Ozone Use at the Monterey Bay Aquarium: A Natural Seawater Facility

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Abstract

In 1984, the Monterey Bay Aquarium opened its doors as a flow-thru natural seawater facility exhibiting primarily regional species. Over the years the aquarium has expanded and ozone was introduced to several life support systems. The aquarium now includes over 2.3 million gallons of exhibits displaying both regional and non-native species. The largest expansion to date, the Outer Bay Wing, opened in 1995 and includes as its centerpiece the Outer Bay Waters (OBW) Exhibit; a 1.2 million gallon semi-closed system that uses ozone as part of its life support system. This paper will concentrate on the history of ozone use in the OBW Exhibit system, research conducted on this system to date, tentative plans for future life support system modifications, and ideas for future research.

Key Words: Ozone; Aquarium; Natural seawater; Foam fractionator; Contact chamber; ORP; Turbidity; Exotic species

Introduction

The Monterey Bay Aquarium (MBA) is a flow-thru natural seawater facility that opened its doors in 1984 with an emphasis on exhibiting regional species (Figure 1). The aquarium is located next to the pristine Monterey Bay National Marine Sanctuary, in the city of Monterey, California (about 2 hours south of San Francisco). The aquarium pumps 1,000 - 1,500 GPM of seawater from the Monterey Bay for use in our exhibits before discharging the water back to the ocean.

Over the years the aquarium has expanded and now includes over 2.3 million gallons of exhibits displaying both regional and non-native species. Exhibit changes and additions incorporating large volume displays, non-native species, and seawater temperatures warmer or colder than ambient seawater all challenged the original open life support system design. As a result, the newer life support systems are typically semi-closed re-circulating systems that receive very low flows of make-up seawater.

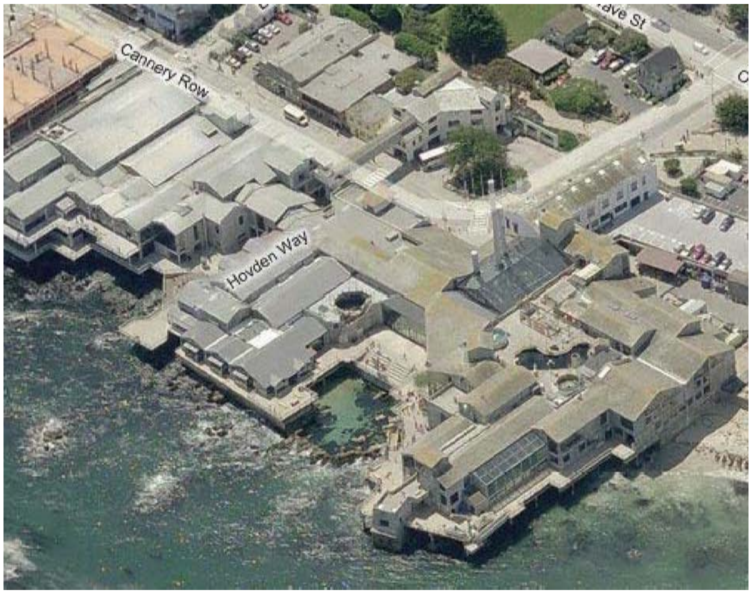

Figure 1. An aerial view of MBA (Microsoft Virtual Earth). The largest expansion of the aquarium to date the Outer Bay Wing which opened in 1995 is shown to the left of Hovden Way in this perspective. The buildings to the right of Hovden Way house the original part of the aquarium that opened in 1984.

The regulatory environment that the aquarium operates within has also become more rigorous over time. Possible discharge of non-native species to the ocean has become a constant issue as infrastructure, exhibits, and regulations change. Sanitization of interactive displays is also of concern. These challenges have been met, in part, by the introduction of ozone to several life support systems.

This paper will present a history of ozone use to date at our facility. However, it will focus on the main exhibit system where ozone is used today, the Outer Bay Waters (OBW) Exhibit. More details on ozone use in other areas of our facility, besides the OBW Exhibit, are available from the authors upon request.

As aquarium systems and facilities go, MBA is not a big user of ozone. The maximum ozone generating capability at our facility, if all generators are online and running at their maximum capacity is less the 17 lb/day O_3. This paper is not meant to be a comprehensive review of ozone use in natural seawater, just the history of our experiences to date at MBA.

Timeline of Ozone Milestones at MBA

Since ozone was introduced at various stages in MBA's history the presentation of a timeline (Figure 2) will be useful. As previously mentioned MBA opened its doors in 1984 as a flow-thru natural seawater facility with primarily regional species on display. The largest expansion to date, the Outer Bay Wing (Figure 1) opened in March 1995 after seven years of construction. The 2nd floor OBW Exhibit galleries were opened first to the public, with the centerpiece being the 1.2 million gallon semi-closed OBW Exhibit which incorporated ozone as an integral part of its life support system. We will describe the OBW Exhibit life support system design in greater detail below.

