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Title RELATIONSHIP BETWEEN RESIDUAL CHLORINE AND COLIFORM DENSITY IN WATER DISTRIBUTION SYSTEMS

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For decades, the sanitary engineer has used chlorine as the final, and in some cases the only, treatment of a potable water to prevent the spread of water-borne diseases. In addition, he also has used coliform organisms as an indicator of the bacteriological quality of the chlorinated water he has produced. Yet never, in all these years of water treatment practices, has there been reported a study of the correlation of the chlorine residuals found in the water of the distribution systems with the bacteriological quality of the water based on the coliform indicator organisms.

In this study, data were collected from seven cities throughout the country. In addition to the results of the coliform tests, the data included the results of total chlorine residual determinations made at the time bacteriological samples were taken. A frequency distribution showing the percent of positive coliform tubes versus the total

chlorine residual was made and an equation fitted to this distribution by means of a least squares analysis.

The results of the analyses show conclusively that a mathematically definable relationship does exist between residual chlorine and coliform density in water distribution systems. It is also shown that regardless of the residual chlorine maintained in a water distribution system, at least 0.45 percent of all coliform tubes examined will show a positive presence of these organisms. This is attributed to the positive nature of the errors involved in the sampling and analytical procedures used in the coliform test.

RELATIONSHIP BETWEEN RESIDUAL CHLORINE AND COLIFORM DENSITY IN WATER DISTRIBUTION SYSTEMS

by

RONALD FRANCIS COENE

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INTRODUCTION

For decades, the sanitary engineer has used chlorine as the final, and in some cases the only, treatment of a potable water to prevent the spread of water-borne diseases. In addition, he also has used coliform organisms as an indicator of the bacteriological quality of the chlorinated water he has produced. Yet never, in all these years of water treatment practices, has there been reported a study of the correlation of the chlorination practices and the chlorine residuals found in the water with the bacteriological quality of the water based on the coliform indicator organisms. Of course the practices of chlorination being used today have developed from just such a relationship, but these correlations have never been made outside the laboratory.

One interesting aspect of this problem can be found in the actual operation of some of the water treatment plants throughout the country. A few of the more conscientious water superintendents or water treatment operators have for years collected water samples on the distribution system and examined them for bacteriological quality and chlorine residuals. In some instances the temperature, turbidity, and pH of the samples were examined also. And most important, this information was recorded, a fact of which the author took full advantage in preparing this thesis. It is important to note that these operators, although never directly correlating the bacteriological quality of the water with the chlorine residual they obtained from their samples, did use the chlorine residual measurement as an indicator of the quality of the water being made available to customers at particular locations within the distribution system.

Another and possibly more important problem than the relationship of chlorine residuals to the bacteriological quality of the water is the relationship between the chlorine residual in finished water to the virological quality of the water. This important point was demonstrated in a report made by the Committee on Public Health Activities of the American Society of Civil Engineers in which they stated:

> Because infectious hepatitis virus survive all normal steps in water treatment except proper free residual chlorination and since viruses survive heavy doses of combined chlorine, the practice of providing free chlorine residual treatment with adequate contact is important, especially when a water supply is known to have been subject to fecal contamination (3, p. 46).

Although acknowledging the fact that chlorination practices and virological quality are important aspects of the problem, this thesis will be confined to attempting to establish a relationship between residual chlorine and bacteriological quality, or more specifically, coliform density, in the water distribution system.

Purpose of this Thesis

The purpose of this thesis is threefold: (1) to investigate and study the data of chlorine residuals and bacteriological results in order to establish a relationship between the two; (2) to develop a workable equation for the correlation if such a relationship is established; and (3) to make recommendations for the application of this correlation by substituting chlorine residual tests for a portion of the bacteriological examinations ordinarily made on a water distribution system. The first two objectives form a basis for the third. The third objective, if initiated, would have a great impact on the water works profession.

By law (44) every city providing water for interstate carriers must take a required number of bacteriological samples each month. For a city with a population of one million, for example, at least 300 water samples must be taken each month from representative points on the distribution system. After collection, they must be brought back to the laboratory for analysis. This analysis requires a minimum of 48 hours incubation in addition to the time required to set up the tests and prepare the equipment and media. By substituting chlorine residual testing for a portion of the bacteriological tests, considerable time could be saved. Chlorine residual tests are rapid and can be conducted at each sampling site instead of having to return the sample to the laboratory.

Scope and Methodology of the Study

To understand better the problem treated in this thesis, it is necessary to investigate the different aspects of the relationship between chlorine residuals and bacteriological quality in the distribution system. The important facets of disinfection along with the microbiological aspects are discussed. In addition, other variables pertinent to the relationship are examined. These include the effect of other water treatment practices on the removal of microorganisms and the analytical methods used for both the chlorine and bacteriological determinations. After this information is presented, the data used in the study are examined according to the variables described in the first parts of the text. Finally, a statistical analysis is presented in order to obtain a workable equation for the relationship being studied. The scope of the statistical analysis considers only two variables -- chlorine residuals and bacteriological quality. The other variables pertinent to this relationship are considered constant.

ASPECTS OF DISINFECTION

In the water works profession, the term disinfection describes the treatment process which results in the death of pathogenic bacteria and other potentially infective organisms in the water. To be an effective and useful inhibitor of infective organisms, Fair and Geyer (18, p. 794) state that a disinfectant must possess the following characteristics: (1) It must be able to destroy any number and all kinds of potentially infective organisms. (2) It must be effective in waters of different chemical composition as well as being effective throughout the temperature range of the water. (3) It must not render the water unpalatable. (4) It must be inexpensive and easy to use. (5) It must be of such a nature so that its concentration in the water being treated can be ascertained. (6) It must be an agent that will maintain a residual concentration for protection against accidental contamination. Chlorine, more than any other disinfectant, most nearly meets these requirements.

Water-Chlorine Chemistry

Chlorine, as it is used in the water works industry, is found as either free available chlorine or combined available chlorine. Although both forms of chlorine are effective bactericidal agents, the relative disinfecting power of free chlorine is approximately 25 times that of combined chlorine.

The term free available chlorine refers to molecular chlorine (Cl_2), hypochlorous acid (HOCl), and the hypochlorite ion (OCl^-). When chlorine is added to water, the following reactions take place:

$$(1) \quad Cl_2 + H_2O \rightleftharpoons HOCl + HCl$$

$$(2) \quad HOCl \rightleftharpoons H^+ + OCl^-$$

The equilibrium in the first equation is generally displaced greatly to the right as very little molecular chlorine will exist in dilute solutions at pH levels greater than 4. The second equation represents the ionization of the hypochlorous acid, and its equilibrium also depends on the pH of the water. The equilibrium that exists between these two forms can best be illustrated by Figure 1 in which the percentage of each constituent is plotted against various pH values.

The bactericidal effectiveness of hypochlorous acid is approximately 80 times greater than the hypochlorite ion. This is shown in Figure 2. As the pH or hydrogen ion concentration increases, the amount of chlorine needed to effect a 99% kill of Escherichia coli in 30 minutes at 2-5° C. must be increased. This is because as the pH increases, the ratio of hypochlorous acid to the hypochlorite ion decreases, as illustrated in Figure 1.

Another way of demonstrating this ratio is to consider that

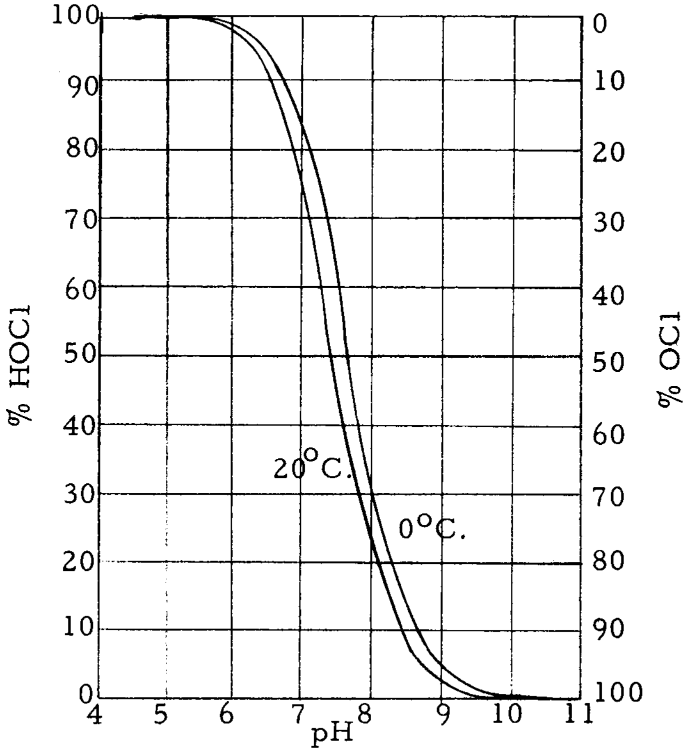

Figure 1. Effect of pH on the distribution of hypochlorous acid and hypochlorite ion in water (38, p. 250).

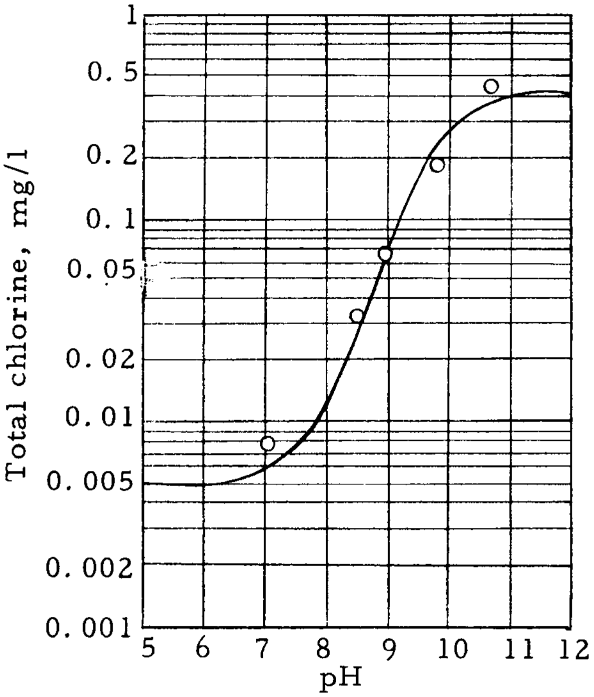

Figure 2. Concentration of free available chlorine required for 99% kill of Esch. coli in 30 min. at 2 to 5 C. (18, p. 805).

0.005 mg/l of chlorine in water of pH 5 will produce the same kill as 0.4 mg/l of chlorine in water of pH 12. The average water treatment plant produces water with a pH of 7 or 8. In maintaining a free chlorine residual in these plants, approximately 50% of the residual will be in the form of hypochlorous acid and 50% as the hypochlorite ion.

Chlorine and hypochlorous acid, as well as being toxic to bacteria and other microorganisms, are very potent oxidizing agents and will react with a variety of substances, including ammonia, to form combined available residuals.

Ammonia reacts with chlorine or hypochlorous acid to form monochloramines, dichloramines, and trichloramines. This reaction is dependent on the pH of the solution as well as the concentration of both the chlorine and ammonia. The reaction equations of chlorine with ammonia are as follows:

$$NH_3 + HOCl \longrightarrow NH_2Cl + H_2O$$

$$NH_3 + 2HOCl \longrightarrow NHCl_2 + 2H_2O$$

$$NH_3 + 3HOCl \longrightarrow NCl_3 + 3H_2O$$

The percentage of chlorine as $NHCl_2$ in relation to pH is shown in Figure 3.

Both monochloramine and dichloramine, as a combined available chlorine residual, are of significant interest in measuring chlorine residuals, although they are only approximately 1/25 as powerful as free available chlorine residuals.

