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

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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

Introduction

- 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.

O_3 & UV for Disinfection in RAS

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

$$\text{microbial reduction} \propto [O_3]_{residual} \cdot t_{contact}$$

O_3 Doses for Disinfection

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

	C*t, mg*min/L
✓ ISAV	0.3
✓ Aeromonas salmonicida	1.6
✓ Yersinia ruckeri	0.45-0.6
✓ Flavobacterium sp.	2.8
✓ Flexibacter sp.	1.6
✓ Streptococcus sp.	0.015
✓ Vibrio salmonicidia	0.45-0.6

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):

	$mW\text{-}sec/cm^2$
✓*Aeromonas salmonicida*	4
✓*Aeromonas hydrophila*	5
✓*Vibrio anguillarum*	4
✓*Yersinia ruckeri*	3
✓*Pseudomonas fluorescens*	5

UV Doses for Disinfection

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

	mW-sec/cm^2
✓ *ISA*	4-10*
✓ *IHN*	1-3
✓ *IPN*	100-200
✓ *Channel catfish virus*	2
✓ *Herpesvirus salmonis*	2
✓ *White spot syndrome baculovirus*	900*

*loss of infectivity

UV Doses for Disinfection

- Wedemeyer (1996):

	mW-sec/cm^2
✓Dose to inhibit growth of *Saprolignia*	230
✓Dose to decrease infectivity of *myxobolus cerebralis*	28
✓Recommended dose for recirculated water	50*
✓Recommended dose for hatchery wastewater	30

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.).

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

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

$$= \#\ \text{mW} \cdot \text{sec/cm}^2$$

UV Doses Required for Disinfection

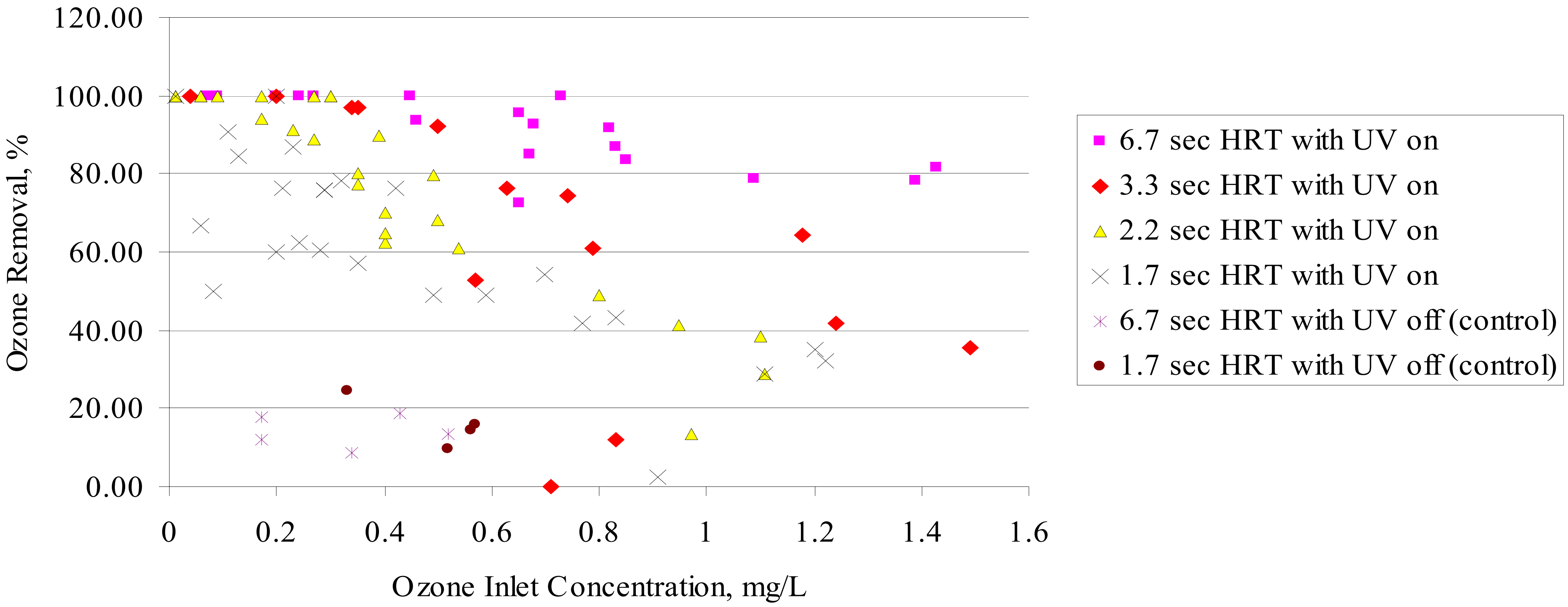
- Prefiltration through 50 μm screens can improve bacterial inactivation with UV by 3.0 $\log_{10}$ units.
  - ✓Liltved and Cripps (1999)

UV Removes Dissolved O_3

- Expose O_3 to high intensity UV light:
  - ✓ wavelength of 250-260 nm

- Other methods to removed O3
  - ✓ Provide extended contact time & let O_3 react away;
  - ✓ Aerate to strip O_3 into air;
    - G:L of 10:1 to 20:1
  - ✓ React O_3 with hydrogen peroxide;
  - ✓ Pass ozonated flow through an activated carbon bed or biofilter.

