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CHLORINE DISINFECTION OF TREATED WASTEWATER

IN A BAFFLED CONTACT CHAMBER AT <1°C

by

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Abstract

This study was designed to examine the disinfection process at low temperatures because effluent in the Arctic and Subarctic can be expected to be in the 0 to 10°C range during a significant portion of each year. Disinfection was considered effective if the effluent contained no more than 1000 total and 200 fecal coliforms/100 ml. Total chlorine residual was monitored with the orthotolidine and iodometric methods, and the membrane filter method was used for all bacteria enumeration.

During the first phase of the study, batch treatment was used to examine three secondary and one primary effluent. The results indicated that effective disinfection was attained in samples from all sources at <1°C when the actual contact time was 60 minutes and the final chlorine residual was approximately 1 mg/l (orthotolidine).

The second phase of the study was conducted in an 8-compartment, over-under baffled, 60-liter contact chamber at <1°C and 10°C. Flow rates providing 30, 60 and 120 minutes theoretical contact time were used. Dye studies at each flow rate indicated that extensive short-circuiting occurred, and that the 120 minute contact time flow rate was the only one which provided 60 or more minutes residence time for the majority of the effluent.

Regardless of the flow rate or chlorine residual maintained, the fecal coliforms were essentially destroyed (<5/100 ml) at <1°C. However, reduction of the total coliforms to <1000/100 ml did not occur when the theoretical contact time was 30 minutes, even when the chlorine residual was 3.3 mg/l (orthotolidine). At 60 minutes theoretical contact time, nearly 2 mg/l chlorine residual (orthotolidine) were required

before the total coliforms were sufficiently reduced. Only slightly more than 0.5 mg/l chlorine residual (orthotolidine) was required for the total coliforms at the 120 minutes theoretical contact time flow rate. The fecal streptococci numbers were generally reduced to a level between those found for the total and fecal coliforms.

Theoretical contact times of 30 and 60 minutes were used at the 10° operating temperature. The results suggested that raising the temperature from <1°C to 10°C caused little or no change in the effectiveness of disinfection.

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Introduction

The use of chlorine as a disinfectant in water and treated wastewater has come under rather intensive study, beginning with the early work of Heathman et. al. (17) and Rudolfs and Gehm (27) in 1936, and the current "State of the Art" has been well documented in several recent publications (2, 5, 26, 35). With the exception of the early study of sewage disinfection by Rudolfs and Gehm (27), nearly all the literature indicates that the disinfecting ability of chlorine is severely hindered by low temperatures (5, 6). However, most of these studies used pure culture-pure water systems to establish the disinfecting characteristics of chlorine without the inherent interferences found in treated wastewater (5). In 1967, Marais et. al. (24) pointed out the need for reliable laboratory studies to establish the disinfecting ability of chlorine in the presence of the inherent interferences found in treated wastewater. Subsequently, some effort has been made in this direction (8, 21, 22), but these studies have not considered the effect of low temperature on the disinfection process.

Over a large portion of the world, water temperatures in waste treatment systems and in effluents from these systems may approach 0°C during several months each year, and disinfection may be difficult to achieve in these cold effluents. Throughout the cold months, the receiving waters into which the effluents are discharged will also have temperatures near 0°C. These very low receiving water temperatures accentuate any problems caused by ineffective chlorine disinfection because cold effluents may contain more enteric bacteria than warm effluents (9, 29), and fecal indicator bacteria survive for longer periods in 0°C receiving water (15) than in warmer receiving water (3). Preliminary evidence also indicates that salmonellae have increased survival at 0°C (34). Therefore, an effective effluent disinfection process is of great importance in cold climates where low temperatures may make disinfection difficult to achieve. However, the process has received little or no special consideration in actual cold climate waste treatment practice.

Minimum effective treated wastewater disinfection, as used throughout this presentation, is based on the disinfection criteria established by the U. S. Environmental Protection Agency, Region X (11). These criteria are: [1] that effluents from chlorine contact chambers shall average less than 1000 total coliforms and 200 fecal coliforms/100 ml when the effluent is discharged into recreational waters and [2] that the total chlorine residual shall not be less than 1 mg/l after 60 minutes of contact time when conclusive coliform data are not available.

In order to determine whether or not effective treated wastewater disinfection could be achieved at less than 1°C (<1°C), a two-phase study was conducted at the Arctic Environmental Research Laboratory. During the first phase, batch treatment with rapid initial chlorine mixing and continuous stirring was used to study effluents from four waste treatment systems at <1°C with controls run in parallel at 25°C (16). These effluents were from a primary sedimentation system, a 15 day detention time aerated lagoon and two extended aeration systems. The results indicated that both chlorine demand and the rate or extent of coliform reduction were decreased at <1°C where compared to the 25°C results. Effective disinfection was attained in effluents from all sources at <1°C within the 60 minutes contact time in the presence of no more than 1 mg/l final total chlorine residual (orthotolidine method). The ease with which effective disinfection was attained varied significantly among the four effluents at <1°C, but there was essentially no difference in the 25°C controls. The primary sedimentation system produced a more uniform effluent which was consistently easier to disinfect than the secondary effluents. However, it did require a slightly greater initial chlorine dose to provide a final 1 mg/l chlorine residual.

When disinfection is conducted using a batch system, theoretical and actual contact time are the same. This is analogous to plug flow in a flow through system. It has been pointed out in several recent publications (7, 8, 20, 21, 23, 28, 30, 35) that plug flow provides the most nearly ideal situation for disinfection because all liquid entering the contact chamber is retained in the chamber for the theoretical contact time. In actual practice, short-circuiting in the contact chamber precludes the attainment of residence time approaching theoretical contact time. Thus, theoretical contact time has little meaning, rendering incorrect the assumption that batch disinfection results can be extrapolated to flow through contact chambers (7).

As was previously discussed, the first phase of this study showed that effective disinfection could be attained with batch treatment at <1°C with no more than 60 minutes contact time in the presence of 1 mg/l or less final total chlorine residual (orthotolidine method). Since higher bacterial quality can be expected in the effluent after batch disinfection than in flow through contact chambers, a second phase of this study was conducted at <1°C using a well baffled flow through chlorine contact chamber. The objective of this study was to determine if minimum effective disinfection could be achieved in a contact chamber built according to the design guidelines established by the U. S. Environmental Protection Agency, Region X (11). Briefly, these design guidelines state that: [1] the chlorine contact chamber must be sized to provide 60 minutes contact time at design flow with 20 minutes contact time at peak hourly flow or maximum pumping rate, which ever is greater; [2] the contact chamber must be designed to minimize short-circuiting; and [3] chlorine must be thoroughly mixed with the treated wastewater to achieve maximum disinfection efficiency.

Materials and Methods

Effluent Source and Sampling

The primary sedimentation system effluent examined during the first phase of this study (16) was from the 2.5 million gallon/day Fairbanks, Alaska city plant. This effluent was selected for further study because it had uniform physical and chemical characteristics, and because it was relatively easy to disinfect in batch treatment. The day prior to each experiment of the second phase, approximately 150 gallons of effluent were collected in 15 gallon polyethylene barrels and transported immediately to the laboratory.

Effluent Preparation After Arrival in the Laboratory

The barrels of effluent were placed in a controlled temperature room where the ambient air temperature was maintained at or slightly below the experiment temperature. The effluent temperature was determined, then cooled to 0.3-0.5°C, or adjusted to 10°C, in three 50 gallon batches using the 55 gallon barrel and cooling apparatus shown in Figure 1. These batches were stirred continuously until the next day.

Flow Through and Batch System Description

Figure 1 is a schematic diagram of the flow through system showing the pattern of effluent and chlorine feed, and movement of the liquid through the contact chamber. The various flow rates were obtained using Holter model ER 161 variable speed pumps equipped with different size tubing. All liquid was moved in Tygon or latex rubber tubing. It was necessary to continuously stir the effluent in the feed barrel and the constant

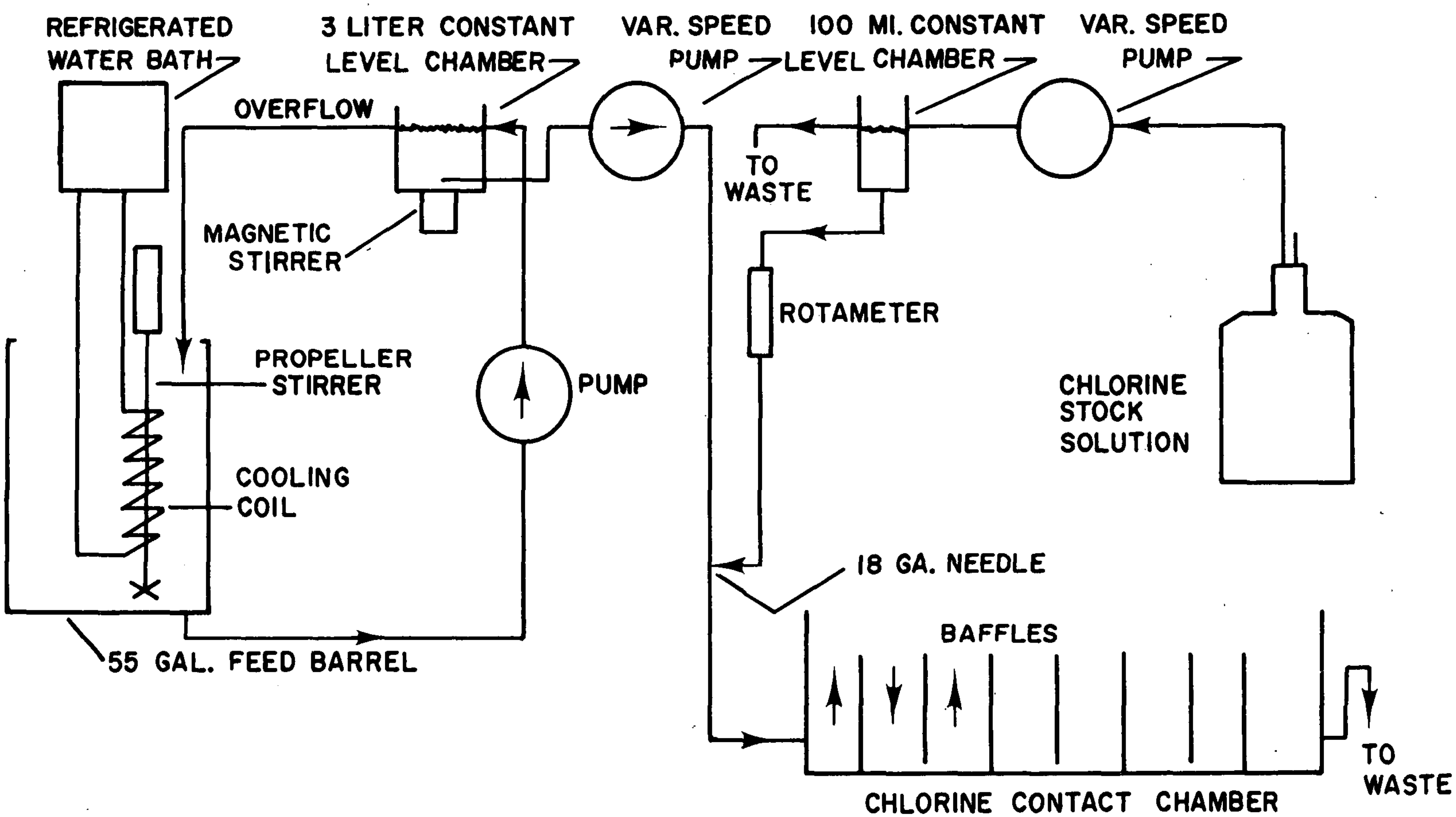

Figure 1. Flow through system used in the disinfection studies.

level chamber to maintain solids in suspension.

The contact chamber was an eight compartment over-under baffled unit, having a 60 liter capacity. Effluent passed the under baffles through a 0.8 cm slot the full width of the chamber, and passed the over baffles at a depth of 0.8 cm. The first seven compartments were the same size, 38.1 cm wide by 16.2 cm deep by 10.2 cm long. The last compartment was 21.3 cm long.

