

Description and Assessment of the Surface Water Filtration and Ozone Treatment System at the Northeast Fishery Center

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Abstract.—A water filtration and ozone disinfection system was installed at the U.S. Fish and Wildlife Service's Northeast Fishery Center in Lamar, Pennsylvania to treat a surface water supply that is used to culture sensitive and endangered fish. The treatment system first passes the surface water through drum filters operated with 60- μm sieve panels in order to exclude the majority of debris, algae, and organisms larger than the sieve openings. After microscreen filtration, two variable speed pumps are operated in parallel to supply between 400 and 2,400 L/min to the ozone treatment system. Ozone contained within an approximately 95% oxygen feed gas is transferred in to the water (at 0.5–0.7 bar) through a downflow bubble contactor following each pump. The ozonated water is then collected and piped to a 15.1- m^3 ozone contact column. The contact column provides approximately 20, 10, or 6.7 min of plug-flow contact time for water flows of 760, 1,500, or 2,270 L/min, respectively. A dissolved ozone probe at the outlet of the ozone contact chamber continuously monitors the dissolved ozone concentration discharged from the contact tank. A proportional-integral-derivative feedback control loop is used to adjust the concentration of ozone generated (and thus added) in order to maintain the dissolved ozone residual discharged from the ozone disinfecting contact tank at a preselected set point (nominally 0.2 mg/L). The water discharged from the ozone disinfecting contact tank then flows by gravity through a second 32.1- m^3 contact tank, which provides additional time for the dissolved ozone to decompose. Any dissolved ozone remaining in the water exiting the second contact vessel is air-stripped, along with any large dissolved oxygen supersaturation, as the water flows by gravity through a forced-ventilated cascade column. This treated water then flows by gravity to the fish culture systems. The ozone system was evaluated during a start-up period from March through June of 2002. During this period, the ozonation and filtration system was found to consistently inactivate bacteria and exclude the majority of debris larger than the microscreen openings, even during extreme changes in surface water quality produced by storm events. Design and performance details are provided to offer insight into the strengths and weaknesses of the individual treatment processes.

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Introduction

Sensitive and endangered fish species are maintained on a surface water supply at the U.S. Fish and Wildlife Service's Northeast Fishery Center in Lamar, Pennsylvania. Surface water is withdrawn from a nearby stream, Fishing Creek. Aquatic life in Fishing Creek can carry fish pathogens. Records and reports on hatcheries in the region indicate that the pathogens that may be present in the surface water supply at the Northeast Fishery Center include

- *Aeromonas salmonicida*
- *Yersinia ruckeri*
- *Flavobacterium columnare*
- *Infectious pancreatic necrosis virus* (IPNV)
- *Trichodina*
- *Epistylis*
- *Trichophyra*
- *Chilodonella*
- *Ichthyophthirius*
- *Scyphidia*
- *Myxobolus cerebralis*
- *Gyrodactylus*
- *Dactylogyrus*
- *Ichthyobodo*

We describe a water filtration and ozonation facility that was installed to exclude vertebrates and invertebrates and to inactivate potential fish pathogens contained in the Fishing Creek water supply before it enters the intensive culture (IC) building.

The facility contains two microscreen drum filters installed with 60- μ m panels to exclude the majority of vertebrates and macroinvertebrates. After the larger organisms and particles have been removed by the microscreen drum filters, ozone is added to inactivate bacteria, viruses, protozoa, micrometazoa, fungi, and other parasites before entry into the IC building. Ozone dose and contact time requirements are not published for many of the fish pathogens listed above (Table 1). However, available data for the elimination of other pathogens were reviewed with respect to ozone concentration and contact time (C^*t) required to pro-

duce microorganism reductions of generally greater than 99% (Table 1). When reported, ozone C^*t requirements ranged widely but were approximately 0.05–0.6 mg/L · min for *Aeromonas salmonicida*, 2.8 mg/L · min for *Flavobacterium*, 0.005–1.0 mg/L · min for *Yersinia ruckeri*, and 0.005–2.2 mg/L · min for IPNV (Table 1). No ozone C^*t data were found for the parasites that were previously encountered at the Northeast Fisheries Center (i.e., *Trichodina*, *Epistylis*, *Trichophyra*, *Chilodonella*, *Ichthyophthirius*, *Scyphidia*, *Myxobolus cerebralis*, *Gyrodactylus*, *Dactylogyrus*, *Ichthyobodo*). The Northeast Fishery Center's ozonation facility was designed to provide a relatively high ozone dose and contact time (i.e., 2.0 mg/L · min of dissolved ozone residual remaining after the water flow exits the disinfecting contact tank. Similar ozone C^*t doses have been used to control specific fish pathogens in the surface water supply at the Dworshak National Fish Hatchery in Ahsahka, Idaho (Owsley 1991), as well as ozone C^*t doses approximately 50% higher at the Cowlitz salmon hatchery in Tacoma, Washington and the Merwin state hatchery in Ariel, Washington (Cryer 1992).

Maintaining a given ozone concentration after a given contact time can be difficult due to ozone's rapid rate of reaction and destabilization in fish culture system water (Bullock et al. 1997). Constituents present in the water are the primary determinants of the rate of ozone decomposition (Summerfelt and Hochheimer 1997). Pure water has an ozone half-life of about 165 min. However, some waters have so much organic carbon and nitrite—both compounds that react with ozone—that ozone dissipates very rapidly and ozone half-life can be as low as several minutes or even several seconds (Summerfelt et al. 1997).

Fortunately, the Fishing Creek surface water supply supports a relatively clean trout fishery. However, this water still exerts an ozone demand that can change with storm events, seasonally (e.g., organic load), and with water temperature changes. Consequently, water samples were col-

TABLE 1. Concentrations/rates needed for ozone disinfection. Unless stated otherwise, values are to achieve $\geq 99\%$ reduction in pathogen concentration.

Organism	Ozone (C^*t) (mg · min/L)	Average ozone concentration (ppm)	Time (min)	Water type	Reference
Bacteria					
<i>Aeromonas hydrophila</i>		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
<i>A. hydrophila</i>		1.0	4	Laboratory effluent, some left after 4 min	(Austin 1983)
<i>A. salmonicida</i>		0.15–0.20	3	Lake, brackish, and seawater	(Lilved et al. 1995)
<i>A. salmonicida</i>		0.1–1.0	1.0	pH 7 distilled water	(Colberg and Lingg 1978)
<i>A. salmonicida</i>		90 mg/h/L	10	Lake (30 mg/L CaCO ₃); Lake (120 mg/L CaCO ₃)	(Wedemeyer and Nelson 1977); (Wedemeyer et al. 1979)
<i>A. salmonicida</i>		0.01	10	Phosphate-buffered distilled	(Wedemeyer and Nelson 1977)
<i>A. salmonicida</i>		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
<i>A. salmonicida</i>		0.4	4	Laboratory effluent	(Austin 1983)
<i>A. cariae</i>		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
<i>A. liquefaciens</i>		0.15–1.0	1.0	pH 7 distilled water	(Colberg and Lingg 1978)
<i>Enterococcus seriolicida</i>	0.186			Yellowtail, seawater	(Sugita et al. 1992)
<i>Flavobacterium</i> sp.		0.7	4	Laboratory effluent	(Austin 1983)
<i>Flexibacter</i> sp.		0.4	4	Laboratory effluent	(Austin 1983)
<i>Pasteurella piscicida</i>	0.084			Yellowtail, seawater	(Sugita et al. 1992)
<i>Pseudomonas fluorescens</i>		0.15–1.0	1.0	pH 7 distilled water	(Colberg and Lingg 1978)
<i>Renibacterium</i> <i>salmoninarum</i>		0.4	4	Laboratory effluent	(Austin 1983)
<i>Vibrio anguillarum</i>	0.123			Yellowtail, seawater	(Sugita et al. 1992)
<i>V. anguillarum</i>		0.15–2.0	3	Lake, brackish, and seawater	(Lilved et al. 1995)
<i>V. anguillarum</i>		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
<i>V. anguillarum</i>		0.4	4	Laboratory effluent	(Austin 1983)
<i>V. salmonicida</i>		0.15–2.0	3	Lake, brackish, and seawater	(Lilved et al. 1995)
<i>Yersinia ruckeri</i>		0.15–2.0	3	Lake, brackish, and seawater	(Lilved et al. 1995)
<i>Y. ruckeri</i>		90 mg/h/L	10	Lake (30 mg/L as CaCO ₃); lake (120 mg/L as CaCO ₃)	(Wedemeyer and Nelson 1977); (Wedemeyer et al. 1979)
<i>Y. ruckeri</i>		0.01	0.5	Phosphate-buffered distilled	(Wedemeyer and Nelson 1977)
<i>Y. ruckeri</i>		0.15–1.0	1.0	pH 7 distilled water	(Colberg and Lingg 1978)

TABLE 1. Continued.

Organism	Ozone (C*t) (mg . min/L)	Average oxone concentration (ppm)	Time (min)	Water type	Reference
<i>Bacillus polynyxa</i> spores		>1	>10	pH 7 distilled water	(Colberg and Lingg 1978)
<i>Bacillus megatherium</i> spores, 99%, pH 7, 10–15°C		0.03	10		(Morris 1976, cited in White 1992)
Enterobacteria	0.002				(Morris 1975, cited in Langlais et al. 1991)
Bacterial spores		0.5			(Morris 1975, cited in Langlais et al. 1991)
<i>E. coli</i>		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
<i>E. coli</i> , 99%, 1°C	0.006–0.02				(Katzenelson 1974, cited in Langlais et al. 1991)
<i>E. coli</i> , 99%, pH 6–7, 5°C	0.02				(Hoff 1987, cited in Langlais et al. 1991)
<i>Mycobacterium fortuitum</i> , 99%, 24°C	0.53				(Farooq et al. 1976, cited in Langlais et al. 1991)
<i>Mycobacterium tuberculosis</i> , 99%, pH 7, 10–15°C		0.005	10		(Morris 1976, cited in White 1992)
<i>E. coli</i> , 99%, pH 7, 10–15°C		0.001	10		(Morris 1976, cited in White 1992)
<i>Streptococcus fecalis</i> , 99%, pH 7, 10–15°C		0.0015	10		(Morris 1976, cited in White 1992)
Viruses					
HIRRV (hirame rhabdovirus)		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
IHNV		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)

TABLE 1. Continued.

