

South Dakota State University

# Open PRAIRIE: Open Public Research Access Institutional Repository and Information Exchange

---

Electronic Theses and Dissertations

---

1987

## Ozonation Pilot Treatment of a Surface Water Supply for Odor Control, Fairmont, Minnesota

Lyle Duane Munce

Follow this and additional works at: <https://openprairie.sdstate.edu/etd>

---

### Recommended Citation

Munce, Lyle Duane, "Ozonation Pilot Treatment of a Surface Water Supply for Odor Control, Fairmont, Minnesota" (1987). *Electronic Theses and Dissertations*. 4460.  
<https://openprairie.sdstate.edu/etd/4460>

This Thesis - Open Access is brought to you for free and open access by Open PRAIRIE: Open Public Research Access Institutional Repository and Information Exchange. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of Open PRAIRIE: Open Public Research Access Institutional Repository and Information Exchange. For more information, please contact [michael.biondo@sdstate.edu](mailto:michael.biondo@sdstate.edu).

Ozonation Pilot Treatment of a Surface Water Supply  
for Odor Control, Fairmont, Minnesota

BY

LYLE D. MUNCE

A thesis submitted in partial fulfillment  
of the requirements for the degree  
Master of Science  
Major in Civil Engineering  
South Dakota State University

1987

SOUTH DAKOTA STATE UNIVERSITY LIBRARY

Ozonation Pilot Treatment of a Surface Water Supply  
for Odor Control, Fairmont, Minnesota

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Dr. Dwayne A. Rollag      Date '    '  
Major Adviser  
Head, Civil Engineering Dept.

## ACKNOWLEDEMENTS

I wish to express my appreciation to Dr. Dwayne Rollag and James Housiaux for their technical guidance and assistance with this investigation. Sincere appreciation is also extended to Jerome Miller, Merlin Waterbury, Merle Prafke, Dave and Larry Holland, Harlan Johnson, Charlie Schaefer and Bill Cole for their participation in the odor panels. I would like to thank Professor Paul Evenson for his assistance in the statistical analysis of the experimental data. The Fairmont Water Treatment Plant staff are gratefully acknowledged for their total cooperation during set up and operation of the pilot plant. A special thank you is extended to Cheryl Havrevold for typing this thesis, and to Brian Hoellein for his aid as a research partner.

Special appreciation is extended to my parents, Jack and Lillian, for their constant support during the preparation of this thesis.

LDM

## TABLE OF CONTENTS

	Page
<u>INTRODUCTION</u> .....	1
<u>LITERATURE REVIEW</u> .....	3
<u>History of Ozonation</u> .....	3
<u>Physical and Chemical Characteristics of Ozone</u> .....	3
<u>Applications of Ozone</u> .....	4
<u>Use of Ozone for Taste and Odor Control</u> .....	4
<u>Ozonation System at Spirit Lake, Iowa</u> .....	11
<u>METHODS AND MATERIALS</u> .....	17
<u>Pilot Plant Description</u> .....	17
<u>Air-Preparation System</u> .....	17
<u>Ozone Generation System</u> .....	20
<u>Ozone Contacting System</u> .....	23
<u>Pilot Plant Operation</u> .....	26
<u>Ozone Generator Calibration</u> .....	26
<u>Operating Procedures</u> .....	28
<u>Transfer Efficiency</u> .....	30
<u>Analyses</u> .....	31
<u>Ozone in Gas</u> .....	31
<u>Ozone Residual in Water</u> .....	33
<u>Odor Analysis</u> .....	33
<u>RESULTS AND DISCUSSION</u> .....	35
<u>Introduction</u> .....	35
<u>Effect of Contact Time on Odor Reduction</u> .....	36
<u>Effect of Ozone Dosage on Odor Reduction</u> .....	39
<u>Effect of Ozonation on Odor Characteristics</u> .....	42
<u>Recommended Ozone Dosage and Contact Time</u> .....	44
<u>Ozone Contact Time</u> .....	44
<u>Ozone Dosage</u> .....	45
<u>Effect of Ozone Residual on Odor Reduction</u> .....	46
<u>CONCLUSIONS</u> .....	49
<u>RECOMMENDATIONS</u> .....	51
<u>LITERATURE CITED</u> .....	52
<u>APPENDIX A</u> .....	54
<u>APPENDIX B</u> .....	57
<u>APPENDIX C</u> .....	62
<u>APPENDIX D</u> .....	75

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Applications of Ozone in Drinking Water Treatment (2).....	5
2	Odors Associated with Various Algae.....	7
3	Operating Conditions for Ozonation System, Spirit Lake, Iowa, (November 1985).....	13
4	Threshold Odor Numbers for Various Ozone Dosages and Contact Times, Fairmont, Minnesota.....	37
5	Effect of Ozonation on Character of Odor Budd Lake Water, Fairmont, Minnesota.....	43
6	Contact Times in Prechlorination/Contact Basins in Existing Plant at Current Flow Rates, Fairmont Water Treatment Plant.....	45
7	Ozone Generator Capacities <sup>1</sup> / <sub>1</sub> at Current Flow Rates, Fairmont Water Treatment Plant...	46
8	Threshold Odor Numbers for Various Ozone Dosages and Contact Times. Detectable Ozone Residuals Indicated.....	48
C1	Threshold Odor Numbers at Various Ozone Dosages Contact Time of 2.5 Minutes.....	63
C2	Threshold Odor Numbers at Various Ozone Dosages Contact Time of 5 Minutes.....	64
C3	Threshold Odor Number at Various Ozone Dosages Contact Time of 10 Minutes.....	65
C4	Threshold Odor Numbers at Various Ozone Dosages Contact Time of 20 Minutes.....	66
C5	Threshold Odor Numbers at Various Ozone Dosages Contact Time of 30 Minutes.....	67
C6	ANOVA of TON Results.....	68
C7	Least Square Means of TON Results.....	69

D1

Volumes and Contact Times for Each Basin  
at the Three Operating Rates at the  
Fairmont Treatment Plant.....

79

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Flow Diagram of Spirit Lake, Iowa Water Treatment Plant.....	14
2	Air Preparation System.....	18
3	Schematic Diagram of Air Preparation System.....	19
4	Ozone Generator.....	21
5	Schematic Diagram of Ozone Generator.....	22
6	Contacting Columns.....	24
7	Rotometers and Connecting Piping.....	24
8	Schematic Diagram of Contacting Columns.....	25
9	Pump, Motor, and Water Flow Meter.....	27
10	Gas Washing Bottles and Wet-Test Meter.....	32
11	Average Threshold Odor Number for Selected Contact Times.....	38
12	Lowest Ozone Dosages Required to Produce a TON of 3 or Less for Selected Contact Times..	40
13	Least Square Means of Threshold Odor Numbers for Selected Ozone Dosages and Contact Times.	41
B1	Water Vapor Pressure Versus Temperature.....	59
C1	Threshold Odor Number versus Ozone Dosage, 2.5 Minute Contact Time.....	70
C2	Threshold Odor Number versus Ozone Dosage, 5 Minute Contact Time.....	71
C3	Threshold Odor Number versus Ozone Dosage, 10 Minute Contact Time.....	72
C4	Threshold Odor Number versus Ozone Dosage, 20 Minute Contact Time.....	73



C5	Threshold Odor Number versus Ozone Dosage, 30 Minute Contact Time.....	74
D1	Schematic Diagram of Fairmont Water Treatment Plant.....	78

## INTRODUCTION

Odor is an important factor in evaluating the quality of water. The presence of odor in water can impair its use for drinking, cooking and recreation. Waters having odors are not necessarily unhealthful to drink, but often are considered so by consumers.

Odors in drinking water supplies originate from natural and/or man-made sources. Man-made odors can be derived from organic and inorganic chemicals used or produced by industry. These odors can come directly from odorous chemicals such as phenols or pyridines. Or, the odors can result from the anaerobic decomposition of chemicals. Sometimes certain chemicals might react with other constituents in the water to produce odor.

Odors from natural causes generally are derived from vegetation, hydrogen sulfide and algae (17) (21). With such a wide variety of causative substances, the most suitable treatment method is not easy to select. Commonly-used methods include air-stripping, activated carbon adsorption and oxidation using aeration, chlorination or potassium permanganate. Ozone, used extensively in Europe for many years, has become increasingly more popular in the U.S. in recent years.

The City of Fairmont uses the water from Budd Lake for its primary supply. This small lake experiences seasonal water quality changes. The seasons that produce the poorest quality in terms of odor, are late summer when excessive algae growth occurs, and early

spring from the accumulation of gases entrapped by the ice cover. At these times relatively expensive treatment with activated carbon and potassium permanganate is required for odor control and even with these measures the results are not always satisfactory.

The objectives of this thesis are as follows.

1. To determine the effectiveness of ozonation in reducing the odor levels of the Fairmont surface water supply.
2. To determine the most economical ozone dosage and contact time for effective odor control.

A small ozonation pilot plant was used in these investigations which also include ancillary studies on the effect of ozonation on trihalomethane formation, chlorine demand, total organic carbon (organic matter), flocculation efficiency, and the costs of ozonation reported by Hoellein (8).

## LITERATURE REVIEW

### History of Ozonation

The Dutch Scientist Van Marum was the first to report the characteristically pungent odor of ozone in the vicinity of electrical machinery in 1785. Schonbein is credited with naming this gas ozone. The first electric-discharge ozone generator was designed by Werner von Siemen in 1857 (15).

Ozonation for water treatment has been in continuous use since 1906 in Nice, France. There were 2 water treatment plants in the United States using ozone in 1940. Whiting, Indiana has been using ozone for taste and odor control continuously since 1941. Water supplying this plant was taken from Lake Michigan. In 1978, there were a total of 1039 water treatment plants using ozone. About 1000 of these were in Europe, 23 in Canada and 6 in the United States (15). By 1985, the number in the United States had increased to 17 with several more under construction (9).

### Physical and Chemical Characteristics of Ozone

Although ozone,  $O_3$ , is an allotrope (different form, usually in the same phase) of oxygen,  $O_2$ , it has considerably different physical and chemical properties from oxygen (9). Ozone has a pungent odor detectable at concentrations as low as 0.01 parts per million by volume. It is a colorless gas at room temperature and is approximately 13 to 20 times more soluble in water than oxygen in

the usual temperatures in water treatment plants. The half-life of ozone in air is about 12 hours whereas in distilled water only 10 to 30 minutes (15).

Ozone is one of the most powerful oxidizing agents used in water treatment, second only to fluorine. It can be explosive at high concentrations (15 to 20 percent or higher), but presents no explosive hazard at the relatively low concentrations produced by ozone generators in water treatment plants (1 to 3 percent in air) (9). The suggested long-term safety limit in air is 0.1 parts per million by volume, about 10 times higher than the detectable limit.

#### Applications of Ozone

The uses of ozone in water treatment are summarized in Table 1. Although, the initial use of ozone was for disinfection, it was soon apparent that ozone brought about many of the other changes in water quality listed in Table 1. In other words ozonation exerts a multiple effect when applied to water, depending on the characteristics of the water. Many of the specific applications of ozone have been discussed by Hoellein (8).

#### Use of Ozone for Taste and Odor Control

The human senses of taste and smell are stimulated by many chemical compounds. The purveyor of drinking water who does not experience taste and odor problems, either periodically or

Table 1. Applications of Ozone in Drinking Water Treatment (20)

---

1. Oxidation of:
    - a. Trihalomethane precursors
    - b. Sulfides
    - c. Cyanides
    - d. Organic compounds causing tastes, odors, and color
    - e. Organics such as:
      - Detergents
      - Pesticides
      - Phenols
      - Humic acids
      - Fulvic acids
      - Tannic acids
    - f. Iron
    - g. Manganese
    - h. Heavy metals
  2. Microflocculation
  3. Suspended solids removal
  4. Improvement of settleability characteristics
  5. Reduction of chlorine demand
  6. Bacterial and viral destruction
  7. Destruction of algae
  8. Conversion of large-molecular weight, less biodegradable organic compounds into smaller, more easily biodegradable organics.
-

sporadically, is indeed the exception rather than the rule.

Although the terms "taste" and "odor" are often used jointly, taste and odor problems in water supplies are concerned almost entirely with just odors (16) (13).

Most tastes and odors in water supplies have their origins with either naturally-occurring organic materials or synthetic organic compounds (20) (17) (21). These materials and compounds generally can be attributed to two different, but not unrelated, causative elements: the actions of humans upon the aquatic environment and natural forces within the environment (16).

Surface water supplies are more commonly linked to tastes and odors than groundwater supplies largely because of the presence of algae. Certain microorganisms, and the growth and decay of algae are the most significant natural odor problems in domestic water supplies. Odors from algae are a complex set of phenomena, resulting from the bacterial degradation of algae, algae waste products, or the algae themselves (16). In Table 2 qualitative descriptions of the odors associated with the presence of a number of common algae are presented (16).

The blue-green algae, green algae, diatoms, and flagellates are the algae groups identified as the cause of various odor problems. When these types of algae are abundant in a water supply they cause unpleasant and objectionable odors (16).

Table 2. Odors Associated with Various Algae (16)

Algal Genus	Algal Group	Odor When Algae Are	
		Moderate	Abundant
Anabaena	Blue-green	Grassy, nasturtium, musty	Septic
Anacystis	Blue-green	Grassy	Septic
Aphanizomenon	Blue-green	Grassy, nasturtium, musty	Septic
Asterionella	Diatom	Geranium, spicy	Fishy
Ceratium	Flagellate	Fishy	Septic
Dinobryon		Violet	Fishy
Oscillatoria	Blue-green	Grassy	Musty, spicy
Scenedesmus	Green	-	Grassy
Spirogyra	Green	-	Grassy
Synura	Flagellate	Cucumber, muskmelon, spicy	Fishy
Tabellaria	Diatom	Geranium	Fishy
Ulothrix	Green	-	Grassy
Volvox	Flagellate	Fishy	Fishy



Certain naturally-occurring inorganic compounds found in surface waters may also cause odors. For example, sulfides, ferrous and manganous ions appear in surface waters. The latter two ions result from thermal stratification and oxygen depletion in the benthic layer of lakes and reservoirs which may trigger the reduction of insoluble iron and manganese deposits. These substances are then released when the lake or reservoir overturns and mixes (16).

Ozone oxidizes both the organic and inorganic compounds in the aqueous phase. The molecules of odoriferous compounds are all electron-rich, while the ozone molecule reacts chemically as if it is electron-deficient. When these two types of molecules are brought into contact, an oxidation-reduction reaction takes place. Oxygen from the ozone molecule saturates the excess electron sites of the molecules of the malodorous substances. During this reaction, ozone is reduced to oxygen and the third oxygen atom is attached to the odor-forming molecule, lowering its threshold odor (26) (17) (21).

Low concentrations of ozone, generally produce large reductions in taste and odor. The degree of oxidation depends on both the contact time and the amount of ozone applied (26) (21).

There are many examples of ozone's effectiveness in the treatment of tastes and odors in drinking water (26) (17) (21). It should be noted that ozone is not effective in all odor-control applications and before considering ozone use in water treatment, a

preliminary study should be conducted to determine if ozonation is actually advantageous.

In an ozonation pilot study on Shoal Lake water in Canada, reported by Sommerville and Rempel (24) Threshold Odor Number (TON) reductions of 50 percent were obtained. Ozone dosages up to 10 mg/l were used. Ferkinhoff (6) reported that when ozonation was installed at Hobart, Indiana, taste and odor problems were virtually eliminated.

