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Dechlorination of water by small, activated carbon filters

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DECHLORINATION OF WATER BY SMALL, ACTIVATED CARBON FILTERS

by

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INTRODUCTION

Purpose of the Study

The purpose of this study was to determine the service life of an activated carbon filter when used to remove chlorine from a small water system that is operated intermittently The service life of the filter is the operation time required to reach a given maximum chlorine concentration in the filter effluent.

Background

The difficulties of securing an adequate underground water supply have led many farmers in the Middle West to construct small farm ponds. Varma and Baumann (1) have shown that a super chlorination-dechlorination system will render these pond waters safe for domestic purposes. Superchlorination-dechlorination consists of maintaining a relatively high chlorine concentration in a water storage tank and removing the excess chlorine before using the water. Varma and Baumann recommended a minimum chlorine concentration of 5.0 mg/l.

Equipment for such a superchlorination-dechlorination system is available commercially and is being used on pond water supplies. One process involves the addition of a solution of sodium hypochlorite to the water to obtain the desired chlorine residual in the storage tank. When disinfection is complete, the excess chlorine is removed by passing the water through an activated carbon filter. Information on the amount of chlorine that can be removed under the intermittent operating conditions

prevailing on such a water system is lacking.

Reason for Dechlorination

A chlorine concentration of 5.0 mg/l imparts a distinct taste and odor to the water. Under normal conditions this water would be considered undesirable for human consumption. The degree of undesirability depends on such things as temperature and pH of the water, and the presence of extraneous materials which might combine with the chlorine to give an even greater taste and odor.

Because of the taste-and-odor problem, that portion of the water intended for human consumption, either for cooking or for drinking, is dechlorinated. Dechlorination is accomplished by passing the water through a layer of activated carbon. The chlorine is adsorbed on the surface of the carbon particles and water with very little or no chlorine residual is obtained. While the removal of chlorine might be considered the primary function of the activated carbon, other undesirable tastes and odors may also be removed.

ACTIVATED CARBON

History

Activated carbon has been defined in the Condensed Chemical Dictionary (2) as follows:

> "Activated Charcoal (Active Carbon)—A more or less pure carbon characterized by a high adsorptive capacity for foreign molecules. This adsorptive power is due partly to the chemical nature of the carbon atom with its attendant free valences and partly to the capillary structure of the charcoal which presents an enormous adsorbing surface...."

The use of charcoal in water treatment is not new. Its history has been traced back almost 4,000 years at which time the Ousruta Sanghita instructed: "It is good to keep water in copper vessels, to expose it to sunlight, and filter through charcoal" (3).

There is a great difference between the aforementioned charcoal and the activated carbons available today. However, the reasons for using either are the same.

In 1883, twenty-two water plants in the United States were using charcoal filters for taste-and-odor control (4). The activated form of carbon was first manufactured in the United States by the Industrial Chemical Company in 1913. However, it was not until the late 1920's that it was used for water treatment. Within twenty years after its introduction, activated carbon was being used in more than a thousand water plants in this country. Carbon and activated carbon have been used in Germany for dechlorination since 1909 (5).

Manufacture and Uses

The quality of an activated carbon is dependent upon the raw material and the activating process used. Various raw materials have been used. Those used most extensively are wood, wood pulp residue, peat, lignite, and shells of nuts such as almond and cocoanut. Other materials that have been used include blood, bones, fish, petroleum sludge, and rubber waste. The primary step in the activating process involves heating the material to temperatures in the order of 600°C to 900°C. The activating process is improved if a metallic salt, such as zinc chloride or calcium chloride, is mixed with the material before heating, or if the material is exposed to an oxidising gas during the heating process.

The resultant product possesses a high adsorption capacity and has been used successfully in industrial processes. Hassler (6) describes these processes, some of which are the purification of sugars and syrups, the purification of fats and oils, the processing of miscellaneous food products, the production of alcoholic beverages, the purification of air, the recovery of solvents, and the treatment of water supplies. Activated carbons have been divided into three basic groups as follows: 1) gas adsorbents, 2) decolorizing and deodorizing carbons, and 3) metal adsorbents (7). It is usually not possible to develop a carbon with more than one of the above-mentioned properties.

Previous Investigations

A hypothetical explanation of the effect of exposed surface in adsorption has been attempted by Langmuir (8). Assuming an adsorbed layer of one-molecule depth, Langmuir has expressed the rate of adsorption as proportional to the fraction of the surface area of adsorbent not covered and the concentration of the adsorbate. The maximum quantity of adsorbed material is reached when the surface of the adsorbent is saturated with adsorbate.

Problems arise when one attempts to apply the Langmuir theory to a practical situation using activated carbon. The first problem is to determine the surface area available in a given quantity of the adsorbent. The second problem arises from the assumption by Langmuir that the adsorbed layer is one molecule deep. The extent to which additional layers of adsorbate would accumulate is not known. The first layer of adsorbate may be able to attract a second layer which in turn may attract a third layer and so on. Therefore, it was not possible to make use of Langmuir's theory in this study.

The Freundlich equation is an empirical formulation of the factors involved in the action of adsorption (9). The equation is

$$\frac{x}{m} = kc^n \qquad (1)$$

where, x is the amount adsorbed, m is the mass of adsorbent, c is the concentration remaining unadsorbed when equilibrium is reached, and k and n are constants determined by experiment and depending on the units used.

This equation is based on allowing sufficient contact time for equilibrium to occur between the adsorbent and the adsorbate. The Freundlich equation is not readily applied to this dechlorination study because of the short contact times involved.

In 1929, Pick (5) reported the results of his study on the dechlorination of drinking water by activated carbon. He studied the effect of filter depth, d, rate of flow of chlorinated water per unit area of filter, v, and chlorine concentration in the filter influent, C_a, on the percentage of chlorine removed by the filter. The tests showed that at a given v and d the percentage of chlorine removed was independent of the initial chlorine concentration. The plotted data were formulated as

$$\log \frac{C_a}{C} = kd \qquad (2)$$

where, C is the chlorine concentration in the effluent, k is a constant depending on the quality of the activated carbon and on the units used, and C_a and d are as defined above.

Pick also observed that when the velocity of filtration was changed by some factor, the depth of filter, to maintain the same percentage of chlorine reduction, was changed by the square root of that same factor. This information, together with Equation 2, was used by Pick to derive an expression for the depth of filter needed to give a desired reduction of chlorine concentration. This depth, d_1, was given as

$$d_1 = \frac{d_2 \sqrt{v}}{0.301} \log \frac{C_a}{C} \qquad (3)$$

where d_2 is the depth of filter needed to reduce the chlorine concentration to one-half its initial value when the filter is operated at a rate of

one cubic centimeter of water per square centimeter of filter area. The other terms are as defined above.

A loss of effectiveness of the activated carbon to remove chlorine was observed by Pick at various towns in Germany. The per cent of chlorine removed was observed to decrease from 85 per cent to 40 per cent over a period of 7 to 35 days, depending on the activated carbon used. The rate of decrease was irregular and no doubt was due to the varied quality of the water being dechlorinated.

No decrease in dechlorinating capacity was observed on a seventy-two hour test with activated carbon at the Engineer Research and Development Laboratory (ERDL) (10). However, in these tests the rate of flow of chlorinated water through the filters decreased throughout the runs.

A similar report from the ERDL (11) covered the results of a series of experiments to determine the effect of pH, chlorine concentration applied, and changes of filtration rates on the dechlorination of water with activated carbon. It was reported that of the factors studied, the rate of filtration had the most pronounced effect on the capacity of a given quantity of carbon. However, the report continues, "It is believed that the dechlorinating capacity of any carbon is more a function of the total quantity of carbon in the filter than its filter area". Powdered activated carbon gave better results than granular carbon.

A further conclusion was that as the chlorine concentration in the influent was increased, there was a gradual decrease in the percentage of chlorine removed. The belief was expressed that as the influent chlo-

rine concentration continued to increase, a maximum quantity of chlorine removed per unit weight of carbon would be reached. This would seem to be at variance with the conclusions of Pick, but here the chlorine concentrations studied approached 40 mg/l while Pick's studies were limited to chlorine concentrations of 10 mg/l in the applied water.

There have been numerous reports concerning the effectiveness of activated carbon when used to control tastes and odors in municipal water supplies. These reports have dealt with the overall problem of taste-and-odor control and have not dealt with any one phase such as chlorine removal. The experiments done by Pick and by ERDL have been of short duration and have not been concerned with the service life of activated carbon filters.

Comparison Tests

The material used in the dechlorination study consists essentially of Standard Black, an activated carbon produced by the West Virginia Pulp and Paper Co. from wood pulp. To this basic material, the manufacturer of the filter unit, Everpure, Inc., adds other materials to aid in the proper mechanical functioning of the unit. The unit is described in the following section on equipment and analytical procedure.

There is no standard test by which the quality of an activated carbon can be determined. A carbon which adsorbs one material readily may be worthless for adsorbing another material. Two carbons which adsorb a given adsorbate with similar results, may give dissimilar results when used on a second adsorbate.

With these facts in mind, a number of different tests were run in an attempt to describe the filter material used. The tests were run on a number of activated carbons to show a comparison of the characteristics of the filter material used in the service-time tests and other activated carbons that may be available for water treatment.

The tests run include per cent moisture, apparent density, fineness, phenol adsorption and gas adsorption. All tests, except gas adsorption, were performed in accordance with standard specifications as reported in the Journal American Water Works Association (12). The gas adsorption test was devised for this study in the hopes of further defining the quality of the activated carbon used. A brief description of each test follows.

For the per cent moisture test, a sample of the carbon was accurately weighed as received, dried for at least four hours in an oven at 140°C, cooled in a dessicator, and reweighed.

For the apparent-density test, a 10-gram sample of each carbon was weighed as received and transferred to a 100-ml graduated cylinder. The base of the cylinder was then tapped on a rubber pad until no settling of the carbon could be observed. The apparent density was reported as the weight in pounds of one cubic foot of the carbon in air.

