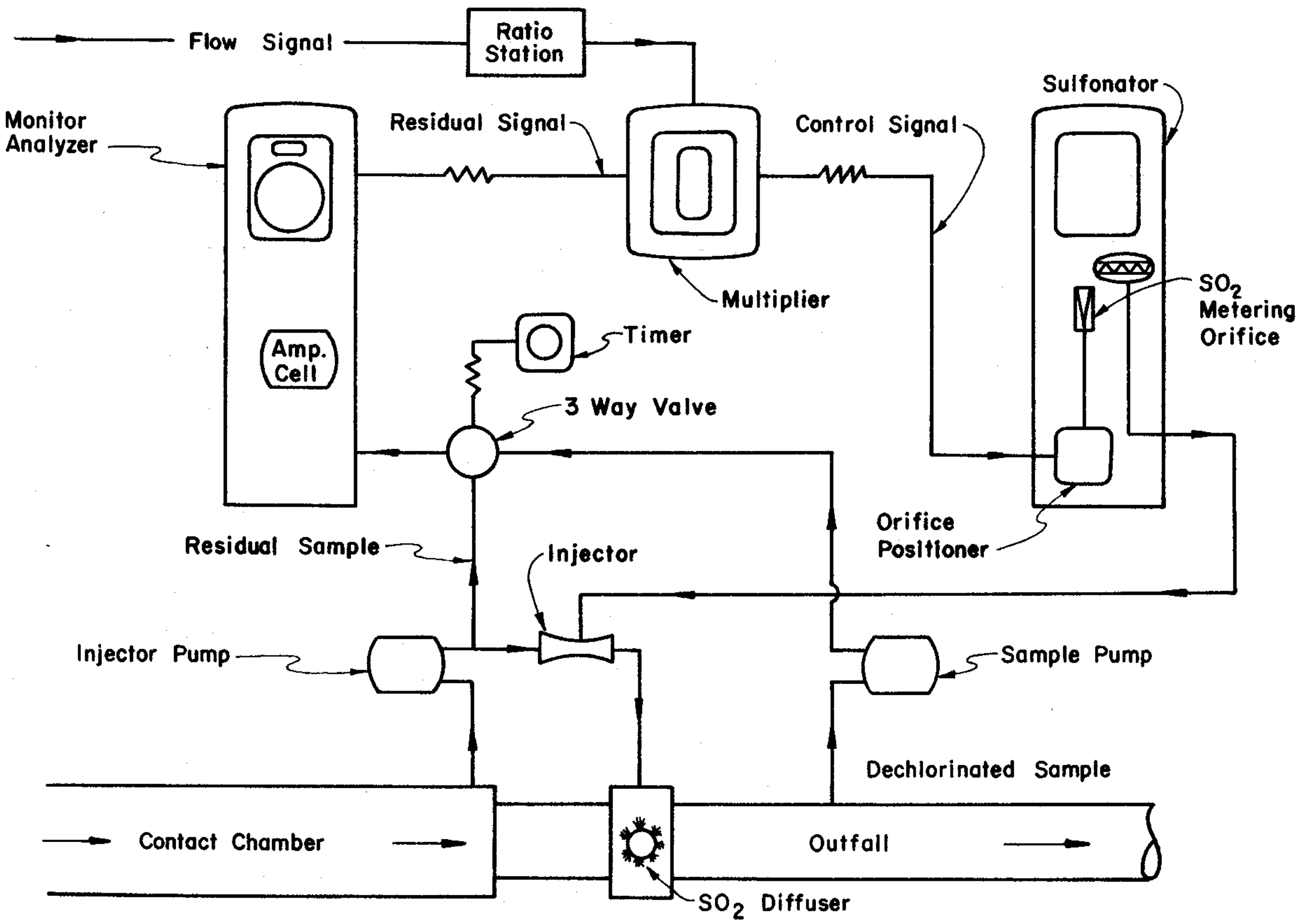


FIGURE 20. DECHLORINATION CONTROL SYSTEM

Another concept for the accurate control of SO_2 is the two step dechloration system described on page 152 and in Figure 3—32 of Reference 44. This system has merit because the lead sulfonator eliminates all the peaks and valleys in the chlorine residual, therefore allowing the following sulfonator to provide a precise trim control. The trim control is adjusted to provide a small excess of SO_2 so that there is no question about the chlorine residual being zero.

As can be seen from the previous discussion, monitoring a dechlorinated residual can only be done inferentially at present. The following three methods are recommended where discharge requirements specify a maximum chlorine residual of 0.10 mg/l or less in the effluent:

Intermittent—This is the simplest, least expensive and most practical method and employs the dechlorination system shown in Figure 20. Monitoring of the dechlorinated sample is accomplished by the control analyzer on an intermittent basis; i.e., for a small, adjustable period of time each hour, say from 5 to 7 minutes. During that period, a continuous dechlorinated sample that is being discharged to waste is diverted to the control analyzer which normally receives the chlorinated sample at the end of the contact chamber. This sample, if properly dechlorinated, will show zero reading on the analyzer. Considering the reliability of chlorination and dechlorination systems that are properly attended and cared for, a zero residual for 5 to 7 minutes per hour around the clock is convincing evidence of a continuous zero chlorine residual.

Continuous—(a) The only instrumentation that would be needed for direct continuous monitoring of a dechlorinated sample is an amperometric chlorine residual analyzer. However, continuous operation of such an instrument on a sample with no chlorine residual presents problems. Two undesirable situations occur. First, the electrodes display a tendency to drift out of calibration when subjected to long periods of zero chlorine residual. Second, the sample lines and electrodes can easily become fouled with organic debris and slime growths due to lack of chlorine residual. It would be possible, however, to set up a daily calibration and maintenance routine whereby the dechlorinated sample line is flushed daily with a slug of hypochlorite. This entire procedure could be carried out, if designed properly, in a few minutes by one operator. This is the only direct method for continuously recording zero chlorine residual.

Continuous—(b) Another method for the continuous monitoring of a dechlorinated effluent is by setting up a chlorination system of a minor flow from the dechlorinated effluent. This is illustrated in Figure 21. A constant flow of dechlorinated effluent is chlorinated to

