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Advances in Closed-Containment Systems for Salmonids

Steven Summerfelt

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Acknowledgments

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Fish Farming:
Major Environmental Challenges

- Climate change
- Limited water supplies
- Water pollution (in & out)
- Limited marine fish meal/oil supplies
- Spread of pathogens (in & out)
- Escapees interacting with wild populations
- Energy consumption

Containment is Necessary for Sustainable Aquaculture

Production Technologies must protect the environment while providing for economic opportunity

Transition to fish farms that minimize water footprint and pollution, while excluding fish, pathogens & contaminants

Containment is Necessary for Sustainable Aquaculture

- Food Security
  - Adopt water reuse systems
  - Exclude chemicals & pathogens
    - Develop a chemical & specific-pathogen-free water supply
    - Source salmon eggs free from obligate pathogens
    - Prevent eggs & fish from introducing pathogens
    - Use buildings & barriers to exclude pathogens from birds/mammals and prevent fish escape
  - Avoid pesticides, antibiotics, & chemotherapeutics
  - Locate the farm adjacent to the major markets

Salmonid Production in a Controlled Environment

- Control photoperiod
- Optimize water temperature
- Maintain healthy water quality
  - Dissolved gas control – CO_2, O_2, N_2
  - Waste metabolite control – NH_3, TSS, BOD, NO_2, NO_3
  - pH, alkalinity, Ca, & Cl^- control
  - Microbiological control
    - – Minimize opportunistic pathogen infections: fungus, flavobacteria
- Control fish feed, density, & swimming speed

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Salmonid Production in a Closed Environment

- Water flow is the engine that powers the system:
  - flow carries dissolved oxygen to the culture unit,
  - flow receives wastes produced in the culture unit,
  - flow carries wastes out of the culture tank to the water treatment processes

Water Quality in Closed-Containment Systems

- Carrying capacity is 1st limited by oxygen
  - the mass of available dissolved oxygen supplied to the culture tank
    - depends on water flow & available oxygen concen.
- Carrying capacity is next limited by waste accumulation in the culture system, e.g.,
  - CO_2
  - TAN, NO_2-N
  - TSS
  - NO3-N

Water Quality in Closed-Containment Systems

- Identify numeric water quality limits for healthy fish culture, e.g.,

Constituent	Water Quality Limits
Dissolved O_2	100% sat.
CO_2	< 20 mg/L
NH_4-N	< 1.5 mg/L
NO_2-N	< 0.4 mg/L
NO_3-N	< 100 mg/L
TSS	< 5-10 mg/L

Water Quality in Closed-Containment Systems

- **GOAL – Maintain water quality that is as good or better than in single-pass systems**

Water Quality in Closed-Containment Systems

- Water quality in culture tanks is controlled by water flow rate (Q), waste production rate (P_{waste}), efficiency of waste removal (f_{rem}) at each unit process:
  - Solids capture
    - filtration
    - Sedimentation
    - ozonation
  - Carbon dioxide removal
    - cascade aeration
  - Ammonia removal
    - biofiltration
  - Nitrate removal
    - System flushing (> 10-20% volume/day) or denitrification

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Water Quality in Closed-Containment Systems

- Select technology providing high TAN & CO_2 removal efficiency
- EXAMPLE: Water quality deterioration at R = 0.8-1.0
  - f_{rem} = 0.8 reuse amplification factor is 1.19-1.25
  - f_{rem} = 0.6 reuse amplification factor is 1.47-1.67
  - f_{rem} = 0.4 reuse amplification factor is 1.92-2.5

$$[Waste]_{tank} = \left\{ \frac{1}{1 - R + (R \cdot f_{rem})} \right\} \cdot \left\{ \frac{P_{waste}}{Q} \right\}$$

$$= \{\text{Reuse Amplification Factor}\} \cdot \{\text{Single Pass Conc.}\}$$

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Closed-Containment Systems for Tilapia

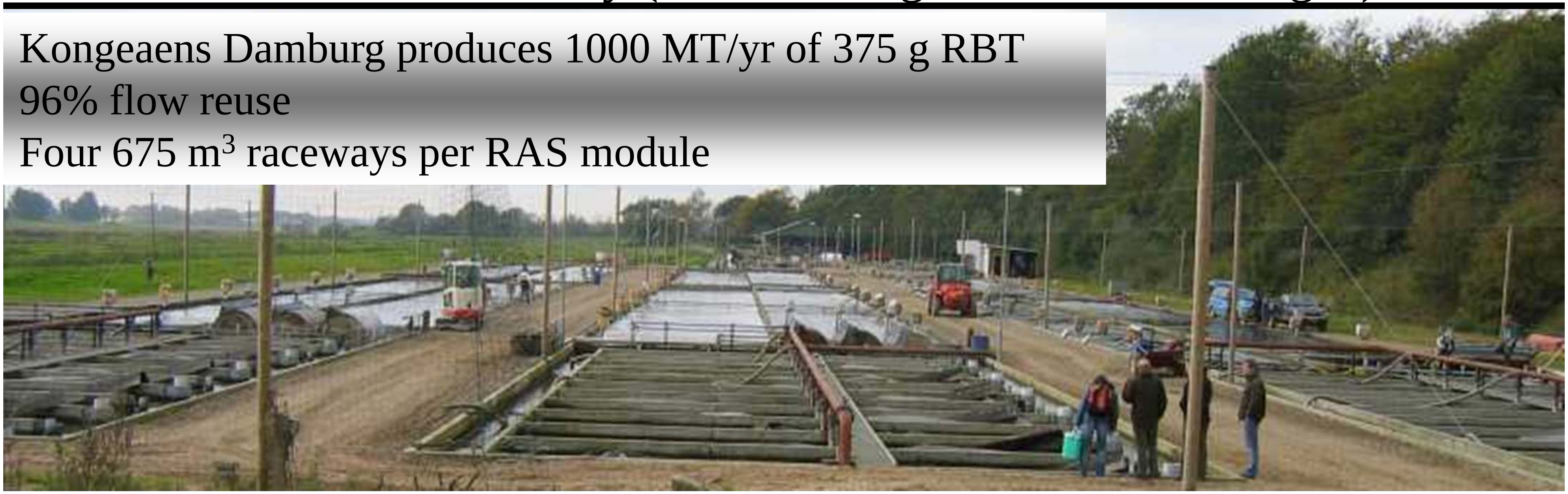
- Tilapia systems: widely applied, but these technologies can fail to maintain the water quality required for salmonids
  - Best & worst outcomes for closed-containment



Danish Model Trout Farms

- Developed by Kaare Michelsen, Dansk Akvakultur
- Four giant air lift pumps per module
  - 900 L/s (14,000 gal/min) recirc flow rate
  - Four raceways per module (1.5 m deep x 6 m wide)
    - Slow biosolids removal degrades water quality, which reduces biofilter efficiency (TAN ~ 3 mg/L; NO2-N ~ 1 mg/L)

Kongeaens Damburg produces 1000 MT/yr of 375 g RBT
96% flow reuse
Four 675 m^3 raceways per RAS module



