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CONTROL OF BACTERIAL GROWTHS IN RAPID SAND FILTERS<sup>a</sup>

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INTRODUCTION

From studies relating to iron removal in Illinois, a number of researchers have reported evidence that nitrification takes place during the filtration of aerated ground waters. Table 1 shows data obtained in evaluations of the performance of iron removal plants. Increased nitrate concentrations and marked depletions in the dissolved oxygen concentrations in the filtered water were the first indications of the presence of nitrifying bacteria. Incomplete removals of iron and the presence of ferrous iron in the filtered water were also reported. Subsequently, Ghosh, et al., using a pilot plant at Clinton, Illinois, reported additional evidence of the growth of nitrifying bacteria in experimental filters (3). Oxygen depletion, the conversion of ammonium ion to nitrite and nitrate, and decreases in pH and alkalinity were observed. Ultimately, as nitrification became more complete, a deterioration in the ability of the filters to remove iron was observed. Moreover, as the bacterial growth accumulated in the filters, increased total bacterial plate counts were observed. The object of the present study was, therefore, to evaluate a method for the control of bacterial growths in rapid sand filters.

SELECTION OF METHOD

About one-third of the iron removal plants in Illinois practice prechlorination prior to filtration for iron removal. Despite the presence of a chlorine

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residual, nitrification, as evidenced by oxygen depletion, proceeds. This may be due in part to the reaction of chlorine with the ammonium ion to form the slowly-reacting chloramines. Breakpoint chlorination, however, can control nitrification. As breakpoint chlorination on a continuous basis can be a costly process where the ammonium ion concentration is high, the periodic disinfection of the filter following backwash offers promise as a more economical treatment.

In this study, potassium permanganate was used in an effort to oxidize accumulated organic matter and control bacterial growth in an experimental iron removal pilot plant. Potassium permanganate can oxidize organic matter over a broad pH range, but most rapidly at high pH (1). As a result, a solution

TABLE 1.—EVALUATION OF PERFORMANCE OF IRON REMOVAL PLANTS IN ILLINOIS

| Town<br>(1) | Fe <sub>T</sub> , in milligrams per liter |                 | Fe <sub>II</sub> , in milligrams per liter |                 | Dissolved Oxygen, in milligrams per liter |                |                 | NH <sub>4</sub> <sup>+</sup> , in milligrams per liter<br>(9) | Increase in NO <sub>3</sub> <sup>-</sup> during Filtration?<br>(10) |
|-------------|---|-----------------|--|-----------------|---|----------------|-----------------|---|---|
|             | Raw<br>(2)                                | Filtered<br>(3) | Raw<br>(4)                                 | Filtered<br>(5) | Raw<br>(6)                                | Aerated<br>(7) | Filtered<br>(8) |   |   |
| Findlay (5) | 4.72                                      | 0.60            | 4.45                                       | 0.59            | 0   | 6.6            | 0               | 11.3  | Yes   |
| Findlay (4) | 4.6                                       | 1.04            | 4.6  | 1.05            | 0.3                                       | 9.2            | 0.6             | —   | —   |
| Tolono (5)  | 1.08                                      | 1.02            | 0.90                                       | 0.92            | 0.2                                       | 7.6            | 0.1             | 4.0   | Yes   |
| Tolono (4)  | 4.96                                      | 3.24            | 4.58                                       | 2.72            | 0.1                                       | 6.7            | 1.0             | —   | —   |
| Argenta (5) | 1.36                                      | 0.28            | 1.20                                       | 0.11            | 0.1                                       | 7.6            | 0.3             | 2.0   | Yes   |
| Argenta (4) | 2.11                                      | 0.96            | 1.39                                       | 0.60            | 0.5                                       | 8.5            | 0.4             | —   | —   |
| Wapella (5) | 5.0                                       | 1.04            | 4.98                                       | 0.79            | 0   | 7.0            | 0.1             | 4.0   | Yes   |
| Wapella (4) | 5.86                                      | 0.73            | 5.08                                       | 0.59            | 0   | 1.2            | 0.7             | —   | —   |
| Danvers (5) | 2.8                                       | 0.82            | 2.28                                       | 0.26            | 0   | 7.4            | 0.3             | 11.3  | Yes   |
| Danvers (4) | 3.34                                      | 1.69            | 2.90                                       | 1.57            | 0   | 7.0            | 0.2             | —   | —   |

of KMnO<sub>4</sub> in 0.1 N Na<sub>2</sub>CO<sub>3</sub> was used in these experiments. The resulting pH was about 10.5.

