

## Characterizations of Assimilable Organic Carbon, Biodegradable Dissolved Organic Carbon, and Bacterial Regrowth in Distribution Systems by Water Treatment

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### 배수관망에서 수처리에 의한 AOC, BDOC 및 세균성장의 특성

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#### ABSTRACT

Two full-scale distribution systems, one treating water by ozonation and another treating water by nanofiltration in parallel with lime softening, were monitored for bacterial growth. Both systems kept disinfectant residuals such as chlorine and chloramine in their respective distribution systems. Bacterial growth was assessed by heterotrophic plate counts (HPC) on R2A agar. In the distribution systems fed by ozonated water, HPCs were correlated ( $R^2 = 0.97$ ) using an exponential model with the assimilable organic carbon (AOC) at each sampling site. Also, it was observed that ozonation caused a significant increase in the AOC concentration of the distribution system (over 100% increase) as well as a significant increase in the bacterial counts of the distribution system (average increase over 100%). The HPCs from the distribution systems fed by nanofiltration in parallel with lime-softening water also displayed an exponential correlation ( $R^2 = 0.75$ ) with an exponential model based on AOC. No significant correlation was found between bacteria growth on R2A agar and BDOC concentrations. Therefore, in agreement with previous work, bacterial growth in the distribution systems was found to correlate with AOC concentrations.

**Keywords:** AOC (assimilable organic carbon), HPC (heterotrophic plate counts), BDOC (biodegradable dissolved organic carbon), THMs (trihalomethanes), Nanofiltration

#### 요 약

배수관망에서의 박테리아 재 증식은 큰 현안문제로 대두되고 있으며 이를 억제하기 위한 염소소독 또한 발암성의 부산물인 THMs(trihalomethanes)등을 생성시킬 우려 때문에 미국에서는 오존살균처리 또는 나노여과(nanofiltration) 법으로 대체해 오고 있다. 그러나 종래의 많은 bench scale 실험결과를 통해 이러한 처리 이후에 잔존하는 미량의 유기물(assimilable organic carbon)이 박테리아 재 증식에 계속하여 영향을 주고 있다는 결과가 AOC(assimilable organic carbon)와 박테리아 재 증식의 상관관계를 통하여 밝혀지고 있다. 그러나 현재까지 이러한 연구결과를 full-scale 규모의 현장시설에서 직접 검토한 예는 없다. 따라서 본 실험은 미국플로리다주에 위치한 두 지역의 full-scale 배수관망 시설을 선정하여 실시하였다. 첫 번째 시설은 오존 살균처리를 그리고 다른 한곳은 나노여과와 석회연수법(lime softening)을 병행한 처리법을 사용하고 있다. 박테리아 증식은 R2A 배지를 사용하는 HPC(heterotrophic plate counts)법으로 평가했으며 오존이 공급된 배수관망에서의 HPC는 각 샘플링 지점의 AOC값을 이용한 지수모델과 높은 상관관계가 있음이 판명되었다( $R^2=0.97$ ). 또한 오존처리는 100%이상의 AOC 농도증가를 나타냈다. 나노여과법과 석회연수법을 병행하고 있는 시설에서도 AOC에

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근거한 지수모델과 상관관계를 나타냈다( $R^2=0.75$ ). 그러나 BDOC(biodegradable dissolved organic carbon)는 박테리아 증식에 있어 매우 낮은 상관관계 값을 표시했다( $R^2=0.11$ ). 결과적으로 종래의 많은 bench scale 실험결과와 같이 AOC는 배수관망에서의 박테리아 증식과 크게 상관관계를 갖고 있는 것으로 밝혀졌다.

## I. Introduction

Organic matter impacts the water quality of distribution systems by generating color, undesired taste, and odors. When a chlorine residual is provided for disinfection, organic compounds are responsible for high chlorine demands and the formation of disinfection byproducts (DBPs). Also, the biodegradable organic matter (BOM) that is not removed during water treatment can potentially lead to the proliferation of bacteria along the distribution system, which deteriorates the water quality, accelerates corrosion rates of pipes, and can potentially increase the incident of bacteriological diseases.

Since the promulgation of the THM (trihalo-methanes) Rule in 1979 and the Surface Water Treatment Rule (SWTR) in 1989, it has been the objective of water treatment to balance microbial removal while minimizing the formation of DBPs. One method to achieve this objective is to disinfect water with disinfectants other than free chlorine, such as ozone, which do not produce DBPs and also to decrease the chlorine residual concentration in the distribution system. Widely utilized in Europe, ozone oxidation is a common process in water treatment for the removal of water pollutants, odors, color, and tastes; and it exhibits strong disinfectant properties. However, even when lowering overall organic carbon levels, ozonation is known to convert part of these large natural organic molecules into smaller, more biodegradable organic molecules commonly quantified as assimilable organic carbon (AOC) or biodegradable dissolved organic carbon (BDOC) concentrations.<sup>1-5)</sup> These serve as "food" sources for heterotrophic bacteria present in the water and pipes throughout the distribution system, and this can result in bacterial regrowth.