Samples which had been dried at 140°C were used for the fineness test. The wet-screen method was then used to determine the percentage of carbon retained on 100-mesh and 200-mesh screens. Though recommended in the specifications, a 325-mesh screen was not available. In the wet-screen method the carbon sample and the screens were

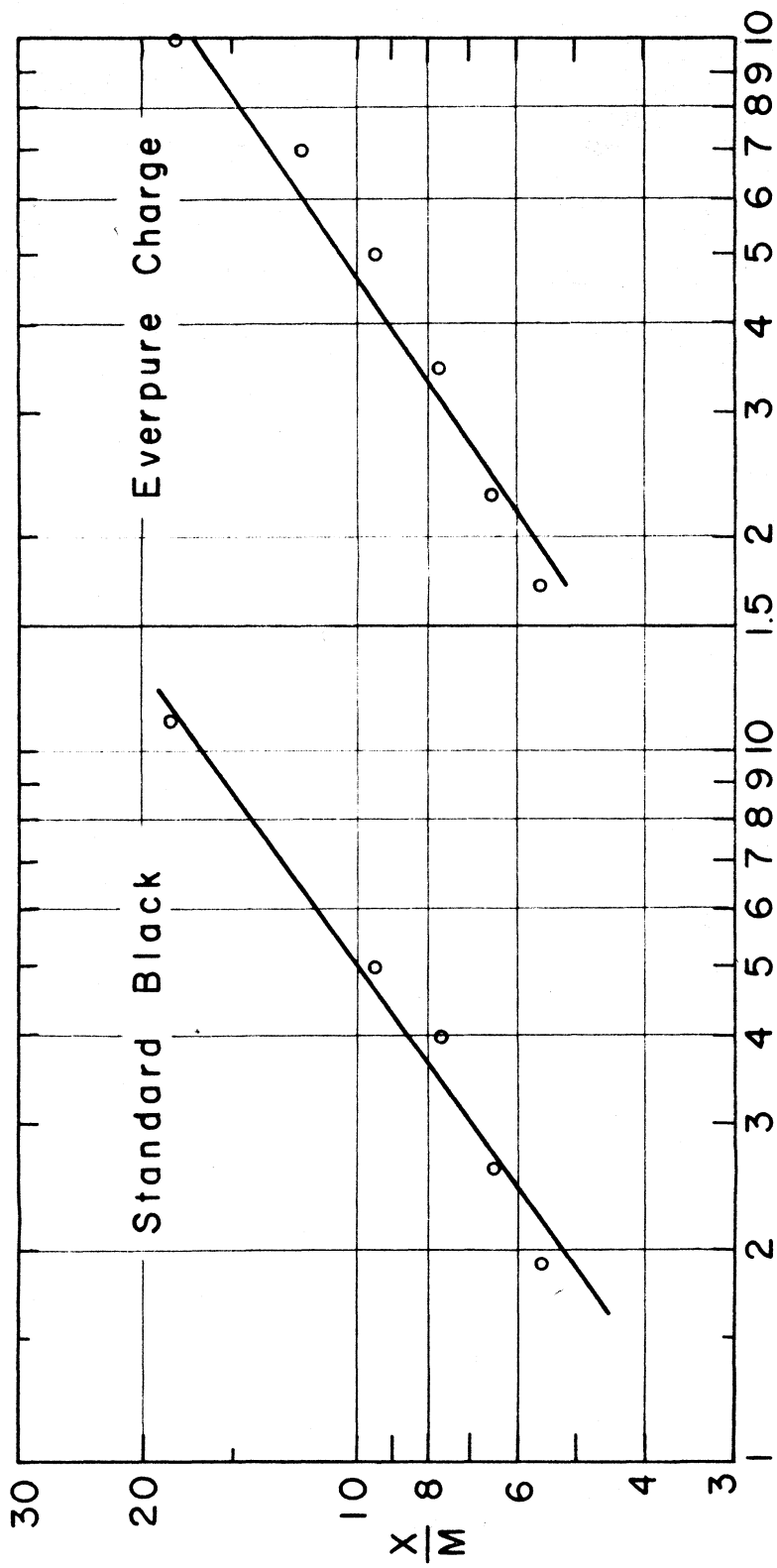
wet thoroughly. A small stream of water was used to wash the finer carbon particles through the screens. The carbon not passing through each screen was dried and weighed. Fineness was then reported as the percentage of the sample passing each screen.

The phenol-adsorption test consisted of adding varying quantities of the activated carbon to a series of samples of aqueous solutions containing a known concentration of phenol (C_6H_5OH). The resultant mixture was then stirred mechanically for one hour. The carbon was removed by filtration in a properly prepared Buchner funnel. One-hundred-milliliter Nessler tubes were then made up from the different samples and the proper colorimetric indicator solutions were added. The color developed in each Nessler tube was compared with the standards to determine the percentage of phenol removed by the various quantities of carbon. Figure 1 was used to calculate the phenol value. In Figure 1, the total ppb of phenol removed per unit weight of carbon, $\frac{x}{m}$, was plotted against the per cent of original phenol remaining. The phenol value was obtained by dividing the per cent of phenol removed by the per cent of phenol removed per unit weight of carbon when, the per cent of phenol remaining is equal to ten. The result is the quantity of carbon required to remove ninety per cent of the phenol. Because of the laborious nature of this test, the phenol value was determined only for the Everpure charge and for Standard Black, the principal component of the Everpure charge.

The gas-adsorption test was devised to indicate the relative ability of the different activated carbons to adsorb nitrogen, or oxygen. The

Figure 1. Phenol-adsorption curves

(Per cent of original phenol remaining versus $\frac{x}{m}$, where, x is the total parts per billion of phenol removed and m is the unit weight of carbon.)

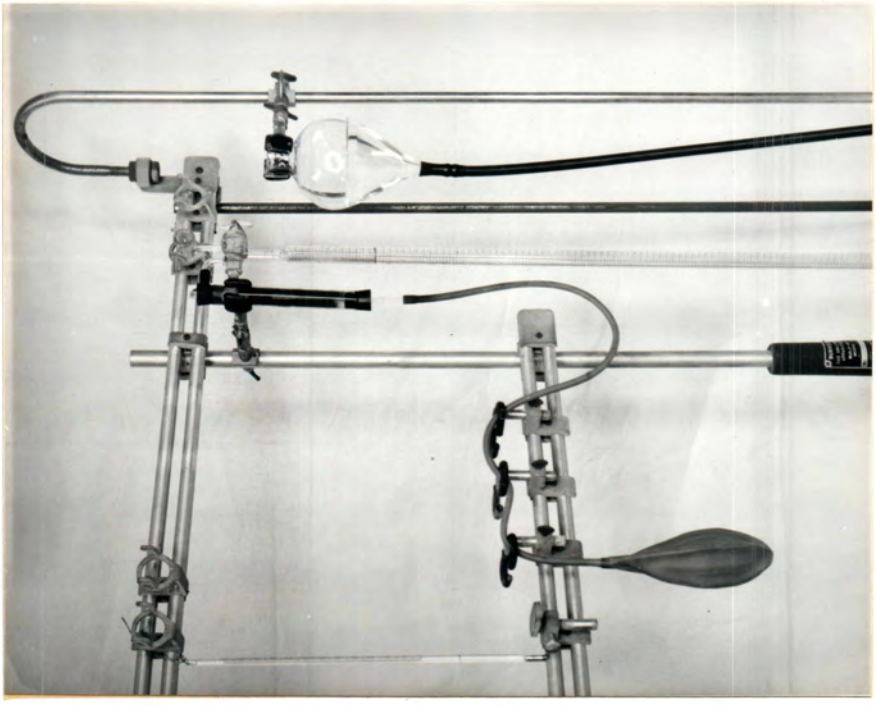

Everpure Charge
Standard Black
X/M
30
20
10
8
6
4
3
1
2
3
4
5
6
7
8
9
10
1.5
Percent of Original Phenol Remaining

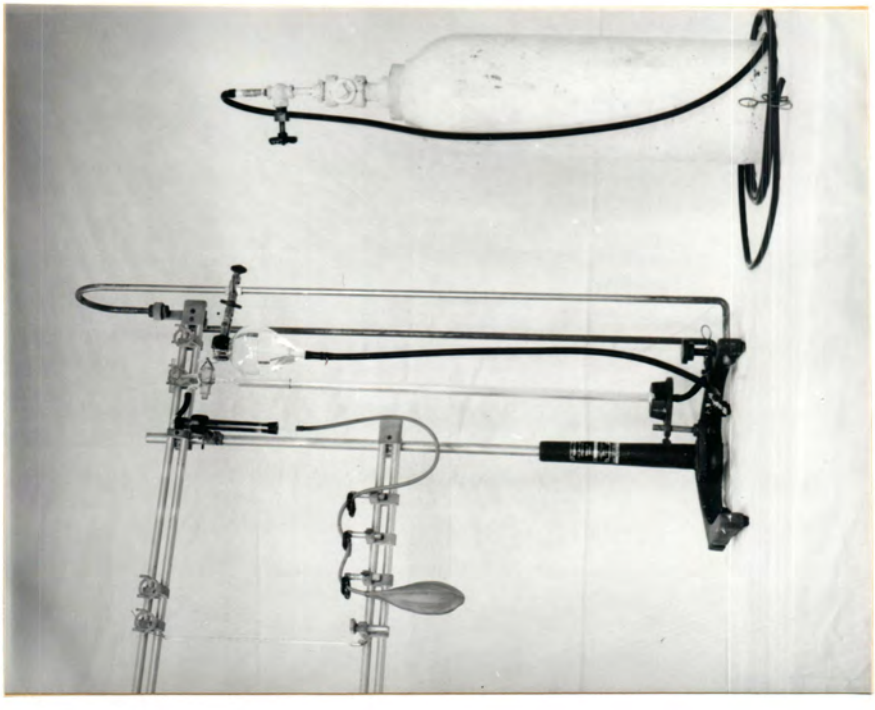
apparatus was set up as indicated in Figure 2. It consisted of a gas-supply cylinder, 100-ml gas burette, leveling bulb, concentrated solution of sodium sulphate, an activated carbon container, a receiving balloon, and rubber tubing, glass tubing, rubber stoppers and pinch clamps.

Approximately 100-mls of the gas were admitted to the gas burette, displacing the sodium sulphate solution. The level of the solution in the leveling bulb was then made equal to that of the solution in the burette. This made the pressure within the burette equal to atmospheric pressure. The elevation of the liquid surface in the burette was recorded. The leveling bulb was then raised putting a slight pressure in the burette. The stopcock was then turned admitting the gas through the activated carbon container and into the receiving-balloon. The gas continued to flow for ten minutes at which time the liquid level was within 10 to 15 mls of the top of the burette.

At this time the leveling bulb was lowered and the gas flowed back out of the receiving balloon, through the activated carbon, and into the gas burette. Again, ten minutes were needed to allow the liquid level to return to within 10 to 15 mls of the bottom of the burette. This entire process was completed four times for each test, for a total of eight passes of the gas through the activated carbon. The level of the solution in the leveling bulb was again made equal to that of the solution in the burette and a final reading was taken on the gas burette. The difference between this reading and the original reading was recorded as the quantity of gas adsorbed by the activated carbon. Two gases, nitrogen and oxygen, were used on each of the carbons tested. Results were re-

Figure 2. Gas adsorption apparatus





ported as milliliters of gas adsorbed per gram of activated carbon used.

The gas adsorption test was tried first on carbon samples that had been heated at 140°C. These samples adsorbed a negligible quantity of gas. Fresh samples were then heated for one hour in the laboratory muffle furnace at 600°C. Samples thus treated adsorbed measurable quantities of gas after they had been cooled to room temperature at about 24°C.

The activated carbon container consisted of a pyrex glass cylinder. The details of this container are indicated in Figure 3. Gas entered the container through the glass tubing inserted in the stopper. Cotton diffusers diffused the gas and prevented the carbon from being blown out of the container.

All test results are shown in Table 1. A description of the different activated carbons is given below.

