Process Requirements for Water Quality Improvements & Disinfection Using Ozonation & UV Irradiation

Steven Summerfelt, Mark Sharrer, Scott Tsukuda, & Michael Gearheart
Freshwater Institute, Shepherdstown, WV
OUTLINE

- Introduction
- O$_3$ & UV for Disinfection in RAS
- O$_3$ dosing rate in RAS
- O$_3$ prevents BGD events in RAS
- O$_3$ & RAS Water Quality
- Process control for full-flow ozonation
- Examples: O$_3$ Followed by UV
Introduction

- Obligate and opportunistic fish pathogens can accumulate in RAS
  - during a disease outbreak when pathogens propagate and shed from their host
  - when no internal water disinfection process is used
Ozonation (O$_3$) and ultra violet (UV) irradiation can be used separately or in combination to treat water in RAS before it returns to the fish culture tanks.

✔ Proactively prevent the accumulation of fish pathogens
Introduction: Ozonation: +/-

- **Advantages:**
  - rapid reaction rate,
    - dissolved ozone half-life only 0-15 sec (Bullock et al., 1997);
  - few harmful reaction by-products in freshwater;
  - oxygen is produced as a reaction end-product.

- **Disadvantages:**
  - ozone is dangerous to humans and fish.
O$_3$ Supports Water Treatment

- Clear & often ‘blue’ water even with zero water exchange

(Courtesy Yossi Tal, Center of Marine Biotechnology, MD)
O$_3$ Supports Water Treatment

- directly oxidizes NO$_2^-$ to NO$_3^-$;
- helps remove color & dissolved organic matter:
  - breaks non-biodegradable compounds into smaller & more biodegradable compounds;
- helps remove dissolved & fine particulate matter
  - precipitates dissolved organic molecules,
  - micro-flocculates fine particulate matter,
  - improving solids removal by settling, filtration, or flotation.
O$_3$ & UV Can Reduce Fish Disease

- Ozone & UV are used in RAS to reduce fish disease, by:
  - improving water quality and reducing fish stress
  - disinfecting the water
    - large reductions in micro-organisms are possible.
O₃ & UV for Disinfection in RAS

- Ozone
  - Must maintain a residual concentration (C) for a given time (t), i.e., Chick-Watson Law:

\[
\text{microbial reduction} \propto [O₃]_{\text{residual}} \cdot t_{\text{contact}}
\]
O₃ Doses for Disinfection

- Must maintain a residual concentration (C) for a given time (t):

<table>
<thead>
<tr>
<th>Organism</th>
<th>C<em>t, mg</em>min/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISAV</td>
<td>0.3</td>
</tr>
<tr>
<td>Aeromonas salmonicida</td>
<td>1.6</td>
</tr>
<tr>
<td>Yersinia ruckeri</td>
<td>0.45-0.6</td>
</tr>
<tr>
<td>Flavobacterium sp.</td>
<td>2.8</td>
</tr>
<tr>
<td>Flexibacter sp.</td>
<td>1.6</td>
</tr>
<tr>
<td>Streptococcus sp.</td>
<td>0.015</td>
</tr>
<tr>
<td>Vibrio salmonicidiae</td>
<td>0.45-0.6</td>
</tr>
</tbody>
</table>
UV Dose

- Achieving UV disinfection requires maintaining a minimum UV dose:
  \[
  \text{UV dose} = (\text{UV intensity}) \cdot (\text{exposure time})
  \]
  \[
  = (\text{mW}/\text{cm}^2) \cdot (\text{sec})
  \]
  \[
  = \text{mW} \cdot \text{sec}/\text{cm}^2
  \]

- 10-30 second contact times are typical (White, 1992).
UV Doses for Disinfection

- Dose to inactivate 99.9% of BACTERIA from Wedemeyer (1996) and Liltved (2001):