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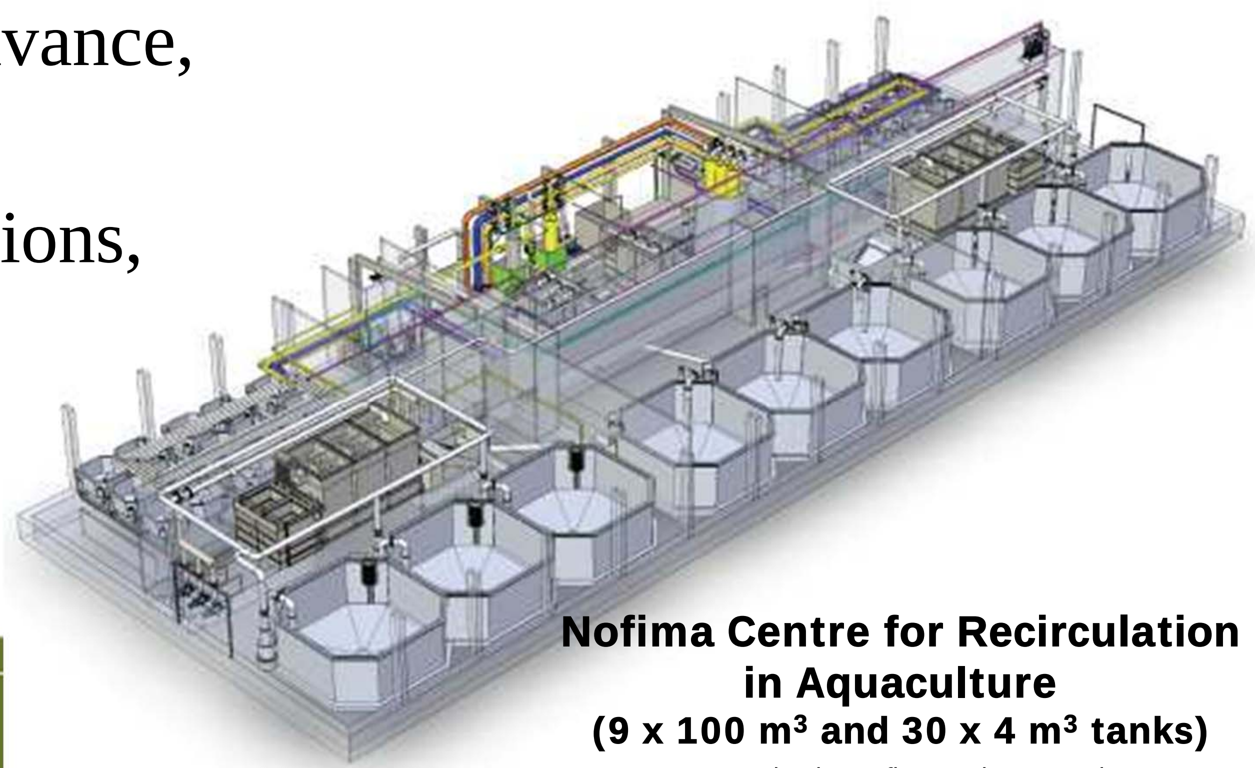
Turn-Key Systems Suppliers

- Complete systems are now supplied, e.g.,
  - Water Management Technologies,
  - Billund,
  - PRAqua,
  - Inter Aqua Advance,
  - HydroGest,
  - Aquatek Solutions,
  - Akva,
  - AquaOptima,
  - others



Nofima Centre for Recirculation in Aquaculture (9 x 100 m^3 and 30 x 4 m^3 tanks)

Drawing by Nofima and AquaOptima

Closed-Containment Research at TCF in Early 1990's

- Cross-flow culture tanks
  - Bacterial gill disease
- Microscreen filtration
- Fluidized sand biofiltration
- Cascade aeration columns
- Low head oxygenation & ozonation
- Sequential stocking of mixed cohorts & graded harvest of rainbow trout

'Garage-Scale Systems Research'

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Closed-Containment Research at TCF Since Late 1990's

- Circular dual-drain culture tanks
- Solids removal (dual-drain tank+settler+drum filter)
- Carbon dioxide stripping (ventilated aeration column)
- Biofilter to control ammonia (fluidized-sand biofilter)
- Oxygenation (LHO + oxygen cones at each tank)
- Color & fine solid removal (ozonation)
- Disinfection & dissolved ozone destruction (O_3 & UV)
- Fish harvest technologies
- Waste management technologies

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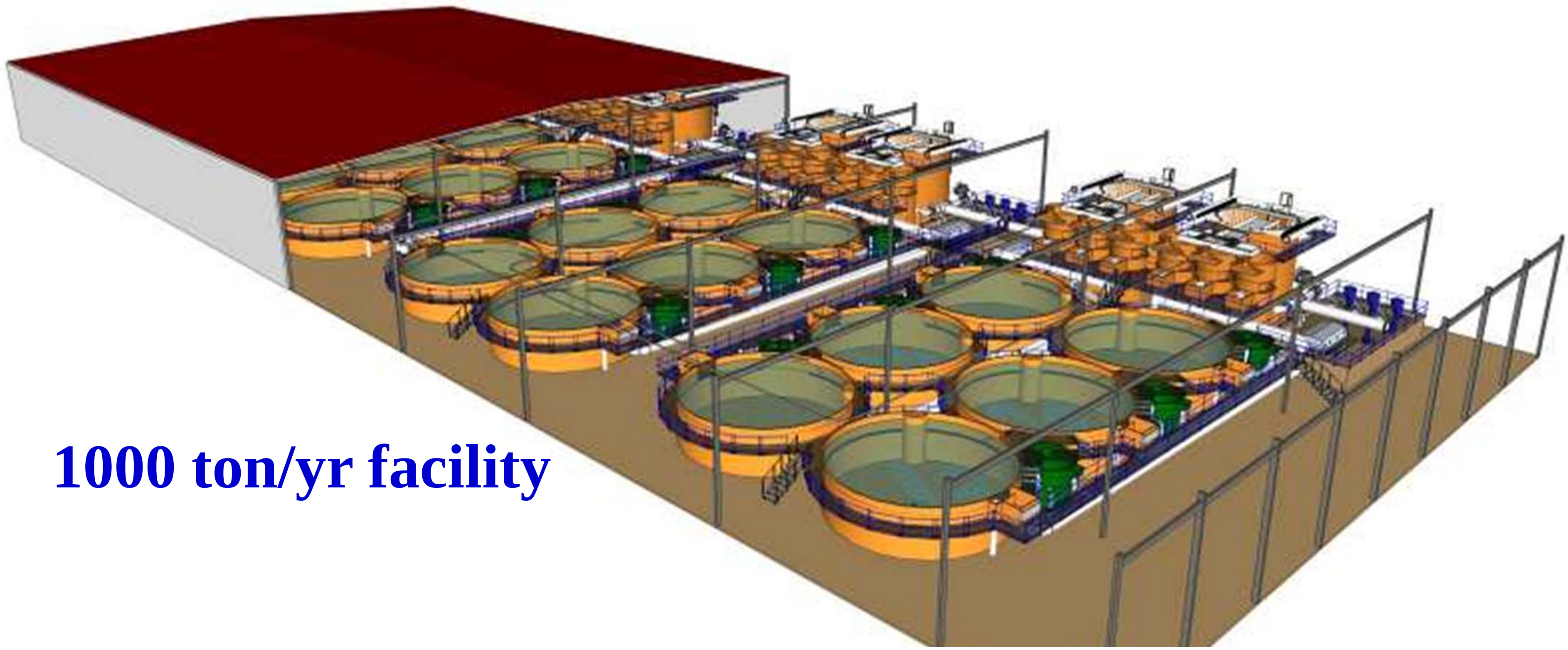
Closed-Containment Research at TCF Since Late 1990's

- Develop large-scale technologies
  - Reduce fixed & variable costs per MTON



1000 ton/yr facility

Most Recent Research at The Conservation Fund

- New ARS 5-Yr Project (2010-2015):
  - Title: "Improving the Sustainability of Land-Based Closed-Containment Systems for Salmonid Food Fish Production"
    - Economics & life-cycle metrics (Brian Vinci's PPT)
    - Technology & fish performance
      - CO_2, O_2, swimming speed, strain, photoperiod, & grain-based feeds (Chris Good's PPT)
      - Tank side CO_2 control & MBR treatment

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Fish at the Freshwater Institute