### PILOT PLANT CONSTRUCTION AND OPERATION

For the studies of filter disinfection, a pilot plant was constructed which consisted of a multiple-pass aerator, reaction-sedimentation tank, and four sand filter units. The schematic representation is shown in Fig. 1. Each filter unit consisted of a 3-in. ID plexiglass tube about 6 ft in length. The filter bed consisted of 30 in. of sand (effective size, 0.5 mm; uniformity coefficient, 1.6) over a 4-in. bed of gravel. The available head over the surface of the filter was 4 ft to 5 ft. The reaction-sedimentation tank provided a detention time of about 1 hr, following 2 min of aeration. The flow through the pilot plant was kept constant using a constant-head overflow device. Rate-of-flow controllers utilizing float valves maintained the flow through the filters at 2 gpm per sq ft within a range  $\pm 10\%$ . The pilot plant was located at the Water Softening Plant at Rantoul, Illinois. The influent to the pilot plant was tapped from the raw water pipeline of the Rantoul plant.

The first few days' operation of the pilot plant indicated that the head loss

reached about 5 ft to 6 ft of water over a filtration period of about 24 hr in all of the filter units. The length of the filter run was therefore set at 24 hr. Head loss readings were recorded at the beginning and the end of each filter run. Samples of raw, aerated, settled water and filter effluent were periodically collected for analysis. Samples were analyzed for dissolved oxygen, total and ferrous iron, ammonia nitrogen, alkalinity, and hardness, according to the procedures set forth in *Standard Methods* (6). The pH and temperature measurements were made immediately after sample collection.

The pilot plant was operated through the period from June, 1967 to November, 1967. On some days the flow through the pilot plant diminished consider-

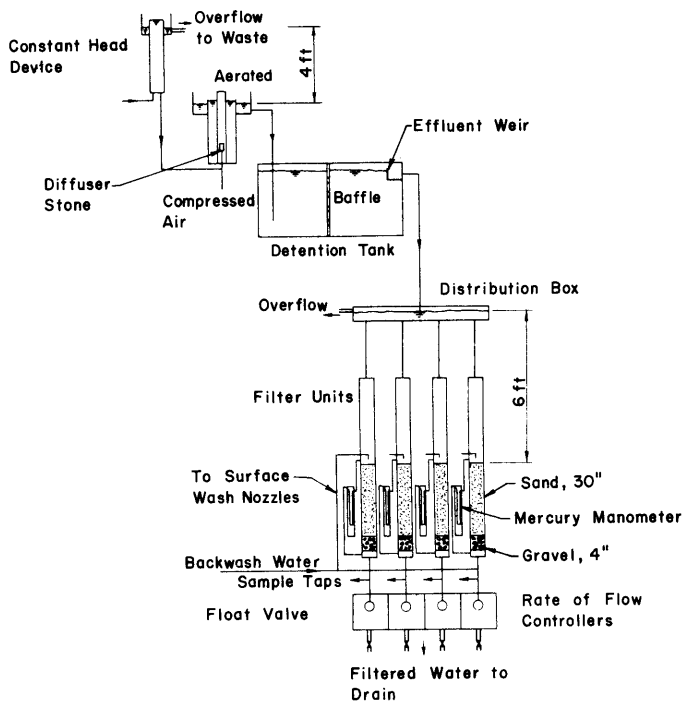


FIG. 1.—SCHEMATIC REPRESENTATION OF PILOT PLANT

ably due to sand-clogging or an air block in the connection hose from the raw water pipe of the Rantoul plant to the pilot plant. Only those filter runs in which the flow was maintained at 2 gpm per sq ft  $\pm$  10% were taken into account in averages computed in this report.