<table>
<thead>
<tr>
<th>Organism</th>
<th>Dose (mW-sec/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeromonas salmonicida</td>
<td>4</td>
</tr>
<tr>
<td>Aeromonas hydrophila</td>
<td>5</td>
</tr>
<tr>
<td>Vibrio anguillarum</td>
<td>4</td>
</tr>
<tr>
<td>Yersinia ruckeri</td>
<td>3</td>
</tr>
<tr>
<td>Pseudomonas fluorescens</td>
<td>5</td>
</tr>
</tbody>
</table>
UV Doses for Disinfection

- Dose to inactivate 99.9% of VIRUSES from Wedemeyer (1996) and Liltved (2001):

<table>
<thead>
<tr>
<th>Virus</th>
<th>mW-sec/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISA</td>
<td>4-10*</td>
</tr>
<tr>
<td>IHN</td>
<td>1-3</td>
</tr>
<tr>
<td>IPN</td>
<td>100-200</td>
</tr>
<tr>
<td>Channel catfish virus</td>
<td>2</td>
</tr>
<tr>
<td>Herpesvirus salmonis</td>
<td>2</td>
</tr>
<tr>
<td>White spot syndrome baculovirus</td>
<td>900*</td>
</tr>
</tbody>
</table>

*loss of infectivity
UV Doses for Disinfection

- Wedemeyer (1996):
  - Dose to inhibit growth of *Saprolignia* 230 mW-sec/cm²
  - Dose to decrease infectivity of *myxobolus cerebralis* 28 mW-sec/cm²
  - Recommended dose for recirculated water 50* mW-sec/cm²
  - Recommended dose for hatchery wastewater 30 mW-sec/cm²
UV Dose

- Actual UV dose applied to water flow depends on:
  - Water flowrate (Q) and operating volume within UV vessel;
  - Lamp intensity (including losses at quartz sleeve);
  - UV transmittance of water (% Transm.).

\[
\text{UV dose} = (\text{UV intensity}) \cdot (\text{exposure time}) \cdot (\text{transmittance factor})
\]

\[
\cong (\text{UV intensity}) \cdot \left( \frac{V_{\text{vessel}}}{Q} \right) \cdot a \cdot \exp(b \cdot \% \text{Transm})
\]

\[
= \# \, \text{mW} \cdot \text{sec/cm}^2
\]
UV Doses Required for Disinfection

- Prefiltration through 50 μm screens can improve bacterial inactivation with UV by $3.0 \log_{10}$ units.
  ✓ Liltved and Cripps (1999)
UV Removes Dissolved $\text{O}_3$

- Expose $\text{O}_3$ to high intensity UV light:
  - wavelength of 250-260 nm

- Other methods to removed $\text{O}_3$
  - Provide extended contact time & let $\text{O}_3$ react away;
  - Aerate to strip $\text{O}_3$ into air;
    - G:L of 10:1 to 20:1
  - React $\text{O}_3$ with hydrogen peroxide;
  - Pass ozonated flow through an activated carbon bed or biofilter.
O₃ Destruction with UV Irradiation

Ozone Inlet Concentration, mg/L vs. Ozone Removal, %

- 6.7 sec HRT with UV on
- 3.3 sec HRT with UV on
- 2.2 sec HRT with UV on
- 1.7 sec HRT with UV on
- 6.7 sec HRT with UV off (control)
- 1.7 sec HRT with UV off (control)

Summerfelt et al. 2004. Aquacultural Engineering
O$_3$ Destruction with UV Irradiation

- $49.3 \pm 0.6$ mW-s/cm$^2$ removed 100% of the dissolved O$_3$ @ inlet O$_3$ concentration $\leq 0.10$ mg/L
- $35.6 \pm 0.3$ mW-s/cm$^2$ could not remove 100% of the O$_3$ @ inlet O$_3$ concentration of $\leq 0.10$ mg/L.
- $80.4 \pm 2.6$ mW-s/cm$^2$ & $153.3 \pm 2.1$ mW-s/cm$^2$ consistently removed 100% of the dissolved O$_3$ when the inlet O$_3$ concentration was $\leq 0.30$ mg/L

Summerfelt et al. 2004. Aquacultural Engineering
Side-stream studies in salmonid RAS determined:

- UV dosages required to inactivate bacteria
  - Sharrer et al. (2005)
- O$_3$ dosages and ‘O$_3$ + UV’ dosages to inactivate bacteria
  - Sharrer and Summerfelt (2007)
Side-Stream O₃ & UV Treatment Study
O$_3$ / UV Side-Stream Study

- Two 1.5 Hp pumps followed by venturi injector and static mixer

- Side-stream flow rate ranged from 3-6% (i.e., 150 and 300 L/min) of the entire recirculating flow
O₃ / UV Side-Stream Study

- Side flow enters down-flow bubble contactor (Marine Biotech) to remove off-gas.

- Magnetic Flow meter (Krohne Inc.) measures flow rate
U-Tube Contactor

- Mean HRT of 16.6 & 8.3 min provided at flows of 150 and 300 L/min.
Sidestream UV Treatment

- Flow irradiated with a tube and shell design Trojan UV Logic model 02AM15

- UV doses (mJ/cm²) calculated using a proprietary spreadsheet supplied by manufacturer (Trojan Technologies, Inc.)
Results: Total Heterotrophic Bacteria

SIDE-STREAM STUDY: Sharrer & Summerfelt (2007)

**Equation 1:**

\[ y = -1.173x + 7.8944 \]

- \( R^2 = 0.1273 \)
- \( p = 0.386 \)

**Equation 2:**

\[ y = -0.942x + 2.8873 \]

- \( R^2 = 0.5531 \)
- \( p = 0.034 \)
**O₃ Followed by UV Irradiation**

- Achieve total heterotrophic bacteria counts 0-2 cfu/ml
- Much better than using UV alone or O₃ alone in a RAS!

**SIDE-STREAM STUDIES:**
Sharrer et al (2005);
Sharrer & Summerfelt (2007)

‘O₃ + UV’ > ‘O₃ alone’ >> ‘UV alone’
## Results: UV Inactivation of Bacteria

- Side-stream studies with no O₃ (Sharrer et al. 2005)
- Heterotrophic bacteria counts

<table>
<thead>
<tr>
<th>Mean UV dose, UV unit, Number of sampling events</th>
<th>Hydraulic residence time within UV unit, mL</th>
<th>Total heterotrophic bacteria counts before UV, cfu/100 mL</th>
<th>Total heterotrophic bacteria counts after UV, cfu/100 mL</th>
<th>Reduction in total heterotrophic bacteria counts</th>
<th>LOG₁₀ reduction in total heterotrophic bacteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1821 ± 86</td>
<td>70.1 ± 2.8</td>
<td>9038 ± 3225</td>
<td>181 ± 71</td>
<td>98 ± 1</td>
<td>1.7</td>
</tr>
<tr>
<td>980 ± 17</td>
<td>36.2 ± 1.1</td>
<td>1708 ± 441</td>
<td>192 ± 68</td>
<td>87 ± 7</td>
<td>0.9</td>
</tr>
<tr>
<td>493 ± 20</td>
<td>22.3 ± 0.3</td>
<td>7749 ± 2289</td>
<td>5145 ± 1754</td>
<td>57 ± 14</td>
<td>0.4</td>
</tr>
<tr>
<td>303 ± 12</td>
<td>12.8 ± 0.0</td>
<td>2215 ± 1074</td>
<td>610 ± 263</td>
<td>81 ± 5</td>
<td>0.7</td>
</tr>
<tr>
<td>150 ± 9</td>
<td>6.4 ± 0.1</td>
<td>7953 ± 3672</td>
<td>328 ± 311</td>
<td>81 ± 19</td>
<td>0.7</td>
</tr>
</tbody>
</table>
## Results: UV Inactivation of Bacteria

- Side-stream studies with no O$_3$ (Sharrer et al. 2005)
- Heterotrophic bacteria counts

