

*Optimizing Design Criteria
for
COMMERCIAL
Recirculating Aquaculture Systems*

*By
Steven Van Gorder*

*FRESH-CULTURE SYSTEMS, INC
PROVIDING RECIRCULATING AQUACULTURE SYSTEMS AND TECHNOLOGIES
SINCE 1984*

***FRESH-CULTURE SYSTEMS, Inc.**
1984 -2014*



FCS – the design, construction and sale of RAS systems for 30 years.



**CURRENT “DEVELOPMENT” PRIORITIES
FOR RECIRCULATING AQUACULTURE SYSTEMS
(RAS)**

- 1) *“Sustainable” Recirc. AquaSystems (SRAS)*
 - ✓ *Low-Head Systems*
 - ✓ *Low-Energy Systems*
 - ✓ *Zero effluent*
 - ✓ *Low-Trophic Level Species Choices – Tilapia*
 - ✓ *Alternative Feeds (less fish meal)*
 - ✓ *Aquaponics*
- 2) *BioFloc (shrimp and tilapia)*
- 3) *Greenwater Systems*

**COMMERCIAL AQUAPONIC PRODUCTION IN
RECIRCULATING AQUACULTURE SYSTEMS
(RAS)**

But it’s also important to differentiate between ...

- *Hobbyist Systems / Small-Scale RAS*
- *Commercial Recirculating Aquaculture Systems*
 - ✓ *“Entry-level” Commercial-Scale*
 - ✓ *RAS for Tilapia vs High-Valued Species*
 - ✓ *Vertical integration*
hatchery/nursery/processing/marketing/hydroponics
 - ✓ *Industrial-Scale Systems -*
“intensive” vs “super-intensive” systems

SMALL-SCALE AND HOBBYIST AQUACULTURE

Rodale Aquaculture Project 1977-1983

*“Is it possible to garden the water
like we garden the soil?”*

Organic Gardening and Farming Pioneer Bob Rodale , 1976



Home Aquaculture:

- *Low-Head Designs*
- *New Species*
- *Integrated ecologically-sound low-cost methods*

Home Aquaculture – Small-Scale and Hobbyist Systems

*Some of the 1st RAS
aquaponic designs anywhere*



Backyard Systems



Basement Systems



*Attached Greenhouse
Systems*



*Community-
Scale
Greenhouse
Systems*



“SUSTAINABLE AQUACULTURE”

Fertilization/Polyculture



*Organically Fertilized Polycultures
of low trophic-level species*



*Early “greenwater” and
“Biofloc” systems*

“SUSTAINABLE AQUACULTURE”

Multi-Trophic Polycultures



Catfish / Buffalofish / Carp



Tilapia



Macrobrachium



Rainbow trout



Red Swamp Crawfish

“SUSTAINABLE AQUACULTURE”
Low-Energy Designs – Temperature Control

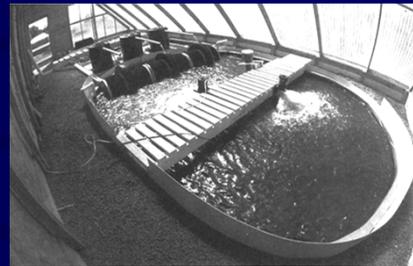
*Season-
extending
Solar
Domes*



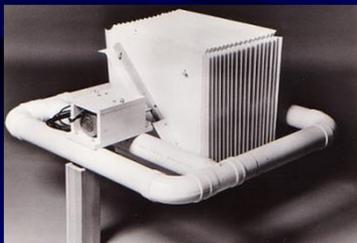
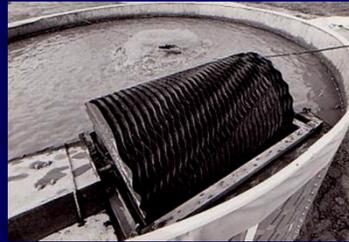
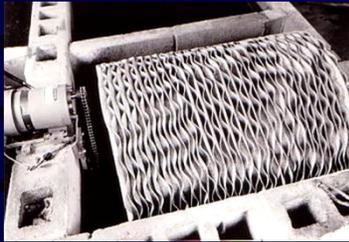
Greenhouses