Organism	Ozone (C*t) (mg . min/L)	Average ozone concentration (ppm)	Time (min)	Water type	Reference
IHNV		70 mg/h/L	10	Lake water (120 mg/L CaCO ₃); lake water (30 mg/L CaCO ₃)	(Wedemeyer et al. 1978); (Wedemeyer et al. 1979)
IHNV		1.0	10	Clearwater River, Idaho	(Cryer and Montgomery 1992)
IPNV		0.01	0.5–1.0	Phosphate-buffered, distilled water	(Wedemeyer et al. 1978)
IPNV		0.1	0.5–2.0	Artificial seawater	(Itoh et al. 1997)
IPNV		0.15–0.20	1	Lake, brackish, and seawater	(Liltved et al. 1995)
IPNV		90 mg/h/L	10	Hard lake water	(Wedemeyer et al. 1978); (Wedemeyer et al. 1979)
IPNV		90 mg/h/L	0.5	(120 mg/L CaCO ₃) Soft lake water	(Wedemeyer et al. 1978); (Wedemeyer et al. 1979)
IPNV		0.15	15	(30 mg/L CaCO ₃) Cold Lake, Alberta, Canada	(Wedemeyer et al. 1979)
IPNV		0.01	0.5–1.0	Phosphate-buffered, distilled water	(Cryer and Montgomery 1992)
YAV		0.1	0.5–2.0	Yellowtail ascites virus in artificial seawater	(Wedemeyer et al. 1978)
Viruses	0.2 ¹¹				(Itoh et al. 1997)
Polio 1, 99%, 5°C	0.2				(Morris 1975, cited in Langlais et al. 1991)
Polio 1, 99%, pH 6–7, 5°C	0.1–0.2				(Roy 1980, cited in Langlais et al. 1991)
Polio virus, 99%, pH 7, 10–15°C					(Hoff 1987, cited in Langlais et al. 1991)
Rotavirus, 99%, pH 6–7, 5°C	0.006–0.06	0.01	10		(Morris 1976, cited in White 1992)
Protozoa <i>Ceratomyxa shasta</i>	0.84–1.99			Cowlitz River, Washington	(Hoff 1987, cited in Langlais et al. 1991)
					(Tipping 1988); (Cryer and Montgomery 1992)

TABLE 1. Continued.

Organism	Ozone (C*t) (mg . min/L)	Average ozone concentration (ppm)	Time (min)	Water type	Reference
PKD (myxozoan) Amoebic cysts	3.36 2.0 ²¹	0.2	16.8		(Jensen 1994) (Morris 1975, cited in Langlais et al. 1991)
<i>Entamoeba histolytica</i> , 99%, pH 7, 10–15°C		0.1	10		(Morris 1976, cited in White 1992)
<i>G. lamblia</i> cysts, 99%, pH 6–7, 5°C	0.5–0.6				(Hoff 1987, cited in Langlais et al. 1991)
<i>G. muris</i> cysts, 99%, pH 6–7, 5°C	1.8–2.0				(Hoff 1987, cited in Langlais et al. 1991)
3 log reduction of Giardia cysts at 10°C and pH 6–9	1.4				(EPA 1989, cited in Langlais et al. 1991)
Fungi					
<i>Phytophthora cinnamomi</i> (plant)		1.5	8		(Mebalds et al. 1998)
<i>Pythium ultimum</i> (plant) <i>Fusarium oxysporum</i> (plant)		1.5	8		(Mebalds et al. 1998)
Alternariaceae (plant)		1.5	4		(Mebalds et al. 1998)
Saprolegnia on trout eggs		1.5	16		(Mebalds et al. 1998)
General recommendations For freshwater systems		0.03	Continuous		(Wedemeyer et al. 1979)
For equipment disinfection		1–5	10–16		(Liao and Daley 1995)
		0.5	30		(Watanabe and Yoshimizu 1998)

lected from the Fishing Creek water supply and sent to Dr. Wendell James of the Alberta Research Council (Vegreville, Alberta, Canada) for ozone demand testing. The ozone demand required to maintain a 0.2 mg/L residual after 10 min was between 2 and 3 mg/L of dosed ozone. These results are similar to, or somewhat less than the results that Cryer (1992) reported for ozonated surface water supplies at the Kitoi Bay hatchery (Alaska) and the Cold Lake fish hatchery (Alberta, Canada). To overcome the ozone demand of the water, especially where this demand can vary with different conditions, the ozonation system was sized large enough to dose a maximum ozone concentration of approximately 5 mg/L to the 1,500 L/min normal operating flow. The ozone generators have a 20:1 turndown, so a proportional-integral-derivative (PID) control loop was installed to automatically adjust the amount of ozone generated in order to maintain an ozone residual of

0.2 mg/L exiting the contact tank used for ozone disinfection.

Description of the Filtration and Ozonation Facility

The filtration and ozonation treatment facility was installed in a new building located between the existing IC building and a fish culture pond. The following sections describe the process flow path in detail (Figure 1).

Surface Water Supply Entry into the Filtration and Ozonation Building

The filtration and ozonation facility was connected to the existing gravity flowing and untreated surface water supply so that this flow could be directed into the filtration and disinfection facility or could bypass the filtration and disinfection facility to gravity flow into the IC building as untreated sur-

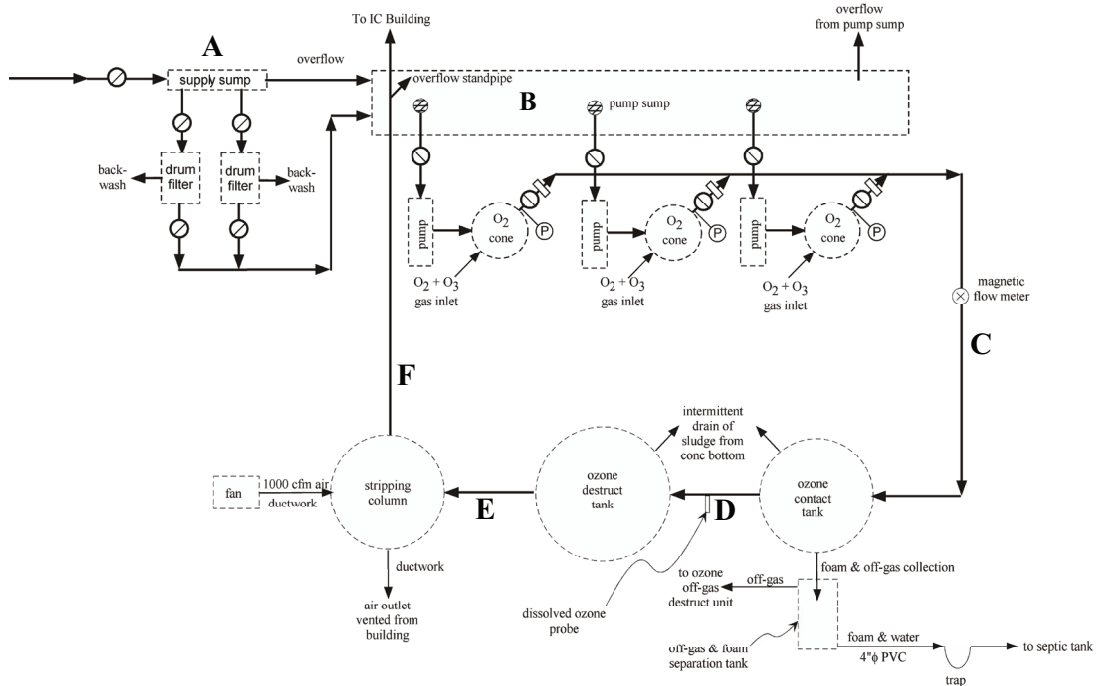


FIGURE 1. Schematic diagram of the ozonation system installed at the Northeast Fishery Center, which also indicates sample site locations.

face water. Once diverted away from the IC building, the rate that water flows into the filtration and ozonation building is controlled with a motor-driven actuator (model no. LVW3000 115A, Valvcon, Milford, New Hampshire) on a 20-cm-diameter butterfly valve that is located on the supply pipe immediately after this pipe has entered the IC building (Figure 1).

Water passing through the actuated butterfly valve enters sump A (Figure 1), which is used as a gravity supply for the microscreen drum filters. The water passing through the drum filters flows into a pump sump (sump B) that contains an overflow pipe to remove excess water (Figure 1). The flow into the filtration and ozonation building is automatically controlled based on the depth of water in sump B. Water depth is monitored using an ultrasonic transducer and a PID controller such that a small excess of water will overflow the pump sump under normal conditions. When water level begins dropping in sump B, the PID control system opens the motor-driven actuated butterfly valve to allow more water to flow into the drum filters and subsequently sump B. In its automatic mode, this control system maintains adequate water depth over the pump intake screens to prevent air from being entrained into the pump intakes and automatically adjusts the motor-driven actuated butterfly valve to send just enough water flow to maintain a slight overflow from sump B.

The programming to control the actuated butterfly valve is accessed through the computer in the building's supervisory control and data acquisition (SCADA) system. The programming can be run in automatic (so that the valve opening is automatically controlled to maintain water level) or manual mode, which allows a fixed open percentage to be selected.