<table>
<thead>
<tr>
<th>Mean UV dose, MJ/cm$^2$</th>
<th>Hydraulic residence time within UV unit, sec</th>
<th>Number of sampling events</th>
<th>Total coliform bacteria counts before UV, cfu/100 mL</th>
<th>Total coliform bacteria counts after UV, cfu/100 mL</th>
<th>Reduction in total coliform bacteria counts</th>
<th>LOG10 reduction in total coliform bacteria across UV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1821 ± 86</td>
<td>70.1 ± 2.8</td>
<td>4</td>
<td>228 ± 144</td>
<td>0 ± 0</td>
<td>100</td>
<td>na</td>
</tr>
<tr>
<td>990 ± 21</td>
<td>35.7 ± 1.3</td>
<td>3</td>
<td>60 ± 25</td>
<td>0 ± 0</td>
<td>100</td>
<td>na</td>
</tr>
<tr>
<td>524 ± 23</td>
<td>22.3 ± 0.4</td>
<td>5</td>
<td>46 ± 21</td>
<td>0 ± 0</td>
<td>100</td>
<td>na</td>
</tr>
<tr>
<td>303 ± 12</td>
<td>12.8 ± 0.0</td>
<td>7</td>
<td>56 ± 19</td>
<td>0 ± 0</td>
<td>100</td>
<td>na</td>
</tr>
<tr>
<td>150 ± 9</td>
<td>6.4 ± 0.1</td>
<td>3</td>
<td>100 ± 55</td>
<td>0 ± 0</td>
<td>100</td>
<td>na</td>
</tr>
<tr>
<td>77 ± 1</td>
<td>3.2 ± 0.0</td>
<td>2</td>
<td>215 ± 205</td>
<td>0 ± 0</td>
<td>100</td>
<td>na</td>
</tr>
</tbody>
</table>
Discussion: UV Inactivation of Bacteria

- **Hypothesis**: Bacteria embedded within particulate matter or had formed bacterial aggregates that effectively shielded them from UV.

- More recent work has confused this issue...
Discussion: O₃ Inactivation of Bacteria

- In addition…
- ….Heterotrophic bacteria were surprisingly resistant to complete O₃ inactivation with relatively high O₃ C*ₜ.
  - 0.9-3.6 min-mg/L O₃
  - But lower bacteria counts were achieved with ozone than when using UV alone.
  - Sharrer and Summerfelt (2007)
Full-Flow $\text{O}_3 + \text{UV}$ Treatment Study

- Freshwater Institute’s Grow-out System.
  - 4700 L/min recycle flow
  - $\text{O}_3$ added with $\text{O}_2$ feed gas in LHO
  - 1.5 min $\text{O}_3$ contact time in LHO sump
  - UV irradiation at 90 MJ/cm$^2$
  - $\text{O}_3 + \text{UV}$ before flow enters culture tank
    - 150 m$^3$ culture tank
    - 30 min HRT
    - 7.3-8.6 mg/L $\Delta\text{DO}$ across tank
    - 73-93 kg/day mean feed rate
Full-Flow O$_3$ + UV Treatment Study

- O$_3$ Control Processes:
  - A proportional-integral-derivative (PID) feed-back control loop automatically adjusted the O$_3$ generated in the O$_2$ feed gas to maintain the O$_3$ residual or ORP at a pre-selected set-point at end of O$_3$ contact chamber.
    - 20 ppb O$_3$
    - 375, 450, & 525 mv ORP
Full-Flow $O_3$ + UV Treatment Study

$O_3$ Control Processes:

- Safety interlocks to shut-off generator when:
  - ORP exceeds 375 mv after UV irradiation (UV fails)
    - to protect fish
  - Water level above LHO dropped when recycle flow stopped
    - to protect staff
  - High $O_3$ gas concentration detected in room (manual shut-down)
    - to protect staff
Full-Flow $\text{O}_3$ + UV Treatment Study

- $\text{O}_3$ concentration generated in the $\text{O}_2$ feed gas was automatically & remotely adjusted at the PCI-Wedeco model GSO40 ozone generator.
Full-Flow $O_3 + UV$ Treatment Study

- $O_3$ & $O_2$ gas control panels
  - stainless steel, teflon, viton components contact dry $O_3$ gas
  - Solenoid valves shut-off ozone
Full-Flow $O_3 + UV$ Treatment Study