*Installation of Surface Wash.*—A problem encountered early in the investigation involved the filter backwash procedure. At the end of the filter run, a filter cake of about 1 in. to 1-1/2 in. thick had accumulated at the top of the filter bed. During the normal backwash procedure, this cake broke into pieces which subsequently settled down into the level of the gravel. Since routine backwash procedures failed to clean the sand that had formed in the cake, a

surface wash was installed in the form of a jet of water at the surface of the sand bed. The surface wash was used prior to backwash. In the experimental filters, it was necessary to apply about 30 gpm per sq ft of backwash water to obtain 50 % expansion of the sand bed. The rate of surface wash was slightly higher to insure complete disintegration of the filter cake.

### BACTERIAL GROWTH IN FILTER

The progress of the bacterial growth in the filter was monitored by measuring the dissolved oxygen in the filtered water. The depletion of dissolved oxygen increased with time, until after about 9 weeks of operation, the dissolved oxygen concentration in the filter effluent was zero. Throughout this period, the aerated and settled water always contained 7 mg per l to 8 mg per

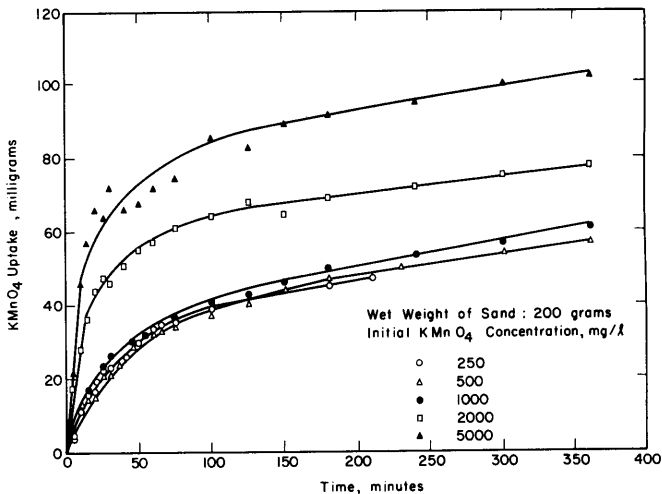


FIG. 2.—CUMULATIVE UPTAKE OF  $\text{KMnO}_4$  VERSUS TIME

l of dissolved oxygen. By the time the water passed from the detention tank, almost all of the ferrous iron had been oxidized. The resulting floc was colloidal and did not settle effectively in the reaction-sedimentation tank. The filters, however, removed the colloidal iron efficiently, both initially and after the development of bacterial growth in the filter. Since the plexiglas filter columns made it possible to examine the appearance of the filter sand closely, it became evident that it was impossible to distinguish visually between clean, fresh and "ripened" filters.

*Determination of Permanganate Dosage.*—In an effort to determine the amount of potassium permanganate which would be consumed in treating the filters in which bacterial growths had been established, one of the four filters of the pilot plant was backwashed and then disconnected. Then the sand was carefully removed from the filter unit and gently, but thoroughly, mixed. Sand aliquots of 200 g (wet weight) were placed in one-liter beakers and measured

amounts of permanganate solutions, 250 mg per l, 500 mg per l, 1,000 mg per l, 2,000 mg per l and 5,000 mg per l  $\text{KMnO}_4$  in 0.1N  $\text{Na}_2\text{CO}_3$ , were added to the beakers. Liquid samples were withdrawn from the beakers to determine the concentration remaining at regular intervals of time. Applying corrections for the amount of permanganate withdrawn for the analysis, the cumulative consumption of  $\text{KMnO}_4$  by the 200 g of sand in each beaker was calculated. Fig. 2 is the plot of cumulative consumption of  $\text{KMnO}_4$  in mg per 200 g of sand versus time. Fig. 2 shows that the initial rate of permanganate consumption is highest for the highest concentration used, and the curves approach an asymptote after about 3 hr. Because of the moisture in the wet sand, the actual initial concentration of permanganate is lower than that indicated on Fig. 2. Because 5,000 mg per l, the highest concentration used, yielded the highest rate and highest ultimate permanganate consumption, this concentration was applied to the filters.