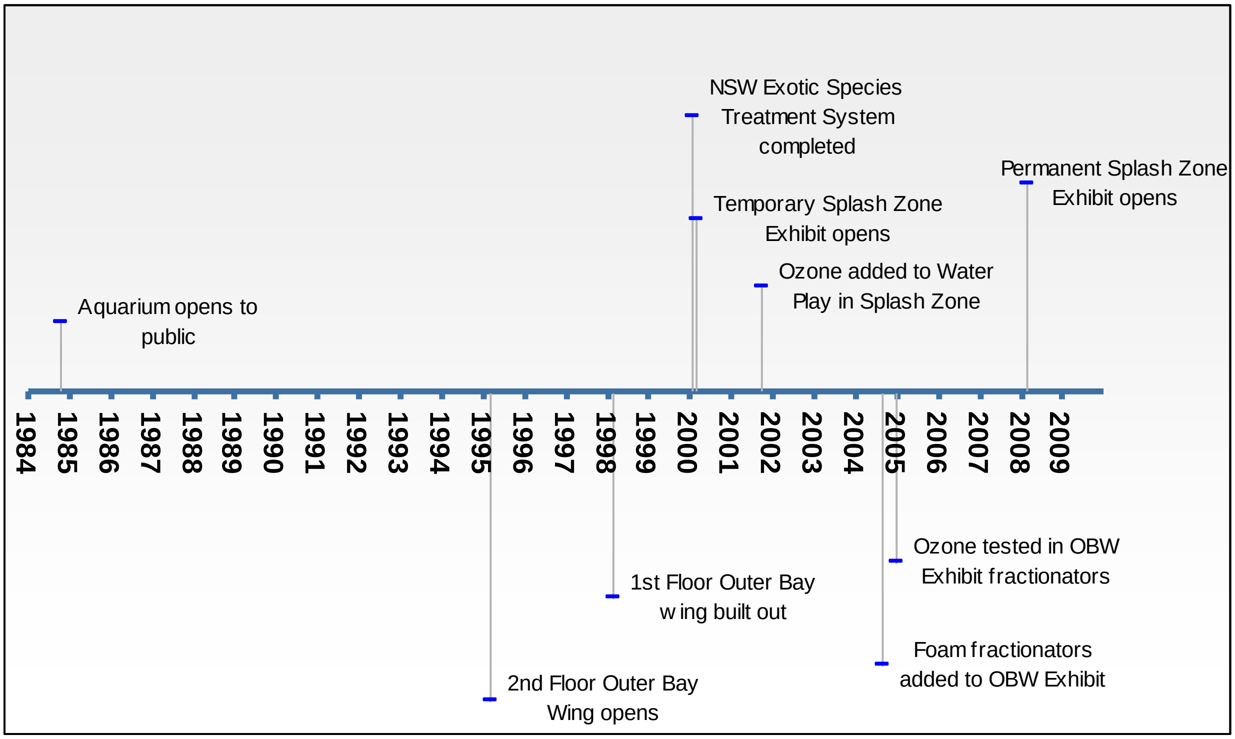

Figure 2. Timeline of some events in the history of MBA relating to ozone use at the facility. The details of each time point are described in the text.

Three years later, in 1998, the 1st floor build-out of the Outer Bay Wing was completed. This floor was designed to hold two rotating exhibit galleries that are changed every 2 to 3 years. Ozone was incorporated into these two life support systems in case it was needed for any future temporary exhibits. The life support systems are primarily re-circulated, temperature-controlled systems where ozone can be used in RK150PE foam fractionators (RK2 Systems Inc., Escondido, CA, USA) that are installed on closed loop side-streams from the system reservoirs. Ozone is supplied through a Mazzei venturi injector from a Hankin S-2 ozone generator (Hankin Atlas Ozone System, Ltd., Scarborough, Ontario, Canada).

Prior to January 2000 seawater discharged from any exhibit or holding tank containing non-native species was discharged to sewer. In 1999 the local sewer district began to regulate salt water discharges and MBA was directed to minimize seawater discharge to the sewer system. Due to concerns of possible introduction of non-native species to the ocean from discharge of exhibit waters in the Nearshore Wing (NSW) in the original part of the aquarium we completed our first exotic species treatment system in February 2000. This system is based on ozone in pressurized contact chambers. The system processes a maximum flow of 250 GPM at an applied dose of 1 - 1.2 mg/L O_3. The pressurized contact chambers operate at 8 - 10 PSI with a contact time of 3.5 - 4 min. All major system equipment is redundant, including pumps, ozone generators, and ozone destruct units; with automatic switchover in the event of equipment failure. Ozone is supplied by Hankin S-10 generators (Hankin Atlas Ozone System, Ltd., Scarborough, Ontario, Canada) through a Mazzei venturi injector into a custom-fabricated fiberglass ozone contact chamber (Custom Structures Inc., San Antonio, TX, USA). The sterilization efficiency of the system is monitored by plate counts of heterotrophic bacteria in pre- and post-ozonation samples. Cell reductions of 92% or greater have been typically obtained to date.

In March 2000 the temporary exhibition Splash Zone opened on the 2nd floor of the NSW. One of the displays in this exhibit is a freshwater interactive designed primarily for children called Water Play. Sanitization of the water in this display is required for public health purposes as directed by the Health Department. Sanitization was initially accomplished by the addition of bromine from an erosion feeder and acid from a small reservoir as automated by a Polaris C-560 ORP/pH pool controller (Polaris, San Marcos, CA, USA). The Polaris controller interprets feedback from the oxidation-reduction (ORP) or pH electrodes separately; it opens the erosion feeder valve or activates the acid pump as needed regardless of the impact that the addition of one chemical has on the measured reading of the other electrode. However, the ORP readings are affected by both the concentration of bromine in the water and the pH reading. Due to heavy bromine consumption in the erosion feeder and difficulties maintaining the Health Department mandated bromine residuals, ozone was added to this system in October 2001. Besides oxidizing organic matter in the water, ozone reacts with the total bromine to free it up for more sanitization thus reducing the amount of chemicals required to maintain the required residuals.

The Water Play water treatment system was recently upgraded during a remodel of Splash Zone into a permanent exhibition that opened in March 2008. The improved sanitization system still uses erosion tablets, an acid reservoir, and an ozone system. A Becs Sys 5 ORP/pH Controller (Becs Technology Inc., Saint Louis, MO, USA) is used for the addition of chemicals. It also provides outputs to our SCADA control system. With these outputs the ozone system is now feedback controlled. An Ozotech Model OZ2-BTULSL-V/PM ozone generator (Ozotech, Inc., Yreka, CA, USA) feeds ozone through a Mazzei venturi injector into a small Retention Vessels Model CT-40SQ pressurized contact chamber (Pentair Water, Chandon, OH, USA). The ozone generator is fed oxygen from an Air-Sep Onyx PSA Oxygen Concentrator (Air Sep Corp., Buffalo, NY, USA). The ozone system is currently running at an applied dose of approximately 0.2 mg/L O_3, at 12 PSI, and with a 1.7 minute contact time. Since this is a new system we are still in the process of dialing in the operational parameters.

In September 2004, two RK1000PE foam fractionators (RK2 Systems Inc., Escondido, CA, USA) were added to the OBW Exhibit life support system. Ozone is piped to these fractionators but has only been tested briefly in January and February 2005.

The Outer Bay Waters Exhibit

The centerpiece of the Outer Bay Wing is the OBW Exhibit (Figure 3), a 1.2 million gallon natural seawater semi-closed system maintained at 20 ^{o}C displaying open-ocean animals, including schooling tunas, sharks, sea turtles, sardines, anchovies, and ocean sunfish. The OBW Exhibit contains the main portion of this volume (~875,000 gallons as viewable volume) with satellite exhibits, holding tanks and life support components containing the rest. The tank itself has maximum dimensions of 35 feet deep, 70 feet long and 30 feet wide front to back. The system receives only 60 – 70 GPM of fresh make-up seawater, which replaces the system volume approximately every 12 – 14 days.