Everpure charge, the material used in the filter units studied, is primarily composed of Standard Black. Materials added to the Standard Black to produce the Everpure charge include diatomaceous earth and other filter aids and a substance that is said to aid the carbon adhere to the septum. Standard Black, Aqua Nuchar, and C-190-N are activated carbons produced by the West Virginia Pulp and Paper Company for use in the water treatment industry. They are made from wood pulp. The Barnebey-Cheney Company produces B-C Black from cocoanut shells. CXAC was an experimental carbon produced from a petroleum base by the National Carbon Company.

Figure 3. Activated carbon container for gas adsorption

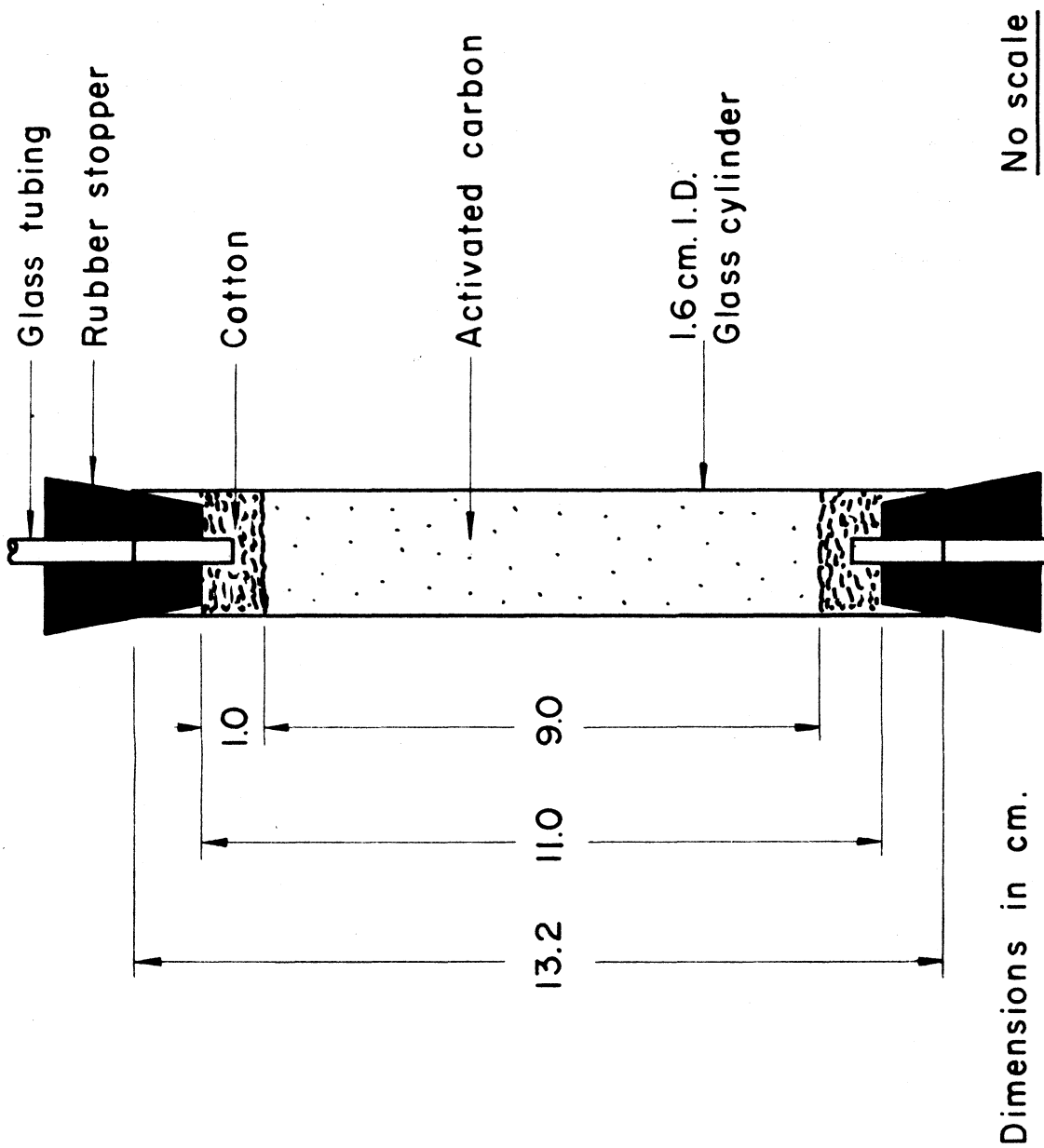

Glass tubing
Rubber stopper
Cotton
Activated carbon
1.6 cm. I.D.
Glass cylinder
No scale
1.0
9.0
11.0
13.2
Dimensions in cm.

Table 1. Comparison test results

Activated carbon	Per cent moisture	Apparent density, lb/ft^3	Fineness, % Passing 100	Fineness, % Passing 200	Phenol value	Gas Adsorption N_2 ml/g	Gas Adsorption O_2 ml/g
Everpure Charge	1.9	23.3	91.9	74.8	5.4	1.1	2.8
Standard Black	1.9	17.7	98.5	87.4	5.5	2.4	0.5
Aqua Nuchar	4.3	22.8	99.4	97.6	-	2.4	0.5
B-C Black	1.9	31.2	98.4	74.7	-	0.8	1.6
C-190-N	2.2	16.1	92.1	72.0	-	0.9	0.9
CXAC	1.2	28.4	98.5	74.8	-	1.1	1.4

EQUIPMENT AND ANALYTICAL PROCEDURES

The Superchlorination-Dechlorination System

The pilot plant shown in Figures 4 and 5 was set up in the laboratory to simulate a typical field installation for superchlorination-dechlorination of a small water supply.

Principal components of the laboratory installation were as follows:

1. an activated carbon prefilter for dechlorinating the university tap water;
2. an open supply tank used to simulate a pond water supply;
3. a pump and a pressure tank to supply water under pressure;
4. an automatic chlorinating device to supply a chlorine solution to the raw water;
5. a water storage tank used to provide contact time between the chlorine and the water;
6. a faucet for securing samples of the chlorinated water;
7. a meter to indicate the rate of flow through the system;
8. an activated carbon precoat filter (the filter to be tested) for dechlorinating the water;
9. a device to provide repitition of a given cycle, called a cycle repeater, and a solenoid-operated shut-off valve to provide intermittent operation.

The prefilter was needed to remove all residual chlorine from the university tap water. This residual varied from 0.0 to about 0.7 mg/l.

Figure 4. Pilot plant for superchlorination—dechlorination tests

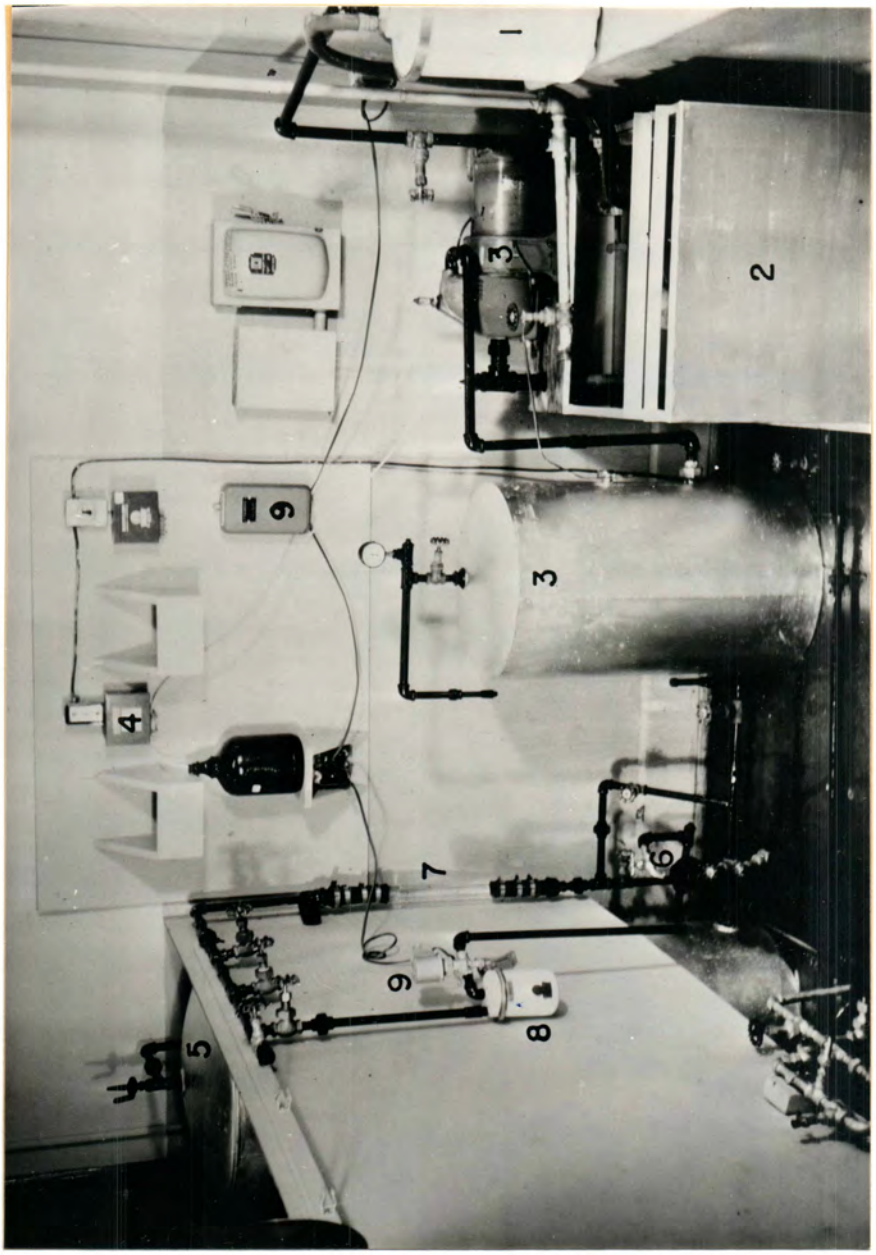
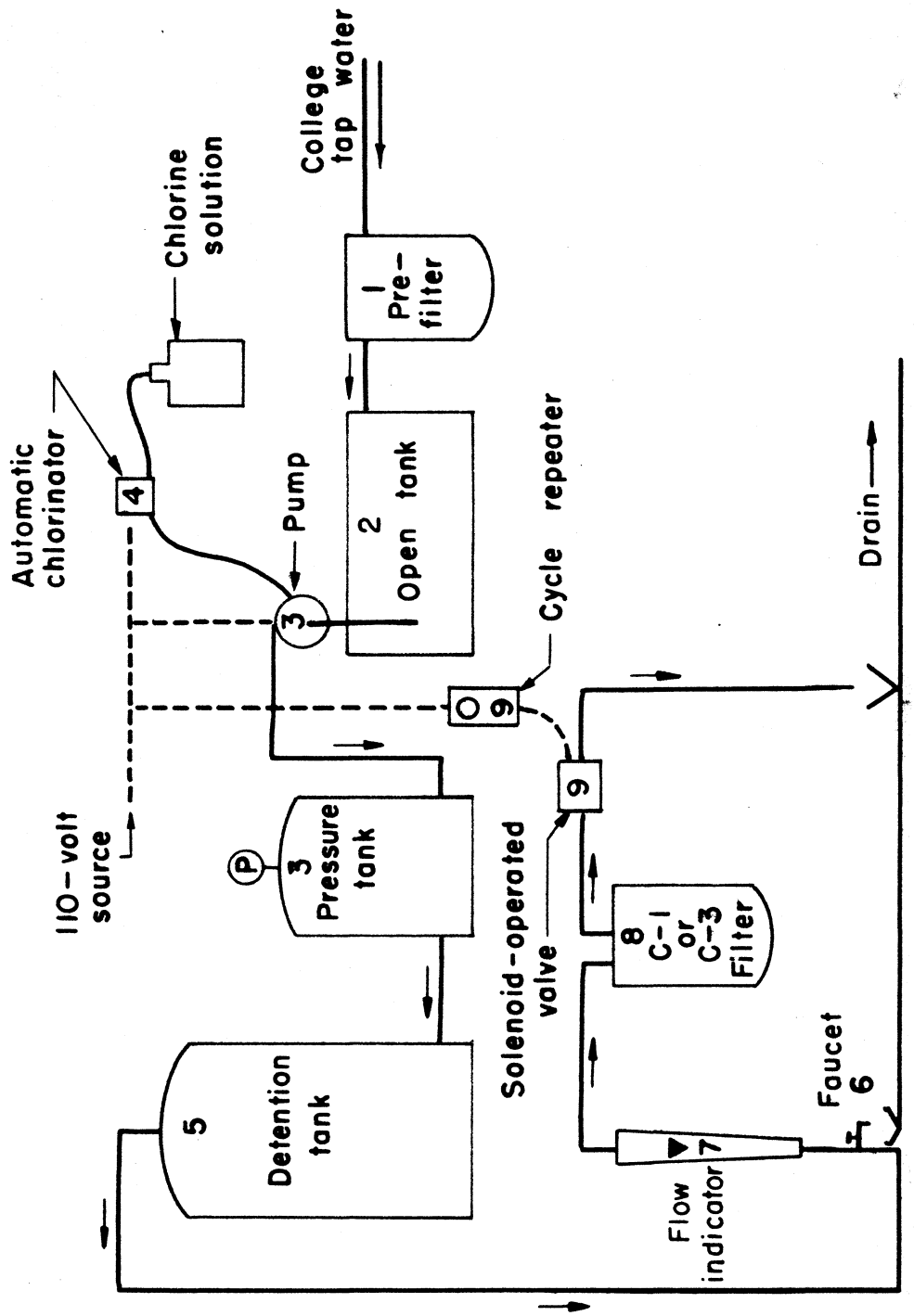