Microscreen Drum Filters

Immediately following sump A, the water is piped through two microscreen drum filters (model RFM 3230, PRA Manufacturing, Nanaimo, British Columbia, Canada) that have

been plumbed in parallel (Figure 1). The drum filters were installed with sieve panels that contain 60- μm openings, which past experience has shown to be small enough to remove the majority of solids larger than approximately 30–60 μm . Flow is passed from the inside to the outside of the drum. When the drum rotates, solids trapped on the filter screen in the cells of the supporting grid are gently lifted out of the water. When the drum filter is operated without rinsing, however, the accumulating particulate matter begins to clog the screens, causing the water level within the drum to increase.

To maintain flow, solids are washed from the filter with a high-pressure spray during drum rotation. Drum rotation can be either continuous or intermittent when automatically controlled with a level switch located within the drum. A drum filter control panel allows the unit to be turned off or placed in either automatic or hand operating modes. During hand control, power is continuously supplied to the drum filter gear motor and to the two-way, normally closed, solenoid valve (type 73218, Parker Hannifin Corporation – Skinner Valve Company, New Britain, Connecticut) on the high-pressure water supply line so that the drum will continuously rotate and backwash. During automatic control, the drum is not rotated or backwashed until the difference in water level between the inside and outside of the drum reaches a predetermined upper level where the rising water triggers a float switch.

Upon receiving the high water level signal, the drum filter control unit provides power to the drum filter's gear motor and solenoid valve so that the drum rotates at least 180° each wash cycle. Once rotation and backwash have been activated, the drum will continue to rotate and backwash until the water level in the drum returns below the high level or until an adjustable time delay has expired. In either mode, the high-pressure wash water sprayed onto the top surface of the drum rinses the solids off the screens into collection troughs where they are piped to a septic tank for later disposal. Wash water production and backwash water

requirements are variable, but the volume of wash water required is typically about 2.6 L/min per operating spray nozzle. Each drum filter has 10 nozzles so each drum filter will require about 26 L (7 gal) of high-pressure wash water for every 1 min of run time.

Under typical operating conditions, one drum filter is left offline as a back-up while up to 2,270 L/min of water flow is passed through the other drum filter, which is backwashed based on drum water levels. In the summer, however, certain types of algae are difficult to wash from the microscreen surface during the normal backwash procedures, reducing the hydraulic capacity of the drum filter. In the event of problematic algae or during a storm event, both drum filters are operated in parallel to provide twice the hydraulic capacity of a single unit.

An overflow pipe was also installed in sump A to allow unfiltered water to bypass the drum filters directly to the pump sump (i.e., sump B) in the event that the drum filter screens are blinded. This overflow connection between the two sumps also ensures that adequate water can be transferred from the supply sump to the pump sump even in the event of a backwash failure or if inlet or outlet valves to/from both drum filters were mistakenly closed at the same time. A float switch installed in sump A activates a high water alarm at the computer if the water level in sump A rises more than approximately 2.5 cm above the invert of the overflow pipe.

The solids backwashed from the drum filters are piped to a septic-type tank where some of the settleable solids are captured and stored. An overflow of the settled water displaced from this septic tank connects to the overflow water discharge pipe coming from the filtration and ozonation facility.

High-Pressure Water Supply System

A common high-pressure water supply system was installed to provide backwash water on demand to both drum filters and to supply hose connections and a sink with nonpotable water. The water supplied to the hose connections and sink first passes

through a pressure-reducing valve. The high-pressure water supply system consists of two high-pressure booster pumps (model 8H75T, Aeromotor Pumps, Inc., Conway, Arkansas) that were plumbed in parallel, two independent electro-mechanical pressure switches (model GHG2, Square D Company, Bethlehem, Pennsylvania), a single backwash pump control panel (model B-DCP208, Northwest-Tech-Con Systems Ltd., Burnaby, British Columbia), a freestanding pressure tank (model WY-350, Amtrol, Inc., West Warwick, Rhode Island), the connecting piping, and the two solenoid valves that independently provide water on demand to each of the two drum filters (Figure 2).

A high water level signal from a switch located within each drum filter is used to activate backwash of that drum filter. When the drum filter controller calls for backwash a normally closed solenoid valve is opened on the high-pressure backwash line (Figure 2), which sends the high-pressure water to the drum filter's spray nozzles.

The two high-pressure pumps are controlled by independent electro-mechanical pressure switches through a single backwash pump control panel that contains a pair of hand-off-auto switches capable of controlling both pumps independently (Figure 2). Each pump runs when switched into the hand mode. When switched into the auto mode, each pump responds to signals from the pressure switches. The lead pressure switch is set for a cut-in of 5.4 bar (80 pound-force per square inch gauge [psig]) and a cut-out of 6.8 bar (100 psig). The lag pressure switch is set at a cut-in of 4.1 bar (60 psig) and a cut-out of 5.4 bar (80 psig).

Both pressure pumps are operated in auto mode during normal operation. As the filters draw backwash water from the pressure tank, the pressure in the tank falls. The first pump starts when the pipeline pressure falls below 5.4 bar (80 psig). This pump will remain running until the pressure switch signals the controller that line pressure has reached 6.8 bar (100 psig). If more water is drawn by backwash and sink/hose use than can be sustained by just the lead pump, then pressure in the tank

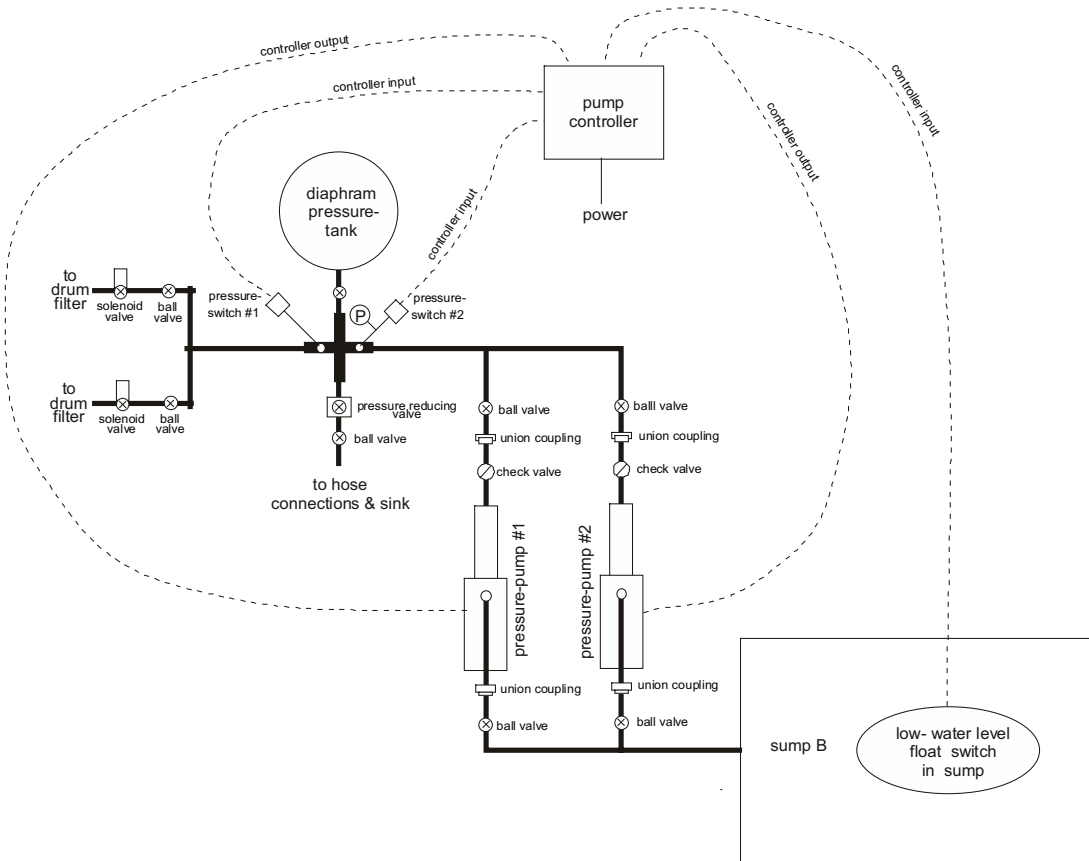


FIGURE 2. Diagram of high-pressure water supply system installed to provide backwash water on demand to both drum filters and to supply hose connections and a sink located with nonpotable water.

can fall below 5.4 bar (80 psig). The controller starts the second pump after pipeline pressure falls below 4.1 bar (60 psig) and stops this pump when pipeline pressure is returned to 5.4 bar (80 psig). The lead pump is turned off when the pipeline pressure has returned to 6.8 bar (100 psig). A light-emitting diode (one for each pump) on the backwash pump control panel's labeled faceplate indicates which pump is running at a given moment.

The high-pressure water system includes a freestanding pressure tank that is typically maintained at pressures between 5.4 bar (80 psig) and 6.8 bar (100 psig) by the automatic control of the two high-pressure pumps (Figure 2). The pressure tank is rated at 8.5 bar (125 psig). The pressure tank serves a use-

ful purpose as long as the pressure tank and line pressure switches are set correctly. The pressure tank air charge is set to 0.14 bar (2 psig) below the cut-in pressure on the lead pressure switch (i.e., about 5.3 bar). If the cut-in and cut-out pressures are 5.4 bar and 6.8 bar, respectively, then this pressure tank will supply 86 L of pressurized storage. Thus, the pressure tank can provide approximately three backwash cycles of pressurized water without activating a backwash pump.