Because of its oxidizing characteristics, chlorine, in its molecular form or as hypochlorous acid, will react with a variety of materials, especially reducing agents. Some of these reactions take place very quickly while others are much slower. This characteristic of chlorine complicates its use because these side reactions reduce chlorine's disinfecting potential. Typical of these side reactions is chlorine's reaction with hydrogen sulfide.

$$H_2S + 4Cl_2 + 4H_2O \longrightarrow H_2SO_4 + 8HCl$$

Other reducing agents which have reactions of interest when combined with chlorine are the ferrous ion (Fe^{++}), the manganous ion (Mn^{++}), and the nitrite ion (NO_2^-).

These side reactions with chlorine constitute what is known in the water industry as chlorine demand. Another way to express this phenomenon is to consider chlorine demand as that amount of chlorine which must be supplied to give the desired free, combined, or total residual after a certain contact period.

Total residual is defined as the sum of the free and combined residuals. Both types of residual may be present in a disinfected water because the reaction of ammonia with hypochlorous acid to give a combined residual depends upon the temperature and the pH of the

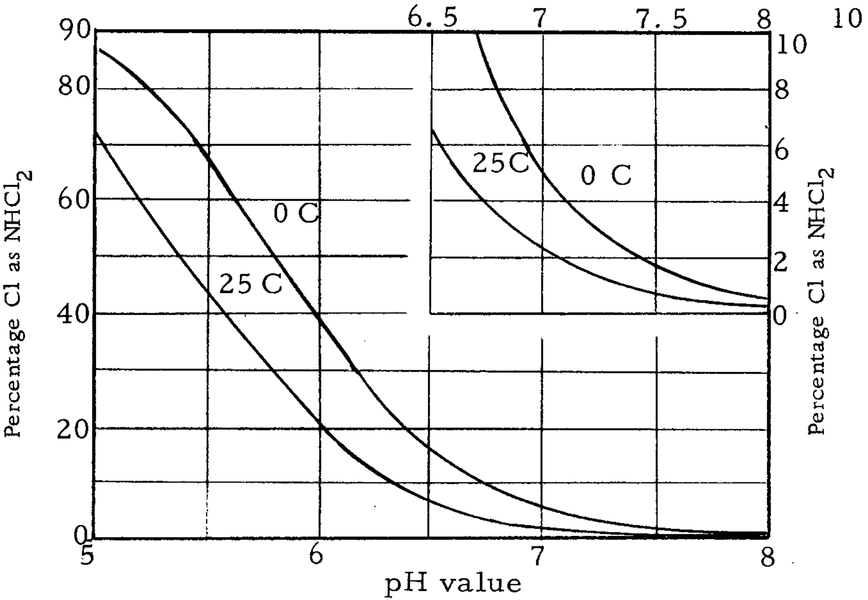

Figure 3. Distribution of chloramines at equimolar concentrations of chlorine and ammonia [Cl_2:NH_3(as N)=5.] (18, p. 808)

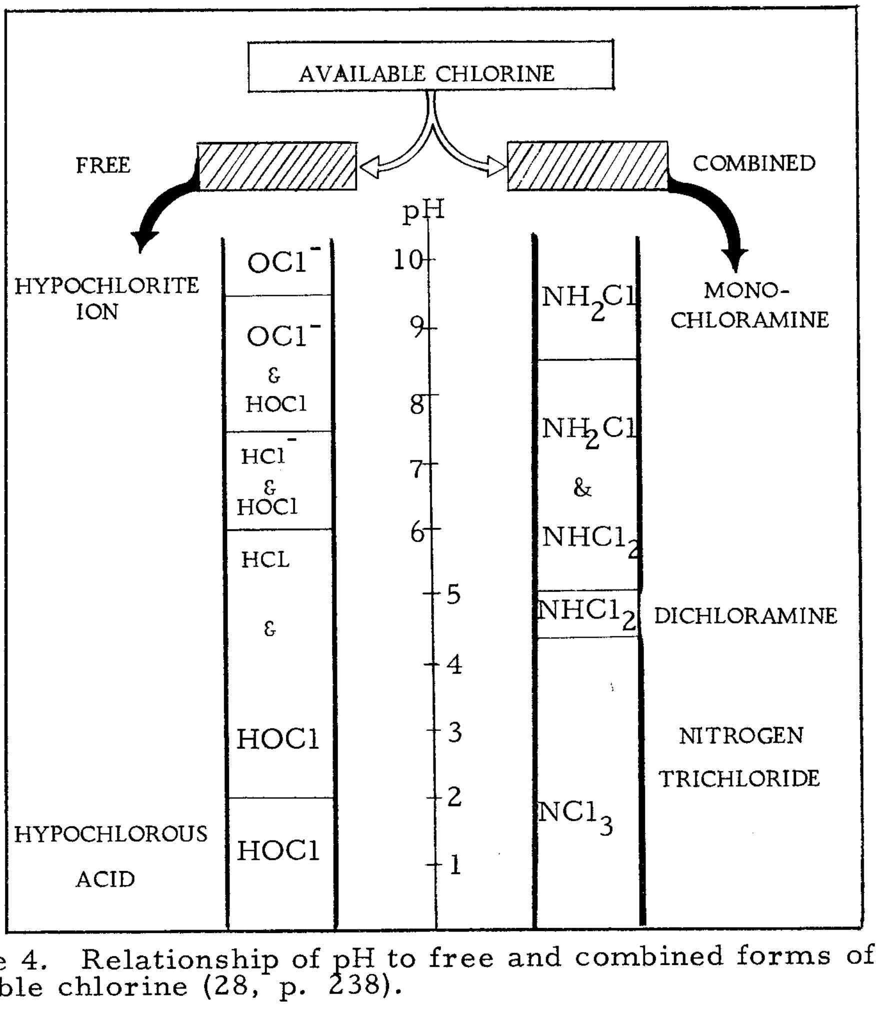

Figure 4. Relationship of pH to free and combined forms of available chlorine (28, p. 238).

water. Figure 4 illustrates the relationship of both free and combined chlorine residuals to pH.

If enough chlorine is added, the point will be reached where all the ammonia will be destroyed, leaving only a free available residual. In water treatment practices, this point is referred to as breakpoint chlorination. This is illustrated in Figure 5. Although reaching this point is not essential for complete disinfection, the practice of breakpoint chlorination has received a great deal of attention in the water works field.

Mechanisms of Chlorine Disinfection

There have been four hypotheses expressed to explain the bactericidal effect of chlorine. They are: (1) chlorine completely oxidizes all the organic material, including bacteria, in the water being treated; (2) chlorine reacts with the bacterial protoplasm to denature this protein material; (3) chlorine reacts with material in the bacterial cell wall to form toxic substances; and (4) chlorine reacts with material of the bacterial cell and inhibits key enzymatic processes (4, p. 509).

None of these four theories have been completely accepted by sanitary engineers. In fact the first theory is considered to be obsolete. Work by Green and Stumpf (18) has led to a more general acceptance of the theory that chlorine inhibits the key enzymatic processes of the bacteria. This reaction has been theoretically described as taking place in two steps -- the penetration through the cell wall by chlorine and the reaction of the disinfectant with the cell enzymes. Once the enzyme system is damaged by the chlorine, the cell is unable to metabolize "food" for its nutritional needs and the cell dies.

Kinetics of Chlorine Disinfection

The effectiveness and speed in which chlorine will react depends on several important factors: (1) concentration of disinfectant, (2) contact time, (3) temperature, (4) pH, and (5) type and density of organisms present.

The efficiency of a disinfectant based on its concentration can be expressed by the following empirical formula

$$c^n t_r = \text{Constant}$$

where "c" is the concentration of the disinfectant, "t_r" the time required to give a constant percentage of organisms killed, and the exponent "n" the coefficient of dilution (18, p. 799). This equation is the result of correlations such as the one shown in Figure 6. This figure gives a plot of the free chlorine residual and the combined chlorine residual against the contact time. It illustrates the

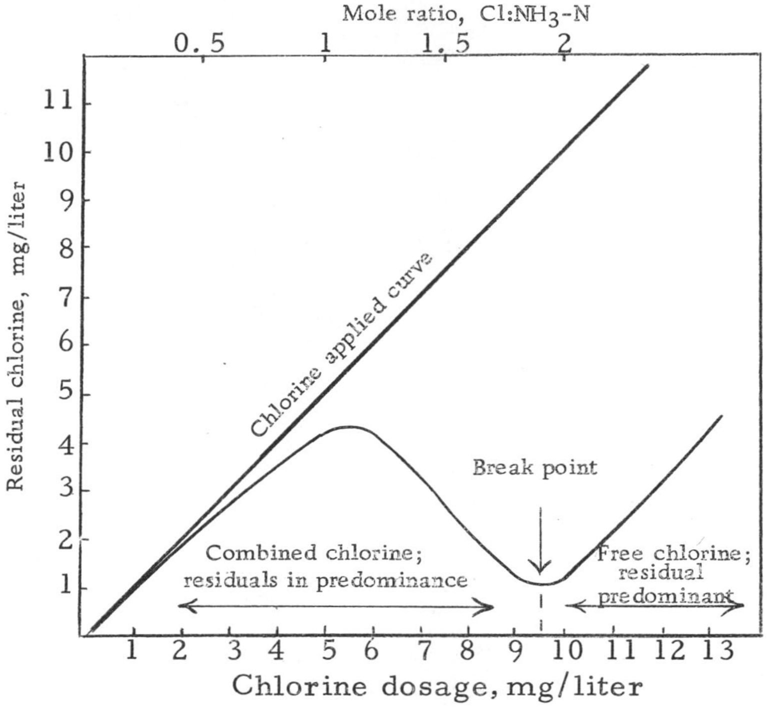

Figure 5. A residual-chlorine curve showing a typical break point. Ammonia-nitrogen content of water, 1.0 mg/l (38, p. 252).

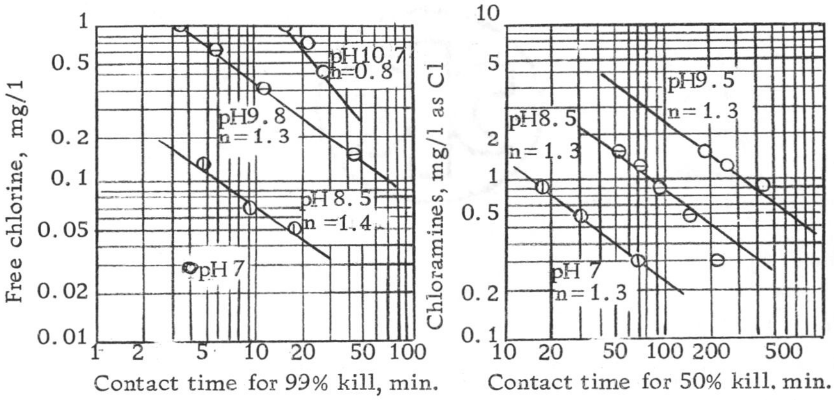

Figure 6. Time-concentration relationships in disinfection. (a) Concentration of free available chlorine required for 99% kill of Esch. coli at 2 to 5C. (b) Concentration of combined available chlorine required for 50% kill of Esch. coli at 2 to 5C. (18, p. 800).

superiority of the free residual over the combined residual.

Contact time as a factor of disinfection is expressed by Chick's Law which states "that the number of organisms killed per unit time is proportional to the number of organisms remaining" (18, p. 798). The relationship can be expressed by the following equation

$$dy/dt = k(N_o - y)$$

where "t" is time, "k" the rate constant, "y" the number of organisms destroyed, and "N_o" the number of organisms initially present. A graphical presentation of this relationship is shown in Figure 7.

The effects of temperature on chlorine disinfection can be summarized by saying that as the temperature decreases the bactericidal effect of chlorine will decrease also. This is most evident at high pH's.

A relationship also exists between the killing power of chlorine and pH. As the pH of the water is increased, the rate and effectiveness of chlorination is reduced. A complete analysis of the effect of pH on chlorination effectiveness, as well as the effects of temperature, contact time, and concentration, has been made by Butterfield, Wattie, Megregian, and Chamber (5;6).