1
2
3
4
5
6
7
8
9

Figure 5. Flow-through diagram of superchlorination-dechlorination pilot plant


College tap water
Chlorine solution
1 Pre-filter
Automatic chlorinator
4
Pump
2 Open tank
3
Cycle repeater
9
Drain
110-volt source
P
3 Pressure tank
9
Solenoid-operated valve
8 C-1 or C-3 Filter
5 Detention tank
Faucet 6
Flow indicator 7

When dechlorinated, the university tap water flowed into the open supply tank which was 36 in. wide, 27 in. long, and 21 in. deep.

A one-half-horsepower Myers Ejecto centrifugal pump was used to pump water into the pressure system from the supply tank. The pump operated intermittently on a pressure control system supplying water to a 48-gallon pressure tank which was 21 in. in diameter and 32 in. high. The air pressure in the tank controlled the operation of the pump automatically. When the pressure in the tank was reduced to 35 psi, the pump was turned on and operated until a pressure of 53 psi was developed. The tank contained about 36 gallons of water at maximum pressure. Most of the tests were conducted at a flow of 1.0 gpm. The instantaneous flow varied between 1.1 gpm at maximum pressure and 0.9 gpm at minimum pressure. For the 1.2-gpm tests, the flow varied between 1.3 gpm and 1.1 gpm. Because of head losses in this system, the pump was unable to deliver a higher rate of flow than 1.3 gpm.

An Everclor chlorinator was used to introduce chlorine solution intermittently into the suction side of the pump. The operating details of the Everclor unit were described by Varma and Baumann (1). One end of the plastic tube, shown in Figures 5 and 6, was inserted into the chlorine bottle and the other end was connected to the suction side of the pump. During the pump operation, reduced pressure on the suction side of the pump caused the chlorine to flow from the chlorine-supply bottle during each Everclor dosing cycle. The Everclor chlorinator was wired directly to the pump and operated only when the pump was in operation. The Everclor's two notched disks rotated on a clock-timer device

which made a complete revolution once a minute when the pump was operating. A switch arm dropped into each notch periodically and energized a solenoid which lifted a plunger. The plunger was used to control the flow through a short section of gum rubber or composition tubing in the feed line. The solenoid was used to open the plunger tube and permit the flow of chlorine solution.

The length of the dose was adjusted by changing the length of the notch between the discs. The longer the notch, the greater the length of time the plunger was lifted. To prevent back flow of water through the chlorine-supply line into the chlorine bottle when the pump was not operating, a check valve was located at the point where the chlorine solution entered the suction side of the pump.

The amount of chlorine fed was controlled either by varying the length of dose or by varying the strength of the chlorine solution. When the chlorine concentration in the supply bottle was 5.2 per cent (Clorox), the length of dose used was 3 seconds. Two such doses were injected per minute of pump operation.

To maintain a greater uniformity of chlorine concentration within the system, it was necessary to increase the number of notches in the rotating disk to four, to increase the length of each notch, and to decrease the chlorine concentration in the supply bottle to about 0.60 per cent.

A 120-gallon cylindrical tank was used as a reaction and detention-time tank to aid in maintaining a uniform chlorine concentration in the system. A faucet was installed for sampling the chlorinated water.

Visual control of the rate of flow was maintained with a Fisher and Porter flowrater. The flowrater could indicate flows between 0.0 gpm and 6.7 gpm.

Everpure, a carbon precoat filter, Model C-3 or C-1, was installed in the line between the flowrater and the solenoid-operated shut-off valve. The filter unit is described in a subsequent section. The shut-off valve was normally closed. When an electric current was applied to a solenoid, the valve opened to permit the flow of water from the system. When the electric current was cut off, the valve resumed the closed position and the flow of water stopped. Timing of the on-off operation was controlled by a Paragon cycle repeater. The cycle repeater is illustrated in Figure 6. As the graduated face of the timepiece rotated counterclockwise, pins inserted in the holes around the periphery of the face operated an on-off switch, and thus permitted an intermittent flow of electric current to the shut-off valve described above.

Three-quarter-inch pipe was used between the tap-water line and the pressure tank. One-half-inch pipe was used throughout the rest of the system.

The Activated Carbon Filter

The filter unit used in this dechlorination study was the Everpure activated carbon filter. The Everpure is a carbon, precoat filter composed of an outer shell within which a replaceable cartridge is housed. The filter housing was indicated by the number 8 in Figure 4.

The replaceable cartridge consists of five main components as

Figure 6 Cycle repeater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follows:

1) a cylindrical brass container;

2) an inlet tube;

3) the Everpure charge;

4) a filter septum;

5) an outlet tube.

These components are illustrated in Figure 7.

The brass container was a sealed unit except for openings for the inlet tube and the outlet tube. The outlet-tube opening was located at the center of the top of the can. The inlet-tube opening was located near the periphery of the top of the can. The outlet of the inlet tube was located near the bottom of the can. The inlet tube and the outlet tube were made of plastic. As water left the inlet tube it came into contact with the Everpure charge which had been placed at the bottom of the container. The water mixed with the carbon and the resultant suspension of carbon in water was deposited on the septum.

The septum was a fabric envelope, folded to provide a large surface area in a small container. The water passed through one of the two layers of the septum shown in Figure 7. The two layers were separated by the inert spacer shown also in Figure 7. The spacer maintained a minimum clearance between the two layers of the septum and permitted the filtered water to flow through the channel thus created, to the effluent tube. The effluent tube was threaded so that it could be screwed into the top of the filter housing.

A minimum flow of 1.5 gpm was maintained for 5.0 minutes after

Figure 7. Components of the Everpure replaceable cartridge

the filter unit was installed. This break-in period provided adequate distribution of the carbon charge on the septum. The precoated septum is shown in Figure 8.

Two replaceable cartridges were used in this study, the C-3 and the C-1. Each cartridge had a diameter of 3.9 in. The C-1 cartridges were 5.5 in. high. The C-3 cartridges were 12.7 in. high.

The septum in each C-1 cartridge was 4.1 in. long by 17.8 in. wide. That portion of each septum where the outlet tube was connected to the septum, was not available for filtration. This gave a net filter area of closely 1.00 square foot.

Two septum sizes were used in the C-3 cartridges. The regular size was 10.2 in. long by 18.4 in. wide, and had a net area of 2.60 square feet. A special septum made for this study, was 5.1 in. long by 8.8 in. wide, and had a net area of 0.58 square foot.

The quantity of carbon used in each filter was different for each run.

Determination of Chlorine Concentration

Three different ranges of chlorine concentration were used in this study. It was necessary to have a relatively high chlorine concentration (0.6 per cent) in the chlorine supply bottle. A lower chlorine concentration (5.0 mg/l) was maintained in the pressure system. A still lower concentration (up to 0.3 mg/l) was observed in the filter effluent. Laboratory experience indicated that it was desirable to use a different method for determining each range of chlorine concentration.