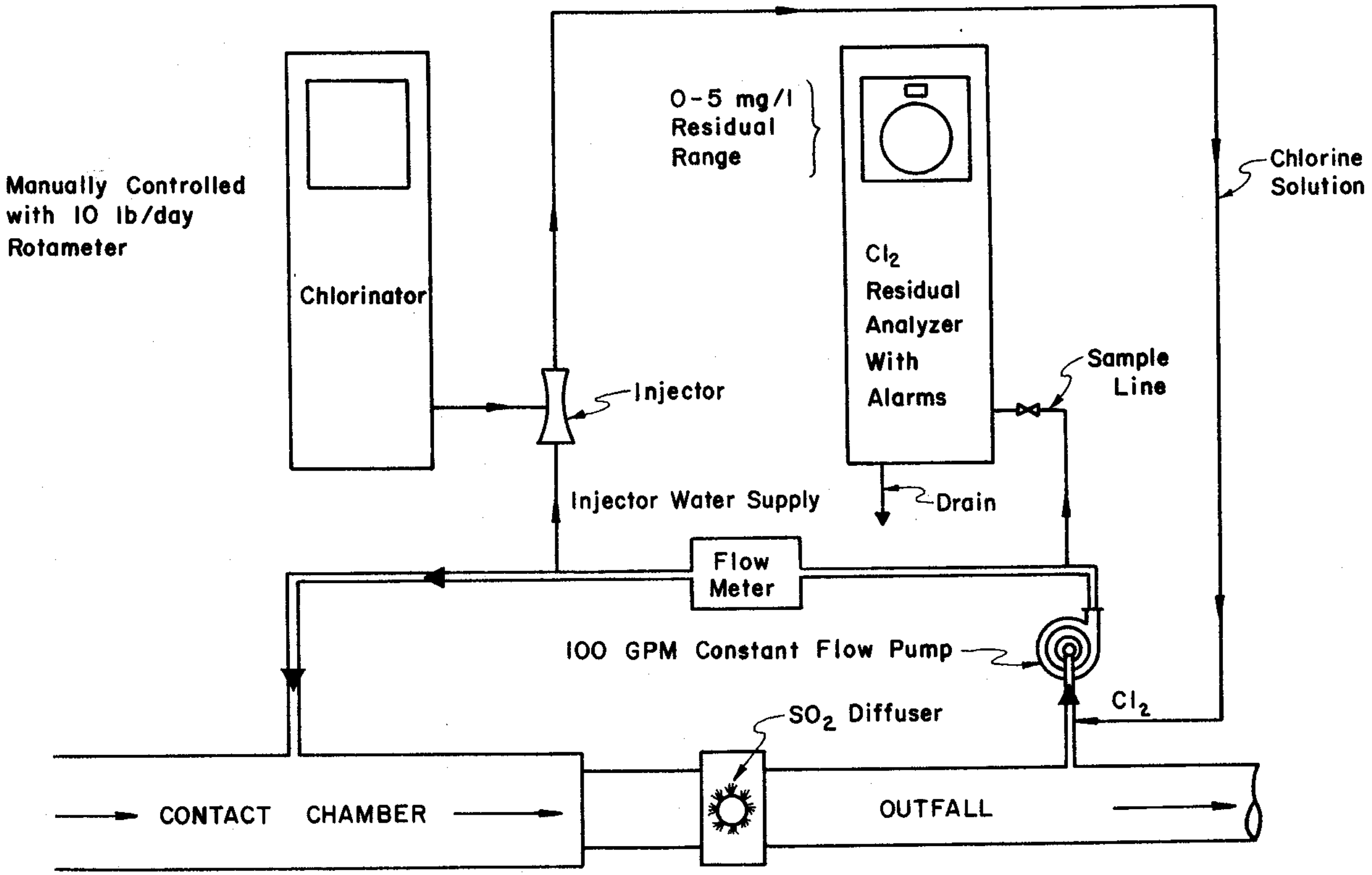


FIGURE 21. DECHLORINATION MONITORING SYSTEM

3.4 DESIGN OF SULFUR DIOXIDE DECHLORINATION SYSTEM

3.41 Mixing

The mixing required for the most efficient use of sulfur dioxide is to provide complete dispersion of the solution in the effluent before it reaches the receiving water. If, for example, the effluent meter is a Parshall flume, adequate mixing will be provided by placing the SO_2 diffuser just upstream from the flume. If the effluent discharges in a closed but surcharged conduit, the sulfur dioxide solution will be completely dispersed within a distance of ten diameters of the conduit, provided the SO_2 solution is discharged into the center of the conduit (41). If there is a weir at the end of the contact tank, excellent mixing will occur when placing the SO_2 diffuser immediately upstream from the weir.

If none of the above situations are available for the mixing of the sulfur dioxide solution, mechanical mixing may be necessary. The mechanical mixer does not have to achieve complete mixing in the times required for chlorine. Complete mixing in 45 to 60 seconds is adequate for dechlorination by SO_2.

3.42 Contact Time

If there is complete rapid mixing of the sulfur dioxide solution, there is little or no reason to provide any contact time, because the chlorine-SO_2 reaction is usually complete in 1–2 minutes.

3.43 Sulfur Dioxide Supply System

Sulfur dioxide is available in either ton containers or tank trucks. The maximum amount available in a single tank truck delivery varies from 17 to 20 tons, based on allowable axle loading of these vehicles. Tank truck operations require that the user provide storage tank facilities for unloading. The trucks are equipped with a compressor for unloading and a 17 ton delivery can be transferred in two to three hours. Storage facilities for SO_2 in bulk should follow the design used for chlorine tank cars or chlorine storage tanks. The system should be designed for continuous weighing using a load cell or beam-type scale rather than liquid level gages. The storage tank should be fitted with a Chlorine Institute tank dome assembly and an air padding system.

Sulfur dioxide can be withdrawn from a storage tank and ton cylinders either as a gas or a liquid. Owing to its low vapor pressure, SO_2 gas reliquefies quite easily. This causes operating problems with the control equipment. This low vapor pressure is also a limiting factor in the movement of the sulfur dioxide from the supply system to the control equipment.

Withdrawing from the gas phase usually requires application of heat to the cylinders. Gas phase systems operate best at 100°F, and it is acceptable practice to apply heat directly to SO_2 ton cylinders provided there is control to limit the heating to 100°F. The maximum gas withdrawal rate at 70°F from a ton container is about 250 lb/day.

Whenever heat is applied to SO_2 cylinders, a pressure reducing valve should be installed immediately downstream from the cylinders to prevent liquefaction in the SO_2 header system.

If the sulfur dioxide is to be withdrawn as a liquid, it is highly desirable to have an air or nitrogen padding system available. This can be an automatic air compressor with an electric dryer similar to air padding systems for chlorine tank cars, or it can be a manually operated system using a nitrogen tank with a pressure regulating valve. Air padding provides the necessary extra pressure required to insure proper movement of the sulfur dioxide. It serves also to insure complete removal of SO_2 from the cylinder or storage tank. A padding system should be able to raise the system pressure to 75 psi.

The materials of construction for a sulfur dioxide supply system are not the same as those for chlorine. The metal of choice for use with SO_2 valves should be 316 stainless steel and not monel or monel trim. The piping system should be the same as for chlorine.

The sulfur dioxide supply system should be continuously monitored by a weighing system. Either a load cell or a beam type scale is satisfactory. A nitrogen cylinder with regulator is also desirable for purging the header system.

An evaporator enhances the flexibility of any sulfur dioxide supply system. It supplies warm gas to the sulfonator and, since there is always a pressure reducing valve downstream from the evaporator, the problem of reliquefaction is eliminated. Furthermore, the use of the evaporator allows the incorporation of an air or nitrogen pad to the system.

Expansion tanks are necessary for extremely long liquid lines. These tanks should be used under the same conditions as those for chlorine.

3.44 Sulfur Dioxide Control System

The first step in designing the control system is the determination of equipment capacity. This is based on the amount of chlorine residual that must be removed to produce a zero residual in the effluent. This figure can vary from a minimum of 2 mg/l to a maximum 10 to 15 mg/l, depending on the local conditions and the efficiency of the chlorination system. When the level of dechlorination is determined, the size of the control equipment is calculated exactly the same as it is for chlorine.

Example: The treatment plant is fitted with a 0 to 100 mgd effluent meter and the expected maximum chlorine residual is 5 mg/l. The sulfonator should have a capacity of $5 \times 8.34 \times 100 =$ 4165 lb/day of SO_2.

Two control systems have been described previously in Section 3.33. Both systems require an effluent flow signal. The feed-forward system can operate from either a combined flow and residual signal which are resolved by a signal multiplier (see Figure 20) or by the use of compound loop control. The latter arrangement sends the effluent flow signal to the sulfur dioxide orifice positioner and the chlorine residual signal to the differential regulator in the sulfonator. This control system is identical to the conventional compound loop control system for the application of chlorine (see Figure 5).

3.45 Injector System

The same rules apply for the handling of sulfur dioxide as apply to chlorine with one exception. Chlorine solution discharging from an injector is limited to 3500 mg/l to prevent breakout of molecular chlorine. Since sulfur dioxide is considerably more soluble in water, the allowable concentration could be raised to 5000 mg/l for a sulfur dioxide solution, thereby utilizing less injector water. However, since mixing efficiency requirements for sulfur dioxide are less than for chlorine, it is recommended that the same 3500 mg/l solution strength requirements be used. In this way, diffuser design for maximum dispersion will be consistent with that for chlorine. Therefore, the engineer should design the sulfur dioxide injector system in the same fashion and with the same materials as for chlorine. This includes pumps, flow meters, gages, alarms, and diffusers.

Remote injectors are imperative because of control problems that might arise from the lag time in long solution lines.

3.46 Safety Equipment

Safety equipment is similar to that used for chlorine.

The breathing apparatus and the emergency container kits used for chlorine are suitable for sulfur dioxide.

A continuous sulfur dioxide leak detector should be supplied with every sulfonation system regardless of SO_2 container size. The SO_2 leak detector is just as necessary as a chlorine leak detector and for the same reasons.

The use of expansion tanks has been described in the section "SO_2 Supply System."

3.47 Alarms

Every sulfonation facility should be equipped with an alarm system that adequately alerts the operators in the event of malfunctions or hazardous situations related to sulfur dioxide supply, sulfur dioxide metering equipment, sulfur dioxide leaks and excess of chlorine residual.

The sulfur dioxide supply system should be monitored for leaks and low pressure. The latter could be an indication of imminent loss of supply. High SO_2 pressure alarms are not necessary. Sulfur dioxide leaks in the supply and control area should be monitored by a permanent SO_2 leak detector which meets OSHA requirements. The detector should be capable of sensing atmospheric SO_2 concentrations as low as 1.0 ppm (by volume).

The sulfonator should be equipped with high and low vacuum sensing devices. Low vacuum signifies failure of the injector system and high vacuum signifies loss of sulfur dioxide supply.

Installations using evaporators require alarms for warning of high and low water bath temperature and low water bath level.

Chlorine residual analyzers used for controlling dechlorination at the end of the contact tank should be equipped with adjustable high and low residual alarms. If the analyzer is to be used as a zero residual monitor, the "low" alarm will alert the operator that there is more than an acceptable amount of chlorine residual in the dechlorinated effluent. The "high" alarm could be used to tell the operator that the chlorine residual in the nondechlorinated effluent might be too low for adequate disinfection. In effect the hi-lo alarms become two types of "low" residual alarms.

Systems using air padding by a compressor with air dryer should have a high humidity alarm on the dried compressed air. Corrosion from moist air is just as critical for SO_2 as it is for chlorine.

3.48 Monitoring System

The subject of monitoring has already been thoroughly discussed and, therefore, only certain design features are pointed out here.