As stated by Fair and Geyer (18, p. 800) it is apparent that the number of organisms present cause no significant difference in the disinfectant power of chlorine. The same cannot be said for the

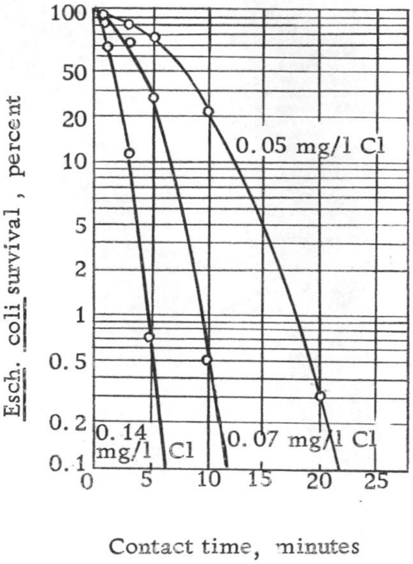

Figure 7. Length of survival of *Esch. coli* in pure water at pH 8.5 and a temperature of 2 to 5 C. (18, p. 799).

type of organisms present, however, as certain strains of bacteria are more resistant to chlorine disinfection than others. This is probably attributed to their structural makeup and their enzymatic processes. Advantage has been taken of this fact in that the coliform group of bacteria, harmless in themselves, are more resistant to chlorine than most bacterial enteric pathogens. Coliforms, therefore, have been used as indicators of bacteriological quality.

MICROBIOLOGICAL ASPECTS

Since the discovery that disease-producing organisms could be transmitted through drinking water, man has been endeavoring to find a means by which the presence of these organisms could be easily detected. In his investigations he determined that certain types of bacteria of enteric origin can transmit disease in water. In addition, he discovered that worms, protozoa, and viruses are also water-borne infective organisms. He also learned, in his search for a means of detecting these organisms, that the presence of the coliform group of bacteria could be accepted as an indicator of microbiological pollution.

Enterobacteria

All but one of the important pathogenic bacteria found in water belong to the family Enterobacteriaceae. The pathogenic bacteria of greatest importance in this family are *Paracolobactrum*, *Salmonella*, and *Shigella*. The coliform group is also found in the Enterobacteriaceae family but, unlike the others, is a harmless type of bacteria found in the human feces. Hundreds of billions of coliforms are excreted per capita daily, and their presence in such large numbers is one reason why they are used as an indicator of the bacteriological quality of the water. Other reasons for using coliforms as indicators are: (1) that direct tests for specific pathogens are impractical, (2) that coliform determinations can be made with relative ease, (3) that quantitative as well as qualitative results can be attained, and (4) that for the most part the coliform group is more resistant to chlorine disinfection than the pathogenic members of the Enterobacteriaceae family.

The coliform group, as defined by Standard Methods (2, p. 494), includes all of the aerobic and facultative anaerobic, Gram-negative, nonspore-forming, rod-shaped bacteria which ferment lactose with gas formation within 48 hours at 35° C.

There are two recognized species in the coliform group -- *Escherichia coli* and *Aerobacter aerogenes*. *Escherichia coli* are normally found only in the intestinal tract of humans and animals, whereas *Aerobacter aerogenes* are found in the soil. The differences between these two species have caused some conflict within the field of sanitary engineering. For it is possible, and it probably has happened, that a coliform test has indicated that a water supply has been contaminated with fecal pollution, and therefore unfit for human consumption, when only the *Aerobacter aerogenes* were present in the sample analyzed. These, because they are of soil rather than fecal origin, do not indicate fecal pollution. Despite the possibility of this happening, the coliform test is still considered satisfactory for determining the bacteriological quality of potable water because, with the daily excretion of E. coli in the hundreds of billions per capita, the chances are good that a positive coliform test is the result of fecal contamination. The acceptance of this test, however, has not halted the search for a more specific and quicker test. The use of enterococci organisms, rather than coliforms, as indicators of bacteriological quality has received some recognition, especially in the surveillance of swimming pool water.

Intestinal Protozoa

Within this family of single-celled animals are two organisms of public health significance -- Histoplasma capsulatum and Endamoeba histolytica. The latter is the most important and is the causative agent of amoebic dysentery.

Neither of these organisms are particularly susceptible to the normal concentration of chlorine in a finished water. Because of their size, however, both organisms are easily removed by effective sand filtration. The coliform test is meaningless with regard to these organisms but, since most water supplies in this country using surface water as their source use sand filtration in their treatment operations, this is not a drawback.

Worms

The public health hazard of worms or blood flukes in this country is somewhat remote. Nematodes and *Schistosomiasis mansoni* are probably the most important members of this group. The *Schistosomiasis mansoni* is easily removed from water through rapid sand filtration, but the nematode is resistant to removal by both filtration and chlorination. Its potential significance as a health hazard, however, is thought to be nill, although Kabler and Chang had investigated the possibility that nematodes were the habitat of a potentially more hazardous microbe, the virus.

Enteroviruses

One of the greatest criticisms of the coliform test as an indicator of the bacteriological quality of water is its inability to detect the presence of viruses. The role of virology in potable water is a relatively new concept, for until recently the methods available to scientists were unable to detect these submicroscopic organisms. Not until water was investigated as the mode of transporting the polio virus was much emphasis placed on the relationship of water and viruses. Since this time, much energy and money has been spent trying to learn more about polio, coxsackie, infectious hepatitis, and other viruses and develop a cause and effect relationship between them and water.

It is interesting to note that the infectious hepatitis virus has never been successfully isolated by scientists. One important fact ascertained about the hepatitis virus, however, is that present chlorination practices are insufficient to cope with it.

Table 1 lists the efficiency of free-chlorine residual with respect to several viruses.

Table 1.[*] Viricidal Efficiency of Free Chlorine in Water

Investigator	Virus	Temp. °C	Final pH	Free chlorine mg per 1	Virus destruction
Chang *et al.*	Part. purif. Theiler's virus in tap water	25-27	6.5-7.0	4.0-6.0	98.6% in 10 min
		25-27	6.5-7.0	4.0-6.0	99% in 5 min
Neefe *et al.*	Feces-borne Inf. Hepat. virus in dist. water	Room	6.7-6.8	3.25	30 min cont. time protected all of 12 volunteers
Lensen *et al.*	Purif. Polio II in dist. and lake water	19-25	7.4-7.9	1.0-1.5	10 min cont. time protected all of 164 inoc. mice
Clarke and Kabler	Purif. Coxsackie A2 in demand-free water	3-6	6.9-7.1	0.58-0.62	99.6% in 10 min
		3-6	6.8-7.1	1.9-2.2	99.6% in 4 min
		3-6	6.9-7.1	3.8-4.2	99.6% in 2 1/2 min
		3-6	8.8-9.0	1.9-2.0	99.6% in 24 min
		3-6	8.8-9.0	3.7-4.3	99.6% in 9 min
		3-6	8.8-9.0	7.4-8.3	99.6% in 5 min
		27-29	6.9-7.1	0.16-0.18	99.6% in 4 min
		27-29	6.9-7.1	0.44-0.58	99.6% in 3 min
		27-29	8.8-9.0	0.10-0.18	99.6% in 10 min
		27-29	8.8-9.0	0.27-0.32	99.6% in 7 min
		27-29	8.8-9.0	0.92-1.0	99.6% in 3 min
Weidenkopf	Purif. Polio I (Mahoney) in demand-free water	0	6.0	0.39	99.6% in 3 1/2 min
		0	6.0	0.80	99.6% in 1 1/2 min
		0	7.0	0.23	99.6% in 8 min
		0	7.0	0.53	99.6% in 4 1/2 min
		0	8.5	0.53	99.6% in 16 min
		0	8.5	1.95	99.6% in 7 1/2 min
		0	8.5	5.00	99.6% in 3 min
Kelly and Sanderson	Purif. Polio I (Mahoney) in demand-free water	25-28	7.0	0.21-0.30	99.9% in 3 min
		25-28	9.0	0.21-0.30	99.9% in 8 min
	Purif. Polio III (Saukett) in demand-free water	25-28	7.0	0.11-0.20	99.9% in 2 min
		25-28	9.0	0.11-0.20	99.9% in 16 min
	Purif. Coxsackie B5 in demand-free water	25-28	7.0	0.21-0.30	99.9% in 1 min
		25-28	9.0	0.21-0.30	99.9% in 8 min
		1-5	7.0	0.21-0.30	99.9% in 16 min
		1-5	8.0	0.21-0.30	99.9% in 30 min
Clarke *et al.*	Purif Adenovirus 3 in demand-free water	25	8.8-9.0	0.20	99.8% in 40sec-50sec
		25	6.9-7.1	0.20	99.8% in 8sec-16sec
		4	8.8-9.0	0.20	99.8% in 80sec-100sec
		4	6.9-7.1	0.20	99.8% in 8sec-10sec

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[*] (3, p. 51)

WATER TREATMENT PRACTICES IN RELATION TO THE REMOVAL OF MICROORGANISMS

It is not sufficient to discuss the relationship between chlorine residuals and coliform density in water distribution systems without first considering some of the processes and methods used in treating water prior to distribution, as well as the problems and practices of distributing the water.

Treatment Practices

Coagulation, sedimentation, filtration, and disinfection have been accepted processes for treating water supplies. As our streams, rivers, and lakes are subjected to increased biological pollution, however, some water treatment facilities have found it necessary to incorporate additional treatment processes in order to maintain the bacteriological quality of the water they produce. Of these methods, there are two of great significance -- presedimentation and predisinfection.

Presedimentation normally involves the impoundment of the raw water supply for as long as a 30-day detention period. This practice is, in many cases, the result of a recommendation of the Drinking Water Standards (44). The recommendation called for additional treatment in plants using a raw water source containing an average coliform pupulation of more than 5,000 organisms per 100 milliliter sample in any one month. In this treatment, water is stored for a period of time sufficient to reduce, by sedimentation, the coliform count to within the Standards set for raw water.

Probably even more significant than presedimentation as an auxiliary treatment is predisinfection -- or, more specifically, prechlorination. The practice of applying chlorine to raw water enables a chlorine residual to be maintained throughout the entire plant and has been found to increase the effectiveness of coagulation and sedimentation in removing coliform bacteria. In some cases chlorine is added at the point of predisinfection in such quantity that the water must be dechlorinated before it is pumped into the distribution system. In other plants, however, additional chlorine must be added to the filter effluent in order that a proper residual be maintained in the distribution system.

Some people in the water works field believe that supplying sufficient chlorine to maintain a residual throughout the plant is the only effective way of producing a water with a zero "chlorine demand". As a result, an effective chlorine residual can be maintained in most instances over the complete distribution system.

Distribution Practices

The quality of water delivered to the consumer can be no better than the system of pipes used to transport it. In order to help insure that a bacteriologically safe water is delivered to the consumer, positive pressures must be maintained in the system at all times, the mains flushed periodically, and, in some instances, auxiliary chlorination used. Another practice, employing an active cross-connection control program on the distribution system, has not received as much attention as it should. This is an important practice because one serious cross-connection can negate all the time and money spent to provide a safe and potable water.

ANALYTICAL METHODS

To understand more fully the variables of residual chlorine and coliform density, a discussion of the methods for each determination will be given.

Chlorine Residual Determination

There are several methods and procedures available for the determination of chlorine residuals. The one receiving widest use, however, is the orthotolidine method, with or without the arsenite modification. The arsenite modification allows for the differentiation between free and combined available chlorine residuals. The orthotolidine test is relatively simple and will produce fairly accurate results as long as a few rules are followed.

The equipment needed for the test for total chlorine residual is a color comparator, comparator cells (test tubes), and the orthotolidine reagent. The procedure is to (1) place one milliliter of orthotolidine reagent per 20 milliliters of sample in the comparator cell, (2) add the required milliliters of sample, (3) allow the maximum color to develop, and (4) make the color comparison with the comparator which has been calibrated to give the residual present. Since maximum color development is temperature dependent, there will be a 3-6 minute delay before the comparison can be made. During this time, the color should develop in the dark. When making the color comparison, a good "north" daylight should be used rather than direct sunlight.