Flow rates through the contact chamber were 0.5, 1.0 and 2.0 liters per minute providing theoretical contact times of 120, 60 and 30 minutes, respectively. The pump speed was adjusted so that it took 60 ± 1 second to fill an appropriate size class A volumetric flask with liquid as it was discharged from the chamber. The flow rate was monitored frequently throughout each run and adjustments in pump speed were made as necessary to maintain the desired flow rate.

Chlorine stock solution was pumped from the reservoir into the constant level chamber, a modified 100 ml polypropylene graduated cylinder with the top closed to minimize volatilization of chlorine. The flow rate was adjusted so that there was a continuous overflow to waste from the constant level chamber rather than returning the overflow to the stock solution reservoir. The constant level chamber was mounted above the contact chamber so that the hydrostatic head would easily permit gravity flow of chlorine through a rotameter used to control and monitor the volume of chlorine being injected into the effluent feed line.

The batch system run in parallel with the flow through system was set up as described previously (16). A 60 minute contact time was used regardless of the flow rate used in the contact chamber.

All studies were conducted in a controlled temperature room with the temperature adjusted to maintain the effluent at <1°C or 10°C in the contact chamber.

Glassware and Glass Distilled Water Preparation

All glassware used during this study was made chlorine demand free (1) and glass distilled water was prepared as described previously (16). Both the glassware and the glass distilled water were allowed to equilibrate at the temperature to be used for the particular disinfection experiment.

Chlorination Methodology

A chlorine stock solution volume sufficient for all needs was prepared by dilution of household bleach (Purex brand) with glass distilled water immediately prior to each experiment. The stock solution was made up to 500, 1000 or 2000 mg/l chlorine depending on the effluent flow rate through the contact chamber and the chlorine residual desired. Varying the chlorine concentration permitted the stock solution flow rate to be maintained at no more than 13 ml/minute, minimizing any dilution effect in the effluent.

Immediately prior to the start of each disinfection experiment, the initial chlorine demand and the 60 minutes contact time chlorine demand were determined in the effluent, as previously described (16).

Total chlorine residual was determined by both the orthotolidine (OT) and iodometric methods as described in Standard Methods (1). At the start of each experiment, chlorine residual determinations were made with both methods in the unchlorinated effluent. The OT method was then used to monitor the residual at predetermined time intervals until a fairly constant concentration was reached. Both methods were then employed throughout the remainder of each experiment.

Bacteria Enumeration

Total coliforms, fecal coliforms and fecal streptococci were enumerated with the membrane filter method (13). The media were M-Coliform Broth (BBL), M-FC Broth (BBL) and KF-Streptococcal Agar (BBL and Difco), respectively. Each time the M-FC Broth was prepared, the pH was measured and adjusted to 7.4 if necessary.

Effluent samples for bacteria enumberation were collected in sterile, 220 ml, polypropylene containers (Falcon Plastics) which contained 0.5 ml of 10 percent sodium thiosulfate solution.

The potential problems and their possible effect on coliform enumeration with the membrane filter method in chlorinated effluents were discussed previously (16).

Physical and Chemical Parameter Measurement

Chemical oxygen demand (COD), total solids (TS), total suspended solids (TSS), volatile suspended solids (VSS), total dissolved solids (TDS), volatile dissolved solids (VDS) and total volatile solids (TVS) were determined by the methods described in Standard Methods (1). Ammonia nitrogen (NH_3-N) and total nitrogen (kjeldahl) were determined according to Techinicon AutoAnalyzer Methodology (31, 32). Nitrite (NO_2-N) and nitrate (NO_3-N) were determined according to U. S. Environmental Protection Agency methods (10). A Leeds & Northrup pH meter (model 7401), equipped with a Leeds & Northrup automatic temperature compensator and a Beckman Combination Probe (GP Glass), was used for pH determinations.

Dye Studies in the Chlorine Contact Chamber

For these experiments, tap water cooled to <1°C was pumped into the contact chamber at rates of 0.5, 1.0 or 2.0 liters/minute. The Rhodamine B dye was injected in the same manner and location as the chlorine in the disinfection studies (Figure 1). Dye concentration was measured using a G. K. Turner Associates model 111 Fluormeter equipped with a flow through door, and recorded on a Beckman model 1005 recorder.

To determine residence time of particles entering the chamber, a volume of dye was rapidly injected and its passage through the system followed. To establish operating time required for constant concentration, dye was injected continuously for several hours. The volume or rate of dye injection and the instrument sensitivity were adjusted so that maximum readings of 60-90 percent of full scale were obtained on the recorder.

Experimental Results

The results presented here were derived from 16 flow through contact chamber experiments. Of these, 14 were conducted at <1°C and two at 10°C using four total chlorine residual:theoretical contact time relationships. As a parallel control with each flow througn experiment, effluent was treated in batch using 60 minutes contact time with a 1 mg/l final total chlorine residual.

The study was conducted from November 15, 1972 to April 15, 1973, during which time the city waste treatment system operating temperature was 8-10°C. Because a large sample volume was collected for each experiment, it was necessary to transport the effluent in an open truck. As a result, the effluent temperature was generally lowered by the ambient air temperature during the trip. Effluent temperature measured immediately after arrival in the laboratory ranged from 0.6°C to 9.2°C. Temperature variations were random throughout the time the study was conducted and there did not appear to be any correlation with the disinfecting characteristics of a particular sample. The only apparent effect resulting from this temperature variation was the length of time required to cool the effluent to 0.3-0.5°C.

The range of values obtained for effluent parameters was generally random throughout the entire study. However, some variation could be expected during the five month period that samples were taken. The chlorine concentration added initially varied with the chlorine demand of each sample and the desired residual in the contact chamber during each series of experiments.

Dye Studies at 60 Minutes Theoretical Contact Time

Figure 2 shows typical results of instantaneous and continuous dye injection at the 60 minute theoretical contact time flow rate. After instantaneous injection, dye was first detected in the effluent from the contact chamber in 14 minutes. Other results showed first dye appearance in 12 to 15 minutes at the same flow rate. The dye concentration then increased rapidly and the peak was reached 42 minutes after injection. The curve produced by dye passage was not symmetrical, and it required 50 to 51 minutes for 50 percent of the dye to pass. Thirty-three percent of the dye was still in the chamber after 60 minutes residence time, which was theoretical contact time at this flow rate. Recently, Kothandaraman *et al*. (21) discussed chlorine contact chamber performance and pointed out that plug flow was represented by a Morril index of 1.0. The Morril index for this chamber at the 60 minute theoretical contact time flow rate was 2.8 which indicated that plug flow was not even approached.

When the dye was injected continuously, elapsed time for first dye appearance was approximately the same as the instantaneous injection. However, the concentration increased at a much slower rate and reached maximum concentration after approximately 160 minutes elapsed time. The dye concentration then continued at a nearly constant level for the remainder of the time the chamber was operated.

Disinfection Studies at <1°C Using 60 Minutes Theoretical Contact Time 1 mg/l Total Chlorine Residual (OT)

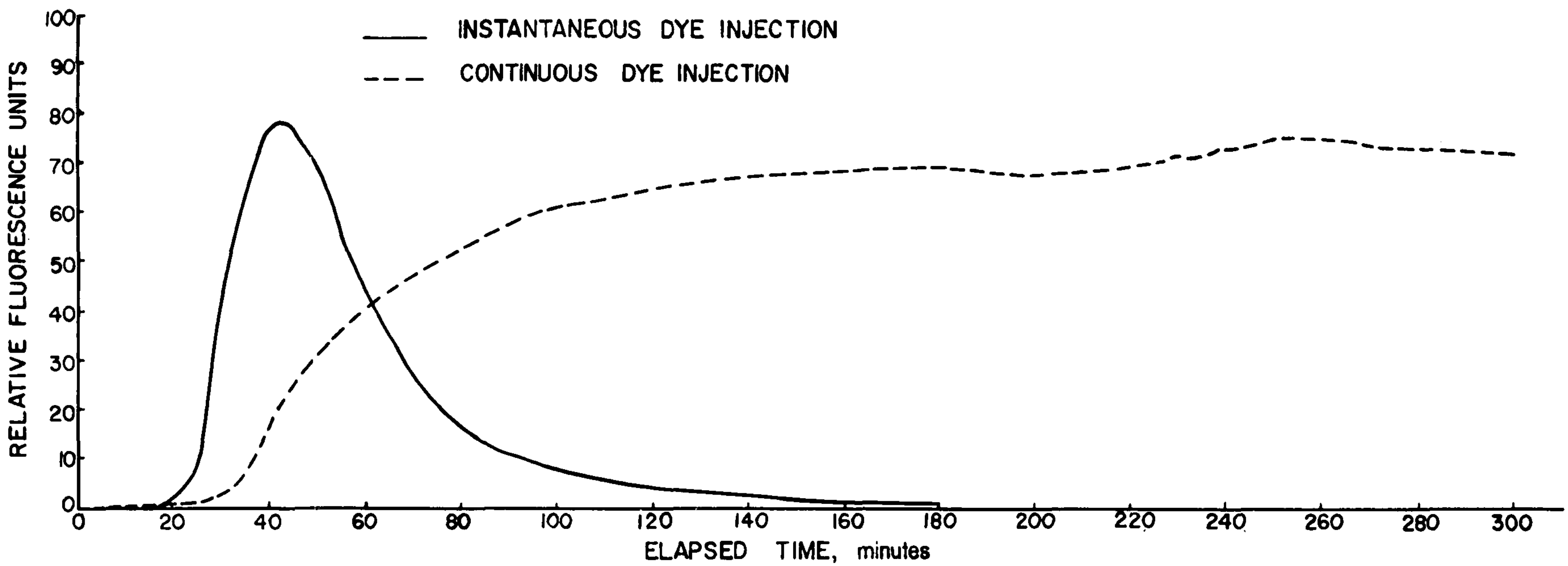

Figure 2. Instantaneous and continuous dye injection in flow through contact chamber studies. 60 minutes theoretical contact time.

The five replicate experiments in the 60 minute theoretical contact time:1 mg/l total chlorine residual (OT) series at <1°C were conducted over a 39 day period. The arithmetic mean, and maximum and minimum parameter values are shown in Table 1. This value range is comparable for most values obtained throughout the study.

Preliminary determinations indicated that total chlorine residual in the contact chamber effluent reached its maximum concentration in about the same elapsed time as observed for the dye. Therefore, monitoring of the effluent for chlorine residual and viable bacteria began after the system had operated for 120 minutes. As shown in Figure 3, the average total chlorine residual (OT) became stable at 0.9-1.0 mg/l after 150 minutes elapsed time, with a range of 0.57-1.5 mg/l for the five experiments in this series. The average iodometric residual reached a concentration of 4.2 mg/l in 120 minutes and continued to increase until it reached 4.5 mg/l at 270 minutes. The minimum and maximum concentrations determined by the iodometric method during the series were 3.4 and 5.0 mg/l, respectively, and the average was 3.4-3.6 mg/l higher than obtained with the OT method.

The average number of total coliforms, fecal coliforms and fecal streptococci surviving disinfection in the presence of these total chlorine residuals are also shown in Figure 3. The initial total coliform count in the unchlorinated effluent ranged from 2.2-3.6 x 10^7/100 ml. When the total chlorine residual in the contact chamber effluent reached its maximum average concentration, the lowest average total coliform count was 3.4 x 10^3/100 ml. The lowest total coliform count recorded for any sample dur-

Parameter	Arithmetic mean	Maximum value	Minimum value	Number of samples
Initial temperature, °C	0.6	0.7	0.4	5
Final temperature, °C	0.5	0.8	0.2	5
Initial pH	7.2	7.4	7.1	5
Final pH	7.3	7.4	7.2	5
Chlorine added as HOCl, mg/l	5.6	6.9	4.6	5
TS, mg/l	444	490	400	5
TVS, mg/l	256	380	200	5
TSS, mg/l	65	81	54	5
VSS, mg/l	49	59	40	5
VDS, mg/l	183	280	120	4[a]
TDS, mg/l	363	400	320	4[a]
NH_3-N, mg/l	16.8	20	14	5
NO_2-N, mg/l	0.020	0.04	<0.01	4[a]
NO_3-N, mg/l	0.052	0.07	0.04	5
Kjeldahl-N, mg/l	24.6	30	20	5
COD, mg/l	235	289	183	5

[a] Results not available for some samples.