A treatment process that removes a wide majority of pathogens, water pollutants, and organic carbon is nanofiltration, which is a type of membrane filtration. When nanofiltration is used in the treatment of water, the subsequent addition of free chlorine for residual is less likely to result in THMs due to the very significant reduction in organic carbon, one

of the precursors of THMs. Some types of membranes may remove a large portion of the BOM present in the water, which may translate into a corresponding reduction in AOC and BDOC concentrations in the finished water entering the distribution system. A significant fraction of the dissolved organic carbon (DOC) removed is also BOM, but since BDOC and AOC can still have significant impacts on biostability at ppm or ppb levels, respectively, there is a need to study the impacts of membrane treatment on these parameters.

The impacts of ozonation and membrane filtration on AOC and BDOC concentrations in finished waters and the corresponding potential impact it has on bacterial regrowth in distribution systems have been investigated in several bench- and pilot-scale studies. These investigations were conducted under controlled conditions. However, little full-scale data are available to quantify changes in the AOC and BDOC concentrations under dynamic field conditions, which are potentially significantly different from bench- and pilot-scale conditions. Therefore, this study had the objectives of conducting complete water quality and biological monitoring of the process and distribution systems treated via ozonation or nanofiltration.

### Nomenclature

AOC	assimilable organic carbon
BDOC	biodegradable dissolved organic carbon
BOM	biodegradable organic matter
DBP	disinfection byproducts
DOC	dissolved organic carbon
HPC	heterotrophic plate count
HRT	hydraulic retention time
MGD	million gallons per day
MSE	mean square of errors
OPC	anionic polymer
OUC	Orlando Utilities Commission
<i>p</i> -value	observed significance level
PBCWUD	Palm Beach County Water Utility Department
$R^2$	coefficient of determination
SOX	sodium hexametaphosphate

SWTR	surface water treatment rule
THM	trihalomethane
TOC	total organic carbon
WTP	water treatment plant

## II. Background

The water industry uses “regrowth” and “aftergrowth” synonymously to describe the unexplained occurrence of coliforms in the distribution system. However, more specific definitions of these terms have been provided.<sup>6)</sup> Regrowth is the recovery of disinfectant-injured cells that have entered the distribution system from the water source or treatment plant, while aftergrowth is the growth of microorganisms native to a water distribution system. Breakthrough is the increase in bacterial numbers in the distribution system resulting from viable bacteria passing through the disinfection process, and growth is the increase in viable bacterial numbers in the distribution system resulting from bacterial growth downstream of the disinfection process.<sup>7)</sup> Mechanisms responsible for the presence of coliform bacteria in drinking water supplies are often unknown or poorly understood, so the term “episode” or “occurrence” is more appropriate to describe the presence of coliform bacteria.<sup>8)</sup> Increased counts of chemoheterotrophic bacteria colonies in distribution system water are the result of bacterial contamination from outside the distribution system or multiplication of bacteria within the system or regrowth.<sup>9)</sup> The major concern involving regrowth is the multiplication of potentially pathogenic or opportunistically pathogenic bacteria.

Organic compounds, either dissolved or particulate (which can be hydrolyzed to a soluble form), provide energy sources for heterotrophic bacteria, which use organic carbon for the production of new cellular materials or as energy. As a result, BOM is gradually consumed as the water travels along a typical distribution system. The potential consequences of this are bacterial proliferation, degradation of the distribution water quality, acceleration of pipe corrosion, and other undesirable effects. Bacterial regrowth is possible even with minute amounts of BOM entering the distribution system (some bacteria, such as *Pseudomonas*, can even grow in distilled water lines). The concentration and nature of compounds promoting growth of bacteria (i.e.,

electron donors, acceptors, and nutrient sources) are generally considered to be the major growth-limiting factors and provide a potential means of control of aftergrowth and regrowth.

**AOC.** AOC refers to a fraction of the total organic carbon (TOC) that can be utilized by specific strains of defined mixtures of bacteria, resulting in an increase in biomass concentration that is quantified. AOC typically comprises just a small fraction (0.1~9.0%) of the TOC.<sup>10)</sup> AOC represents the most readily degradable fraction of BDOC/BOM. The inoculum for the AOC bioassay can be composed of a mixture of pure bacterial strains cultivated in laboratory conditions (*Pseudomonas fluorescens* P17 and *Spirillum* NOX), mixtures of environmental bacteria<sup>11)</sup> characterized by a great nutritional versatility, or mixtures of bacteria that utilize groups of specific compounds.<sup>9)</sup> Bacterial growth is monitored in the water samples by colony counts, and the average growth ( $N_{avg}$ ) observed during the incubation is converted into AOC units (as  $\mu\text{g/l}$  as acetate-carbon). This is done by using the growth yield of the bacteria derived from calibration curves obtained using standard concentrations of organic compounds (e.g., acetate or oxalate). A significant correlation exists between the AOC concentration and the density of heterotrophic bacteria in distribution water supplies.<sup>9,12)</sup> Van der Kooij<sup>9)</sup> showed that heterotrophic bacteria in a nonchlorinated system did not increase when AOC was lower than 10  $\mu\text{g/l}$ , while LeChevallier *et al.*<sup>12)</sup> suggested that regrowth may be limited by AOC levels less than 50~100  $\mu\text{g/l}$  in systems maintaining a chlorine residual.