200 ton Production in 10 yrs

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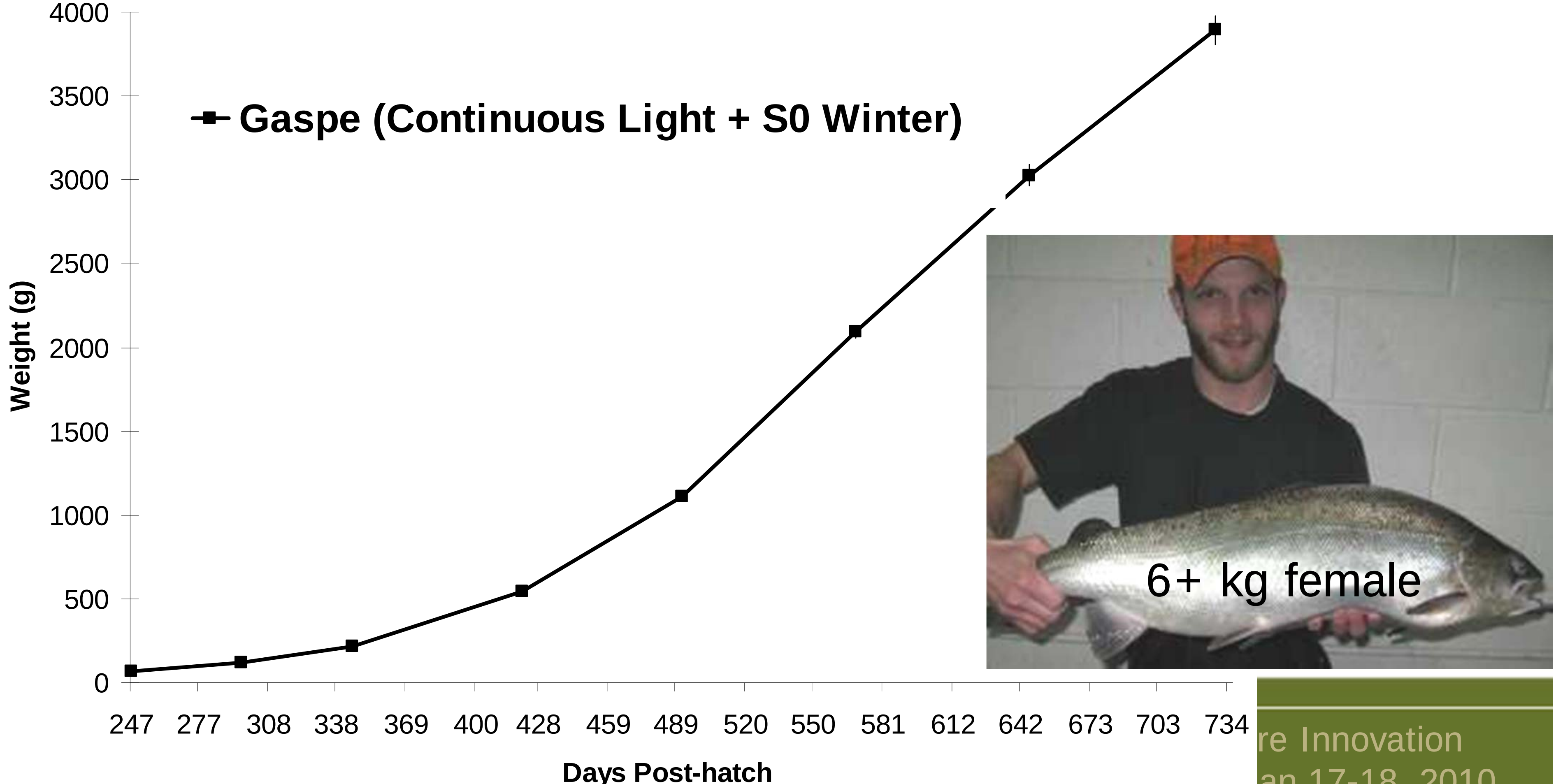
Atlantic Salmon Results to Date

- Rapid Atlantic salmon growth (4 kg) in freshwater to 24-month post-hatch in "strain x photoperiod" study



Atlantic Salmon Results to Date

- Atlantic salmon appear to handle 80 kg/m^3 density better than rainbow trout
- Minor fungus in ‘hard’ freshwater

Taking Advantage of Large & Deep Circular Culture Tanks

- Large and deep tanks are more efficient in fixed & variable costs!

(Courtesy of Josh Goldman)

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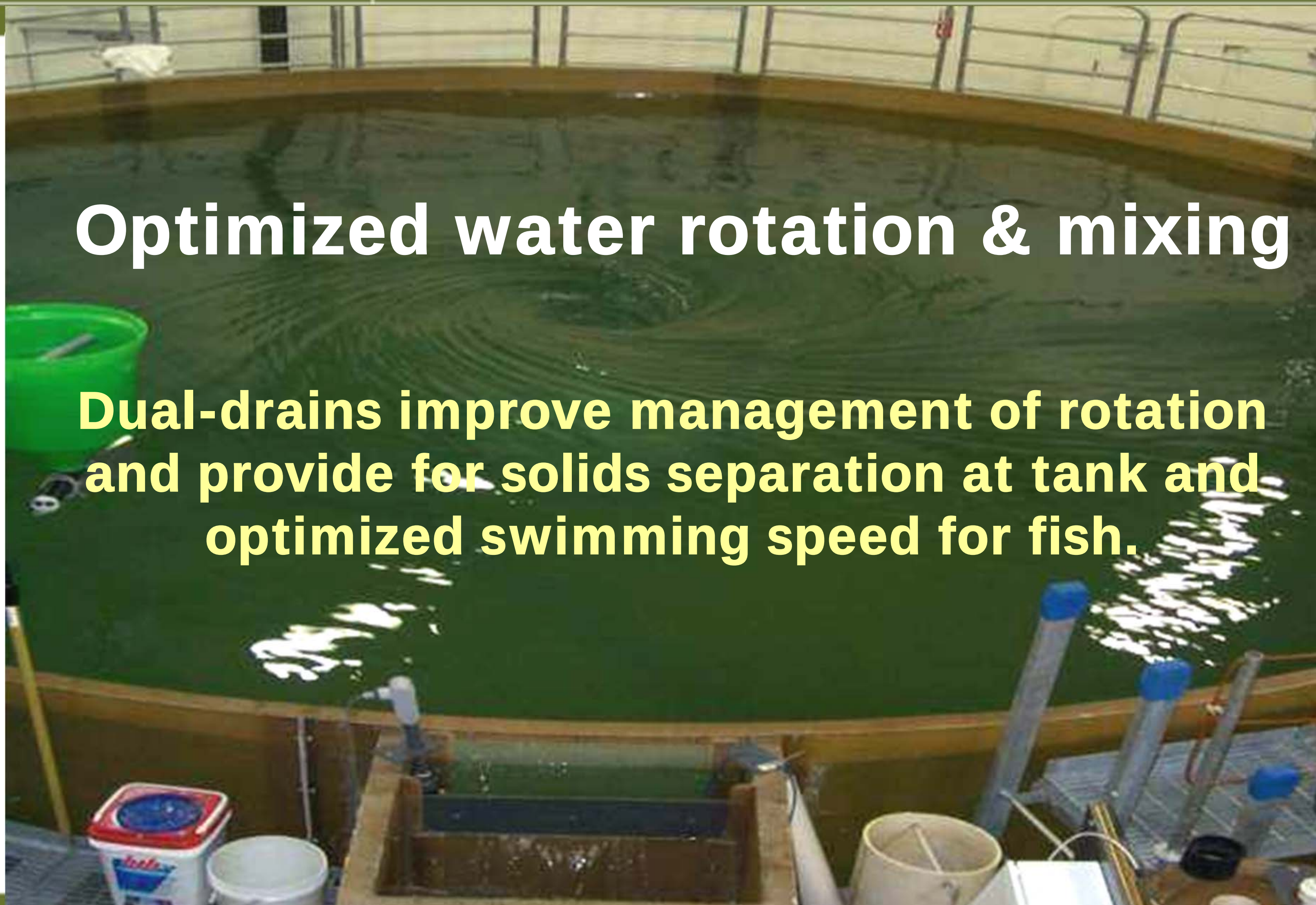
Improve Culture Tank Hydraulics