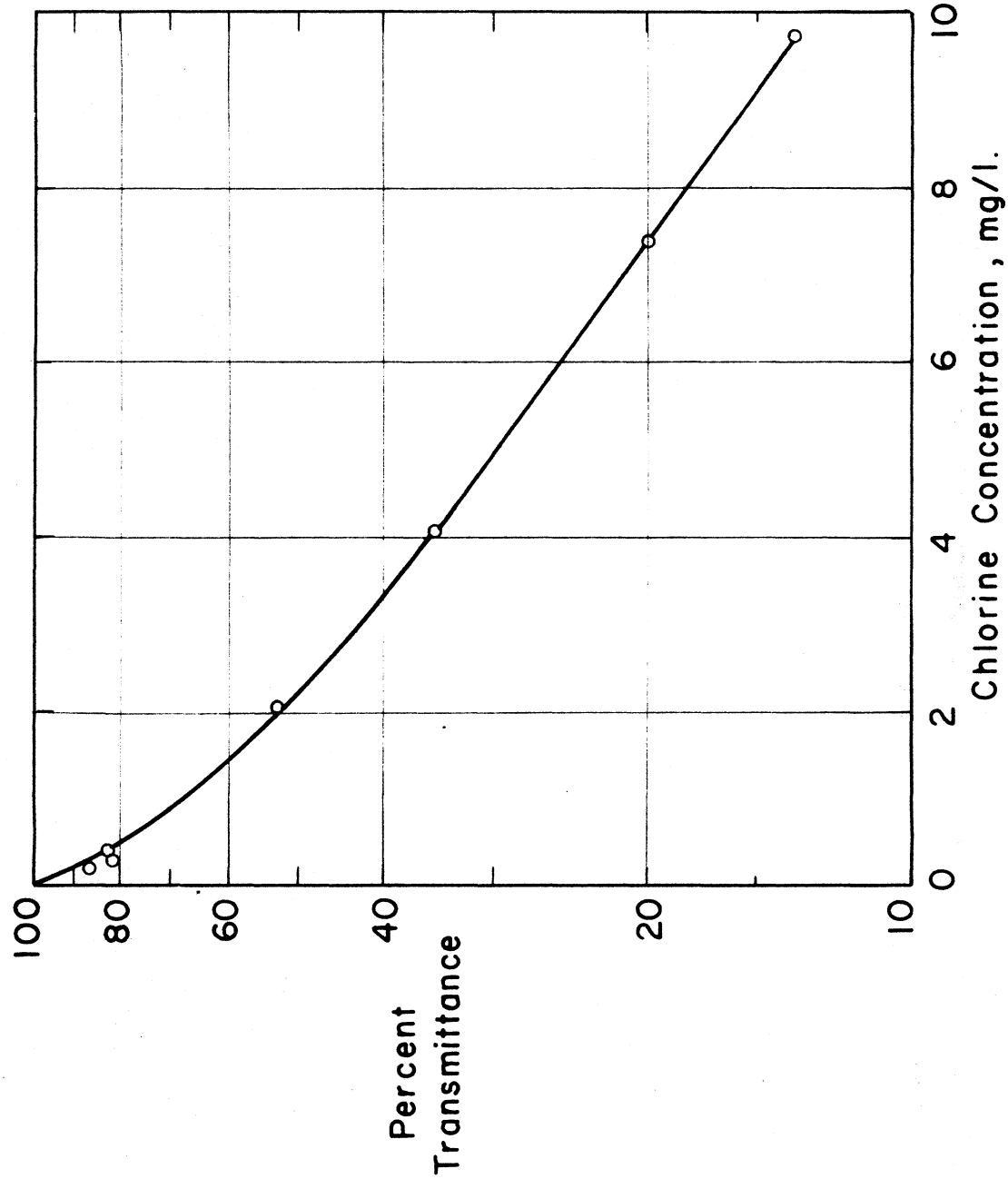
Figure 8. Precoated septum

The iodometric method (13) was used to determine chlorine concentrations in the supply bottle. The iodometric method for chlorine determination could have been used to determine the concentration of chlorine in the pressure system. However, the relatively large samples needed to give reproducible results made this method undesirable for routine tests. Therefore, a Bausch and Lomb Spectronic 20 Colorimeter was used for chlorine determinations at the 5.0-mg/l level.

The colorimeter was calibrated at the 490-millimicron wave length. The calibration was accomplished as described below. The colorimeter was used to measure the intensity of the color developed from the addition of 0.5 ml of standard orthotolidine solution to 10.0-ml samples containing various concentrations of chlorine. Samples of like concentrations were titrated by the iodometric method to determine the chlorine concentrations. Color intensities, expressed in terms of per cent transmittance, were plotted against chlorine concentrations, expressed in milligrams per liter, as shown in Figure 9. With the colorimeter thus calibrated, it was possible to determine the chlorine concentration of a sample by adding orthotolidine to the sample and measuring the per cent transmittance as indicated by the colorimeter.

The calibration curve indicates some inaccuracy in the observations below chlorine concentrations of about 1.0 mg/l. The inaccuracy of the colorimeter at low concentrations suggested that a third method be used at this level. Modified Scott permanent chlorine standards were prepared in 50.0-ml Nessler tubes (13). Standards were prepared to give very nearly the same colors as would be produced by the addition of

Figure 9. Calibration curve for chlorine determination by Bausch and Lomb Spectronic 20 colorimeter at a wave length of 490 millimicrons


100
80
60
40
20
10
Percent
Transmittance
0
2
4
6
8
10
Chlorine Concentration, mg/l.

orthotolidine solution to chlorine concentrations of 0.0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.50 mg/l.

Determination of Activated Carbon Quantity

As stated in the section on the activated carbon filter, the filter units were enclosed in a sealed brass cylinder. The carbon charge had been placed in the cylinder at the factory. The exact quantity of carbon could not be determined without cutting the cylinder open and hence destroying the filter unit. It was necessary to conduct the test on the filter unit and then determine the quantity of charge used.

When a test was terminated, the unit was removed from the system. The cylinder was cut open and the septum removed. The activated carbon layer was scraped off the septum and placed in a weighing vessel. The scraped septum was then placed in a container and, with the aid of hot water and a brush, the remaining activated carbon was removed. When all significant amounts of carbon were removed from the septum, the carbon suspension, now in the container, was filtered on a double thickness of Whatmann No. 12 filter paper.

The carbon reclaimed on the filter paper was added to the scrapings in the weighing vessel. The vessel was placed overnight in a drying oven at 140°C. The dried carbon and the weighing vessel were weighed and the tare weight of the weighing vessel and filter paper were subtracted from the total weight to give the weight of the activated carbon used in the filter unit.

FILTER SERVICE-LIFE TESTS

Preliminary Run

The first phase of the testing program was devoted to a long-term preliminary run. This preliminary run was designed to determine the capabilities of the superchlorination-dechlorination system. Except for a few brief breakdowns, the system was operated continuously for three weeks. During this time certain modifications were made in the system. Characteristics of the filter performance were also noted.

The first problem encountered was in maintaining a constant flow rate through the system. It was originally planned to include a Trident water meter in the system as a check on the total quantity of water treated. A Halsey-Taylor flow regulator was also included to maintain a constant flow through the filter. It was soon apparent that the pump could not deliver an adequate flow with the flow regulator and the water meter included in the system. When these two devices were removed, an adequate flow could be maintained.

The second problem consisted of maintaining a chlorine concentration of 5.0 mg/l in the system. A cut-and-try method was used. A solution of sodium hypochlorite was inserted in the chlorine supply bottle. The system was then operated at 1.0 gpm until sampling indicated that equilibrium was achieved. The chlorine concentration in the supply bottle was increased if the chlorine concentration in the system was less than 5.0 mg/l. The reverse was done if the chlorine concentration in the system exceeded 5.0 mg/l. This procedure was continued until the

system could be maintained at the desired chlorine concentration.

During the course of the subsequent tests, the connection between the chlorine-supply line and the suction side of the pump became loosened. The pump sucked air into the system along with the chlorine solution. As a result, less chlorine was used and the 5.0 mg/l was not maintained. The test had to be terminated. When a new supply line was installed and the connection repaired, the system reached an equilibrium concentration other than 5.0 mg/l. This different concentration was probably due to the new supply line having a different inside diameter than the original supply line. The cut-and-try process previously described was repeated until 5.0 mg/l of chlorine could be maintained in the system.

Other factors affecting the chlorine concentration in the system were temperature and chlorine demand of the water. During the course of the tests, the temperature of the water remained near 60°F. Any marked variation from this temperature was accompanied by a change in the chlorine concentration. After the system had been idle for a time, such as overnight, it was necessary to operate the system for about five hours before the temperature and chlorine concentration would return to the desired levels.

As stated previously, a carbon prefilter was used to dechlorinate the tap water before it was admitted into the supply tank. The relatively small variations in chlorine residual noted in the system indicated that this dechlorinated water had little or no chlorine demand. One exception was noted. After installing a fresh unit in the prefilter, the

chlorine concentration in the system decreased to less than 3.0 mg/l. Attempts to adjust the chlorine concentration by the cut-and-try method failed. It was believed that carbon was passing through the prefilter and entering the system. The difficulty was eliminated by installing a new filter unit in the prefilter.

The preliminary run also indicated characteristics of the activated carbon filters to be tested. At a flow of 1.0 gpm and a chlorine concentration of 5.0 mg/l, there was ample carbon in the Everpure charge to remove all of the chlorine from the water. When chlorine appeared in the filter effluent, the rate of increase in the effluent appeared to be proportional to the logarithm of the quantity of water treated. It was noted, also, that improved reduction of chlorine resulted after the flow had been interrupted. That is, following a rest period, the activated carbon gave better chlorine removal than before the rest period.

Intermittent Operation

This study was intended to determine the service life of carbon filters when subjected to the type of operation existing in farm water supplies. To approach the conditions existing in these small water supplies, an intermittent type of operation was necessary. Also, the preliminary test indicated that an improved removal resulted when the flow was intermittent. Therefore, it was decided to conduct the filter tests on an intermittently operated system.

The operating pattern of the use of water for domestic purposes is extremely erratic. On periods vary from a few seconds to a few min-

utes. Off periods may be as long as four or five hours. Tests conducted on such an erratic flow pattern would give neither reproducible results for similar filters nor comparable results for dissimilar filters. A repeating cycle was therefore needed in the laboratory tests.

Data on the average ratio of the length of the off period to the length of the on period are not available. It was decided to use a cycle of operation that would exert more strain on the filter in a test than would be exerted on the filter in a household. It could then be assumed that a filter unit used in a household would give results equal to or better than a similar unit tested in the laboratory.

The cycle used in the laboratory consisted of a 2.0-minute on period followed by a 4.0-minute off period. This cycle was adhered to in all but one of the service-life tests. The final test was operated on a cycle of 4.0 minutes on and 2.0 minutes off. The final test was conducted to see if the pattern used affected the service time of a filter.

Effluent Chlorine Concentrations

No standard chlorine concentration has been established. Different persons find different concentrations of chlorine objectionable. The objectionable concentration varies upward from a trace of chlorine. Municipal water systems are generally operated to maintain a maximum chlorine concentration of about 0.20 mg/l (14).

The effluent chlorine concentration at which the filter would be replaced by the consumer depends on the concentration the consumer considers undesirable. Since the allowable chlorine concentration in

the effluent varies among consumers, different levels of effluent concentrations were considered in this study. These concentrations were 0.05, 0.10, 0.20, and 0.30 mg/l of chlorine.

Test Procedure

To prepare the system for a test, it was necessary to operate the equipment for a period of time long enough to allow the water temperature and chlorine concentration to come to equilibrium. Generally, a period of one or two days was required.

When the desired chlorine concentration was attained in the system, a fresh filter unit was installed in the filter housing. Water was admitted to the filter unit at a slow rate until the filter unit was filled and water flowed from the outlet pipe. The time was noted and the flow was increased to 1.5 gpm for 5.0 minutes. This break-in flow, recommended by the manufacturer, was continuous. The activated carbon was precoated on the septum during the break-in procedures. After 5.0 minutes, the flow was reduced to the desired rate, 1.0 or 1.2 gpm, and the intermittent cycle was begun.

During the course of the run, the chlorine concentration in the system was maintained as close to 5.0 mg/l as possible. The maximum variation from 5.0 mg/l that was tolerated before a test was abandoned was 0.3 mg/l. That is, when the chlorine concentration in the system was greater than 5.3 mg/l or less than 4.7 mg/l, the run was not accepted. These limits were established because it was thought that more stringent limits would have prevented the completion of an

adequate number of tests.