The continuous monitoring system shown on Figure 21 utilizes the chlorination of a minor flow of dechlorinated effluent at a constant dosage. The following example illustrates the use of this system:

> A constant regulated flow of 100 gpm of dechlorinated effluent can be discharged back into the chlorine contact chamber. A small wall-mounted, manually-controlled chlorinator equipped with a 10 lb/day rotameter is used to chlorinate the 100 gpm of dechlorinated effluent. Assuming a 2 mg/l dosage, this would require a chlorine feed rate of 2.4 lb/day

assuming no chlorine demand other than excess sulfite ion. A sample of the rechlorinated effluent is sent to a monitoring analyzer. The amount of chlorine or sulfur dioxide residual can then be calculated for any moment of operation by comparing the residual analyzer reading with the effluent flow and chlorinator feed rate. If more reliability is required, a chlorinator can be furnished which can be fitted with a chlorine flow recorder. Then from the chlorine flow, dechlorinated effluent flow and analyzer reading, the precise chlorine residual or excess of sulfur dioxide can be accurately determined.

3.49 Sample Lines

All sample lines must be provided with means for flushing to remove slime growths. Sample lines carrying dechlorinated effluent will be subject to a rapid development of organic debris and slimes throughout the transport system. Any such biofouling introduces errors in the analyzer system, whether it be for control or for monitoring.

Sample lines should be designed to provide velocities up to 10 feet per second. This acts to decrease dead time in the control loop and produces some scouring action.

The sampling point for coliform bacteria determination for proof of disinfection should be 5–10 feet upstream from the SO_2 diffuser. Otherwise effects of regrowth after dechlorination may distort the proof of disinfection.

3.50 Reliability

The dechlorination system can fail due to the same reasons which cause failure of the chlorination system. Therefore, the reliability provisions discussed in Section 2.37 are generally applicable to sulfonation systems.

4. PROCESS MONITORING AND CONTROL

4.1 CHLORINE RESIDUAL ANALYTICAL METHODS

4.11 General

Precise measurement and control of the magnitude of the chlorine residual in wastewater is critical in preventing adverse effects associated with over- or underchlorination. Process control, however, is complicated by the improper use of the available standard methods of chlorine analyses. The concern over the presence of measurable toxic chlorine concentrations of 0.1 mg/l or less in wastewater demands the use of the most precise analytical method of measurement that is practi-

In conducting chlorine requirement tests in the laboratory, samples of wastewater are collected and chlorinated using varying dosages to give a range of chlorine residual concentrations. A mixer having the same G value as the full-scale plant should be used for initial mixing. Aliquots of the chlorinated samples are then withdrawn with time for chlorine residual and bacteriological analyses. The results of the test indicate the chlorine residual and contact time requirements necessary to obtain specific coliform densities under ideal conditions.

4.22 Correlation of Laboratory Results with Full-Scale Facilities

Results obtained in laboratory studies can be correlated with plant-scale results, provided that the initial mixing is comparable, the chlorine control system is good, and the plant contact tank provides a distribution of residence times approaching that of a plug flow reactor. Therefore, the designer should utilize the laboratory results as a guide and then design the chlorination facilities to approach ideal conditions.

However, as can be seen from Table 1 (Section 1.23), the actual plant-scale chlorine requirements may be as much as 100 percent higher than those estimated in the laboratory if the chlorination systems are not properly designed. This demonstrates the need to apply an appropriate safety factor to laboratory data. From Table 3 (Section 1.23), it is apparent that the daily average initial coliform levels may vary by a factor of 10 or more in the same effluent. Consequently, the results of the chlorine requirements tests can also vary by the same amount. In order to obtain adequate data, it is necessary to conduct daily chlorine requirement tests for at least two weeks on each effluent. The data can then be statistically evaluated by plotting the values of R x t against Y_2/Y_1 on log-log graph paper and/or doing a least squares regression analysis on a computer (see Equation 12). The resulting regression line can be used to estimate the chlorine residual required to achieve a given degree of disinfection for that particular effluent under ideal conditions. Experience will show what multiplication factor to use to achieve plant-scale results.

When planning for plant enlargements or upgrading existing systems, studies on the existing chlorination system will provide much useful data. Results of coliform and chlorine residual tests performed at various points of the existing contact tank can be analyzed by the above method and used to predict the performance of the new system, provided, of course, that the effluent qualities and the systems are comparable.

4.3 RECORDS AND REPORTS

Records will serve to establish a reliable continuing record of proof of performance, justifying decisions, expenditures, and recommendations. They also serve as a source of information for plant operation, modification, and maintenance.

Adequate records of disinfection are also important from the standpoint of regulatory agencies. Records will facilitate public health surveillance and enable the regulatory agencies to assess compliance with state regulations.

There are two classes of records which should be maintained at a wastewater treatment plant using chlorination: (1) records of a descriptive, planning, or inventory type related to the physical plant; and (2) records of performance.

4.31 Physical Facilities

The following records, referring to the chlorination-dechlorination unit, should be available for reference at the plant:

1. Design engineer's report, including basis of design, equipment capacities, population served, design flow, reliability features, and other data.
2. Contract and "as built" plans and specifications.
3. Shop drawings and operating instructions for all equipment.
4. Costs of each equipment item.
5. Detail plans of all piping and electrical wiring.
6. Complete record of each piece of equipment including name of manufacturer, identifying number, rated capacity, and dates of purchase and installation.
7. Supply of chlorine and dechlorinating agent, including reserves and availability estimate.

4.32 Records of Operation

Daily records should be kept of the following:

1. Chlorine—daily quantities used, both for pre- and postchlorination; chlorine residuals, including method used (preferably continuous recording of residuals); dosage.
2. Sulfur dioxide (or other dechlorinating agent)—daily quantities used; dosage.
3. Wastewater flow—preferably continuous recording; total daily flow treated; maximum, minimum, and average daily.
4. Results of bacteriological analyses—coliform bacteria and other required tests.
5. Daily inspection, including record of operational problems, equipment breakdowns, periods of chlorinator outage, diversions to emergency disposal, and all corrective and preventive action taken.

An example of a daily record form is shown in Table 8.

In addition, the following important records and plans should be kept at each facility:

1. Routine equipment maintenance schedule and record.
2. Annual equipment inspection and maintenance record.
3. Plan for prearranged repair service.
4. Emergency plan for chlorinator failure.
5. Emergency plan for accidental chlorine or sulfur dioxide release.

4.33 Reports

Monthly operating reports should be prepared, containing information on chemical usage, wastewater flows, laboratory analyses and significant operational problems.

TABLE 8
OPERATIONAL RECORD OF A CHLORINATION-DECHLORINATION PLANT

MONTH ______________________ OPERATOR ______________________

DAY	TOTAL FLOW, MG	CHLORINE USE, LB/DAY		SO_2 USE LB/DAY	CHLORINE RESIDUAL, mg/l			INTERRUPTIONS IN TREATMENT
		Prechlorin.	Postchlorin.		Total	Max.	Min.	
1								
2								
3								
through								
31								
Sum								
Mean								

Significant Operational Problems: ______________________

5. OPERATION AND MAINTENANCE

5.1 OPERATION–CHLORINATION EQUIPMENT

5.11 Chlorine Supply System

100- and 150-Pound Cylinders–Operating personnel should know the maximum allowable cylinder withdrawal rates. At 68°F the allowable rate for these cylinders is about 40 lb/day. Higher rates will produce undesirable excessive cooling of the cylinder. The withdrawal rate is less at lower temperatures.

Never connect a "hot" cylinder to a chlorine supply system. Allow cylinders that have been exposed to sunlight to cool off overnight. If a hot cylinder must be connected, it should be artificially cooled by a minor flow of cold water. This can best be done by wrapping the cylinder with water absorbent material such as burlap and then pouring a continuous but small stream of water on the top of the cylinder. At multicylinder installations where the chlorine feed rate is in excess of 40 lb/day, an easy way to cool off a hot cylinder is to connect it singly to the supply system and withdraw the gas at rates higher than 40 lb/day. As an example, withdrawing chlorine from a 100-pound or 150-pound cylinder at 100 lb/day will reduce the temperature (and consequently the pressure) by at least 20°F in the first 30 minutes.

The flexible connection is the most vulnerable part of a cylinder supply system. To insure the ability to replace these connections without hazard to the operator, connect an auxiliary cylinder valve between the cylinder outlet valve and flexible connection.

Ton Containers–Ton containers have two outlet valves. One is for liquid withdrawal and one is for gas withdrawal. When used for gas withdrawal, ton containers behave in the same way as do the 100-pound and 150-pound cylinders. The maximum withdrawal rate at 68°F is about 400 pounds per day. However, these containers must be positioned so that the two outlet valves line up in a vertical plane. In this position, the top valve is for gas withdrawal and the bottom valve is for liquid withdrawal. If these two outlet valves are not aligned vertically, serious difficulties will be encountered. A gas phase withdrawal system may withdraw liquid chlorine, which will severely damage the chlorination equipment. A liquid withdrawal system will withdraw gas; this will immediately reflect in a severe loss of chlorine supply.