“SUSTAINABLE AQUACULTURE”
Aquaponics/Community-Scale Designs



*“SUSTAINABLE AQUACULTURE”
Low-Energy Designs – RBC’s & Aerators*



*“SUSTAINABLE AQUACULTURE”
Low-Energy Designs – RBC’s & Gravity Separators*



paddlewheel-driven rbc's / 55 gallon drum clarifiers / efficient aeration

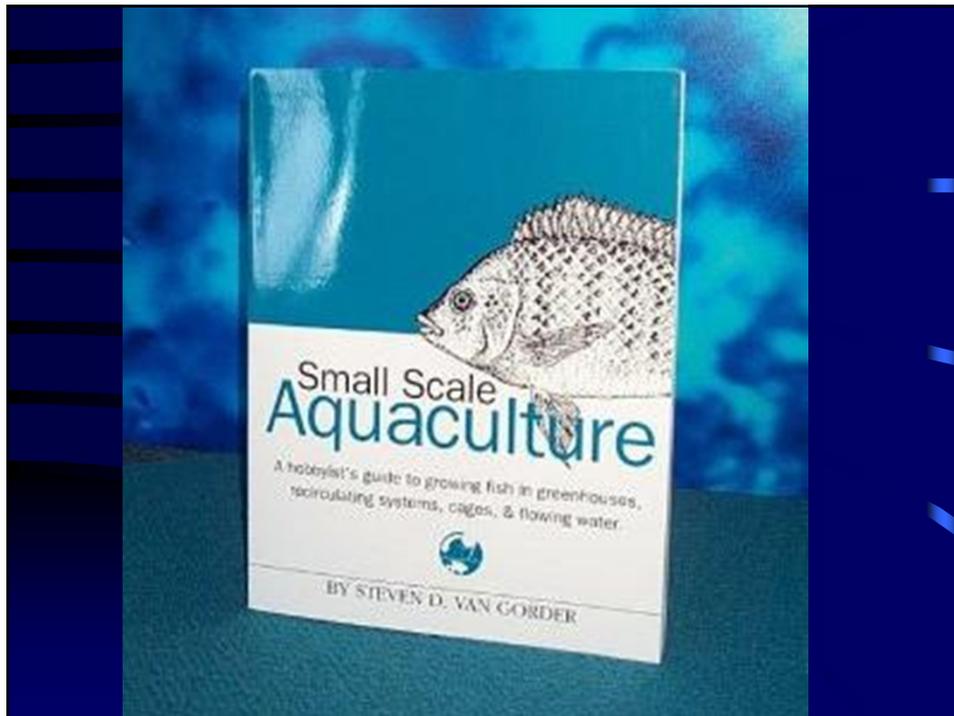
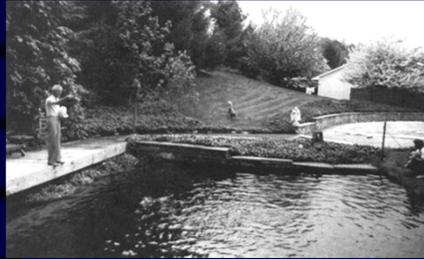
“SUSTAINABLE AQUACULTURE”
The Rodale Backyard Fish Farm



“SUSTAINABLE AQUACULTURE”
Small-Scale Cage Culture Systems



***“SUSTAINABLE AQUACULTURE
Small-Scale Flow-Through Systems***



Growing Interest in "Sustainable Aquaculture" 1976-1983



New Alchemy Institute



BioSphere Project - Arizona



*University of Arizona
Kevin Fitzsimmons*



Rodale Aquaculture Conference

"SUSTAINABLE AQUACULTURE" 2014 - Small-Scale Aquaponics

There are dozens of examples of hobbyist and small-scale aquaponics designs.



*Unless you're selling
these systems, this is
not a form of
commercial aquaponics*



DEFINING COMMERCIAL RECIRCULATING AQUACULTURE

RECIRCULATING AQUACULTURE

SCALE AND TECHNOLOGY PERSPECTIVES

**SMALL-SCALE
HOBBYIST
AQUACULTURE**



**LOW-HEAD
“SUSTAINABLE”
RAS**



**COMMERCIAL
INDUSTRIAL-SCALE
AQUACULTURE**



**SUPER-INTENSIVE
“HIGH-TECH”
RAS**



DEFINING “COMMERCIAL-SCALE” RAS (Minimum Requirements)

- *Recirculating Aquaculture Systems can include either:*
 - *Dedicated Fish Production in closed systems, or*
 - *Aquaponics, combining hydroponic vegetable production with finfish production.*
- *Aquaponics can be further sub-divided into 2 categories:*
 - *Hydroponic vegetable production balanced exactly with the fish biomass and the feed input levels.*
 - *Independent fish production and hydroponics systems, using the RAS waste stream as the nutrient source for the vegetable production.*

DEFINING “COMMERCIAL-SCALE” RAS

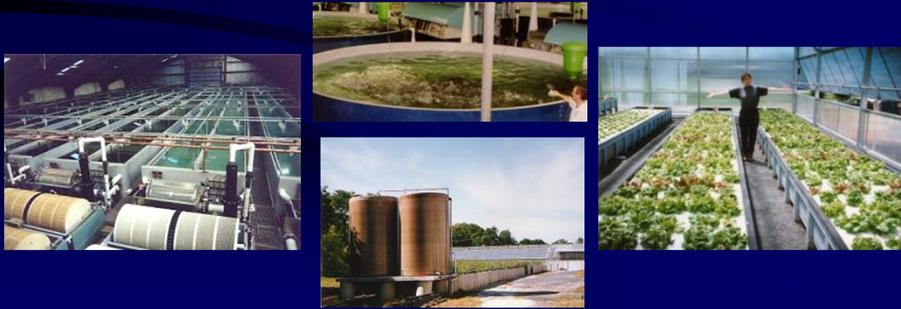
- ❖ *Commercial-scale “balanced” aquaponics*
 - *By far the most common design alternative being considered*
 - *The fish are often used only as a source of nutrients*
 - *Almost exclusively “tilapia culture systems”*
 - *Others are more qualified to discuss this topic*



DEFINING “COMMERCIAL-SCALE” RAS

❖ *Independent fish culture / hydroponic systems*

- *Commercial quantities of fish and/or vegetables*
- *Hydroponic nutrients derived from the fish waste stream
... for whatever level of hydroponics is desired*
- *Must maintain state-of-the-art water quality control systems*
- *Should be able to support a variety of high-value fish species*



DEFINING “COMMERCIAL-SCALE” RAS (Minimum Requirements)

- *Many believe that Recirculating Aquaculture Systems, including Aquaponics, cannot be commercially viable unless pursued on an “industrial-scale”.*

This is debateable, but ...