O_3 Destruction with UV Irradiation



Summerfelt et al. 2004. Aquacultural Engineering

O_3 Destruction with UV Irradiation

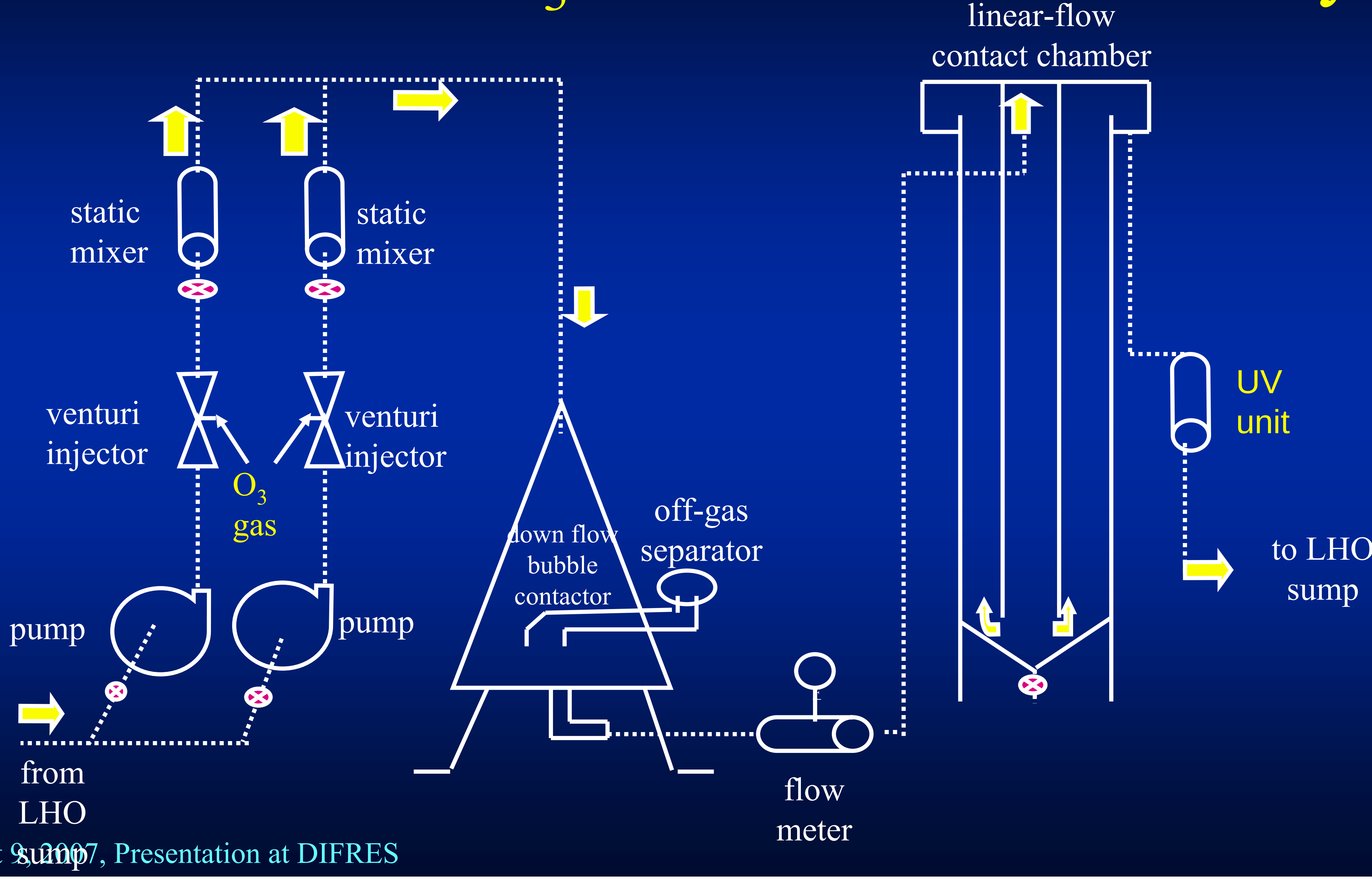
- 49.3 ± 0.6 mW-s/cm^2 removed 100% of the dissolved O_3 @ inlet O_3 concentration ≤ 0.10 mg/L
  - ✓ 35.6 ± 0.3mW-s/cm^2 could not remove 100% of the O_3 @ inlet O_3 concentration of ≤ 0.10 mg/L.
- 80.4 ± 2.6 mW-s/cm^2 & 153.3 ± 2.1 mW-s/cm^2 consistently removed 100% of the dissolved O_3 when the inlet O_3 concentration was ≤ 0.30 mg/L

Summerfelt et al. 2004. Aquacultural Engineering

O_3 Followed by UV Irradiation

- 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 O_3 & 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

O_3 / 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.