In liquid withdrawal, never manifold a hot ton cylinder with others that are at a cooler temperature. Cool off the hot cylinder by the same procedure described for cooling the 100- and 150-pound cylinders. If this practice is not followed, it could be possible to fill "cool" partially empty ton cylinders by one or more new "hot" cylinders. Filling a cylinder to liquid capacity could result in eventual hydrostatic rupture of the filled cylinder(s). Such a situation would obviously cause a disastrous chlorine accident. Therefore, always be sure that the new cylinder being connected is at the same temperature as the cylinders already connected before turning them into the system. This will be revealed by the vapor pressure of the cylinders. The operator is cautioned to connect the new cylinder(s) in such a way that he can verify and compare the vapor pressure between the new cylinders and those already in use. If there is a significant difference in these pressures, the new cylinders will have to be allowed to reach the temperature of the cylinders on the line by remaining in the storage area overnight before being connected. Otherwise, the new cylinders will have to be artificially cooled as described for the 100- and 150-pound cylinders.

The best way to operate a ton container supply system using liquid withdrawal is to use a group of cylinders until empty. When this occurs, secure the empty cylinders and activate a new "full" group of cylinders until empty and so on. It is best never to turn a new cylinder into a supply system of partly full cylinders.

Manifolding ton containers on gas withdrawal does not present the same hazards as those on liquid withdrawal. A "hot" cylinder with a vapor pressure of say 70–80 psi when manifolded to cool cylinders will simply supply all the gas required until it cools to the vapor pressure of the other cylinders. This is the pinciple of the automatic switchover system.

Start-up (Gas System)—Probably the most critical period in the operation cycle occurs when a system is put into service for the first time after a prolonged shutdown.

First, check that all union joints on the supply system are properly gasketed and tight and then check that all chlorine supply valves are closed.

Second, check the injector system for proper vacuum at the chlorinator vacuum gage and freedom of the chlorine solution lines of obstruction. This can be done by observing the appropriate gages, or, if such gages do not exist, disconnect the vacuum line to the injector and place the hand over the inlet to the injector. If the injector is performing properly, the injector vacuum will be felt immediately. If the suction is feeble, then the injector and solution line hydraulics are not proper and should be investigated further.

When the injector system is operating properly, the chlorine gas may be turned on, but before doing so the chlorine feed rate should be in a partially open position; about 25 percent of maximum feed rate. Automatic control chlorinators should be placed in the manual mode for this type of start-up.

Third, open one cylinder slightly by cracking the outlet valve. Progressively check all joints for leaks and begin opening the valves leading from the opened cylinder to the chlorinator. If there are no leaks, proceed to open the required number of cylinders. The chlorinator is now ready for further testing, that is, for rangeability, automatic control and so on.

Tanks Cars and Storage Tanks—The most important operating consideration for this type of supply system is proper instruction. A qualified representative from the chlorine supplier should be engaged to demonstrate the use of safety equipment and to outline safety precautions and preventive maintenance procedures. The most critical time for these large systems is the original start-up, or start-up after a prolonged shutdown.

Start-up (Liquid System)—The procedure for start-up on a system using liquid chlorine is generally similar to that using gas; however, the one big difference is caused by the presence of an evaporator.

The evaporator is an extension of the chlorine container system. Whatever occurs in the container is reflected in the evaporator. The danger existing in a liquid system is the possibility of trapping chlorine liquid in a pipeline. If this occurs and there is a significant temperature rise, the liquid chlorine will expand and may rupture the pipe. For this reason, the liquid line between the evaporator and the chlorine supply system should always remain open while the evaporator is operating (42).

The first step preparatory to starting up a liquid system is to verify that the system is dry. This can be done by heating the water in the evaporator and passing dry air (—40°F dew point) through the evaporator cylinder and all the chlorine lines between the containers and the chlorinators. This may take several hours but it is worthwhile, for it can save many days of maintenance time.

When the operator is convinced that the system is dry and if the evaporator water bath is at the appropriate temperature (about 170°F), the system is ready to be started. First, start the injector water and proceed exactly as in the start-up procedure using gas; then follow the same procedure to check for chlorine leaks.

Always start a liquid system first with gas. If the system is started on liquid and there is a leak, many times more gas is released at the leak: one volume of liquid chlorine is equivalent to 456.8 volumes of gas. Furthermore, it takes that much longer to empty the system of liquid to repair the leak.

Superheat—The proper operation of an evaporator depends on the water bath temperature that will provide 20°F superheat to the gas being vaporized. This condition is dependent on the vapor pressure of the liquid. For example, read the liquid vapor pressure on the evaporator instrument panel and determine the corresponding liquid temperature from the chlorine vapor pressure curve. Then read the chlorine gas temperature of the gas exiting the evaporator. This gas temperature should be kept 20°F higher than the corresponding liquid temperature obtained from the chlorine vapor pressure curve. When it is no longer possible to achieve 20°F of superheat, the chlorine container vessel in the evaporator must be cleaned or the immersion heaters must be replaced.

Excessive Chlorine Supply Pressure—A condition that is likely to be encountered in tank cars and sometimes in ton containers is abnormally high chlorine vapor pressure. In tank cars this is usually caused by excessive air padding. The vapor pressure in a newly arrived tank car should be about 85 to 90 psi at 70°F ambient. If the pressure is greater than this, the chlorine liquid temperature has risen too much or the car has been excessively air padded. In these cases, the chlorination system should be used to withdraw on the gas phase directly from the new tank car long enough to reduce the vapor pressure down to about 70—75 psi. After equilibrium at this pressure and absence of leaks has been verified, the system can then be switched to the liquid phase utilizing the evaporators to provide gas to the chlorinators.

To Stop or Secure an Installation—First, shut off the chlorine supply system. If the shutdown is to be of short duration, any auxiliary valve near the chlorinator may be used for this purpose. If it is to be a long shutdown or for major repairs, it is best to shutdown at the main container valve. In this way, the chlorine pressure in the entire system can be reduced to zero gage pressure.

When the chlorine pressure gage on the chlorinator reaches zero and if a disassembly of equipment is involved, remove the plastic plug usually located in the chlorinator inlet pressure reducing valve assembly; this evacuates all the chlorine gas within the chlorinator piping.

After the chlorine has been purged to the satisfaction of the operator, the injector system may be shut down, thus securing the entire installation.

At this point, replace the plastic plug.

5.12 Chlorine Control and Metering System

Injector System—The control and metering system will not function without an adequate injector system. The injector system provides the power to pull gas from the containers through the chlorinator and then dissolves this gas into the injector water supply to provide a chlorine solution at the point of application. All injector systems should be operated with sufficient water to provide a solution concentration not to exceed 3500 mg/l of chlorine. This usually figures to be 40 gallons per day per pound of chlorine.

The injector system should be evaluated as follows: turn on the water supply and allow the hydraulics of the system to stabilize. With the chlorine supply secured, the injector system should be indicating a vacuum in excess of 20 inches Hg. Otherwise, something is wrong. Assuming the vacuum valve is operating properly, open the chlorine supply to the chlorinator and adjust the chlorine feed rate to about 25 percent of full scale. If the system is adequate, the admission of the chlorine to the injector may only lower the vacuum to about 15 inches Hg or higher. As long as this vacuum does not deteriorate rapidly, it can be assumed the injector system is in order. Let the system remain at this condition momentarily then change the chlorine feed rate to 100 percent of full scale. If the injector system is adequate, the chlorine feed rate response will be instantaneous and the injector vacuum gage will not deteriorate much below 15 inches Hg. In large installations where 100 percent of full scale is 2000 lb/day or more, and where the injector back pressure is

Upon startup, the needle valve is adjusted so that the chlorinator will just barely pull the maximum amount of chlorine. The discharge pressure at this condition is noted. The needle valve is then adjusted to raise this pressure by 5 psi to provide some safety factor. As the impeller of the pump wears due to usage, the needle valve may be closed further to maintain the proper pressure.

Chlorinators—If the chlorinator feed rate adjustment is manual, there are no critical adjustments to be made. The unit is adjusted manually to give the desired residual. No further adjustment or calibration is necessary. It is important, however, to choose a rotameter of the proper and most useful range. For example, if the desired feed rate is 15 lb/day, a 30 lb/day rotameter would be a wiser selection than a 100 lb/day size.

When the chlorine feed rate is paced by a flow signal, the chlorinator must be adjusted for zero and span. These adjustments are carefully outlined in the manufacturer's instruction book. This adjustment is usually a combination of signal input and mechanical linkage, depending on the type of signal—pneumatic or electric.

The important point when attempting adjustments to the chlorinator control mechanism is that these adjustments can only be made properly when there is a flow of chlorine through the machine. Furthermore, a chlorinator is not designed for zero flow conditions while the injector is in operation. Thus, the zero adjustment is contingent upon a mechanical linkage. As long as the injector is operating and even though the chlorine metering orifice is adjusted to read zero on the rotameter scale, some chlorine will be passing through the chlorinator. This is easily verified. Shut off the inlet gas valve to the chlorinator and watch the chlorine gas gage pressure on the chlorinator instrument panel gradually creep towards zero.

The most important aid to chlorinator adjustment and calibration is the use of signal simulators to simulate input signals from flow and dosage measurement devices to the chlorinator. The signal simulators used should have the capability of providing input signals over the entire range of the chlorinator.