Figure 3. A picture of the main window of the OBW Exhibit, a 1.2 million gallon natural seawater semi-closed system, which is the centerpiece of the Outer Bay Wing.

Initial Life Support System

Water returning from the exhibit flows through six parallel sand filters followed by a full flow concrete ozone contactor and an aeration tower / head tank (Figure 4). Seawater is pumped through the sand filters at a rate of ~1,250 GPM each (7,500 GPM in total) thereby turning over the entire system volume through sand filtration every ~2.7 hr. Portions of the water supplied to the exhibit from the sand filters are diverted to a heat exchange loop, the ozone injection header, and the satellite exhibits / holding tanks. In December 2005 the supply to the satellite exhibits, as shown in Figure 4 was changed. A booster pump was installed to deliver post aeration tower water to the satellite exhibits in order to provide them with seawater of more consistent dissolved oxygen concentrations.

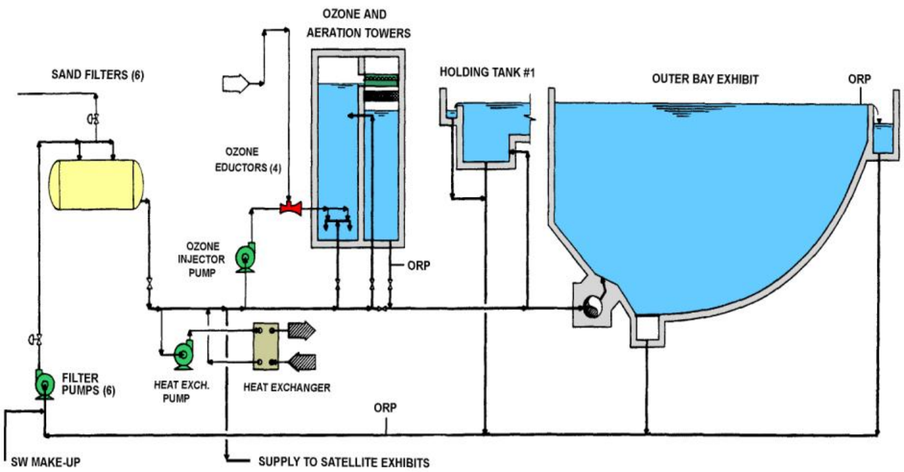

Figure 4. The Outer Bay life support system as initially constructed.

Ozone injection occurs in a 250 GPM side stream drawn off the supply from the sand filters. Flow is split to four 2-inch Mazzei venturi injectors running at a slight vacuum. Flow from the injectors then rejoins the main system flow in the large distribution header risers located at the bottom of the contact chamber (Figure 5).

Ozone is generated by a PCI ozone generator Model F-7 (PCI Ozone & Control Systems, Inc., West Caldwell, NJ, USA) capable of producing up to 7 lb O_3 / day. The output of this generator has been mechanically reduced to produce a maximum of 3.5 lb O_3 / day so that we can run the generator at closer to maximum output for greater efficiency. Compressed air flows through oil removal filters followed by desiccation in a Hankison Compressed Air Dryer Model DH-45 (Hankinson, Canonsburg, PA, USA) before being fed to the ozone generator. Three pairs of Hach/GLI gold ORP sensors, currently models 2010R1 or RD2P6 (Hach Co., Loveland, CO, USA), monitor ORP in the system and control the ozone generator putting it into air prep (disabling ozone generation) or enabling ozone generation as the ORP set-points dictate. The first pair of ORP sensors is located in the exhibit itself and function to monitor ORP levels only. The second pair of ORP sensors is in the return line from the exhibit to the sand filters. The final pair of sensors is in the supply piping to the exhibit down-stream of the ozone contact chamber and aeration tower (Figure 4). Primary generator control is achieved through the set-points on the post-aeration tower ORP sensors (the current high set-point is 635 mV; low set-point is 550 mV). These high and low set-points function to enable or disable ozone generation as needed. The return ORP sensors also have set-points that can disable ozone generation if needed (the current high set-point is 435 mV; low set-point is 350 mV).