When using the arsenite modification of the orthotolidine method for measuring chlorine residuals, a second test is made in addition to the test described above. The same procedure is followed as before except that an amount of sodium arsenite equal to the amount of orthotolidine used is added to the water sample within five seconds after the sample has been added to the comparator cell. A color comparison is made as before. The residual measured is the result of the free available chlorine in the sample, and the difference between this result and that of the total residual test is the combined available chlorine residual in the sample.

Other than acknowledging the fact that there are materials in the water that can possibly interfere with the color development of the test, no further discussion will be given to this subject. A complete treatment of this problem, as well as the methods and procedures for other chlorine residual tests, is given in Standard Methods (2, p. 81-103).

Coliform Determination

Currently there are two acceptable methods for determining the coliform density of water in the distribution system -- the tube method and the membrane filter technique. Only a discussion of the tube method will be given as only this method was employed to obtain the data for this thesis.

The tube method for determining the presence of the coliform group in a water sample relies on the ability of the organisms to metabolize a media so that a gas is formed. To perform the test, five fermentation tubes containing either sterile lactose or lauryl tryptose broth are each inoculated with a ten milliliter portion of the water to be tested. The inoculated fermentation tubes are then incubated at 35° C. ± 0.5° C. Each tube is examined at the end of 24 hours and, if no gas has formed, again at 48 hours. Gas of any amount in 48 hours constitutes a positive Presumptive Test; no gas in 48 hours constitutes a negative Presumptive Test.

The test will then be continued and be carried through the Confirmed and/or Completed tests. Rather than outline these procedures, reference is made to Standard Methods (2, p. 492-508) where a complete treatment of these tests is given.

The results of the tube test are reported as the number of positive tubes out of five.

DATA USED IN STUDY

In November 1960, the Public Health Service, Division of Environmental Engineering and Food Protection, initiated three research projects in the field of public water supply, known as the Water Supply Study Projects. One of the three projects was a study of the quality control procedures on interstate carrier water supplies. In conjunction with this project, one of the objectives was to investigate the possibility of substituting chlorine residual tests for a portion of the bacteriological examinations made on water distribution systems as required by the PHS Drinking Water Standards.

Origin of Data

The three Public Health Service study projects called for the surveying, sampling, and collecting of data from water treatment facailities in 141 cities in 49 states. Since many of the cities used more than one source and treatment facility for their water supply, there were actually more than 190 treatment facilities surveyed in the study. Each plant was visited at least once, at which time composite samples were taken, the plant surveyed, a questionnaire filled out, and a year's operating record collected. In addition, an attempt was made at each plant to secure a record of the bacteriological examinations and chlorine residual tests made on the water distribution systems.

The questionnaire filled out at each plant was designed to describe the physical characteristics of each facility. Questions as to the type of supply, the type of treatment used, the training of the plant operators, the capacity of the plant, the kind and amount of chemicals used, and the type of distribution systems were included.

The yearly operation data sheet showed the monthly averages of the daily figures for the amount of water produced, the amount of chemicals added, and the physical, chemical, and bacteriological tests made on the water. A copy of this data sheet and a copy of the questionnaire are found in the Appendix.

The information received from those communities where bacteriological and chlorine data were available was placed on punch cards. The data included the month and year the sample was collected, the total chlorine residual, and the number of positive bacteriological tubes. Where the information was available, the free chlorine residual, the pH, and the turbidity of the sample were also recorded.

As the author was responsible for the editing and preparation of the data from each plant for automatic data processing during his two years of duty with the Public Health Service in Washington, D. C., this information was made available to him for his thesis.

Of the 141 cities visited, only seven had recorded both the results of the chlorine residual tests and bacteriological examinations of their distribution systems. It must be understood that although records must be maintained as to the bacteriological quality of the water in the distribution system, it is not required that chlorine residual tests be made or recorded. In many cities, chlorine residual tests were made at the time of bacteriological sampling, but the results were never recorded.

It is the data from these seven cities that have been used in this thesis to define the relationship between residual chlorine and coliform density in water distribution systems.

Treatment Practices and Operations Records of Each City

In order to appreciate the full significance of the relationship between the two variables being studied -- bacteriological quality and chlorine residuals -- a discussion of some of the operational characteristics of six of the seven cities will be given. The operational data on the seventh city were not available.

General information as to the type of plant, type of supply, average daily production, and population served is given in Table 2. As was agreed when the data were collected, a code has been used to conceal the identity of the cities. Two of the cities, "D" and "E",

Table 2. General Information on Study Cities

City Code	Type of Plant	Type of Supply	Average Daily Pumpage (MGD)	Population Served (Thousands)
A	P-D	SWS	13.0	66
B	P-D	SWS	94.0	750
C	P-D-I-H	SWS	40.0	198
D. 1	P-D	SWS	38.0	188
D. 2	P-D	SWS	32.0	387
E. 1	P*-D	SWS	10.7	55
E. 2	P*-D	SWS	11.5	55
F	P-D-I	SWS	180.0	1,000

Code:

P = Purification

D = Disinfection

I = Iron and Manganese Removal

H = Softening

SWS = Surface Water Supply

* = Plant does not use any form of filtration, only coagulation and sedimentation.

had two water treatment facilities rather than one; these are referred to in code as "D. 1", "D. 2", "E. 1", and "E. 2".

A code, given at the bottom of Table 2, was also used to identify the type of plant in each city. The term purification, as it is used in the table, refers to coagulation, sedimentation, and filtration, except in city "E" where only coagulation and sedimentation were used. This difference with city "E" is stressed because it presented an important problem in analyzing the data. The other codes used in the table are self-explanatory.

Another matter of importance to note with regard to Table 2 is that all plants obtained their water from a surface supply. This was not deliberate. In fact, a special effort was made to obtain data from cities using ground water as their source of supply, but to no avail. It was thought at the outset of the study that an interesting correlation might be found if data were available from both types of sources.

A summary of the chlorination practices of each plant is given in Table 3, along with the amount of contact time provided in the clear well. The figures given for contact time are based on the design capacity of the plant. As a result, the figures are, in most instances, conservative. In those treatment plants in which a free available chlorine residual is maintained throughout the plant, the ammonia, if used, is not added until after filtration. In every case

Table 3. Applied Chlorine, Residual Chlorine, and Contact Time for Treatment Plants of Study Cities

City Plant	Amount of Chlorine Applied			Amount of Ammonia Applied	Chlorine Residual Through Plant		Contact Time in Clear Well
	Pre- mg/l	Inter- mg/l	Post- mg/l	mg/l	Free mg/l	Total mg/l	minutes
A	1.01	----	----	0.14*	----	0.26	45
B	7.67	0-0.9	0.38	0.18	0.30	-----	216
C	10.07	----	2.10	----	2.5	-----	60
D. 1	9.15	0.13	0.13	0.29	1.0	-----	300
D. 2	4.50	0.12	0.12	0.21	1.0	-----	300
E. 1	----	5.04	-----	1.65*	----	2.0	550
E. 2	----	1.79	2.69	0.74	----	1.7	not available
F	6.67	1.13	0.13	----	1.0	----	260

* Added at the time of pre- or intermediate disinfection

the residual carried through the plant is a result of either pre- or intermediate chlorination. In those plants practicing post chlorination, the chlorine added as the water leaves the plant increases the residual over the amount maintained through the treatment plant.

Information on the distribution systems for each of the cities is presented in Table 4. This table, as well as stating whether or not auxiliary chlorination was used in the distribution system, gives the number of miles of distribution mains in each city and the number of bacteriological samples analyzed each month.

Table 4. Size, Bacteriological Sampling, and Auxiliary Chlorination of Distribution Systems for Study Cities

City Plant	Size of Distribution System (miles)	Number of Bacteriological Samples per Month	Auxiliary Chlorination Used?
A	197	44	Yes
B	4250	280	No
C	650	200	Yes
D. 1 and D. 2	1250	450	No
E. 1 and E. 2	208	122	No
F	1400	460	Yes

Sampling from each distribution system took place on a definite schedule. All samples were taken from predetermined locations on the system and, in most instances, each location was sampled several times each month. For example, a community collecting 200 samples per month might possibly have 50 sampling stations, each site being sampled 4 times a month.

Chlorine and Bacteriological Data

The chlorine and bacteriological data used in the study were obtained from the seven cities as a result of sampling conducted over a period of one to three years. A total of 28, 398 samples were collected. The minimum information recorded for each sample was the month and year the sample was collected, the total chlorine residual, and the number of positive bacteriological tubes.

All coliform tests performed used the tube method in which a fifty milliliter water sample was divided into five-ten milliliter standard portions. The Presumptive Test and the Confirmed and/or Completed Test were made on each sample as outlined in Standard Methods (2, p. 495-498). The results of these analyses were reported as the number of positive tubes.

Chlorine residual tests reported in the data are expressed as a total residual. Since it is known that the residual tests were made at the time the bacteriological sample was taken rather than back at the laboratory where the coliform analyses were performed, it is assumed that the orthotolidine method for obtaining total chlorine residuals was used. Since only city "F" reported a free chlorine residual as well as total residual, correlation attempts were made using only total chlorine residuals.

STATISTICAL ANALYSES OF THE DATA

The first approach in the analyses of the data was to use the data from one city as a model and to compare this model with the data from the other six cities. Since there were insufficient data from some of the cities, this approach was found to be impractical. As a result, the statistical analyses were made on the combined data from all cities. It should be noted that the data from both cities "D" and "E" were obtained from one distribution system even though each system was served by two treatment plants.

Frequency Distribution Analyses

After deciding on the approach, the first step made was to employ a frequency distribution on the data. The distribution was based on total chlorine residual, using 0.1 mg/l as the frequency range. The response in each range was the percent of positive tubes.

The frequency distribution of all the data used in the study is summarized in Table 5. Individual frequency distributions for each city, as well as the IBM 1620 Fortran source program used to develop the frequency distributions, are found in the Appendix.

Two problems became evident after the frequency distributions were developed. The first was that in the data from each city there

Table 5. Frequency Distribution of Data from all the Cities
Total Chlorine Residual vs. Bacteriological Results

Total Chlorine Residual Range (mg/l)	Total Number of Tubes in Range	Total Number of Positive Tubes in Range	Percent of Positive Tubes in Range
0.00 - 0.09	31,715	1338	4.12
0.10 - 0.19	12,720	185	1.45
0.20 - 0.29	13,515	119	0.88
0.30 - 0.39	12,830	106	0.83
0.40 - 0.49	17,260	129	0.75
0.50 - 0.59	12,950	82	0.63
0.60 - 0.69	12,275	56	0.46
0.70 - 0.79	5,460	25	0.46
0.80 - 0.89	4,300	33	0.76
0.90 - 0.99	2,250	6	0.27
1.00 - 1.09	4,785	19	0.40
1.10 - 1.19	610	1	0.16
1.20 - 1.29	580	7	1.21
1.30 - 1.39	385	3	0.78
1.40 - 1.49	405	4	0.99
1.50 - 1.59	3,360	11	0.33
1.60 - 1.69	615	8	1.30
1.70 - 1.79	500	10	2.00
1.80 - 1.89	600	1	0.17
1.90 - 1.99	470	7	1.49
2.00 - 2.09	2,025	26	1.28
2.10 - 2.19	545	14	2.57
2.20 - 2.29	225	6	2.67
2.30 - 2.39	260	0	0.00
2.40 - 2.49	170	2	1.17
2.50 - 2.59	820	6	0.73
2.60 - 2.69	80	0	0.00
2.70 - 2.79	25	0	0.00
2.80 - 2.89	15	2	13.33
2.90 - 2.99	5	0	0.00
3.00 - 3.09	220	2	0.91
3.10 - 3.19	0	0	0.00
3.20 - 3.29	5	0	0.00
3.30 - 3.39	5	1	20.00
3.40 - 3.49	5	1	20.00

were a few samples in which all five tubes of the coliform test were positive, whereas in the same chlorine residual range there were no samples in the coliform test which showed four, or even three, positive tubes. This phenomenon can be observed in the frequency distributions of the data of each city found in the Appendix. This problem, particularly evident in the data from city "B", will be discussed more completely in a later section.