Special adjustments are required for chlorinators operating on a variable vacuum signal as the sole means of controlling the chlorine feed rate. This mode is commonly used for straight residual control. The special adjusting procedure is outlined in the manufacturer's instruction manual and has to do with the zero adjustment of the chlorine inlet reducing valve. The accuracy of this adjustment, as well as the overall accuracy of this method of control, is greatly improved by the use of an external pressure reducing valve installed in the supply system upstream from the chlorinator inlet. This valve takes the burden off the pressure reducing valve in the chlorinator. Without that additional valve, the chlorinator inlet pressure reducing valve would be the primary instrument of control in a variable vacuum system.

Chlorine Residual Analyzer—This unit has zero, span, and temperature adjustments. If a thermistor is used, it automatically compensates for temperature changes in the sample.

The zero adjustment is a simple one. The sample flow to the analyzer is shut off, or one lead to the cell is disconnected (depending on the manufacturer). Under these conditions the indicator or pen on the recorder should go to zero. If not, the potentiometer marked zero is rotated until the pen reads zero. The span adjustment depends upon the calibration.

The analyzer should be calibrated by one of the acceptable methods used to measure chlorine residuals in wastewater. The following are the most popular: amperometric titration, starch-iodide titration, or the Palin DPD-FAS titrimetric procedure (35). The back-titration procedure should be used unless the effluent is a highly polished tertiary effluent.

A signal simulator is desirable to have available whenever extensive calibration of the analyzer is required. This instrument provides check points throughout the entire range of the cell output.

Once the analyzer has been put into operation, it is not necessary to respan the instrument each day. It is more desirable to plot a graph of the indicated versus the titrated sample readings. The curves of each of these groups of reading should indicate a span adjustment either upward or downward. This procedure should be done at first on a weekly basis, inasmuch as most wastewater systems require respanning the analyzer once a week.

Two critical points should be observed in the operation of a wastewater analyzer. First, the sample pH must be kept at 4.5–5.0 by the addition of a buffer solution. Multicolored pH papers are satisfactory for this determination. Second, sufficient potassium iodide (KI) must be added to the pH 4 buffer solution to allow the chemical reaction between the KI and the chloramine residual to go to completion. The chlorine residual reacts with the potassium iodide to release free iodine in proportion to the total residual. The analyzer cell measures the free iodine (or free chlorine). Therefore, the amount of potassium iodide that is to be added to the buffer solution depends on the sample flow rate through the analyzer cell and the magnitude of the chlorine residual. The cell flow rate varies from one manufacturer to another. For example, the Wallace and Tiernan (W&T) cell uses about 250 cc/minute. Since they use a fresh water dilution technique this amounts to a

5.2 OPERATION—DECHLORINATION EQUIPMENT

5.21 Sulfur Dioxide Supply System

General—The vapor characteristics of sulfur dioxide make it prone to reliquefaction—an undesirable situation when attempting to meter a gas. Unless the container is artificially padded with a "propellant," the cylinder pressure at room temperature will be about 35 psi. If the cylinders are stored outdoors in a "carport" type structure, the SO_2 gas will surely reliquefy in the header between the container and sulfonator. One way to relieve this situation is by the application of heat to the cylinders followed by a pressure reducing valve installed immediately downstream from the cylinders. A better alternative is to install an evaporator and artifically raise the vapor pressure of the cylinders by an air pad system or a bottle(s) of nitrogen. The design considerations to provide an operable system have been described previously in this manual (see Sections 2.33, 3.43).

Ton Containers—The present supply (1980) of sulfur dioxide in shippable containers is generally limited to the one ton size. If the gas phase of these containers is to be used, then heat must be applied to the containers. Strip heaters or hot air blower type heaters that are arranged to automatically shut off at 100°F are required. Care must be taken that heat applied to SO_2 cylinders is not directed to adjacent chlorine cylinders. Sulfur dioxide gas phase systems do not operate satisfactorily at ambient temperatures much below 85°F. They operate best at 100°F with an external reducing valve in the SO_2 header adjacent to the cylinders. The installation of an evaporator for these systems is the most practical solution. The same is true for the bulk storage tanks.

Although manufacturers of sulfur dioxide may claim that gas withdrawal rates from ton containers can be as high as 500 lb/day, the operator is best served if the withdrawal rate is kept to 225–250 lb/day. The reliquefaction problem is kept to a minimum at this rate.

5.22 Sulfur Dioxide Control and Metering System

Injector System—The only difference between the use of an injector system for sulfur dioxide and chlorine is that SO_2 gas is much more soluble in water than is chlorine. Therefore, if the operation of a sulfur dioxide injector system is fashioned the same as that for chlorine, the operator will be well on the side of safety. This is recommended as the proper operating procedure. Therefore, use 3500 mg/l as the maximum strength of sulfurous acid solution to prevent breakout of molecular SO_2 at the point of application.

Booster Pumps—The same applies here as for the chlorination system (see Section 5.12).

Sulfonators—Since sulfonators are identical in every respect to chlorinators, the same operating procedures are required. This includes adjustments and calibration. See "Chlorinators" under Section 5.12.

Analyzers—At present (1980), the chlorine residual analyzer is the only instrument available for the control of the sulfur dioxide system. This is well documented in other sections of this manual. If instrumentation ever becomes available to measure the concentration of sulfurous acid (H_2SO_3) or the sulfite ion (SO_3^{--}), the operating requirements are certainly to be substantially different from those of chlorine residual analyzers.

5.3 MAINTENANCE—CHLORINATION EQUIPMENT

5.31 Chlorine Supply System

General (150-Pound and Ton Containers)—The most vulnerable part of a chlorine supply system are the flexible connections. These are usually made of 2000 pound annealed copper tubing, cadmium plated. Whenever these connections are exposed to the moisture in the atmosphere during a cylinder change, corrosion sets in. Internal corrosion of these flexible connectors is a function of the number of times the tubing is exposed to the atmosphere. A positive way to determine the reliability of a flexible connection is to bend it slightly. If it "screeches," discard it immediately. This phenomenon signifies that internal corrosion is excessive and the tubing is liable to rupture prematurely by crystallization.

The supply system should be checked regularly for any signs of a leak. The potentially most dangerous leaks are the ones that start out in such small magnitude that they cannot be detected by the usual application of an aqueous ammonia solution and are undetectable by the average sense of smell. However, there are telltale signs for such minute leaks. One sign is the gathering of moisture near or at the point of leakage. Another is the sign of discoloration of the metal at the leaking joint. This occurs even in the most arid climates. Any chlorine leak will, over a period of time, cause a discoloration of the cadmium plated chlorine header valves and flexible connections. Even if the hardware were not cadmium plated, the discoloration caused by dezincification of the brass and the

Never reuse a gasket that has been in a joint after the joint has been disassembled.

The question of lead gaskets versus asbestos or paper composition gaskets is a continuing controversy. The paper or asbestos-type gasket tends to cover up gross deficiencies in chlorine cylinder outlet valve maintenance. This gasket is favored by the chlorine cylinder packagers. A paper composition gasket can develop a serious leak by failure during operation. This type of gasket should be avoided, because a gasket failure during operation can result in a much more serious leak than with a lead gasket. The failure of a lead gasket has never been proved to be the cause of a chlorine leak once that system was connected without leaks. Once a lead gasket has passed the leak test of a joint, it will never result in a chlorine leak at that particular joint providing it is not disturbed by disassembly and reassembly. A lead gasket joint will leak from the very beginning if it is not properly seated. This is the reason a lead gasketed joint should be regasketed each time it is disassembled.

Ton Containers—The same advice for this size cylinder is applicable as the advice for the 100- and 150-pound cylinders. The exception is the more rapid deterioration of the flexible connections. These should be discarded after each 50 tons of chlorine or 12 months service, whichever is sooner.

Tank Cars and Storage Tanks—The maintenance watchword of these systems is the continuous surveillance for leaks. As with any other chlorine supply system, the most critical time is during start-up procedures. Flexible connections for these supply systems should be plugged with corks when not in use and stored in a heated room.

Replacement of diaphragm protected pressure gages and pressure switches should be considered on a once in 3 to 5 years basis, unless other maintenance information prevails.

Safety Equipment—Emergency kits for all sizes of tanks should be maintained and ready for instant use. Practice using these devices should be a part of the plant maintenance schedule. The same applies to the emergency breathing apparatus. Special safety drills at prescribed intervals should be made available for all operating personnel on both the use and handling of the container emergency kits and the breathing apparatus.

Evaporators—This piece of equipment is subject to filling with a gooey mass of sludge that accumulates from inherent impurities in liquid chlorine. The amount of this sludge which accumulates in the bottom of the liquid chlorine vessel is primarily a function of the amount of chlorine passing through the evaporator. In general, evaporators should be inspected for sludge once a year or after passing 250 tons of chlorine—whichever comes first. In addition to this, the operator should keep a close watch on the evaporator "superheat." If this cannot be maintained at 20°F, it signifies that the evaporator is losing capacity due to sludge buildup in the liquid container or there is an immersion heater failure. All evaporators are housed in a removable cabinet which hides from view piping and instrument connections all of which are capable of producing chlorine leaks. These should be inspected every six months.

Immersion heaters can and do build up a scale deposit from hardness in the water-bath water. This can be so severe as to require annual replacement. Although the water-bath surfaces are cathodically protected from corrosion, the anodes used are sacrificial. Therefore, annual inspection and possible replacement of these anodes is desirable. The ammeter on the evaporator instrument panel does provide an indication of whether or not the cathodic protection system is functioning properly. Regardless of this indication, annual inspection is desirable.