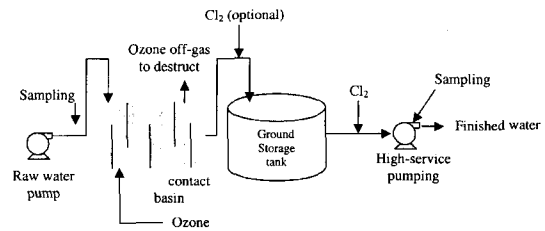
**BDOC.** The BDOC content represents the fraction of DOC that has been assimilated and/or mineralized by a heterotrophic flora.<sup>13)</sup> The inoculum for the test consists of environmental bacteria suspended or alternately fixed on a support, such as sand or porous beads. BDOC is the difference between the initial DOC of the water sample and the minimum DOC observed during the incubation period of 28 d for suspended indigenous bacteria or 5~7 d for bacteria attached to sand.<sup>14)</sup> Joret *et al.*<sup>15)</sup> suggested that BDOC values represent 10~30% of the total DOC content of drinking water. An absence of biodegradable organics after water treatment to limit bacterial regrowth has been recommended in the literature.<sup>10,16)</sup> Servais *et al.*<sup>17)</sup> have associated

biological stability, which corresponds to no BDOC consumption within the distribution system, with a BDOC concentration of 0.16 mg/l or less in the finished water. More recently, Volk *et al.*<sup>14)</sup> determined values of 0.15 mg/l at 20°C and 0.30 mg/l at 15°C for achieving biological stability in distribution systems of Paris suburbs. Finally, coliform occurrences were related to the existence of BDOC content greater than 0.10~0.15 mg/l.<sup>14)</sup>

**Experimental Section**

**Ozone WTP.** The Orlando Utilities Commission (OUC) Pine Hills Plant (Florida, USA) initially treated high quality Floridan aquifer water for the oxidation of hydrogen sulfide gas, corrosion control, and disinfection. The treatment did not involve aeration since the source water has relatively low sulfide levels (average 0.44 mg/l as total sulfide). Until May 1999, the treatment for hydrogen sulfide consisted solely of chlorination; in addition, caustic (pH control) fluoride and hydrofluorosilicic acid were added to the process stream. Raw water from five wells was pumped to a common raw water main, which passed through a chemical feed vault where the raw water was chlorinated (2.5 mg/l Cl<sub>2</sub>) to oxidize the hydrogen sulfide gas to elemental sulfur. Fluoride was also added in the chemical feed vault. The prechlorinated water then flowed through two water storage reservoirs in series where the precipitated sulfur could settle and collect. Water from the second water storage reservoir then flowed through a second chemical vault where additional chlorine (2.0 mg/l Cl<sub>2</sub>) was added to provide the residual required in the water distribution system. Sodium hydroxide was also added in the chemical feed vault to raise the pH to approximately 8.5 for corrosion control.

After May 1999, the raw water was diverted to two baffled, multi-zone, contact tanks where ozone was diffused into the first zone to oxidize the hydrogen sulfide gas to sulfate. The ozone contact tanks were sized to provide 10 min. of total detention time at the maximum daily flow. Air was diffused into the water near the outlet end of the contact tanks to raise dissolved oxygen concentration close to the saturation limit and to assist in stripping any remaining ozone. The contact tanks were closed and operated at a slightly negative pressure. The



**Fig. 1.** Orlando Utilities Commission (OUC) Pine Hills Process diagram for ozone oxidation.

ozone-treated water then flowed through a chemical feed vault where chlorine (2.0 mg/l) was added. The ozone dose averaged 4.7 mg/l during the study. At this high ozone dose, along with the lack of biological filtration after ozonation, a significant increase in the AOC levels entering the distribution system was expected. Figure 1 is a diagram of the ozone oxidation process at Pine Hills. As shown, ozone was introduced into raw water for sulfide oxidation followed by chlorination for residual disinfection. Sampling points were located in the part of the distribution system that contained water from just the Pine Hills plant. The plant was on line at a capacity of  $9.4 \times 10^4$  m<sup>3</sup>/d (25 MGD) and averaged  $6.9 \times 10^4$  m<sup>3</sup>/d (18.3 MGD) during the study.