Table 1. Effluent Sample Parameters from Flow Through Contact Chamber Studies at <1°C.
60 Minutes Theoretical Contact Time, 1 mg/l Total Chlorine Residual (OT).

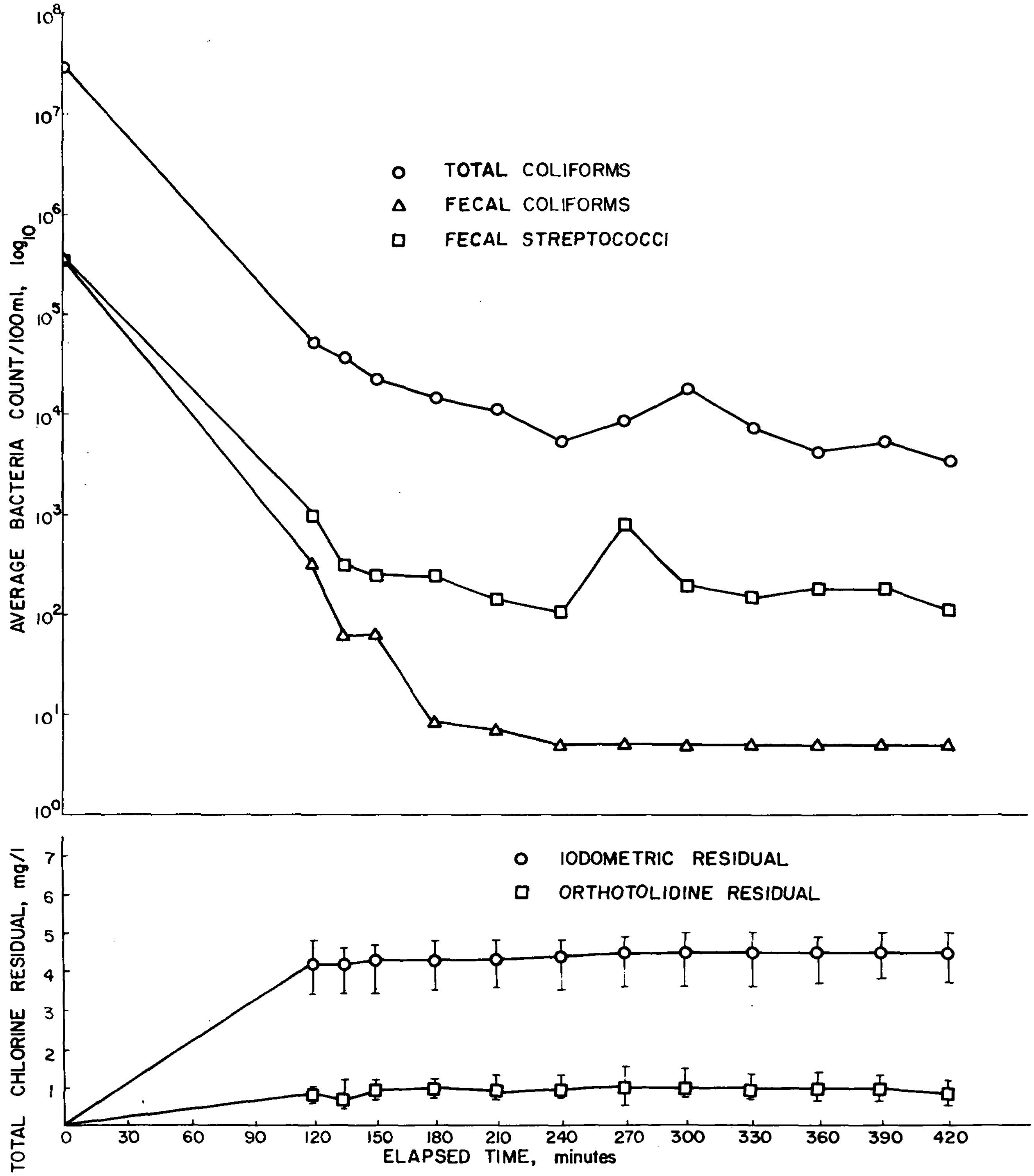

Figure 3. Average number of bacteria surviving disinfection at <1°C with corresponding total chlorine residual average and range. 60 minutes theoretical contact time, 1 mg/l chlorine residual (OT).

ing the series was 1.8 x 10^3/100 ml. From an initial count of 6.8 x 10^4-7.0 x 10^5/100 ml in the unchlorinated effluent, the fecal coliforms were rapidly reduced to <100/100 ml. They continued to decrease in all samples during this series until, after 240 minutes elapsed time, all samples contained <5/100 ml (shown as 5/100 ml in Figure 3). The average fecal streptococci number was reduced to <1000/100 ml from initial counts of 2.1-6.1 x 10^5/100 ml. The lowest average number was 110/100 ml with 30/100 ml as the lowest count in any sample.

Disinfection Studies at <1°C Using 60 Minutes Theoretical Contact Time 2 mg/l Total Chlorine Residual (OT)

In the 60 minute theoretical contact time:2 mg/l total chlorine residual (OT) series at <1°C, four replicate experiments were conducted during a 23 day period. The arithmetic mean, maximum and minimum parameter values for the effluent samples examined in this series are presented in Table 2.

The total chlorine residual, total coliform, fecal coliform and fecal streptococci results for this series of experiments are shown in Figure 4. Monitoring of the effluent was begun after the system had operated for 120 minutes. The average total chlorine residual, as measured by the OT method, continued to increase from 1.4 mg/l at 120 minutes to 2.3 mg/l at 420 minutes elapsed time. The minimum and maximum concentrations were 1.1 mg/l at 120 minutes and 2.5 mg/l at 420 minutes, respectively. The residual, as measured by the iodometric method, did not show the continuous increase found with the OT method but became stable at 5.6-5.8 mg/l

Parameter	Arithmetic mean	Maximum value	Minimum value	Number of samples
Initial temperature, °C	0.4	0.6	0.3	4
Final temperature, °C	0.5	0.6	0.4	4
Initial pH	7.2	7.3	7.0	4
Final pH	7.3	7.4	7.1	4
Chlorine added as HOCl, mg/l	6.8	7.7	6.3	4
TS, mg/l	470	540	440	4
TVS, mg/l	285	340	240	4
TSS, mg/l	70	110	52	4
VSS, mg/l	49	78	35	4
VDS, mg/l	188	220	160	4
TDS, mg/l	363	400	330	4
NH_3-N, mg/l	19.0	22	14	4
NO_2-N, mg/l	0.022	0.04	0.01	4
NO_3-N, mg/l	0.072	0.08	0.07	4
Kjeldahl-N, mg/l	23.8	25	23	4
COD, mg/l	263	332	215	4

Table 2. Effluent Sample Parameters from Flow Through Contact Chamber Studies at <1°C.
60 Minutes Theoretical Contact Time, 2 mg/l Total Chlorine Residual (OT).

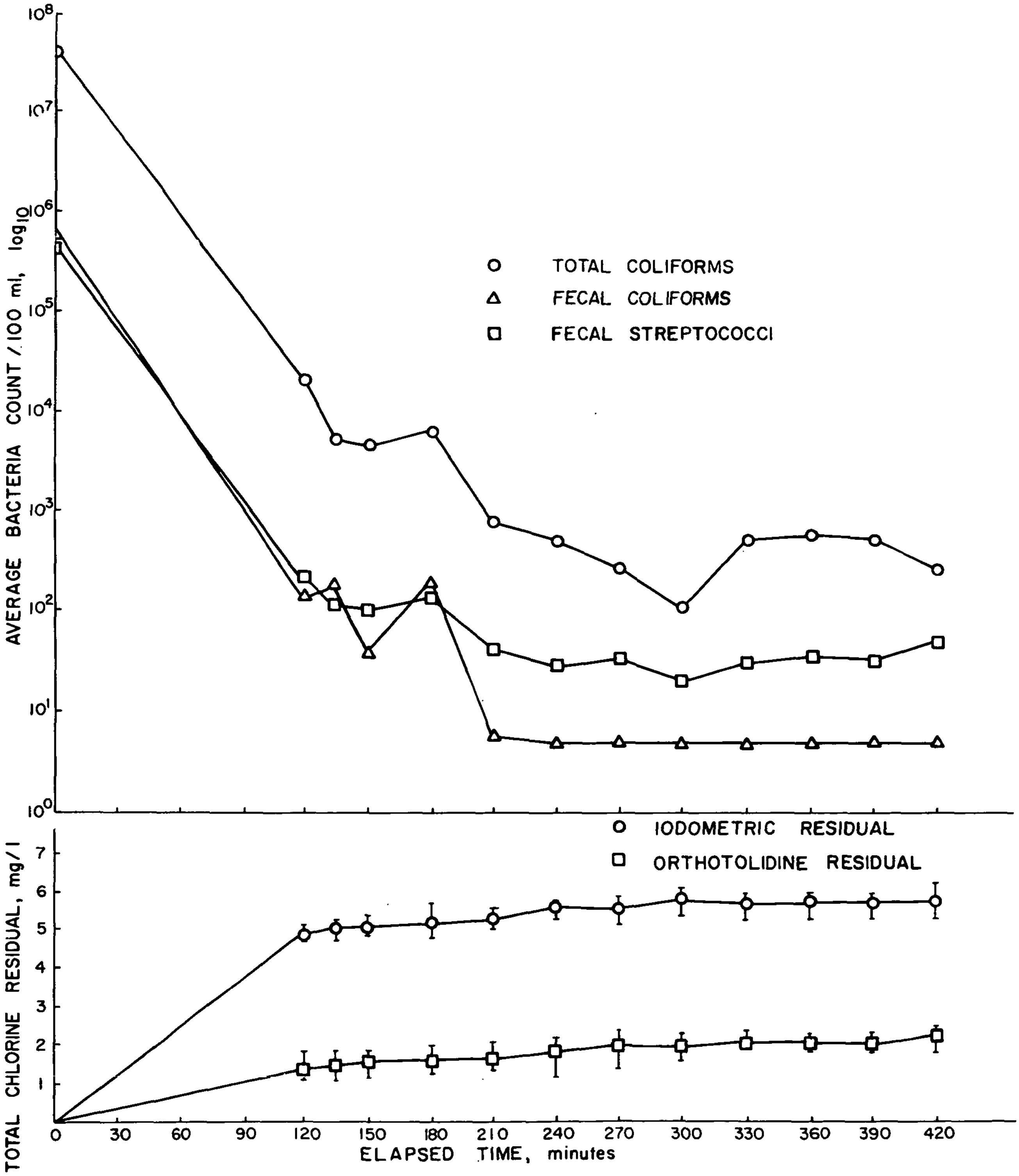

Figure 4. Average number of bacteria surviving disinfection at <1°C with corresponding total chlorine residual average and range. 60 minutes theoretical contact time, 2 mg/l chlorine residual (OT).

after 240 minutes elasped time. During the time when the average residual was stable, the minimum and maximum residuals recorded were 5.2 mg/l and 6.2 mg/l, respectively.

The total coliforms in the unchlorinated effluent ranged from 1.6 to 7.4 x 10^7/100 ml, and were reduced to an average of 2.2 x 10^4/100 ml of effluent from the contact chamber after 120 minutes of elapsed time. The total coliforms continued to decrease until the average number surviving disinfection was 830/100 ml after 210 minutes with the range of 420/100 ml to 1.5 x 10^3/100 ml. The count/100 ml remained >1000 in one of the four experiments during this series and ranged between 1.1 and 1.7 x 10^3 throughout that experiment. In spite of the high numbers in one experiment, the average count remained <1000/100 ml after 210 minutes with a low of 120/100 ml. The lowest total coliform number recorded during this series was 23/100 ml.