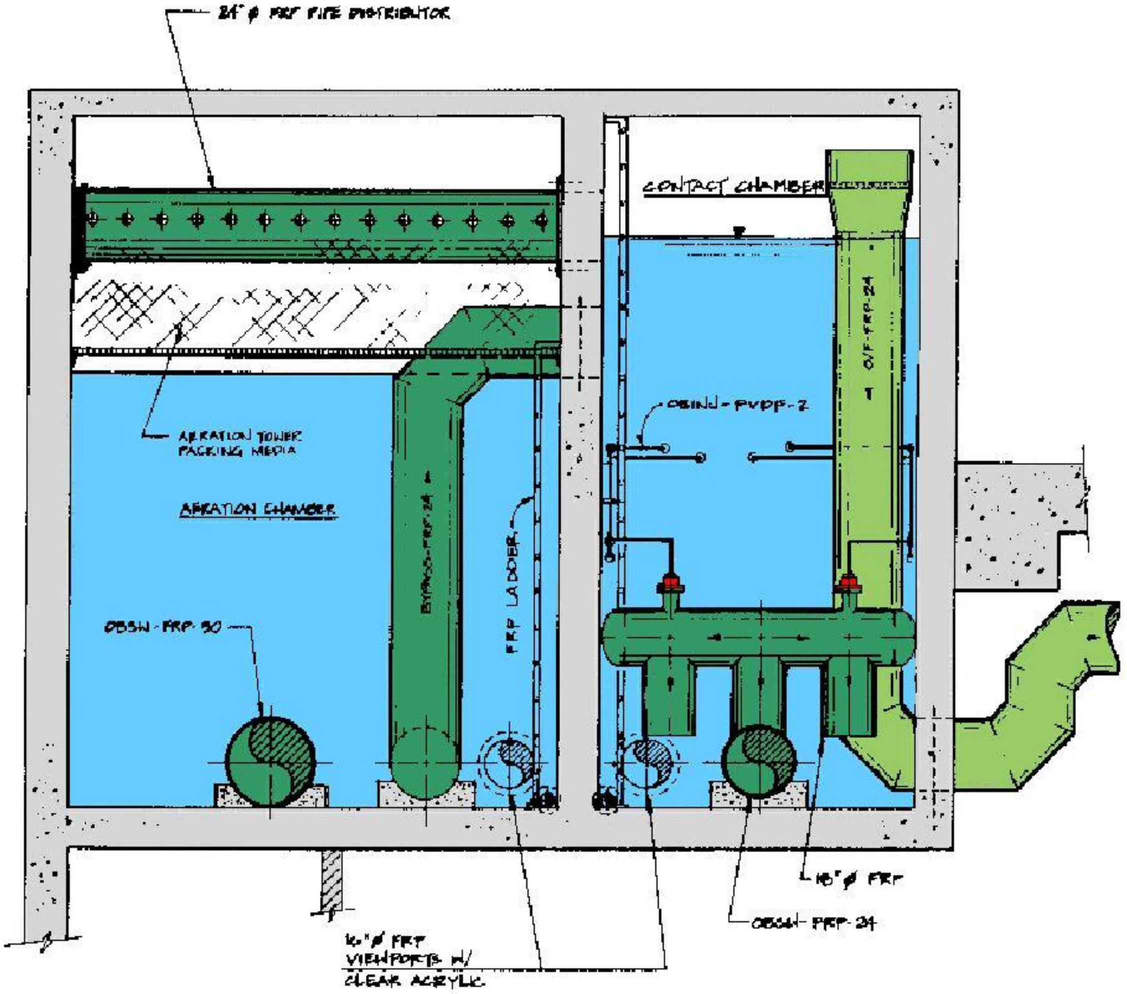

Figure 5. Cross-section of the ozone contact chamber (right side) and aeration tower (left side). Water enters the contact chamber either through the header risers, the ozone injector side-stream, or the bypass. One of the header risers and two of the ozone injection side-stream piping connections (shown in red) are visible in the base of the contact chamber. The bypass is shown rising through the aeration tower before it empties back into the contact chamber. Water exits the contact chamber by flowing into aeration tower where it is discharged back to the exhibit through a 30-inch pipe located at its base.

The main re-circulated water flow can enter the ozone contact chamber (Figure 5) through two routes, the contactor header, the bypass, or both. The contactor header is located at the bottom of the contact chamber. The header is horizontal with two risers made from 18" diameter fiberglass pipe. Ozonated water is introduced at two locations on each riser (Figure 5, shown in red). The bypass rises through the aeration tower and joins the ozonated water from the header near the top of the contact chamber. The piping is sized such that all of the re-circulated flow can be sent to either the contactor header or the bypass.

In concept, by adjusting the flow sent to the bypass, you can regulate the flow to the contactor header and thereby vary the ozone applied dose. As reported previously, due to the size of the contactor header risers, water velocity through the header is critical for efficient ozone injection and mixing in the contact chamber (Phillips and Weidner-Holland 1998). At flows less then 3,000 GPM through the header large bubbles can be seen coming out of the header near the injection points. Since the contact chamber is an integral part of the building it is difficult to modify. The ozone applied dose must be kept low to minimize the formation of residual oxidants or hypobromite, since we have no way to remove them.

Due to problems with large bubble formation at low velocities in the contactor header essentially all of the post-filter flow (~7,500 GPM) is directed through the contactor header. Only a trickle of water goes through the header bypass in order to keep the bypass pipe from going anoxic. Assuming a perfect 100% transfer efficiency in the Mazzei venturi, the calculated ozone applied dose in the contact chamber is ~0.04 mg/L O_3.

OBW Water Clarity Research

During the first 7 to 8 years of operation fish biomass and food rations both increased in the OBW Exhibit (Figure 6). This resulted in a marked decrease in water clarity such that in 2001 the aquarium funded a project to study water clarity in the OBW system and examine ways to improve it with the ultimate goal of proposing changes to the life support system. Much of this data has already been presented (Phillips et al., 2003; Phillips et al., 2004) so only an overview of the study methods and results will be presented here.

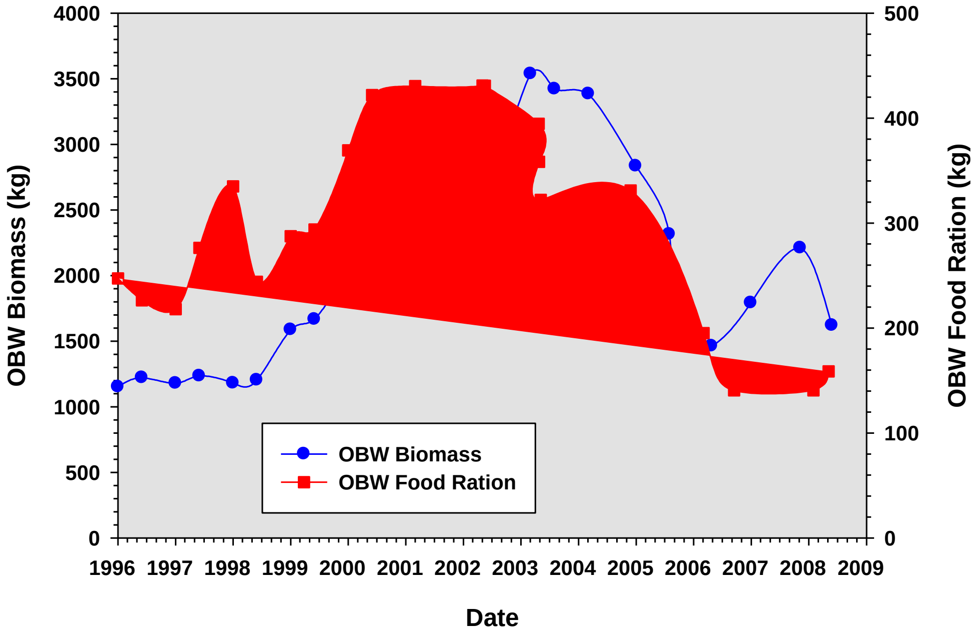

Figure 6. Fish biomass and food rations in the OBW Exhibit since opening.

A preliminary study was conducted in March 2001 to examine short-term trends in turbidity, particle size distributions, and bacterial densities in the OBW Exhibit. Pilot-scale foam fractionation and ozone contacting systems were installed on the OBW Exhibit in June 2001 to determine the effectiveness of these treatment systems at improving water clarity. The effect of ozone applied doses ranging from 0.0 (Air) to 0.3 mg/L O_3 in the foam fractionator and 0.2 to 1.0 mg/L O_3 in the ozone contactor were examined. Treated and untreated seawater were examined for various water quality parameters including turbidity, bacterial densities, ORP, residual ozone, hypobromite, bromate, DPD free chlorine, dissolved oxygen, and pH (Phillips et al., 2004).