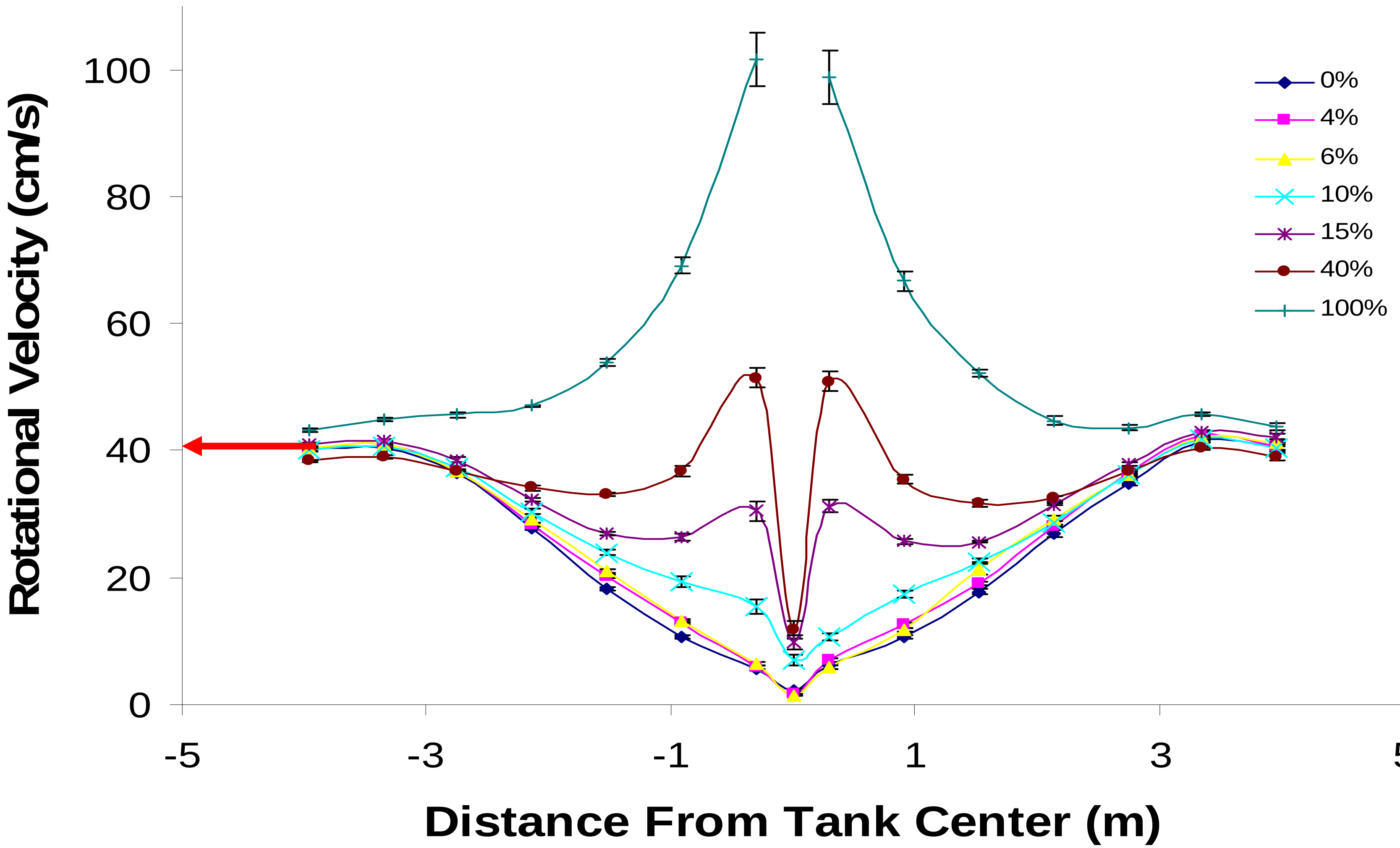


Optimized water rotation & mixing

Dual-drains improve management of rotation and provide for solids separation at tank and optimized swimming speed for fish.

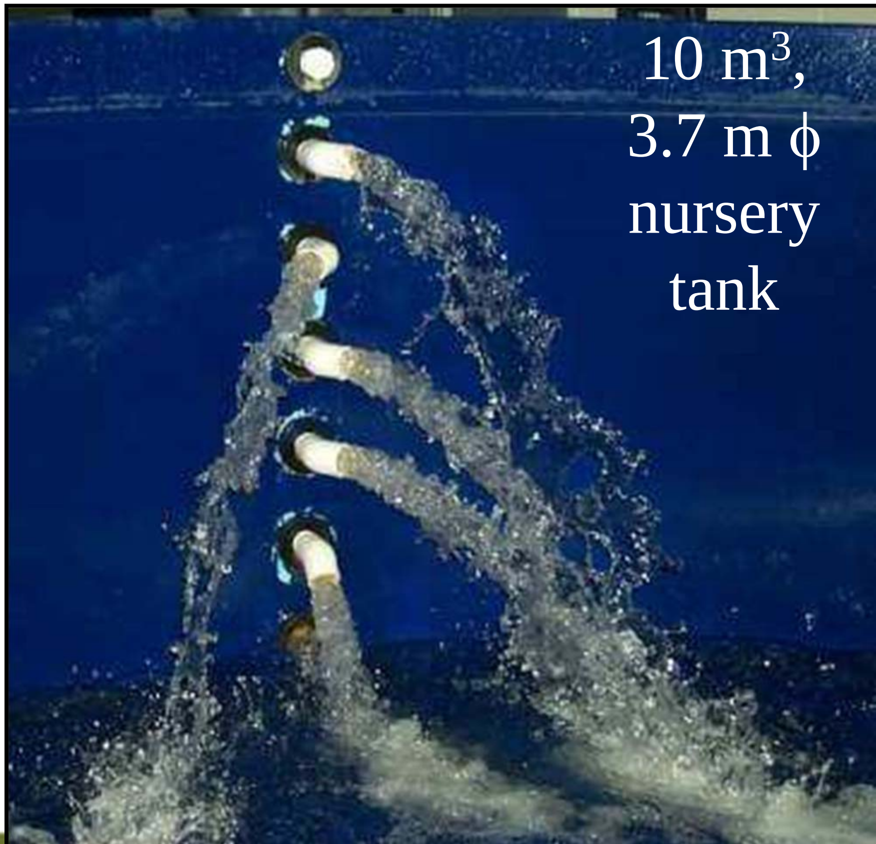
Managing Rotational Velocity in Large Circular Tanks