Variable Speed Process Pumps and Sump B

The process water passing through the drum screens is collected in sump B. Swivel type

joints were installed on the elbows going into the pump sump from the three pump intakes, thus eliminating the need to shut the entire system down in the event the inlet strainers would clog up. Between 380 and 2,270 L/min of this microscreen filtered water is pumped from sump B through the ozone treatment process. To accomplish this, water is piped out of sump B to three 7.5-hp pedestal mounted variable speed centrifugal pumps (model SSH 8-1/4 imp, Gould Pump, Seneca Falls, New York). The three pumps were plumbed in parallel (Figure 1), one of which serves as a back-up while one or both of the other two are operated on automatic PID control. In automatic mode (set at the SCADA system computer terminal), the PID controller is programmed to adjust the output of one or two pumps in order to maintain a constant water pressure in the pipe supplying the IC building. In automatic mode, the pump controller balances the water flow demand of the IC building with the water flow pumped through the treatment building by maintaining a constant water pressure in the pipeline supplying the IC building. However, the pipeline supplying the IC building follows the two ozone contact columns and the gas stripping column, which produces some lag time in the pump control routine. The variable speed pumps can also be manually set to produce a constant water flow rate.

Ozone Gas Transfer Cones

Each pump supplies water to a downflow bubble contactor (Figures 1 and 3). The three downflow bubble contactors were fabricated by Marine Biotech, Inc. (Beverly, Massachusetts) in fiberglass reinforced plastic (FRP) using a vinyl ester ozone resistant resin (Atlac 580, Reichhold Chemical Inc., Durham, North Carolina). Each downflow bubble contactor is a cone-shaped cylinder (1.68 m tall) that is wider at its base (0.86 m) than at its top (10 cm). Water flow and the ozonated oxygen feed-gas both enter the top of the cone within a high turbulence zone that increases bubble shear and mixing.

Depending upon water flow rate through

the cone, the water velocity entering the top of the cone ranged from 0.8 to 2.4 m/s. This water velocity decreased in inverse proportion to the square of the cone's expanding diameter as the flow of water and bubbles travel down into the cone. The ozonated oxygen bubbles are captured in the cone when the water velocity is reduced to less about 0.3 m/s, which is the approximately the buoyant velocity of the bubbles (Boyd and Watten 1989). The water velocity at the base of each cone ranged from 0.011 to 0.033 m/s, which prevented captured bubbles from washing out of the cone during normal operating conditions. However, when maximum ozone doses were targeted, the feed gas flow rate to each cone was increased and the resulting gas:liquid loading rates were excessive (on the order of 0.03:1) and the overloaded gas bubbles could not be absorbed in the cone. However, based on the concentration of ozone gas supplied to the cone and concentration of ozone in the off-gas vented from the contact tanks (when off-gas was present), ozone absorption efficiencies in the cones exceeded 99%.

Water pressure inside the cone was typically 0.5–0.6 bar (8–9 psig), which is one factor that helped to increase ozone dissolution. Additionally, ozone is also about 13 times more soluble than oxygen, and its reaction with constituents in the water increases the rate of ozone transfer (Summerfelt and Hochheimer 1997).

Water Flow Monitoring

A magnetic flowmeter (Aquaflux 020K, Krohne, Inc., Peabody, Massachusetts) was installed to monitor the total combined flow of water pumped from the pump-cone pairs before the water is piped into the ozone contact column (Figure 1). The flow rate is displayed locally and on the computer terminal in the SCADA room.

Ozone Generators and Ozone Gas Supply Piping

Two ozone generators (model Ozat CFS-3, Ozonia North America, Elmwood Park, New

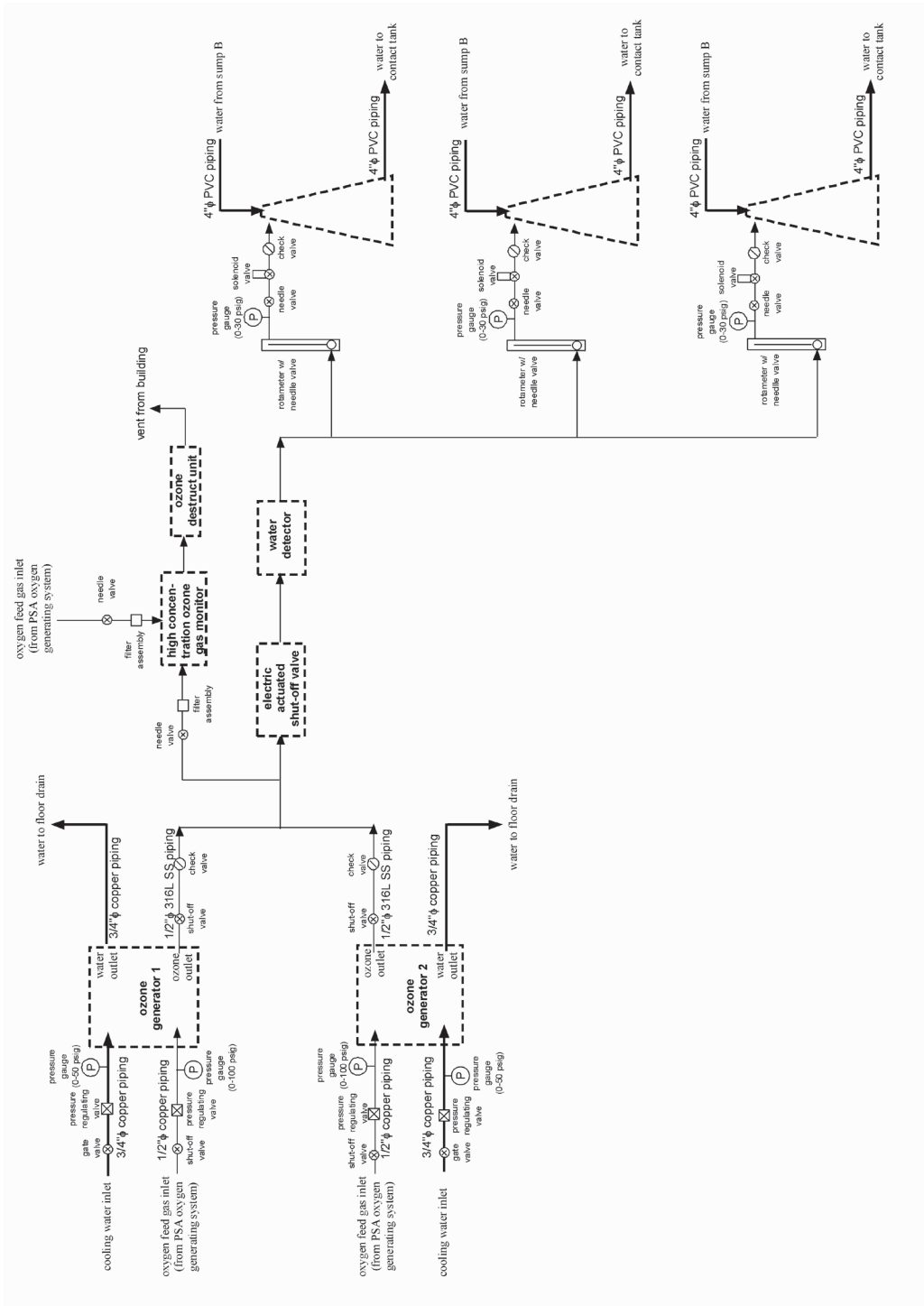


FIGURE 3. Process flow of the oxygen feed gas as it passes through the ozone generators to the downflow bubble contactors.

Jersey) were installed in parallel so that either generator could add ozone to a purified oxygen feed gas (Figures 3 and 4). According to the manufacturer, each ozone generator can produce approximately 6 kg ozone per day at 6% concentration in an oxygen feed gas supply that is supplied at 2.5–7.0 bar pressure. Each ozone generator produces sufficient ozone to dose a maximum ozone concentration of 2.8 mg/L into a 1,500 L/min normal operating flow, which is sufficient to meet the measured 2–3 mg/L ozone demand of the water.

Each generator accepts a 4–20 milliamp analog input signal from the computer controlled SCADA system to adjust ozone generator output from 5% to 100%, which is a 20:1 turndown ratio. Ozone generator output is adjusted by the PID control loop so as to maintain a constant 0.2 mg/L of ozone

residual concentration following the first ozone contact tank (Figure 4).

All material exposed directly to dry ozone gas are 316 stainless steel, Teflon, viton, or other material that resists ozone oxidation. The ozone gas supply piping also incorporates a 316 stainless steel water detector (PCI-Wedeco, West Cladwell, New Jersey) to identify backflow of water from the ozone transfer cones before this water could reach the ozone generator (which would only occur if a check valve failed). In the event of water detection, the water detector turns off both ozone generators and signals an electric shutoff valve to close, which prevents water from backing up into the ozone generators via the ozone gas supply pipe.