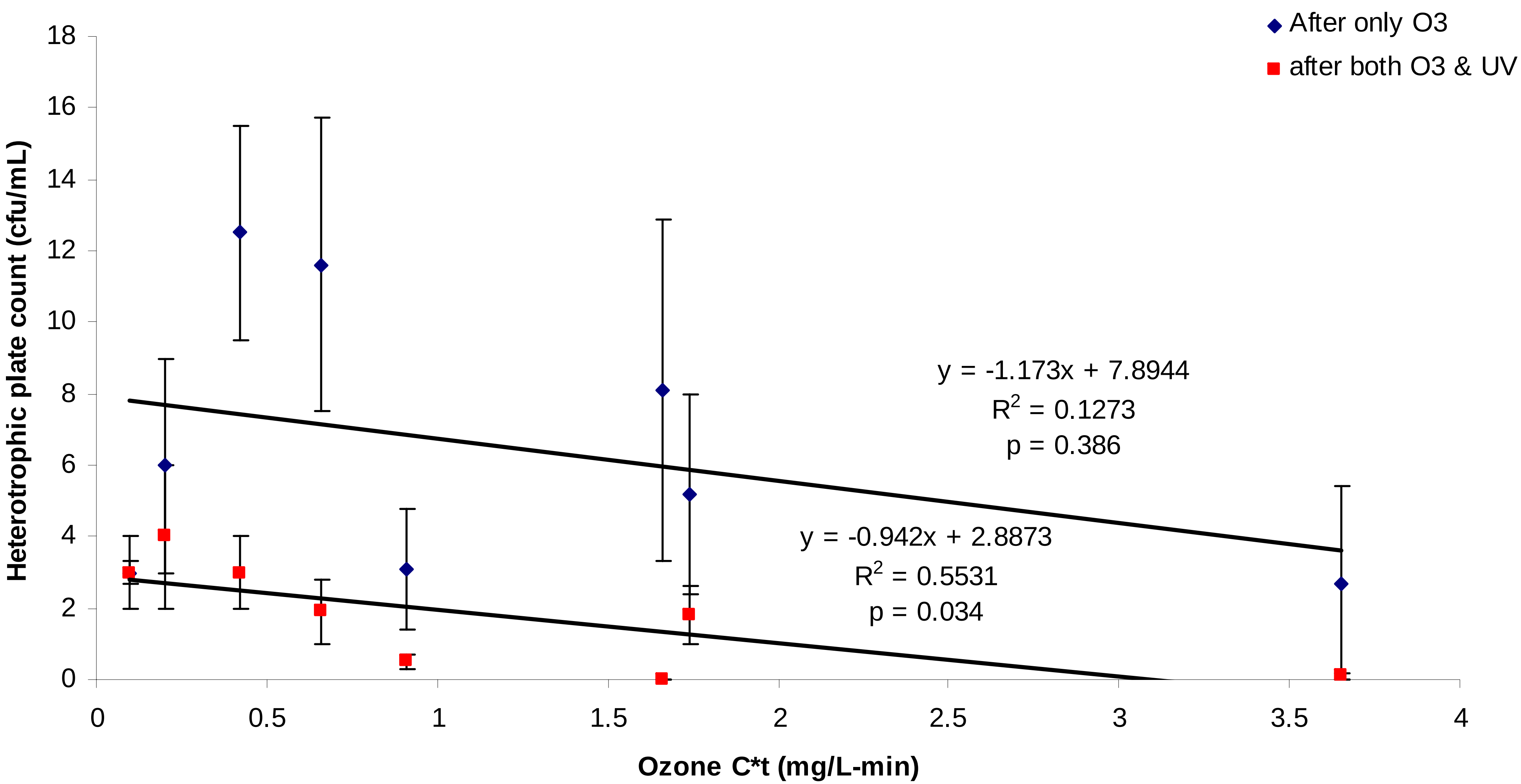
Sidestream UV Treatment

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

- UV doses (mJ/cm^2) calculated using a proprietary spreadsheet supplied by manufacturer (Trojan Technologies, Inc.)