*Application of Permanganate.*—Of the three filters remaining in the pilot plant, one was operated throughout the study as a control. The other two, designated Filter I and Filter II, were prepared for permanganate treatment. After the usual backwash procedure for all three filters, the two to be treated were drained. The potassium permanganate solution was left in the filters for three hours and was then drained. The filters were again backwashed until the backwash water was free of any permanganate color. Finally, the filters, including the control, were returned to operation.

*Regrowth of Bacteria in Filters.*—Sampling was continued through many of the succeeding filter runs in order to evaluate the effectiveness of the permanganate treatment in the control of the bacterial growth in the filters. It was observed that the bacterial growth reappeared in about 4 weeks. This may have been due, at least in part, to seeding from the sedimentation tank where bacterial slime had also accumulated. The residual bacterial population remaining on the filter sand after the permanganate treatment may also have hastened the regrowth of bacteria in the filters.

## RESULTS AND ANALYSIS

*Effect of Permanganate Treatment.*—Since the object of this study was to ascertain the effectiveness of potassium permanganate in controlling the bacterial growth in the filters, the data of this study are presented so as to afford a comparison of the performance of the filters before and after the treatment. Table 2 summarizes the average value of the hydraulic characteristics of the pilot plant filter units. Table 2 shows that the flow conditions, both initially and at the end of a filter run, were essentially the same both for the permanganate-treated (Filters I and II) and the control filter. The length of filter runs was maintained at an essentially constant rate for about 24 hr, at an avg rate of flow of 2 gpm per sq ft. There was, however, a significant decrease in the initial and final headloss readings in all the filters including the control following permanganate treatment. Therefore the reduction in headloss values was not necessarily the effect of permanganate treatment, although the reduction was slightly more marked in the treated filters than in the control. It is thought that the loss of fines from the filter sand through successive filter backwashing may have brought about the reduction in the final headloss readings.

Table 3 presents the average values for the water quality characteristics of samples collected at 4 hr to 6 hr intervals during two separate filter runs; the first, approximately one week before, and the second, immediately follow-

TABLE 2.—HYDRAULIC CHARACTERISTICS OF PILOT PLANT FILTERS

| Filter<br>(1)               | Average initial flow, in gallons per minute per square foot<br>(2) | Average final flow, in gallons per minute per square foot<br>(3) | Average initial head loss, in feet of water<br>(4) | Average final head loss, in feet of water<br>(5) | Average length of filter run, in hours<br>(6) |
|-----------------------------|--|--|--|--|---|
| Filter I <sup>a</sup>       | 2.10   | 1.91   | 0.75   | 7.6  | 23.2  |
| Filter I <sup>b</sup>       | 2.10   | 1.95   | 0.69   | 5.3  | 23.8  |
| Filter II <sup>a</sup>      | 2.09   | 1.98   | 0.76   | 6.4  | 23.5  |
| Filter II <sup>b</sup>      | 2.13   | 1.99   | 0.70   | 4.5  | 23.7  |
| Control Filter <sup>a</sup> | 2.10   | 1.99   | 0.77   | 6.4  | 23.8  |
| Control Filter <sup>b</sup> | 2.12   | 1.92   | 0.69   | 5.2  | 23.7  |

<sup>a</sup> Filter performance prior to treatment with potassium permanganate.

<sup>b</sup> Filter performance following treatment with potassium permanganate.