Copper piping and fittings connect the oxygen feed gas supply from oxygen generators to the ozone generators and separate

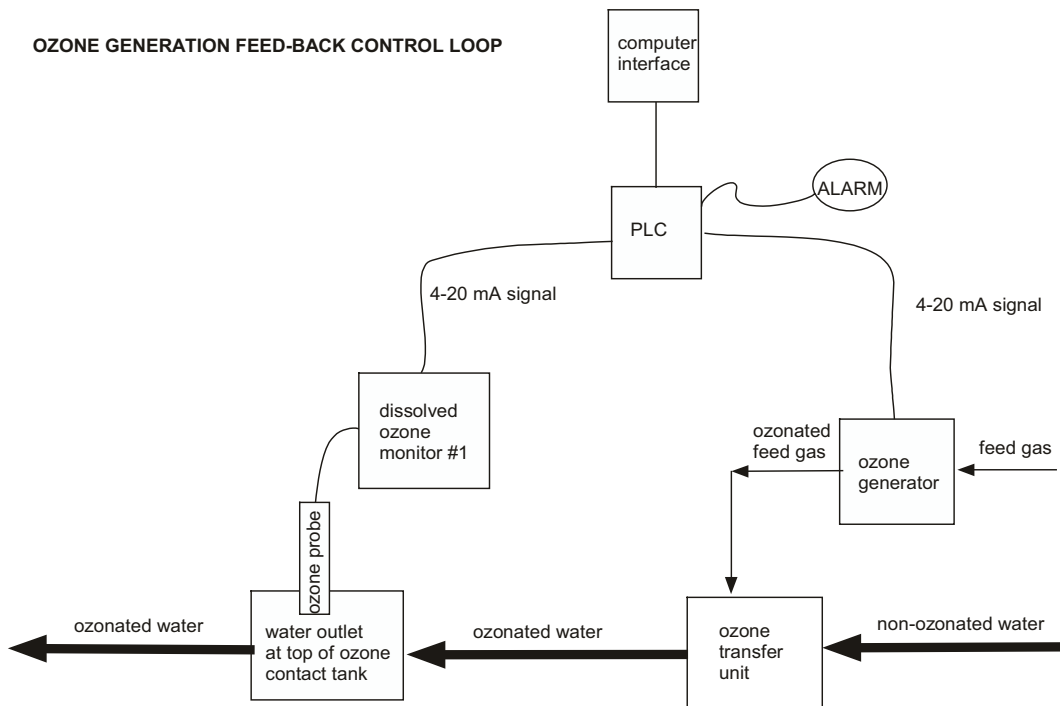


FIGURE 4. This process flow diagram shows a programmable logic controller (PLC) that is monitoring an analog signal coming from a dissolved ozone monitor. The PLC uses this information in a proportional-integral-derivative (PID) control routine that determines the analog control signal to send to the ozone generator to adjust ozone production so as to maintain the desired dissolved ozone concentration at the outlet of the ozone contact tank.

copper pipelines carry cooling water to and from the ozone generator.

The flow rate of ozone and oxygen feed gas were adjusted with a rotameter (model P-03234-57, Cole-Parmer Instrument Company, Vernon Hills, Illinois) mounted in front of each gas transfer cone (Figure 3). After the rotameter, the ozonated oxygen feed gas was piped through a check valve (Figure 3) to prevent backflow of water into the feed gas pipeline when the pressure in this pipeline drops below the pressure of water in the cone. A solenoid valve is also located on the ozonated oxygen feed gas line between the downflow bubble contactor and the rotameter (Figure 3). This solenoid valve is automatically opened and closed by a flow switch as the process water pump is turned on and off. The flow switch is located on the water pipeline immediately after the water exits the process pumps and its control of the solenoid valve on the ozone feed gas pipeline ensures that feed gas is only supplied to a downflow bubble contactor that is simultaneously receiving flowing water.

The concentration of ozone generated in the oxygen feed gas is continuously monitored using a high-concentration ozone gas monitor (model HC-400, PCI-Wedeco, West Cladwell, New Jersey; Figure 3). The concentration of ozone in the gas discharged from the foam and off-gas separator (Figure 1) is also monitored using a high concentration ozone gas monitor.

The ozone generators and the pressure swing adsorption (PSA) oxygen generators are located in a room within the treatment building that incorporates a ventilation system that can provide six air exchanges per hour in order to control nitrogen and heat accumulation.

Ozone Off-Gas Destruct Unit

An ozone destruct unit (model VOD-10, PCI-WEDCO, West Caldwell, New Jersey) was installed to destroy ozone in the off-gas discharged from the foam and off-gas separator and from the ozone gas monitors. The ozone off-gas destruct unit is a combined thermal/

catalytic unit that manufacturer claims can achieve $\geq 99\%$ destruction of ozone. The ozone off-gas destruct unit has a demister located in front of the destruct unit and incorporates a blower to pull ozone off-gas from where it collects at the top of the ozone contact column, through the pipeline, and through the ozone off-gas destruct unit.

Oxygen Generators

To produce ozone, an enriched oxygen-feed gas is generated using one or two PSA oxygen generators. According to their manufacturer (model OG-100, Oxygen Generating Systems Inc., Niagara Falls, New York), each PSA oxygen generator should be capable of generating 50 standard L/min (100 standard ft³/h) of oxygen gas at outlet pressure of at least 45 psig (3 bar). The two PSA oxygen generators were plumbed in parallel to operate the units independently or simultaneously. The oxygen generation system includes two screw-type air compressors (model SSR-EP10, Ingersoll Rand Corporation, York, Pennsylvania), an air dryer, air filters, and an air receiver tank.

The concentration of oxygen gas produced is monitored (model 1W-G, Oxyguard International A/S, Birkerod, Denmark) to determine if the PSA oxygen generators are functioning.

Contact Column for Ozone Disinfection

The ozonated water flowing from each pump-cone pair is collected and piped to the ozone contact column (Figures 1 and 5), which contains an effective water volume of approximately 15 m³ (4,000 gal). Red Ewald, Inc. (Karnes City, Texas) manufactured the contact column for ozone disinfection (as well as the contact column for ozone destruction and the gas stripping column) using FRP and a vinyl ester ozone resistant resin (Derakane, Dow Chemical Company, Midland, Michigan). The contact column for disinfection is 7.9 m tall. The contact column consists of two cylinders—both sym-

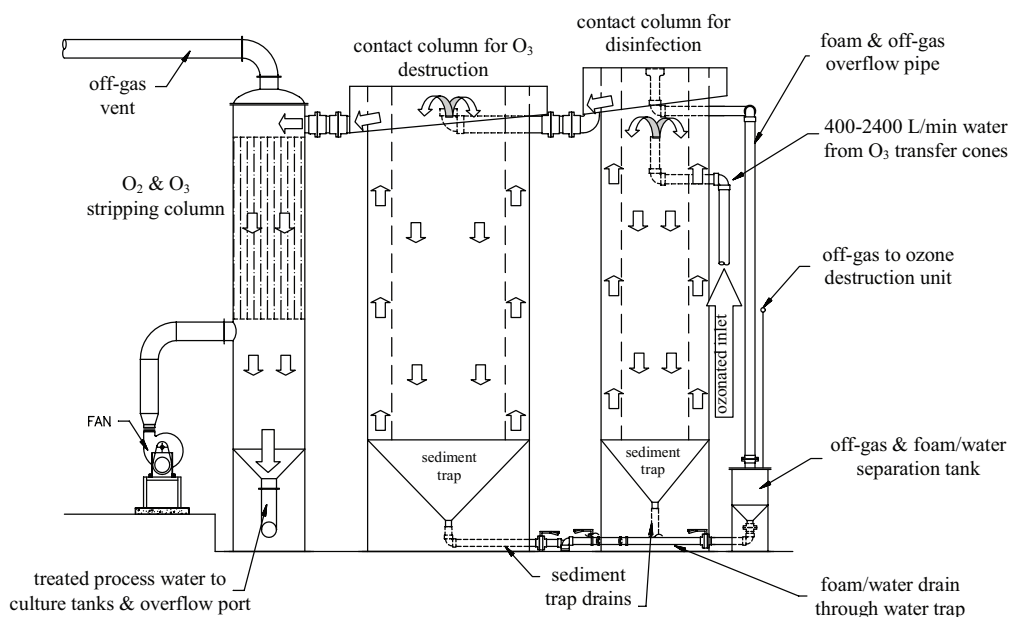


FIGURE 5. Diagram showing the ozonated water flow path through 15-m³ and 32-m³ tanks that first provide plug-flow ozone contacting for microbiological inactivation and then time for ozone decay before the water cascades down through an air-stripping column on its way to the IC building. Drawing courtesy of Oak Point Associates, Biddeford, Maine.

metrically centered along the vessels central axis—supported by a 1.8-m-tall skirt over a cone-bottomed sediment trap (Figure 5). The center cylinder is 1.2 m diameter and 6.1 m tall and is mounted within the 1.8-m-diameter by 6.1-m-tall outer cylinder (Figure 5). The process water is piped into the top of the center cylinder and then flows in a plug-flow manner down 6.1 m within the center cylinder and then flows back up within the annular space between the two cylinders (Figure 5).

The uppermost 0.46–0.76 m of the outer cylinder has a 2.4-m-diameter external cylinder to act as a 0.30-m-wide collection launder that directs the water flow into a 0.25-m-nominal-diameter outlet pipe (Figure 5). The collection launder gathers the water flow using eight 15-cm-diameter holes directed into the 1.8-m-diameter cylinder (Figure 5). An FRP lid covers the top of the vessel to prevent any ozone gas that might strip from the water to enter the building. The center

cylinder also has a solid plate flanged at its top (as shown in Figure 5). The cone-bottom below the outer most cylinder functions as a sediment trap (Figure 5). A valve at the base of this sediment trap (accessed through a 0.6-m manway penetrating the skirt) can be opened to drain this vessel or to routinely flush trapped sediment to a floor drain. The contact column is analogous to a relatively short but fat U-tube gas transfer device that sits above ground and has a sediment trap built into its base to simplify cleaning.

This contact column provides about 20, 10, or 6.7 min of ozone contact time for water flows of 760, 1,500, or 2,270 L/min, respectively. A dissolved ozone probe at the outlet of the ozone contact chamber has been installed to continuously monitor the dissolved ozone concentration discharged from the contact tank (Figures 1, 4, and 5). The dissolved ozone concentration discharged from the ozone contact tank is maintained at 0.2 mg/L using a PID

feedback control loop that proportions the amount of ozone generated (and thus added to the water) based on the signal supplied by the dissolved ozone monitor.

Foam and Off-Gas Collection Sump

Any off-gas or foam collecting at the top of the first ozone contact column vents and overflows, respectively, to a dewatering and off-gas collection sump located on the floor beside the contact column for ozone disinfection (Figures 1 and 5). The foam and off-gas collection sump has a conical base to drain foam and also has a vent through the lid to pipe the off-gas out the top of this vessel and on to an ozone destruct unit (Figure 5). After the ozone-destruct unit, this off-gas is vented from the building. Little if any foam has come out of the contact column. However, if foam were collected, it would drain through a water trap and into the septic tank. The purpose of the water trap is to prevent ozone-containing off-gas from escaping through the foam/water drain.