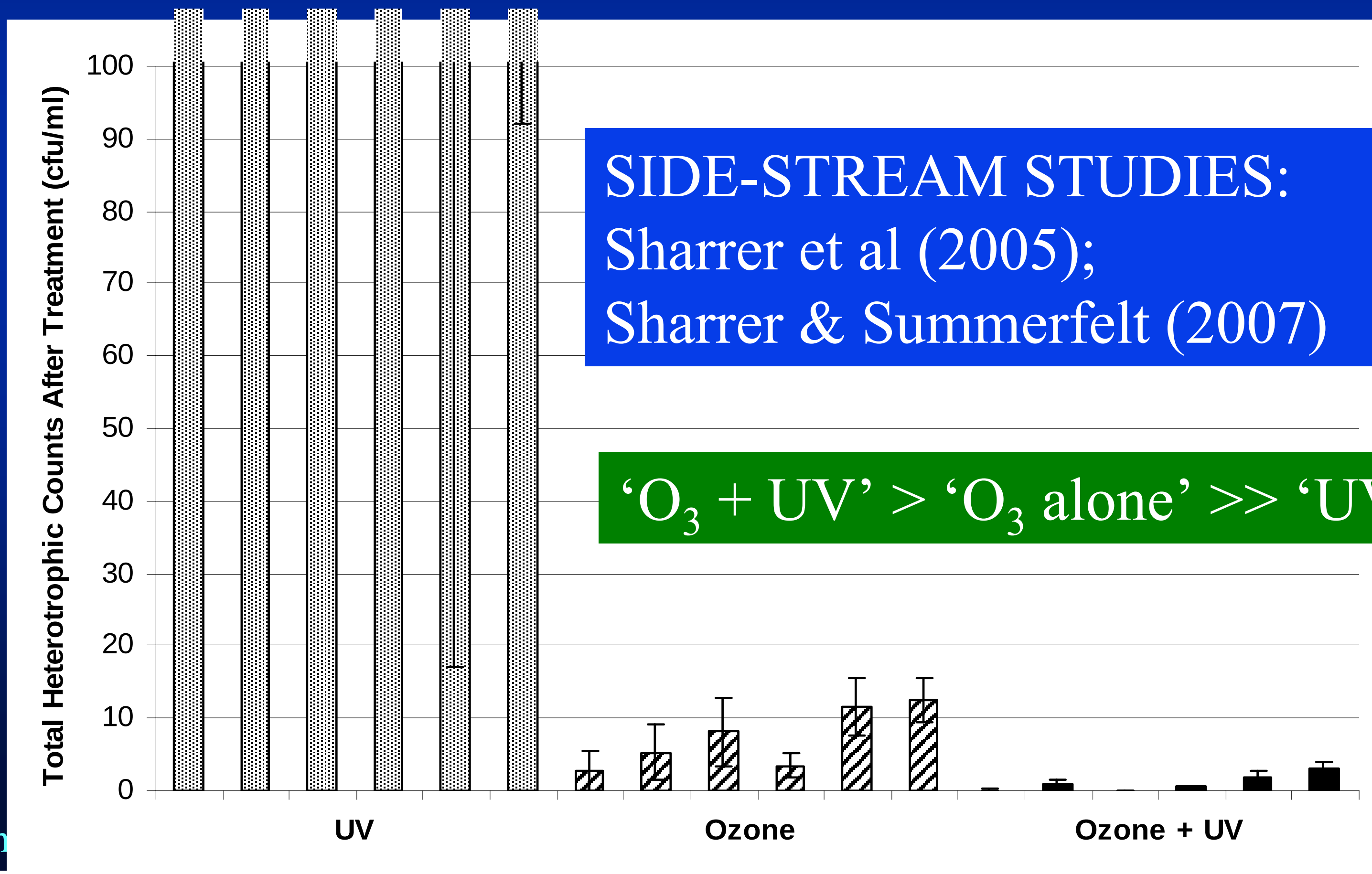
Results: Total Heterotrophic Bacteria

SIDE-STREAM STUDY: Sharrer & Summerfelt (2007)



O_3 Followed by UV Irradiation

- Achieve total heterotrophic bacteria counts 0-2 cfu/ml
  - ✓Much better than using UV alone or O_3 alone in a RAS!



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

'O_3 + UV' > 'O_3 alone' >> 'UV alone'

Results: UV Inactivation of Bacteria

- Side-stream studies with no O_3 (Sharrer et al. 2005)
- Heterotrophic bacteria counts

Mean UV dose,	Hydraulic residence time within UV unit,	Number of sampling events	Total heterotrophic bacteria counts before UV, cfu/100 mL	Total heterotrophic bacteria counts after UV, cfu/100 mL	Reduction in total heterotr. bacteria counts	LOG10 reduction in total heterotrophic bacteria
1821 ± 86	70.1 ± 2.8	4	9038 ± 3225	181 ± 71	98 ± 1	1.7
980 ± 17	36.2 ± 1.1	4	1708 ± 441	192 ± 68	87 ± 7	0.9
493 ± 20	22.3 ± 0.3	8	7749 ± 2289	5145 ± 1754	57 ± 14	0.4
303 ± 12	12.8 ± 0.0	7	2215 ±1074	610 ± 263	81 ± 5	0.7
150 ± 9	6.4 ± 0.1	3	7953 ± 3672	328± 311	81 ± 19	0.7

Results: UV Inactivation of Bacteria

- Side-stream studies with no O_3 (Sharrer et al. 2005)
- Heterotrophic bacteria counts