No difference was observed between the raw water temperature before ( $24.9 \pm 0.74^\circ\text{C}$ ) and after ( $24.8 \pm 1.08^\circ\text{C}$ ) the introduction of ozonation as a treatment process. In general, the water temperature in the plant effluent varied from a minimum of 21°C to a maximum of 27°C (i.e., average of  $25 \pm 1.5^\circ\text{C}$  before and  $26 \pm 0.7^\circ\text{C}$  after the introduction of ozonation). Finally, the distribution system water temperature, which averaged  $25 \pm 2.6$  and  $25 \pm 2.3^\circ\text{C}$  before and after the introduction of ozonation as a treatment process. Therefore, the AOC and BDOC incubation temperatures (25 and 22~25°C, respectively) were indicative of distribution system temperatures.

Sample collection was performed by following the guideline outlined in Standard Methods 9060A (18). In addition to the plant effluent, there were five distribution systems sampling points: two with average hydraulic residence times (4 and 6.5 h) and three with maximum hydraulic residence times (10.5, 18.5, and 27 h). A total of 12 monthly

sampling campaigns were conducted during which temperature, pH, turbidity, and chlorine residual were measured at the time of sampling. Total coliforms, HPCs, UV-254, DOC, BDOC, and AOC were measured within 24 h of sampling at the University of Central Florida.

**Nanofiltration and Lime-Softening WTP.** The raw water to WTP 3, operated by Palm Beach County Water Utilities Department (PBCWUD), was from the Biscayne Aquifer, a shallow, surficial aquifer, with significant surface influence and some saltwater intrusion. WTP 3 divided the raw water

into two streams (one treated via lime softening and one treated via nanofiltration) and combined the two effluents just prior to the distribution system. WTP 3 with an ultimate projected design capacity of 36 MGD and current design capacity of  $6.0 \times 10^4$   $m^3/d$  (15.8 MGD) averaged  $4.4 \times 10^4$   $m^3/d$  (11.5 MGD) of actual flow during the 1-yr study. WTP 3 used a 32:16 nanofiltration array made of thin-film composite spiral-wound elements (TFCS 8929ULP-membrane element; Fluid Systems, San Diego, CA, USA) designed to reject hardness at 95% and chloride ion at 85%. The nanofiltration train was

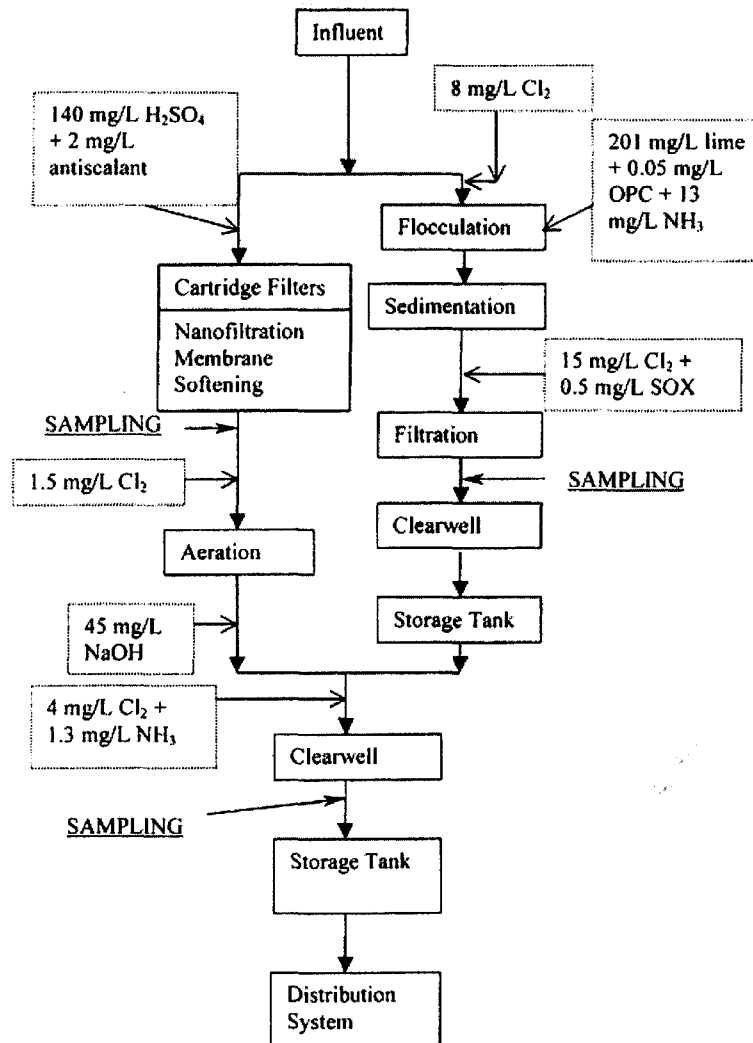


Fig. 2. Process schematic for Palm Beach Water Utilities Department (PBCWUD)'s Water Treatment Plant 3.

designed for  $3.5 \times 10^4 \text{ m}^3/\text{d}$  (9.3 MGD), and averaged  $3.0 \times 10^4 \text{ m}^3/\text{d}$  (7.8 MGD) during the study. Before the water was passed through the cartridge filters, 140 mg/l of sulfuric acid and 2 mg/l of antiscalant (proprietary) were added. After the water passed through the cartridge filters and the membranes, 1.5 mg/l of chlorine was added. The water was then aerated, and 45 mg/l of sodium hydroxide was added to the finished water from the nanofiltration train.