Fresh chlorine solution was prepared and standardized iodometrically as needed to replenish the chlorine-supply bottle throughout the run. The chlorine concentration in the system was measured with the colorimeter every four hours. The chlorine concentration in the filter effluent was measured by comparison with the Scott Standards at various time intervals depending on the filter being tested and the stage of the run. Chlorine measurements were made most frequently between the time of appearance of chlorine in the effluent and the time when the effluent concentration reached about 1.5 mg/l. Thereafter, the concentration in the effluent increased slowly so fewer samples were taken.

The temperature of the water and the pH of the water were also measured and recorded. These quantities varied only slightly during the tests. Measurements of pH were made by a Beckman pH meter. The pH of the water in all stages of chlorination and dechlorination remained at 7.7.

Test Results

The results of tests on eight filter units were plotted as shown in Figures 10 and 11. In these figures, the concentration of chlorine in the filter effluent, E, in mg/l, was plotted against the time, T, in hours, required to reach that chlorine concentration. T, the service life, included only that amount of time during which water flowed through the filter. The time during which the flow was interrupted was not included in the service life.

Figure 10. Filter service-life curves 1, 3, and 7

(Concentration of chlorine in the filter effluent, E, in mg/l, versus service life, T, in hours.)

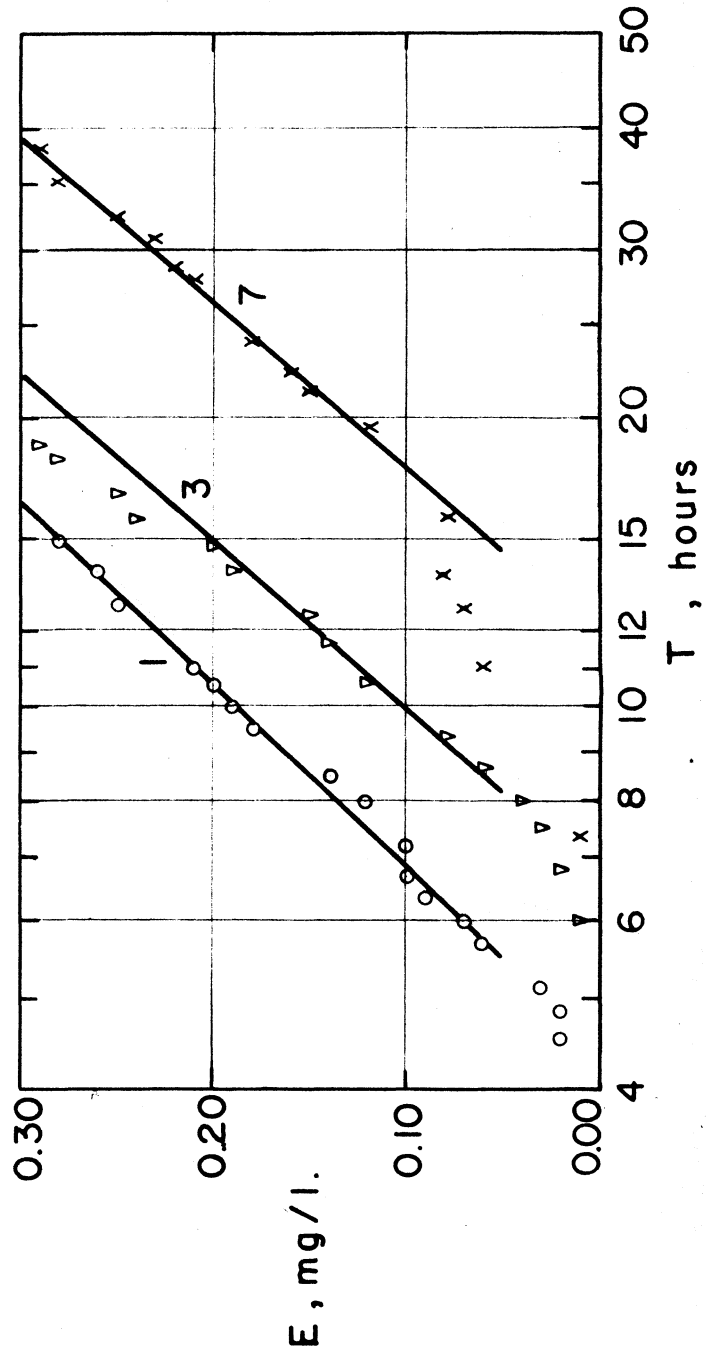

0.30
0.20
0.10
0.00
E, mg/l.
4
6
8
10
12
15
20
30
40
50
T, hours
1
3
7

Figure 11. Filter service-life curves 2, 4, 5, 6, and 8

(Concentration of chlorine in the filter effluent, E, in mg/l, versus service life, T, in hours.)

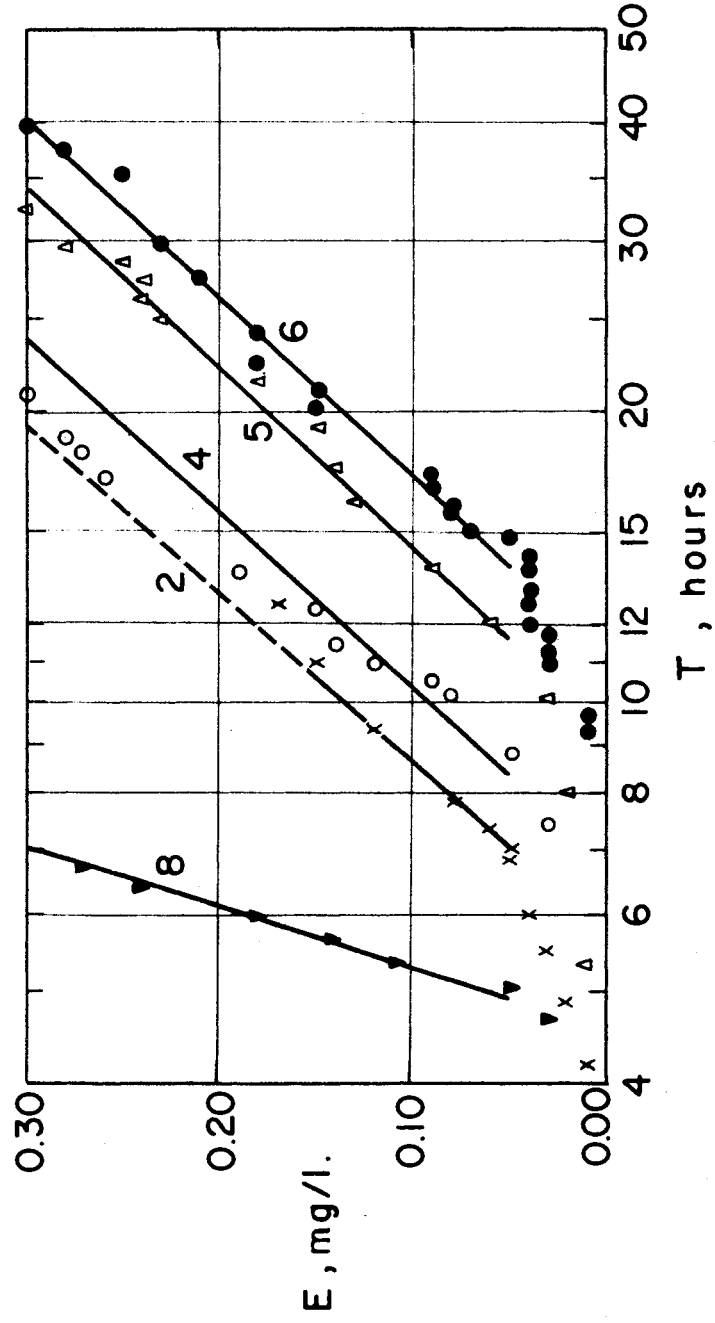

0.30
0.20
0.10
0.00
E, mg/l.
4
6
8
10
12
15
20
30
40
50
T, hours
2
4
5
6
8

Table 2. Test conditions

Test No.	Area, sq. ft.	Flow, gpm.	Carbon, grams	G, grams / gpm.	A, hours
1	0.58	1.0	55.5	55.5	4.5
2	0.58	1.0	62.5	62.5	5.8
3	1.00	1.0	66.5	66.5	6.7
4	1.00	1.0	73.2	73.2	6.8
5	2.60	1.2	122.0	101.7	9.3
6	2.60	1.0	125.0	125.0	11.2
7	2.60	1.0	126.7	126.7	12.0
8	1.00	1.2	78.0	65.0	4.6

pH of raw water 7.7
pH of chlorinated water 7.7
pH of dechlorinated water 7.7
Ave. water temperature 60°F

Tests 1 through 7, represented by Lines 1 through 7 in Figures 10 and 11, were operated on a repeating cycle consisting of a 2.0-minute on period followed by a 4.0-minute off period. Test 8, represented by Line 8 in Figure 11, was operated on a repeating cycle consisting of a 4.0-minute on period followed by a 2.0-minute off period.

A tabulation of the test conditions is given in Table 2. The ratio of grams of carbon to the rate of flow in gpm is given in the second column from the right in Table 2. This ratio has the units of grams divided by gallons per minute, and is indicated by the letter G. The value of T when E equals 0.0 is given in the last column in Table 2. This value, indicated by the letter A, is the intercept obtained by extending the straight lines in Figures 10 and 11.

Tests 1 and 2 were conducted on C-3 cartridges each having a sep-

tum area of 0.58 square foot. The rate of flow through each unit was 1.0 gpm. The cartridge used in Test 1 contained an activated carbon charge of 55.5 grams. The cartridge used in Test 2 contained a charge of 62.5 grams. Test 2 was terminated at 13.0 hours because of inability to maintain an adequate flow.

Tests 3 and 4 were conducted on C-1 cartridges, each having a septum area of 1.00 square foot. The flow rate through each unit was 1.0 gpm. The cartridge in Test 3 contained a charge of 66.5 grams of activated carbon. The cartridge used in Test 4 contained a charge of 73.2 grams.

Test 5 was conducted on a C-3 cartridge with a septum area of 2.60 square feet and a charge of 122.0 grams. The rate of flow during Test 5 was 1.2 gpm.

Tests 6 and 7 were conducted at a flow of 1.0 gpm. The C-3 cartridges used in these tests had a septum area of 2.60 square feet. The cartridge used in Test 6 contained a charge of 125.0 grams. The cartridge used in Test 7 had a charge of 126.7 grams.

Test 8 was conducted on a C-1 cartridge having a septum area of 1.00 square foot and an activated carbon charge of 78.0 grams. The flow rate was 1.2 gpm.

Tests other than the eight described above were started but could not be completed because of operational difficulties.

The straight line which best fits the data for each test was determined by a slight modification of the method of least squares. This method, described more completely by Wallis and Roberts (15), deter-

mines the line such that the mean of the squares of the vertical deviations between each observation and the line will be a minimum. A sample calculation using this method of least squares is included in the Appendix.