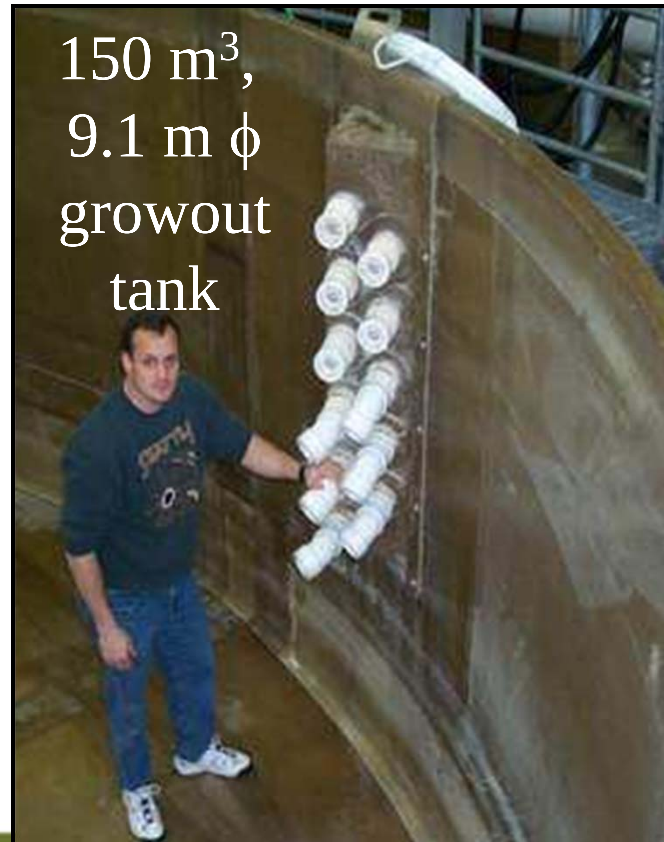
- HRT = 33 min, U_O = 341 cm/s



Culture Tanks: Flow Injection

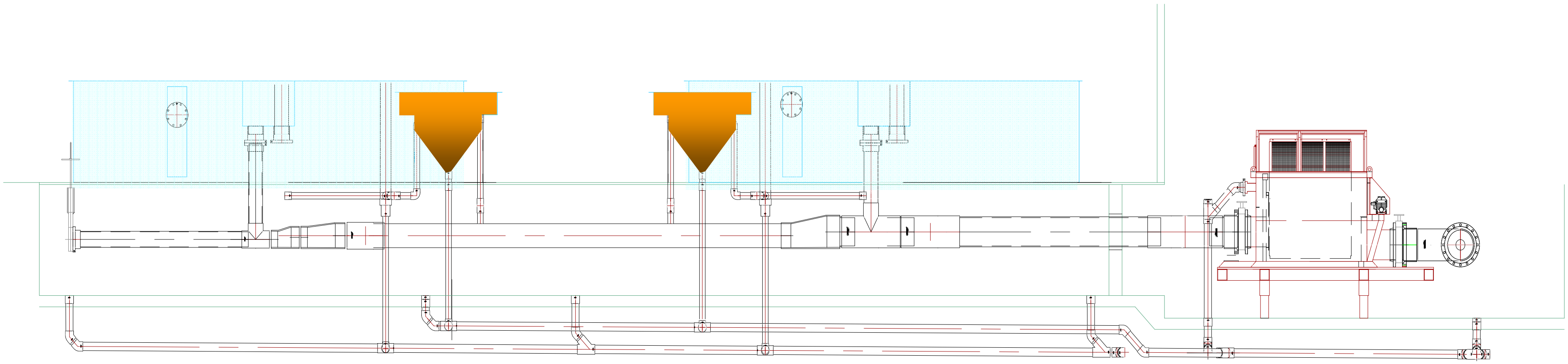
- Developed adjustable inlet nozzles systems to optimize water rotational velocities & mixing.





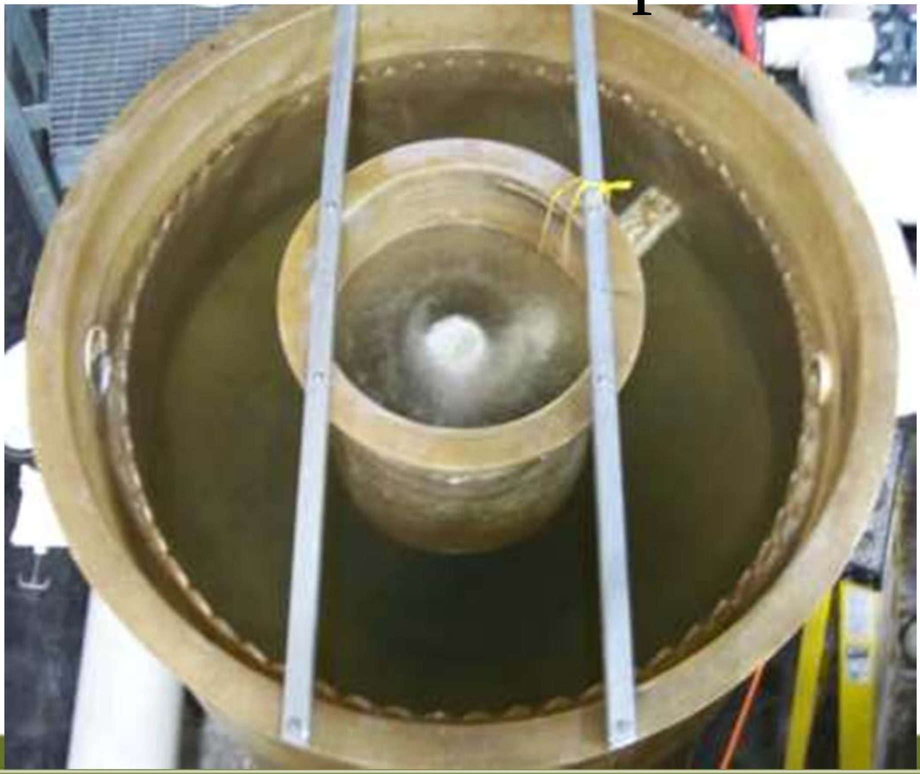
Example R & D: Large-Scale Dual-Drain Tanks

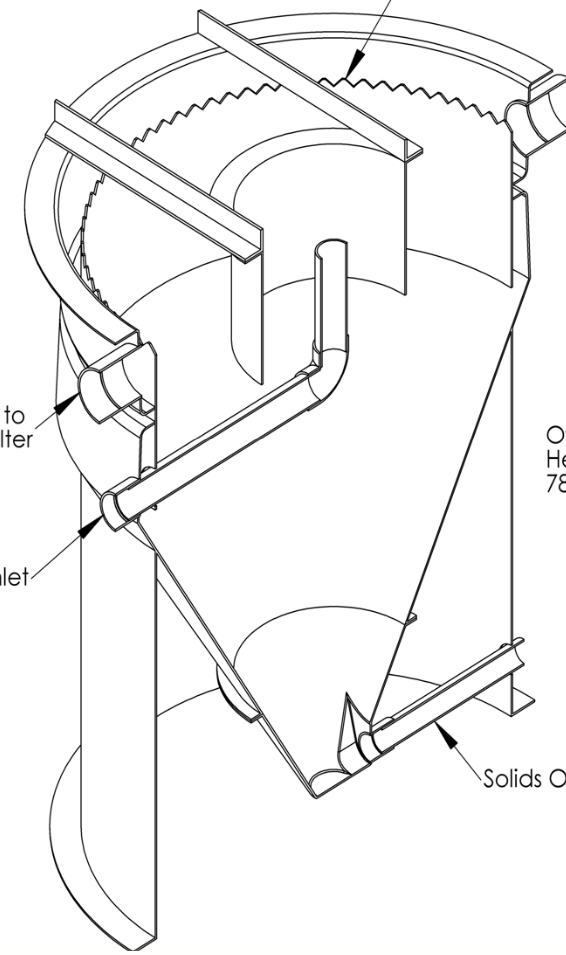
- Optimize solids removal at culture tank and across downstream processes
  - Identified surface loading rate & rotational period criteria
  - Improved solids capture in concentrated underflow across radial flow settler (improvement over swirl separ.)



Radial Flow Settler Treats Bottom-Center Tank Drain

- Determined RFS removes 80% of TSS, 2x better than swirl separator





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Improve Fish Harvest Technologies

- Developed sidewall harvest box
  - Clam-shell grader used to crowd fish so they slide into dewatering area

Large-Scale Biofilters

- Developed theoretical and practical guidelines for a modified pipe-manifold fluidized-sand biofilter,