Contact Column for Ozone Destruction

The water discharged from the first contact tank flows by gravity through a 25-cm pipe to a second larger 32-m³ contact tank (Figures 1 and 5), which provides approximately 40, 20, or 13 min of further contact time to allow the majority of remaining ozone residual to react away within flows of 760, 1,500, or 2,270 L/min, respectively. The contact column for ozone destruction is 7.6 m tall, including the column's 1.8-m-tall skirt (Figure 5). The contact column for ozone destruction is built similarly to the contact column for ozone disinfection, except that the column for ozone destruction is larger in diameter and slightly shorter. Also, the contact column for ozone destruction contains a center cylinder that is 1.8 m in diameter and 5.8 m tall (Figure 5). The uppermost 0.46–0.76 m of the outer cylinder has a 3.4-m-diameter external cylinder to act as a 0.30-m-wide collection launder. The launder directs the

water flow into a 25-cm-nominal-diameter outlet pipe to carry the water exiting the contact column to the top of the stripping column (Figure 5).

Gas Stripping Column

The water exiting the second ozone contact tank can contain low levels of dissolved ozone and high concentrations of dissolved oxygen (typically 20–40 mg/L of dissolved oxygen). The high dissolved oxygen supersaturation levels are produced when the purified oxygen feed-gas that is used to carry the ozone is transferred in the downflow bubble contactors. To remove the dissolved ozone and supersaturated levels of dissolved oxygen, the water exiting the second contact tank is piped into a stripping column where it cascades down through 2.7 m of tubular media (5 cm diameter; NSW Corporation, Roanoke, Virginia) and countercurrent to an air flow of 28 standard m³/min. The stripping column is 1.2 m diameter and 7.5 m tall, including a 1.7-m-tall skirt. Water flow is piped into the side of the stripping column near its top (Figure 5). Water then flows down through a perforated plate and cascades down through the tubular polyethylene media, collecting in a pool at the base of the cylinder. Water flow exits the stripping column through a pipe located at the base of this cone-bottomed vessel and is piped directly to the IC building.

A domed lid at the top of the stripping column contains ducting to vent the air from the top of the vessel (Figure 5). A “squirrel cage” type fan blows approximately 28 standard m³/min of air into the side of the stripping column immediately below the media support screen. This air passes up through the tubular media in a direction that is countercurrent to the water flow, producing a G:L of approximately 10:1–70:1 (depending on water flow rates). The air is ported out the top of the stripping column and is transferred through ducting to vent outside the building (Figure 1 and 5).

The pipeline traveling from the stripping column to the IC building runs through

sump B. A stand-pipe teeing off of this pipeline and located directly over sump B allows excess water to overflow into sump B. The stand-pipe also limits the maximum water level that can collect within the lower portion of the stripping column, preventing water from backing up into the stripping column's air inlet port. Thus, the lower portion of the stripping column acts as a sump to supply water pressure to the IC building.

Recarbonation Process for pH Control

A pH control system was installed to recarbonate the water and lower the pH to 7.5 because pH levels can exceed 9 during the summer months when photosynthetic respiration in the water removes dissolved carbon dioxide. The recarbonation process decreases pH by adding carbon dioxide gas in the reservoir at the base of the cascade column. Carbon dioxide gas is highly soluble in water and is added within a pumped side-stream system that proportions carbon dioxide gas into the water using a 3/4-hp centrifugal pump (MAG1, Jacuzzi Inc., Little Rock, Arkansas), a venturi-injector (model no. V1584, Mazzei Injector Corporation, Bakersfield, California), and an electromechanical needle valve (model EPV-375SS, Hass Manufacturing Company, Troy, New York) on the carbon dioxide supply line. This side-stream flow is mixed back into the treated flow being discharged to the IC building. A PID control loop turns on the side-stream pump and proportions in carbon dioxide gas based upon the pH of the water being discharged to the IC building. The amount of carbon dioxide added to the water depends upon how much the treated water's pH must be dropped to maintain a level of 7.5.

Dissolved Ozone, Oxygen, and pH Monitoring of Treated Water Sent to IC Building

A dissolved oxygen probe, a dissolved ozone probe, and a pH probe were installed to

monitor water quality in the pipeline carrying flow from the stripping column to the IC building (Figure 6). These probes help to ensure that the fish in the IC building are not exposed to dangerous levels of oxygen or ozone gas, as well as high or low pH values.

Monitoring of Ozone in the Generator Room and Ozone Treatment Building

To ensure that human health is protected at all times, the filtration and ozonation facility was designed to incorporate ozone destruction equipment, room and building ozone-in-air monitoring, rapid room and building ventilation systems, and audible/visual/dial-out alarms. Under all conditions, ozone off-gas is captured and vented outside the building through an ozone destruction unit. Therefore, no ozone gas should escape into the building. To ensure that ozone gas is not present, the room and building air is monitored using a low-concentration ozone gas monitor (model LC-400, PCI-Wedeco, West Cladwell, New Jersey). Portable ozone gas monitoring equipment (model C-30ZX, Eco Sensors, Inc., Santa Fe, New Mexico) was also supplied to warn staff of unsafe ozone concentrations. If the low-concentration ozone gas monitors detect an unsafe level of ozone gas within the ozone generation room or the building, the ventilation fans are automatically turned on to provide rapid air exchange and the ozone generators are automatically shut down. Audible, visual, and dial-out alarms are also activated if an unsafe concentration of ozone is detected in the building or ozone monitoring room. A switch to remotely shut off the ozone generator was also installed immediately inside the entry door.

Supervisory Control and Data Acquisition System

A SCADA system was supplied by AEC Engineering (Freeport, Maine) to provide a central location to monitor and adjust the control routines through a convenient com-

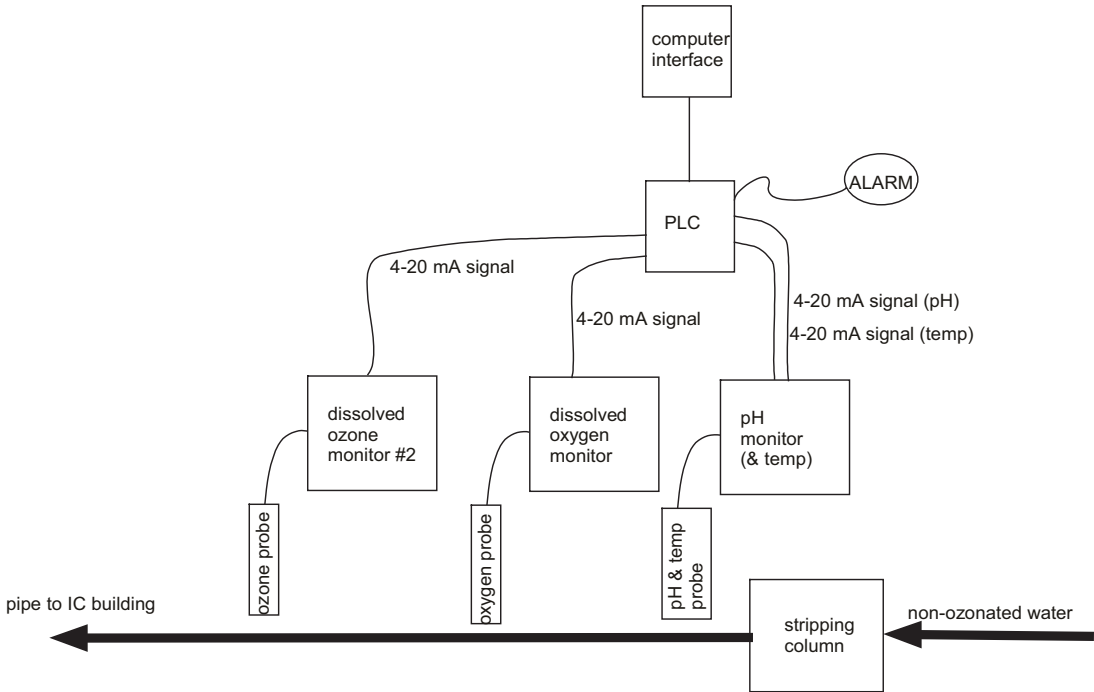


FIGURE 6. Schematic of the process flow illustrating how the programmable logic controller (PLC) is used to monitor signals coming from the dissolved ozone monitor, the dissolved oxygen monitor, and the pH monitor. The PLC activates an alarm in the event that any of these values deviate past a given set point.

puter interface. The SCADA system provides continuous real-time data monitoring of the treated water flow rate, the ozonated gas supply flow rate, the ozone gas concentration produced, the ozone generator output level, and the dissolved ozone concentration following the disinfection contact tank, as well as the pH, temperature, dissolved oxygen concentration, and dissolved ozone concentration in the treated water supplied to the IC building. The SCADA system also monitors the water level in sump B, as well as monitored and controlled the water pressure in the pipeline supplying water to the IC building.