The lines in Figures 10 and 11, representing Tests 1, 2, 5, 6, 7, and 8, were determined by the method of least squares. All of the above-described lines, with the exception of Line 8, had nearly the same slope when plotted on the semi-logarithmic paper. The least squares method gave lines of slightly different slope for Tests 3 and 4. However, for presentation in the figures and for further calculations, lines for Tests 3 and 4 were drawn with the same slope as Tests 1, 2, 5, 6, and 7 and in such a manner as to give a reasonable fit for the data.

Experimental Service-Life Equation

The straight line plots of Tests 1 through 7 on semi-logarithmic paper may be represented by the expression

$$T = A\,(10)^{M\,E} \qquad (4)$$

where, T and E are as described above, A is a variable depending on the value of G, and M is a function of the slope of the line. All lines for Tests 1 through 7 have the same slope so M is a constant.

The slope of the lines was measured as 1.1. The length of one logarithmic cycle of the plotting paper is 5.0 inches. The length of one unit on the E scale is 10.0 inches. The value of M is the product of the reciprocal of the slope and the ratio of the two scale factors, and is equal to 1.82. Equation 4 was then written as

$$T = A\,(10)^{1.82E} \qquad (5)$$

Using the values of A and G in Table 2, A was plotted against G to determine the relationship between these two variables. This relationship was plotted in Figure 12. According to the modified method of least squares described by Wallis and Roberts (15), G is given by the expression

$$G = 10.6\,A + 2.1 \qquad (6)$$

which may be written as

$$A = \frac{G-2.1}{10.6} \qquad (7).$$

Equation 5 can then be written as

$$T = \frac{G-2.1}{10.6}\,(10)^{1.82E} \qquad (8)$$

where, T is the service life in hours, G is the ratio of grams of carbon to flow in gpm, and E is the chlorine concentration, in mg/l, in the filter effluent at the time T.

For simplicity, and to be consistent with the accuracy attainable in a study such as this, Equation 8 was rewritten as

$$T = \frac{G-2}{11}\,(10)^{1.8E} \qquad (9)$$

where T, G, and E are as described above and their values are within the range of the values studied.

The accuracy of Equation 9 was checked by assuming values for G and E and solving for T. The calculated value of T was then compared with the value of T indicated in Figures 10 and 11. Table 3 indicates these comparisons.

Figure 12. Relationship between Q, the ratio of grams of carbon to the rate of flow in gallons per minute, and A, the intercepts of the service life curves

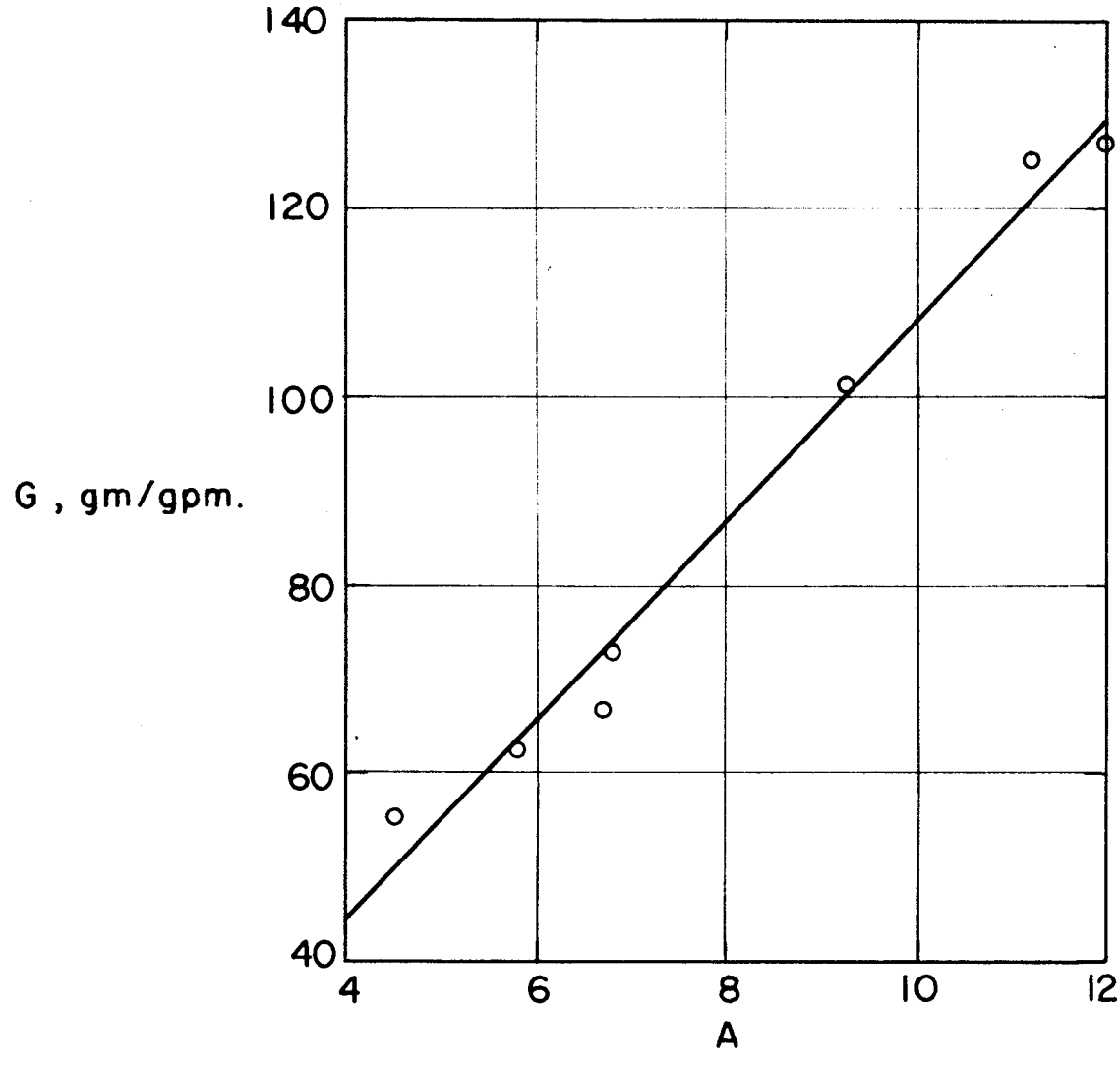

140
120
100
80
60
40
G , gm/gpm.
4
6
8
10
12
A

Table 3. T calculated from Equation 9 vs. T indicated in Figures 10 and 11.

G, $\frac{\text{grams}}{\text{gpm}}$	E, mg/l	Calculated T, hours	Indicated T, hours
125	0.1	16.8	17.0
125	0.2	25.8	26.4
125	0.3	38.8	40.5
55.5	0.1	7.5	6.9
55.5	0.2	11.5	10.5
55.5	0.3	17.5	16.2

Equation 9 was developed for Tests 1 through 7 and therefore can be applied only to an operating cycle consisting of a 2.0-minute on period followed by a 4.0-minute off period. The equation is also restricted to filters using the same quality of activated carbon as used in this study.

Dechlorinating Capacity

The dechlorinating capacity of the activated carbon filter used in Test 6 was calculated from the information given in Figure 11. The service life of said filter was 40 hours when a concentration of 0.30 mg/l of chlorine was in the filter effluent. Since the rate of flow was 1.0 gpm, the total quantity of treated water was 2,400 gallons.

The cost of using such a filter was calculated assuming that the filter is used to dechlorinate only that quantity of water which is used for drinking and cooking. A family of four persons does not ordinarily consume more than ten gallons of water per day. The 2,400 gallons of water

dechlorinated by filter 6 could have served a family of four for nearly 250 days, or about eight months. The cost of the replaceable filter cartridge is about $10.00. The cost of water used for drinking and cooking would amount to slightly more than $1.00 per month.

The foregoing analysis was based on a pattern of operation consisting of a 2.0-minute on period followed by a 4.0-minute off period. There are indications that a longer rest period will increase the service life of the filter. Therefore, the $1.00 per month figure is somewhat higher than would be expected under normal operating conditions.

INTERPRETATION OF RESULTS

Analysis of Service-Life Curves

According to the curves in Figures 10 and 11, and according to Equation 9, the decrease in the ability of activated carbon to adsorb chlorine does not vary linearly with time. An examination of the curve for Test 7 shows that the concentration of chlorine in the filter effluent, E, increased from 0.10 to 0.20 mg/l in 8 hours. The increase in E from 0.20 to 0.30 mg/l occurred in 13 hours. The longer the filter was in operation, the less the chlorine concentration increased per hour.

This variation in chlorine removal with time cannot be explained by the Langmuir hypothesis (8). According to Langmuir the rate of adsorption is proportional to the fraction of the surface area available for adsorption and the concentration of the adsorbate. In this study the concentration of the adsorbate was held constant at 5.0 mg/l. Therefore, the rate at which the carbon surfaces were covered should have varied directly with time and the reduction in the capacity of the carbon to remove the adsorbate should also have been proportional to time, assuming a constant flow is maintained. This was not found to be the case. Another explanation is needed. A hypothetical reason for the observed variation in dechlorinating capacity is given in the following section.

Adsorption and Absorption

In a discussion of various adsorption theories, Hassler (6) made the statement, "Adsorption is primarily a surface phenomenon, but it is

often accompanied by a deeper penetration of the vapor or solute into the body of the solid adsorbent. This deeper penetration is akin to the formation of a solid solution and is termed absorption. . . . it is seldom practicable to distinguish clearly between absorption and adsorption . . ."

This penetration, or absorption, of the adsorbate into the body of the adsorbent may explain the results obtained in this study. Since the individual carbon particles are porous, there are many interstitial passageways which could allow the chlorine, once it has been adsorbed, to migrate into the carbon particle and thus make more surface area available for adsorption of more chlorine.

On the basis of this absorption hypothesis, it can be shown that the type of service-life curve obtained in this study was to be expected.