The initial fecal coliform numbers were 5.2-7.3 x 10^5/100 ml, and were reduced to <200/100 ml by the time the first sample was taken at 120 minutes elapsed time. After a somewhat unstable period, the count was reduced to <5/100 ml at 240 minutes in all experiments and remained at this very low level. Fecal streptococci, initially 3.4-6.0 x 10^5, were reduced to an average of <100/100 ml of contact chamber effluent after 210 minutes elapsed time and remained fairly stable.

Dye Studies at 30 Minutes Theoretical Contact Time

Typical results for instantaneous and continuous dye injection at the 30 minutes theoretical contact time flow rate are shown in Figure 5. In

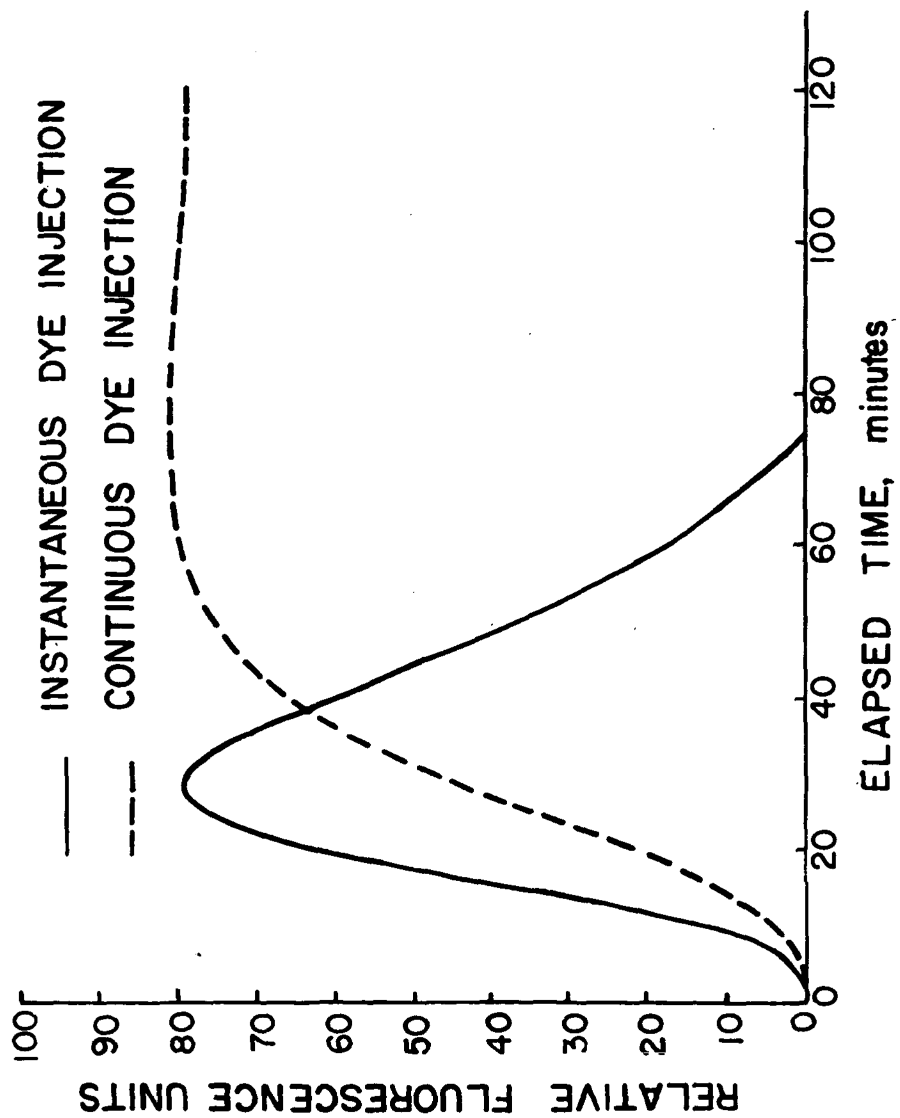

Figure 5. Instantaneous and continuous dye injection in flow through contact chamber studies.
30 minutes theoretical contact time.

all instantaneous injection trials, four minutes were required for the dye to be detected in effluent from the contact chamber. The dye concentration increased rapidly and reached its peak 28 minutes after injection. At this flow rate, 58 percent of the dye remained in the chamber for the 30 minutes theoretical contact time, and it required 32 to 33 minutes for 50 percent of the dye to leave the contact chamber. Only four percent of the dye had 60 minutes or more residence time. The Morril index was found to be 2.9 indicating a considerable divergence from plug flow.

Although time of initial dye detection in the continuous injection studies was nearly the same as for the instantaneous injection, the concentration increased at a slower rate. Maximum concentration was reached after about 65 minutes and remained essentially stable as long as dye was being injected.

Disinfection Studies at <1°C Using 30 Minutes Theoretical Contact Time 2.5 mg/l Total Chlorine Residual (OT)

The three replicate experiments for the 30 minute theoretical contact time:2.5 mg/l total chlorine residual (OT) series were conducted over a 34 day period. During this time, several of the effluent parameter values shown in Table 3 deviated from the typical range for the entire study period. The ammonia and Kjeldahl nitrogen concentrations were all higher than those found during any other series. Several other parameters had consistently high values even though maximums for the entire study were not necessarily obtained during this series. These parameters were: initial and final effluent temperature in the contact chamber, total solids, volatile

Parameter	Arithmetic mean	Maximum value	Minimum value	Number of samples
Initial temperature, °C	0.6	0.9	0.2	3
Final temperature, °C	0.9	1.0	0.9	3
Initial pH	7.2	7.5	7.1	3
Final pH	7.4	7.6	7.2	3
Chlorine added as HOCl, mg/l	8.5	11.3	6.7	3
TS, mg/l	497	500	490	3
TVS, mg/l	233	250	220	3
TSS, mg/l	89	110	71	3
VSS, mg/l	73	88	55	3
VDS, mg/l	137	160	120	3
TDS, mg/l	403	420	390	3
NH_3-N, mg/l	29.0	32	27	3
NO_2-N, mg/l	0.033	0.04	0.03	3
NO_3-N, mg/l	0.053	0.08	0.03	3
Kjeldahl-N, mg/l	32.0	34	31	3
COD, mg/l	306	320	283	3

Table 3. Effluent Sample Parameters from Flow Through Contact Chamber Studies at <1°C.
30 Minute Theoretical Contact Time, 2.5 mg/l Total Chlorine Residual (OT).

suspended solids, total dissolved solids, nitrite nitrogen and COD.

Following initial chlorine injection, the contact chamber was operated for 60 minutes before starting chlorine residual and bacteriological monitoring. The results are presented in Figure 6. At 60 minutes elapsed time, the average total chlorine residual (OT) reached 1.6 mg/l. The concentration continued to increase, reaching a 1.9 mg/l plateau after 90 minutes. Between 120 and 135 minutes, a second concentration increase began and reached 2.5 mg/l when the sample was taken at 150 minutes elapsed time. The average total chlorine residual then remained quite stable at 2.5-2.6 mg/l. Between 150 and 210 minutes elapsed time, the minimum and maximum values determined by the OT method were 1.8 and 3.3 mg/l, respectively. The average chlorine residual by the iodometric method ranged between 5.3 and 5.7 mg/l starting with the measurements at 150 minutes. During the same time period, the minimum concentration was 4.6 mg/l and the maximum was 7.2 mg/l.

The total coliforms in the unchlorinated effluent ranged between 1.2 and 2.3 x 10^7/100 ml. Those surviving disinfection averaged <1 x 10^4/100 ml after 90 minutes elapsed time with the lowest average number being 2.7 x 10^3/100 ml. During one experiment in this series, numbers <1000/100 ml were recorded at two time intervals with the lower being 630/100 ml. From initial numbers of 3.8-8.9 x 10^5/100 ml, the average fecal coliform count was reduced to 23/100 ml after 90 minutes elapsed time. The average then remained very low, except for the 120 minute samples which contained an average count of 160/100 ml (450/100 ml maximum). The initial fecal strep-

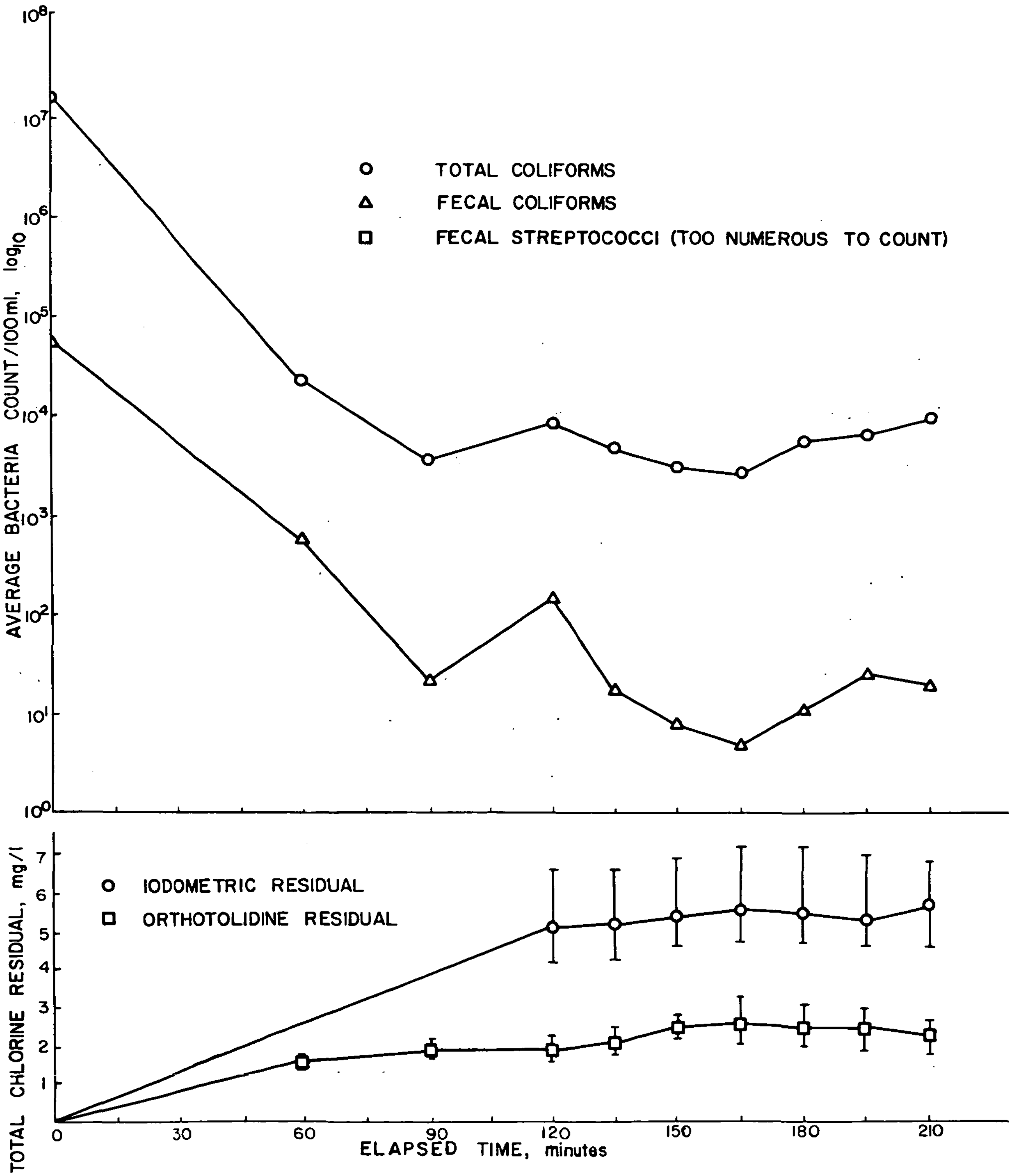

Figure 6. Average number of bacteria surviving disinfection at <1°C with corresponding total chlorine residual average and range. 30 minute theoretical contact time, 2.5 mg/l chlorine residual (OT).

tococci count was 5.1-9.5 x 10^5/100 ml in this series of experiments, and their removal by disinfection presented somewhat of an anomaly. During the first experiment 110-210/100 ml remained in effluent from the contact chamber after 90 minutes elapsed time. The count was >500/100 ml throughout the second experiment and was recorded as Too Numerous To Count (TNTC). Effluent volumes for filtration were adjusted during the third experiment to accommodate the higher number. However, >2.3 x 10^3 streptococci were present and were again recorded as TNTC. Since no average number could be established, fecal streptococci results are not shown in Figure 6.