Preliminary Study Results

Turbidity results obtained with a Hach FilterTrak 660 Laser Nephelometer (Hach Co., Loveland, CO, USA) fluctuate on a predictable weekly cycle that is driven by feeding events (Figure 7). The weekly food ration shown in Figure 6 is split into four portions that are fed-out on Tuesday, Thursday, Saturday, and Sunday. Rapid increases in turbidity are observed following feeding events but decline within a few hours. Turbidity trends then begin increasing again 5 – 6 hours after a feeding and typically do not return to baseline for 40 to 46 hours following a feeding. The turbidity increases following back-to-back Saturday and Sunday feedings are usually greater but tend to return to the baseline within ~48 hours of the Sunday feeding (Phillips et al., 2004).

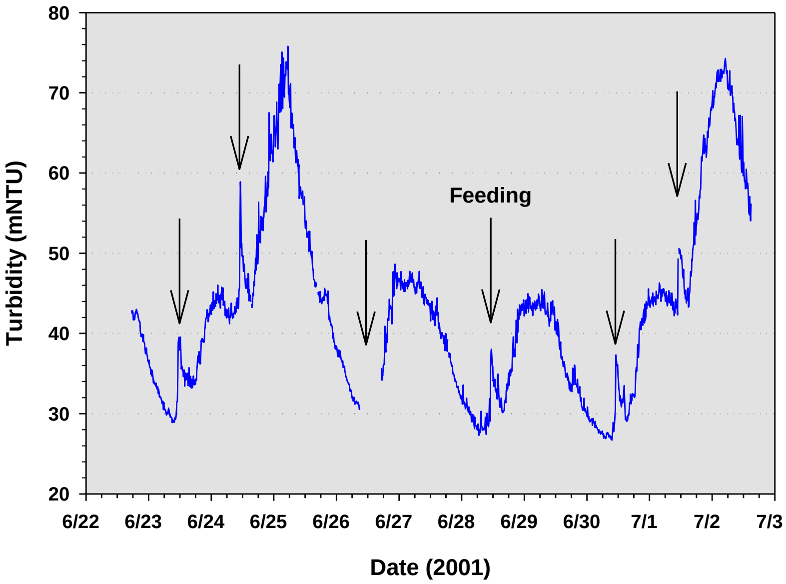

Figure 7. Turbidity trends in the OBW Exhibit June 23 to July 2, 2001. Arrows indicate tank feedings.

Grab samples were collected from the OBW Exhibit every 3 hours and examined for total particle counts using a Beckman Coulter Multisizer 3 Coulter Counter (Beckman Coulter Inc., Fullerton, CA, USA) and for bacterial densities as determined by flow cytometry measurements conducted by Texas A&M University. Particle counts increased following a feeding and did not begin to decline until 21 hours afterwards. The highest proportion of the particle densities were found in the lower size classes (0.7 to 1.5µm), with over 99% of the particles counted being less then 1.5µm in size (Phillips et al., 2003; Phillips et al., 2004). Particle counts and size distributions were unfortunately only available during the preliminary study.

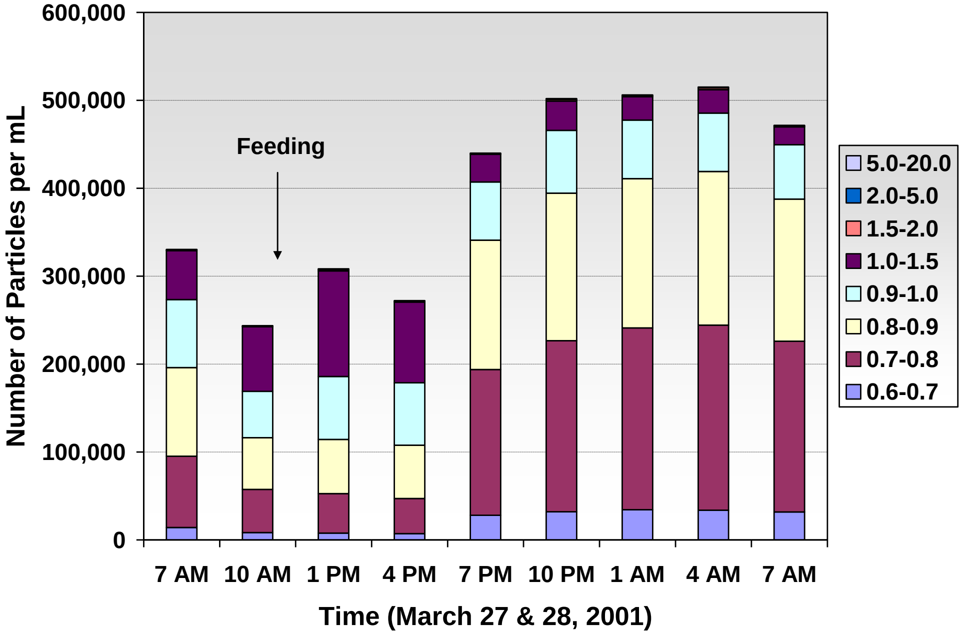

Figure 8. Total particle counts in various size classes measured in the preliminary study, March 27 – 28, 2001, as determined using a Beckman Coulter Multisizer 3 Coulter (Phillips et al., 2003).

Bacterial densities determined via flow cytometry were of the same order of magnitude as the number of particles in the 0.7 - 1.5 µm range. Taken together this demonstrates that turbidity in the OBW Exhibit is largely due to particles less then 1.5 µm in size and is driven by fluctuations in the bacterial population which is in turn driven by feeding events (Phillips et al., 2004).

Pilot Scale Results

In June 2001 a pilot-scale system was installed in the 3rd floor service area of the OBW Exhibit. Regulated flows of seawater drawn from the exhibit overflow box could be sent to an ozone contactor, a foam fractionator, or to a bypass for modeling side-streams (Figure 9). Post-ozone contactor and post-ozone fractionator seawater was directed to a small aeration tower before entering the mixing tank. Sample ports were installed in order to collect post-contactor, post-frationator, bypass, and post-mixing tank water. Details of the equipment used can be found in Phillips et al. (2004).