The second problem that became evident as the frequency distributions were developed was that there were a number of samples with positive tubes recorded with a chlorine residual greater than 1.0 mg/l. This was especially true in the data from cities "C" and "E". One explanation for these results, at least for city "E", was that the raw water was treated by only coagulation, sedimentation, and disinfection, and not by filtration. In addition, the raw source used by city "E" had an average MPN index of greater than 20,000. It is known that at times, because there was no filtration used in city "E", that the turbidity of the finished water would exceed three units. Therefore it is possible to assume that with turbidities of that magnitude, the finished water would exhibit particulate matter of such size that bacteria could inhabit them. This could result in the reduction of the effectiveness of chlorine disinfection.

No immediate explanation could be found for the rather unusual bacteriological results obtained from samples with chlorine residuals greater than 1.0 mg/l in city "C". In the final analysis this irregularity was of little consequence because the correlation developed dealt with data which reported a total chlorine residual of less than 1.10 mg/l.

Least Squares Analyses

The first step made in developing an equation for the relationship between chlorine residuals and coliform density was to plot the data from the frequency distribution. The midpoints of the chlorine residual ranges were plotted as the abscissa. This is shown in Figure 8. It should be noted again that only the data with chlorine residuals of less than 1.10 mg/l were used. The decision to use only these data was predicated on the basis that the data above this residual did not appear to follow any given pattern. In fact, as explained earlier, the results obtained beyond the 1.10 mg/l residual were irregular and deviated from what one would expect to find. As a result of this decision, approximately 8 percent of the data was not used in making the correlation.

Before attempting any solution, certain conditions were placed on the data. They were:

1. All errors with respect to the bacteriological analyses are

positive. That is to say that a negative result would never be observed; only a zero or positive result can be shown by the coliform test.

2. The percent of positive tubes, "y", should be weighted as to its variance according to the formula

$$W_y = \sqrt{\frac{n}{(1 - \bar{y})\,\bar{y}}}$$

where "W_y" is the weight given the "y" value in each chlorine residual range, "n" the total number of tubes in that range, and "$\bar{y}$" the proportion of tubes positive in that range.

3. The values of the chlorine residuals are considered to be without error.

Several mathematical models were analyzed in an attempt to find an equation that would best fit the data. The first model used was of the exponential form

$$y = A + Be^{Cx}$$

in which "y" is the percent of positive tubes, "x" the chlorine residual, and "A", "B", and "C" are constants. This model was tried because laboratory tests have shown that the bactericidal efficiency of chlorine fits this type of model. Preliminary work using a graphical solution indicated that this model did not lend itself to an evaluation using the least squares analysis. The reason for this was that the value of "A" in the equation was such that logarithms of negative numbers resulted which could not be evaluated.

A second attempt was made using a hyperbolic model of the form

$$y = A + \frac{B}{(x + C)}$$

in which the value of "y" is the percent of positive tubes, "x" the total chlorine residual, and "A", "B", and "C" are constants. A graphical solution was first used and was found to approximate the actual curve of the data. The constants of the model equation were then evaluated using the least squares analysis. A curve of the equation using the constants as evaluated was then plotted and compared to the curve of the actual data. Although the plot of the equation compared favorably with the plot of the actual data, a change was made in the model in hopes of an even better fit. The model in its final form is as follows:

$$y = A + \frac{B}{(x + C)^2}$$

In making the least squares analysis, the method used was that outlined in Deming (13, p. 148-159). It involved the development of a set of normal equations from the model as well as making initial estimates of the three parameters, A, B, and C. The actual calculations were performed using an IBM 1620 computer program, a copy of which is in the Appendix.

The least squares analysis using this method depends entirely on the best estimate made for the three parameters, A, B, and C. As a result, after the first set of calculations were made, the values obtained for A, B, and C were then used as the estimates in a second evaluation of the parameters. The equation developed which defines the relationship between total chlorine residuals and coliform density is as follows:

$$y = 0.449 + \frac{0.044}{(x + 0.059)^2}$$

A comparison was made between the actual data points obtained from the frequency distribution and the points computed from the equation. This comparison is shown as a numerical tabulation in Table 6 and is represented graphically in Figure 8.

Table 6. Percent of Positive Tubes vs. Total Chlorine Residual

Total Chlorine Residual (mg/l)	Percent of Positive Tubes	
	From the Equation	From the Data
0.045	4.578	4.12
0.145	1.518	1.45
0.245	0.930	0.88
0.345	0.721	0.83
0.445	0.624	0.75
0.545	0.571	0.63
0.645	0.538	0.46
0.745	0.518	0.46
0.845	0.503	0.76
0.945	0.493	0.27
1.045	0.485	0.40

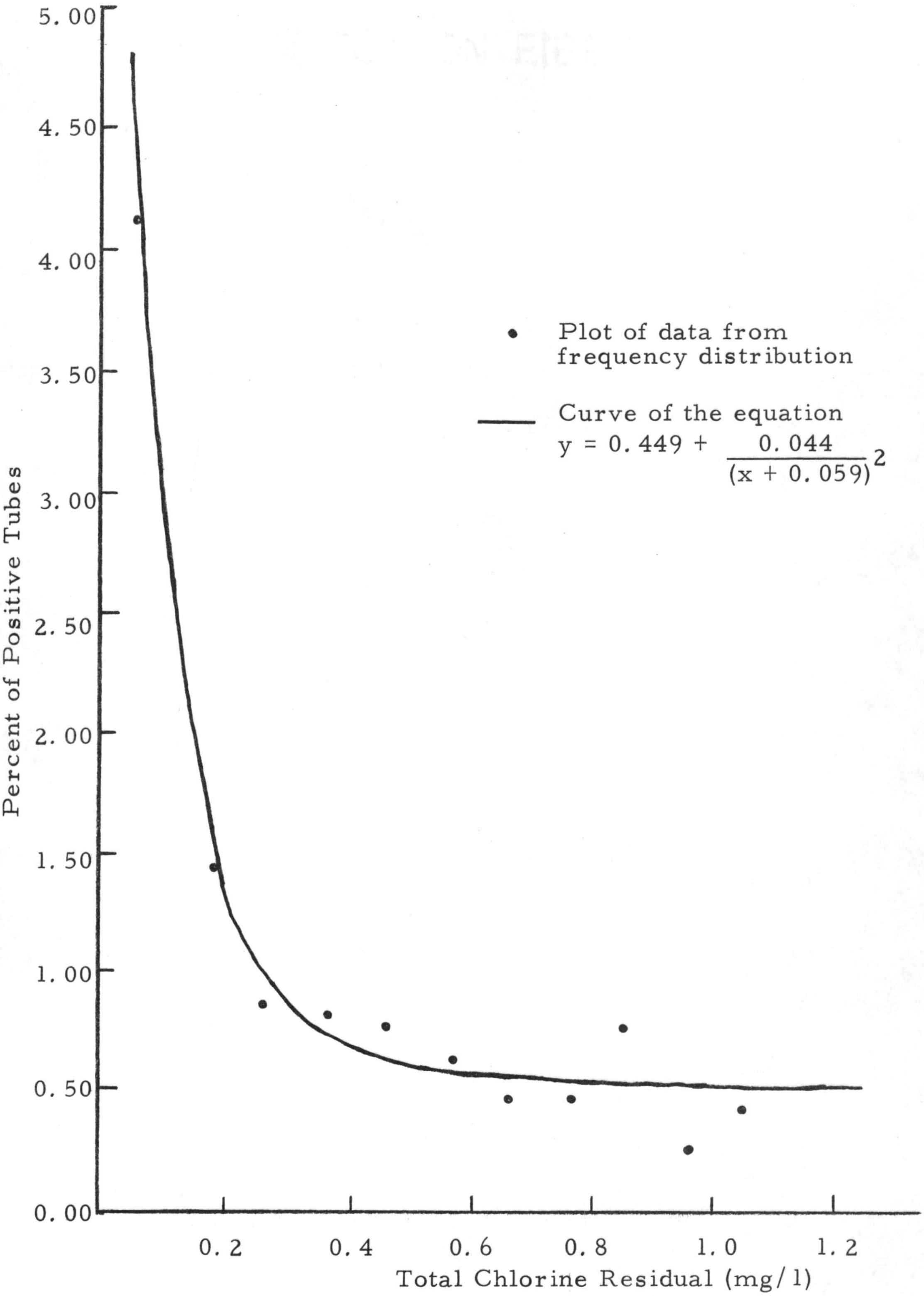

Figure 8. Percent of Positive Tubes vs. Total Chlorine Residual

RESULTS

One of the most enlightening aspects of this study is the development of an expression for the relationship between chlorine residuals maintained in the distribution system and the bacteriological quality of the water in the system. Even more important than this, however, is that the correlation shows that no matter what residuals are maintained in the system, at least 0.45 percent of all tubes examined will show a positive coliform growth. This phenomenon can best be shown by examining the equation developed.

The value of the constant "A" in the equation represents the position of the "y" asymptote of the expression -- or the limiting positions which the tangent to the curve approaches. This aspect can best be explained by referring to an earlier discussion concerning a few samples in the frequency distribution analyses which showed five out of five tubes positive but did not, in the same chlorine residual frequency range, show any samples with four out of five positive tubes. This irregularity, it is believed, is the result of errors in the technique of sampling and in the laboratory analyses. As a result, the equation developed expresses two relationships -- the bactericidal efficiency of chlorine residuals in the distribution system and the errors in sampling and laboratory analyses.

CONCLUSIONS

1. From the study of the data from seven cities throughout the United States and its territories, a relationship has been defined between total chlorine residual and coliform density in water distribution systems. This relationship is expressed by the equation

$$y = 0.449 + \frac{0.044}{(x + 0.059)^2}$$

where "y" is the percent of positive coliform tubes examined and "x" the total chlorine residual.

2. In defining this relationship, it has also been shown that regardless of the chlorine residual maintained, at least 0.45 percent of all coliform tubes examined were positive. It has been concluded that this phenomenon is the result of errors in sampling technique and laboratory procedures.

3. It appears from the results obtained that a water treatment operator could substitute chlorine residual tests for a portion of the bacteriological examinations made on the water of a distribution system. It is suggested, however, that before any use is made of this concept, that the operator of a treatment plant obtain data such as was used in this study and re-evaluate the constants of the model equation. This should be done because the characteristics of the

water produced, the treatment practices employed, and the methods of distribution are known to vary considerably from community to community.

RECOMMENDATIONS FOR FUTURE RESEARCH

In view of some of the problems experienced in preparing this thesis, the following recommendations are made for future research:

1. An attempt should be made to investigate the correlation developed in this report using data obtained from communities using a ground water, rather than surface water, source of supply.

2. A correlation should be made using free available chlorine residual as the form of the disinfectant.

3. Additional investigations should be made to determine the effects of such factors as the pH and turbidity of the water in the distribution system on the correlation developed.

4. Studies should be conducted to determine how treatment practices affect the relationship developed. Of special concern would be the effect of the different chlorination practices.