McLaughlin, reporting on the effectiveness of ozonation of Philadelphia's water supply (14), noted that ozone not only reduced the odor quantitatively, but also changed the residual odor to a "sweet" or "flowery" character.

It was reported in 1981, that of the 8 water treatment plants in the U.S. using ozonation, taste and odor control was the major treatment objective in at least 5 of them (20). Bartuska, reporting on one of these plants at Whiting, Indiana (1)(2) observed an average TON reduction of 83 percent and that the ozone dosage was not considered critical as long as a residual of at least 0.1 mg/l were maintained.

LePage reported that results of pilot studies conducted on water from Lake Erie for use by the City of Monroe, Michigan (11). The most severe odors (TON of 8) were eliminated in the pilot study using ozone dosages of 1.0 and 1.5 mg/l. As a result of these studies, Monroe built an 18-MGD plant that uses ozonation for taste

and odor reduction. After continuous operation had started, odor complaints dropped from a high of 100 on a single day before ozonation to none after ozonation was in operation (12).

In 1982, Nusz reported on pilot studies conducted on water from the James River serving as the major supply for Huron, South Dakota (17). During the study period raw water TONs ranged from about 7 in late June to over 40 in mid July. The following conclusions were drawn from these studies.

1. Aeration alone did not change or reduce the odor of the raw water.
2. Ozone consistently changed the characteristic odor of the raw water from a condition described as "fishy" to one described as "pleasant".
3. The TONs of the raw water were reduced at all ozone dosages, 4 to 24 mg/l, except at 12 mg/l where the TON actually increased.
4. Ozone dosages of 4 or 8 mg/l at a 20-minute contact time produced suitable water relative to odor reduction.
5. Activated carbon and potassium permanganate were not effective in reducing or changing the raw-water odor at the dosages used.
6. The coagulation-flocculation-sedimentation processes reduced odor intensity but did not change the characteristic "fishy" odor of the water.

Studies similar to those of Nusz were conducted by Lee (10) on water from Lake Kampeska at Watertown, South Dakota. As was found in Huron, ozonation changed the odor from an unpleasant, fish odor to a sweet, pleasant odor. Also, aeration alone did not have any effect on the odor of the lake water. The most cost-effective operating conditions for odor reduction were 4 mg/l ozone dosage at a contact time of 10 minutes.

Finally, ozone can be quite effective in eliminating tastes and odors because (4) (7):

- a. Ozone is the most powerful oxidizing agent commonly used in water treatment (except for fluorine) so that organic compounds not affected by other oxidants are oxidized by ozone;
- b. Ozone reacts rapidly thereby requiring relatively short contact times;
- c. Excess ozone simply reverts to oxygen in a relatively short time; and
- d. Since ozone is often carried in air, aeration occurs simultaneously with oxidation thereby stripping any volatile compounds causing odors.

#### Ozonation System at Spirit Lake, Iowa

In 1985 the construction of an ozonation facility treating water from Spirit Lake, Iowa was reported in the literature (22). A field survey of the Spirit Lake water treatment plant was conducted

in November, 1985. This plant was recently expanded and up-graded to include an ozonation system. The improvements included:

1. increase in plant capacity from one MGD to 3.0 MGD;
2. installation of an 18-in. diameter intake extending 580 feet into Big Spirit Lake;
3. expanding and upgrading the existing intake pump station including a new 1600 gpm raw water pump;
4. installation of a static mixer into the raw water line used for flash mixing;
5. conversion of an existing detention tank to a flocculation basin;
6. installation of 2 1000-gpm plate-settling units;
7. construction of an ozonation contact tank and ozonation generation, distribution and destruction system;
8. providing a new chlorination system;
9. installation of a new control system; and
10. construction of a 40 x 100 ft building addition to house the new facilities.

Construction began in June, 1983 and the new facilities placed into operation in August, 1984. The total project cost was \$1,090,000 with about \$170,000 for the ozonation system. The major reason for providing the ozone facilities was to improve the control of odors from the raw water source Big Spirit, a large, shallow lake.

Previous odor-control efforts relied primarily on the use of activated carbon and potassium permanganate.

A flow diagram of the current water treatment facilities may be found in Figure 1. As shown in this figure, the plant includes pre-ozonation, softening and filtration.

The ozone generator capacity is 75 pounds of ozone per day. The air-drying system uses 3 types of desiccant and operates at 450°F. This air-preparation equipment keeps the dew-point well below the recommended -40°F temperature. The pressure through the generation system is 7.5 psi.

The contact basin for ozonation has a volume of 52,500 gallons which provides a contact time of 25 minutes at a flow rate of 2,100 gpm. Water depth in the 2-compartment basin is about 16 feet.

Operating conditions during the plant visit are listed in Table 3.

Table 3. Operating Conditions for Ozonation System, Spirit Lake, Iowa, (November 1985)

Ozone Generation Rate, lb. ozone/day	10
Amount of Ozone in Supply Gas, percent	0.2
Applied Ozone Dose to Raw Water, mg/l	0.7
Raw Water Flow Rate, gpm	1100
Ozone Residual in Contact Basin Effluent, mg/l	0.02-0.05
Contact Time, min	47

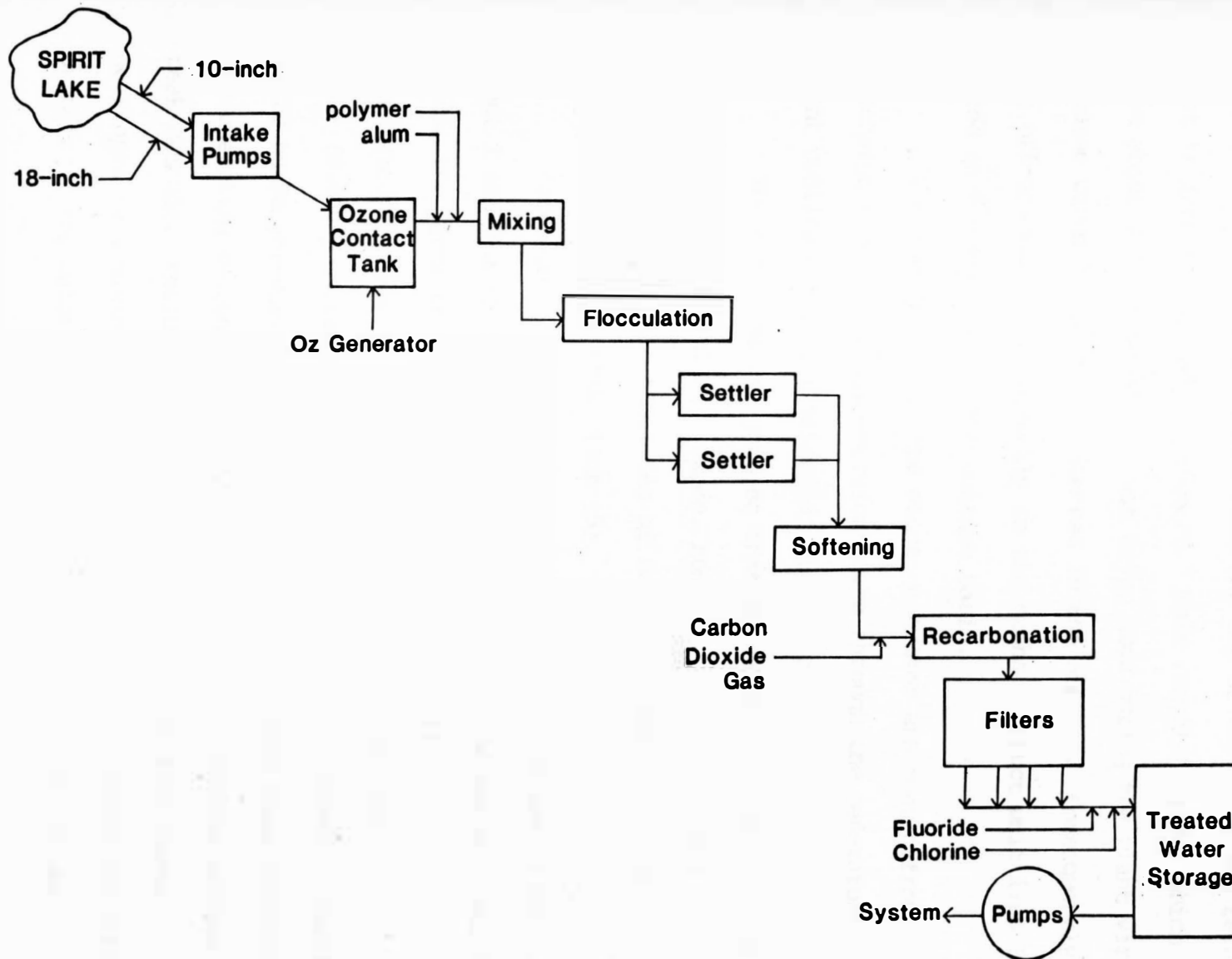


Figure 1. Flow Diagram of Spirit Lake, Iowa Water Treatment Plant

A compressor, located on the roof of the contact basin, can be used to remove unused ozone from the top of the basin and re-inject it into the second compartment. This recycle system, which uses about 7 Kw of power, was not being used during the plant visit because ozone could not be detected in the off-gas. Consequently, the off-gas was routed directly to the ozone destruct unit also located on the top slab of the contact basin.

Cooling waters for the ozone generator are routed from the discharge side of the high-service pumps through the generator. Spent cooling water is discharged into the contact basin.

The plant was designed so that ozone can be injected after flocculation and settling. Ozone, however, cannot be added in more than one location at a time. As of November, 1985, only raw water has been ozonated at this plant (5).

According to the operator (5) the ozone dose varied between about 1 and 2 mg/l throughout the year. The dosage was adjusted to ensure the presence of a detectable residual. The use of ozone has eliminated the need for activated carbon which saves the utility about \$9,000 per year. Ozone has also reduced the chlorine demand by 20 to 50 percent. Although there is no operating data collected, the operating personnel have not experienced any problems meeting peak demands. Excluding one incident, when septic conditions developed in a mixing basin, there have been no complaints of taste or odor in the water since the start-up of the new facilities.



Ozone operating costs during the plant visit were estimated to be about 3.3 cents per 1000 gallons treated.

## METHODS AND MATERIALS

### Pilot Plant Description

The pilot plant used in these studies was designed by DeBoer and Rollag (3) and constructed by Emery Industries Inc., Cincinnati, Ohio. The system includes processes for air preparation, ozone generation, and ozone contacting.

#### Air-Preparation System

A photograph of the air-preparation system is shown in Figure (2). Figure (3) includes a schematic of the air preparation system. From this figure, it can be seen that atmospheric air is first filtered and then compressed to a pressure of 100 psig (690 KPa). According to Pulice (18), filtering removes 99 percent of the air-borne organisms and 0.4 micron or larger particulates. Any moisture, dust, and oil present in the air are then removed as the air flows through a second filter, desiccant dryer and coalescer. Air pressure is subsequently reduced to 15 psig (100 KPa), using a pressure-reducing valve, before entering the ozone generator. The purpose of the air-preparation system is to ensure maximum ozone production under all operating conditions. Any moisture in the air feed can lead to the formation of nitric acid that can corrode electrodes, lower ozone production, and cause dielectric failure.

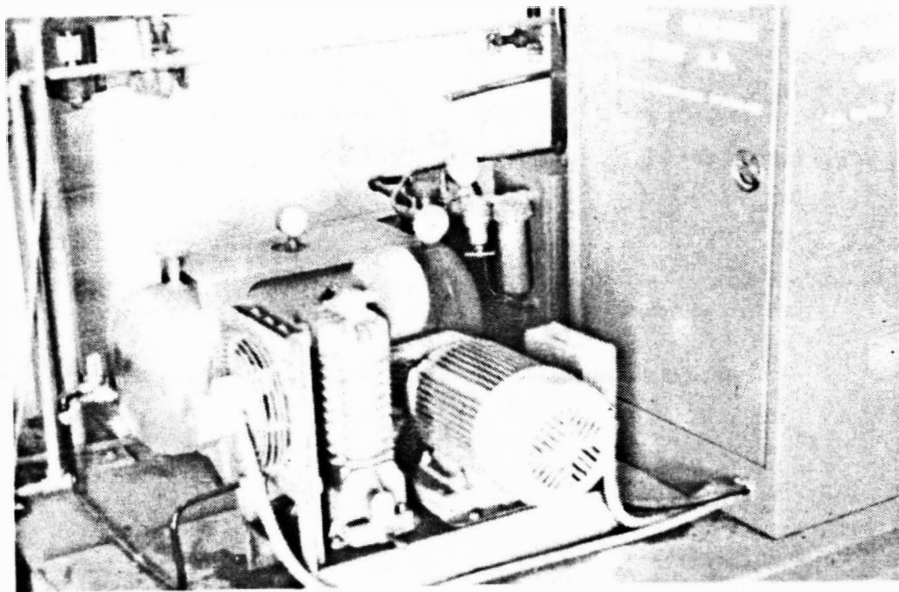


Figure 2. Air Preparation System

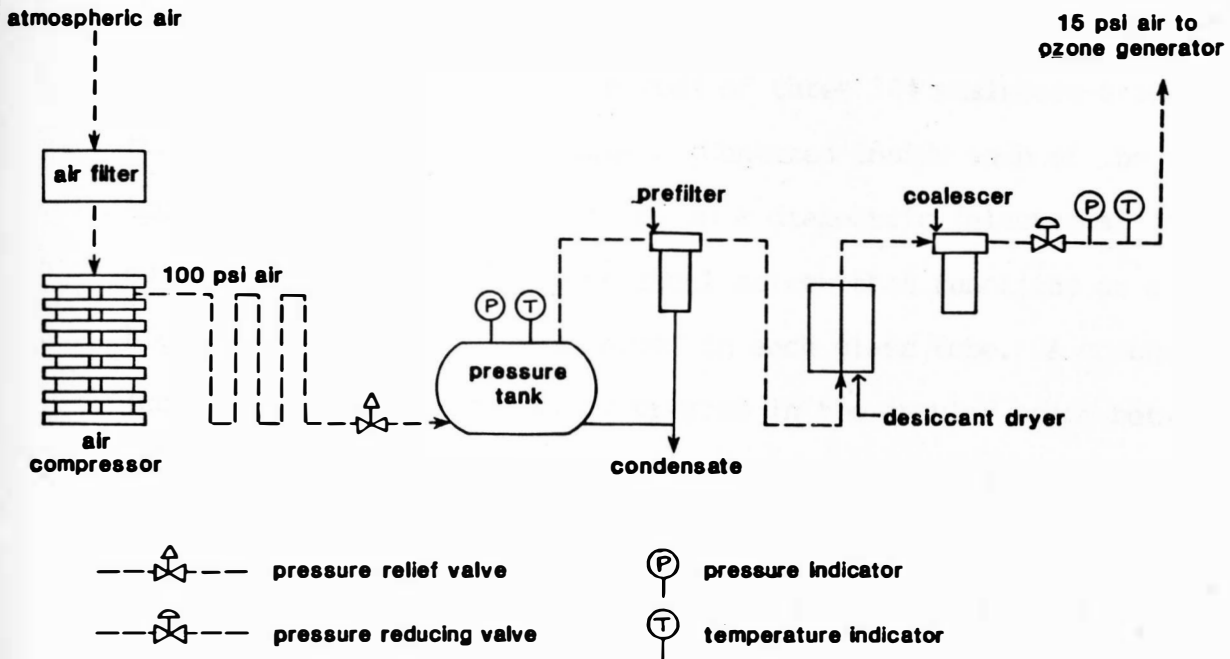


Figure 3. Schematic Diagram of Air Preparation System

### Ozone Generation System

The ozone generator was a tube-type, air-fed, water-cooled unit. The unit operated at a low-frequency (60 Hz), variable power supply voltage. A photograph of the ozone generator is shown in Figure (4). Figure (5) is a schematic diagram of the ozone generator. The ozone generator consisted of three 304 stainless-steel tubes enclosed in a water jacket. Centered inside each of the three tubes is a glass tube that serves as a dielectric (electrical insulator). A tubular stainless-steel screen that functions as a high-voltage electrode is inserted in each glass tube. A corona (continuous electric spark) is created in the annular space between the glass and steel tubes when a voltage is applied across the dielectric. The prepared air then enters the generation module at the proper pressure of 15 psig (100 KPa) and passes through the corona.