- Transfer $O_3$ in an $O_2$ carrier gas at the LHO
Full-Flow $O_3$ + UV Treatment Study

- $O_3$ transfers in LHO
- $O_3$ contacting in:
  - LHO
  - LHO sump
  - Channel to UV unit
  - HRT of 1.5 min
Full-Flow $\text{O}_3 + \text{UV}$ Treatment Study

- UV irradiation channel unit delivered 90 MJ/cm$^2$

Courtesy PRAqua Technologies (BC)
O$_3$ Followed by UV Irradiation

- Total Heterotrophic Plate Counts, cfu/ml

<table>
<thead>
<tr>
<th></th>
<th>Before Ozone</th>
<th>After Ozone</th>
<th>After UV</th>
<th>% Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Ozone &amp; No UV</td>
<td>466 ± 147</td>
<td>509 ± 139</td>
<td>530 ± 145</td>
<td>NA</td>
</tr>
<tr>
<td>Ozone @ 375 mv &amp; No UV</td>
<td>48 ± 9</td>
<td>22 ± 5</td>
<td>21 ± 3</td>
<td>56.3</td>
</tr>
<tr>
<td>Ozone @ 375 mv + UV</td>
<td>124 ± 27</td>
<td>81 ± 18</td>
<td>3 ± 1</td>
<td>97.6</td>
</tr>
<tr>
<td>Ozone @ 450 mv + UV</td>
<td>50 ± 12</td>
<td>22 ± 4</td>
<td>0 ± 0</td>
<td>100</td>
</tr>
<tr>
<td>Ozone @ 525 mv + UV</td>
<td>386 ± 348</td>
<td>225 ± 209</td>
<td>0.4 ± 0.3</td>
<td>99.9</td>
</tr>
<tr>
<td>Ozone @ 20 ppb + UV</td>
<td>47 ± 11</td>
<td>8 ± 2</td>
<td>0 ± 0</td>
<td>100</td>
</tr>
</tbody>
</table>

FULL-FLOW STUDY: Summerfelt et al. (In Prep.)

Oct 9, 2007, Presentation at DIFRES
### O$_3$ Followed by UV Irradiation

- **Total Coliform Plate Counts, cfu/100ml**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Before Ozone</th>
<th>After Ozone</th>
<th>After UV</th>
<th>% Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Ozone &amp; No UV</td>
<td>27203 ± 7458</td>
<td>30065 ± 8209</td>
<td>31123 ± 8327</td>
<td>NA</td>
</tr>
<tr>
<td>Ozone @ 375 mv &amp; No UV</td>
<td>1293 ± 326</td>
<td>571 ± 229</td>
<td>636 ± 304</td>
<td>55.8</td>
</tr>
<tr>
<td>Ozone @ 375 mv + UV</td>
<td>2800 ± 665</td>
<td>2293 ± 763</td>
<td>26 ± 15</td>
<td>99.1</td>
</tr>
<tr>
<td>Ozone @ 450 mv + UV</td>
<td>2702 ± 1054</td>
<td>864 ± 236</td>
<td>5 ± 2</td>
<td>99.8</td>
</tr>
<tr>
<td>Ozone @ 525 mv + UV</td>
<td>1418 ± 505</td>
<td>439 ± 107</td>
<td>3 ± 2</td>
<td>99.8</td>
</tr>
<tr>
<td>Ozone @ 20 ppb + UV</td>
<td>3195 ± 939</td>
<td>498 ± 272</td>
<td>3 ± 1</td>
<td>99.9</td>
</tr>
</tbody>
</table>

FULL-FLOW STUDY: Summerfelt et al. (In Prep.)
O₃ Followed by UV Irradiation

- Total Heterotrophic Bacteria Plate Count
  - < 1 cfu/ml @ ORP of 450 mv & 525 mv & O₃ of 20 ppb
    - 3+ LOG₁₀ reduction