The lime-softening train in parallel with the nanofiltration train from WTP 3 was designed to treat  $2.5 \times 10^4 \text{ m}^3/\text{d}$  (6.5 MGD) and averaged  $1.4 \times 10^4 \text{ m}^3/\text{d}$  (3.7 MGD) during the study. Before flocculation, 8 mg/l chlorine was added to the influent water. Then, 201 mg/l of lime, 0.05 mg/l OPC, an anionic polymer, and 13 mg/l of ammonia were added to it during flocculation. After sedimentation, 15 mg/l chlorine and 0.50 mg/l sodium hexametaphosphate (SOX), to keep filters from solidifying, were added to the water. The effluents from both the nanofiltration and lime-softening trains were blended and had 4 mg/l of chlorine and 1.3 mg/l of ammonia added to the blended water, which was then sent to a 5 million gallon storage tank. Figure 2 shows a schematic of WTP 3. All chemical additions to the nanofiltration train remained constant during a 3-month period in which the lime-softening train was off line.

The water temperature ranged from a minimum of 21.3°C to a maximum of 28.8°C (average of 25.6°C). Therefore, the AOC and BDOC incubation temperatures (25 and 22~25°C, respectively) were indicative of distribution system temperatures.

Sample collection was performed by following the guideline outlined in Standard Methods 9060A.<sup>18)</sup> The permeate sampling point was located immediately after the membranes but prior to post-membrane chemical additions. There were five distribution system sampling points: two with average hydraulic residence times (6 and 10 h), and three with maximum hydraulic residence times (22, 28, and 30 h). A total of 12 monthly sampling campaigns was conducted during which temperature, pH, turbidity, and chlorine residual were measured at the time of sampling. Total coliforms, HPC, UV-254, DOC, BDOC, and AOC were measured within 24 h of sampling at the University of Central Florida.

Sampling extended from September 1998 through August 1999. For a 3-month period (November 1998-January 1999) during sampling, the lime train was shut down.

**HPCs.** HPCs were performed by spread plating on R2A agar incubated at 22°C for 7 d, according to Standard Method 9215B.<sup>18)</sup> Results were expressed in colony-forming units per milliliter (cfu/ml). The procedure was performed entirely inside a laminar flow hood (model 62674, Envirco Corporation, Albuquerque, NM) equipped with a HEPA filter.

**AOC.** AOC was measured using the rapid method of LeChevallier *et al.*,<sup>19)</sup> except that plate counts were used to enumerate bacteria rather than ATP fluorescence, in conjunction with Standard Methods 9217<sup>18)</sup> and the method of van der Kooij.<sup>20)</sup> The procedure used a temperature of 25°C for sample incubation and is outlined in great detail in ref 21. Quality control for the AOC bioassay was performed using blank controls, 100 µg/l sodium acetate standards, and duplicate samples. The 100 µg/l sodium acetate standards inoculated with P17 produced an average AOC of  $93.80 \pm 20.00 \text{ µg/l}$  as acetate-C, while for NOX, they produced an average AOC of  $77.20 \pm 12.53 \text{ µg/l}$  as acetate-C. Experimental yield values from acetate standards for P17 ( $4.08 \pm 0.81 \times 10^6 \text{ cfu/µg}$  of acetate-C) and NOX ( $9.26 \pm 1.50 \times 10^6 \text{ cfu/µg}$  of acetate-C) compared reasonably well with the literature values as specified in Standard Methods ( $4.1 \times 10^6$  and  $1.2 \times 10^7 \text{ cfu/µg}$  of acetate-C for P17 and NOX, respectively). Literature yield values were used for the AOC calculations to conform to the Standard Method.<sup>18)</sup> No controls were made to assess the effect of the thiosulfate (used to neutralize chlorine residual) since it has been determined not to affect AOC concentration<sup>22)</sup> and is included in the Standard Method.

**BDOC.** The procedure for BDOC determination followed the technique using sand fixed bacteria.<sup>21,23,24)</sup> In this method, there were two incubation flasks per sample plus two controls used in the BDOC method: sample flasks 1 and 2 (duplicates with 300 ml of sample each), activity control flask (300 ml of 2 mg/l sodium acetate solution), and inhibition control flask (300 ml of sample plus 3 ml of 200 mg/l sodium acetate stock solution). Approximately  $100 \pm 10 \text{ g}$  of drained biological sand was placed in

each incubation flask, and 300 ml of water/sample was poured into each incubation flask containing sand. The initial TOC of the water sample was measured and labeled as DOC. The sample flasks were then incubated at room temperature (22~25°C), and on days 3~6, the DOC concentration of each water sample was measured. The incubation continued until a minimum DOC value was reached.