Heat generated by the corona is removed by circulating water through the jacket surrounding the three stainless-steel tubes. The optimum temperature for the ozone generator is 70°F (21.1°C). This will minimize dielectric failure, and practically eliminate dielectric warpage (18). A variable modulating valve was used to control the water flow rate so that the operating temperature could be maintained at the optimum 70°F (21.1°C).

This process caused a small percentage, typically one to three percent, of the oxygen (O<sub>2</sub>) in the prepared air to be

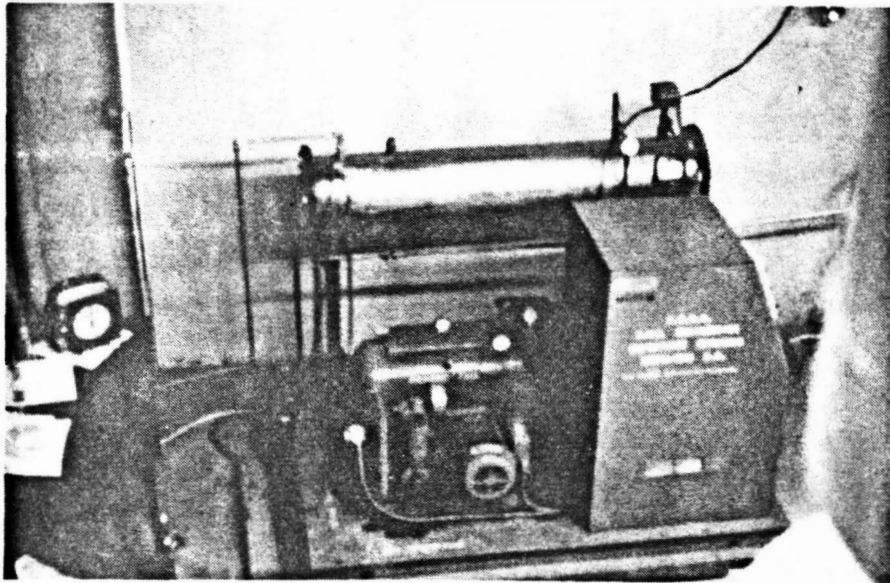


Figure 4. Ozone Generator

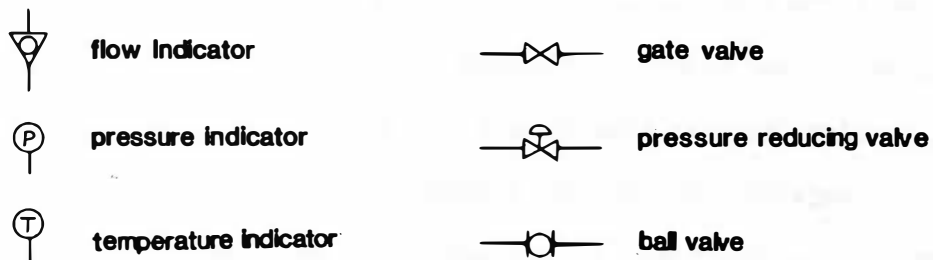
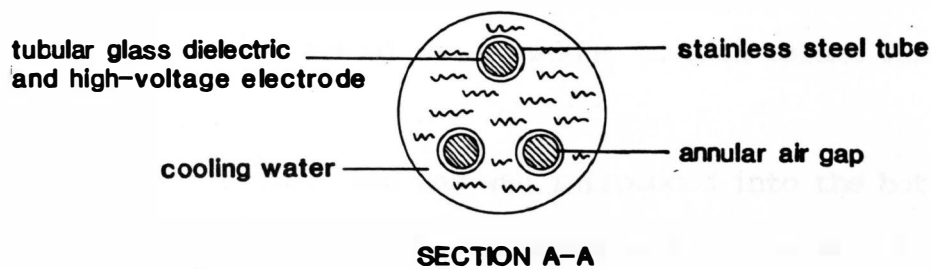
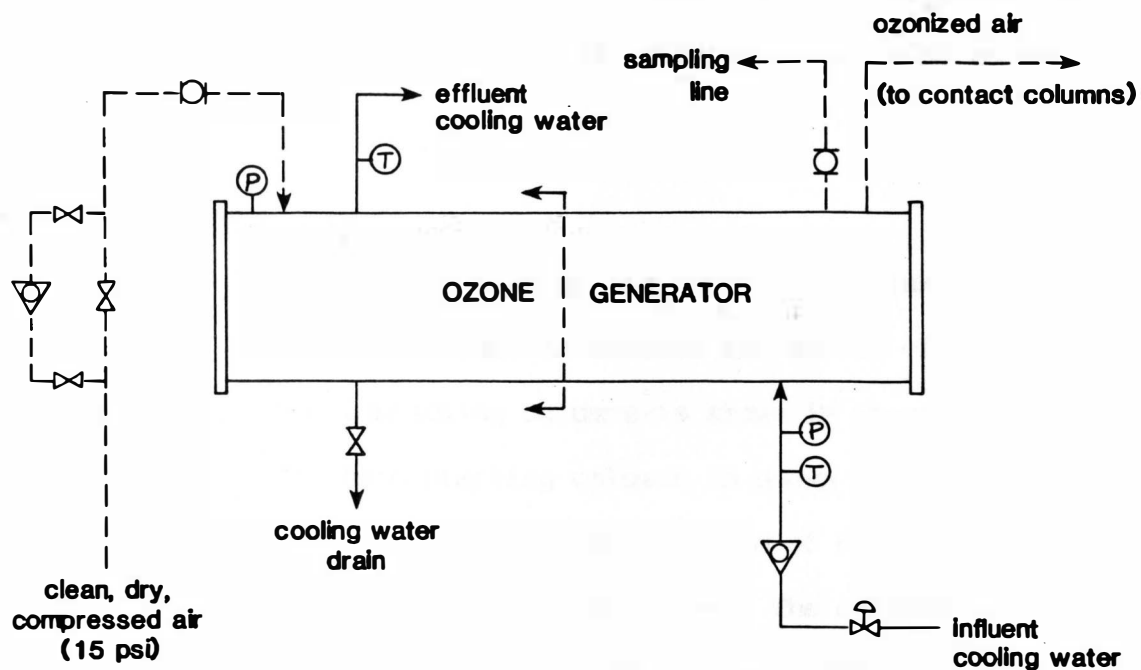


Figure 5. Schematic Diagram of Ozone Generator

converted to ozone ( $O_3$ ) (18). The ozone gas was then collected and piped through a 0.5-in. (1.27 cm) 304 stainless-steel tube to the contact columns.

### Ozone Contacting System

Figure (6) is a photograph of the contacting columns. A photograph of the rotometers used to control the amount of ozonated feed gas entering the contacting columns is shown in Figure (7). A schematic diagram of the contacting columns is shown in Figure (8).

The two contact columns were constructed of 6-inch (15.2-cm) inside diameter (ID) 304 stainless-steel pipe. The columns were comprised of two 6-foot (1.83-m) flanged sections, and one 2-foot (0.62-m) section. This gave a total column height of 14 feet (4.27 m), while the actual water height in each column was 12.5 feet (3.81 m).

The ozonized feed gas was introduced into the bottom of both columns through porous stainless-steel diffusers. By the use of the rotometers and proper plumbing, the ozone feed gas flow could be divided to provide the desired amount to each column. Any unused ozone off-gas was carried from the top of each contact column through tygon tubing to the atmosphere outside the treatment plant.

Feed water was pumped to the top of the first column using a 0.5-inch (1.27-cm) positive displacement pump. The pump was powered by a one-horsepower (0.75 KW) variable-speed DC motor, which facilitated accurate control of the pumping rate. The water flowed



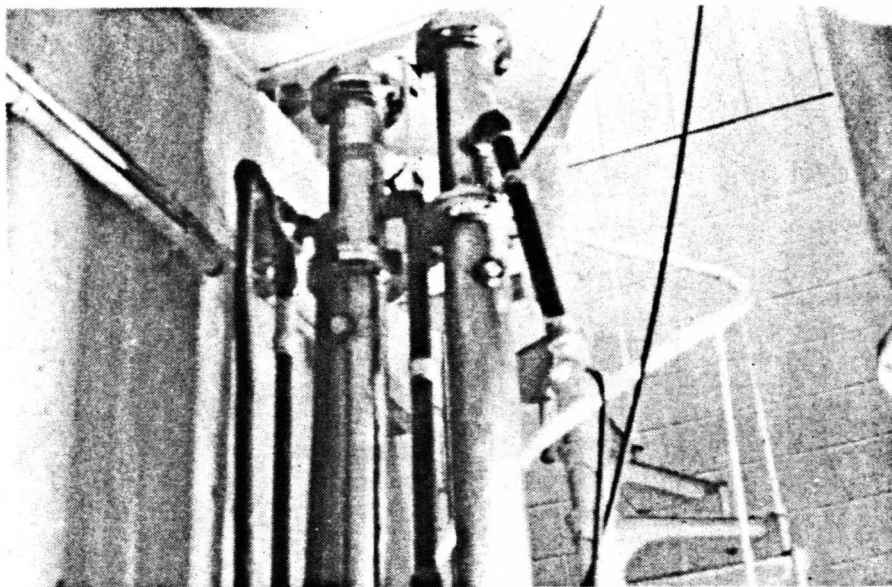


Figure 6. Contacting Columns

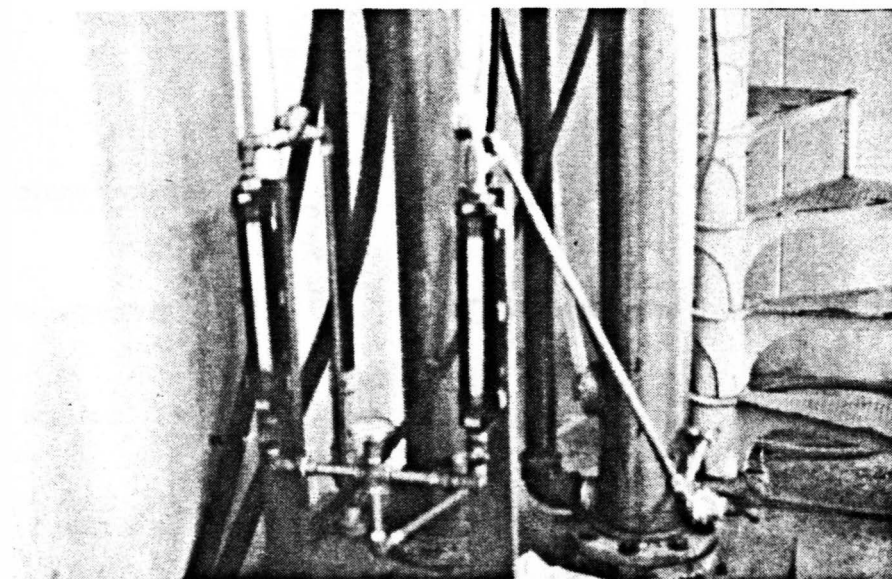


Figure 7. Rotometers and Connecting Piping

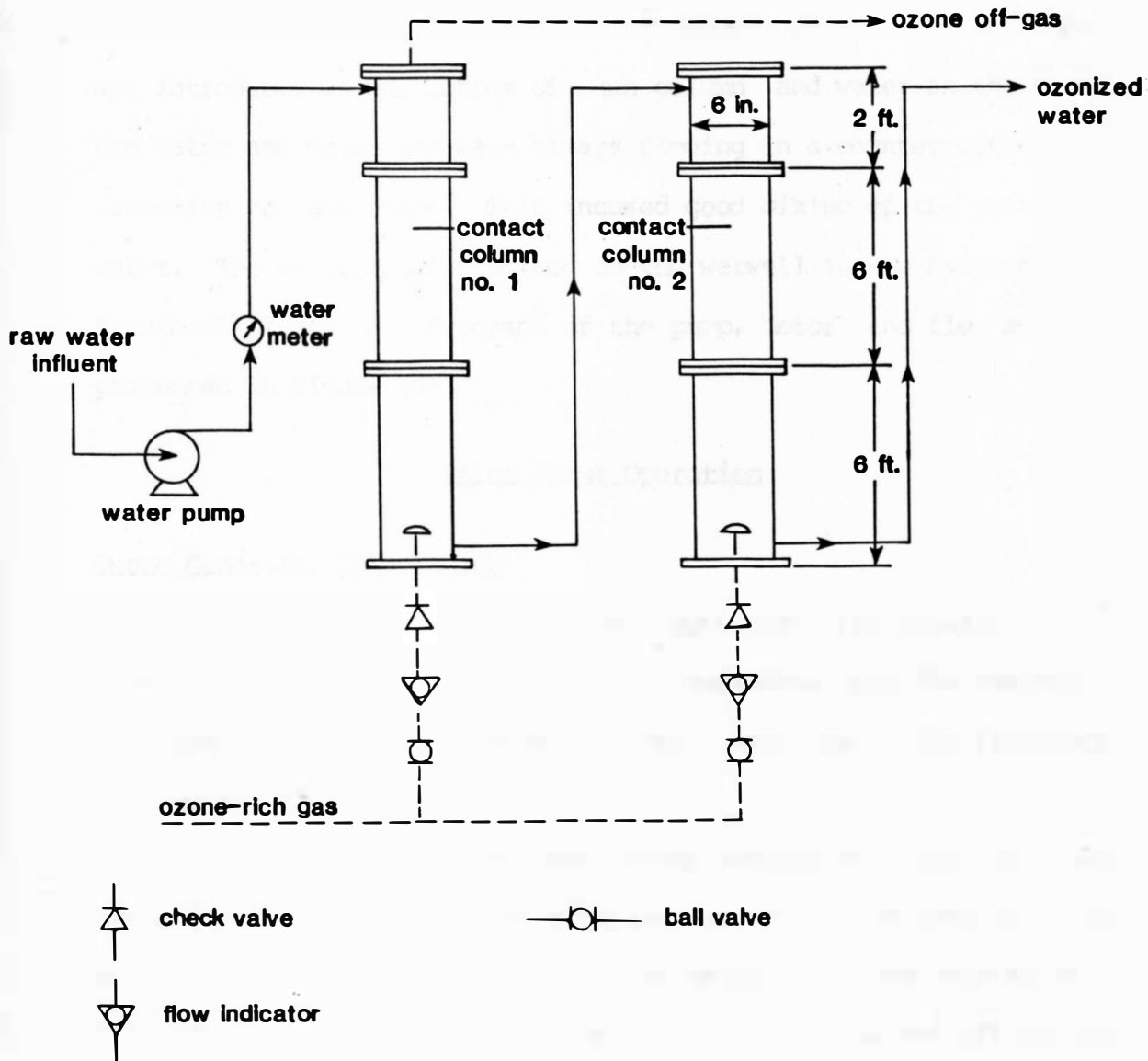


Figure 8. Schematic Diagram of Contacting Columns

down through the first column, and up to the top of the second column through a 2-inch (5.08-cm) PVC pipe. The water flowed down the second column, then back up another 2-inch (5.08-cm) PVC pipe used to control the water level in the second column. Since ozone was introduced at the bottom of each column and water at the top, the water and ozone gas were always flowing in a counter-current direction to each other. This insured good mixing of the ozone and water. The water was discharged to the wetwell in the Fairmont treatment plant. A photograph of the pump, motor, and flow meter is presented in Figure (9).