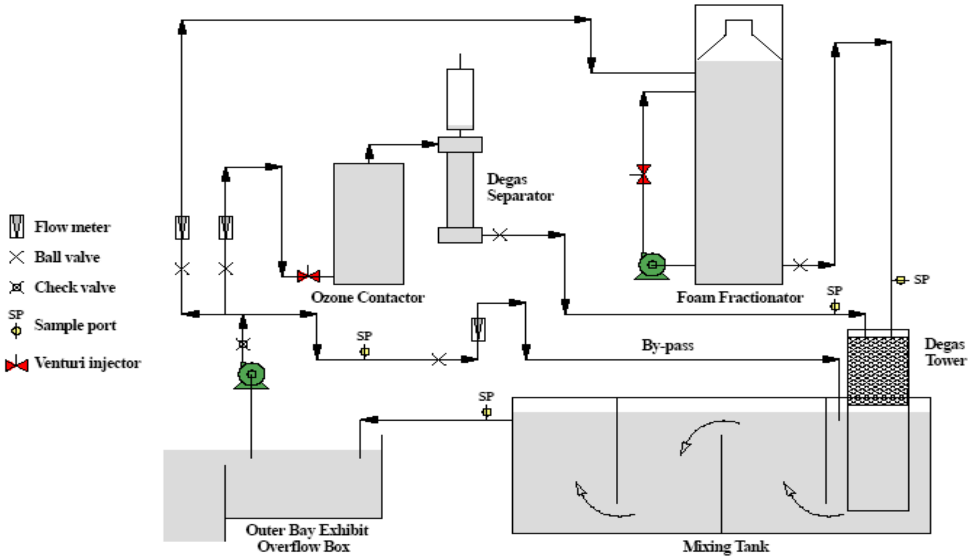

Figure 9. Flow diagram of the pilot scale system (Phillips et al., 2004).

Pilot-scale system experiments were conducted on Wednesdays or less frequently on Fridays when exhibit turbidity was on a downward trend in order to minimize fluctuations in untreated water quality (Figure 7). A total of 28 experimental trials on the ozone contactor and 32 trials on the foam fractionator were conducted (Phillips et al., 2004). In most of these trials the water quality parameters mentioned above were monitored in treated and untreated water. The results obtained are summarized in Table I and Figure 10.

Table I. Summary of the water quality results for the ozone contactor and foam fractionator (Phillips et al., 2004).

Variable	Ozone Contactor	Foam Fractionator
Ozone Dose (mg/L)	0.2 to >1.0	0.0 (Air) to 0.1
Turbidity Reduction	None, turbidity increase	Significant, average 20%
Bacteria Reduction ($\log_{10}$)	Significant, 0.3 to 2.8[a]	Moderate, <0.1
Oxidation-Reduction Potential	Exponential increase[a]	Exponential increase[a,b]
Residual oxidants (mg/L)	Significant, 0.2 to 1.2[a]	Moderate, <0.1[a,b,c]
Residual ozone (mg/L)	Not detected	Not detected
Dissolved Oxygen (% Saturation)	Increase of 40 to 49%	Increase of 12 to 15%
pH	Minor increase	Minor increase

[a] Increased with ozone applied dose.

[b] When ozone was applied.

[c] Less than 0.1 mg/L at ozone doses up to 0.1 mg/L.

Ozone doses commonly used in ozone contactors (0.2 to 1.0 mg/L O_3) consistently increased the turbidity. The turbidity increase in the contactor was very significant at ozone doses above 0.3 mg/L O_3 and supplementary testing demonstrated that the increase was not due to dissolved gases or residual oxidants. Turbidity was reduced by an average of 20% in the foam fractionator over the range from zero (air) to 0.1 mg/L O_3 (Phillips et al., 2004).

The cause of the turbidity increase at higher applied doses is difficult to ascertain. Studies of ozone use in water treatment have shown that ozone may cause flocculation thereby increasing turbidity. Ozone oxidizes dissolved and particulate organic materials into smaller subunits some of which may flocculate together (AWWA, 1991). It is possible that an increase in number of smaller and/or larger organic molecules or particles resulted in a turbidity increase in the Outer Bay system seawater. Unfortunately we do not have corresponding particle count data to substantiate these theories (Phillips et al., 2004).

Disinfection, as measured by heterotrophic plate counts of viable bacteria, was significant in the ozone contactor. Bacterial reduction was moderate in the foam fractionator with no significant improvement in disinfection with the addition of ozone up 0.1 mg/L O_3. However, flow cytometry results demonstrated that bacteria were physically removed by the fractionator (Phillips et al., 2004).

The ORP increased exponentially as soon as any ozone was added to the seawater (Figure 10). Trends were similar for both the ozone contactor and foam fractionator. The ORP increase was very rapid up to an ozone dose of about 0.1 mg/L O_3 and then the trend shifted to a slow, gradual incline (Phillips et al., 2004).

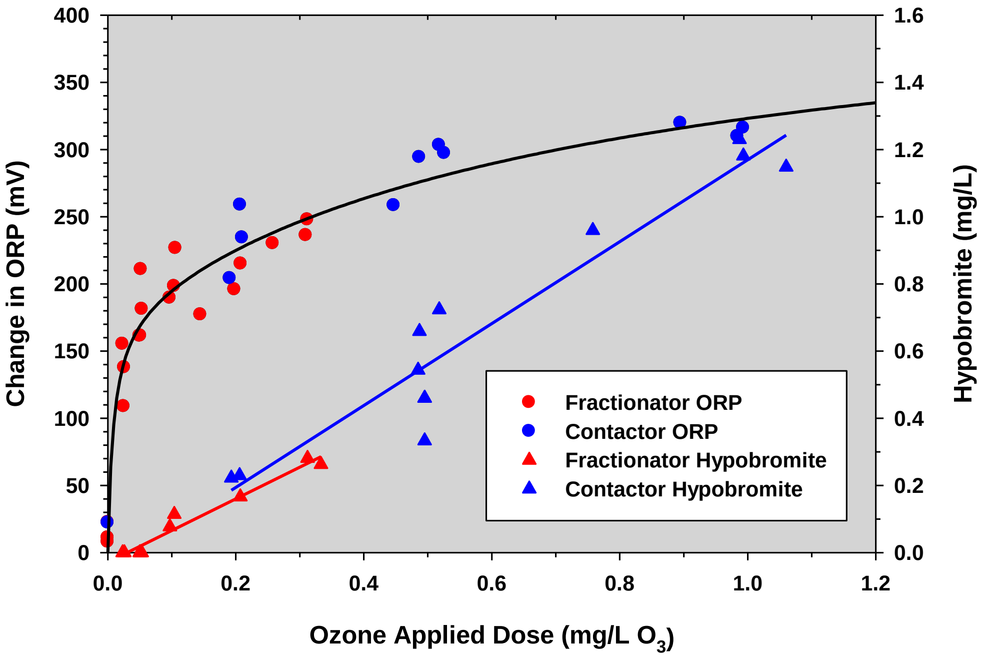

Figure 10. Change in ORP and hypobromite concentrations observed at various ozone applied doses in the foam fractionator and contactor during the pilot scale testing.