Mean UV dose, MJ/cm2	Hydraulic residence time within UV unit,sec	Number of sampling events	Total coliform bacteria counts before UV, cfu/100 mL	Total coliform bacteria counts after UV, cfu/100 mL	Reduction in total coliform bacteria counts	LOG10 reduction in total coliform bacteria across UV
1821 ± 86	70.1 ± 2.8	4	228 ± 144	0 ± 0	100	na
990 ± 21	35.7 ± 1.3	3	60 ± 25	0 ± 0	100	na
524 ± 23	22.3 ± 0.4	5	46 ± 21	0 ± 0	100	na
303 ± 12	12.8 ± 0.0	7	56 ± 19	0 ± 0	100	na
150 ± 9	6.4 ± 0.1	3	100 ± 55	0 ± 0	100	na
77 ± 1	3.2 ± 0.0	2	215 ± 205	0 ± 0	100	na

Discussion: UV Inactivation of Bacteria

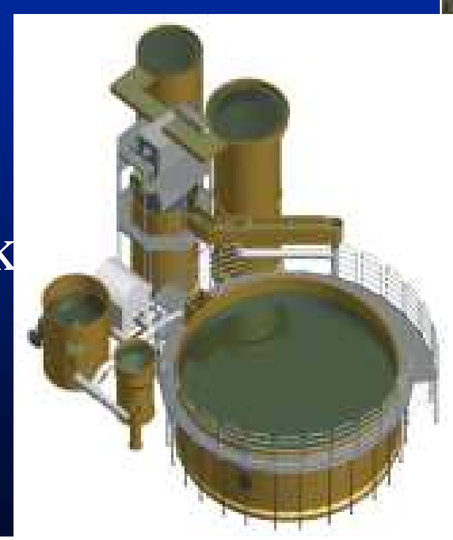
- *Hypothesis*: Bacteria embedded within particulate matter or had formed bacterial aggregates that effectively shielded them from UV.
- More recent work has confused this issue…

Discussion: O_3 Inactivation of Bacteria

- In addition…
- ….Heterotrophic bacteria were surprisingly resistant to complete O_3 inactivation with relatively high O_3 C*t.
  - ✓ 0.9-3.6 min-mg/L O_3
  - ✓ But lower bacteria counts were achieved with ozone than when using UV alone.
  - ✓ Sharrer and Summerfelt (2007)

Full-Flow O_3 + UV Treatment Study

- Freshwater Institute's Grow-out System.
  - ✓4700 L/min recycle flow
  - ✓O_3 added w/ O_2 feed gas in LHO
  - ✓1.5 min O_3 contact time in LHO sump
  - ✓UV irradiation at 90 MJ/cm^2
  - ✓O_3 + UV before flow enters culture tank
    - 150 m^3 culture tank
    - 30 min HRT
    - 7.3-8.6 mg/L ΔDO 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 O_3 + UV Treatment Study

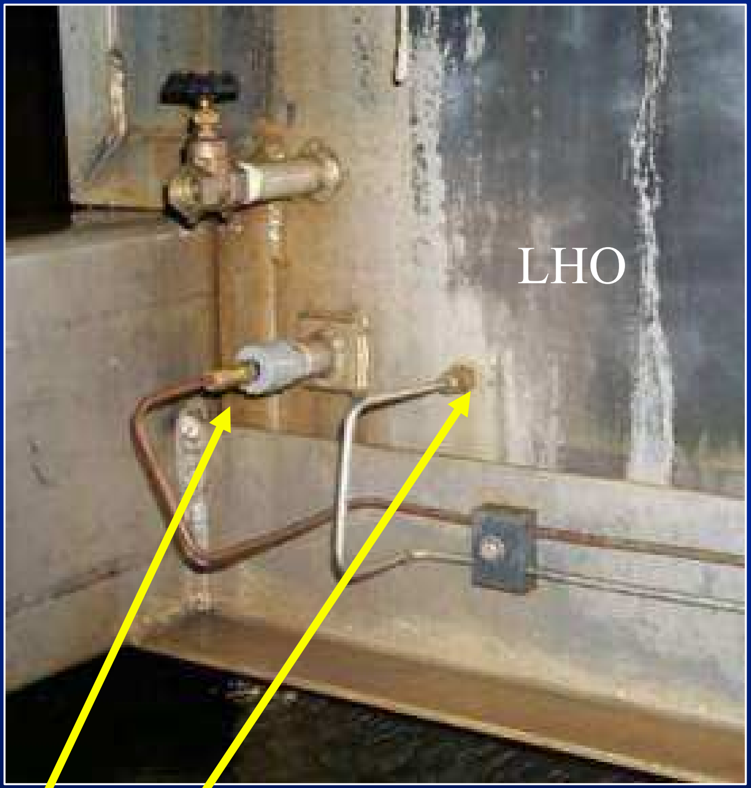
- O_3 concentration generated in the O_2 feed gas was automatically & remotely adjusted at the PCI-Wedeco model GSO40 ozone generator.