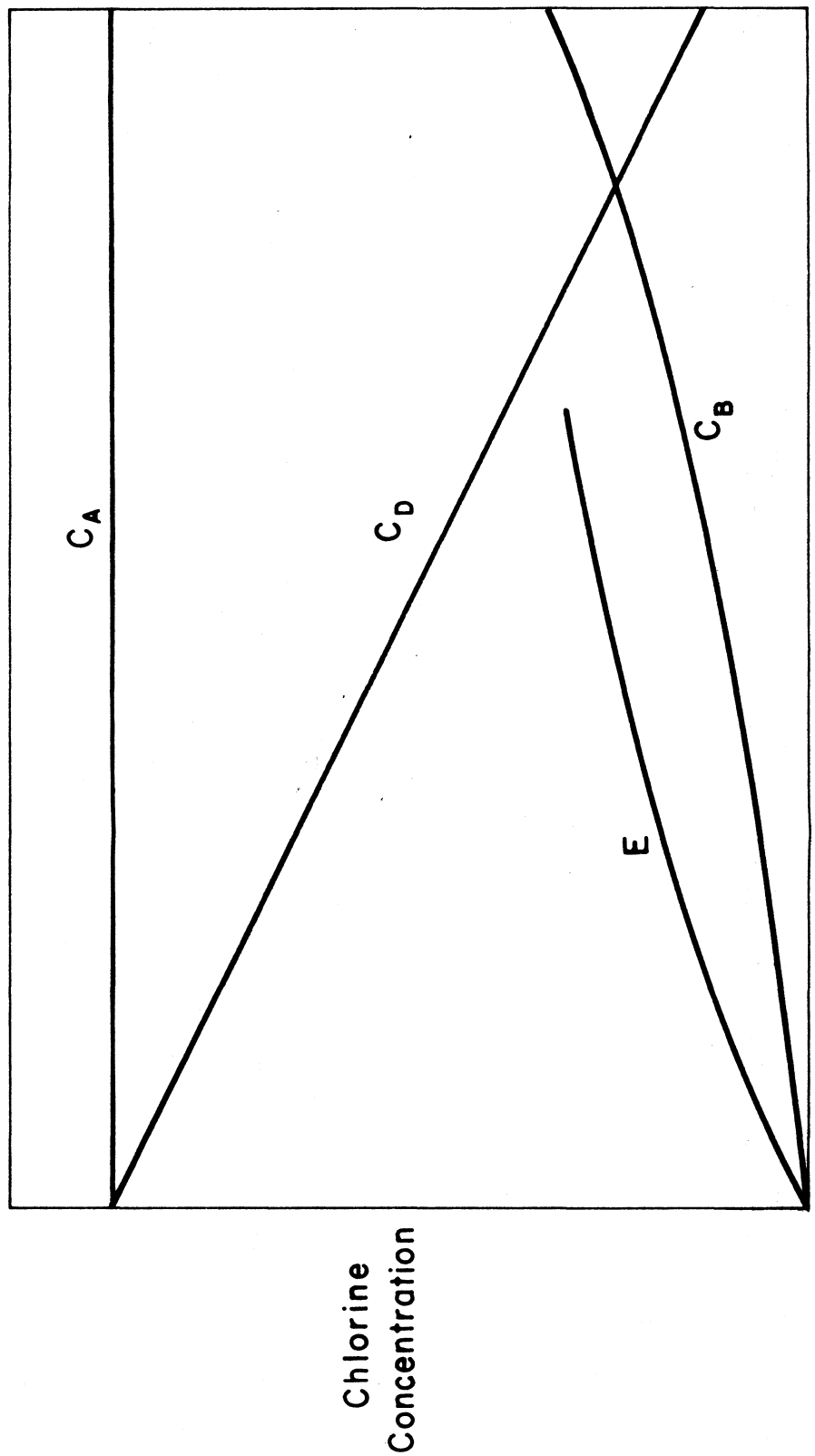
Hypothetical Service-Life Curves

The curves in Figure 13 have been developed on the basis of the aforementioned adsorption-absorption hypothesis. The ordinate in Figure 13 represents chlorine concentration. The abscissa represents time. The scales for the curves shown are not necessarily the same, so no units are shown. The ordinate and the abscissa are plotted on arithmetic scales. A description of the four curves in Figure 13 is given below.

C_A represents the chlorine concentration applied to the filter. This quantity is considered to be a constant throughout the service-life test and is therefore shown as a straight, horizontal line.

Figure 13. Hypothetical service-life curves

(C_A is the chlorine concentration applied to the filter. C_D is the chlorine concentration removed by the adsorptive capacity of the carbon. C_B is the chlorine concentration removed by the surface area that has been re-exposed due to absorption. E is the chlorine concentration in the filter effluent and is equal to $C_A - C_D - C_B$)


C_A
C_D
C_B
E
Time
Chlorine Concentration

C_D represents the concentration of chlorine that can be removed by the carbon due to the adsorptive capacity of the carbon particles. This adsorptive capacity is assumed to be a function only of the surface area of the carbon particles. It is further assumed that when T equals zero, there is just sufficient surface area to remove all of the chlorine that is applied. That is, $C_D = C_A$. At the next instant, a portion of the carbon surface is occupied by adsorbed chlorine and that surface area so occupied is not available for dechlorination. The quantity C_D is reduced. Since the concentration of chlorine applied, C_A, is constant, the rate at which C_D diminishes will also be a constant. Therefore, C_D will decrease linearly with T.

C_B represents the quantity of carbon surface area that has been covered with chlorine but has been re-exposed due to the absorption of that chlorine into the minute passageways leading into the interior of the carbon particle. When T equals zero, no chlorine is available for absorption. Also, no carbon surface can be reclaimed and $C_B = 0$. Moments later, when C_D has decreased because some chlorine has been adsorbed, chlorine is available for absorption and the absorption slowly begins. When C_D has decreased sufficiently to allow a build up of chlorine on the carbon particles, the rate of absorption of chlorine increases. The rate of absorption continues to increase until a maximum rate is attained. The maximum rate depends on either the concentration of chlorine applied, C_A, or on the quality of the carbon, whichever is critical.

$$E = C_A - (C_D + C_B) \tag{10}$$

When this subtraction is performed graphically, the resultant curve is as indicated in Figure 13. This curve, indicated by the letter E, rises relatively sharply at first, and continues to rise at a decreasing rate. This decreasing rate of increase is a characteristic of the service-life curves which were shown in Figures 10 and 11.

The different slopes obtained from the different off-on patterns of operation used in this study may also be explained by the adsorption-absorption hypothesis. Absorption is not an instantaneous reaction as adsorption is believed to be. Sufficient reaction time is necessary before the effect of absorption is significant.

In the service-life tests, the reaction time is a function of the off time. In Test 8 the off time was equal to one-half of the on time. In Tests 1 through 7, the off time was equal to twice the on time. The surface area made available by absorption was, therefore, of less significance in Test 8 than in the other tests. As a result, the concentration of chlorine in the effluent from filter 8 increased at a more rapid rate than did the chlorine concentration in the effluent from the other filters.

This combination adsorption-absorption theory can be extended to predict the results that might be obtained when the off time is increased to approach the off times that would be encountered in a domestic water supply.

The longer the filter is shut off, the more time is available for absorption. Since absorption makes more surface area available for adsorption, the dechlorinating capacity of the filter increases. Therefore, increased shut-off time will increase the service-life of the filter.

It may be possible, for a time, to maintain a constant value of chlorine concentration in the filter effluent. This would occur when the rate at which chlorine is absorbed into the carbon particles just equals the rate at which chlorine is adsorbed on the surface of the particles. The concentration of chlorine in the filter effluent would remain constant until the absorbing power of the carbon particles approached saturation. The rate of absorption would then decrease and the concentration increase. The increase would be at a faster rate after saturation than it was before saturation because of the decreased absorption capacity.

SUMMARY

The object of this study was to determine the service life of an activated carbon filter when used to dechlorinate a small water supply. A pilot plant was assembled in the laboratory to simulate the operating conditions to which a filter would be subjected

In order to obtain reproducible results, a definite pattern of operation was used in seven different tests. For comparison, an eighth test was run, using a different pattern of operation. The concentration of chlorine in the filter influent was held constant in all tests. The rate of flow was held constant during each test, but was varied among tests.

Service-life curves were determined by measuring the chlorine concentration in the filter effluent and plotting that chlorine concentration against time. From these curves, an expression for the service life, T, was determined in terms of the quantity of carbon divided by the rate of flow, G, and the chlorine concentration in the filter effluent, E. The expression for service life is

$$T = \frac{G-2}{11}(10)^{1.8E} \qquad (9)$$

where, T is measured in hours, G is measured in grams of carbon per rate of flow in gpm, and E is measured in mg/l. This equation for service life is restricted to filters operating on a pattern consisting of a 2.0-minute on period followed by a 4.0-minute off period.

The operating pattern has a definite effect on the service life of a filter. Longer rest periods give more time for the carbon particles to absorb the chlorine and hence make additional surface area available for

adsorption. It has been shown how adsorption and absorption work together to give the type of service-life curve obtained in the laboratory tests.

The cost of dechlorinating water to be used for cooking and drinking was calculated as less than $1.00 per month for a family of four persons. When flow patterns in ordinary domestic services are imposed on the filter, the service life will be increased and the cost of dechlorination will be decreased.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The service life of an activated carbon filter is given by Equation 9 on page 65 and is materially affected by the pattern of off-on time to which the filter is subjected. Adequate service life may be expected from an activated carbon filter of the type used in this study. The adsorption-absorption hypothesis explains why intermittent operation is important to the life of a dechlorinating filter.

Recommendations

On the basis of this study the following recommendations are made:

1. Use an activated carbon filter when objectionable tastes and odors are created by superchlorination.

2. Additional tests should be made to determine the increase in service life when longer rest periods are used.

3. Additional tests should be made to determine how the concentration of chlorine in the filter influent affects the service life.

4. An extended test should be made to demonstrate the type of curve resulting when the absorption capacity of the carbon is expended.

ACKNOWLEDGMENTS

The writer is grateful to Professor Harold E. Babbitt for his guidance throughout this study. The writer is also grateful to Professor E. Robert Baumann for initiating this study and to Everpure Inc., for supplying equipment and funds.

APPENDIX

Calculation of the equation representing the service-life data from Test 5 is shown below. The method used for the calculation is the modified method of least squares mentioned on page 51. In this calculation, E and T, as used throughout this study, are indicated by x and 10^y, respectively. The resultant equation is of the form $y = mx + a$ where, m is the slope of the line and a is the intercept. The number of observations is indicated by the letter n.

	(E) x	(T) 10^y	(Log_{10} T) y	x^2	xy
1	0.03	30.0	1.477	0.0009	0.0443
2	0.06	36.0	1.556	0.0036	0.0934
3	0.09	41.0	1.613	0.0081	0.1452
4	0.13	48.5	1.686	0.0169	0.2192
5	0.14	52.5	1.720	0.0196	0.2408
6	0.15	58.0	1.763	0.0225	0.2644
7	0.18	64.5	1.810	0.0324	0.3258
8	0.23	75.0	1.875	0.0528	0.4312
9	0.24	79.0	1.898	0.0576	0.4555
10	0.24	82.0	1.914	0.0576	0.4594
11	0.25	86.0	1.934	0.0625	0.4835
12	0.28	89.0	1.949	0.0784	0.5457
13	0.30	98.0	1.991	0.0900	0.5973
Totals	2.32		23.186	0.5029	4.3057

$\bar{x} = 0.178$, $\bar{y} = 1.784$

$$m = \frac{\Sigma xy - \frac{\Sigma x \Sigma y}{n}}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}} = \frac{4.306 - \frac{(2.32)(23.19)}{13}}{0.5029 - \frac{5.382}{13}}$$

$$m = \frac{0.168}{0.0889} = 1.89$$

$a = \bar{y} - m\bar{x} = 1.784 - (1.89)(0.178)$

$a = 1.448$

When the constants are inserted into the general equation, the result is

$y = 1.89x + 1.45$

or

$\text{Log}_{10} T = 1.89E + 1.45.$

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