- *Successful “entry-level” systems will require:*
 - *Imaginative business planning*
 - *Specialized, proven RAS technologies*
 - *Niche marketing strategies*
 - *Exceptional quality cultured products*
 - *Significant capital investment*

DEFINING “COMMERCIAL-SCALE” RAS (Minimal “Entry-Level” Requirements)

- *A realistic and carefully articulated business plan describing ...*
 - ✓ *An owner-operated business - full-time commitment*
 - ✓ *Threshold level profit potential - \$30,000-\$100,000 / year?*
 - ✓ *Established markets for the anticipated product*
- *RAS with continuous year-round production*
 - ✓ *Approaching weekly harvest capabilities (market-driven)*
 - ✓ *Maintenance of multiple graded populations of fish*
 - ✓ *Stable and dependable production*
 - ✓ *Technically viable/proven aquaculture designs*
 - ✓ *A threshold harvest capacity of fish/vegetables*

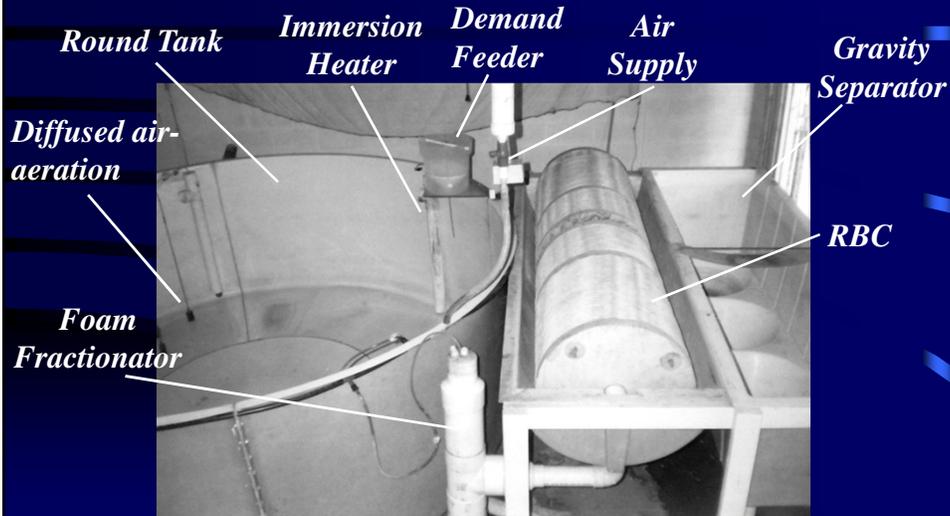
COMMERCIAL-SCALE ADAPTATIONS

Besides defining a particular minimum “scale”, what technical modifications define a commercial RAS?

INCREASING INTENSIFICATION Design Categories (Unit Processes)

- *Tank number, size & design*
- *Biofiltration*
- *Clarification*
- *Dissolved Oxygen Control –
Aeration/Oxygenation/Ozonation*
- *Carbon Dioxide Control*
- *pH Control*
- *Feeding strategies*
- *Proportional energy costs in all categories*

*FCS – First Commercial-Scale Research Systems,
Northampton - Kutztown, Pennsylvania
1984-1986*



*FCS – First Commercial-Scale Research Systems,
Northampton - Kutztown, Pennsylvania
1984-1986*

Low-energy designs:

- *Insulated/covered tanks.*
- *Off-peak electrical immersion heaters*
- *Low-head biofilters, clarifiers, aeration*



Commercial-Scale Designs LOW-HEAD SYSTEM



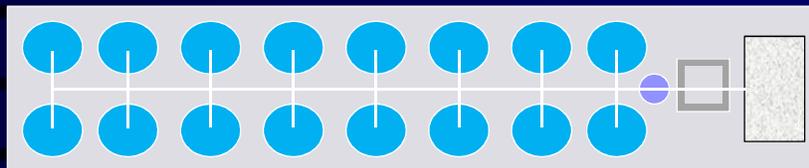
16 Tank RAS
Complete De-centralization

2.5 HP Air Blower Provides:

- rotational tank flow (peripheral airlift pumps)
- circulation of water between system components (airlift)
- aeration (diffused air)
- clarification (gravity separators)
- foam fractionation (diffused air)
- carbon dioxide sparging (diffused air)
- rotation of Rotating Biological Contactors (paddlewheel)

Determining Production Capacity

“Satellite Tank System Design”
16 Tanks - Totally Centralized

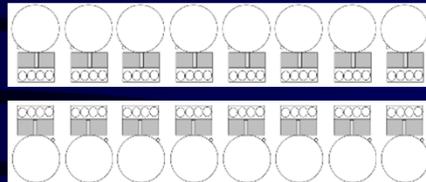


PRODUCTION CAPACITY

Staggered tank stocking with fingerlings
6 month growout cycle
2 harvests / tank / year
0.3 lbs/gallon density
 $600 \text{ lbs} \times 16 \times 2 = 19,200 \text{ lbs}$

Determining Production Capacity

“Multiple-Tank / Density Manipulation Systems”
16 Tanks - Totally De-centralized



*8 tanks x 8.7
 harvests/year
 600 lbs x 8 x 8.7
 = 41,700 lbs*

PRODUCTION CAPACITY

Patented density manipulation system design

Every 6 weeks ...