### Pilot Plant Operation

#### Ozone Generator Calibration

Ozone production is dependent upon the type, quality, and flow rate of the feed gas. It is also dependent upon the temperature and pressure in the ozone generator, and finally the frequency and voltage of the power supply.

Recently it has been reported by Rakness and Hegg (19) that the ratio of the ozonized gas flow rate to water flow rate (G/L) is an important factor in ozone contactor design. It was pointed out that G/L ratios of between 0.2 and 0.5 are desirable and G/L ratios between 0.5 and 1.0 acceptable. When the ratios exceed 1.0 transfer efficiencies are reduced.

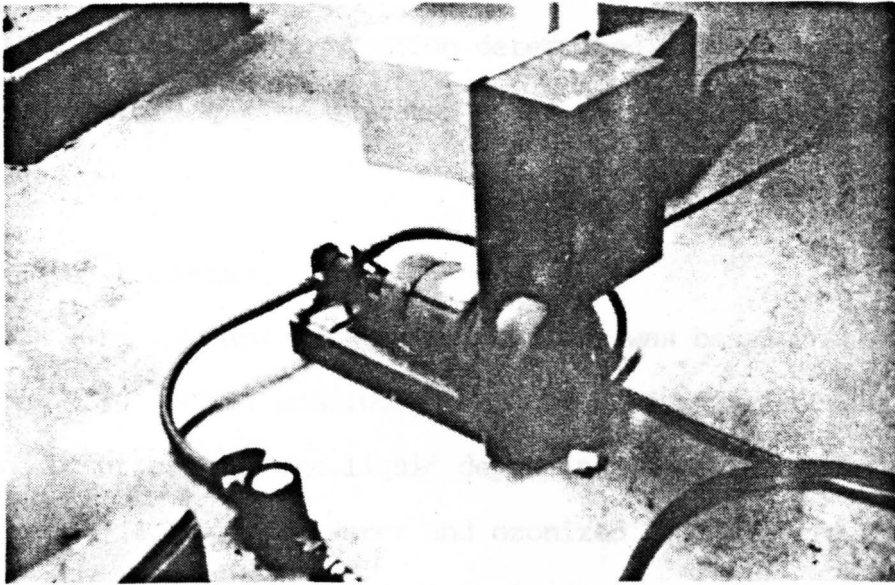


Figure 9. Pump, Motor, and Water Flow Meter

The discussion of the pilot plant operation is based on the following parameters defined below.

$Q_1$  = liquid (water) flow rate (gpm)

$Q_g$  = gas (ozonized air) flow rate (scfm)

$P$  = ozone generator power input (Watts)

$V$  = liquid volume in the columns (gallons)

$T$  = liquid detention time in columns (minutes)

$C_i$  = ozone concentration in ozonized air (mg/l)

$D$  = applied ozone dosage (mg/l)

$$T = V/Q_1 \quad (1)$$

$$C_i = f(P, Q_g) \quad (2)$$

$$D = C_i (Q_g/Q_1) \quad (3)$$

As shown by Equation 1, detention time is a function of liquid volume and water flow rate. However, since the volume of the contact columns was held constant, detention time became a function of the water flow rate only. Using the positive-displacement pump and the variable-speed DC motor, the water flow rate could be varied from 1 gpm to 11 gpm (3.8 lpm to 41.6 lpm). The contact column volumes were 18.4 gal (69.6 liters) for one column and 36.8 gal (139.3 liters) for both columns. Therefore, using either one or both columns all the desired detention times of 2.5, 5, 10, 20, and 30 minutes could readily be attained.

Equation 2 shows that the ozone concentration was a function of the air and water flow rates. After the proper air flow rate was

selected to obtain the desired gas-to-liquid ratio, it was held constant throughout the studies of a particular detention time. Therefore, the ozone concentration became a function of the power input only.

Finally, Equation 3 indicates that the applied ozone dosage was a function of the ozone concentration in the ozonized air, the water flow rate, and the air flow rate.

Solving Equation 3 for  $C_i$  and substituting  $V/T$  for  $Q_1$ , it was to obtain the following equation: possible

$$C_i = DV/TQ_g \quad (4)$$

However, because  $V$  and the ozonated air flow rate were held constant once the desired gas-to-liquid ratio was obtained, Equation 4 could be simplified to:

$$C_i = K (D/T) \quad (5)$$

where:  $K = \text{constant}$

Thus, given any ozone dosage and corresponding detention time, the required ozone concentration ( $C_i$ ) of the ozonized air could be determined easily. Once  $C_i$  was determined, the ozone generator variac setting could be obtained from the generator calibration curve developed by Stoebner (26).

### Transfer Efficiency

During each run a sample of the contact column off-gas was collected and the ozone concentration determined. Then, knowing the ozone concentration in the contacting gas and the off-gas, the ozone

transfer efficiency could be calculated using the following equation.

$$E = ((C_i - C_o)/C_i)100 \quad (6)$$

where:  $C_i$  = ozone concentration in contacting gas (lb/day)

$C_o$  = ozone concentration in off-gas (lb/day)

E = transfer efficiency (%)

### Analyses

#### Ozone in Gas

Ozone concentrations in gas were determined using a variation of the iodometric method described in Standard Methods Sec. 422 for the measurement of ozone residuals (25). Three to 9 liters of the gas to be analyzed were passed through two gas washing bottles connected in series at a rate of 1.5 l/min. Each washing bottle contained 400 ml of a one percent potassium iodide (KI) solution. The effluent from the second washing bottle was passed through a wet-test meter to measure the volume of gas. The set-up is shown photographically in Figure (10). The KI solution was then transferred to an Erlenmeyer flask where 10 ml of 2N sulfuric acid ( $H_2SO_4$ ) was added to reduce the pH to below 2. The sample was then titrated with 0.1N sodium thiosulfate ( $Na_2S_2O_3$ ). A starch solution was used as the end point indicator. The volume of the titrant along with the gas flow rate and water flow rate were used to

calculate the actual ozone concentration in milligrams/liter (mg/l).  
The calculations may be found in Appendix B.

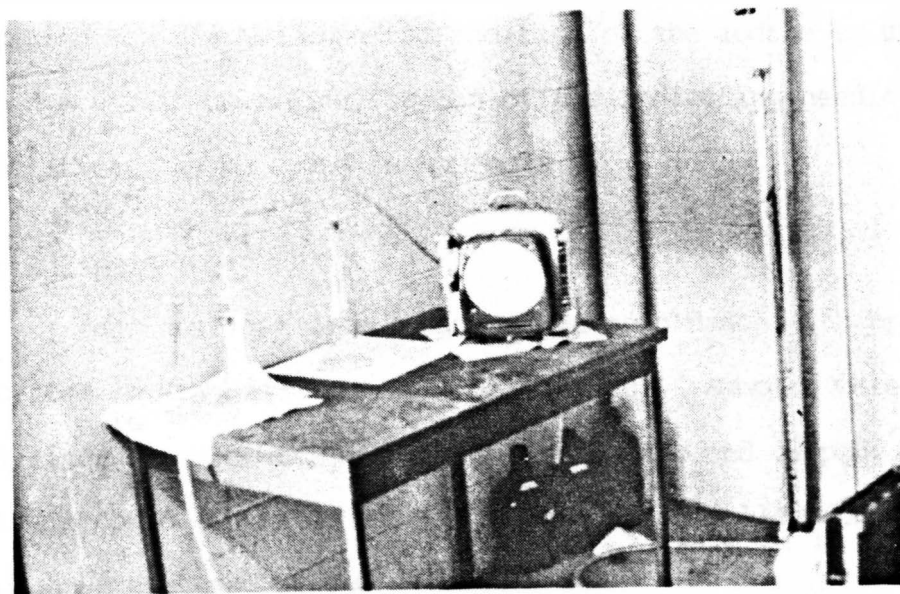


Figure 10. Gas Washing Bottles and Wet-Test Meter



### Ozone Residual in Water

The ozone residual in water was determined using a Fisher-Porter Model 17T2000 amperometric titrator. A 250-ml graduated cylinder containing 10 ml of 0.00564 N Phenylarsine Oxide (PAO) was used to collect 200 ml of water for analysis. The sample and PAO were then transferred to a 250-ml beaker to which 4 ml of pH 4 acetate buffer were added along with 1 ml of a 5 percent KI solution. This mixture was then placed on the titrator and titrated amperometrically with 0.00705 N iodine solution. The end point of the titration was reached when the addition of the iodine solution caused a slight upward deflection of the indicating needle. The calculations may be found in Appendix B.

### Odor Analysis

Odor analyses were conducted in accordance with procedures described in Standard Methods (25) Sec. 207. Samples were collected in 4-liter glass containers filled to the top and capped. If the analysis could not be conducted on the day of collection, the samples were stored at 4°C.

Odor-free water was prepared by passing demineralized water through an activated carbon filter. Using odor-free water, aliquots of the sample were diluted to a total volume of 200 ml in 500-ml glass-stoppered Erlenmeyer Flasks. Typical dilutions contained 10, 20, 40, 65, and 100 ml of sample water. In addition to these 5 dilutions one Erlenmeyer flask contained 200 ml of undiluted

sample water and another contained 200 ml of odor-free water to be used as a blank.

In so far as possible, the same panelists were used through the entire study. Non-smokers were selected and the analyses conducted at least 30 minutes after eating. For each panelist, the Threshold Odor Number (TON) was calculated using the lowest dilution for which an odor was detected. Because of the human factor, anomalous responses sometimes occurred. For example, a low concentration of sample water would sometimes be called positive (having an odor) while a higher concentration would be called negative (lacking odor). When this occurred the TON was determined after the point where no more anomalous responses occurred.

The following equation was then used to calculate each individual TON.

$$\text{TON} = 200 \text{ ml}/(\text{ml of sample water in dilution}) \quad (7)$$

The TON of the entire panel was calculated using the geometric mean of the individual TON's. The calculations may be found in Appendix B.

## RESULTS AND DISCUSSION

### Introduction

The Fairmont Water Treatment Plant obtains its primary water supply from Budd Lake. Odors develop in this water mostly in the spring, late summer and fall. The odors originate from natural sources such as the decomposition of vegetation and algae.

These investigations were conducted to determine the effectiveness of ozonation in reducing odors. The experiments related to odor reduction were carried out in September and October, 1985 and March and April, 1986, when odors in the water were most evident. The odors in the fall were characterized as "fishy" or "swampy" while the waters in the spring were described as "grassy" or "musty". The Threshold Odor Numbers (TONs) of the treated water from the Fairmont Water Treatment Plant during these times averaged about 8 during these periods.

The ozonation pilot system was moved to Fairmont August 14, 1985. About two days were required to assemble the system for operation. The first two weeks of operation were devoted to calibrating the ozone generator and flow rates. This time was also used to train the odor panel, consisting of city employees from the Power Plant, Water Treatment Plant and Wastewater Treatment Plant, and perform preliminary threshold odor number (TON) analyses.

The water from Budd Lake was ozonated at various contact times and ozone dosages. Odor of the raw and ozonated water was

determined in terms of the TON. The Secondary Drinking Water Standard for odor, established by the U.S. Public Health Service and adopted by the U.S. Environmental Protection Agency, is a TON of 3. Drinking water having a TON of 3 or less is generally considered acceptable in terms of odor by the general public.

The threshold odor numbers (TONs) obtained from the odor-reduction studies were plotted versus ozone dosage for each contact time. These plots and the data they were plotted from may be found in Tables C1 through C5 and Figures C1 through C5 in Appendix C. The TONs at the ozone dosages shown in Table 4 were obtained from these figures. Raw-water TONs varied from 3.6 to 9.5. The averages for each contact time are also presented in Table 4.

#### Effect of Contact Time on Odor Reduction

From Table 4, it is apparent that there was no direct relationship between TON and contact time at the ozone dosages studied. This outcome would be anticipated, however, since such results have been reported in the literature (17).

The shortest contact time where all TONs were below the recommended limit of 3 was 20 minutes. For the contact times studied, which span the usual range of contact times encountered in ozonation practice for odor control, all of the TONs obtained were averaged and plotted in Figure 11. It can be seen from this figure that all but one of these averages meet or exceed the recommended

Table 4. Threshold Odor Numbers for Various Ozone Dosages and Contact Times, Fairmont, Minnesota

	Contact Time, min					Average
	2.5	5	10	20	30	
Raw Water (ave. for each contact time)	7.7	6.3	6.1	3.8	3.8	
Aerated Water (0 mg/l ozone)	5.6	4.2	5.4	4.0	2.0	
Ozone Dosage, mg/l						
0.5	4.2	5.0	2.8	0.0	1.7	2.7
1.0	3.0	4.3	2.5	0.6	1.5	2.4
2.0	2.5	3.7	3.4	1.8	3.5	3.0
4.0	1.9	1.6	2.3	2.4	1.9	2.0
6.0	-	1.6	2.3	2.2	1.8	2.0
8.0	-	-	1.5	2.1	1.6	1.7
10.0	-	-	1.6	1.8	1.5	1.6
12.0	-	-	1.6	1.4	1.7	1.6
16.0	-	-	3.2	2.4	2.0	2.5
20.0	-	-	1.7	2.0	2.1	2.0
24.0	-	-	-	0.8	2.2	1.5
Average	2.9	3.2	2.3	1.6	2.0	

limit for odor (TON of 3). The plotted data indicate that contact times of 20 and 30 minutes produce the most acceptable results.

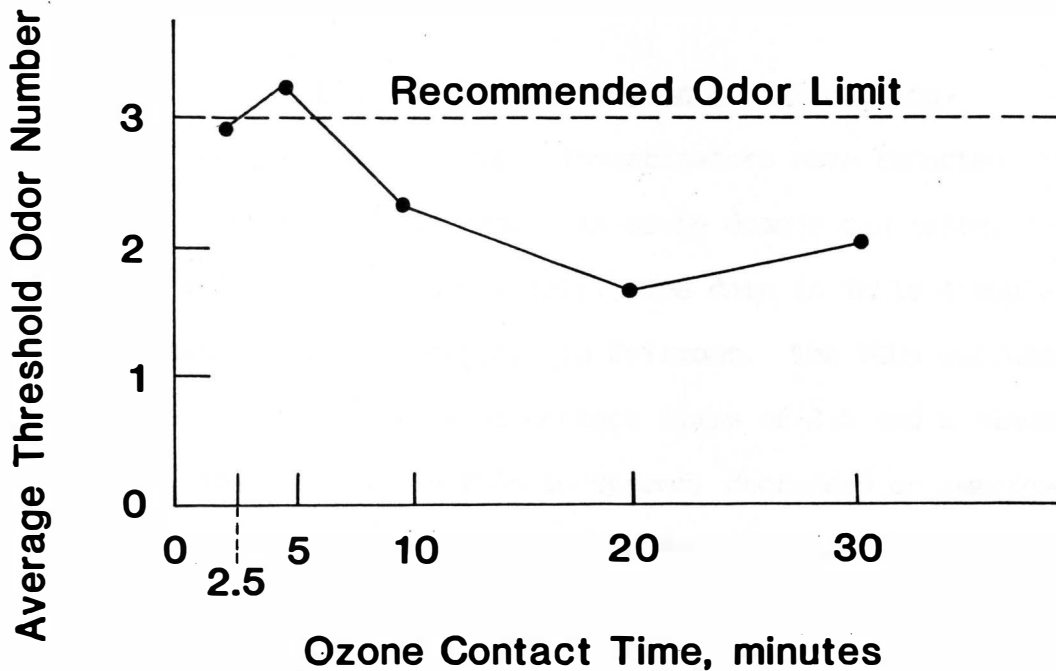


Figure 11. Average Threshold Odor Number for Selected Contact Times

A statistical analysis of the data was performed and is presented in Appendix C. This analysis revealed that statistically, there were differences between the TONs obtained at the shorter contact times (5 minutes or less) and the TONs obtained at the longer contact times (10 minutes or more) at the 95 percent confidence level.