TABLE 3.—CHARACTERISTICS OF WATER DURING PILOT PLANT OPERATION

| Sample<br>(1)               | Dissolved oxygen, in milligrams per liter<br>(2) | Fe <sub>T</sub> , in milligrams per liter<br>(3) | Fe <sub>II</sub> , in milligrams per liter<br>(4) | pH<br>(5) | Ammonia, in milligrams per liter as nitrogen<br>(6) | Alkalinity, in milligrams per liter as CaCO <sub>3</sub> equivalent<br>(7) | Total bacterial plate count, number per milliliter<br>(8) |
|-----------------------------|--|--|---|-----------|---|--|---|
| Raw water <sup>a</sup>      | 0.1  | —  | 1.40  | 7.6       | 1.41  | 374  | 2,505   |
| Raw water <sup>b</sup>      | 0.8  | 1.90   | 1.37  | 7.5       | 1.99  | 354  | 3,530   |
| Aerated <sup>a</sup>        | 7.2  | 1.07   | 0.83  | 7.9       | 1.43  | 366  | 118   |
| Aerated <sup>b</sup>        | 7.3  | 1.44   | 0.42  | 7.8       | 2.00  | 354  | 467   |
| Settled <sup>a</sup>        | 7.1  | 0.81   | 0.16  | 7.9       | 1.49  | 367  | 183   |
| Settled <sup>b</sup>        | 7.0  | 1.28   | 0.14  | 7.8       | 1.52  | 365  | 448   |
| Filter I <sup>a</sup>       | 0.1  | 0.07   | 0.07  | 7.6       | 0.08  | 354  | 2,220   |
| Filter I <sup>b</sup>       | 7.3  | 0.08   | 0.00  | 7.8       | 2.38  | 364  | 462   |
| Filter II <sup>a</sup>      | 0.1  | 0.03   | 0.04  | 7.6       | 0.17  | 354  | 4,240   |
| Filter II <sup>b</sup>      | 7.4  | 0.08   | 0.00  | 7.8       | 1.80  | 364  | 308   |
| Control Filter <sup>a</sup> | 0.1  | 0.05   | 0.06  | 7.6       | 0.29  | 351  | 3,450   |
| Control Filter <sup>b</sup> | 0.1  | 0.10   | 0.00  | 7.5       | 0.60  | 351  | 1,930   |

<sup>a</sup> Performance prior to treatment with potassium permanganate.

<sup>b</sup> Performance following treatment with potassium permanganate.

ing the permanganate treatment. Since there was little variation in these values during either filter run, only average values are reported. Included in the table are values for the raw, aerated, settled water and various filter effluent samples. The settled water is equivalent to the filter influent. Table 3 com-

pare the values of parameters listed for conditions at all stages of treatment, both before and after the application of permanganate.

Certain of the changes in water quality which occur during filtration are interrelated. For example, nitrification is the process in which ammonium ion is oxidized to nitrite and nitrate. During nitrification, hydrogen ions are released and oxygen is consumed. Consequently, a portion of the alkalinity is consumed and a reduction in pH is brought about. Prior to permanganate treatment, all the filters showed such changes.

**Stoichiometric Relationships.**—For Filter I prior to permanganate treatment, for example, the observed changes were:

1. The influent pH of 7.9 was reduced to 7.6 at the effluent.
2. The influent ammonia-nitrogen concentration of 1.49 mg per l was reduced to 0.08 mg per l.
3. The influent alkalinity of 367 mg per l was reduced to 354 mg per l as  $\text{CaCO}_3$  equivalent.
4. The influent DO of 7.1 mg per l was reduced to 0.1 mg per l at the effluent.

The nitrification reaction may be written as,



from which the following ratios are obtained:

$$\left. \begin{array}{l} \text{NH}_4^+ - \text{N} : \text{O}_2 = 1 : 4.56, \text{ in milligrams per liter} \\ \text{and } \text{NH}_4^+ - \text{N} : \text{O}_2 = 1 : 2, \text{ as molar ratio.} \end{array} \right\} \dots\dots\dots (2)$$

The depletion of ammonia nitrogen from 1.49 mg per l to 0.08 mg per l would therefore involve an oxygen demand of  $(1.49 - 0.08) \times 4.56 = 6.6$  mg per l. The observed oxygen demand was  $7.1 - 0.1 = 7.0$  mg per l. The observed DO depletion is in good agreement with the calculated value, especially if the difference can be assumed to be due partly to the respiratory requirements of nonnitrifying bacteria.