Cleaning the evaporator liquid container consists of dismantling and removing the chlorine vessel and flushing this with cold water until the flushing water is clean. The inside is visually inspected for pitting. If the pitting is severe, the vessel should be replaced.

After all the flushing water has been removed, the evaporator is reassembled and the water-bath is filled and heated to 180° F. Then an aspirator is attached so that a vacuum can be exerted on the inside of the vessel. The vacuum should be about 25 inches Hg and should continue for 24 hours with the water-bath at 180° F to remove all moisture from the inside of the chlorine vessel.

Chlorine Gas Filter—This unit should be inspected every six months. The filter element should be replaced at each inspection and the sediment trap washed in cold water and dried before reassembly. The lead gasket at the flanged joint should also be replaced.

External Chlorine Pressure Reducing Valve—Chlorine impurities are most likely to precipitate out at points of pressure drop. So whatever impurities are not picked up by the filter described above will plate out on the spring loaded valve stem and seat of this unit. Deposits that cannot be removed with a soft cloth can be removed with isopropyl alcohol or trichlorethylene. The spring opposing the diaphragm action in this valve will eventually suffer from metal fatigue. Depending on local conditions, the life of this spring is from 2 to 5 years.

5.32 Chlorine Control and Metering System

Injectors—All injectors have removable internal components. These consist of a throat and tailway and an adjustable stem assembly. The one-inch or fixed throat injectors do not have an adjustable stem. Injectors should be disassembled and cleaned every six months or oftener if required. Even though the velocities through an injector provide a certain amount of scouring, iron or manganese in the injector water will plate out on the throat, thereby reducing the efficiency of the injector. This deposit is easily removed by washing with muriatic acid. Abrasion from sand in the injector water can damage the throat and tailway. This can be determined from visual inspection.

Booster Pumps—Maintenance of booster pumps is the same as for any other pump except that an injector water pump must put out a minimum specified flow at a minimum critical pressure. As soon as these are not achieved, the chlorinator injector system will fail even though the pump appears outwardly to be doing a satisfactory job.

Chlorinators—Modern chlorinators consist of a series of spring-loaded diaphragm units that form the basis for control of the chlorine gas through the installation with certain vacuum values at various points. Therefore, it is essential that all the joints be vacuum-tight for proper operation.

Most of the maintenance problems occur from metal fatigue of the springs in the various diaphragm assemblies, and from improper stem and seat closure in these diaphragms caused by impurities in the chlorine gas. All springs should be replaced every two years; the stem and seat units should be inspected and cleaned annually.

The rotameter tube and float assembly should be removed and cleaned periodically at least every six months. The chlorine metering orifice should be dismantled for inspection after six months operation, because impurities deposited here will give a clue as to the condition of the rest of the system.

Automatic control devices are made up of plug-in transistorized components which give long and reliable service provided the circuitry is balanced by proper calibration procedures at the time of start-up. Devices with moving parts such as potentiometers or alarm devices dependent upon mercury switches are subject to wear, and will require eventual replacement. The operator should have on hand spares for these items. Reversible motors used in control devices are also subject to failure even though they do give long and reliable service. The operator should check the source and availability of these motors. The best advice for the operator is to consult the manufacturer for a reasonable spare parts list to keep on hand, even though the installation consists of standby equipment.

Chlorine Residual Analyzer—This unit if arranged for control of the chlorination system must be carefully maintained. In wastewater application, the most vulnerable part of the analyzer is the sample flow to the cell, next is the condition of the electrodes and finally the maintenance of the reagent addition system.

Wastewater analyzers are subject to calibration drift owing to organic content of the sample. Therefore, frequent calibration of zero and span adjustment is necessary. Most plants calibrate the analyzer once a day.

All wastewater analyzers must be equipped with a motorized disc-type filter. This filter should be operated so that it is continuously flushed to waste with the drain valve in the wide-open position. The operator should keep a spare outer filter case on hand at all times. This piece is subject to frequent failure due to corrosion.

In some analyzers there is an additional filter of some sort downstream from the motorized unit. These filters should be cleaned on a regular daily basis. If there are other screens upstream from the motorized filter, these screens should also be cleaned on a regular basis.

The sample flow to the cell should be checked on a daily basis.

All of the sample lines beginning at the suction of the sample pumps should be purged on a regular basis to remove organic deposits, slimes and grease. These accumulations cause gross inaccuracies in the analyzer system.

The electrodes should be cleaned on a weekly or bi-weekly basis depending on the operation of the analyzer. If the output signal is erratic and the cell refuses to remain in proper calibration, the electrodes should be cleaned. The operator is advised to follow the manufacturer's recommended procedure for cleaning these electrodes and placing the analyzer back into operation.

The reagent additive system will not require any regular maintenance unless the pumping system fails to perform properly.

Amperometric Titrator—The best maintenance for this unit is frequent use. The electrodes should be soaked when idle in an iodine solution (10 mg/l conc.) and cleaned periodically. If a regular routine such as this is followed, the titrator will show sharp responses with clear-cut end points and repeatable results.

5.4 MAINTENANCE–DECHLORINATION EQUIPMENT

5.41 Sulfur Dioxide Supply System

The characteristics of sulfur dioxide are so similar to chlorine that everything said under this same heading for chlorine is applicable to sulfur dioxide system. (See Section 5.31.) The only exception is possibly the life of the diaphragm protectors on the gas pressure gages and switches. Because SO_2 vapor pressure is less than half that of chlorine, the wear on these units is much less.

As for corrosivity, the active ingredient sulfurous acid (H_2SO_3) is equally aggressive as its

6. REFERENCES CITED

1. Bagot, A., City of San Francisco, Personal Communication (September 30, 1970).
2. *Chlorine Manual,* 4th Ed., The Chlorine Institute, Inc., New York, NY (1969), pp. 6, 10, 12–14.
3. Collins, H. F., and Selleck, R. E., "Process Kinetics of Wastewater Chlorination," SERL Report No. 72-5, Sanitary Engineering Research Laboratory, University of California, Berkeley (November 1972).
4. Collins, H. F., Selleck, R. E., and White, G. C., "Problems in Obtaining Adequate Sewage Disinfection," *Jour. Sanitary Engr. Div., ASCE,* 97, SA 5, 549 (October 1971).
5. Collins, H. F., Selleck, R. E., and Saunier, B. M., "Optimization of the Wastewater Chlorination Process," Presented at Nat. Conf. Environ. Engineering, ASCE, Seattle, WA (July 1976).
6. Collins, H. F., White, G. C., and Sepp, E., "Interim Manual for Wastewater Chlorination and Dechlorination Practices," California State Water Resources Control Board Publ. No. 53 (May 1974).
7. Deaner, D. G., "Effect of Chlorine on Fluorescent Dyes," *Jour. WPCF,* 45, 507 (March 1973).
8. Esvelt, L. A., Kaufman, W. J., and Selleck, R. E., "Toxicity Removal from Municipal Wastewaters," SERL Report No. 71-7, Sanitary Engineering Research Laboratory, University of California, Berkeley (October 1971).
9. Fair, G. M., and Geyer, J. C., *Elements of Water Supply and Wastewater Disposal,* John Wiley and Sons, NY (1958).
10. Heukelekian, H., and Day, R. V., "Disinfection of Sewage with Chlorine, II. Method and Uniformity of Distribution of Chlorine in Sewage Plants," *Sew. and Ind. Wastes,* 23, 47 (January 1951).
11. Kovach, J. L., "Activated Carbon Dechlorination," *Ind. Water Engr.,* (October/November 1973) pp. 30–32.
12. Kim, B. R., Snoeyink, V. L., and Schmitz, R. A., "Removal of Dichloramine and Ammonia by Granular Carbon," *Jour. WPCF,* 50, 122 (1978).
13. Langston, P. B., "The Use of Granular Activated Carbon Beds for Dechlorination, Organic Removal, and Turbidity Control," Manuscript, Pittsburg Activated Carbon Co.
14. Longley, K. E., "Turbulence Factors in Chlorine Disinfection of Wastewater," *Water Research,* 12, 813, (1978).

17. Marske, D. M., and Boyle, J. D., "Chlorine Contact Chamber Design–A Field Evaluation," *Water and Sewage Works* (January 1973) pp. 70–77.

18. McKee, J. E., et al., "Report on the Disinfection of Settled Sewage," California Institute of Technology, Pasadena, California (April, 1957).

19. Moore, E. W., "Fundamentals of Chlorination of Sewage and Wastes," *Water and Sewage Works*, 98:3 (1951).

20. Pick, R., *Vom Wasser,* 3, 71 (1930).

21. "Process Design Manual for Carbon Adsorption," EPA Technology Transfer (October 1971).

22. Rebhuhn, M., and Argaman, Y., "Evaluation of Hydraulic Efficiency of Sedimentation Basins," *Jour. Sanitary Engr. Div., ASCE,* 91, SA 5 (October 1965).