Dye Studies at 120 Minutes Theoretical Contact Time

Typical results of instantaneous and continuous dye injection at the 120 minute theoretical contact time flow rate are shown in Figure 7. Dye was first detected in effluent from the chamber 28 minutes after instantaneous dye injection (28 to 30 minutes for all results). The concentration increase was essentially continuous, but did not produce a smooth curve at this flow rate. The first point of interest on this curve is that the area remaining under the curve after 60 minutes elapsed time indicated that 73 percent of the dye was still in the contact chamber. The peak was reached in 65 minutes, and 81 to 82 minutes were required for 50 percent of the dye to be discharged in the effluent. Only 24 percent of the dye had a residence time equal to or greater than the 120 minutes theoretical contact time. The dye concentration curve was extrapolated to zero at 225 minutes to permit an approximate Morril index determination. This index was 3.4 indicating a rather extreme departure from plug flow.

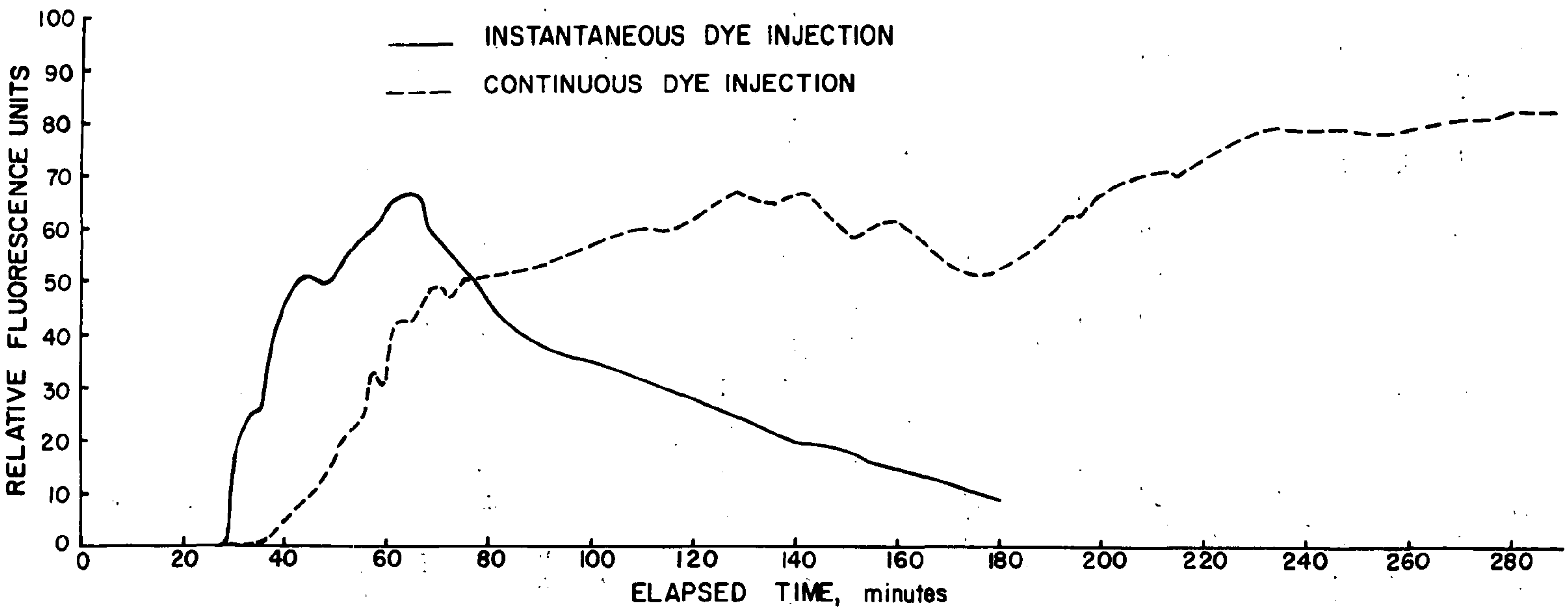

Figure 7. Instantaneous and continuous dye injection in flow through contact chamber studies. 120 minutes theoretical contact time.

The curve produced by continuous dye injection was erratic throughout most of the 280 minutes the contact chamber was operated. There appeared to be an unstable concentration plateau which started at about 105 minutes and continued until 165 minutes had elapsed. The dye concentration then increased and approached a fairly stable plateau between 230 and 280 minutes elapsed time.

Disinfection Studies at <1°C Using 120 Minutes Theoretical Contact Time 1 mg/l Total Chlorine Residual (OT)

The two experiments in this series were conducted during an 18 day period. The parameter values for both experiments are shown in Table 4. These are comparable to other values obtained throughout the study.

Bacteriological and total chlorine residual results for both experiments are presented in Figures 8 and 9. Monitoring of the total chlorine residual by both methods was started after 60 minutes elapsed time. Little or no residual (OT) appeared in the contact chamber effluent prior to 120 minutes, but then a continuous increase was observed, reaching a maximum concentration of about 0.8 mg/l. There was approximately 60 minutes difference between the two experiments in the time required to reach both the 0.5 mg/l residual level and the maximum residual level measured by the OT method. When the first chlorine residual samples were taken at 60 minutes, the iodometric method indicated the presence of 0.76 and 1.0 mg/l chlorine, and continued to show an increase to stable concentrations of 2.7 and 2.9 mg/l. These concentrations were both recorded initially at the 330 minute elapsed time sampling.

Parameter	Experiment #1	Experiment #2
Initial temperature, °C	0.8	0.6
Final temperature, °C	0.8	---
Initial pH	7.0	7.2
Final pH	7.0	7.3
Chlorine added as HOCl, mg/l	5.2	4.5
TS, mg/l	410	410
TVS, mg/l	---	250
TSS, mg/l	59	57
VSS, mg/l	49	36
VDS, mg/l	300	140
TDS, mg/l	340	320
NH_3-N, mg/l	21	16
NO_2-N, mg/l	0.01	0.01
NO_3-N, mg/l	0.03	0.03
Kjeldahl-N, mg/l	24	20
COD, mg/l	241	202

Table 4. Effluent Sample Parameters from Flow Through Contact Chamber at <1°C.
120 Minutes Theoretical Contact Time, 1 mg/l
Total Chlorine Residual (OT).

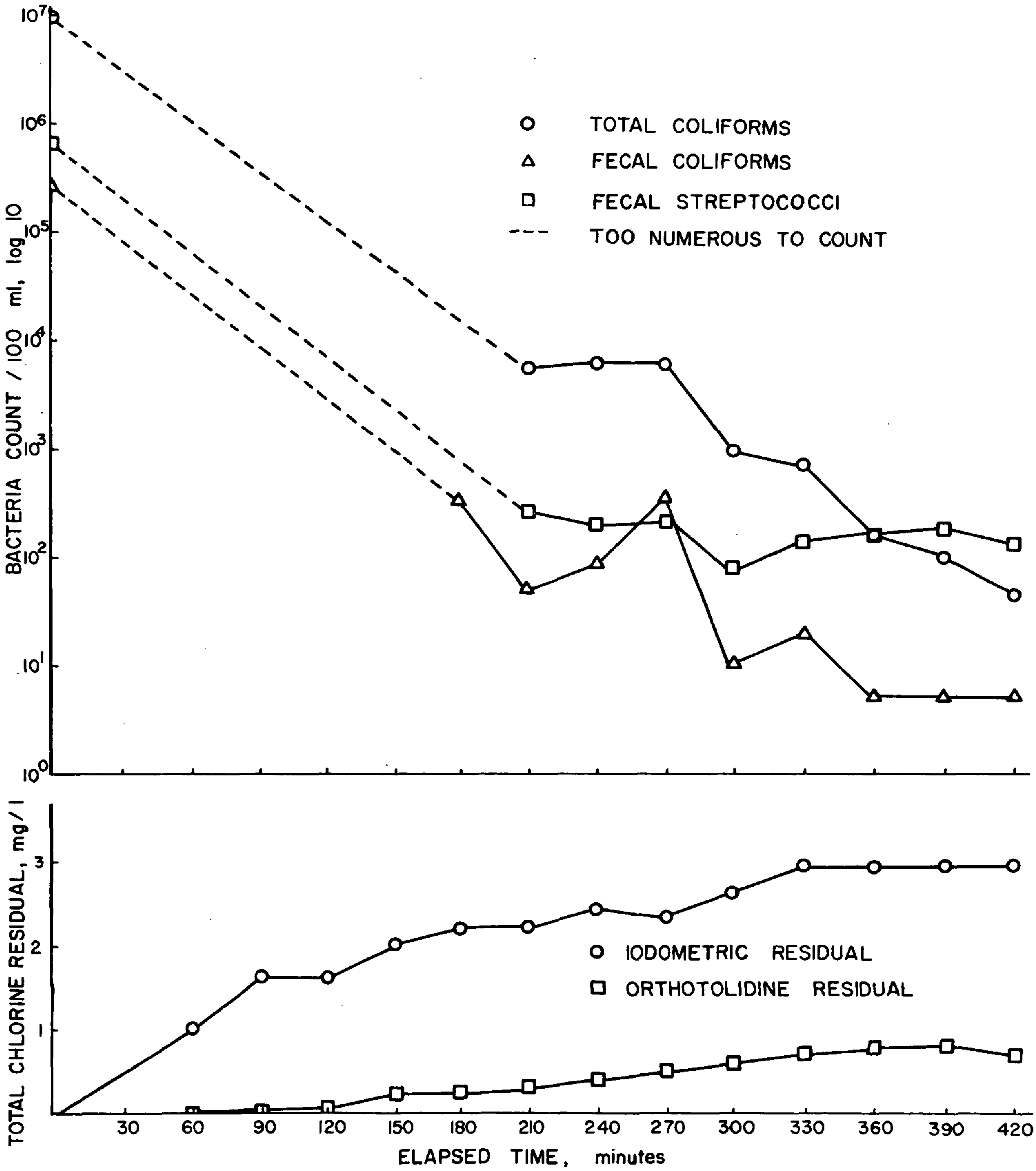

Figure 8. Number of bacteria surviving disinfection at <1°C with corresponding total chlorine residuals.
120 minutes theoretical contact time, 1 mg/l residual (OT).