In conclusion, it would appear from an evaluation of the odor numbers obtained for the selected contact times that the water should be ozonated for at least 20 minutes for effective odor control.

#### Effect of Ozone Dosage on Odor Reduction

From previous studies, investigators have reported that for a given contact time, increases in ozone dosage can raise, lower or have no effect on odor level (17). The data in Table 4 would seem to indicate this same response in Fairmont. The TONs decreased with increases in ozone dosage at contact times of 2.5 and 5 minutes. However, instances where TONs increased, decreased or remained unchanged with increases in ozone dosages are evident at the other contact times.

In Figure 12, the lowest ozone dosage that produced TONs of 3 or less are plotted for each contact time studied. From this figure, it can be seen that these ozone dosages ranged from 0.5 mg/l to 4 mg/l.

A statistical analysis of variance (ANOVA) of the TON data for the selected ozone dosages and contact times was performed and is presented in Appendix C. This analysis did not reveal any statistical difference at the 95 percent confidence level. This was probably due to the relatively low odor levels that were obtained.

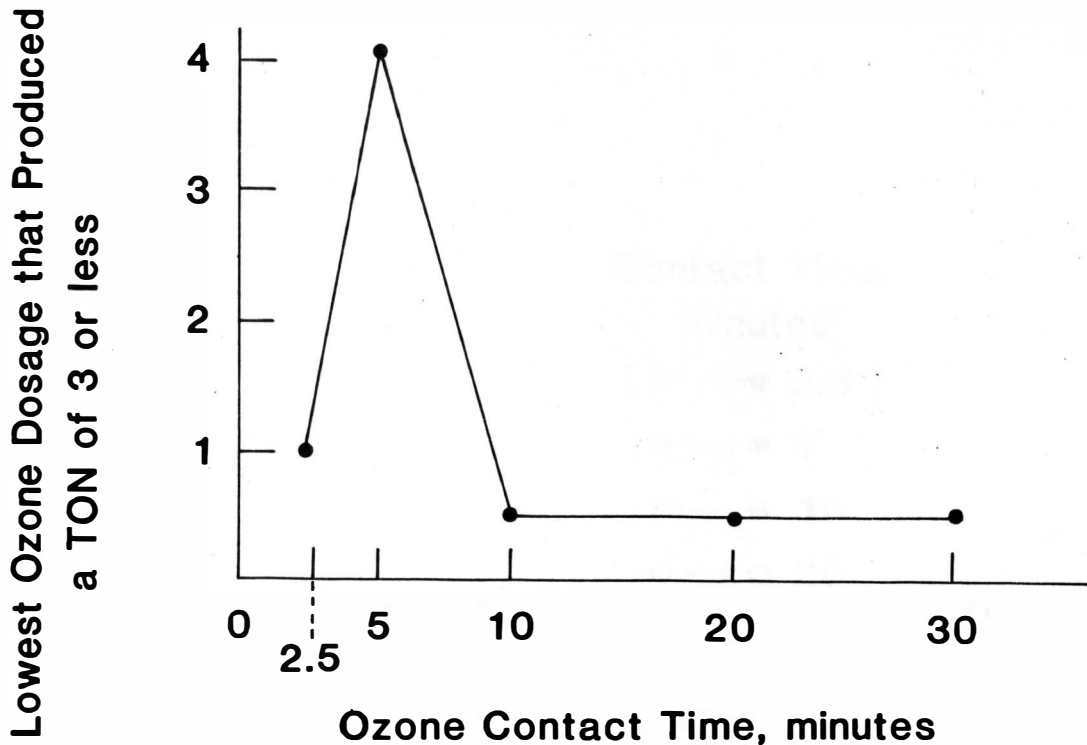


Figure 12. Lowest Ozone Dosage Required to Produce a TON of 3 or Less for Selected Contact Times

The least square means for TONs obtained at the ozone dosages and contact times selected have been plotted in Figure 13. From this figure, it can be seen that at the shorter contact times (5 minutes or less), the higher ozone dosages produced TONs that were lower than those obtained at lower ozone dosages. Also, at the longer contact times (10 minutes or more), there was less variation in TONs for different ozone dosages at the longer contact times than at the shorter times. This would seem to indicate that for ozone dosages up to 5.3 mg/l, the amount of ozone added exerted less effect on TONs at the longer contact times than at the shorter times.



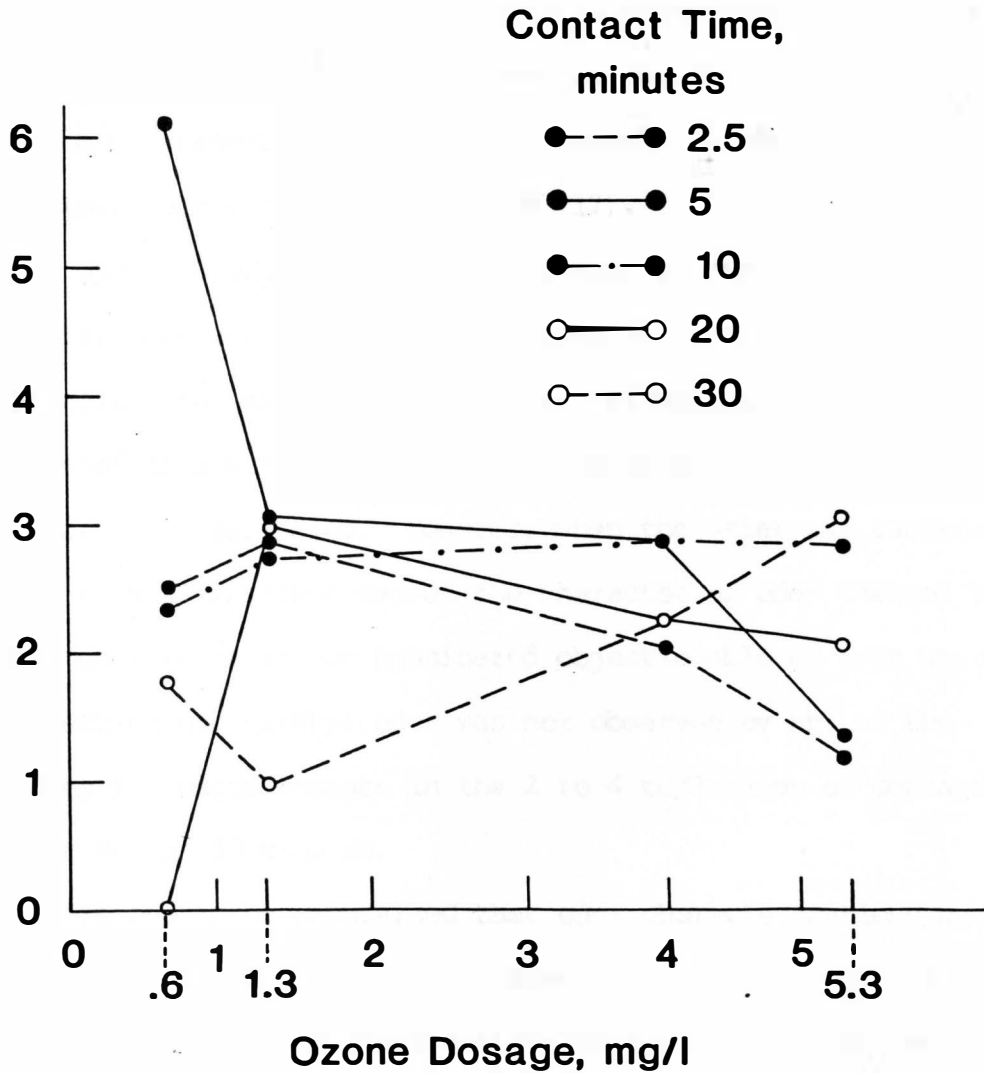


Figure 13. Least Square Means of Threshold Odor Numbers for Selected Ozone Dosages and Contact Times

### Effect of Ozonation on Odor Characteristics

Ozone can completely destroy (oxidize) most odor-causing compounds in water at very high dosages. However, investigators have found that this is not necessary to achieve effective odor control (14) (17). This is attributed to the ability of ozone to transform unpleasant odors to unobjectional, pleasant odors at relatively low, more economical, dosages (17).

Odor characteristics of the water, as described by the odor panelists, have been summarized in Table 5. The raw water was characterized as having an objectional "fishy" or "swampy" odor. Aeration of this water did not exert any effect on these objectionable odor characteristics. However, when the water was ozonated, even at relatively low dosages, the character of odor changed to a "musty" odor which is not considered objectionable by most users. The objectionable (fishy) odor was not observed by any of the panelists for ozone dosages in the 2 to 4 mg/l range at contact times of 20 or 30 minutes.

It should be emphasized that odor characterizations by odor panelists are highly subjective. Generally, the presence of an odor can be detected by most individuals with a reasonable degree of consistency. However, opinions can vary widely when these same individuals are asked to describe the character of the odor detected.

Table 5. Effect of Ozonation on Character of Odor,  
Budd Lake Water, Fairmont, Minnesota

Degree of Treatment	Odor Characteristics
1. Untreated Raw Water	Fishy, Swampy
2. Aerated at Contact Times of 2.5, 5, 10 and 20 minutes	Fishy, Swampy
3. Ozonated	
a) Ozone Dosage 1.3 mg/l at Contact Times of:	
1) 2.5, 5 and 10 minutes	Musty
2) 20 minutes	Sweet
3) 30 minutes	Musty
b) Ozone Dosage 2-4 mg/l at Contact Times of:	
1) 2.5, 5 and 10 minutes	Mostly musty; sweet, medicinal and fishy mentioned
2) 20 and 30 minutes	Musty, medicinal and sweet; no mention of fishy odor
c) Ozone Dosage 4-8 mg/l at Contact Times of 2.5, 5, 10, 20 and 30 minutes	Musty, medicinal, sweet

### Recommended Ozone Dosage and Contact Time

It should be noted that in recommending operating conditions for a full-scale water treatment plant from pilot data, a certain degree of conservatism is warranted. For example, if it is desired to provide a treated water with a TON of 3 or less, operating conditions that produce water with TONs well below 3 should be selected to account for operating differences between pilot systems and full-scale water treatment plants and variations in raw-water quality and rates of water treatment. To collect meaningful data, a pilot system is operated at a constant flow and relatively constant influent water quality. In a full-scale plant, raw-water quality varies as well as flow. Despite those variations the plant is expected to provide treatment stability, that is, a constant treated-water quality no matter what variations occur in flow or quality of the raw water.

### Ozone Contact Time

From results previously described, the shortest contact time in which ozonation produced water with TONs all below the recommended limit of 3 was 20 minutes. To provide for flow variations and more stable effluent quality, a contact time of at least 30 minutes should be used for a full-scale ozonation facility. The present pre-chlorination/contact basins have a volume of about 73,140 gallons. A summary of the contact times that could be achieved if these basins were used for ozonation may be found in

Table 6. It is apparent from this table that these existing basins would provide the recommended ozone contact time except at the maximum treatment rate. The feasibility of converting these basins to an ozone contact basin would depend on the geometry of the basins, their structural condition and the requirements of the Minnesota regulatory agency.

Table 6. Contact Times in Prechlorination/Contact Basins in Existing Plant at Current Flow Rates, Fairmont Water Treatment Plant

	Rate of Water Treatment, gal/min		
	1,600	2,400	2,800
Contact Time, min.	45.7	30.5	26.1

#### Ozone Dosage

The results of the pilot studies indicate that an ozone dosage of 0.5 mg/l is required to obtain TONs of 3 or less at contact times of 20 minutes or more. Dosages of 2 to 4 mg/l at contact times greater than 20 minutes were required to eliminate any trace of fishy odor from the water. It is recommended that the ozone generator be large enough to apply dosages of at least 4 mg/l at all flow rates. Furthermore, to provide additional treated water stability, consideration should be given to providing ozone generation capacity to apply an 8 mg/l dosage, with a final recommendation made on the basis of cost differential between a 4 mg/l and 8 mg/l

capacity. If the 4 mg/l capacity is selected, provisions should be included in the design to facilitate future expansion to the 8 mg/l capacity. In Table 7, the ozone generator capacities, in terms of the daily ozone output, are presented for the two recommended maximum outputs. It should be emphasized that the ozone generator capacity represents the maximum output capability of the equipment. The annual cost of operation of the ozone treatment system should be based on an anticipated dosage of 1 to 2 mg/l during the odor season and about 1 mg/l (for pre-disinfection) the remainder of the year.

Table 7. Ozone Generator Capacities<sup>1</sup> at Current Flow Rates, Fairmont Water Treatment Plant

Ozone Dosage, mg/l	Rate of Water Treatment, gal/min		
	1,600	2,400	2,800
4.0	76.8	115.0	134.0
8.0	154.0	230.0	269.0

<sup>1</sup> lbs Ozone per day

#### Effect of Ozone Residual on Odor Reduction

One of the methods used to operate an ozonation system is to adjust the output of the ozone generator to produce a detectable ozone residual in the contact-tank effluent. Supposedly, the presence of an ozone residual assures that there is sufficient ozone in the contact tank to obtain adequate odor reduction (1) (2).

In Table 8, the TONs for various ozone dosages and contact times are presented. The TONs for the runs where an ozone residual was detected in the contact tank effluent are indicated on the table. It is apparent from the table that in two instances, the presence of an ozone residual did not result in a TON below the recommended limit of 3 for odor control. It is worth noting, however, that the average TON for all samples where an ozone residual was present was 2.03, whereas the average TON of samples where no residual could be found was 2.67. Thus TONs were about 24 percent lower when ozone residuals were present. Nonetheless, it must be concluded that the presence of an ozone residual in the contact tank effluent is not a totally reliable method for controlling the ozone process for odor control.

Table 8. Threshold Odor Numbers for Various Ozone Dosages and Contact Times. Detectable Ozone Residuals Indicated

Ozone Dosage, mg/l	Contact Time, minutes				
	2.5	5	10	20	30
0.4-0.7	2.5	5.5	2.4	0	1.8*
1.3	2.3	2.6*	2.5*	-	1.3
2.2-2.7	2.7*	3.5	4.1	2.5	4.1*
3.8-4.0	1.9*	1.6*	2.4*	-	1.9*
5.0-5.5	1.3*	1.6*	2.6	2.3*	1.9*
7.5-9.5	-	1.5*	1.6*	2.0*	1.5*
12.3-13.1	-	-	1.6*	1.3*	1.7*
15.9-17.2	-	-	3.2*	2.9*	2.0*
21.4-26.3	-	-	1.3*	1.3*	2.2*

\*Ozone residual detected in contact tank effluent

Note: Average TON when ozone residual was detected in contact tank effluent: 2.03  
Average TON when ozone residual was not detected in contact tank effluent: 2.67



## CONCLUSIONS

The following conclusions were drawn from pilot studies in which the Fairmont surface water supply from Budd Lake was ozonated at dosages ranging from 0.4 to 26.3 mg/l and contact times from 2.5 to 30 minutes to ascertain the effectiveness of ozonation in reducing to odor levels of the water.