23. Sawyer, C. N., "Hypochlorination of Sewage," *Sew, and Ind. Wastes,* 29, 978 (September 1957).

24. Scaramelli, A. B., and Digiano, F. A., "Effect of Sorbed Organics on the Efficiency of Ammonia Removal by Chloramine–Carbon Surface Reactions," *Jour. WPCF,* 49, 693 (1977).

25. Selleck, R. E., Collins, H. F., and White G. C., "Kinetics of Wastewater Chlorination in Continuous Flow Processes," Presented at 5th Int'l Water Poll. Research Conf., San Francisco, California (July/August 1970).

26. Selleck, R. E., and Collins, H. F., "The Significance of Wastewater Disinfection," Unpublished (1973).

27. Selleck, R. E., Saunier, B. M., and Collins, H. F., "Kinetics of Bacterial Deactivation with Chlorine," *Jour. Environmental Engr. Div., ASCE,* 104, EE 6, 1197, (December 1978).

28. Selna, M. W., and Parkhurst, J. D., "Pomona Virus Study," Prep. For California State Water Resources Control Bd. by Los Angeles County San. Districts (June, 1977).

29. Selna, M. W., Miele, R. P., and Baird, R. B., "Disinfection for Water Reuse," Pres. at Disinfection Seminar, AWWA Annual Convention, Anaheim, California (May 1977).

30. Sepp, E., and Jopling, W., "California Experience with Fecal Coliform Bacteria," Proc. Symposium on Fecal Coliform Bacteria in Water and Wastewater, California Department of Public Health, Berkeley, California (May 1968).

31. Sepp, E., "Tracer Evaluation of Chlorine Contact Tanks," California Department of Health, Berkeley, California (1977).

32. Sepp, E., and Bao, P., "Design Optimization of the Chlorination Process, Volume I: Comparison of Optimized Pilot System with Existing Full-Scale Systems," Prep. for U. S. EPA by California Department of Health Services, Berkeley, California (1980).

34. *Sewage Treatment Plant Design,* ASCE Manual of Engr. Practice No. 36, by Joint Committee of ASCE and WPCF (1959).

35. *Standard Methods for the Examination of Water and Wastewater,* by APHA, AWWA and WPCF, 14th Ed. (1975).

36. Stasiuk, W. N., Hefling, L. J., and Shuster, W. W., "Nitrogen Removal by Catalyst-aided Breakpoint Chlorination," *Jour. WPCF,* 46, (1974).

37. Stone, R. W., Kaufman, W. J., and Horne, A. J., "Long-term Effects of Toxicants and Biostimulants on the Waters of Central San Francisco Bay," SERL Report No. 73-1, Sanitary Engineering Research Laboratory, University of California, Berkeley, California (May 1973).

38. Suidan, M. T., Vernon, L., and Schmitz, R. A., "Reduction of Aqueous HOCl with Activated Carbon," *Jour. Environmental Engr. Div., ASCE,* 103, EE 4, (August 1977).

39. Trussell, R. R., and Chao, J. L., "Rational Design of Chlorine Contact Facilities," *Jour. WPCF,* 49, 659 (1977).

40. "Wastewater Chlorination for Public Health Protection," Proc. 5th Annual Sanitary Engineering Symposium, Bureau of Sanitary Engineering, California Department of Public Health, Berkeley, California (May 1970).

41. White, G. C., "Chlorination and Dechlorination: A Scientific and Practical Approach," *Jour. AWWA,* 60, 540 (May 1968).

42. White, G. C., *Handbook of Chlorination,* Van Nostrand Reinhold Co., New York (1972).

43. White, G. C., "Disinfection Practices in the San Francisco Bay Area," *Jour. WPCF,* 46, 84 (January 1974).

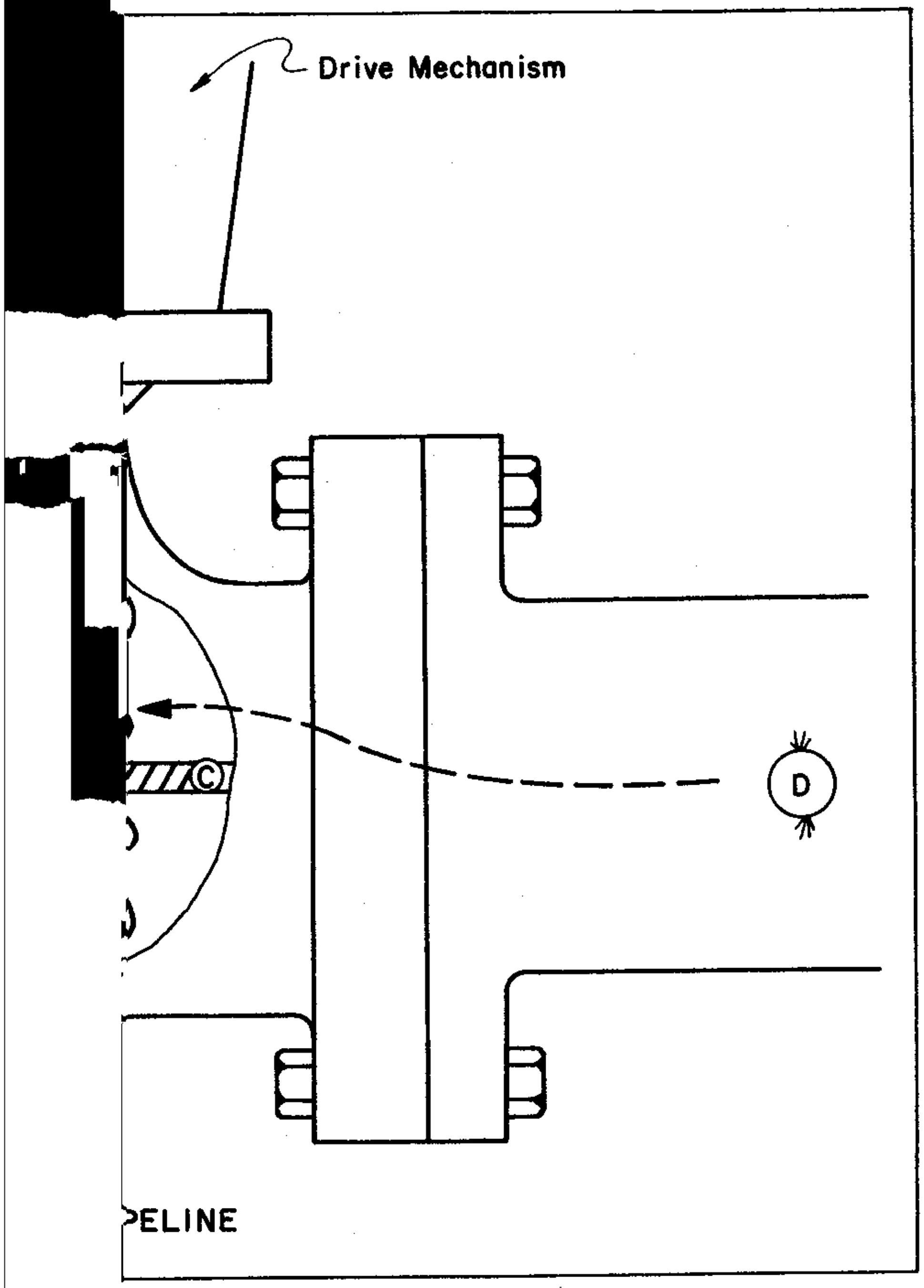
44. White, G. C., *Disinfection of Wastewater and Water for Reuse,* Van Nostrand Reinhold Co., New York (1978).