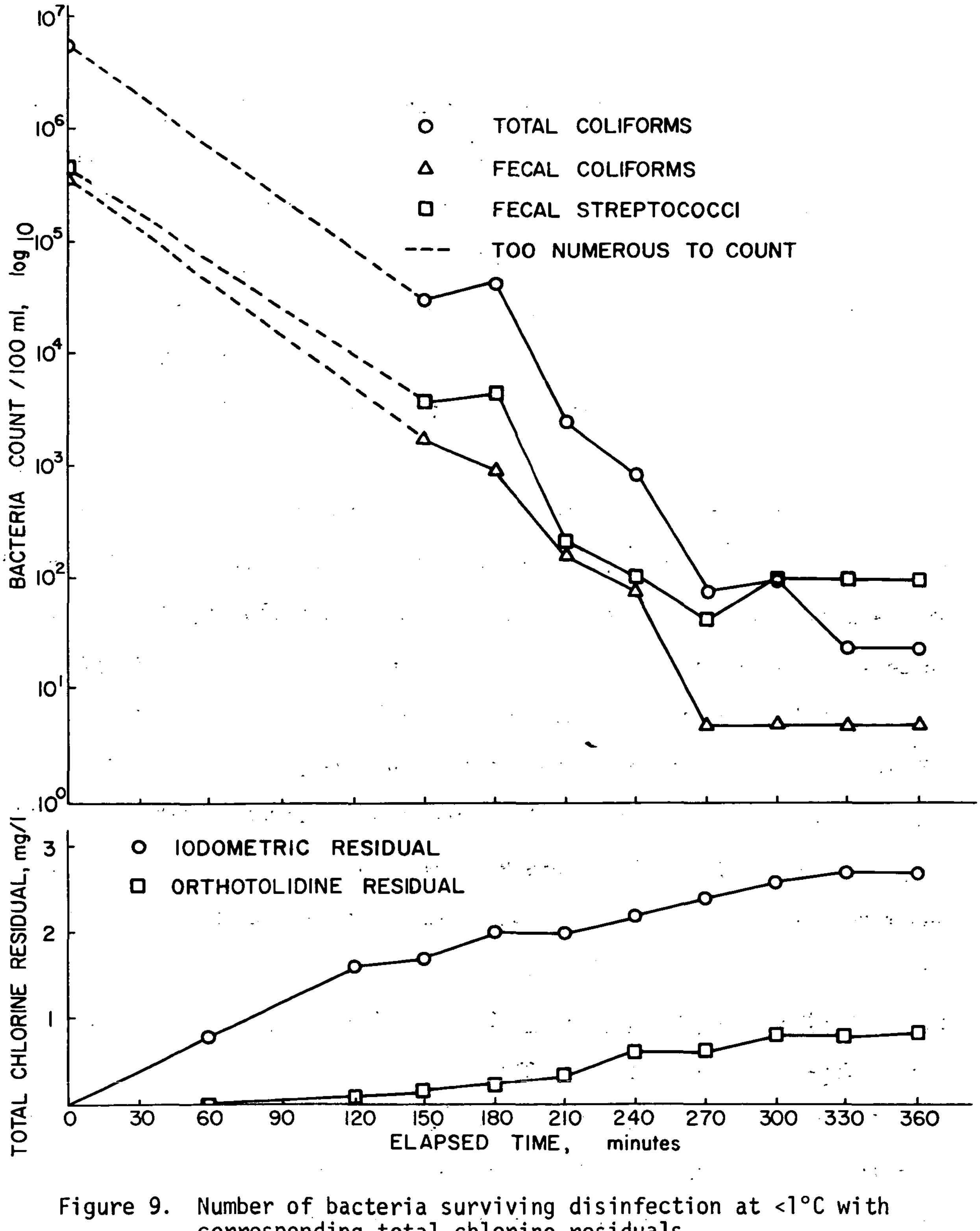

Figure 9. Number of bacteria surviving disinfection at <1°C with corresponding total chlorine residuals.
120 minutes theoretical contact time,
1 mg/l chlorine residual (OT).

The total coliform numbers were 5.5 and 9.2 x 10^6 in the unchlorinated effluent, and were reduced to <1 x 10^4/100 ml at the 210 minutes elapsed time. The elapsed time for total coliform reduction to <1000/100 ml was about 300 minutes in Figure 8 (980/100 ml) and 240 minutes in Figure 9 (850/100 ml) which were the times required for the chlorine residual to reach 0.5 mg/l (OT). Although the elapsed times differed by 60 minutes, the rates of decrease were similar with final counts of 45/100 ml (Figure 8) and 25/100 ml (Figure 9).

The initial fecal coliform counts of 2.7 and 3.7 x 10^5 were reduced to <200/100 ml in no more than 210 minutes elapsed time. There was considerable dissimilarity in the rates of decrease after 210 minutes, but the numbers were reduced to <5/100 ml during the last 60 minutes the system was operated. The fecal streptococci initial counts were 4.7 and 6.6 x 10^5/100 ml. The number of these bacteria surviving disinfection in the two experiments followed nearly the same rate of decrease with 280/100 ml (Figure 8) and 220/100 ml (Figure 9) remaining viable at 210 minutes elapsed time. When the last samples were taken, the effluent still contained 140/100 ml (Figure 8) and 100/100 ml (Figure 9).

Batch Treatment Disinfection at <1°C 60 Minutes Using Contact Time, 1 mg/l Total Chlorine Residual (OT)

A batch treatment control was run in parallel with each of the 14 disinfection experiments conducted in the flow through system at <1°C. The solids, nitrogen and the COD concentrations (Tables 1, 2, 3, 4) apply to the effluent used for batch treatment. Other parameters for batch treatment at <1°C are presented in Table 5. It was not possible to maintain a uniform temperature throughout the controlled temperature room because the air flow patterns created warm and cold spots. Although the room temperature was adjusted to maintain <1°C in the contact chamber, some parts of the room deviated more than 1°C from this setting. The temperature variation affected the small effluent volume used for batch treatment, resulting in batch temperatures which exceeded 1°C during five of the experiments. This is reflected in the average and maximum temperatures shown in Table 5. During two of the experiments, it was not possible to obtain final counts for total coliforms, fecal coliforms or fecal streptococci and the total coliforms were TNTC in a third experiment. This biased the final average and maximum bacteria counts in Table 5 to some extent, but the numbers reported still indicate what was generally found.

Disinfection Studies at 10°C

An attempt was made to obtain comparative disinfection results with the flow through system at 10°C. However, the transition from winter to spring in the Fairbanks area began approximately one month earlier than expected in 1973 and flow through the city waste treatment system increased. The increased flow may have caused dilution of the wastewater in the system as shown by the parameter values in Table 6. Most of these concentrations were either lower than the minimum values recorded or in the low end of the value range found during the <1°C studies, suggesting that direct comparison with the <1°C results would be unsatisfactory. Nevertheless, two experiments were conducted to acquire some information on what might

Table 5. Effluent Parameters of Samples Subjected to 60 Minutes Batch Disinfection at <1°C in Parallel with the Flow Through System.

Parameter	Average	Maximum	Minimum	Number of samples
Initial temperature, °C	0.9	1.9	0.4	14
Final temperature, °C	1.0	2.4	0.4	14
Initial pH	7.2	7.5	7.0	14
Final pH	7.2	7.5	7.0	14
Chlorine added as HOCl, mg/l	5.4	7.8	4.2	14
Final chlorine residual: iodometric method, mg/l	3.9	4.9	3.0	13[c]
orthotolidine method, mg/l	0.98	1.5	0.46	14
Initial total coliform count/100 ml	2.7×10^{7}	7.4×10^{7}	5.5×10^{6}	14
Final total coliform count/100 ml	132	470	30	11[c]
Initial fecal coliform count/100 ml	4.8×10^{5}	8.9×10^{5}	6.8×10^{4}	14
Final fecal coliform count/100 ml	20	220	<5[b]	12[c]
Initial fecal streptococci count/100 ml	5.2×10^{5}	9.5×10^{5}	2.1×10^{5}	14
Final fecal streptococci count/100 ml	67	230	5[a]	12[c]

[a] Average of less than 20 colonies per filter when triplicate filters were examined.
[b] No coliform colonies on any filter when triplicate filters were examined.
[c] Results not available for some samples.

Parameter	Experiment #1	Experiment #2
TS, mg/l	400	370
TVS, mg/l	210	210
TSS, mg/l	78	56
VSS, mg/l	40	34
VDS, mg/l	150	120
TDS, mg/l	300	330
NH_3-N, mg/l	13	12
NO_2-N, mg/l	0.01	0.01
NO_3-N, mg/l	0.04	0.03
Kjeldahl-N, mg/l	17	15
COD, mg/l	170	150

Table 6. Effluent Parameters Common to Samples Examined at 10°C.

be expected when the effluent temperature in the contact chamber was raised from <1°C to 10°C.

One experiment was conducted with 60 minutes theoretical contact time and 1 mg/l total chlorine residual (OT) in the contact chamber and the second with 30 minutes theoretical contact time and 2 mg/l total chlorine residual (OT). In parallel with each experiment, batch treatment was conducted at both <1°C and 10°C using 60 minutes contact time and 1 mg/l total chlorine residual (OT). Figure 10 shows the results of the 60 minutes theoretical contact time experiment. The total chlorine residual (OT) reached the maximum concentration plateau of 0.76-0.85 mg/l after 180 minutes elapsed time, and 120 minutes was required to reach the 2.2-2.5 mg/l plateau measured by the iodometric method. The total coliforms were reduced from an initial count of 3.0×10^7/100 to a low of 1000/100 ml after 180 minutes elapsed time. The count then increased to $2.0\text{-}2.5 \times 10^3$/100 ml where it remained. Starting with 4.0×10^5 fecal coliforms/100 ml, disinfection reduced the count to 5/100 ml at the 180 minute elapsed time sampling and the number did not increase after this time. The initial fecal streptococci count of 3.9×10^5/100 ml was reduced to 95/100 ml after 180 minutes, and remained near this number.

The 30 minute theoretical contact time results are presented in Figure 11. The total chlorine residual (OT) reached the plateau in no more than 60 minutes and remained in the 1.5-1.7 mg/l range. During the same time period, the iodometric total chlorine residual was on a 3.1-3.4 mg/l plateau. The total coliforms started with an initial count of 1.7 x

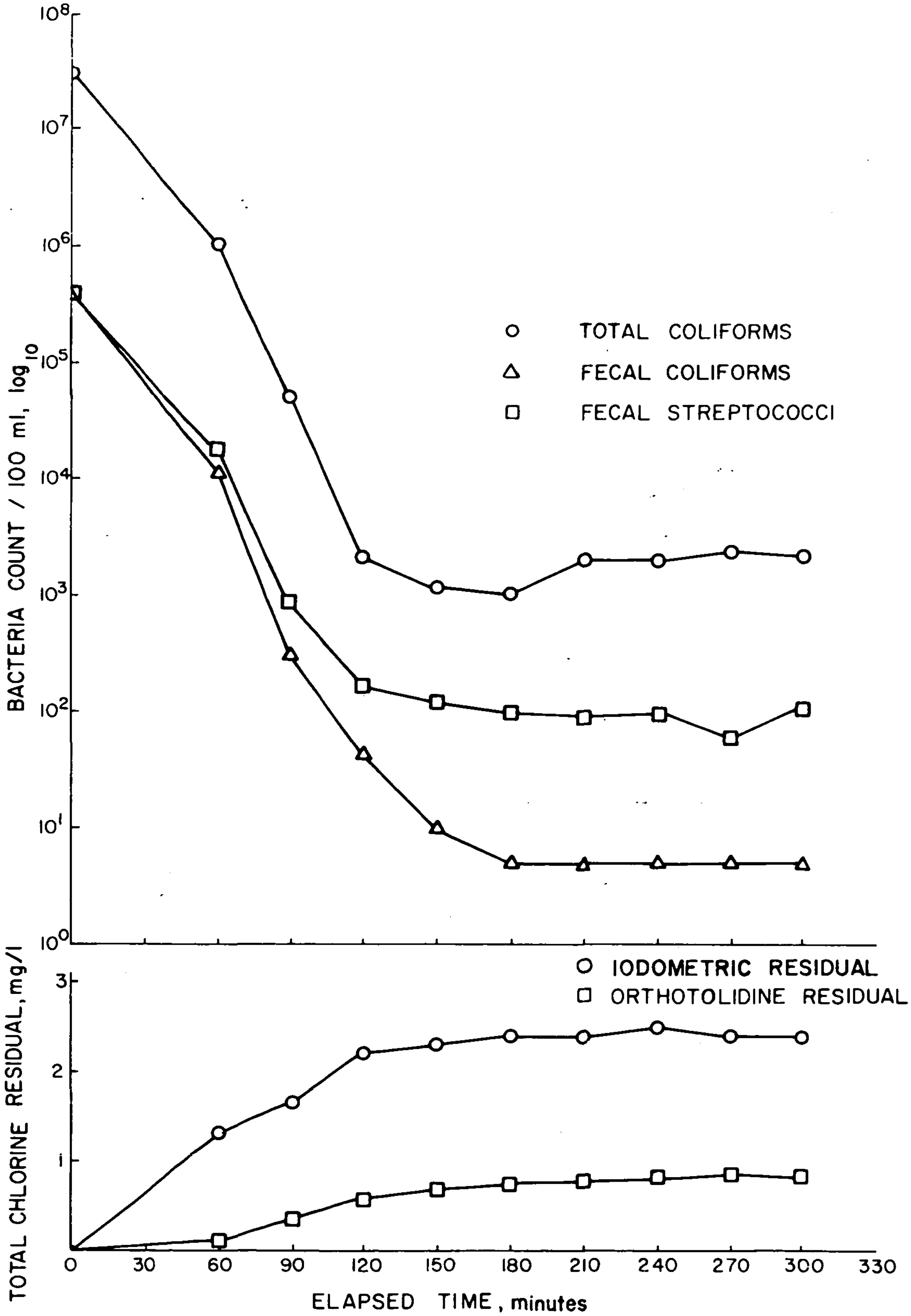

Figure 10. Number of bacteria surviving disinfection at 10°C with corresponding total chlorine residuals.
60 minutes theoretical contact time,
1 mg/l chlorine residual (OT).