8 tanks are harvested

7 tanks are subdivided

1 tanks is stocked with fingerlings

First Commercial-Scale Designs LOW-HEAD SYSTEMS

PRODUCTION CAPACITY

Tank size – 10’ diameter (2000 gallons) (15 production tanks)

Feed capacity - 10 lbs/day/tank

Max. density - 0.3 lb/gallon

System capacity - 40,000 lbs/year (8 tanks harvested every 6 weeks)

System limitations (to allowing increased feed levels)

- *Providing stable levels of dissolved oxygen*
- *Controlling levels of unionized ammonia*
- *Controlling settleable solids levels*
- *Limited emergency options*
- *Off-flavor and aesthetic concerns*

TOTAL ENERGY REQUIREMENT

2.5 HP - 0.4 kwh’s/lb of production

COMMERCIAL-SCALE ADAPTATIONS

INCREASING INTENSIFICATION

- ❖ *Any RAS design is only as good as its least effective unit process (measured by feed level)!*
- ❖ *All water treatment unit processes must be designed for the anticipated maximum daily feed input, not the average.*
- ❖ *All integrated RAS unit processes should be co-engineered.*

COMMERCIAL-SCALE ADAPTATIONS

Tank Design - Materials

- ❑ *The materials used for tank construction must be durable, smooth, inert, and non-toxic.*
- ❑ *If the material can be penetrated, at some point it will be, and the culturist should consider the consequences in terms of lost stocks and profits.*

Tank Construction Options

- *Fiberglass*
- *Concrete (treated)*
- *Plywood/liner*
- *Steel with epoxy paint*
- *Corrugated steel/liner*

COMMERCIAL-SCALE ADAPTATIONS

Tank Design - Configuration

- *The tank hydraulics must be completely self-cleaning*
- *The tank is the 1st element of the clarification system*
- *All waste solids must exit the tank → clarifier within minutes*
- *Co-engineered for a hydraulic retention time < 1 hour*



Rectangular tank



Round tank



Cross-flow tank

COMMERCIAL-SCALE ADAPTATIONS

Tank Design – Number and Size

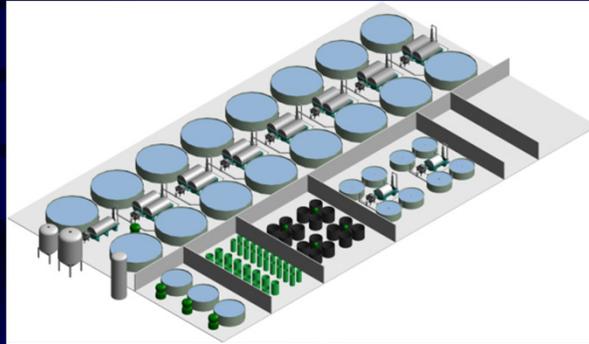
The tank number and size will be determined by the fish management strategy .

- *This strategy must consider the requirement for semi-continuous stocking and harvesting capabilities.*
- *Requires designs for both nursery and grow-out systems (and in some cases larval and fry culture systems).*
- *The tank size and number, coupled with the anticipated density at harvest, will dictate the production capacity of the facility.*
- *The fish species sometimes prefers a particular tank design.*

COMMERCIAL-SCALE ADAPTATIONS

Tank Options - Centralization

The number of tanks maintained by each Water Treatment System determines the level of “CENTRALIZATION”.



This is THE MOST important factor influencing both the “bio-security” of the system, and its cost!

COMMERCIAL-SCALE ADAPTATIONS

Tank Design - Centralization

Management Strategies and Options

*Fewer / Larger Water Treatment Systems > Reduced costs > Multiple satellite tanks sharing water > Efficient management of multiple cohorts > **More potential for catastrophic loses, least cost***

*More / Smaller Independent Water Treatment Systems > Increased costs > Greater biosecurity > **Reduced potential for catastrophic loses, greater cost***

Density Manipulation > Independent RAS modules > increased production, bio-security

COMMERCIAL-SCALE ADAPTATIONS Aeration System Design

Maintenance of adequate levels of dissolved oxygen is the first “limiting factor” to commercial production.