The continuous data monitoring system is also used for real time evaluation of ozone system conditions. For example, the continuous real-time data monitoring of the treated water flow rate, the ozonated gas supply flow rate, the ozone gas concentra-

tion, the ozone generator output level, and the dissolved ozone concentration following the disinfection contact tank were used to calculate and display in real time the mean hydraulic retention times, the mass ozone application rate, the ozone dose applied, and the resulting ozone disinfecting C^*t . The disinfecting rate (C^*t) is

$$\text{Contact time} = \left\{ \frac{1 \text{ min}}{\text{flow rate water (FMI) L}} \right\} \cdot \left\{ \frac{3.78 \text{ L}}{\text{gal}} \right\} \cdot \left\{ \frac{4,000 \text{ gal}}{\text{contact tank}} \right\} = \text{## min}$$

$$\begin{aligned} \text{Mass ozone applied} &= \left\{ \text{flow rate oxygen (FMO}_2\text{)} \frac{\text{L}}{\text{min}} \right\} \cdot \left\{ \frac{\text{m}^3}{1,000 \text{ L}} \right\} \\ &\cdot \left\{ \frac{1.331 \text{ kg O}_2}{\text{m}^3} \right\} \cdot \left\{ \frac{1,440 \text{ min}}{\text{d}} \right\} \cdot \left\{ \frac{\text{mol O}_2}{32 \text{ g O}_2} \right\} \\ &\cdot \left\{ \frac{2 \text{ mol O}_3}{3 \text{ mol O}_2} \right\} \cdot \left\{ \frac{48 \text{ g O}_3}{\text{mol O}_3} \right\} \\ &\cdot \{100 \cdot \text{O}_3 \text{ percentage in feed gas}\} \\ &= \text{## kg O}_3 / \text{d} \end{aligned}$$

$$\begin{aligned} \text{Ozone dose applied} &= \left\{ \text{Mass ozone applied} \frac{\text{kgO}_3}{\text{d}} \right\} \\ &\cdot \left\{ \frac{10^6 \text{ mg}}{\text{kg}} \right\} \cdot \left\{ \frac{1}{\text{flowrate water (FM1)}} \frac{\text{min}}{\text{L}} \right\} \\ &\cdot \left\{ \frac{\text{d}}{1,440 \text{ min}} \right\} \\ &= \text{## mg/L of ozone applied} \end{aligned}$$

Ozone disinfecting rate:

$$\begin{aligned} C \cdot t &= \left\{ \text{Ozone residual concentration (DO3M1)} \frac{\text{mgO}_3}{\text{L}} \right\} \cdot \\ &\left\{ \text{contact time for ozone disinfection in min} \right\} \\ &= \text{##} \frac{\text{mgO}_3}{\text{L}} \cdot \text{min} \end{aligned}$$

Water Quality Testing Methods

The ozone system was evaluated during a start-up period from March through June, 2002. Depending on the water quality parameter, water samples were collected 1–3 times daily. Samples were collected in 5 d spanning the start-up period, for a total of 12–13 sampling events. Water samples were collected before microscreen filtration and immediately following all of the subsequent unit processes: microscreen filtration, ozone addition in the downflow bubble contactors, the contact column for ozone disinfection, the contact column for ozone destruction, and the gas stripping column (Figure 1, locations A, B, C, D, E, and F). Water samples containing ozone were tested immediately for dissolved ozone concentration using a Palintest dissolved ozone test (Palintest, Ltd., Tyne & Wear, England). Samples were also stored in bottles on ice and were tested within 24–48 h for total organic carbon (TOC), dissolved organic carbon (DOC), pH, alkalinity, total suspended solids (TSS), true color, and turbidity.

Total suspended solids concentrations were measured using APHA (1985) method 209 C. Color samples were filtered through 0.5- μm filter paper before being analyzed based upon a Pt-Co standard using APHA (1985) method 204 B and a Hach Chemical Company DR2000 or DR3000 spectrophotometer at 455 nm wavelength. Turbidity was measured with a Hach Chemical Company Ratio/XR turbidimeter using APHA

(1985) method 214 A. The pH of the water samples were measured with a bench top pH meter using APHA (1998) method 4500 (H+ B). Alkalinities of water samples were measured by titration using APHA (1998) method 8203. Samples collected for DOC analyses were filtered through 1.5- μm filter paper and placed in glass sample vials. Sample aliquots (5 mL) were acidified with 2 normal sulfuric acid and purged for 3 min with ultra pure air (hydrocarbon concentration < 0.5 mg/L). Nonpurgable dissolved organic carbon constituents were then combusted under heated (720°C) catalyzed conditions and measured with an infrared detector using a total organic carbon analyzer (TOC-Vcpn, Shimadzu, Kyoto, Japan).

Total organic carbon and DOC samples were analyzed at the USDA Agricultural Research Service's National Center for Cool and Cold Water Aquaculture. All other water quality parameters, except for dissolved ozone, were analyzed at the Conservation Fund Freshwater Institute in Shepherdstown, West Virginia.

Water Quality Testing Results

During the evaluation period, inlet water (after microscreen filtration, i.e., location B in Figure 1) temperatures, alkalinity, pH, true color, turbidity, TSS, TOC, and DOC ranged from 4–17°C, 39–68 mg/L (as CaCO_3), 7.0–8.5, 4–30 Pt-Co units, 2–57 NTU, 1.6–60 mg/L, 1.0–3.7 mg/L, and 1.0–3.3 mg/L, respectively (Table 2). Excluding storm event data, inlet water (after microscreen filtration, i.e., location B in Figure 1) temperature, alkalinity, pH, true color, turbidity, TSS, TOC, and DOC averaged (\pm SE), respectively: 11.0 \pm 1.4°C, 59 \pm 2 mg/L (as CaCO_3), 7.9 \pm 0.2, 4.5 \pm 0.3 Pt-Co units, 3.5 \pm 5 NTU, 2.6 \pm 0.3 mg/L, 1.6 \pm 0.1 mg/L, and 1.5 \pm 0.1 mg/L (Table 2). Nitrite-nitrogen levels were not measured during the study, because nitrite-nitrogen concentrations in Fishing Creek have traditionally been less than 0.1 mg/L. Bacterial inactivation data are reported in a companion paper (Barbash et al., in press).

TABLE 2. Minimum, maximum, and mean water temperature, alkalinity, pH, true color, turbidity, TSS, TOC, and DOC entering the ozone contacting process (location B in Figure 1) during the evaluation period.

	Temp. (°C)	Alkalinity (mg/L as CaCO ₃)	pH	True color (Pt-Co)	Turbidity (NTU)	TSS (mg/L)	TOC (mg/L)	DOC (mg/L)
Minimum	4.8	39	7.0	4	2	1.6	1.0	1.0
Maximum	17.0	68	8.5	30	57	60	3.7	3.3
Mean ± SE*	11.0 ± 1.4	59 ± 2	7.9 ± 0.2	4.5 ± 0.3	3.5 ± 5	2.6 ± 0.3	1.6 ± 0.1	1.5 ± 0.1

Discussion

Construction of the filtration and ozonation facility at the U.S. Fish and Wildlife Service's Northeast Fishery Center was completed in late 2001 for a total cost of about US\$1 million. The performance of each of the treatment component is discussed below.

Microscreen Filters

The microscreen filters were installed with 60- μ m sieve panels to exclude particles larger than the screen opening. The microscreen filters were intended to exclude particles or organisms that would be sufficiently large to shield potential fish pathogens from ozone inactivation. According to the bacteria inactivation data reported in Barbash et al. (in press), inactivation of bacteria appeared to be excellent. It is still uncertain, however, if the microscreen filtration and ozonation process would be sufficient to kill or exclude all of the fish parasites that were of concern. Long-term operating experience with the filtration and ozonation system will be required to determine whether 60- μ m sieve panels are effective at ensuring exclusion or inactivation of the fish parasites. If not effective, a higher degree of filtration, using either finer mesh sieve panels or sand filtration, would be required.

During routine conditions, TSS concentration entering and exiting the microscreen drum filter averaged 4.0 ± 0.6 mg/L and 2.9 ± 0.4 mg/L, respectively. During a storm event that occurred during one of the sampling days, TSS concentrations entering and exiting the microscreen drum filter averaged 42 and

40 mg/L, respectively. Under either condition, the macrosized particles must not have been a major component of the TSS because mean TSS removal efficiency across the drum filter was only $28 \pm 2\%$ during normal flow conditions and 6% during a storm event.

Ozonation Systems

During start-up, the two ozone generators were used in combination or individually, and the generators were operated at different output levels (from 18% to 100% output) to generate ozone production rates ranging from 0.9 to 5.5 kg/d. The ozone was transferred to water flows of 760–2,270 L/min in order to produce ozone doses ranging from 0.8 to 3.5 mg/L. The ratio of the oxygen gas flow (at standard conditions) to water flow (i.e., G:L) ranged from 0.007:1–0.032:1. Calculations of the mean theoretical hydraulic retention time within the contact column used for ozone disinfection ranged from 7 to 21 min. The mass of ozone applied, the ozone demand of the water, and the water flow rate, all combined to produce an ozone residual \times contact times (i.e., c^*t) that ranged from 1 to 21 mg/L \cdot min at the outlet of the contact column for ozone disinfection.