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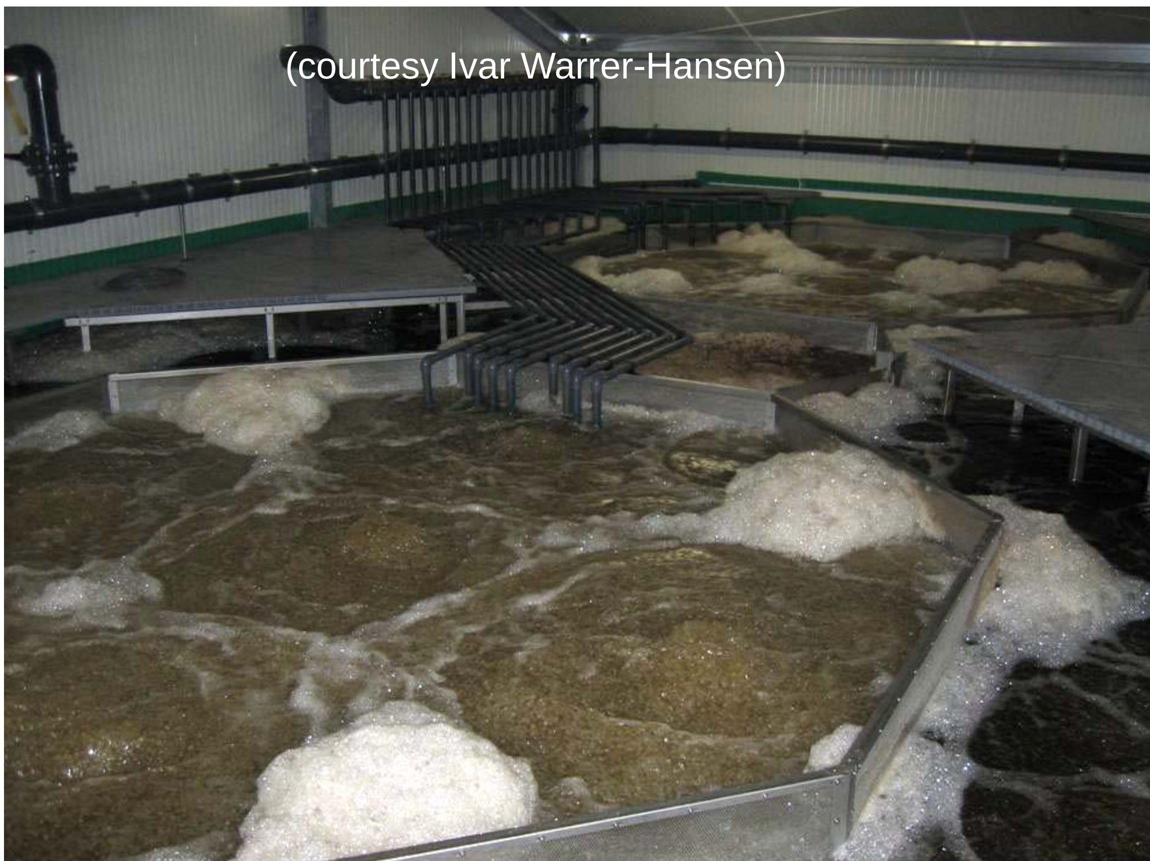
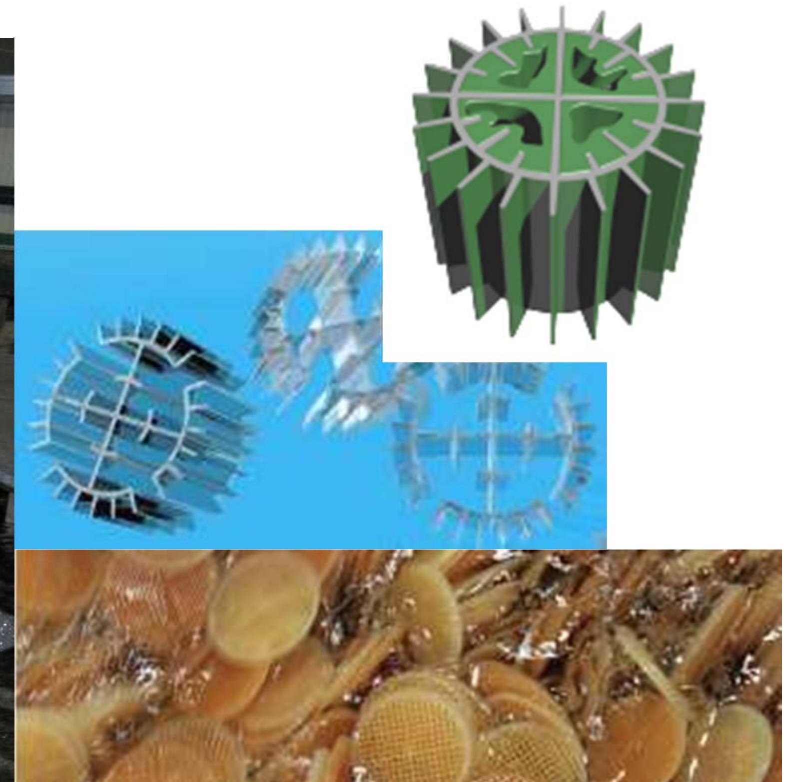
Fluidized Sand Biofilters

- Fine sand fluidized biofilters (100+) are used in large-scale recycle systems:
  - scale to treat flows > 13,000 L/min
  - provide high 70-90% TAN removal efficiencies
  - maintain low (< 0.2 mg/L) nitrite-nitrogen levels
  - provide compact and capital cost efficient treat.
    - high specific surface areas (4,000-45,000 m^2/m^3)
    - low media cost ($40-70/$m^3$ of sand)
  - Extremely robust & reliable if properly designed

Moving Bed Biofilters

- Norwegians, Danes, and others have developed moving bed biofilters, which are used in RAS





Large Scale Technologies for O_2 & CO_2 Control

- Developed theoretical & practical guidelines for integration of O_2 & CO_2 technologies into RAS.
  - BAT for many new commercial and state/federal RAS.

Large Scale Technologies for O_2 & CO_2 Control

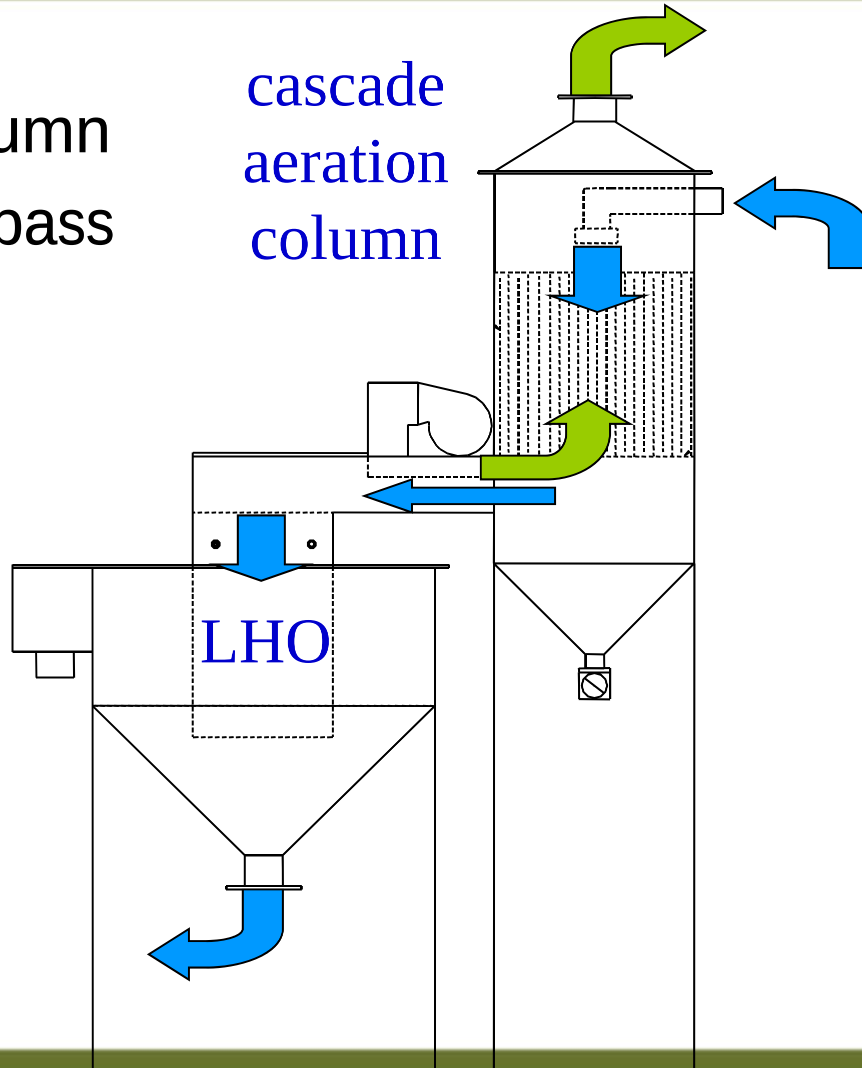
- CO_2 accumulates to inhibitory levels with:
  - excessive available dissolved O_2 consumption,
    - cumulative dissolved O_2 consumption > 6-12 mg/L
      - depending on CO_2 stripping efficiency per pass
  - systems with oxygenation but little aeration
  - systems with slow tank turnover