Low-Head Methods for Replenishing Dissolved Oxygen Levels:



Diffused air



Surface aerator



Surface agitator

COMMERCIAL-SCALE ADAPTATIONS Aeration → Oxygenation

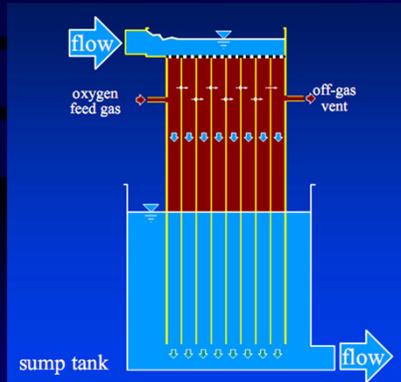


Most significant impediment – Energy / Technology

*Requires “Pure Oxygen Technologies”
Access to LOX or Oxygen Generation capabilities*

COMMERCIAL-SCALE ADAPTATIONS Oxygenation System Design

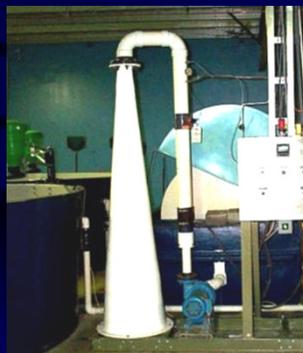
❖ *Low-Head Oxygenator (LHO) for Replenishing Dissolved Oxygen Levels:*



Provides supersaturated levels of dissolved oxygen at low head, but at reduced efficiencies (70-75%).

COMMERCIAL-SCALE ADAPTATIONS Aeration System Design

❖ *Moderate-Head Methods for Replenishing Dissolved Oxygen Levels:*



Requires a pump to supply the correct flow rate at 12 psi of pressure, dissolving the oxygen at 100% efficiency.

Pure oxygen / oxygen saturator

Commercial-Scale Designs
MODERATE-HEAD SYSTEMS

USE OF PURE OXYGEN

Options

1. *Diffusers*
 - ✓ *Too inefficient except for emergency use*
2. *Low-Head Oxygenator*
 - ✓ *Low-energy but still somewhat inefficient*
3. *Oxygen Saturators*
 - ✓ *Very efficient but at some energy cost*

Ozone option available with oxygen saturator technologies ...

- *improved water quality*
- *eliminates off-flavors*
- *sterilization options*
- *simplified tank and plumbing maintenance*

Commercial-Scale Designs
MODERATE-HEAD SYSTEMS

USE OF PURE OXYGEN

w/ Oxygen Saturators

Positives

1. *Additional production capacity / fish density*
2. *Additional emergency options –RAPID RESPONSE*
3. *Simplified stock management/harvests*
4. *Ozone option*

Negatives

1. *Requires pumps @ moderate pressure (12 psi)*
2. *Requires additional CO₂ sparging technologies*
3. *More sophisticated controls*
4. *Requires rapid emergency response (incr. densities)*

First Commercial-Scale Designs
LOW-HEAD SYSTEMS – WITH OXYGEN SATURATORS



*0.3 HP x 0.75 = 0.225 kw x 24 hrs = 5.4 kwh/day
At \$0.08/kwh = \$0.43/tank/day
to culture an additional 2.7 lbs of fish/day (\$0.16/lb)*

*Addition of 1/3 HP Pump (sidestream) w/ Oxygen Saturator
40,000 > 55,000 lbs/year RAS*

FCS COMMERCIAL-SCALE FACILITIES
1984-1988



*First Commercial-Scale Designs
LOW-HEAD SYSTEMS (with Oxygen)*

PRODUCTION CAPACITY

*Tank size - 10' diameter (1800 gallons)
Feed capacity - 12 lbs/day/tank
Max. density - 0.5 lb/gallon
System capacity - 55,000 lbs/year (using density
manipulation technology)*

System limitations (to adding additional feed)

- Controlling settleable solids levels*
- Controlling levels of unionized ammonia*
- Controlling levels of carbon dioxide*

TOTAL ENERGY REQUIREMENT

7 HP (0.8 kwh's / lb production)

***SPRAY-TOWER/PACKED COLUMN...
CONTROLS CARBON DIOXIDE LEVELS***

*With the use of
pure oxygen,
it is essential to
include designs for
the sparging of
carbon dioxide
from the water.*



COMMERCIAL-SCALE ADAPTATIONS

Clarifier Design

Design Requisite: The clarifier must remove suspended and settleable solids of the finest particle size possible.

Particle Size Removal Capacity

- *Settling tanks (determined by “residence time” but $> 100 \mu$)*
 - ✓ *Gravity settler*
 - ✓ *Centrifugal separator*
 - ✓ *Radial flow settler*
- *Protein skimmer (foam fractionator) (1-30 μ)*
- *Microscreen drum filter (determined by screen sieve)*
- *Bead filter (20-30 μ)*

SOLIDS CONTROL – CLARIFIER DESIGN



**CONE BOTTOM
GRAVITY SEPARATOR**

Gravity separators provided limited but effective solids control to 120 μ .

Combined with foam fractionation for removal of fine particulates.



BEAD CLARIFIER

Bead clarifiers effectively remove fine particulates to $< 30 \mu$. However, they cannot sustain high flow rate/low head design requirements.

Are excellent for larval and fry culture systems.