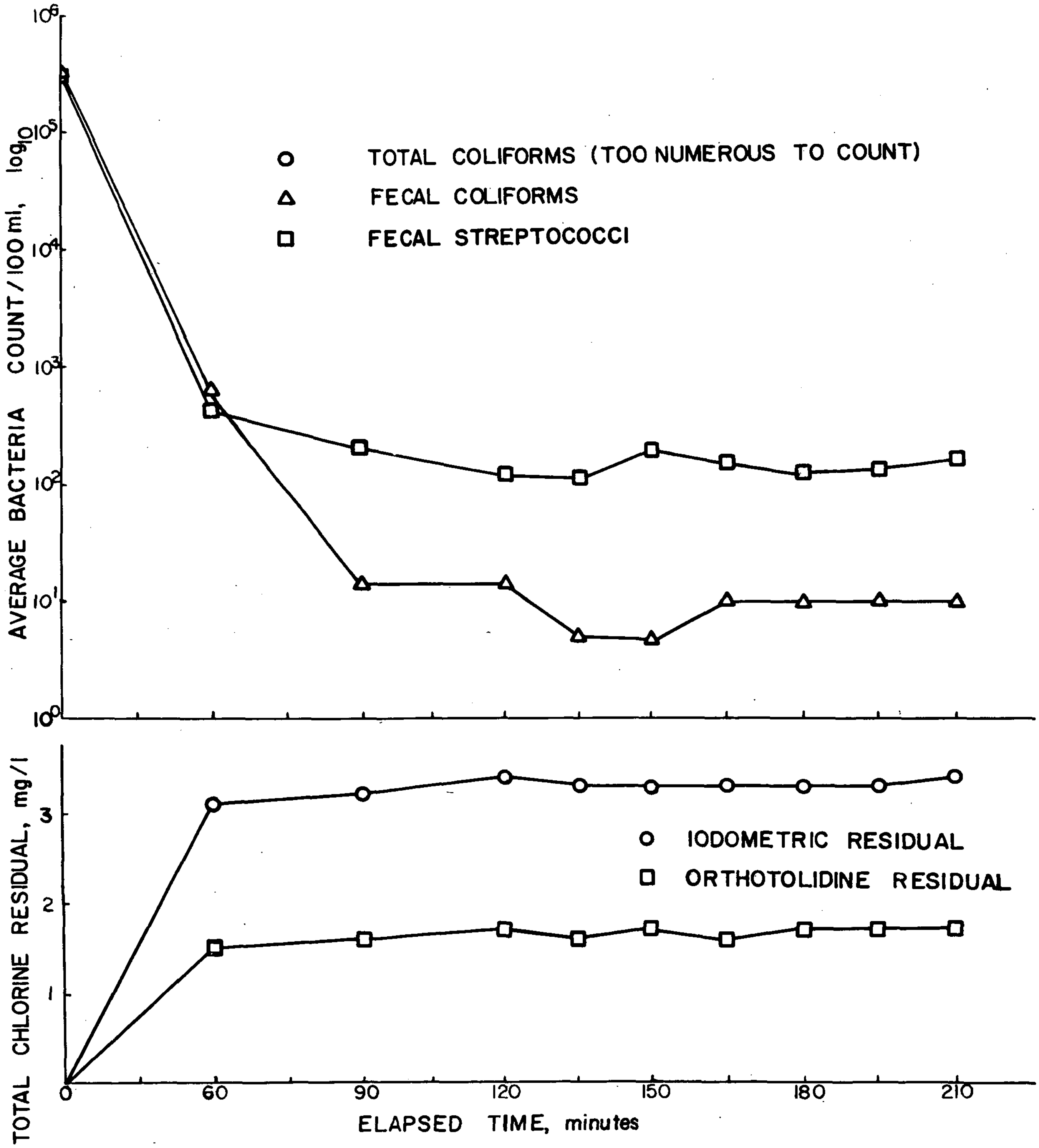

Figure 11. Number of bacteria surviving disinfection at 10°C with corresponding total chlorine residual.
30 minutes theoretical contact time,
2 mg/l chlorine residual (OT).

10^7/100 ml and were reduced to 3.1 x 10^4/100 ml after 60 minutes elapsed time. The count then remained >8.3 x 10^3/100 ml which was reported as TNTC and does not appear in Figure 11. The initial fecal coliform count of 3.4 x 10^5/100 ml was reduced to 15/100 ml after 90 minutes, and remained in the 5-10/100 ml range after that time. The initial count of 3.2 x 10^5 fecal streptococci/100 ml was reduced to 210/100 ml at the 90 minute sampling and remained between 130 and 200 for the rest of the time the contact chamber was operated.

The parameter values for the batch controls at 10°C and <1°C, along with the temperature and pH values for the contact chamber, are shown in Table 7. When the effluent was brought to the laboratory, a small portion was cooled immediately to <1°C and the rest was adjusted to 10°C. As soon as the effluent was brought to temperature, samples were taken for an immediate total coliform, fecal coliform and fecal streptococci count (experiment #2 only). The results indicated that changing the effluent temperature did not alter the numbers of bacteria present. The effluent was then held overnight at those temperatures. When the initial counts were made at the start of each experiment on the second day, there was a four to six fold difference in the total coliform numbers at the two temperatures. However, this does not provide an adequate explanation for the poor total and fecal coliform results at 10°C in experiment #1.

Table 7. Effluent Parameters of the 10°C Flow Through System and Parallel 60 Minute Batch Disinfection at 10°C and <1°C.

Parameter	Experiment #1			Experiment #2		
	Flow through system[a]	Batch		Flow through system[b]	Batch	
		10°C	<1°C		10°C	<1°C
Initial temperature, °C	10.0	10.3	0.1	10.1	10.2	0.8
Final temperature, °C	10.0	10.5	0.5	10.3	10.2	1.1
Initial pH	7.1	7.1	7.4	7.2	7.2	7.2
Final pH	7.1	7.2	7.4	7.2	7.2	7.3
Chlorine added as HOCl, mg/l	5.0	5.0	5.0	5.0	3.8	3.8
Final chlorine residual: iodometric method, mg/l	----	2.7	2.9	----	2.6	2.7
orthotolidine method, mg/l	----	1.1	1.2	----	1.0	1.0
Initial total coliform count/100 ml	3.0x10^{7}	3.0x10^{7}	5.3x10^{6}	1.7x10^{7}	1.7x10^{7}	4.0x10^{6}
Final total coliform count/100 ml	----	----[c]	75[d]	----	90	95
Initial fecal coliform count/100 ml	4.0x10^{5}	4.0x10^{5}	4.0x10^{5}	3.4x10^{5}	3.4x10^{5}	1.2x10^{5}
Final fecal coliform count/100 ml	----	TNTC[f]	5[d]	----	5[d]	<5[e]
Initial fecal streptococci count/100 ml	3.9x10^{5}	3.9x10^{5}	5.1x10^{5}	3.2x10^{5}	3.2x10^{5}	3.6x10^{5}
Final fecal streptococci count/100 ml	----	260	180	----	10[d]	50[d]

[a] 60 minute theoretical contact time.
[b] 30 minute theoretical contact time.
[c] Large number of background colonies made coliform colonies uncountable.
[d] An average of less than 20 colonies per filter when triplicate filters were counted.
[e] No coliform colonies on any filter when triplicate filters were examined.
[f] Too numerous to count.

Discussion

The hydraulic performance of chlorine contact chambers having various configurations has been the subject of considerable study and discussion during the past few years (7, 21, 23, 28, 30, 33, 35). The two major considerations pointed out in these reports are: that the chlorine should be thoroughly and rapidly mixed with the wastewater before entering the contact chamber, and that the contact chamber design should be such that the hydraulic performance approaches plug-flow. Even attaining plug-flow would not be adequate unless the actual residence time of the thoroughly mixed wastewater and chlorine in the contact chamber is long enough for the enteric bacteria to be reduced to an acceptable number.

In current disinfection practice, non-plug-flow (short-circuiting) characterizes contact chamber hydraulic performance. The extent of short-circuiting is a measure of the degree to which the chlorine and wastewater have less than theoretical residence time before leaving the chamber. The degree of short-circuiting may be such that the effluent is inadequately disinfected unless excessive chlorine has been added before entering the chamber. These problems will continue to exist as long as wastewater disinfection receives minimal design and operational attention.

The configuration of the contact chamber used in this study, and the method of adding chlorine before entering the contact chamber, provided a system which is comparable to any system that might be designed in accordance with the previously mentioned guidelines (11). Short-circuiting was a serious problem even though the contact chamber was well baffled. When the dye studies at the three flow rates were compared (Figures 2, 5, 7), the amount of dye having a residence time at least equal to the theoretical contact time decreased with decreasing flow rate. That is, short-circuiting appears to be magnified at lower flows. However, the amount of dye having at least 60 minutes residence time increased with decreasing flow rate. Plug-flow was not approached at any of the flow rates, and only the 120 minutes theoretical contact time provided residence time approximating that obtained with 60 minutes batch treatment. In other words, a reactor volume twice the design volume would probably provide more adequate exposure time.

The disinfection guidelines (11) recommended a 1 mg/l total chlorine residual after 60 minutes contact time, but did not specify a method for chlorine residual determination. Since the OT method is still widely used for monitoring chlorine residual, it was selected for use during the first phase of the study (16). Minimum effective disinfection (less than 1000 total and 200 fecal coliforms/100 ml of effluent) could be reliably achieved at <1°C in the presence of 1 mg/l total chlorine residual (OT) after 60 minutes contact time, but the reliability decreased as residual concentrations decreased below 1 mg/l.

It has been well established that there can be a considerable difference between the total chlorine residual concentrations measured in treated wastewater by the OT and iodometric methods (1, 25). The difference in concentrations measured by the two methods is usually in the 2 to 5 mg/l range and may be even greater (1), the iodometric method indicating the higher residual. Some of the residual measured with the iodometric method, and not measured with the OT method, is probably in a tightly bound form which is ineffective in the disinfection process (25). However, there is evidence that disinfection can proceed even when no chlorine residual can be demonstrated with the OT method (7, 25).

All of the results presented here show that the total chlorine residual measured by the iodometric method is significantly greater than that measured by the OT method. If the recommended 1 mg/l total chlorine residual (11) is measured with the iodometric method, it is obvious that an actual contact time considerably longer than 60 minutes would be required to achieve effective disinfection at <1°C and probably at 10°C; assuming effective disinfection could be attained at all with such low residual.

Since there is no apparent correlation between the total chlorine residual measurements with the two methods, both the OT and iodometric methods were used during this study. The OT method was used as the basis for establishing the desired residual, and the iodometric method was used for comparative purposes. The results (Figures 3, 4, 6, 8, 9, 10, 11) showed that operating temperatures of <1°C apparently did not alter the previously observed differences between the two methods.