If the decrease in ammonia-nitrogen  $(1.49 - 0.08)/14 = 0.10$  mM per l, the amount of hydrogen ion liberated is  $2 \times 0.10 = 0.20$  mM per l. This amount of acid liberated would be capable of neutralizing an equivalent amount of alkalinity, 0.1 mM per l or 10 mg per l as  $\text{CaCO}_3$  equivalent. Thus, the calculated effluent alkalinity will be  $(367 - 10) = 357$  mg per l, which agrees well with the observed value of 354 mg per l.

**Inhibition of Bacterial Activity.**—Following permanganate treatment, as shown in Table 3, the ammonium ion and the dissolved oxygen concentrations remained the same. The alkalinity and pH also were unaltered, except for a slight observed increase in alkalinity which may have been due to the  $\text{Na}_2\text{CO}_3$  used in the permanganate treatment. The bacterial count was significantly reduced.

As far as iron removal was concerned, there was little change. Iron removal was satisfactory prior to permanganate treatment, and remained so afterwards. This is in contrast with the observations of Ghosh, who showed a significant breakthrough of iron during filtration in a "ripened" filter (3) using a raw water which had a COD of 35 mg per l. There were some important differences in the conditions in these different studies, however. In

the present study, the temperature of filter effluent ranged from 14.2° C to 16.4° C, with an average of 15.0° C. As biologic activity increases with increasing temperature, the lower temperatures may have inhibited or delayed a significant iron breakthrough of iron. Another difference was the more complete oxidation of ferrous iron in the present study than in the earlier one.

**Bacteria Attached to Filter Sand.**—The effectiveness of permanganate in reducing the number of bacteria attached to the filter sand was determined by comparing the concentration of bacteria on sand before and after the permanganate treatment. The bacterial count was determined by first dislodging the bacteria from the filter sand into sterile water by vigorous shaking and then determining the total plate count of the resulting bacterial suspension. The total plate count was quantitatively related to the amount of sand used in the test. Table 4 shows the results of these tests for samples of sand withdrawn from two depths of the permanganate-treated filter (Filter II) and the control filter. The permanganate treatment reduced the number of bacteria on sand by roughly an order of magnitude.

TABLE 4.—BACTERIAL GROWTH ON SAND

| Sampling depth,<br>in inches <sup>a</sup> | TOTAL BACTERIAL PLATE COUNT, NUMBER PER GRAM<br>OF SAND |   |  |   |
|---|---|---|--|---|
|   | Filter I  |   | Control Filter                               |   |
|   | Prior to<br>permanganate<br>treatment<br>(2)            | Following<br>permanganate<br>treatment<br>(3) | Prior to<br>permanganate<br>treatment<br>(4) | Following<br>permanganate<br>treatment<br>(5) |
| (1)                                       |   |   |  |   |
| 4.5                                       | $6.5 \times 10^4$                                       | $7.5 \times 10^3$                             | $4 \times 10^4$                              | $4.5 \times 10^4$                             |
| 14.5                                      | $3.9 \times 10^4$                                       | $2.0 \times 10^3$                             | $11.1 \times 10^4$                           | $4.2 \times 10^4$                             |

<sup>a</sup> Depth measured from top of filter bed.

**Progress of Bacterial Growth.**—The progress of bacterial growth as evidenced by the depletion of dissolved oxygen during filtration is illustrated in Fig. 3. The dissolved oxygen concentration in the filter influent averaged over the entire period of observation is shown in the figure for comparison. The dissolved oxygen concentration in the effluents from Filters I and II gradually decreased until the 55th day when the oxygen was almost totally depleted. The filters were treated with the permanganate solution on the 73rd day of filter operation. The treatment was effective in restoring dissolved oxygen in the filter effluent. The dissolved oxygen was maintained for about 20 days after which depletion began again. The dissolved oxygen was once again almost totally depleted 45 days after the permanganate treatment suggesting the reestablishment of the bacterial growth.