Large Scale Technologies for CO_2 Control

- Technologies to remove CO_2:
  - Forced-ventilated cascade columns
  - Aeration basins, including moving bed biofilters
  - Airlift pumps
  - ~~Diffused aeration within the culture tank~~

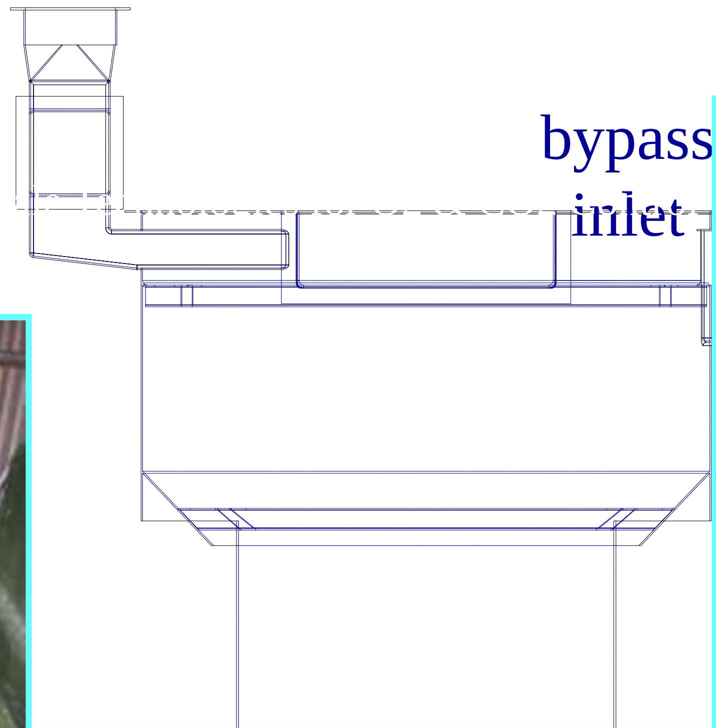
Large Scale Technologies for O_2 & CO_2 Control

- Forced-ventilated cascade column
  - Strip 50-60% of CO_2 each pass
- Low head oxygenation
  - Create $O_2 \geq 200\%$ sat.
- Return flow to culture tank
  - Control $CO_2 \leq 20$ mg/L
  - Maintain O_2 of 100% sat.



Large Scale Technologies for O_2 & CO_2 Control

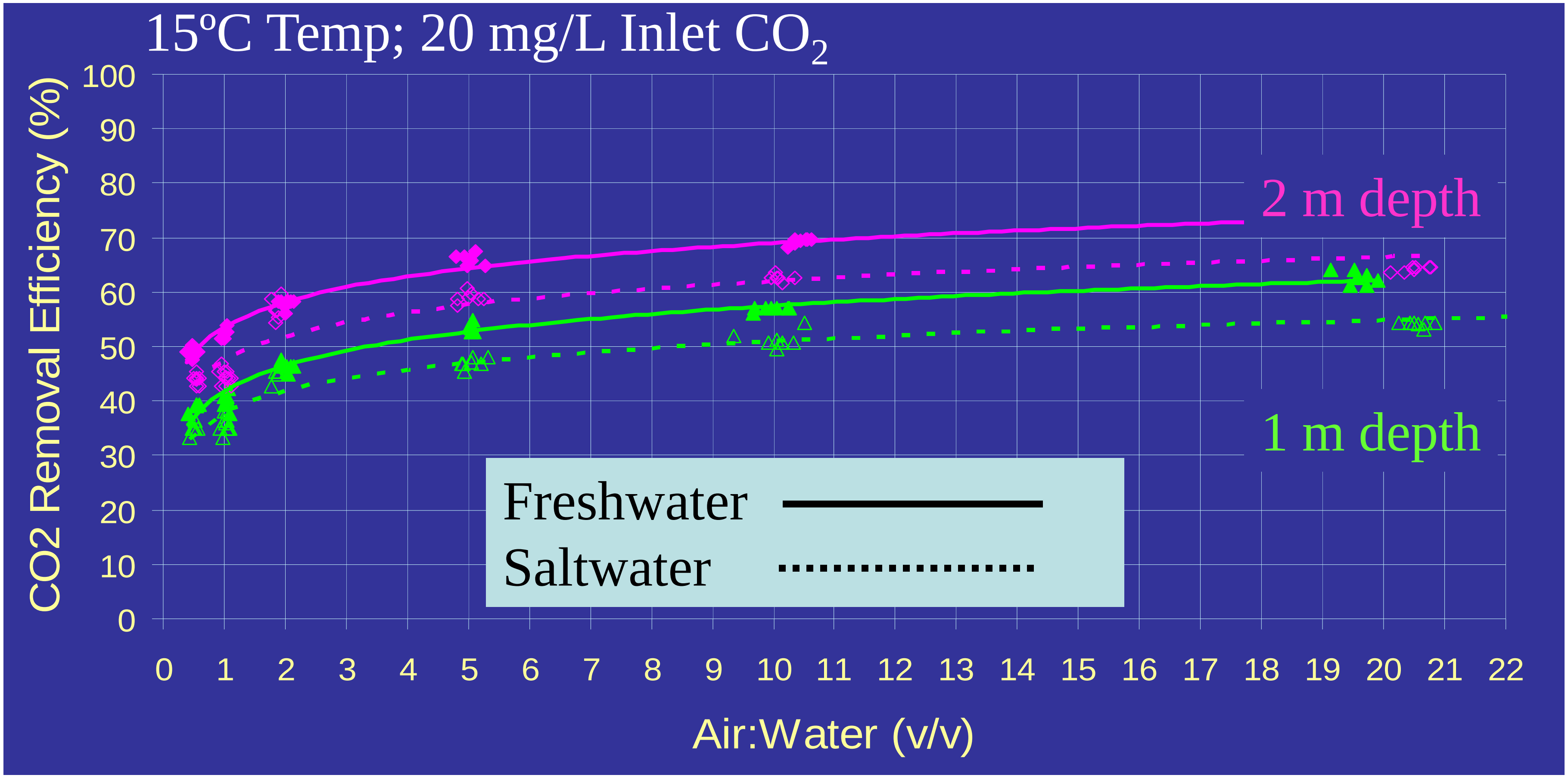
Forced-Ventilated Cascade Columns



LHO sump tank

Large-Scale Technologies for O_2 & CO_2 Control

- Collected data & developed models of CO_2 stripping



Oxygenation Technologies

- Evaluated first commercial-scale low head oxygenation (LHO) units, plus many others
  - Low head/energy (1-1.5 psig)
  - Efficiently produces up to 150-200% O_2 saturation
  - Vents N_2 & avoids TGP
  - Scales to high flows
    - treats entire recycle flow

Oxygenation Technologies

- Evaluated oxygen cones for dynamic O_2 control on a side-stream flow returning to culture tank
  - Cones are widely used in closed-containment systems
  - Higher energy requirements at 8-30 PSIG pressure
  - Creates higher TGP than LHO units
  - Maximizes O_2 transfer efficiency