Some of the chemical and physical effluent quality parameters (Tables 1, 2, 3, 4, 6), as well as effluent residence time in the contact chamber, appeared to affect the chlorine demand. The chlorine concentration to satisfy this demand, and to maintain a particular residual, seemed to be closely related to the ammonia nitrogen concentration and more casually related to solids components. After the chlorine demand was satisfied, the effluent quality parameters apparently were not a significant factor in the disinfection process as <1°C with effluent from this source. Similar observations have been made under other operating conditions (7).

Under some operating conditions, the disinfection process has been shown to be dependent on the contact time and total chlorine residual as measured by the amperometric method (7, 35). Since the amperometric and iodometric methods give essentially the same results (1, 25), disinfection at <1°C would be expected to be more closely related to the total chlorine residual as measured by the iodometric method than by the OT method. However, this relationship was somewhat less obvious than expected at both operating temperatures (<1°C and 10°C). Regardless of the flow rate through the contact chamber, a chlorine residual measureable by the OT method was necessary before significant bactericidal action was apparent (Figures 3, 4, 6, 8, 9, 10, 11). The extent of the reduction was thus dependent upon both total chlorine residual concentration (OT), and residence time.

Reduction of total coliforms to an acceptable number (<1000/100 ml) proved difficult to accomplish in the flow through system at <1°C. In fact, this level of disinfection was not attained at the 60 minutes theoretical exposure time until the total chlorine residual (OT) approached 2 mg/l (Figures 3 and 4). With the 30 minutes theoretical residence, a total chlorine residual (OT) of 3.3 mg/l was not effective (Figure 6).

Extending the theoretical reaction time to 120 minutes permitted effective disinfection to be achievea with only a 0.5-0.6 mg/l total chlorine residual (OT) as shown in Figures 8 and 9. When the residual was increased to approximately 0.8 mg/l, the total coliforms were held at <100/100 ml of effluent. This suggested that the contact time is at least as important for total coliform reduction as the maintenance of a particular chlorine residual. Probably the most significant point was that the 120 minutes theoretical contact time was the only one which provided 60 or more minutes residence time for more than 50 percent of the effluent.

No problems were encountered in reducing the fecal coliform numbers to <200/100 ml of effluent (minimum effective disinfection) at <1°C. Average numbers of <5/100 ml were eventually achieved at all flow rates (Figures 3, 4, 6, 8, 9). However, minimum effective disinfection was not attained at the 30 minutes theoretical contact time until the chlorine residual (OT) was in excess of 1.6 mg/l (Figure 6). When the theoretical contact time was 120 minutes, approximately 0.3 mg/l total chlorine residual (OT) was required for minimum effective disinfection (Figures 8 and 9). Again, as with the total coliforms, this suggested that residence time in the contact chamber is as important as total chlorine residual.

The reason for enumerating fecal streptococci in water pollution control has generally been to aid in more accurately defining the source of warm-blooded animal pollution (14). Even though the intestinal tract of man and other warm-blooded animals is a normal habitat of these bacteria (1), no guidelines have been established for the number of fecal streptococci permitted in effluent from disinfection contact chambers. The fecal streptococci have a different cell structure than the coliforms and related bacteria, consequently treated wastewater disinfection with chlorine would not necessarily affect these groups in the same manner. During this series of experiments at <1°C, some possible differences were noted. When the theoretical contact time was 60 minutes, increasing the chlorine residual from 1 mg/l (Figure 3) to 2 mg/l (Figure 4) affected the fecal streptococci in a manner very similar to that observed with the total coliforms. When the theoretical contact time was reduced to 30 minutes, chlorine appeared to be less effective against the fecal streptococci than against either coliform group (Figure 6). At the 120 minutes theoretical contact time flow rate (Figures 8 and 9), the reduction in fecal streptococci numbers was very similar to that found with 1 mg/l and 60 minutes contact time. This was in contrast to the rather sharply reduced numbers of total coliforms at 120 minutes contact time. Thus, it appeared that the contact time was the controlling factor in fecal streptococci reduction until a certain minimum was reached (approximately 60 minutes) with additional contact time having little apparent effect. After this minimum time was reached, the chlorine residual concentration (OT) became the factor controlling fecal streptococci numbers in the contact chamber effluent.

It has been demonstrated during this series of experiments (Table 5), and during the first phase of the study (16), that effective disinfection of treated wastewater could be achieved with a high degree of reliability at <1°C if the actual contact time was 60 minutes (batch treatment) and the total chlorine residual was 1 mg/l (OT). These results also indicated that batch treatment provided an effluent bacterial quality far superior to that obtained in the short-circuit plagued contact chamber, unless the flow rate through the chamber provided 60 or more minutes of actual residence time for a large portion (>50 percent) of the effluent (Figures 8 and 9). This points out that batch treatment laboratory results cannot necessarily be extrapolated to operating contact chambers, an observation supported by studies conducted under other conditions (7).

Experiments conducted in the contact chamber at 10°C were too limited in number for the results to give more than an indication of what might occur if the temperature was raised from <1°C to 10°C. The contact chamber results (Figures 10 and 11) did suggest that any improvement in effluent bacterial quality would be minimal. This suggestion was also supported by the parallel batch treatment results at 10°C and <1°C (Table 7). Probably the most interesting observations from the limited 10°C studies were the apparent changes in numbers of bacteria present at 10°C and <1°C during the 24 hours the effluent was held at the two temperatures before the disinfection studies were started. The total coliform numbers increased several fold at 10°C, while they remained the same or decreased at <1°C. The fecal coliform numbers showed no change at 10°C and either no change or a decrease at <1°C. The fecal streptococci either did not change or showed a slight increase in numbers at both temperatures.

These results suggested that at least some portion of the total coliform population was sufficiently cold adapted that significant reproduction could occur at temperatures near their minimum for growth. Similar low temperature reproduction has been observed previously in a mountain stream (18).

During both the batch (16) and contact chamber studies at <1°C, fecal coliforms were usually absent from the chlorinated effluent samples after a shorter contact time in the presence of a lower chlorine residual than was required to reduce the total coliform numbers to their minimim acceptable level. This suggests that fecal coliforms are more susceptible to chlorine disinfection at <1°C than are the total coliforms. Other work has indicated that this also occurs at warmer temperatures (7). The potentially detrimental effects on surface water quality in arctic and subarctic regions resulting from this difference in susceptibility to chlorine disinfection, and the current trend to de-emphasize or not use total coliform bacteria in determining recreational water quality, have been discussed previously (16). It has already been suggested that total coliforms should be retained and used in conjunction with fecal coliforms for determining water quality (7, 16). This is particularly important in the Arctic and Subarctic because there is little chance that any coliform bacteria come from other than sewered sources during the winter months.

It has been shown (16) that chlorine varied significantly in its ability to disinfect effluent from different sources at <1°C, and it has been reported that similar variations can be found with time in effluent from the same source (7, 19). This points out the fallacy of arbitrary chlorine residual and contact time criteria, since the only real measure of adequate disinfection is the number of enteric bacteria being discharged into a receiving water. It has been suggested that the chlorine residual:contact time relationship must be determined for the effluent from each source if effective disinfection is to be attained (5, 19). In addition, the relationship must be determined at all operating temperatures encountered in the disinfection system, particularly the lowest temperature.

The toxicity of residual chlorine to the biota in receiving waters has been a subject of increasing interest during the past few years. A comprehensive literature review has recently been prepared (4) pointing out that the residual chlorine can be toxic at very low concentrations, and several interim criteria were suggested for permissible concentrations of total residual chlorine in receiving waters. One particular criterion is probably of more interest than the others in relation to this study: "In areas receiving wastes treated continuously with chlorine, total residual chlorine should not exceed 0.01 mg/l for the protection of more resistant organisms only, or exceed 0.002 mg/l for the protection of most aquatic organisms." No mention was made of the method used to determine the chlorine residual, but it was pointed out that the total chlorine residual measured with the amperometric method was most closely related to biological activity. Thus, the 0.002 mg/l residual was probably measured either by the amperometric or iodometric method. It has also been demonstrated that toxic effects persist for several days (12).

Temperature was not included as a factor in any of the proposed toxicity criteria. The indigenous aquatic organism sensitivity to the total chlorine residual is essentially unknown at low temperatures. It is likely, however, that chlorine toxicity in receiving waters with temperatures approaching 0°C is as great or greater than at warmer temperatures. If this toxicity is superimposed on the low dissolved oxygen concentrations found in many arctic and subarctic rivers during the winter months, there may be extremely serious consequences (6).

Considering that the total chlorine residual necessary for effective disinfection at <1°C (Figures 4, 8, 9) was between 2.7 and 6.2 mg/l when measured by the iodometric method, it is apparent that a very large dilution would be needed to reduce the chlorine residual to 0.002 mg/l or less. Since most arctic and subarctic rivers have very low discharge during the winter months, the least dilution would be available when the highest total chlorine residual would probably be required for effective disinfection. If effective disinfection is to be achieved using chlorine, and toxicity in receiving waters minimized, dechlorination of the effluent before discharge must be considered in waste treatment plants operating in cold climates. Dechlorination methodology has been discussed recently (35), and it has been demonstrated that dechlorinated effluents are no more toxic to aquatic organisms than are the unchlorinated effluents (12).

This discussion has pointed out the lengths to which one must go if effective chlorine disinfection of treated wastewater is to be attained at <1°C and at 10°C. The current practice of giving minimal attention to the disinfection process not only fails to provide an effective barrier to the spread of enteric disease, but also ignores the toxic effect of chlorine on the indigenous aquatic organisms in the receiving water. To reduce this to a universal language: current practice is simply pouring money down a rat hole, with the public footing the bill and not realizing how little they are getting for their money. Since the use of chlorine as a disinfectant will no doubt persist for some time, technology must be improved so that effective disinfection is achieved under all but possibly the most extreme conditions. This means that disinfection must be given the role of a unit process having equal importance with other unit processes in the treatment system. However, under no conditions can disinfection be considered a substitute for adequate treatment of the waste.

Conclusions

1. Effective treated wastewater disinfection can be achieved at <1°C in the presence of a 1 mg/l or less total chlorine residual, if the effluent receives sufficient contact time and the total chlorine residual is measured by the orthotolidine method.

2. The contact time is at least as important as a particular total chlorine residual for attaining effective disinfection at low temperatures. Since the chlorine residual:contact time relationship for effective coliform reduction varies with effluent source and temperature, this relationship should be determined for each source and set of operating conditions.

3. The use of total coliforms, in conjunction with fecal coliforms, is necessary for ascertaining the effectiveness of treated wastewater disinfection and the quality of receiving waters at temperatures approaching 0°C.

4. The health effects resulting from inadequately disinfected effluents being released into the receiving water make it imperative that the extent of enteric pathogenic bacteria survival, as compared to that of coliform bacteria, be determined in receiving waters approaching 0°C.

5. The source and significance of "non-fecal" coliforms (those not giving a positive elevated temperature test) found in waste treatment systems during the winter should be determined. Particular emphasis should be given to the portion of the population which appears to have a significant increase in numbers at 10°C.

6. Operating temperatures of <1°C had little or no effect on the 2-5 mg/l

difference between the orthotolidine and iodometric methods of determining total chlorine residual. However, one method for total chlorine residual determination should be specified in order to eliminate possible confusion.

7. Treated wastewater disinfection must be considered a unit process which is given equal consideration with all other processes in the waste treatment system. This means that the "State of the Art" should be consolidated so that design criteria employing the best technology can be developed for rapid mixing of effluent and chlorine ahead of the contact chamber and for contact chamber design which actually minimizes short-circuiting and allows for maximum rather than average flow.

8. Total chlorine residual toxicity to the indigenous aquatic organisms in the receiving water should be established for receiving water temperatures approaching 0°C. Emphasis should be given to determining the possible synergistic effects on the organisms, of the chlorine toxicity and low dissolved oxygen concentrations frequently found in arctic and subarctic rivers during periods of ice cover.

9. Evaluation of disinfectants, other than chlorine, for possible application in effluents at low temperatures, should be accelerated.

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