- Total Coliform Bacteria Plate Count
  - 3-5 cfu/100ml @ ORP of 450 mv & 525 mv & O₃ of 20 ppb
    - 3 LOG₁₀ reduction
How much $O_3$ dose must be added to overcome the $O_3$ demand of the RAS water?
# Results: Ozone Dose Required

- Mean ozone concentration (± S.E.) in side-stream study

<table>
<thead>
<tr>
<th>Dosed (mg/L)</th>
<th>Entering Column (mg/L)</th>
<th>@ Middle of Column (mg/L)</th>
<th>Exiting Column (mg/L)</th>
<th>Mean HRT (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85 ± 0.04</td>
<td>0.75 ± 0.02</td>
<td>0.41 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td>8.3</td>
</tr>
<tr>
<td>0.78 ± 0.06</td>
<td>0.62 ± 0.03</td>
<td>0.27 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td>8.3</td>
</tr>
<tr>
<td>0.75 ± 0.07</td>
<td>0.51 ± 0.02</td>
<td>0.20 ± 0.01</td>
<td>0.05 ± 0.00</td>
<td>8.3</td>
</tr>
<tr>
<td>1.2 ± 0.1</td>
<td>0.96 ± 0.04</td>
<td>0.44 ± 0.02</td>
<td>0.22 ± 0.01</td>
<td>16.6</td>
</tr>
<tr>
<td>1.0 ± 0.2</td>
<td>0.55 ± 0.07</td>
<td>0.24 ± 0.02</td>
<td>0.10 ± 0.01</td>
<td>16.6</td>
</tr>
<tr>
<td>0.87 ± 0.09</td>
<td>0.43 ± 0.04</td>
<td>0.15 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>16.6</td>
</tr>
</tbody>
</table>
**Results: O₃ Dose Required**

- Mean O₃ concentration & dose applied per kg feed with only 1.5 min HRT for O₃ contacting

<table>
<thead>
<tr>
<th>Treatment</th>
<th>ORP (mv)</th>
<th>Dissolved Ozone, Probe (ppb)</th>
<th>Dissolved Ozone, Ampoule (ppb)</th>
<th>Ozone Applied per Feed (g/kg)</th>
<th>Ozone Dose Applied (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>375 mV + UV</td>
<td>375 ± 0</td>
<td>3 ± 0</td>
<td>0 ± 0</td>
<td>28 ± 4</td>
<td>0.38 ± 0.04</td>
</tr>
<tr>
<td>450 mV + UV</td>
<td>450 ± 0</td>
<td>7 ± 2</td>
<td>2 ± 1</td>
<td>29 ± 3</td>
<td>0.39 ± 0.06</td>
</tr>
<tr>
<td>525 mV + UV</td>
<td>525 ± 0</td>
<td>12 ± 3</td>
<td>7 ± 2</td>
<td>29 ± 2</td>
<td>0.34 ± 0.04</td>
</tr>
<tr>
<td>20 ppb + UV</td>
<td>607 ± 32</td>
<td>20 ± 0</td>
<td>22 ± 3</td>
<td>27 ± 3</td>
<td>0.34 ± 0.05</td>
</tr>
</tbody>
</table>

FULL-FLOW STUDY: Summerfelt et al. (In Prep.)

Oct 9, 2007, Presentation at DIFRES
Discussion: O₃ Dose Required

- Relatively low O₃ demand of RAS water:
  - @ 8 - 16 minutes HRT (sidestream study)
    - only 0.75 - 1.2 mg/L O₃ transferred into flow to maintain 0.05, 0.1, and 0.2 mg/L of O₃ at contact column outlet
  - @ 1.5 minute HRT (full-flow study)
    - 0.34 - 0.39 mg/L O₃ transferred into flow to maintain 375, 450, 525 mv ORP or 20 ppb O₃ at contact column outlet
    - 27 - 29 g O₃ per kg feed
    - Disinfecting surface water would require 10 x this dose!
O$_3$ Dosing Rate –
O$_3$ Prevents BGD Outbreaks