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

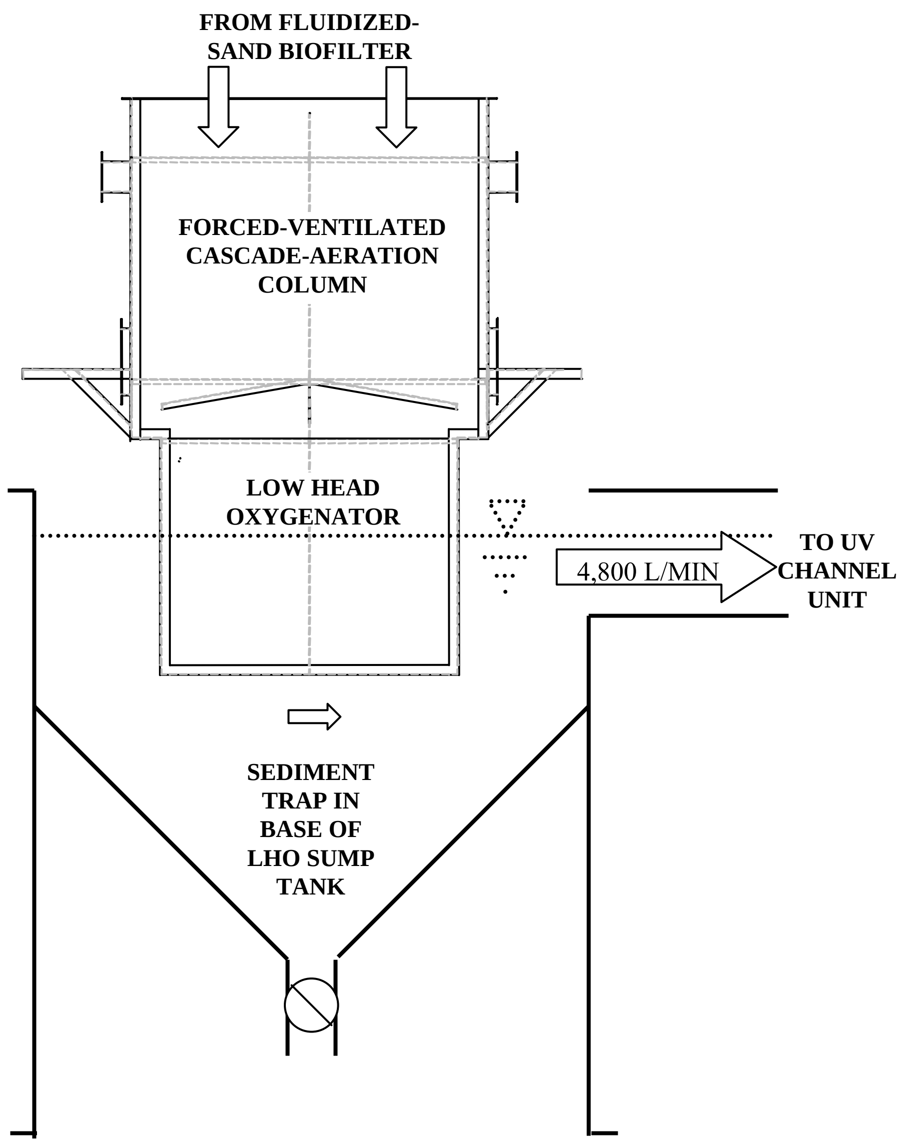
- Transfer O_3 in an O_2 carrier gas at the LHO