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APPENDIX

WATER QUALITY CONTROL QUESTIONNAIRE

WATER SUPPLY STUDY PROJECTS
WATER SUPPLY ACTIVITIES GEP, DES

PHS - 3696
1/61

Budget Bureau No. 68-6101
Approval Expires January 31, 1962

WATER QUALITY CONTROL QUESTIONNAIRE

A. GENERAL INFORMATION

Do not use this
(Code Column)
CODE

1. City ______________________ : : : : : :
2. Address ______________________
3. State ______________________
4. Region ______________________
5. Ownership ______________________ : :
   (Public or Private)
6. Type of Supply ______________________ : :
   (SWS, GWS or combination of both)
7. River Basin ____________ ____________ : : : : :
   (Major Basin) (Sub-Basin)
8. Type of Plant ______________________ : : :
   (P-purification, D-disinfection, I-Iron & Manganese removal, H-Softening, or combination of these)
9. Personnel:
   - (a) Is the plant operated under the supervision of certified personnel? (Yes or No) Circle : :
   - (b) What is the highest level of formal training in water treatment plant operation possessed by a plant operator? (Circle appropriate information found below)
     - (1) College or University with Degree
     - (2) College or University without Degree
     - (3) State Short Course
     - (4) None
10. Were there any changes in plant construction or operation in the past year which would affect the quality of the finished water? (Yes or No) : :
    If so, describe: ______________________
    ____
    ____
    ____
    ____

CODE

11. Over-all plant capacity:
    a. Design ________mgd : : : : : :
    b. Operated ________mgd : : : : : :
12. Peak daily demand for water (average)___mgd : : : : : :
13. Average daily demand for water (over-all)___mgd : : : : : :
14. Population served __________thousands : : : : :
15. Service connections ________thousands : : : :
16. Are there any physical or operational defects as outlined in the PHS publication No. 525, "Manual of Recommended Water Sanitation Practice," which would affect the quality of the finished water (Yes or No) : :
    If so, describe: ______________________________
    ____
    ____
    ____
    ____

B. SOURCES OF SUPPLY

1. Ground Water Supply: (Yes or No) : :
    a. Distance of wells or springs from major surface water sources ______ miles : : : :
    b. Are springs adequately protected from sanitary defects? (Yes or No) : :
    c. Are wells adequately protected from sanitary defects? (Yes or No) : :
2. Surface Water Supply: (Yes or No) : :
    a. Type of sources: : : :
        (1) River
        (2) Stream or Creek
        (3) Lake
        (4) Impounded reservoir
        (5) Infiltration gallery
        (Circle appropriate information)
    b. Total raw water reservoir capacity: : :
        (1) Unlimited (4) 10-100 mg
        (2) 0-1 mg (5) 100-1000 mg
        (3) 1-10 mg (6) 1000+ mg
        (Circle appropriate information)

c. Possible sources of pollution : : :
(1) None
(2) Untreated domestic sewage
(3) Unprotected watershed
(4) Untreated industrial wastes
(5) Treated domestic sewage
(6) Treated industrial wastes
(Circle appropriate information)
If other, describe: ________________
____
____
____

d. Distance of raw water intake from nearest possible sources of pollution: : :
(1) Less than 1 mile
(2) 1-5 miles
(3) 5-10 miles
(4) 10-50 miles
(5) 50 - 100 miles
(6) 100+ miles
(Circle appropriate information)

C. TREATMENT PLANT

1. Chemical Feed: (Yes or No) : :

Agents	Type of Feed	Average Dose	
a. Alum	________	________	: : :
b. Lime	________	________	: : :
c. Soda Ash	________	________	: : :
d. Ferric Chloride	________	________	: : :
e. Ferric Sulfate	________	________	: : :
f. Coagulent Aid	________	________	: : :
g. Activated Carbon	________	________	: : :

(Answer above questions with the appropriate coded information found below)

Type of Feed	Average Dose
(1) None	(1) None
(2) Gravimetric	(2) 0-0.5 grains/gallon
(3) Volumetric	(3) 0.5-10 " "
(4) Manual	(4) 1.0-3.0" "
(5) Combination	(5) 3.0-5.0" "

(17.3 ppm = 1 grain/gallon)

2. Chlorination and Ammoniation: (At treatment plant)

(a)

	No. of Chlorinators	Total Cap. of Chlorinators in 100 lbs/day	Average Chlorine Daily Dosage lbs/day	No. of Ammoniators	Total Cap. of Ammoniators lbs/day	Average Ammonia Daily Dosage lbs/day	
Predisinfection	____	____	____	____	____	____	: : : : : : : : : : : : : : : : : : : :
Intermediate disinfection	____	____	____	____	____	____	: : : : : : : : : : : : : : : : : : : :
Post disinfection	____	____	____	____	____	____	: : : : : : : : : : : : : : : : : : : :

(b) Is a free chlorine residual carried through the plant? (Yes or No) : :

(c) What is the average amount of this residual? : : :
______________________ ppm

3. Chlorine residuals in finished water: (Yes or No) : :

(a) Frequency of residual testing ________ Per Day : : :

(b) Is a continuous recording device used? (Yes or No) : :

(c) Analytical results:

	Free Chlorine Residual mg/liter	Total Chlorine Residual mg/liter	
Minimum daily average	________	________	: : : : :
Minimum during any day	________	________	: : : : :
Minimum monthly average	________	________	: : : : :

4. Flocculating and Settling Basins: (Yes or No) : :

	Number	Detention	Average Cap. of each	Type	
(a) Rapid or Flash	______	______ min.	_____ gals.	Hydraulic or Mechanical	: : : : : : : :
(b) Slow	______	________ min.	___ thous. gals.	Hydraulic or Mechanical	: : : : : : : : : : :

(Circle appropriate type)

(c)Settling Basins:

1. Number of basins _______ : : :
2. Average detention time of basins _________(hours) : : : :
3. Average capacity___(thousand gals.) : : : : :
4. Type of basins (Up-flow or gravity) : :
   (Circle appropriate information)

5 Filters: (Yes or No)

(a)

	No.	Avg. Area each sq. ft.	Filter Media	(Actual) Effective size (mm)	Uniformity coeff.	Depth (Inches)	Operated Cap. mgad	Type of Underdrainage System*
Rap.								
Slow								

: : : : : : : : : :
: : : : : : : : : :
: : : : : : : : : :
: : : : : : : : : :

*Use coded information found below
(1) Drilled manifold
(2) False bottom

(b) Are rate of flow controllers used? (Yes or No) : :

6. Clear Wells: (Yes or No) : :
   a. Capacity __________mg. : : : :
   b. Detention time at rated capacity____min. : : : :

D. LABORATORY DATA

1. Bacteriological Examination, Coliform Group.

Number of Water Samples Examined Monthly	Raw	Applied	Finished	Distribution

: : : : : : :
: : : : : : : :

(Attach 1 year bacteriological results)

2. Laboratory Procedures:
   a. Are "Standard Methods" followed? (Yes or No): :
   b. Has laboratory been approved by the State health authority? (Yes or No) : :
3. Chemical and Physical Examinations:
   Indicate frequency of following chemical and physical tests:

Mark if made - (d- daily (a- annually (x- never done
(w- weekly (c- continuously
(m- monthly (r- routinely
(If made several times per time-period shown, mark 5/d, 3/w) etc.

	Raw	Finished	Distribution	
Alkalinity				: : : : : : :
Arsenic				: : : : : : :
Calcium				: : : : : : :
Chlorides				: : : : : : :
Chromium Hexavalent				: : : : : : :
Color				: : : : : : :
Copper				: : : : : : :
Fluoride				: : : : : : :
Hardness				: : : : : : :
Iron				: : : : : : :
Lead				: : : : : : :
Manganese				: : : : : : :
Magnesium				: : : : : : :
pH				: : : : : : :
Phenols				: : : : : : :
Selenium				: : : : : : :
Sodium				: : : : : : :
Sulfates				: : : : : : :
Taste & Odor				: : : : : : :
Total Solids				: : : : : : :
Turbidity				: : : : : : :
Zinc				: : : : : : :

(Attach records for at least(1) year)

E. DISTRIBUTION SYSTEM

1. Length of distribution system ____(hund. miles) : : : :
2. Is there a practice of disinfecting new mains? (Yes or No) : :
3. When repairs are made to distribution mains, are they disinfected? (Yes or No) : :
4. Bacteriological samples taken on distribution system:
    a. Total number taken per month by all agencies__________ : : : : :

b. How are sampling points selected? : :
  1. At random 2. On a definite schedule
  (Circle appropriate information)

c. Is sodium thiosulfate used in sample bottles? : :
  (Yes or No)

d. Are chlorine residuals taken at time of sampling? (Yes or No) : :
  (If so, attach record of chlorine residuals vs. bacteriological results for the past 3 years)

5. Inter-connections (3" main or larger): (Yes or No) : :
  a. Are the inter-connections with unapproved water supplies? (Yes or No) : :
    (1) Is the direction of the flow reversible from unapproved to approved supply? (Yes or No) : :
    (2) Number of times in the past year the inter-connections were used_______ : : :

6. Reservoirs: (Yes or No)

	Number of each	Total Cap. (mg)	Total No. of Chlori-nators	No. of Reservoirs without chlorinators	Area Use Above Cover*	
Covered	___	___	___	___	___	: : : : : : : : : : :
Uncovered	___	___	___	___	___	: : : : : : : : : :

*Use coded information found below:
(1. Parking 2. Recreation 3. None)

7. How often is the distribution system surveyed for sanitary defects?_______per/year : : :

8. In the opinion of the investigator, is there a satisfactory program for the removal of sanitary defects? (Yes or No) : :

9. In the opinion of the investigator, is there a plumbing code adequately enforced? (Yes or No) : :

F. SKETCHES SHOWING PLANT LAYOUT

(These should be obtained from Water Plant Supt.)

G. GENERAL REMARKS

____

____

____

REGION_____________________ DATE_____________________
DIVISION_____________________ REPORT BY_____________________

YEARLY OPERATION REPORT OF WATER TREATMENT PLANT

CODE NUMBER____________________
MONTHLY OPERATING AVERAGES* OF WATER TREATMENT PLANT FOR CITY OF ______________________________ PLANT______________________________

	Filter Data		Chemical Application											Physical Properties							
	Date	Water Filtered	% Wash Water	Aluminum Sulfate	Na_2-CO_3	Calcium Oxide	Activated carbon	Pre-chlorine	Intermedicate Chlorine	Post-chlorine	Pre-ammonia NH_3	Fluoride		Color		Turbidity			Odor		Temperature
														Raw	Tap	Raw	Applied to filter	Tap	Raw	Tap	Raw
		mg		gpg	gpg	gpg	ppm	ppm	ppm	ppm	ppm	lbs.	ppm	S.U.	S.U.	S.U.	S.U.	S.U.			F°
	xx.x 6-8	xxx.xx 9-13	x.x 14-15	xx.x 16-18	x.x 19-20	x.x 21-22	x.x 23-24	xx.x 25-27	x.x 28-29	x.x 30-31	x.x 32-33	xxxx 34-37	x.x 38-39	xxx 40-42	xx 43-44	xxx 45-47	xxx 48-50	x.x 51-52	xx 53-54	55 x	xx 56-57
1																					
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					

*These are daily figures based on a month's operation except for the number of bacteriological portions which should be a months total.

Chemical Analyses (ppm)

	Date	pH		Free CO_2	Calcium		Magnesium		Chlorides		Alkalinities			Hardness		Residual Chlorine										Fluoride		
																Mixing Chamber		Applied to filter		Filter Effluent		Plant Tap		Distribution System				
		Raw	Tap	Raw	Raw	Tap	Raw	Tap	Raw	Tap	Raw	Applied to filter	Tap	Raw	Tap	Free	Total	Free	Total	Free	Total	Free	Total	Free	Total	Raw	Plant Tap	Dist. Syst.
	xx.x 6-8	xx.x 9-11	xx.x 12-14	xx.x 14-17	xxx 18-20	xxx 21-23	xxx 24-26	xxx 27-29	xxx 30-32	xxx 33-35	xxx 36-38	xxx 39-41	xxx 42-44	xxx 45-47	xxx 48-50	x.x 51-52	x.x 53-54	x.x 55-56	x.x 57- 58	x.x 59-60	x.x 61-62	x.x 63- 64	x.x 65-66	x.x 67-68	x.x 69-70	x.x. 71-72	x.x 73-74	x.x 75-76
1																												
2																												
3																												
4																												
5																												
6																												
7																												
8																												
9																												
10																												
11																												
12																												

Bacteriological Analyses

Coliform Organisms

				Raw						Plant Tap						Distribution System					
	Date	Agar plate ct. Bacteria ml		10 ml Portion		100 ml Portion		MPN	M.F. Avg. M.D.	10 ml Portion		100 ml Portion		MPN	M.F. Avg. M.D.	10 ml Portion		100 ml Portion		MPN	M.F. Avg. M.D.
		Raw	Tap	No.	% Pos.	No.	% Pos.		/100ml	No.	% Pos.	No.	% Pos.		/100ml	No.	% Pos.	No.	% Pos.		/100ml
	xx.x 6-8	xxxxxx 9-14	xx 15-16	xxxx 17-20	xx.x 21-23	xxxx 24-27	xx.x 28-30	xxxxx 31-35	xx 35-37	xxxx 38-41	xx.x 42-44	xxxx 45-48	xx.x 49-51	xx.x 52-54	xx 55-56	xxxx 57-60	xx.x 61-63	xxxx 64-67	xx.x 68-70	xx.x 71-73	xx 74-75
1																					
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					

WATER SUPPLY STUDY PROJECTS
WATER SUPPLY ACTIVITIES GEP.
DES
(For Administrative and Discussion Purposes only.)