- Bullock et al. (1997); Summerfelt et al. (1997)
  - 0.025 kg O$_3$ per kg feed input
    - improved water quality and microscreen filter performance
    - reduced mortalities associated with Bacterial Gill Disease (BGD)
    - eliminated chemical treatments required to control BGD
    - did not reduce bacteria counts by even 1 log$_{10}$
  - 0.036-0.039 kg O$_3$ per kg feed input
    - same type and magnitude of benefits of lower ozone dose
    - much more likely to kill fish
O$_3$ Prevents BGD Events

- In a less than optimum RAS design (Bullock et al. 1997):
Ozone Dosing Rate

- Brazil (1996) found:
  - 0.025 and 0.045 kg $O_3$ per kg feed
    - produced best water quality
  - 0.013 kg $O_3$ per kg feed
    - was all ozone dose necessary to maximize fish growth
Ozonation & Water Quality

- $O_3$ improves water quality in intensive RAS’s.
  - Produces excellent water quality in RAS without resorting to high daily water exchange rates.
  - Improved water quality can reduce fish health problems.
## Tank Water Quality in Trout RAS

<table>
<thead>
<tr>
<th></th>
<th>STUDIES W/ NO OZONE</th>
<th>High Exchange (2.6% makeup)</th>
<th>Low Exchange (0.26% makeup)</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg Feed per m³ makeup</td>
<td></td>
<td>0.53</td>
<td>5.3</td>
</tr>
<tr>
<td>TAN (mg/L)</td>
<td></td>
<td>0.47 ± 0.02</td>
<td>0.84 ± 0.09</td>
</tr>
<tr>
<td>Nitrite (mg/L)</td>
<td></td>
<td>0.03 ± 0.005</td>
<td>0.013 ± 0.005</td>
</tr>
<tr>
<td>Nitrate (mg/L)</td>
<td></td>
<td>14 ± 0</td>
<td>99 ± 3</td>
</tr>
<tr>
<td>cBOD₅ (mg/L)</td>
<td></td>
<td>3 ± 0</td>
<td>13 ± 1</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td></td>
<td>3 ± 0</td>
<td>14 ± 0</td>
</tr>
<tr>
<td>CO₂ (mg/L)</td>
<td></td>
<td>11 ± 0</td>
<td>13 ± 1</td>
</tr>
<tr>
<td>O₂ (mg/L)</td>
<td></td>
<td>9.8 ± 0.1</td>
<td>9.2 ± 0.2</td>
</tr>
<tr>
<td>True Color (Pt-Co units)</td>
<td></td>
<td>16 ± 1</td>
<td>103 ± 5</td>
</tr>
<tr>
<td>UV Transmittance (%)</td>
<td></td>
<td>86 ± 0</td>
<td>45 ± 1</td>
</tr>
</tbody>
</table>
**O₃/UV & Water Quality in Trout RAS**

- Water quality after O₃ & UV treatment (flow entering fish tank)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>TAN (mg/L)</th>
<th>NO₂-N (mg/L)</th>
<th>TSS (mg/L)</th>
<th>Color (Pt-Co)</th>
<th>UV Trans. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Ozone &amp; No UV</td>
<td>0.11 ± 0.01</td>
<td>0.06 ± 0.03</td>
<td>4.0 ± 0.9</td>
<td>9.5 ± 2.2</td>
<td>90.2 ± 1.5</td>
</tr>
<tr>
<td>Ozone @ 375 mv &amp; No UV</td>
<td>0.10 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>3.0 ± 1.2</td>
<td>0.3 ± 0.3</td>
<td>95.7 ± 0.3</td>
</tr>
<tr>
<td>Ozone @ 375 mv + UV</td>
<td>0.13 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>2.1 ± 0.4</td>
<td>1.7 ± 0.3</td>
<td>94.9 ± 0.2</td>
</tr>
<tr>
<td>Ozone @ 450 mv + UV</td>
<td>0.11 ± 0.01</td>
<td>0.01 ± 0.01</td>
<td>2.5 ± 0.5</td>
<td>0.7 ± 0.3</td>
<td>95.3 ± 0.2</td>
</tr>
<tr>
<td>Ozone @ 525 mv + UV</td>
<td>0.14 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>2.4 ± 0.6</td>
<td>1.0 ± 0.6</td>
<td>95.9 ± 0.3</td>
</tr>
<tr>
<td>Ozone @ 20 ppb + UV</td>
<td>0.10 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>2.2 ± 0.2</td>
<td>1.7 ± 0.3</td>
<td>96.8 ± 1.0</td>
</tr>
</tbody>
</table>
O$_3$/UV & Water Quality in Trout RAS