1. Although there was a statistical difference between the threshold odor numbers (TONs) obtained at the shorter contact times (5 minutes or less) and the TONs obtained at the longer contact times (10 minutes or more) at the 95 percent confidence level, no direct relationship between TON and contact time could be found for each ozone dosage studied.
2. A contact time of at least 20 minutes is required to reduce all TONs to levels below the recommended odor limit of 3.
3. For a given contact time, increases in ozone dosage were found to raise, lower or have no effect on odor levels (TONs).
4. Based on a comparison of the least square means for the TONs obtained, it would appear that at the shorter contact times (5 minutes or less), the higher ozone dosages produced TONs that were lower than those obtained at the lower ozone dosages. For ozone dosages

of about 5 mg/l or less, the amount of ozone applied apparently exerts less effect on the reduction in TONs at longer contact times than at shorter contact times.

5. Aeration alone did not change the character of the raw-water odors.
6. Ozonation, even at relatively low dosages, changed the character of the raw water from an objectionable, fishy odor to a musty unobjectionable odor.
7. Ozone dosages of 2 to 4 mg/l and contact times of 20 to 30 minutes are required to completely eliminate objectionable, fishy odors from the raw water.
8. The TONs obtained when an ozone residual exists in the contact tank effluent are generally lower than those obtained when there was no ozone residual.
9. The presence of an ozone residual in the contact tank effluent apparently does not completely insure that the TON of the effluent will be less than the recommended limit.

## RECOMMENDATIONS

The following recommendations are based on the results of the pilot studies and the need to provide a margin of safety due to variations in raw-water quality and in the rate of water flow through the treatment plant.

1. It is recommended that an ozone contact time of at least 30 minutes be used for a full-scale ozonation facility.
2. It is also recommended that a maximum ozone generator capacity of at least 134 and ideally 270 pounds per day be provided. If the lower capacity is selected, the ozonation system should be designed to facilitate future expansion to the higher capacity.

LITERATURE CITED

1. Bartuska, J. F., "Ozonation at Whiting, Indiana", American Water Works Association Journal, 33, 11, 1941, pp 2035-2050.
2. Bartuska, J. F., "Ozonation at Whiting: 26 Years Later", Public Works, 98, 8, 1967, pp 112-114.
3. DeBoer, D. E., Design, Construction and Performance Evaluation of an Ozonation Pilot Plant, Master of Science Thesis, South Dakota State University, Brookings, South Dakota, 1980.
5. Dodds, D., Personal Communication, Water Treatment Plant Superintendent, Spirit Lake, Iowa, November, 1985.
6. Ferkinhoff, T. O., "Ozone Solves Color, Odor and Taste Problem in Hobart Plant", American City, 50, 11, 1935, pp. 47-48.
7. Hann, V. A., "Water Quality Improvement With Ozone", Engineering News Record, 139, 1947, pp. 59-61.
8. Hoellein, Brian, "Ozonation Pilot Treatment of a Surface Water Supply, Ancillary Studies, Fairmont, Minnesota", M.S. Thesis, South Dakota State University, Brookings, South Dakota, 1987.
9. Kersten, Warren, "Ozonation of a Municipal Groundwater Supply and Water Purification Plant Treatment Process Modifications to Prevent Trihalomethane Formation", M.S. Thesis, South Dakota State University, Brookings, South Dakota, 1987.
10. Lee, Pin-Shi Peter, "Ozonation of a Municipal Surface Water Supply to Reduce Trihalomethanes, Odor, Chlorine Demand, and Organics", M.S. Thesis, South Dakota State University, Brookings, South Dakota, 1986.
11. LePage, W. L., "Ozone treatment at Monroe, Michigan", Second International Symposium on Ozone Technology, R. G. Rice, P. Pichet, and M. A. Vincet, editors, International Ozone Institute, Cleveland, Ohio, 1976, pp. 198-210.
12. LePage, W. L., "The Anatomy of an Ozone Plant", American Water Works Association Journal, 73, 2, 1981, pp. 105-111.
13. Lin, S. O., "Tastes and Odors in Water Supplies: A Review", Water and Sewage Works, 125, 2, 1978, pg. 49.
14. McLaughlin, M. J., "Ozonation Tests of Philadelphia Water Supply", Water Works Engineerins, 86, 20, 1943, pp. 1131-1134.

15. Miller, Wade, et al., "An Assessment of Ozone and Chlorine Dioxide Technologies for Treatment of Municipal Water Supplies", EPA-600/2-78-147, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, p. 19.
16. Montgomery, J. M., Water Treatment Principles and Design, John Wiley and Sons, 1985, pp. 374-393, 656-674.
17. Nusz, D. E., Ozonation of a Municipal Surface Water Supply to Reduce Odor and Enhance Flocculation, Master of Science Thesis, South Dakota State University, Brookings, South Dakota, 1982.
18. Pulice, D. J., "Is Ozone the Solution to Your Water Treatment Problems", Public Works, 117, 6, 1986, pp. 81-84.
19. Rakness, K. L., and B. A. Hegg, "Ozone Disinfection Design and Operation Considerations", Presented at the WPCF Disinfection Pre-Conference Workshop, Atlanta, Georgia, October 2, 1983.
20. Rice, R. G., "Uses of Ozone in Drinking Water Treatment", Ozone in Water Treatment-Applications, Operations, and Technology, American Water Works Association Technical Resource Book, 1985, pp. 3-16.
21. Rollag, D. A., "Pilot Studies Demonstrating the Feasibility of Ozonation for Selected Municipal Water Supplies", College of Engineering, SDSU, Brookings, SD, 1982.
22. Sindelar, Gary, "First Iowa Ozone Plant On-Line", Journal American Water Works Association, 77, 8, 1985, pp. 93-94.
23. Singer, P. C., "Trends in Ozonation", American Water Works Association Journal, August, 1985, pp. 19-22, 26-30, 91.
24. Sommerville, R. C. and Rempel, G., "Ozone for Supplementary Water Treatment", American Water Works Association Journal, 64, 6, 1972, pp. 377-382.
25. Standard Methods for the Examination of Water and Wastewater, 16th Edition, American Public Health Association, Washington, D. C., 1985.
26. Stoebner, R. A., Ozonation of a Municipal Groundwater Supply to Reduce Iron, Manganese, and Trihalomethane Formation, Master of Science Thesis, South Dakota State University, Brookings, South Dakota, 1980.

APPENDIX A

Selected Symbols and Abbreviation



Selected Symbols and Abbreviations

¢	= Cents
cfm	= cubic feet per minute
cm	= centimeter
°C	= degrees Centigrade
DC	= Direct Current
\$	= dollars
EPA	= Environmental Protection Agency
°F	= degrees Fahrenheit
ft	= feet
gal	= gallon
gpm	= gallons per minute
H <sub>2</sub> SO <sub>4</sub>	= sulfuric acid
Hg	= Mercury
hr	= hours
H <sub>z</sub>	= Hertz
ID	= Inside Diameter
in	= inch
KI	= Potassium Iodide
KPa	= Kilo pascals
KV	= Kilovolts
KW	= Kilowatts
l	= liters
lb	= pounds

l/min	= liters per minute
lpm	= liters per minute
m	= meter
mg	= milligram
mg/l	= milligrams per liter
MGD	= million gallons per day
mm	= millimeter
min	= minute
N	= normality
$\text{Na}_2 \text{S}_2 \text{O}_3$	= sodium thiosulfate
$\text{O}_2$	= oxygen
$\text{O}_3$	= ozone
PAO	= phenylarsine oxide
psia	= pounds per square inch atmospheric
psig	= pounds per square inch gage
$^{\circ}\text{R}$	= degrees Rankine
$Q_g$	= gas flow rate
$Q_l$	= liquid flow rate
scfm	= standard cubic feet per minute
TON	= Threshold Odor Number



## APPENDIX B

Experimental Calculations

### Experimental Calculations

#### A. Ozone Concentration:

$$C_i = (\text{Wt } O_3) / V_1$$

where: C = ozone concentration in gas (mg/l)

Wt  $O_3$  = Weight of ozone trapped in potassium iodide solution (mg)

$$= (N) (\text{ml titrant}) (24)$$

where: N = normality of sodium thiosulfate titrant

$V_1$  = corrected volume of gas measured by the wet-test meter (liters)

$$= (V_2) (P_1/P_2) (T_2/T_1)$$

where:  $V_2$  = actual volume of gas measured by the wet-test meter (liters)

$P_1$  = adjusted pressure = atmospheric pressure + wet-test meter monometer deflection - water vapor pressure (from Figure B1) (inches  $H_2O$ )

$$= \text{_____ inches of } H_2O$$

where: atmospheric pressure = \_\_\_\_\_ inches Hg

$$= x (13.6)$$

$$= \text{_____ inches } H_2O$$

$P_2$  = standard pressure = 1 atmosphere  
= 406.8 inches  $H_2O$

$T_1$  = wet-test meter temperature ( $^{\circ}R$ )

$T_2$  = standard temperature = 536.6  $^{\circ}R$

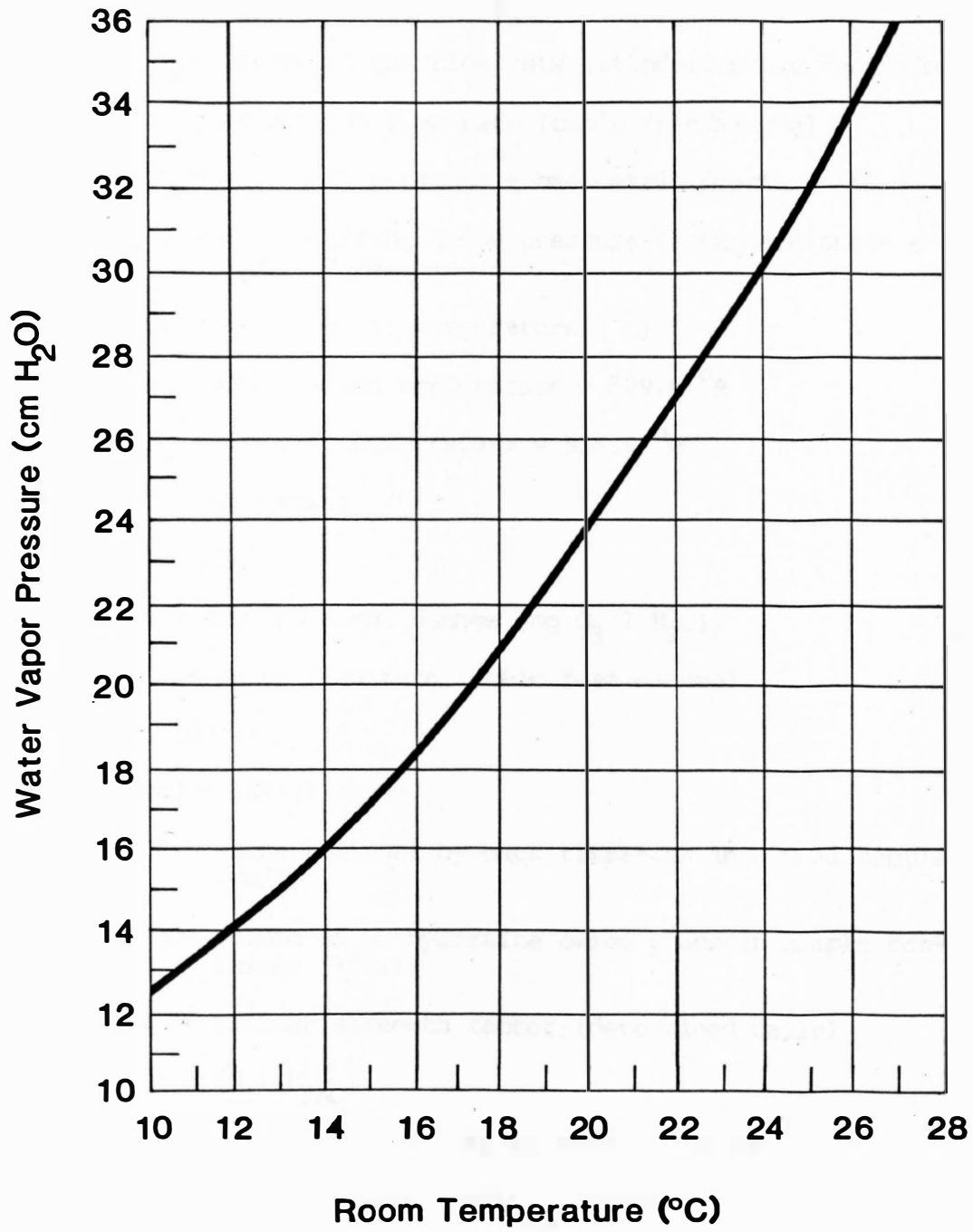


Figure B1. Water Vapor Pressure Versus Temperature

## B. Gas Flow Rate:

$$Q_g = Q_2 (P_3/P_4) (T_3/T_1)^{1/2} (T_2/T_3)$$

where:  $Q_g$  = corrected gas flow rate (standard cubic feet/minute)

$Q_1$  = actual gas flow rate (cubic feet/minute)

$P_3$  = gage back pressure + barometric pressure (psia)

$P_4$  = Standardizing gauge pressure + standard pressure  
= 14.7 psia

$T_1$  = ozonized air temperature ( $^{\circ}$ R)

$T_2$  = Calibration temperature = 529.6  $^{\circ}$ R

$T_3$  = Standard temperature = 536.6  $^{\circ}$ R

## C. Applied Ozone Dosage:

$$D = (C_i) (Q_g/Q_1)$$

where: D = applied ozone dosage (mg  $O_3$ /l  $H_2O$ )

$Q_1$  = water flow rate (cubic feet/minute)

## D. Ozone Residual:

$$OR = [(PAO - (K) (I))] (0.677)$$

where: OR = ozone residual by back titration in 200 ml sample  
(mg/l)

PAO = volume of phenylarsine oxide placed in sample container (10 ml)

K = titrant strength factor (determined daily)

$$= (N_I) (N_{PAO})$$

where:  $N_I$  = normality of iodine titrant

= approximately 0.00705

$N_{PAO}$  = normality of phenylarsine oxide

= 0.00564

I = volume of iodine titrant (ml)

## E. Threshold Odor Number:

$$\text{T.O.N.} = [(\text{T.O.N.}_1)(\text{T.O.N.}_2)\dots\dots(\text{T.O.N.}_n)]^{1/n}$$

where:  $\text{T.O.N.}_1, \text{T.O.N.}_2$  = individual threshold numbers  
for each panel member

where:  $\text{T.O.N.}_1,$   
 $\text{T.O.N.}_2$  = 200 ml/ml of  
sample water in dilution

APPENDIX C

Experimental Data and Statistical Analyses



Table C1. Threshold Odor Numbers at Various Ozone Dosages  
Contact Time of 2.5 Minutes