SOURCE PROGRAM FOR FREQUENCY DISTRIBUTION

IBM 1620 FORTRAN

```
C        CHLORINE FREQUENCY DISTRIBUTION              RON COENE
C        NOTE - SWITCH 1 ON - - OUTPUT ON TYPEWRITER
C                 SWITCH 1 OFF -  OUTPUT ON PUNCH CARDS
C                 SWITCH 1 AND 2 ON - OUTPUT ON BOTH
C        FIRST CARD OF DATA MUST GIVE NUMBER OF RANGES (3-COLUMN FIELD)
C        LAST CARD OF DATA MUST HAVE A 9 PUNCH IN CC 16
         DIMENSION D(36, 6), TT(36), TP(36), PP(36)
   113   READ 1,  K
     1   FORMAT(I 3)
     2   CONTINUE
         DO  10 I  =  1, K
         DO  10 J  =  1, 6
    10   D(I, J) = 0. 0
     6   READ 5,  FQ1,  NTB1, FQ2, NTB2, FQ3, NTB3, FQ4, NTB4
5 FORMAT (12X, F3. 2, I 1, 10X, F3. 2, I1, 10X, F3. 2,I1  , 10X,F3. 2, I1)
         IF (NTB1-9) 7, 100, 100
     7   I  =  0
         J  =  1
    15   I  =  I + 1
         IF(FQ1) 99, 25, 16
    16   I  =  I + 1
         IF(FQ1 - 0. 09)25, 25, 20
    20   FQ1 = FQ1  -  0. 10
         GO TO 16
    25   IF(NTB1)99, 30, 27
    27   J  =  J  +  1
         NTB1  =  NTB1  -  1
         GO TO 25
    30   D(I, J) = D(I, J)  + 1.0
         IF(NTB2-6)34, 6, 6
    34   I  =  0
         J  =  1
    35   I  =  I  +  1
         IF(FQ2)99, 45, 36
    36   I  =  I  +  1
         IF(FQ2  -  0. 09)45, 45, 40
    40   FQ2  =  FQ2  -  0. 10
         GO TO 36
    45   IF(NTB2)99, 50, 47
    47   J  =  J  +  1
         NTB2  =  NTB2  -  1
         GO TO 45
    50   D(I, J) = D(I, J) + 1. 0
         IF(NTB3-6)54, 6, 6
```

```
 54   I = 0
      J = 1
 55   I = I + 1
      IF(FQ3)99, 65, 56
 56   I = I + 1
      IF(FQ3 - 0.09)65, 65, 60
 60   FQ3 = FQ3 - 0.10
      GO TO 56
 65   IF(NTB3) 99, 70, 67
 67   J = J + 1
      NTB3 = NTB3 - 1
      GO TO 65
 70   D(I, J) = D(I, J) + 1.0
      IF(NTB4 -6)74, 6, 6
 74   I = 0
      J = 1
 75   I = I + 1
      IF(FQ4)99, 85, 76
 76   I = I + 1
      IF(FQ4 - 0.09)85, 85, 80
 80   FQ4 = FQ4 - 0.10
      GO TO 76
 85   IF(NTB4)99, 90, 87
 87   J = J + 1
      NTB4 = NTB4 = 1
      GO TO 85
 90   D(I, J) = D(I, J) + 1.0
      GO TO 6
100   DO 105 I = 1, K
      TT(I) = (D(I,1 )+D(I, 2)+D(I, 3)+D(I, 4)+D(I, 5)+D(I, 6))*5.0
      IF(TT(I))99, 101, 102
101   TT ( I ) = 1.0
102   TP(I) = D(I, 2)+D(I, 3)*2.0+D(I, 4)*3.0+D(I, 5)*4.0+D(I, 6)*5.0
105   PP(I) = ((TP(I))/(TT(I)))*100.0
      IF (SENSE SWITCH 1)106, 107
106   DO 96 I = 1, K
      F = I
      R =F / 10.0 - 0.11
 96   PRINT 97, R, D(I, 1), D(I, 2), D(I, 3), D(I, 4), D(I, 5), D(I, 6), TT( I ), TP( I ),  PP( I )
 97   FORMAT (F5.2, F8.0, 7F7.0, F6.2)
      IF  (SENSE SWITCH 2) 107, 112
107   DO 108 I = 1, K
      F = I
      R = F / 10.0 - 0.11
108   PUNCH 93, R, D(I, 1), D(I, 2), D(I, 3), D(I, 4), D(I, 5), D(I, 6), TT( I ), TP( I ), PP( I )
 93   FORMAT (F5.2, F8.0, 7F7.0, F6.2)
112   PAUSE
      GO TO 113
 99   STOP
      END
```

FREQUENCY DISTRIBUTION FOR CITY "A"

Total Chlorine Residual Range	Number of Samples With 0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes	Total Number of Tubes	Total Number of Positive Tubes	Percent of Positive Tubes
0.00 - 0.09	554	4	0	0	0	0	2790	4	0.14
0.10 - 0.19	510	0	0	0	0	0	2550	0	0.00
0.20 - 0.29	205	0	0	0	0	0	1025	0	0.00
0.30 - 0.39	35	0	0	0	0	0	175	0	0.00
0.40 - 0.49	9	0	0	0	0	0	45	0	0.00
0.50 - 0.59	0	0	0	0	0	0	0	0	0.00

FREQUENCY DISTRIBUTION FOR CITY "B"

Total Chlorine	Number of Samples With							Total	
Residual Range	0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes	Total Number of Tubes	Number of Positive Tubes	Percent of Positive Tubes
0.00 - 0.09	2700	307	120	68	29	44	16,340	1087	6.65
0.10 - 0.19	986	64	25	10	2	2	5,445	162	2.98
0.20 - 0.29	870	27	13	3	2	2	4,585	80	1.74
0.30 - 0.39	1227	35	9	3	1	2	6,385	76	1.19
0.40 - 0.49	1414	42	10	2	2	2	7,360	86	1.16
0.50 - 0.59	912	24	4	2	1	2	4,725	52	1.10
0.60 - 0.69	402	4	2	1	0	1	2,050	16	0.76
0.70 - 0.79	109	3	3	0	0	1	580	14	2.42
0.80 - 0.89	118	3	1	0	0	0	610	5	0.82
0.90 - 0.99	2	0	0	0	0	0	10	0	0.00
1.00 - 1.09	22	1	0	0	0	1	120	6	5.00

FREQUENCY DISTRIBUTION FOR CITY "C"

Total Chlorine Residual Range	Number of Samples With						Total Number of Tubes	Total Number of Positive Tubes	Percent of Positive Tubes
	0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes			
0.00 - 0.09	187	3	1	0	0	1	960	10	1.04
0.10 - 0.19	105	1	0	0	0	0	530	1	0.18
0.20 - 0.29	107	0	0	0	0	0	535	0	0.00
0.30 - 0.39	154	5	0	0	0	0	795	5	0.62
0.40 - 0.49	47	0	0	0	0	0	235	0	0.00
0.50 - 0.59	181	0	1	0	0	0	910	2	0.21
0.60 - 0.69	31	0	0	0	0	0	155	0	0.00
0.70 - 0.79	132	1	0	0	0	0	665	1	0.15
0.80 - 0.89	52	0	0	0	0	0	260	0	0.00
0.90 - 0.99	245	1	0	0	0	1	1235	5	0.48
1.00 - 1.09	186	1	1	0	0	0	940	3	0.31
1.10 - 1.19	0	0	0	0	0	0	0	0	0.00
1.20 - 1.29	1	0	0	0	0	0	0	0	0.00
1.30 - 1.39	0	0	0	0	0	0	0	0	0.00
1.40 - 1.49	0	1	0	0	0	0	5	1	20.00
1.50 - 1.59	556	4	0	0	0	0	2800	4	0.14
1.60 - 1.69	0	0	0	0	0	0	0	0	0.00
1.70 - 1.79	0	0	0	0	0	0	0	0	0.00
1.80 - 1.89	1	0	0	0	0	0	5	0	0.00
1.90 - 1.99	0	0	0	0	0	0	0	0	0.00
2.00 - 2.99	248	2	0	0	0	1	1225	7	0.55
2.10 - 2.19	0	0	0	0	0	0	0	0	0.00
2.20 - 2.29	0	0	0	0	0	0	0	0	0.00
2.30 - 2.39	0	0	0	0	0	0	0	0	0.00
2.40 - 2.49	0	0	0	0	0	0	0	0	0.00
2.50 - 2.59	111	4	0	0	0	0	275	4	0.69
2.60 - 2.69	0	0	0	0	0	0	0	0	0.00
2.70 - 2.79	0	0	0	0	0	0	0	0	0.00
2.80 - 2.89	0	0	0	0	0	0	0	0	0.00
2.90 - 2.99	0	0	0	0	0	0	0	0	0.00
3.00 - 3.09	40	2	0	0	0	0	210	2	0.95
3.10 - 3.19	0	0	0	0	0	0	0	0	0.00
3.20 - 3.29	0	0	0	0	0	0	0	0	0.00
3.30 - 3.39	0	1	0	0	0	0	5	1	20.00
3.40 - 3.49	0	0	0	0	0	0	0	0	0.00

FREQUENCY DISTRIBUTION FOR CITY "D"

Total Chlorine Residual Range	Number of Samples With 0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes	Total Number of Tubes	Total Number of Positive Tubes	Percent of Positve Tubes
0.00 - 0.09	1991	99	23	11	3	4	10,655	210	1.97
0.10 - 0.19	704	7	1	1	0	0	3,565	12	0.33
0.20 - 0.29	1323	12	5	1	1	1	6,715	34	0.50
0.30 - 0.39	955	6	3	1	0	1	4,830	20	0.41
0.40 - 0.49	1762	14	3	1	0	2	8,910	33	0.37
0.50 - 0.59	1341	5	4	1	0	1	6,760	21	0.31
0.60 - 0.69	1861	18	3	2	0	1	9,425	35	0.37
0.70 - 0.79	744	3	2	1	0	0	3,750	10	0.26
0.80 - 0.89	496	4	1	0	0	0	2,505	6	0.23
0.90 - 0.99	124	0	0	0	0	0	620	0	0.00
1.00 - 1.09	118	0	0	0	0	0	590	0	0.00
1.10 - 1.19	27	0	0	0	0	0	135	0	0.00
1.20 - 1.29	15	0	0	0	0	0	75	0	0.00
1.30 - 1.39	1	0	0	0	0	0	5	0	0.00
1.40 - 1.49	2	0	0	0	0	0	10	0	0.00
1.50 - 1.59	1	0	0	0	0	0	5	0	0.00
1.60 - 1.69	3	0	0	0	0	0	15	0	0.00

FREQUENCY DISTRIBUTION FOR CITY "E"