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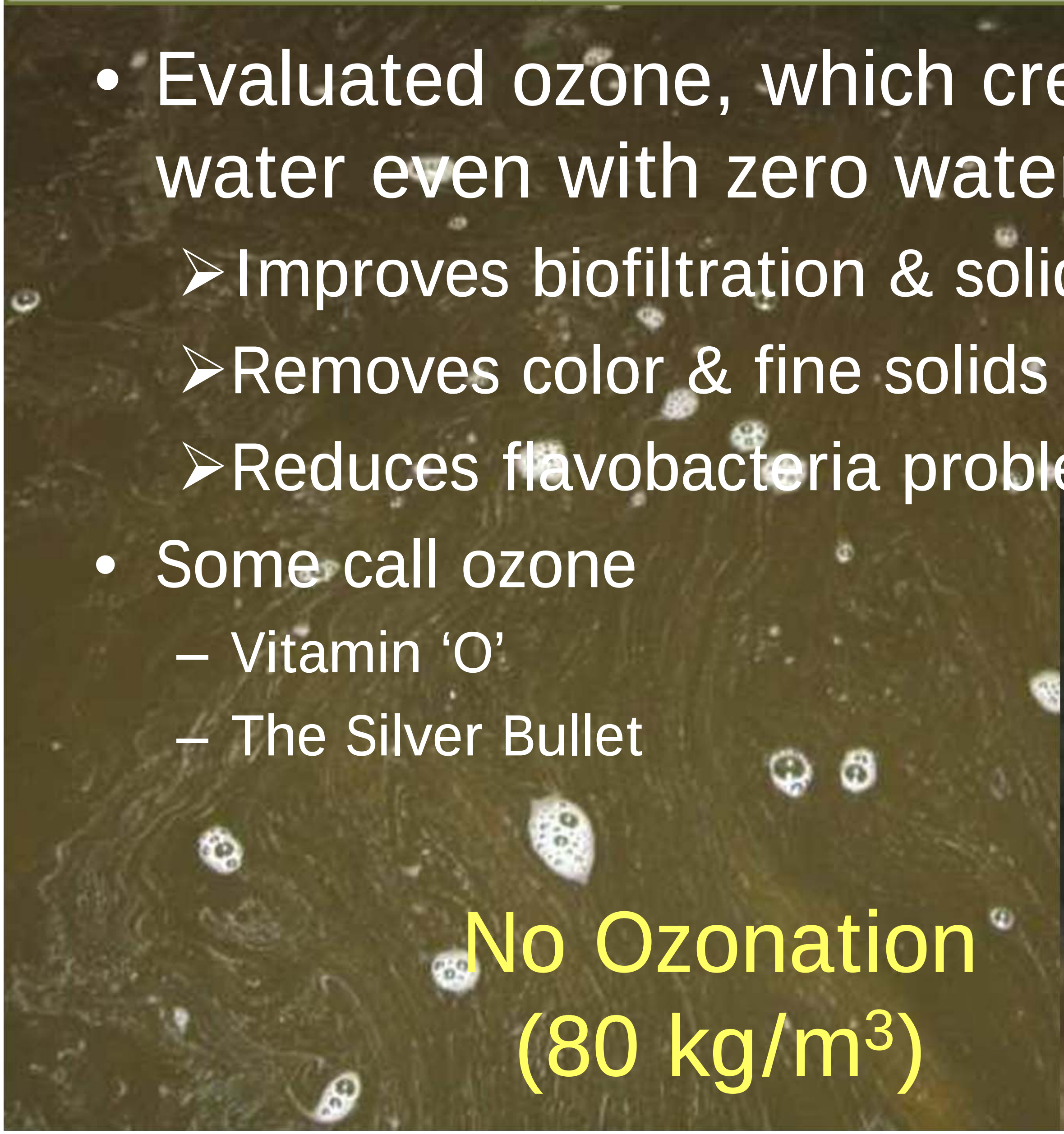
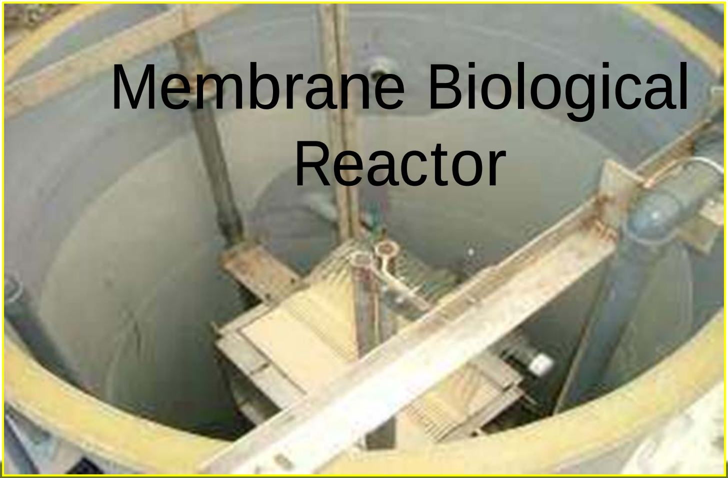
Ozonation of Recirculated Water

- Evaluated ozone, which creates clear 'blue' water even with zero water flushing
  - ➢Improves biofiltration & solids removal
  - ➢Removes color & fine solids
  - ➢Reduces flavobacteria problems
- Some call ozone
  - – Vitamin 'O'
  - – The Silver Bullet



Biosolids Dewatering & Wastewater Treatment Technologies



Biosolids Dewatering & Wastewater Treatment Technologies

- Percentage of waste removed in thickening processes.

	Geotextile Bags	Gravity Thickening Cones	Inclined Belt Filter	Membrane Biological Reactor
TSS	95	92	96	> 99.9
$cBOD_5$	57	47	89	100
Total Nitrogen	39	58	86	97.9
Total Ammonia Nitrogen	-1461	-101	-24	81
Total Phosphorus	68	74	92	99.9
	WORST		BETTER	BEST

Membrane Biological Reactor

- TSS & BOD treated to about 1 mg/L
  - More than 99.9% removal
  - Permeate is suitable for reuse (removes heavy metals)
- Reclaim heat, salts, and alkalinity in water

INLET MLSS PERMEATE

Summary of Outcomes

- Work with Stakeholders:
  - Transfer technology to industry suppliers & consultants (we don't own the technology):
    - PRAqua
    - Marine Biotech
    - Water Management Technologies
    - States West Water Resources Corp
    - Coseco
    - others...

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Summary of Outcomes

- Example, tech transfer to PRA in late 1990's:
  - Target Marine Hatcheries, BC
  - Marine Harvest Canada's Big Tree Creek Hatchery
  - Pacific Aqua Salmon Farmers (Intern. Aqua Foods) Bingham Hatchery (ME) & Crystal Waters (BC)

Summary of Outcomes

- Work with leading & pioneering commercial producers:
  - Confidence in technology is increasing
  - Scale of investment has increased to $5-50 million dollar projects
  - Current U.S. projects with projected total capital investment of ~ $60 million
    - Arctic char
    - Atlantic salmon
    - sea bream, perch

Summary of Outcomes

- State and Federal Agencies
  - Approx. $150 million in new public fish culture facilities have been built during past 5 yrs or are under construction.

Conclusions

- Closed-Containment Systems have improved food security & reduced environmental impact:
  - Clean water and healthy fish
  - Small water footprint
  - Near zero waste discharge
  - Reduced antibiotic & chemotherapeutic use
  - Zero escapees - prevent genetic impacts on natural populations

Conclusions

- Closed-Containment Systems have become more cost effective with economies of scale
- Pilot systems must be used to determine salmon performance, quality, and production costs at commercial scale.

Need for Research

- Establish salmon salmon growth, survival, and feed conversion during all production phases while reared to harvest size
- Determine final harvest size, fillet yield and color, and percent sexual maturity at harvest size, i.e., ideally before the majority of fish sexually mature.
- Establish key production costs, i.e., system electric consumption, oxygen consumption, bicarbonate consumption, and labor to maintain the system and harvest the fish.
- Demonstrate that no vaccination, antibiotics, pesticides, or formalin are required when salmon are farmed in biosecure, freshwater, closed-containment systems.
- Characterize waste discharge concentrations and loads exiting the system and after wastewater treatment options and define the performance of the fish exclusion barriers used to prevent salmon escape.