Applied Ozone Dose	Testing Date	Ozone Residual	Absorbed Ozone Dose	TON		% Red in TON
				Raw	O <sub>3</sub>	
.67	9/14/85	0	.64	7.3	2.45	66
1.30	9/14/85	0	1.03	7.3	2.27	69
2.65	9/15/85	.17	2.15	7.3	2.71	63
3.96	9/15/85	.25	3.27	7.3	1.92	74
5.28	9/22/85	.01	3.70	9.5	1.28	87

Table C2. Threshold Odor Numbers at Various Ozone Dosages  
Contact Time of 5 Minutes

Applied Ozone Dose	Testing Date	Ozone Residual	Absorbed Ozone Dose	TON	% Red in TON
.62	9/8/85	0	.53	5.54	-4.5
1.27	9/12/85	.169	1.04	2.55	65
2.63	9/13/85	0	2.28	3.49	52
3.92	9/13/85	.34	3.01	1.57	78
5.45	9/22/85	.004	4.08	1.59	83
7.50	3/30/86	1.57	6.36	1.45	27.5



Table C3. Threshold Odor Number at Various Ozone Dosages  
Contact Time of 10 Minutes

Applied Ozone Dose	Testing Date	Ozone Residual	Absorbed Ozone Dose	TON	% Red in TON
.66	9/16/85	0	.53	2.35	67.8
1.34	9/22/85	.01	1.14	2.52	73
2.67	9/22/85	0	1.94	4.09	57
3.96	9/28/85	.01	1.91	2.36	55
5.27	9/28/85	0	3.28	2.58	51
8.10	3/27/86	1.9	6.98	1.57	57
12.25	3/30/86	2.24	10.20	1.59	57
15.86	3/30/86	2.91	13.15	3.17	13
21.4	3/30/86	4.08	19.58	1.26	66

Table C4. Threshold Odor Numbers at Various Ozone Dosages  
Contact Time 20 Minutes

Applied Ozone Dose	Testing Date	Ozone Residual	Absorbed Ozone Dose	TON	% Red in TON
.46	3/31/86	0	.41	0	100
2.6	3/31/86	0	2.14	2.9	18.9
4.97	3/31/86	.11	4.08	2.3	37
8.9	3/26/86	.36	7.57	2.0	45
13.1	3/26/86	.73	10.84	1.26	66
17.2	3/26/86	1.52	13.84	2.9	21
22.7	3/26/86	2.4	17.80	1.26	66

Table C5. Threshold Odor Numbers at Various Ozone Dosages  
Contact Time of 30 Minutes

Applied Ozone Dose	Testing Date	Ozone Residual	Absorbed Ozone Dose	TON	% Red in TON
.42	3/31/86	.11	.42	1.83	42
1.34	3/24/86	0	1.06	1.26	66
2.2	3/31/86	.11	1.98	4.13	-13
3.8	3/31/86	.11	3.27	1.87	49
5.23	3/25/86	.19	4.96	1.9	64.8
9.52	3/25/86	.23	8.57	1.45	60
11.9	3/26/86	.40	9.10	1.68	54
15.98	3/26/86	1.11	11.07	2.0	45
26.3	3/25/86	2.98	13.15	2.23	39

Table C6. ANOVA of TON Results

---

<u>Source</u>	<u>DF</u>	<u>Sum of Squares</u>	<u>Mean Square</u>	<u>F Value</u>
model	19	122.96892	6.47204	6.36
error	72	73.28256	1.01781	
corrected total	91	196.25148		

<u>Source</u>	<u>DF</u>	<u>Type I SS</u>	<u>F Values</u>
time	4	17.67960	4.34
conc	3	7.12921	2.33
time . con	12	98.16010	8.04

---

Table C7. Least Square Means of TON Result

Least Square Means									
TIME	TON	PROB	LSMEAN(I)=LSMEAN(J)						
	LSMEAN	I/J	T	HO	1	2	3	4	5
5	2.98750	1				0.2036	0.0139	0.0007	0.0067
10	2.58250	2	0.02036				0.1846	0.0218	0.1438
20	2.11479	3	0.0139	0.1846				0.3548	0.9972
30	1.76375	4	0.0007	0.0218	0.3548				0.3122
2.5	2.11600	5	0.0067	0.1438	0.9972	0.3122			

Note: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

CON	TON	PROB	LSMEAN(I)=LSMEAN(J)					
	LSMEAN	I/J	T	HO	1	2	3	4
4	2.18793	1				0.2552	0.3198	0.6097
0.6	2.53760	2	0.2252				0.8880	0.1001
1.3	2.49450	3	0.3198	0.8880				0.1333
5.3	2.03160	4	0.6097	0.1001	0.1333			

Note: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

TIME	CONC	TON LSMEAN	LSMEAN NUMBER
5	4	1.70000	1
5	0.6	5.98000	2
5	1.3	2.95000	3
5	5.3	1.32000	4
10	4	2.50800	5
10	0.6	2.48600	6
10	1.3	2.66800	7
10	5.3	2.66800	8
20	4	2.44666	9
20	0.6	-0.00000	10
20	1.3	3.12250	11
20	5.3	2.89000	12
30	4	2.28500	13
30	0.6	1.69000	14
30	1.3	1.00000	15
30	5.3	2.08000	16
2.5	4	2.00000	17
2.5	0.6	2.53200	18
2.5	1.3	2.73200	19
2.5	5.3	1.20000	20