Total Chlorine	Number of Samples With							Total Number	Percent of
Residual Range	0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes	Total Number of Tubes	of Positive Tubes	Positive Tubes
0.00 - 0.09	60	0	0	0	0	0	300	0	0.00
0.10 - 0.19	1	0	0	0	0	0	5	0	0.00
0.20 - 0.29	0	0	0	0	0	0	0	0	0.00
0.30 - 0.39	5	0	0	0	1	0	30	4	13.33
0.40 - 0.49	7	0	0	0	0	0	35	0	0.00
0.50 - 0.59	8	0	1	0	0	0	45	2	4.44
0.60 - 0.69	12	0	0	0	0	1	65	5	7.69
0.70 - 0.79	24	0	0	0	0	0	120	0	0.00
0.80 - 0.89	30	1	0	0	0	0	155	1	0.64
0.90 - 0.99	23	0	0	0	0	0	115	0	0.00
1.00 - 1.09	53	0	0	0	0	0	265	0	0.00
1.10 - 1.19	56	1	0	0	0	0	285	1	0.35
1.20 - 1.29	69	2	0	0	0	1	360	7	1.94
1.30 - 1.39	63	3	0	0	0	0	330	3	0.90
1.40 - 1.49	63	1	1	0	0	0	325	3	0.92
1.50 - 1.59	102	3	0	0	1	0	530	7	1.32
1.60 - 1.69	110	1	2	1	0	0	570	8	1.40
1.70 - 1.79	95	3	1	0	0	1	500	10	2.00
1.80 - 1.89	118	1	0	0	0	0	595	1	0.16
1.90 - 1.99	88	5	1	0	0	0	470	7	1.48
2.00 - 2.09	142	6	5	1	0	0	770	19	2.46
2.10 - 2.19	102	3	1	3	0	0	545	14	2.56
2.20 - 2.29	99	6	0	0	0	0	525	6	1.14
2.30 - 2.39	52	0	0	0	0	0	260	0	0.00
2.40 - 2.49	33	0	1	0	0	0	170	2	1.17
2.50 - 2.59	48	0	1	0	0	0	245	2	0.81
2.60 - 2.69	16	0	0	0	0	0	80	0	0.00
2.70 - 2.79	5	0	0	0	0	0	25	0	0.00
2.80 - 2.89	2	0	1	0	0	0	15	2	13.33
2.90 - 2.99	1	0	0	0	0	0	5	0	0.00
3.00 - 3.09	2	0	0	0	0	0	10	0	0.00
3.10 - 3.19	0	0	0	0	0	0	0	0	0.00
3.20 - 3.29	1	0	0	0	0	0	5	0	0.00
3.30 - 3.39	0	0	0	0	0	0	0	0	0.00
3.40 - 3.49	0	1	0	0	0	0	5	1	20.00

FREQUENCY DISTRIBUTION FOR CITY "F"

Total Chlorine Residual Range	Number of Samples With						Total Number of Tubes	Total Number of Positive Tubes	Percent of Positive Tubes
	0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes			
0.00 - 0.09	95	3	0	1	2	0	505	14	2.77
0.10 - 0.19	108	1	1	2	0	0	560	9	1.60
0.20 - 0.29	92	1	1	0	0	0	470	3	0.63
0.30 - 0.39	113	1	0	0	0	0	570	1	0.17
0.40 - 0.49	104	1	0	0	0	1	530	6	1.13
0.50 - 0.59	101	0	0	0	0	0	505	0	0.00
0.60 - 0.69	74	0	0	0	0	0	370	0	0.00
0.70 - 0.79	68	0	0	0	0	0	340	0	0.00
0.80 - 0.89	65	0	0	1	0	0	330	3	0.90
0.90 - 0.99	54	0	0	0	0	0	270	0	0.00
1.00 - 1.09	27	0	0	0	0	0	135	0	0.00
1.10 - 1.19	37	0	0	0	0	0	185	0	0.00
1.20 - 1.29	26	0	0	0	0	0	130	0	0.00
1.30 - 1.39	10	0	0	0	0	0	50	0	0.00
1.40 - 1.49	12	0	0	0	0	0	60	0	0.00
1.50 - 1.59	5	0	0	0	0	0	25	0	0.00
1.60 - 1.69	6	0	0	0	0	0	30	0	0.00

FREQUENCY DISTRIBUTION FOR CITY "G"

Total Chlorine Residual Range	Number of Samples With						Total Number of Tubes	Total Number of Positive Tubes	Percent of Positive Tubes
	0-pos. tubes	1-pos. tube	2-pos. tubes	3-pos. tubes	4-pos. tubes	5-pos. tubes			
0.00 - 0.09	29	1	1	0	1	1	165	12	7.27
0.10 - 0.19	12	1	0	0	0	0	65	1	1.53
0.20 - 0.29	36	0	1	0	0	0	185	2	1.08
0.30 - 0.39	9	0	0	0	0	0	45	0	0.00
0.40 - 0.49	27	1	0	1	0	0	145	4	2.75
0.50 - 0.59	1	0	0	0	0	0	5	0	0.00
0.60 - 0.69	42	0	0	0	0	0	210	0	0.00
0.70 - 0.79	1	0	0	0	0	0	5	0	0.00
0.80 - 0.89	82	1	2	1	0	2	440	18	4.09
0.90 - 0.99	0	0	0	0	0	0	0	0	0.00
1.00 - 1.09	539	6	2	0	0	0	2,735	10	30.36
1.10 - 1.19	1	0	0	0	0	0	5	0	0.00
1.20 - 1.29	2	0	0	0	0	0	10	0	0.00
1.30 - 1.39	0	0	0	0	0	0	0	0	0.00
1.40 - 1.49	1	0	0	0	0	0	5	0	0.00
1.50 - 1.59	0	0	0	0	0	0	0	0	0.00
1.60 - 1.69	0	0	0	0	0	0	0	0	0.00

SOURCE PROGRAM FOR LEAST SQUARES ANALYSIS

IBM 1620 FORTRAN

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C        LEAST SQUARES ANALYSIS                    RON COENE
C        ALL SWITCHES OFF AT START
C        AT FIRST PAUSE TURN SW 1 ON
C        AT SECOND PAUSE TURN SW 1 OFF AND TURN SW 2 ON
C        AT THIRD PAUSE TURN SW 2 OFF AND TURN SW 3 ON
         DIMENSION X(12), TT(12), TP(12), W(12), Y(12), FX(12), FB(12), FC(12)
         DIMENSION FO(12), FA2(12), FB2(12), FC2(12), FO2(12), Z(12), SL(12)
    1    READ 2, N
    2    FORMAT (I2)
         SUMY = 0.
         SUMY2 = 0.
         DO 15 I = 1, N
         READ 11, X(I), TT(I), TP(I)
   11    FORMAT (F4.3, F7.0, F6.0 )
         Y(I) = (TP(I) / TT(I))
         SUMY = SUMY + Y(I) * 100.0
         SUMY2 = SUMY2 + ( Y(I) * 100.0 ) **2
   15    W(I) = SQRT (TT(I) / (Y(I) * ( 1. - Y(I))))
         EA = 0.451159
         EB = 0.043364
         EC = 0.043435
         FA = -1.
         FY = 1.
         DO 20 I = 1, N
         FB(I) = - (1. / (X(I) + EC) ** 2 )
         FC(I) = (2. * EB) / (( X(I) + EC) ** 3 )
         FX(I) = (2. *EB) / (( X(I) + EC) ** 3 )
         FO(I) = ( Y(I) * 100. ) - EA - (EB / (X(I) + EC) **2 )
         SL(I) = SQRT ((FY) **2 / W(I))
         FA2(I) = FA / SL(I)
         FB2(I) = FB(I) / SL(I)
         FC2(I) = FC(I) / SL(I)
   20    FO2(I) = FO(I) / SL(I)
         AA = 0.
         AB = 0.
         AC = 0.
         AO = 0.
         BA = 0.
         BB = 0.
         BC = 0.
         BO = 0.
         CA = 0.
         CB = 0.
         CC = 0.
         CO = 0.
```

```
      OO  =  0.
      DO 25 I  =  1,  N
      AA  =  AA + FA2(I) **2
      AB  =  AB  + FA2(I) * FB2(I)
      AC  =  AC + FA2(I) * FC2(I)
      AO  =  AO + FA2(I) * FO2(I)
      BA  =  BA  + FB2(I)  * FA2(I)
      BB  =  BB  + FB2(I) **2
      BC  =  BC  + FB2(I) * FC2(I)
      BO  =  BO  + FB2(I) * FO2(I)
      CA  =  CA + FC2(I) * FA2(I)
      CB  =  CB  + FC2(I) * FB2(I)
      CC  =  CC + FC2(I) **2
      CO  =  CO + FC2(I) * FO2(I)
25    OO  =  OO + FO2(I) ** 2
      BC1  =  BC  -  ((AB * AC) / AA)
      BO1  =  BO  -  ((AB * AO) / AA)
      BB1  =  BB  -  ((AB ** 2 ) / AA)
      CC2 =  CC -  ((AC**  2) / AA)  - ((BC1**2)/BB1)
      CO2 =  CO -  ((AC*AO)  / AA)  - ((BC1*BO1)/BB1)
      SS1  =  OO -  ((AO**2) / AA)  - ((BO1**2)/BB1)-((CO2**2) / CC2)
      D1   =  (AA*BB*CC) + (BA*CB*AC) + (CA*AB*BC)
      D2   =  (AA*BC*CB) + (AB*BA*CC) + (AC*BB*CA)
      D    =  D1  - D2
26    AN1  =  (AO*BB*CC) + (AC*BO*CB) + (AB*BC*CO)
      AN2  =  (AB*BO*CC)+  (AC*BB*CO) +  (AO*BC*CB)
      AN   =  AN1  - AN2
      A1   =  AN/D
      BN1  =  (AO*BC*CA) + (AC*BA*CO) + (AA*BO*CC)
      BN2  =  (AA*BC*CO) + (BA*CC*AO) + (CA*AC*BO)
      BN   =  BN1  - BN2
      B1   =  BN/D
      CN1  =  (AA*BB*CO) + (BA*CB*AO) +  (CA*AB*BO)
      CN2  =  (AO*BB*CA) + (BO*CB*AA) + (CO*AB*BA)
      CN   =  CN1  - CN2
      C1   =  CN/D
      SS2  =  OO - (AO*A1) - (BO*B1) -  (CO*C1)
      IF (SENSE SWITCH  1 ) 41,  27
27    IF (SENSE SWITCH 2 ) 46,  28
28    IF (SENSE SWITCH 3 ) 51,  29
29    A  =  EA  - A1
      B  =  EB  - B1
      C  =  EC  - C1
      DO 30 I = 1,  N
      Z(I) = A + (B / (X(I) + C) **2)
30    PRINT 35,  X(I),  Z(I)
35    FORMAT (4HX = ,  F6. 3,  5H Y = ,  F 7. 3/ )
      PRINT 36,  SS1,  SS2
36    FORMAT (6HSS1 = ,  F14. 8,  10H   SS2 = ,  F14. 8 //// )
      PRINT  37,  SUMY,  SUMY2
```

```
37      FORMAT (7HSUMY = , F14.8, 10H SUMY2 = , F14.8 //// )
        PRINT 40, A, B, C
40      FORMAT (4HA = , F10.8, 5HB = , F10.8, 5H C = , F10.8 //// )
        PAUSE
        AO = 1.
        BO = 0.
        CO = 0.
        GO TO 26
41      PRINT 45, A1, B1, C1
45      FORMAT (5HA1 =, F12.8, 6HB1 = , F12.8, 6HC1 = , F12.8 ////)
        PAUSE
        AO = 0.
        BO = 1.
        CO = 0.
        GO TO 26
46      PRINT 50, A1, B1, C1
50      FORMAT (5HA2 = , F12.8, 6HB2 = , F12.8, 6H C2 = , F12.8 ////)
        PAUSE
        AO = 0.
        BO = 0.
        CO = 1.
        GO TO 26
51      PRINT 55, A1, B1, C1
55      FORMAT (5HA3 = , F12.8, 6H B3 = , F12.8, 6H C3 = , F12.8 ////)
        PAUSE
        GO TO 1
        END
```