Ozone demand was found to be dependent upon water temperature and the concentration of organic carbon present in the water (Figure 7). A model to predict ozone decay kinetics as a function of the water temperature and organic carbon concentration has been developed (S. Summerfelt, unpublished data). However, the ozone decay data collected under the widely varying

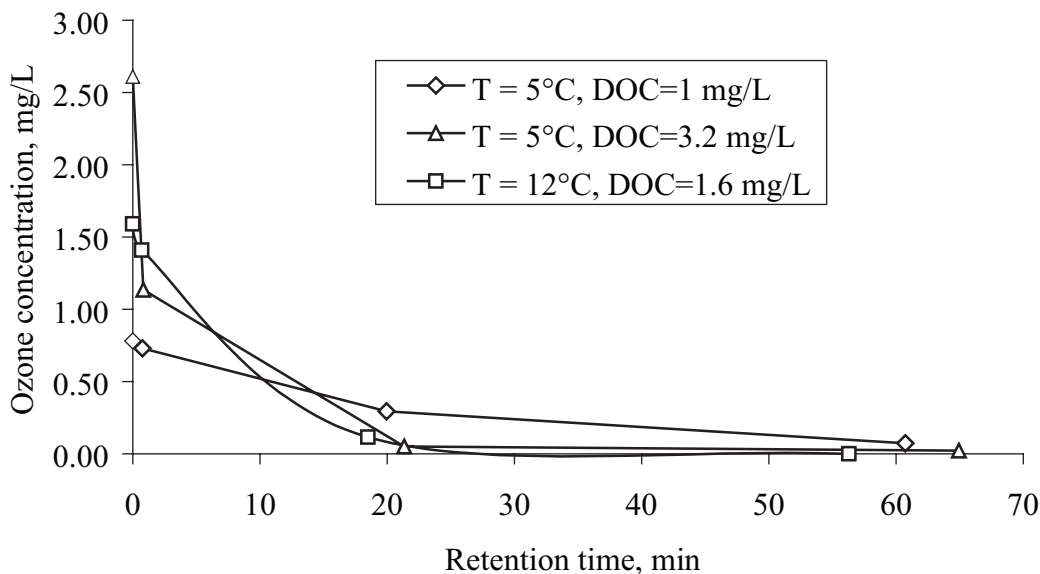


FIGURE 7. Three sample data sets illustrating the dependence of ozone decay upon water temperature and the concentration of organic carbon present in the water.

conditions encountered during the system start-up period indicates that the instantaneous (i.e., within seconds of gas transfer to the water) ozone demand is highest when organic carbon levels are elevated (Figure 7). The rate of ozone decay was also found to increase with increasing organic carbon concentration and increasing water temperature (Figure 7), which was expected. These are significant findings because they point to the need for excess ozone production capacity in order to maintain bacterial reduction levels even when organic carbon levels and water temperatures are both elevated. The model should allow ozone demand of a surface water to be estimated based on its organic carbon content and temperature, although other factors such as pH, alkalinity, and nitrite also have an affect.

The ozonation and filtration system was able to consistently disinfect the surface water during this start-up period, even during extreme changes in water quality that were produced by storm events and water temperatures changes that were produced as the seasons changed (Barbash et al., in press).

This consistency was significant because it showed that the increased ozone demand of the water could be overcome simply by increasing the ozone generator output.

The ozonation system was also found to reduce the water's true color by $70\% \pm 7\%$. However, no significant reductions in turbidity or TSS were produced by ozonation followed by passage through the two contact tanks, which might also act as settling basins because they provide 20–60 min of total hydraulic retention time. These findings do not support the findings of Rueter and Johnson (1995), who reported that colloidal clay settling was improved by ozonation. Of note, settled solids are being flushed periodically from the sediment traps located at the bottom of the two contact tanks. However, due to variability in the TSS data, TSS inlet and outlet concentrations were not significantly different across the two contact columns.

The PID feedback control loop that proportions the amount of ozone generated (and thus the mass of ozone added to the water flow) based on the signal supplied by the dissolved ozone monitor (located after

the contact tank for ozone disinfection, Figures 1 and 4) was able to maintain the preselected set point dissolved ozone concentration. The preselected set point for dissolved ozone was typically 0.2 mg/L. However, a large lag time (approximately 7–21 min) was created as the water flowed from the down-flow bubble contactors to the end of the contact tank for disinfection. Approximately 2–4 h were required for the PID controller to reach the set-point ozone concentration in response to a large change in conditions (e.g., large changes in water flows or temperatures or changes in ozone residual set-point levels). Yet, the PID control system was able to automatically maintain a disinfecting level of dissolved ozone when sufficient oxygen feed gas was supplied to allow a greater mass of ozone to be generated as the ozone generator's output was ramped up. That is, if the ozone generators were operated at only 30–50% of their maximum ozone generation capacity, then the PID control loop had extra capacity to increase ozone production as required to meet increasing ozone demands.

Perhaps the two weakest points within the entire filtration and ozonation system were (1) the reliance on a dissolved ozone probe that must be calibrated for accuracy, and (2) the installation of a PSA oxygen generation system that had a maximum oxygen production capacity that was less than would be desired to meet maximum ozone demands. The entire PID system used to maintain a disinfecting ozone residual was completely dependent on these two weaknesses. First, the dissolved ozone probe had to be recalibrated periodically to correct for drift. Calibration of the dissolved ozone probe took hours and required a trained and skilled technician. Second, the PSA oxygen generation system only supplied up to 27 standard L/min of oxygen flow at a pressure ≥ 3 bar (44 psig), which was approaching the minimum oxygen feed gas pressure required to operate the ozone generators and was much lower than expected.

The PSA oxygen generating system had been chosen because the cost to produce oxygen on site was lower than it would have been to purchase liquid oxygen at this site.

The U.S. Fish and Wildlife Service decided that it would be better to pay for more capital equipment up front than to pay a higher operating cost later. However, from a systems performance point of view, a liquid oxygen supply would have provided a much larger oxygen supply volume to draw from during periods of increased ozone demand. A liquid oxygen supply is also nearly 100% reliable, which is not the case for the mechanically based PSA oxygen generating system.

Control Systems

The Northeast Fishery Center's filtration and ozonation facility is highly automated, relying on four PID control systems that control

- the rate that water flow is allowed into the treatment building,
- the water flow rate pumped through the treatment columns and to the IC building,
- the ozone production rate required to maintain an ozone disinfecting residual, and
- the amount of carbon dioxide gas addition required to recarbonate the treated water supply to decrease its pH during periods when strong photosynthetic respiration is occurring in Fishing Creek and the water supply pond.

The only weakness discovered in any of the four PID control systems was in the PID control loop that was used to adjust ozone production to maintain a given ozone residual (described above in the discussion of the Ozonation systems, the weakness was having to rely upon a dissolved ozone probe that must be calibrated for accuracy [which was possible, but time consuming] and having installed a PSA oxygen generation system that had a maximum oxygen production capacity that was less than intended to meet maximum ozone demands). The remaining PID control systems worked practically flawlessly. As well, the central SCADA system supplied by AEC Engineering (Freeport, Maine) provided a convenient central location to monitor and adjust the control routines through a computer interface.

The filtration and ozonation facility also relied on an automated high-pressure water supply system that supplies nonpotable but pressurized water to the drum filters and to the sink upon demand. This high-pressure water supply system also worked reliably once problems with the mounting of the pressure pumps were corrected.

Gas-Stripping Column

After the water exits the second contact tank, any further ozone residual was stripped along with any large dissolved oxygen supersaturation as the water passed through the countercurrent, forced-ventilated cascade column (Figures 1 and 5). The water entering the gas stripping column typically contained 0.01–0.1 mg/L of dissolved ozone and 20–40 mg/L of dissolved oxygen. The gas stripping column was able to reduce the dissolved ozone and dissolved oxygen levels to nondetectable and less than 105% of saturation during all but the most extreme conditions. In one instance, where ozone concentrations were increased far beyond normal operating conditions, the dissolved ozone levels entering the stripping column were measured at 0.4 mg/L, yet, passage through the stripping column still reduced the dissolved ozone concentration to 0.04 mg/L. Therefore, the gas stripping column was a nearly fail-safe process to ensure that the fish in the IC building were never exposed to unsafe levels of dissolved gases.

Conclusions

The performance data provided in this paper and Barbash et al. (in press) indicate that a microscreen filtration and ozonation system can be successfully used to inactivate microorganisms and exclude the majority of debris larger than the microscreen sieve panel openings in a surface water supply. The design details that were provided will offer insight into the strengths and weaknesses of the individual treatment processes, which should prove useful to other fish culture facilities that are working on the design of a

water disinfection system. This paper should reinforce the importance of (1) using a liquid oxygen supply rather than an onsite PSA oxygen generation system, and (2) providing excess ozone generation capacity, which will be required to maintain the desired ozone concentration at the outlet of the contact tank when water quality deteriorates unusually or during high water temperature extremes. It is also worth noting that (3) the microscreen drum filters installed with 60- μ m screens appeared to more than adequately exclude particles that could interfere with ozone inactivation of bacteria and which indicated that sand filtration would not be required; (4) the air stripping column removed any residual dissolved ozone and also brought all other dissolved gas concentrations toward their saturation levels before the water was sent to the IC building—it was especially important to reduce dissolved oxygen concentrations from more than 200% of saturation to less than 105% of saturation; (5) calibration of the dissolved ozone probe was time consuming but absolutely critical for proper system operation—an ORP based control system could be considered as an alternative; (6) the sediment traps simplified periodic flushing of solids from the bottom of the ozone contact basins; (7) the off-gas and foam separation tank was found to be unnecessary as no foam was observed to be produced; and (8) the water recarbonation process was a relatively simple process that effectively countered pH swings produced by photosynthetic activity in the water supply.

An ultraviolet irradiation system could have been used to destroy the dissolved ozone residual (Summerfelt et al. 2004) as an alternative to the forced-ventilated cascade aeration column. However, ultraviolet irradiation would not have brought the dissolved gas concentration back to near saturation as did the aeration column. Also, an ultraviolet irradiation system would require approximately annual lamp replacement, even if it did impart a much lower headloss than the cascade aeration column.

Based on experiences with a microscreen filtration and ultraviolet irradiation system

used to inactivate *Aeromonas salmonicida* in a surface water supply at another U.S. Fish and Wildlife Service fish hatchery in the northeast region, the ozonation system at the Northeast Fisheries Center was both more complex to operate and more expensive to construct than a ultraviolet (UV) irradiation system of similar flow capacity. In addition, UV irradiation systems do not typically produce toxic residuals that can escape their contact chamber. However, the ozone C^*t (2.0 mg/L · min) supplied by the ozonation system at the Northeast Fisheries Center appears to be sufficient to inactivate many of the known fish pathogens (Table 1), whereas a design ultraviolet irradiation dose of 35,000 $\mu\text{W}\cdot\text{s}/\text{cm}^2$ is not expected to provide as much broad spectrum pathogen protection as the 2.0 mg/L · min ozone C^*t , especially during periods of high turbidity that can severely limit transmittance of ultraviolet irradiation in a surface water supply.

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