SOLIDS CONTROL – CLARIFIER DESIGN



CONE BOTTOM GRAVITY SEPARATOR



MICROSCREEN DRUM CLARIFIER

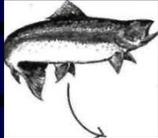

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BEAD CLARIFIER

*Improved efficiency from
120 μ > 30 μ removal capability
Most significant impediment - \$\$\$\$\$\$*

Biofiltration in Recirculating Aquaculture Systems (RAS)



Bacterial Nitrification of Ammonia

BIOFILTER

Ammonia
(NH₃)

$\xrightarrow[\text{O}_2]{\text{Nitrosomonas}}$

$\xrightarrow[\text{O}_2]{\text{Nitrobacter}}$

$\xrightarrow[\text{O}_2]{\text{Nitrospira}}$

Nitrite
(NO₂⁺)

Nitrate
(NO₃⁺)

Nitrifying bacteria, concentrated on the biofilter media surfaces, convert ammonia to nitrite and then to relatively harmless nitrate, proportionally to feed input levels.

Moving Bed BioReactors (MBBR's)

*Effective but
high-energy
biofiltration
systems.*



*Center for Marine
Biotechnology*



*AES Low-Space
Bioreactor*



*Open-containment
Bioreactors*

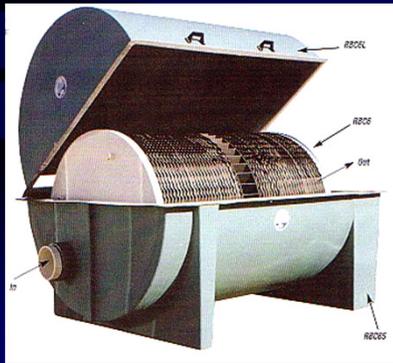


Commercial Aquaculture Systems using Rotating Biological Contactors

- From 1985-1995, several aquaculture facilities were designed and operated using dozens of small (0.6 m diameter) floating/ air-driven RBC's, for the commercial production of finfish in closed systems.



- Larger biofilters (1.22 m diameter) were designed and built to accommodate larger-scale fish production facilities.
- Constructed with neutral buoyancy, allowing frictionless rotation of the non-weight bearing central shaft within the guiding channels of the fiberglass staging unit.



- *Rotation is affected by the injection of air below, and/or water onto a centrally placed paddlewheel.*
- *Using spokes and rigorous attachment methods, the media is secured to the rotating shaft, and since no gear motor is required, is rotated at full 50% submergence.*



Several 10,000 ft² (930 m²) RBC's are rotated during acclimation procedures using only a small linear air compressor.



Commercial Aquaculture Systems using Rotating Biological Contactors

- For over 15 years, the larger RBC's have been incorporated in closed recirculating production facilities for the commercial production of striped bass, hybrid striped bass, yellow perch, steelhead trout, coho salmon and tilapia.

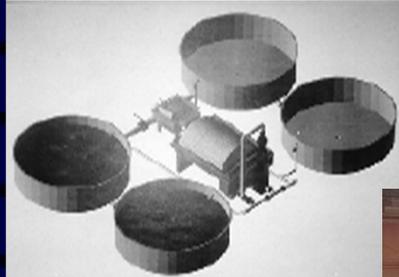


Commercial-Scale Designs MODERATE - HEAD SYSTEMS

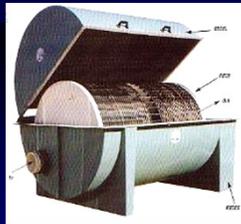
COST / EFFICIENCY ADAPTATIONS

- *Increased "Centralization" (4 tank systems)*
- *Microscreen Drum Clarifiers (servicing 4 tanks)*
- *Expanded biofiltration designs - 4' diameter RBC*
- *Central pump for all component requirements*
 - ✓ *Combined recycle / circular flow in tanks*
 - ✓ *Oxygenation (at 12 psi)*
 - ✓ *Rotation of RBC's*
 - ✓ *Flow to CO₂ spargers*

*Commercial-Scale Designs
MODERATE - HEAD SYSTEMS*



4-tank "quads"



*Commercial-Scale Designs
MODERATE - HEAD SYSTEMS*

*SPECIFICATIONS FOR INCREASING PRODUCTION LEVELS
(Increased "Centralization")*

PRODUCTION CAPACITY

Requires increased biofiltration

- Tank size - 10' diameter (2000 gallons)*
- Feed capacity - 15 lbs/day/tank*
- Max. density - 0.5 lb/gallon*
- System capacity - 65,000 lbs/year*
(using density manipulation strategy)

Commercial-Scale Designs
MODERATE - HEAD SYSTEMS

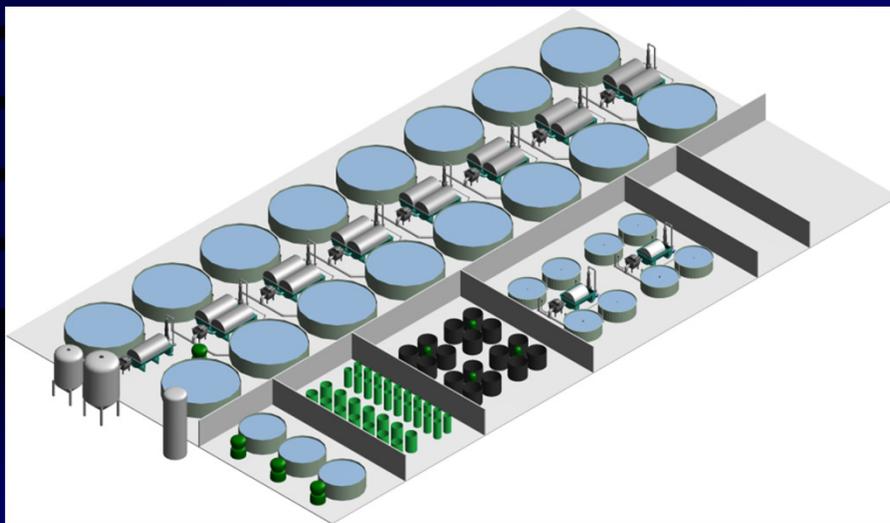
SPECIFICATIONS FOR INCREASING PRODUCTION LEVELS
(Increased Tank Size)