Residual oxidants (hypobromite as measured by titration or by DPD) in the pilot-scale system increased in a linear fashion with ozone dose in both the contactor and the fractionator (Figure 10). The rate of increase was slightly more rapid in the contactor. Formation of hypobromite can be very significant in an ozone contactor. Hypobromite is a strong and unstable oxidant capable of reacting with chemical compounds and biological materials (Grguric et al., 1994). Due to the relatively low applied dose used in fractionators, the formation of hypobromite should be minimal or moderate (Phillips et al., 2004).

The relationships between ozone applied dose and ORP and ozone applied dose and residual oxidants (hypobromite) were very different (Figure 10). ORP increased exponentially at very low ozone doses, whereas residual oxidants increased in a linear manner with ozone dose. For safe and optimal life support system operation it is important to understand these relationships for each particular system and water type (Phillips et al., 2004).

Ozone contacting and foam fractionation supersaturated dissolved oxygen in the treated water. This supersaturation was easily removed by passive de-aeration techniques. Ozone contacting and foam fractionation also raised the pH of treated seawater, but only very slightly (Phillips et al., 2004).

Water quality in the Outer Bay system varied widely during the course of our pilot-scale studies. This dynamic environment made it difficult to repeat experiments under similar conditions. While the data collected do not demonstrate a significant advantage to using low doses of ozone in a foam fractionator, the authors are not thoroughly convinced that the use of ozone in a foam fractionator will not enhance an exhibit system over time. Similar experiments need to be conducted under more controlled conditions and additional water quality parameters need to be examined (e.g., total organic carbon, particle size distribution) (Phillips et al., 2004).

OBW Exhibit Remodel - Foam Fractionators Addition

Based on the results of our pilot scale studies we focused on foam fractionation to improve water clarity in the OBW Exhibit. To that end two parallel flow RK1000PE foam fractionators were added to the system in September 2004. Each fractionator draws 1,200 GPM of water from the exhibit with a fractionator residence time of ~1.6 min (Figure 11). The fractionators discharge treated water to the top of the ozone contact chamber from which it flows directly to the aeration tower. The aeration tower is now operating at a water velocity of 0.083 ft/sec, which is close to the maximum we are comfortable running. Currently the fractionators are running on air but they were briefly tested with ozone in January – February 2005, results of which are presented below.

Figure 11. A picture of the two RK1000PE foam fractionators that were added to the OBW Exhibit life system in September 2004.

The addition of the fractionators reduced the system turn-over time through filtration (sand filter and foam fractionators) from ~2.7 hours to ~2 hours. Within the first several weeks of fractionator operation water clarity visually improved in the Outer Bay system. Increases in turbidity are still observed in association with exhibit feeding events and the familiar weekly pattern in turbidity is still apparent, but the increases are generally lower (Figure 12).

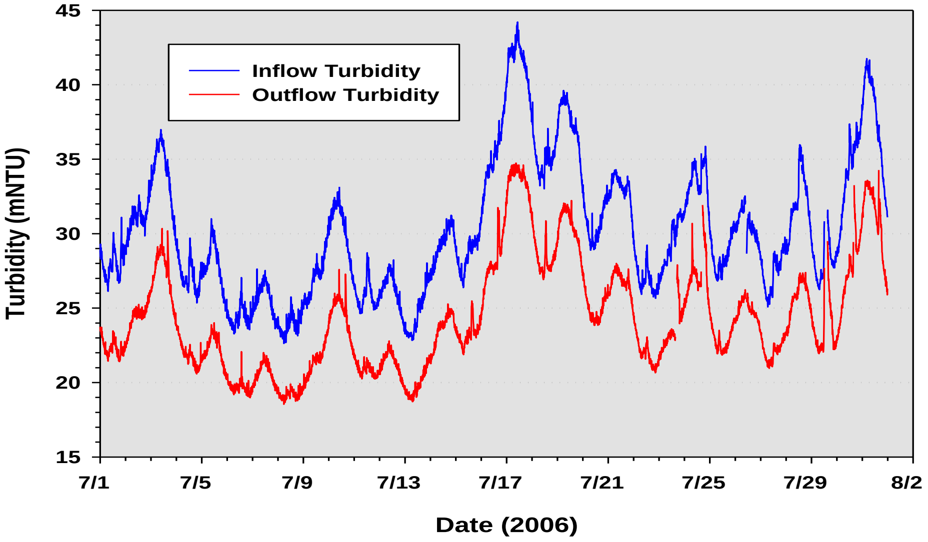

Figure 12. Turbidity measurements from July 2006 that were collected simultaneously from influent and effluent of a fractionator installed on the OBW Exhibit. These data show an average decrease in turbidity of 19% on a single pass through the fractionator.

Turbidity measurements collected simultaneously from fractionator influent and effluent typically demonstrate an 18 to 21% decrease in turbidity on a single pass through the fractionators which is consistent with results from our pilot scale study (Figure 12). Under normal circumstances the percent reduction seems reasonably constant across the range of influent turbidity that we have experienced. No discernable changes in dissolved oxygen saturation or pH of Outer Bay system seawater have been noted since the fractionators were placed in operation (Phillips et al., 2004).

Ozone use in the OBW Exhibit Foam Fractionators

As currently operated ozone is applied intermittently to our large ozone contactor at a low applied dose of approximately 0.04 mg/L O_3. The ORP sensors located downstream of the aeration tower (Figure 4) turn the ozone off (switch the generator to air-prep) when the high ORP set-point is reached (the current high set-point is 635 mV). The same sensors enable ozone again once the ORP has declined below the low set-point (the current low set-point is 550 mV). As a result ozone cycles on and off in the contactor and is typically applied to the contactor approximately 30% of the time. Given the lower flow rate through the fractionators (2,400 GPM) as opposed to the contact chamber (7,500 GPM), it seemed reasonable that using the same ozone applied dose in the fractionators (0.04 mg/L O_3) could enable continuous operation with ozone while maintaining the same or better water clarity in the system. The ORP readings should drop and remain below the high set-points even if ozone is injected continuously in the fractionators.