**Detention Time = 2.5 Minutes**

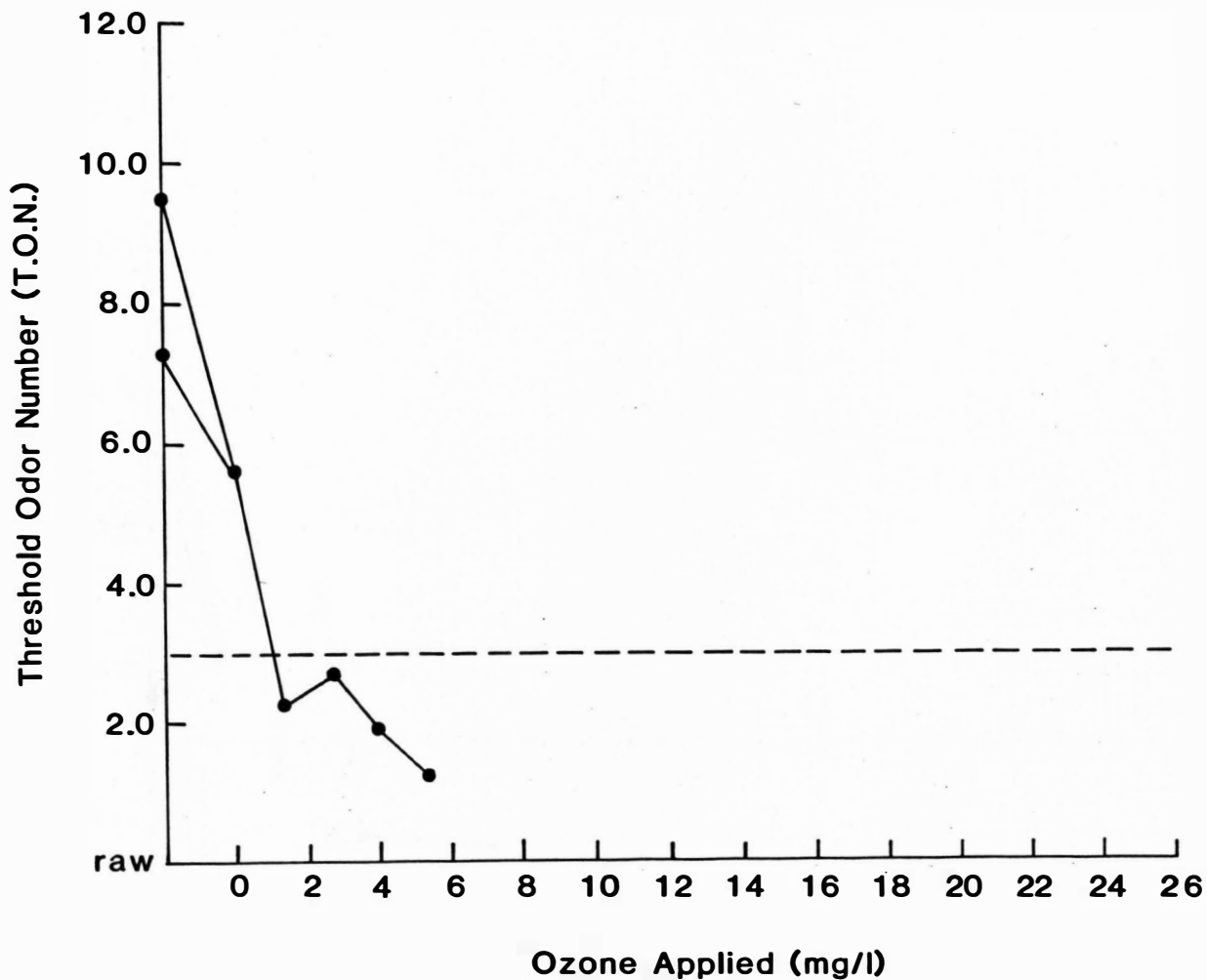


Figure C1. Threshold Odor Number versus Ozone Dosage,  
2.5 Minute Contact Time

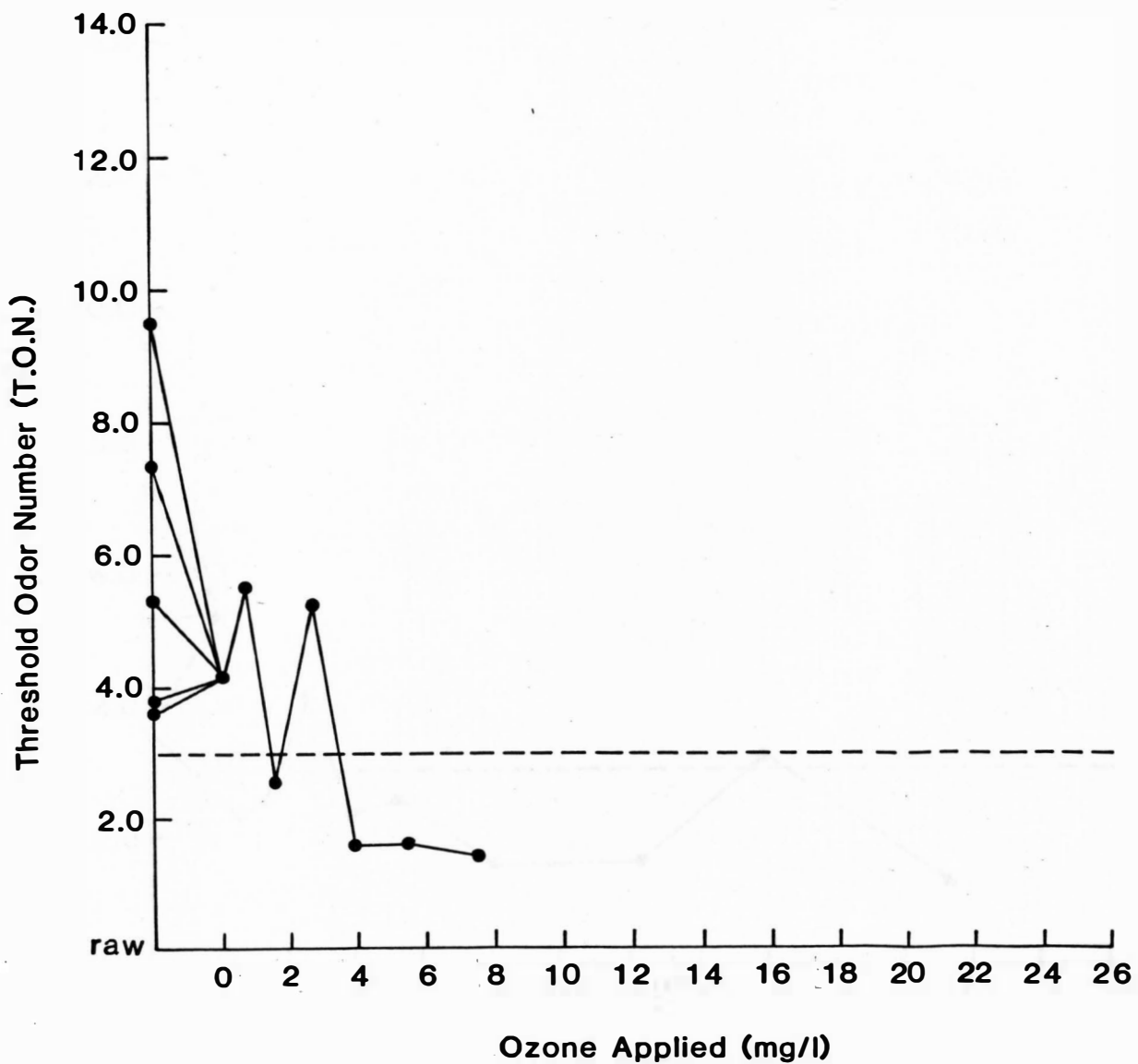
**Detention Time = 5 Minutes**

Figure C2. Threshold Odor Number versus Ozone Dosage, 5-minute Contact Time

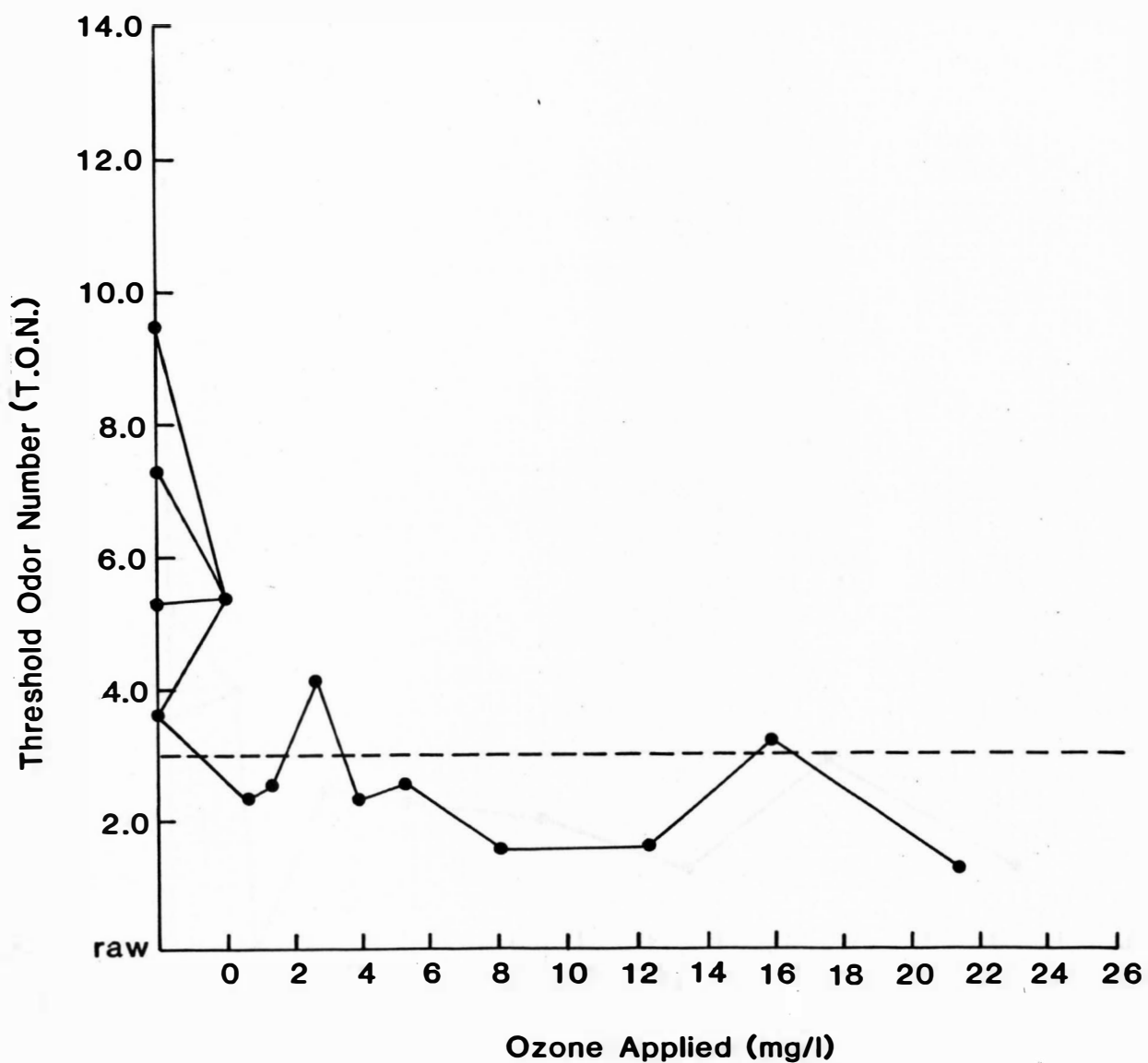
**Detention Time = 10 Minutes**

Figure C3. Threshold Odor Number versus Ozone Dosage, 10-minute Contact Time



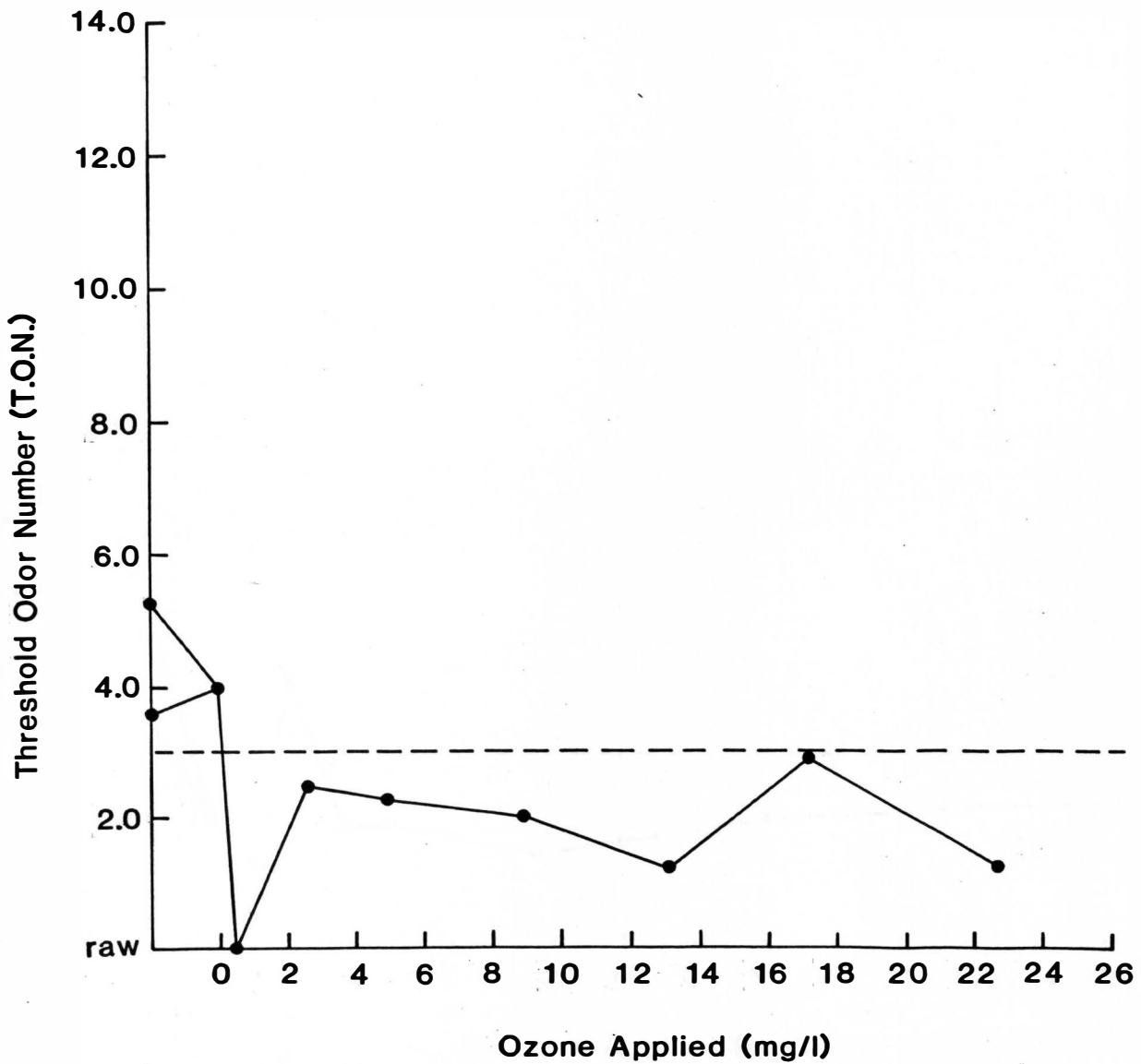
**Detention Time = 20 Minutes**

Figure C4. Threshold Odor Number versus Ozone Dosage  
20-minute Contact Time

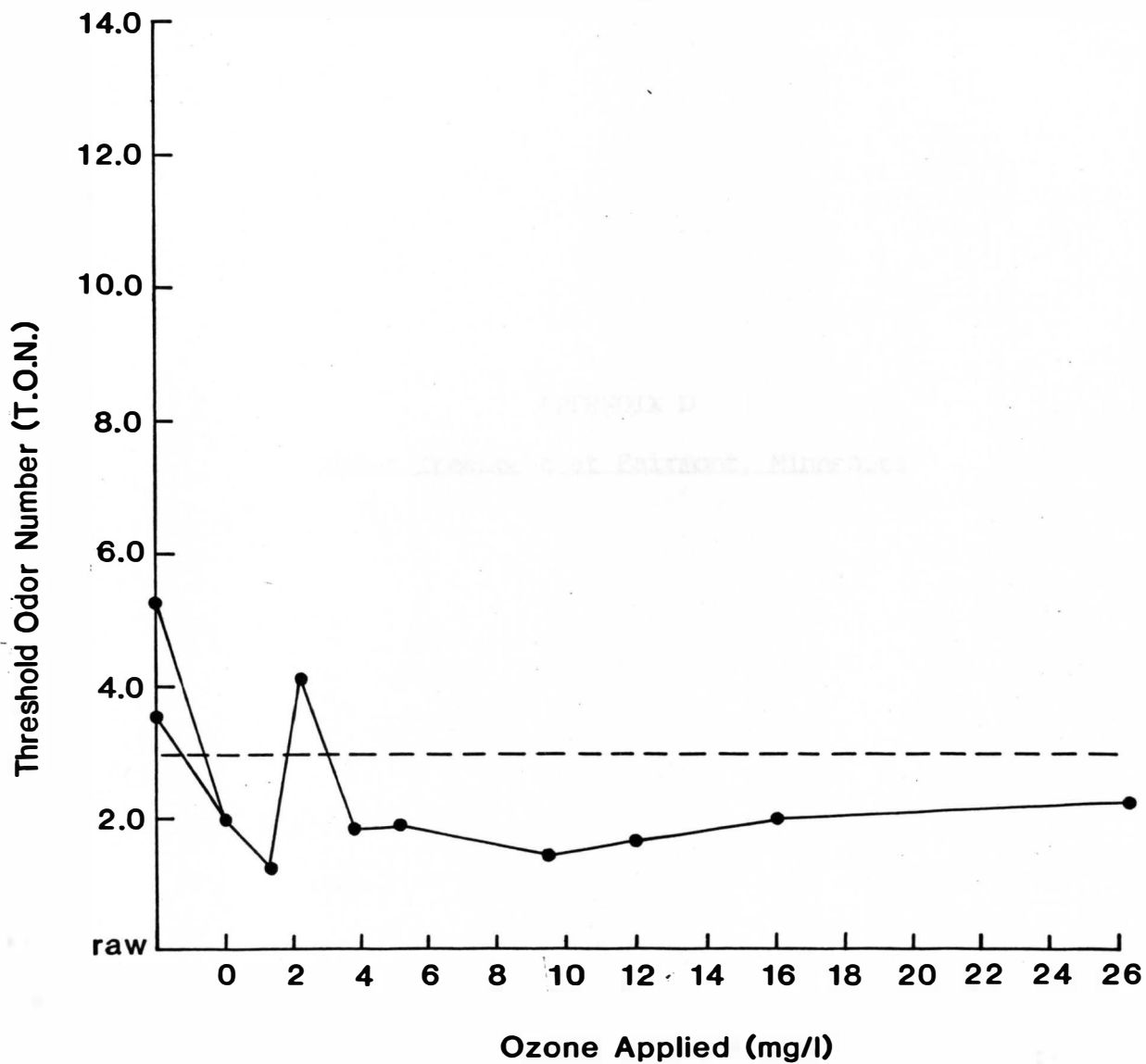
**Detention Time = 30 Minutes**

Figure C5. Threshold Odor Number versus Ozone Dosage, 30-minute Contact Time

APPENDIX D

Water Treatment at Fairmont, Minnesota



## Water Treatment at Fairmont

### History

The existing water treatment plant in Fairmont was constructed over a number of years with separate improvements made to it at different times. The source of water for the city of Fairmont and this plant is Budd Lake. This lake is fairly small and very susceptible to environmental influences.

In 1978, a new intake line and wetwell were added to the plant along with two new intake pumps. The new line was extended a greater distance into the lake to obtain better quality water during periods when water levels in the lake are low. At the same time, a groundwater supply well was constructed. This well is used only as a backup for the water supply from Budd Lake.

It has been stated that the Fairmont water treatment plant has a maximum capacity of 4.5 MGD, however the actual current maximum operating capacity is 4.0 MGD. The plant is presently capable of operating at 3 pumping rates: 1600 gpm (2.3 MGD), 2400 gpm (3.5 MGD), or 2800 gpm (4.0 MGD).

### Treatment Process

A schematic layout of the treatment plant is shown in Figure (D1). Table (D1) contains a list of the volumes and detention times of each basin at the specified flow rates. After raw water is pumped into the plant, it flows through a microscreen to

small particles and algae. The water then passes to a contact basin where activated carbon, alum, ammonia, and sometimes potassium permanganate are added. The water then flows into the prechlorination basins.

At this point the flow can be divided into 3 separate flow streams each having its own mixing basin where lime, soda-ash, polyphosphate, and possibly a coagulant aid are added. Each stream also has its own flocculation and settling basins. Streams 1 and 2 can each handle approximately 25 percent of maximum flow, while flow stream 3 can accommodate the other 50 percent.

After settling, the 3 flow streams are recombined and directed to a recarbonation basin where carbon dioxide is added to lower the pH. Following this step the water flows to the 3 rapid sand filters. The filtered water is then chlorinated, fluoridated and discharged to the clearwell. The clearwell serves as temporary storage, and a contact basin for the chlorine and fluoride. From the clearwell the water is pumped via high service pumps to the distribution system.



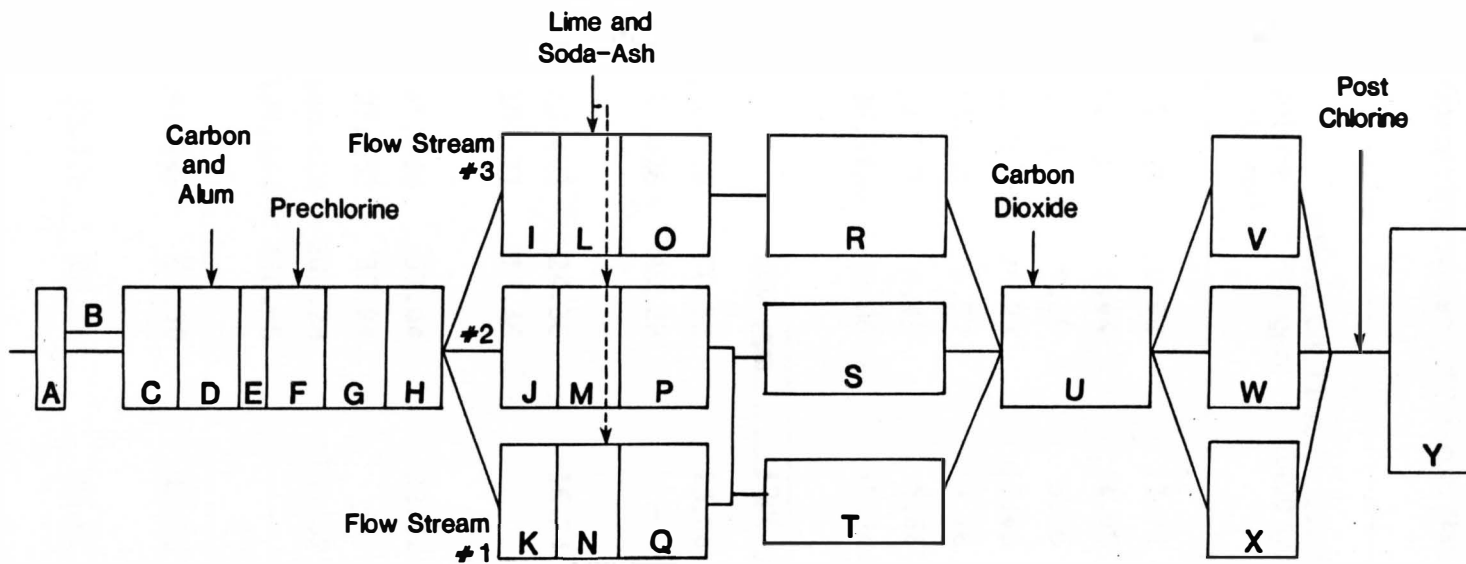


Figure D1. Schematic Diagram of Fairmont Water Treatment Plant

Table D1. Volumes and Contact Times for Each Basin at the Three Operating Rates, Fairmont Water Treatment Plant

Basin	Volume (gallons)	Detention Time At Flow Rates (Minute)		
		1600 gpm	2400 gpm	2800 gpm
A: Wetwell	33,420	20.88	13.92	11.94
B: Raw Water Inlet	11,907	7.44	4.96	4.25
C: Microstrainer	15,020	9.39	6.26	5.36
D: Chemical Feed	32,366	20.23	13.49	11.56
E: Contact Basin	10,034	6.27	4.18	3.58
F: Prechlorine Feed	13,580	8.49	5.66	4.85
G, H: Chlorine Contact (each)	36,570	22.86	15.24	13.06
		<u>800 gpm</u>	<u>1200 gpm</u>	
I: Chlorine Contact	30,818	30.52	25.68	
J, K: Chlorine Contact (each)	37,026	46.28	-	
L: Rapid Mix	19,493	24.36	16.24	
M, N: Rapid Mix (each)	10,771	13.46	-	
O: Slow Mix	45,628	57.04	38.02	
P, Q: Slow Mix (each)	27,152	33.94	-	
R: Clarifier	160,222	200.28	133.52	
S, T: Clarifier (each)	127,160	158.95	-	
U: Recarbonation Basin	101,286	63.30	42.20	36.17
V, W, X: Filters (each)	32,770	20.48	13.65	11.70
Y: Clearwell	640,000	6.67 hrs.	4.4 hrs.	3.8 hrs.