**Statistical Analysis.** The monitoring data (2-yr for the ozone plant and 12-month for the nanofiltration/lime-softening plant) was regressed using SPSS version 9.0 (Chicago, IL, USA) and interpreted based on a 95% confidence level.

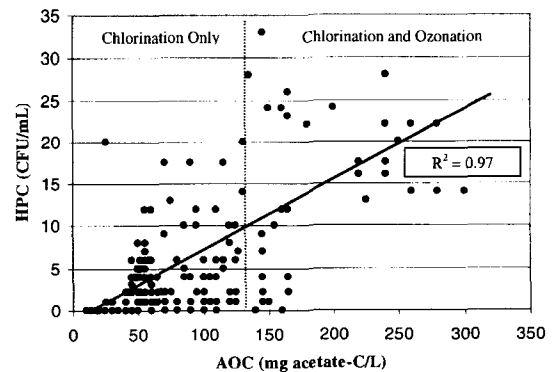
### III. Results and Discussion

**Ozone Distribution System.** The Pine Hills WTP, operated by OUC, was monitored from May 1998 to May 2000. Until May 1999, the raw water was treated via the addition of chlorine for hydrogen sulfide (2.5 mg/l Cl<sub>2</sub>) and for residual (2.0 mg/l Cl<sub>2</sub>). In May 1999, the treatment process was switched to ozonation for hydrogen sulfide removal (4.7 mg/l O<sub>3</sub>) and chlorination for residual disinfectant (2.0 mg/l). In each campaign there were seven sampling sites, the raw water, the plant finished water, and in the distribution system two average hydraulic retention time sites (HRTs of 4 and 6.5 h) and three maximum HRT sites (10.5, 18.5, and 27 h). The raw water to the plant was the deep Floridan aquifer, which displayed very stable and low organic carbon concentrations, averaging an AOC of 75 ± 35.0 µg/l as acetate-C, a BDOC of 0.11 ± 0.16 mg/l, and an average DOC concentration of 1.12 ± 0.43 mg/l prior to ozone. HPCs for the raw water averaged 178 ± 93 cfu/ml, and 2 mg/l of chlorine, as Cl<sub>2</sub> was added to the treated water.

Prior to ozone, the plant effluent and distribution system from the Pine Hills plant displayed an AOC from 62 to 81 µg/l as acetate-C and a BDOC of 0.12~0.23 mg/l. The  $\delta$ AOC (i.e., sampling site AOC - raw water AOC) or the increase in AOC caused by raw water treatment was approximately zero before ozone, and HPCs ranged from 3 to 7 cfu/ml. After the ozone was added, the plant effluent and distribution system AOC significantly increased ( $p$ -value < 0.0001) to 128~161 µg/l as acetate-C, while the  $\delta$ AOC increased to an average of 60 µg/l as

acetate-C. Therefore, AOC after ozone approximately doubled, which agreed with previous studies.<sup>1,3,25</sup> As expected, the AOC of the treated water significantly increased due to ozonation, probably because of the partial oxidation of larger organic carbon compounds to carboxylic acids facilitated by ozone oxidation.<sup>1,4,16,17</sup> The BDOC ranged from 0.19 to 0.40; however, the BDOC was highly variable and thus not significantly different ( $p$ -value = 0.707) from before ozone. Finally, like AOC, the HPCs increased to 8~15 cfu/ml, approximately double, which was significantly different from before ozone ( $p$ -value < 0.0001).

Figures 3 and 4 show the AOC and BDOC vs. HPC, respectively. There are 12 points in each plot because of six before ozone (plant effluent and five distribution system sampling sites) and six after ozone. Each sampling point is the average of 1 yr of sampling either before or after ozone. Figure 3 shows that the AOC increased significantly after the introduction of ozone and that there was a significant relation between HPCs and the AOC at plant effluent and distribution system both before and after ozone. The disinfectant residual was not included as a variable in the prediction model since its addition remained constant at 2.0 mg/l. Before ozone, the distribution system averaged 1.04 ± 0.34 mg/l while after ozone it was 1.17 ± 0.24 mg/l in the distribution system; thus, not significantly different. A series of linear as well as nonlinear regression models were tested in order to try all possible combinations and to determine the best prediction



**Fig. 3.** HPC vs. AOC for the OUC Pine Hills WTP effluent and five distribution system sites before and after ozone.

model based on 95% confidence. Of the models tested, HPC as a function of AOC (eq 1), displayed the most significant prediction model:

$$HPC = 2.00 \times e^{(0.011 \times AOC)} \quad (1)$$

This relation produced an adjusted  $R^2$  of 0.97 and MSE of 3.37. On the other hand, all BDOC models showed weak relations with HPCs as seen from Figure 4. When BDOC and HPC were regressed, the best  $R^2$  obtained was 0.12, which indicates a weak relation. Figure 5 shows the actual average HPCs vs. the AOC model (i.e., eq 1) predicted counts. It was determined that there was no significant difference between the actual and the predicted HPCs ( $p$ -value = 0.997).