O_2 & O_3
gas supplies

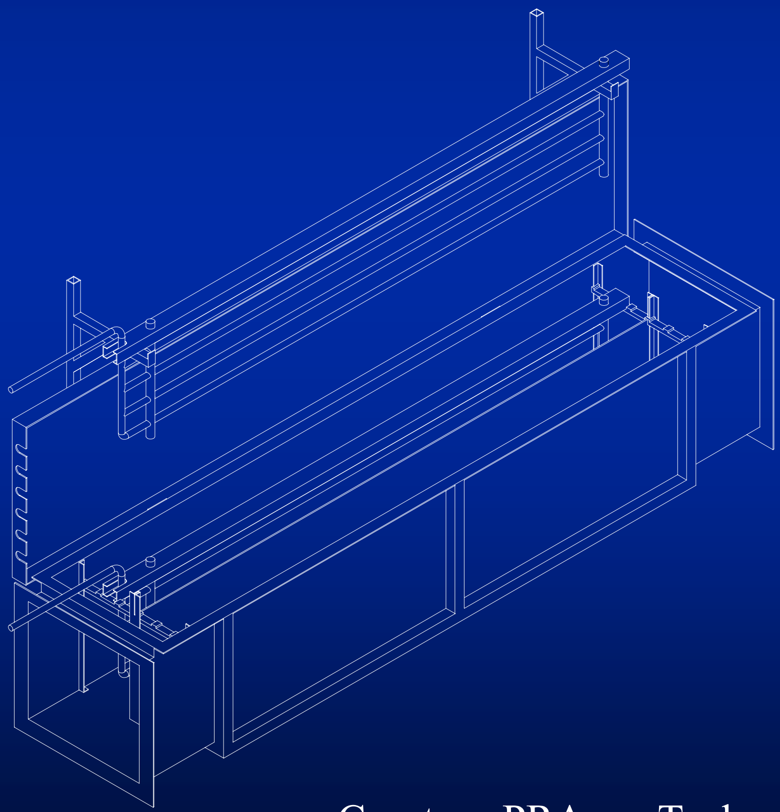
Full-Flow O_3 + UV Treatment Study

- O_3 transfers in LHO
- O_3 contacting in:
  - ✓LHO
  - ✓LHO sump
  - ✓Channel to UV unit
  - ✓HRT of 1.5 min



Full-Flow O_3 + 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

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

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

O_3 Followed by UV Irradiation

- Total Coliform Plate Counts, cfu/100ml

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

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

O_3 Followed by UV Irradiation

- Total Heterotrophic Bacteria Plate Count
  - ✓ < 1 cfu/ml @ ORP of 450 mv & 525 mv & O_3 of 20 ppb
    - 3+ LOG_{10} reduction
- Total Coliform Bacteria Plate Count
  - ✓ 3-5 cfu/100ml @ ORP of 450 mv & 525 mv & O_3 of 20 ppb
    - 3 LOG_{10} 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

Dosed (mg/L)	Entering Column (mg/L)	@ Middle of Column (mg/L)	Exiting Column (mg/L)	Mean HRT (min)
0.85 ± 0.04	0.75 ± 0.02	0.41 ± 0.01	0.21 ± 0.01	8.3
0.78 ± 0.06	0.62 ± 0.03	0.27 ± 0.01	0.11 ± 0.01	8.3
0.75 ± 0.07	0.51 ± 0.02	0.20 ± 0.01	0.05 ± 0.00	8.3
1.2 ± 0.1	0.96 ± 0.04	0.44 ± 0.02	0.22 ± 0.01	16.6
1.0 ± 0.2	0.55 ± 0.07	0.24 ± 0.02	0.10 ± 0.01	16.6
0.87 ± 0.09	0.43 ± 0.04	0.15 ± 0.02	0.04 ± 0.01	16.6

Results: O_3 Dose Required

- Mean O_3 concentration & dose applied per kg feed with only 1.5 min HRT for O_3 contacting

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

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

Discussion: O_3 Dose Required

- Relatively low O_3 demand of RAS water:
  - ✓@ 8 - 16 minutes HRT (sidestream study)
    - only 0.75 - 1.2 mg/L O_3 transferred into flow to maintain 0.05, 0.1, and 0.2 mg/L of O_3 at contact column outlet
  - ✓@ 1.5 minute HRT (full-flow study)
    - 0.34 - 0.39 mg/L O_3 transferred into flow to maintain 375, 450, 525 mv ORP or 20 ppb O_3 at contact column outlet
    - 27 - 29 g O_3 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

STUDIES W/ NO OZONE	**High Exchange** (2.6% makeup)	**Low Exchange** (0.26% makeup)
kg Feed per m^3 makeup	0.53	5.3
TAN (mg/L)	0.47 ± 0.02	0.84 ± 0.09
Nitrite (mg/L)	0.03 ± 0.005	0.013 ± 0.005
Nitrate (mg/L)	14 ± 0	99 ± 3
$cBOD_5$ (mg/L)	3 ± 0	13 ± 1
TSS (mg/L)	3 ± 0	14 ± 0
CO_2 (mg/L)	11± 0	13 ± 1
O_2 (mg/L)	9.8 ± 0.1	9.2 ± 0.2
True Color (Pt-Co units)	16 ± 1	103 ± 5
UV Transmittance (%)	86 ± 0	45 ± 1

O_3/UV & Water Quality in Trout RAS

- Water quality after O_3 & UV treatment (flow entering fish tank)

	TAN (mg/L)	NO_2-N (mg/L)	TSS (mg/L)	Color (Pt-Co)	UV Trans. (%)
No Ozone & No UV	0.11 ± 0.01	0.06 ± 0.03	4.0 ± 0.9	9.5 ± 2.2	90.2 ± 1.5
Ozone @ 375 mv & No UV	0.10 ± 0.01	0.02 ± 0.01	3.0 ± 1.2	0.3 ± 0.3	95.7 ± 0.3
Ozone @ 375 mv + UV	0.13 ± 0.02	0.01 ± 0.01	2.1 ± 0.4	1.7 ± 0.3	94.9 ± 0.2
Ozone @ 450 mv + UV	0.11 ± 0.01	0.01 ± 0.01	2.5 ± 0.5	0.7 ± 0.3	95.3 ± 0.2
Ozone @ 525 mv + UV	0.14 ± 0.02	0.01 ± 0.01	2.4 ± 0.6	1.0 ± 0.6	95.9 ± 0.3
Ozone @ 20 ppb + UV	0.10 ± 0.02	0.01 ± 0.01	2.2 ± 0.2	1.7 ± 0.3	96.8 ± 1.0

O_3/UV & Water Quality in Trout RAS

- Water quality after O_3 & UV treatment (flow entering fish tank)
  - ✓Mean NO2-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.