- Water quality after O$_3$ & UV treatment (flow entering fish tank)
  - Mean NO$_2$-N dropped from 0.06 mg/L to 0.01-0.02 mg/L
  - Mean TSS dropped from 4.0 mg/L to 2.1-2.5 mg/L
  - Mean True Color dropped from 9.5 Pt-Co to 0.7-1.7 Pt-Co
  - Mean UV Transmittance rose from 90.2% to 94.9-96.8%
Ozone & Microscreen Filtration

- Microscreen filter improvements with ozone:
  - ✓ TSS removal increased 33%
  - ✓ wash cycles reduced 35%
  - ✓ sludge water production reduced 53%
  - ✓ sludge water settled sludge volume reduced 77%

(Summerfelt et al., 1997)
Ozone & Solids Removal

- Also improves solids removal via
  - Foam fractionation
    - Sander & Rosenthal (1975)
    - Otte and Rosenthal (1979)
    - Williams et al. (1982)
  - Settling
    - Wilczak et al. (1992)
    - Reuter and Johnson (1995)
Ammonia and Ozone

- In freshwater systems:
  - Ozone does not oxidize significant NH$_3$ to NO$_3$ until pH > 9
Ammonia and Ozone

- In saltwater systems (if sufficient bromide is present),
  - ozone will react with bromide to produce hypobromous acid and this will react with ammonia to produce nitrogen gas while producing $H^+$ that consumes alkalinity

$$O_3 + Br^- + H^+ \rightarrow HOBr + O_2$$

$$3HOBr + 2NH_3 \rightarrow N_2 + 3Br^- + 3H^+ + 3H_2O$$

$$HCO_3^- \rightarrow CO_2 + H_2O$$

(Haag and Hoigne, 1984; Tanaka and Matsumura, 2002)
Ammonia and Ozone

- In saltwater systems (if sufficient bromide is present),
  - Tanaka and Matsumura (2002) showed that ozonation will not form BrO₃⁻ as long as TAN is still present in the water.

\[
\begin{align*}
O_3 + Br^- + H^+ & \rightarrow HOBr + O_2 \\
3HOBr + 2NH_3 & \rightarrow N_2 + 3Br^- + 3H^+ + 3H_2O \\
HCO_3^- & \rightarrow CO_2 + H_2O
\end{align*}
\]

(Tanaka and Matsumura. 2002. Journal Chemical Technology and Biotechnology)
Nitrite and Ozone

- Ozone stoichiometrically oxidized nitrite to nitrate:
  - reduced nitrite concentration in water
Process Control for Full-Flow Ozonation
Process Control for Full-Flow O₃

- ORP & dissolved O₃ probe measurements

![Graph showing ORP (mV) and dissolved O₃ (ppb) with set point at 20ppb O₃]
Process Control for Full-Flow O$_3$

- ORP probe vs dissolved O$_3$ probe
  - ORP was easier to calibrate & maintain
  - ORP & dissolved O$_3$ similar to tune for PID control
  - ORP was just as effective to monitor and automatically control O$_3$ dose
  - Dissolved O$_3$ probe was quick to respond to changes
  - ORP was slow to respond to sudden drop in dissolved O$_3$
Example: $\text{O}_3$ Followed by UV

- Three salmon smolt systems (~12 m$^3$/min/system) at Nutreco’s Big Tree Creek Hatchery (BC)

(system designed by PRAquac Technologies)
Example: $O_3$ Followed by UV

- Parr & smolt RAS’s (1000-1400 L/min/system) at USDA National Cold Water Marine Aquaculture Center