PRODUCTION CAPACITY

Requires increased biofiltration and pumping capacity

- Tank size* - 12' diameter (3000 gallons)
- Feed capacity* - 15 lbs/day/tank
- Max. density* - 0.5 lb/gallon
- System capacity* - 80,000 lbs/year
(using density manipulation strategy)

EVOLUTION – Most Significant Limiting Parameter
SCALE
INDUSTRIAL-SCALE RAS DESIGNS



INDUSTRIAL-SCALE RAS DESIGNS



*4-tank
nursery systems*



*2-tank
grow-out systems
(20 – 25 diameter)*



Commercial-Scale Designs MODERATE - HEAD SYSTEMS

SPECIFICATIONS FOR INCREASING PRODUCTION LEVELS (Increased Tank Size)

PRODUCTION CAPACITY

Requires increased biofiltration and pumping capacity

- Tank size - 20' diameter (10,000 gallons)*
- Feed capacity - 65 lbs/day/tank*
- Max. density - 0.5 lb/gallon*
- System capacity - 330,000 lbs/year*
(using density manipulation strategy)

*Commercial-Scale Designs
MODERATE - HEAD SYSTEMS*

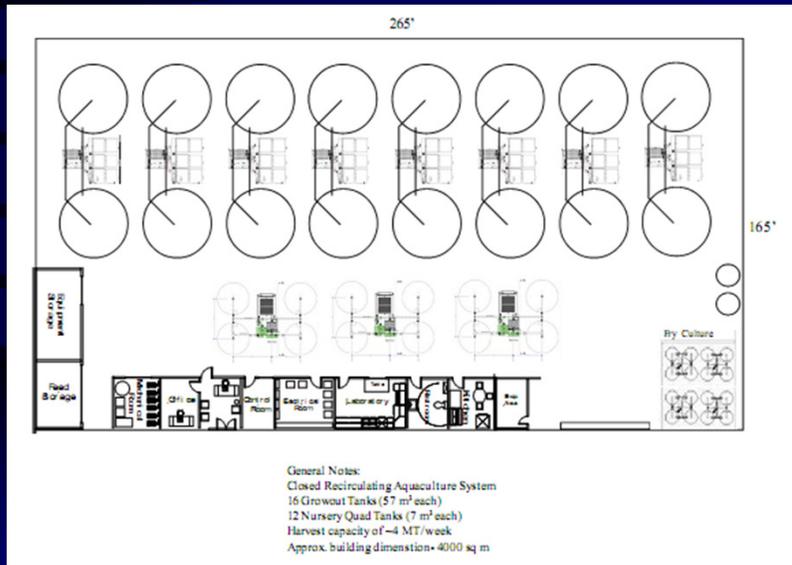
*SPECIFICATIONS FOR INCREASING PRODUCTION LEVELS
(Increased Tank Size)*

PRODUCTION CAPACITY

Requires increased biofiltration and pumping capacity

- Tank size - 25' diameter (15,000 gallons)*
- Feed capacity - 100 lbs/day/tank*
- Max. density - 0.5 lb/gallon*
- System capacity - 500,000 lbs/year*
(using density manipulation strategy)

*Fresh-Culture Recirculating Aquaculture System
250 ton target capacity*



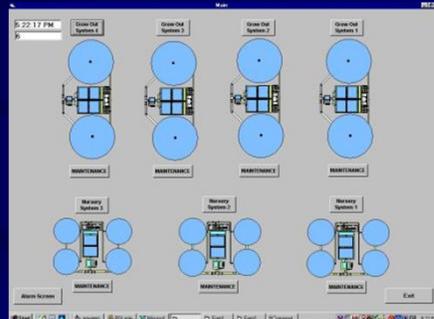
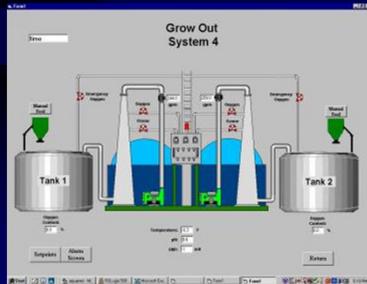
Additional Design Considerations

Water Temperature Control Options

- *Room temperature control*
- *Electrical immersion heaters*
- *Counter flow immersion coils*



Computer Monitoring and Control Options



Feed Management Options



- *Manual feeding*
- *Demand feeding*
- *Automatic feeding*
with or w/o central distribution systems
- *Timed / computer controlled*
 - ✓ *Vibratory*
 - ✓ *Auger*
 - ✓ *Belt*