45. WPCF and ASCE, *Design and Construction of Sanitary and Storm Sewers,* WPCF Manual of Practice No. 9 (1970).

7. APPENDIX

FIGURE

TABLE


Drive Mechanism
D
C
ELINE

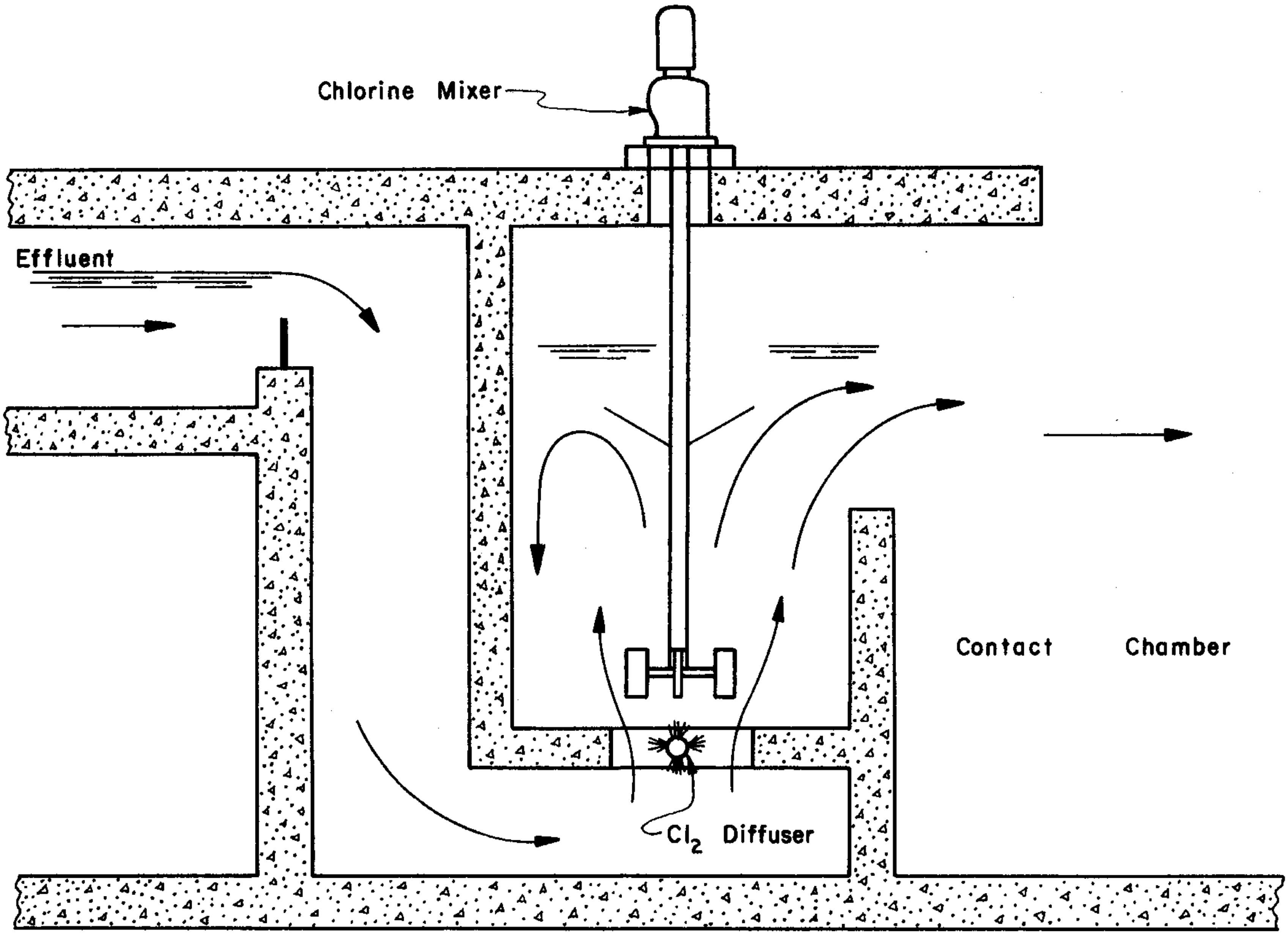
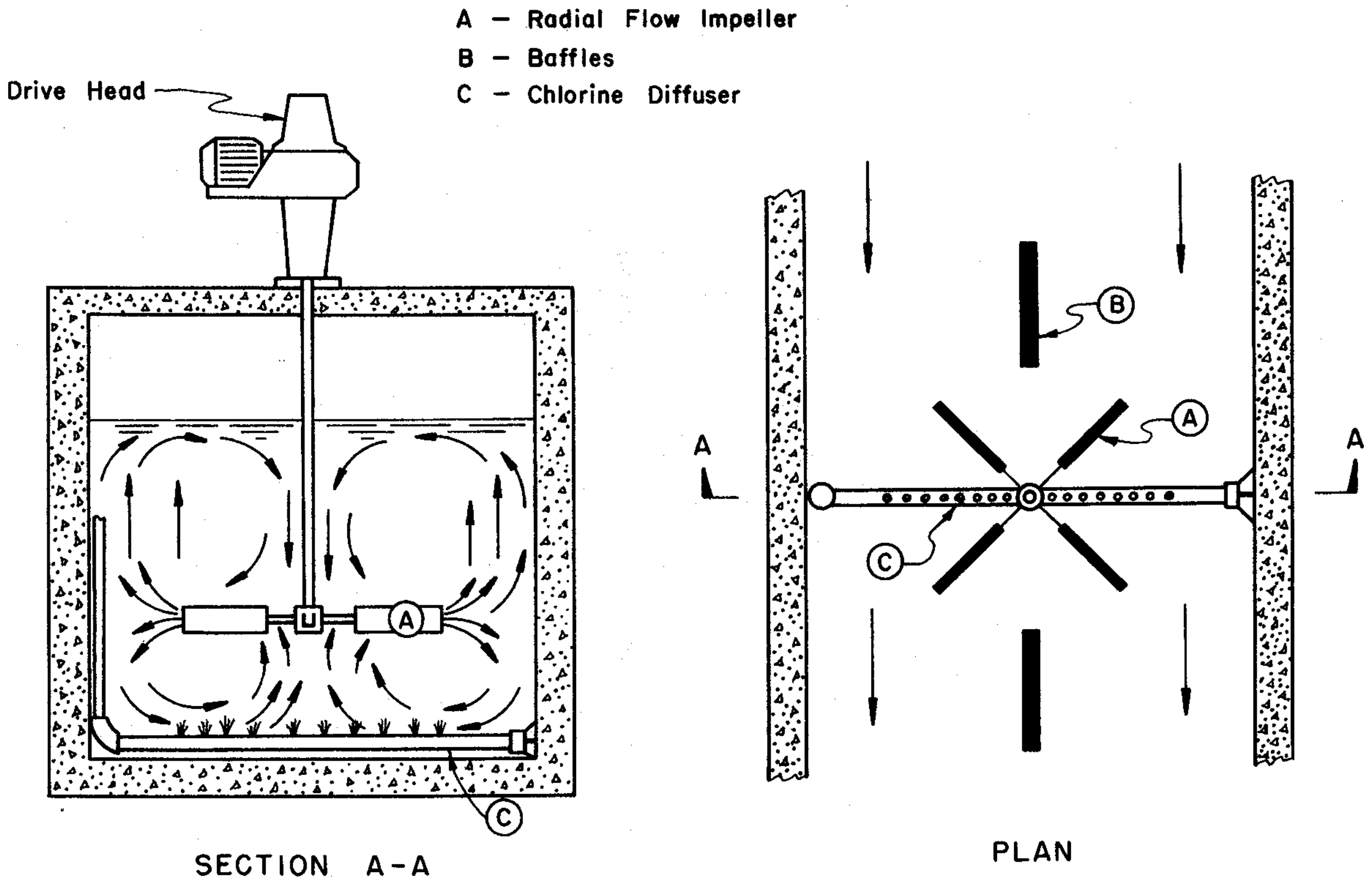


FIGURE A-2 A MECHANICAL CHLORINE MIXING DEVICE



SECTION A-A

PLAN

FIGURE A-3. AN OPEN CHANNEL TYPE MECHANICAL MIXER

TABLE A–1
EXAMPLE CALCULATION OF DISPERSION NUMBER d

TIME, t MIN.	DYE CONCENTRATION, C, FLUORESCENCE UNITS	t C	t² C
40	0		
45	10	450	20,250
50	49	2,450	122,500
55	78	4,290	235,950
60	72	4,320	259,200
65	61	3,965	257,725
70	50	3,500	245,000
75	37	2,775	208,125
80	21	1,680	134,400
85	15	1,275	108,375
90	9	810	72,900
95	5	475	45,125
100	4	400	40,000
105	2	210	22,050
Sum:	413	26,600	1,771,600

$T = V/Q = 72.3$ Min.

$$t_a = \frac{\Sigma\, tC}{\Sigma\, C} = \frac{26{,}600}{413} = 64.4 \text{ Min.};\ t_a^2 = 4148.2$$

$$s_t^2 = \frac{\Sigma\, t^2C}{\Sigma\, C} - t_a^2 = \frac{1{,}771{,}600}{413} - 4148.2$$

$$= 4289.6 - 4148.2 = 141.4$$

$$s^2 = s_t^2/t_a^2 = 141.4/4148.2 = 0.034$$

$$d = s^2/2 = 0.034/2 = \underline{\underline{0.017}}$$

For definition of symbols see Section 2.32 and Glossary of Abbreviations.

TABLE A—2
GLOSSARY OF ABBREVIATIONS

SO_2 — sulfur dioxide gas
Cl_2 — chlorine gas
BOD — biochemical oxygen demand
COD — chemical oxygen demand
TSS — total suspended solids
TOC — total organic carbon
Y_1 — initial bacterial concentration
Y_2 — final bacterial concentration after chlorination
R — chlorine residual after contact
t — chlorine contact time
b — an intercept when $Y_2/Y_1 = 1.0$
n — slope of curve in $Y_2/Y_1 = (Rt/b)^n$
r — correlation coefficient
G — mean velocity gradient
P — power/volume
μ — absolute viscocity of fluid
T — theoretical detention time, volume/flow rate
f(t) — residence time distribution function
t_i — minimum contact time
t_{10} — time for 10 percent dye to pass
t_{90} — time for 90 percent dye to pass
t_m — modal contact time
t_a — average contact time
t_{90}/t_{10} — Morril Index
d — reactor dispersion number
s_t^2 — variance of time—concentration curve
C — tracer concentration
s^2 — s_t^2/t_a^2 = reduced variance
f — Darcy-Weisbach friction factor
D — pipe diameter
L — length; flow length in baffled tank
W — flow width
L/W — flow length-to-width ratio
H — depth of water
H/W — depth-to-width ratio
V — volume
Q — flow rate