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

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

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

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

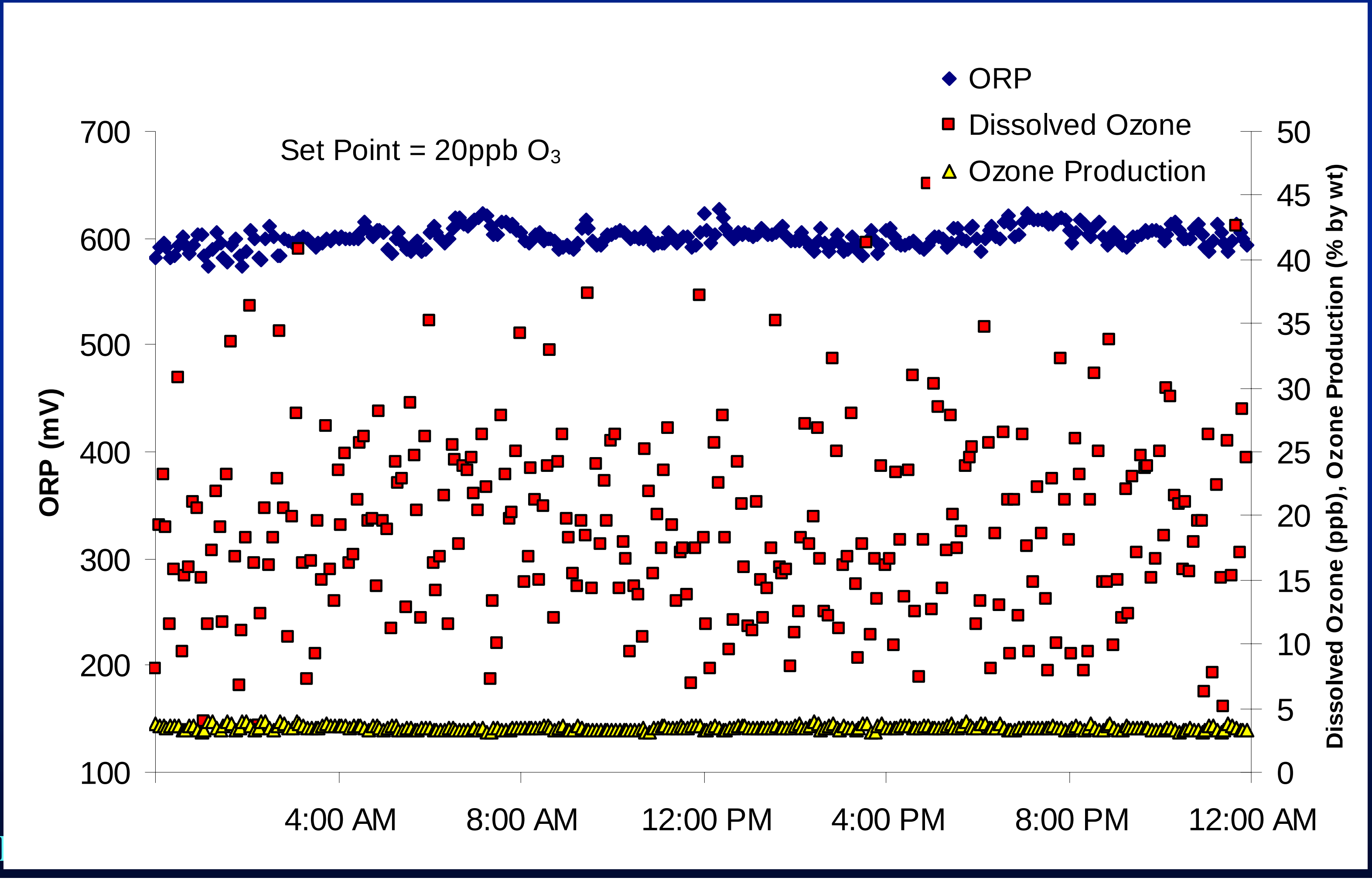
Nitrite and Ozone

- Ozone stoichiometrically oxidized nitrite to nitrate:
  - ✓reduced nitrite concentration in water

Process Control for Full-Flow Ozonation

Process Control for Full-Flow O_3

- ORP & dissolved O_3 probe measurements



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 O3 probe was quick to respond to changes
  - ✓ORP was slow to respond to sudden drop in dissolved O_3

Example: 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 PRAqua Technologies)

Example: O_3 Followed by UV

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