Fish Species Options



Yellow perch



Rainbow trout



Coho salmon

Striped bass
Hybrid striped bass
Yellow perch
Red drum
Barramundi
Cobia
Sea bass
Sea bream
Rainbow trout
Coho salmon



Cobia



Seabass



Hybrid striped bass

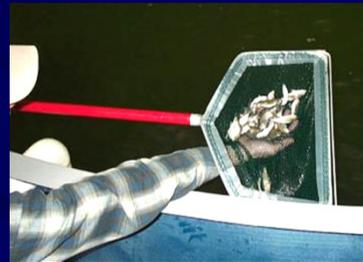
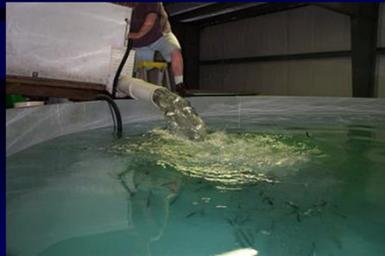
Aesthetic Considerations Practical and Public Relations Influences



- Tank Design
- Building architecture
- Product packaging
- Ozone
 - Improves aesthetics
 - Aids biofiltration
 - Improved fish health & management
 - Eliminates off-flavors

Stocking and Stock Manipulation

- *Delivery of fingerlings*
- *on-site hatchery?*
- *Maintaining multiple cohorts*
- *Grading of fish populations*
- *“Warehousing” of fingerlings*
- *Density manipulations*



Vertical Integration – Hatchery Systems

Increased scale allows for the consideration of a variety of options not possible at “entry-level”, or on a severely limited budget.



Live-food systems for larval culture



Larval and fry culture systems

Harvesting Options

- Manual harvesting techniques, using crowders, seines, nets, scales, totes, ice, CO₂, etc.
- Automated fish pumps, counters, graders



Processing and Marketing Considerations



Processing equipment options



Live sales to Asian market



Whole on-ice



Processed and packaged

Waste Treatment Considerations Reed Beds / Greenhouse Aquaponics

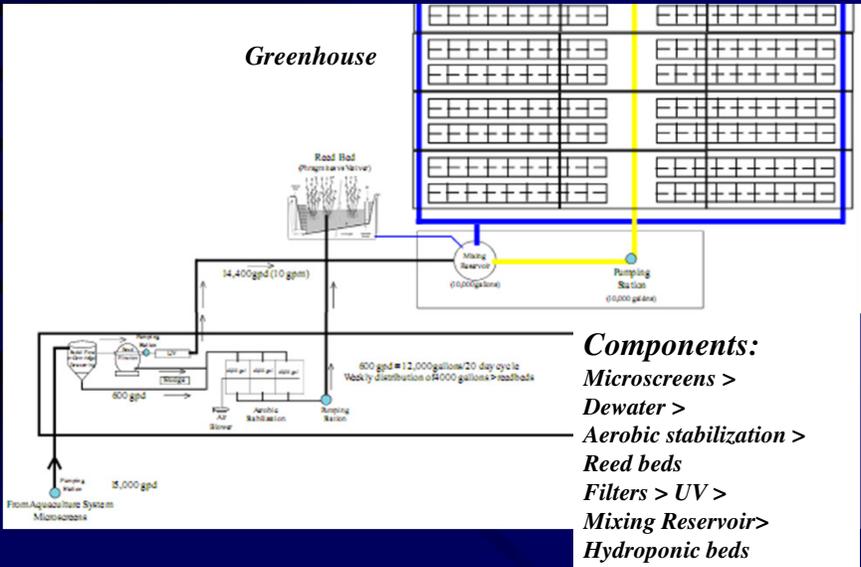


< Aerobic stabilization,
and reed bed,
waste management systems

Greenhouse aquaponics
systems >



Integration of RAS waste treatment facility with hydroponic greenhouse facility



- Components:**
- Microscreens >
 - Dewater >
 - Aerobic stabilization >
 - Reed beds
 - Filters > UV >
 - Mixing Reservoir >
 - Hydroponic beds

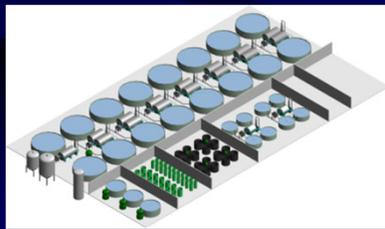
Phased "Entry" Options



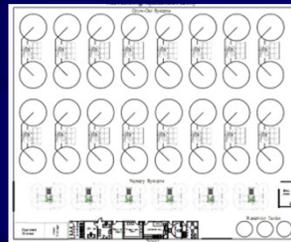
Entry-level growout → Nursery



Larger-scale growout systems



330,000 lb/yr production



1 million lb/yr production

CONSIDERATIONS FOR RAS DESIGN EVOLUTION

- 1) Higher density levels
- 2) Higher overall production levels
- 3) High-valued species options
- 4) Expanded processing and marketing options
- 5) Emergency response options (oxygen)
- 6) Elimination of off-flavors (ozone)
- 7) Computer and telemetry control options
- 8) Higher % recirculation – water conservation
- 9) Waste treatment options – reed beds/aquaponics
- 10) Vertical integration potential
- 11) Proportional cost of increased energy use??