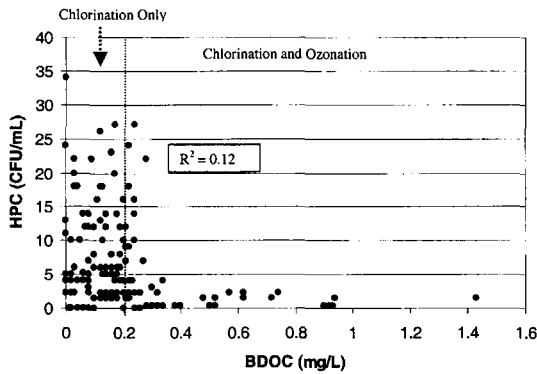


Fig. 4. HPC vs. BDOC for the OUC Pine Hills WTP effluent and five distribution system sites before and after ozone.

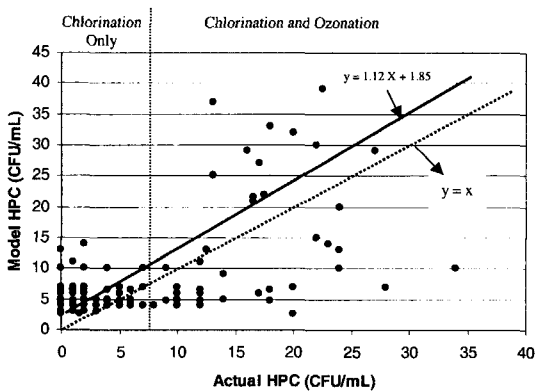


Fig. 5. AOC model predicted (dotted line) vs. actual HPCs for the OUC Pine Hills WTP effluent and five distribution system sites before and after ozone.

**Nanofiltration in Parallel with Lime Softening.**

The Biscayne Aquifer supplies all municipal water systems from Palm Beach County southward, including the pipeline system to the Florida Keys. It is a highly permeable wedge-shaped unconfined aquifer that is more than 61 m (200 ft) thick in coastal Broward County and thins to an edge 56.3~64.4 km (35~40 mi) inland in the Everglades. The Biscayne Aquifer is composed primarily of quartz sand, which permits rapid infiltration of rainfall. Unusual weather patterns were experienced during the 12-month sampling period. Heavy rainfall events occurred during the months of February through the beginning of May, and a strong drought followed until the initial days of July, when heavy rainfall happened again. This unstable weather was associated with record high temperatures recorded in the PBCWUD raw water and distribution system. During the period of monitoring, the raw water AOC averaged  $141 \pm 140.00 \mu\text{g/l}$  as acetate-C, BDOC was  $2.8 \pm 1.48 \text{ mg/l}$ , DOC averaged  $11.8 \pm 3.09 \text{ mg/l}$ , and HPC was  $231 \pm 74.68 \text{ cfu/ml}$ . During each sampling campaign, there were nine sampling sites: raw water, nanofiltrate, lime-softening effluent, plant effluent, two average HRT sites (8 and 10 h), and three maximum HRT sites (22, 28, and 30 h).

The AOC of the plant effluent (blended water between nanofiltration and lime softening) and five distribution system sampling sites ranged from 20 to  $440 \mu\text{g/l}$  as acetate-C, while the  $\Delta\text{AOC}$  ranged from  $-121$  to  $124 \mu\text{g/l}$  as acetate-C. The BDOC ranged from 0.00 to  $1.39 \text{ mg/l}$ , and the DOC ranged from 1.83 to  $5.16 \text{ mg/l}$ . Finally, the HPC of the plant effluent and distribution system ranged between 0 and  $20 \text{ cfu/ml}$ , and the chloramine residual ranged from 3.0 to  $5.0 \text{ mg/l}$ . Therefore, the data were highly variable, probably due to the high variability of the raw water. As with the ozone plant, several linear and nonlinear regression models were tested where HPC was the y-variable and AOC and BDOC were tried as x-variables. HPC was best predicted as an exponential function of AOC (eq 2) with an  $R^2$  of 0.75 and MSE of 14.86:

$$HPC = 1.86 \times e^{(0.0049 \times AOC)} \quad (2)$$

Figure 6 shows the AOC concentrations vs. HPC, which somewhat supports the finding that a relation



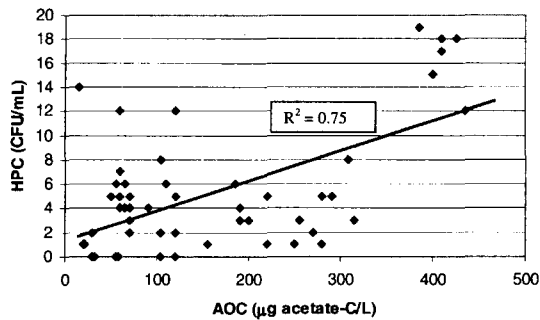


Fig. 6. HPC vs. AOC for the Palm Beach County WTP effluent and five distribution system sites.