In January and February 2005 the new fractionators were tested with ozone. Air was supplied to the contactor injectors (no ozone) and ozone was routed to the fractionators at an initial applied dose of about 0.04 mg/L O_3. As expected, ORP readings dropped as soon as ozone was switched to the fractionators (Figure 13). Approximately 19 days into the trial the ozone applied dose in the fractionator was raised to 0.05 mg/L O_3 which resulted in a rise of ~50mV in the ORP reading downstream of the aeration tower.

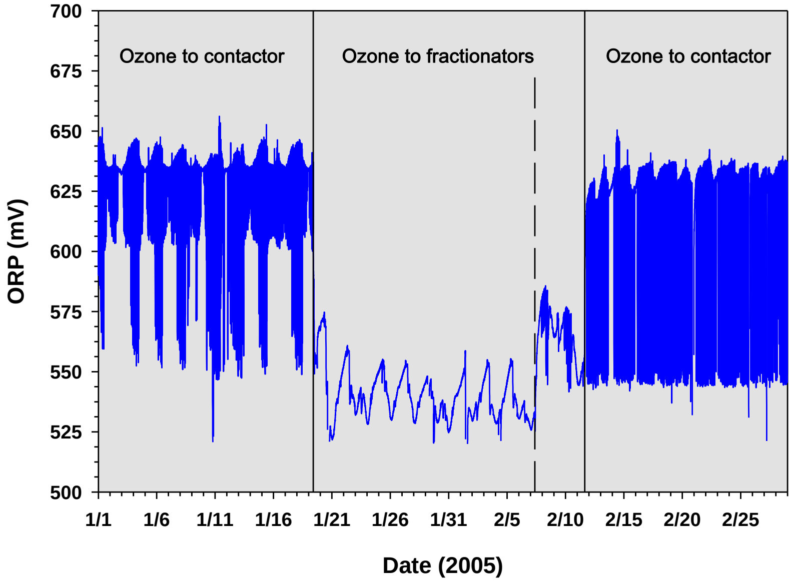

Figure 13. ORP trends measured by one of the Hach/GLI gold ORP sensors in the post aeration tower line (Figure 4) that supplies water to the OBW Exhibit. During the period shown (January through February 2005) ozone was switched from the ozone contactor to the fractionators and back to the contactor. The solid black lines delineate when ozone was sent to the fractionators and air was supplied to the injectors in the contact chamber. When ozone was supplied to the contactor (areas to the left and right of the solid black lines) an applied dose of 0.04 mg/L O_3 was used. The ozone applied dose in the fractionators was initially set to 0.04 mg/L O_3 but was later raised to 0.05 mg/L O_3 as delineated by the dashed black line.

The turbidity of exhibit water returning to the sand filters was monitored continuously during this study using a Hach FilterTrak 660 Laser Nephelometer. The turbidity trend showed a gradual increase in its baseline during this four-week trial. From a visual perspective the clarity of the tank as viewed from the main exhibit window also declined during this period.

The results of this trial indicate that we can indeed operate the fractionators with ozone continuously while achieving lower ORP readings in the system (Figure 13); however the desired water clarity could not be maintained. There were some extraneous circumstances that may have affected the results of this experiment. The last two of the OBW filters were re-sanded 2 months prior to this trial. Turbidity data collected pre- and post-filter generally showed increased turbidity down-stream from the filter for almost 2 months following re-sanding. As a result, the exact cause of the increase in the baseline turbidity observed during this fractionator trial remains uncertain. The turbidity increase was likely due to an increase in the bacteria population due to lower sanitization in the fractionators but we lack definitive supporting data. Given time constraints we have been not been able to repeat this experiment nor have we operated the contactor and fractionators with ozone simultaneously to date.

Tentative OBW Exhibit LSS Modifications

MBA is currently discussing a remodel of the Outer Bay Wing, including the OBW Exhibit. Planning is in the early stages but we are already looking seriously at several major modifications to the OBW Exhibit life support system.

Our primary goal would be to side stream a smaller portion of the re-circulated flow (~800 - 1,200 GPM) through pressurized ozone contact chambers at a higher applied dose. The pressurized ozone contactors would be followed by activated carbon filtration to remove residual oxidants. We anticipate that smaller contactors operated at higher applied doses followed by carbon filtration will have minimal impacts on system ORP and residual oxidants.

If we are able to install a pressurized ozone contactor side-stream, then the second goal would be to modify the existing concrete contactor and aeration tower / head tank. Basically we would penetrate the existing wall separating the contact chamber and aeration tower and make the contact chamber part of the aeration tower. This would require substantial reconfiguration of the supply piping to the aeration tower, a completely new water distribution system incorporating low pressure spray nozzles at the top of the tower, and all new packing media.

Finally the addition of foam fractionators substantially decreased turbidity in the OBW Exhibit and we are pleased with the results. If space and adequate structural support can be found for the equipment we would like to add two additional RK1000PE fractionators to further reduce the turnover time through filtration (sand filtration and foam fractionation).

Future Research

It is always very difficult for us to find time in our daily aquarium routine to conduct basic research and the possibilities for research in aquarium life support and water quality seem endless. For starters, we would like to repeat some of our past experiments. We would like to better define why turbidity increases in our natural seawater system as ozone applied dose is increased. It is unclear to us if the turbidity increase is due to flocculation of existing particles, formation of fine particles, dissolution of compounds, or something else. Obtaining accurate particle size distributions, turbidity, and possibly total and dissolved organic carbon measurements will be critical in answering this question.

We would also like to experiment more with ozone in our existing contact chamber and foam fractionators. What is the best application of ozone in our existing equipment (contact chamber or fractionators or both) to achieve the best water quality in our OBW Exhibit? In our initial 2005 study when ozone was applied to the fractionators only, ORP declined in the system (Figure 12) and turbidity gradually increased. Determining the cause of this increase in turbidity is critical to understanding the best use of ozone in our current life support equipment.

Lastly, we are interested in conducting a survey and comparison of different ORP electrodes, including gold and platinum probes, under similar conditions. This would include ORP readings, response times to changes in ORP, differences between gold and platinum sensors, influence of calibration methods, and routine maintenance requirements.

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