**Required Dosage of Permanganate.**—A few rough calculations can be made based on the results of these studies to estimate the dosage of permanganate required for the disinfection of a filter having a 30 in. depth of sand supported by 12 in. of gravel. Assuming 35 % porosity for sand and 50 % porosity for gravel, and 6 in. depth of solution standing on the top of the sand bed, the void

volume per sq ft of the filter bed plus freeboard volume amounts to about 14 gal. The chemical requirement, using 5,000 mg per l of  $\text{KMnO}_4$  in 0.1N  $\text{Na}_2\text{CO}_3$ , is then calculated as 0.59 lb of  $\text{KMnO}_4$  and 0.62 lb of  $\text{Na}_2\text{CO}_3$  per sq ft of filter bed. Thus, for treating a 10 ft  $\times$  10 ft filter bed, it is estimated that a solution containing 59 lb of  $\text{KMnO}_4$  and 62 lb of  $\text{Na}_2\text{CO}_3$  in 1,400 gal of water would be needed. If the solution feed tank is situated far away from the filter, the required storage capacity in the connecting pipelines must be taken into account.

At the end of the contact period in the filter, the solution could be pumped back into the solution feed tank and reused for the next application. It would be necessary, however, to make up the strength of the solution because the original solution would be reduced both by the permanganate consumption and the moisture adhering to the filter sand. This make-up requirement of the chemicals is estimated to be about 30 % of the original amount.

Inhibition of Nitrification by Chlorine.—As part of a broad study of biologically mediated chemical changes in rapid sand filters, Baliga observed

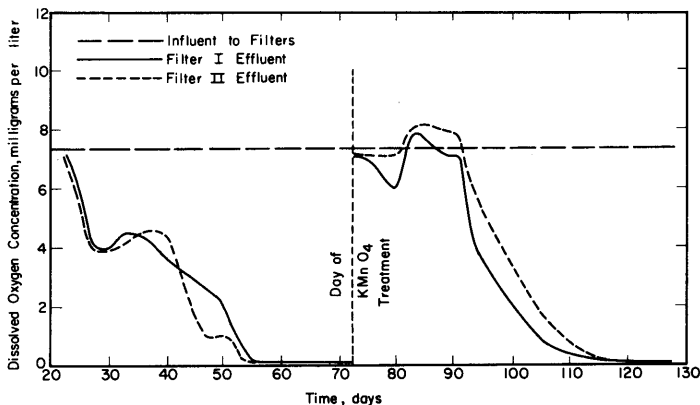


FIG. 3.—DISSOLVED OXYGEN CONCENTRATION VERSUS TIME

the effect of periodic applications of chlorine during backwash on the progress of nitrification (2). Using a molar concentration of chlorine equivalent to the concentration of permanganate used in the present study, and adjusting the pH to four, he found that chlorine treatment would inhibit nitrification after 7 hr of contact. However, the inhibition was not complete and total oxidation of ammonium ion was observed again within a week. Treatment with chlorine did not significantly alter the COD of sand samples taken from the filter bed, even though it did inactivate the heterogenous bacteria, as determined by total plate count. It was concluded that longer contact times and more frequent applications would be required if chlorine was used to inhibit nitrification in rapid sand filters.

### CONCLUSIONS

Bacterial growth accumulates in sand filters used for iron removal in spite of normal backwash, and even surface wash, procedures. Dissolved

oxygen depletion and nitrification can occur where the raw water contains ammonium ion.

Potassium permanganate is effective in reducing the bacterial growth in the filter, preventing dissolved oxygen depletion and inhibiting nitrification. However, the bacterial growth may become reestablished so that another application of potassium permanganate is required. It appears that periodic applications of permanganate would be necessary to control the bacterial growth found in rapid sand filters.

#### ACKNOWLEDGMENTS

The pilot plant was located and these studies were conducted at the Rantoul Water Softening Plant, Rantoul, Ill. The wholehearted cooperation of the City of Rantoul and its Water Department is gratefully acknowledged. This work was supported, in part, by a grant to the University of Illinois from the Carus Chemical Company, La Salle, Ill., and in part, by a grant from the Water Resources Center at the University of Illinois, Urbana, Ill.

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#### APPENDIX I.—REFERENCES

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#### APPENDIX II.—NOTATION

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The following symbols are used in this paper:

$Fe_T$  = total iron concentration; and  
 $Fe_{II}$  = ferrous iron concentration.