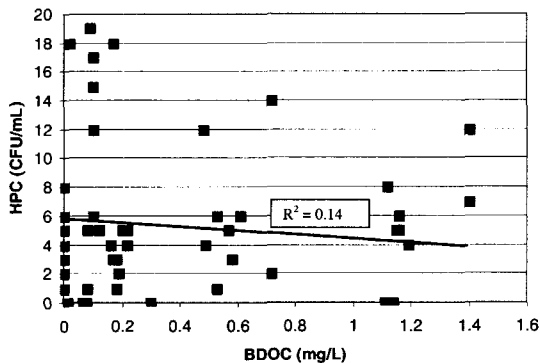


Fig. 7. HPC vs. BDOC for the Palm Beach County WTP effluent and five distribution system sites.

exists between HPCs and AOC for the plant effluent and distribution systems. Figure 7, BDOC vs. HPC, also supports the findings that BDOC was not significant in the prediction of HPCs with the best regression model showing an  $R^2$  of 0.14. Finally, Figure 8 shows the model-predicted HPCs vs. the actual HPCs, and it was determined that there was no significant difference between them ( $p$ -value = 0.773).

In summary, this study determined that a switch from chlorination to ozonation significantly increased ( $p$ -value < 0.0001) the AOC of the plant effluent and distribution system sampling sites probably due to the breakdown of larger organic carbon compounds, such as humic and fulvic acids, into compounds quantifiable as AOC. Also, a switch to ozone also caused a significant increase in HPCs ( $p$ -value < 0.0001), which agreed with the increase in AOC concentration. This increase resulted in HPCs that

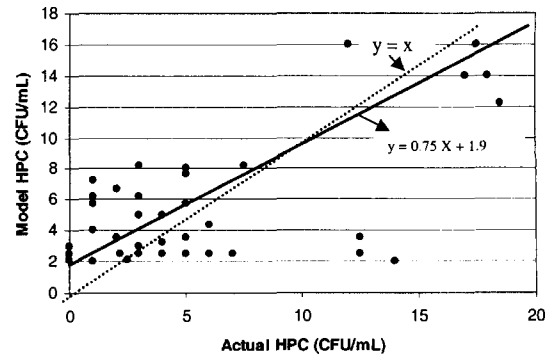


Fig. 8. Model predicted (dotted line) vs. actual HPCs for the Palm Beach County WTP effluent and five distribution system sites.

were still fairly low, probably because of the chlorine residual that was maintained in the distribution system. A significant relation ( $R^2 = 0.97$ ) was determined to exist between HPCs and the AOC concentrations in the distribution system fed by chlorinated water and later by ozonated chlorinated water. Likewise, in a system treating raw water via nanofiltration and lime softening, a relation ( $R^2 = 0.75$ ) was found to exist between HPCs and AOC concentrations in the plant effluent and distribution system even in the presence of a significant chloramine disinfectant residual. Finally, for both distribution systems monitored, BDOC was not related to HPCs probably because BDOC measures large molecular weight organic carbon compounds that are not as readily available for bacterial degradation as AOC compounds are.

A significant number of studies have been conducted at bench- or pilot-scale to evaluate the dynamics of distribution systems, with specific emphasis on the impact of water quality on the microbiological quality of these systems. Such studies, while quite informative, are limited in their ability to simulate the complex dynamics of operating full-scale distribution systems. Specifically, the impact of the concentrations of BOM on the microbiological quality of full-scale systems in the presence of all the other compounding factors is still in dispute.

This article deals with the correlation between AOC concentration and biological activity measured by HPC count. Significant correlations have been found using two different treatments: (1) ozonation

treatment and (2) nanofiltration in parallel with a lime softening unit. Both experiments exhibited correlation between AOC and HPC, while no correlation was found between BDOC and HPC for both treatments.

Ozonation is good in terms of lowering THMs potential by decreasing the disinfectant demand (ozone is an oxidant that can therefore play the role of pre-disinfectant). However, the drawback of using ozone is that it leads to an increase in AOC concentration and it is known that THM result from reactions between organic matter and chlorine. Thus ozone appears to be beneficial in one hand and detrimental in the other hand in terms of lowering THM potential.

It has been suggested that AOC repulsion by advanced membrane processes (NF: nanofiltration and RO: reverse osmosis) is a function of charge repulsion and that in hard waters, with low pH, AOC tend not to be rejected by the membrane.<sup>26)</sup> Therefore if NF or RO is to be used to decrease AOC concentration it is advised to include a treatment before the membrane unit to increase the pH and soften the water.<sup>26)</sup> By doing so, the overall membrane charge remains mainly negative, rejecting AOC.

As a combination of lowering AOC and THM potential, it is proposed to use a biological activated filter after the ozone unit to consume the AOC produced by the oxidative reactions of ozone with organic matter, followed by a softening and pH stabilization step prior to a membrane filtration unit (NF or RO).<sup>27)</sup> The treatment being finally completed by pH stabilization and disinfection.<sup>27)</sup>

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