Water Quality Within RAS

Water Quality Within RAS

- Water quality within RAS depends upon the water flow (Q) and efficiency of waste removal (f_{rem}) at each unit process:
  - ✓ Solids capture
    - filtration
    - Sedimentation
    - ozonation
  - ✓ Carbon dioxide removal
    - aeration
  - ✓ Ammonia removal
    - biofiltration

Water Quality Within RAS

- Treatment efficiency (f_{rem}) controls water quality!
  - ✓ Not system exchange rate!

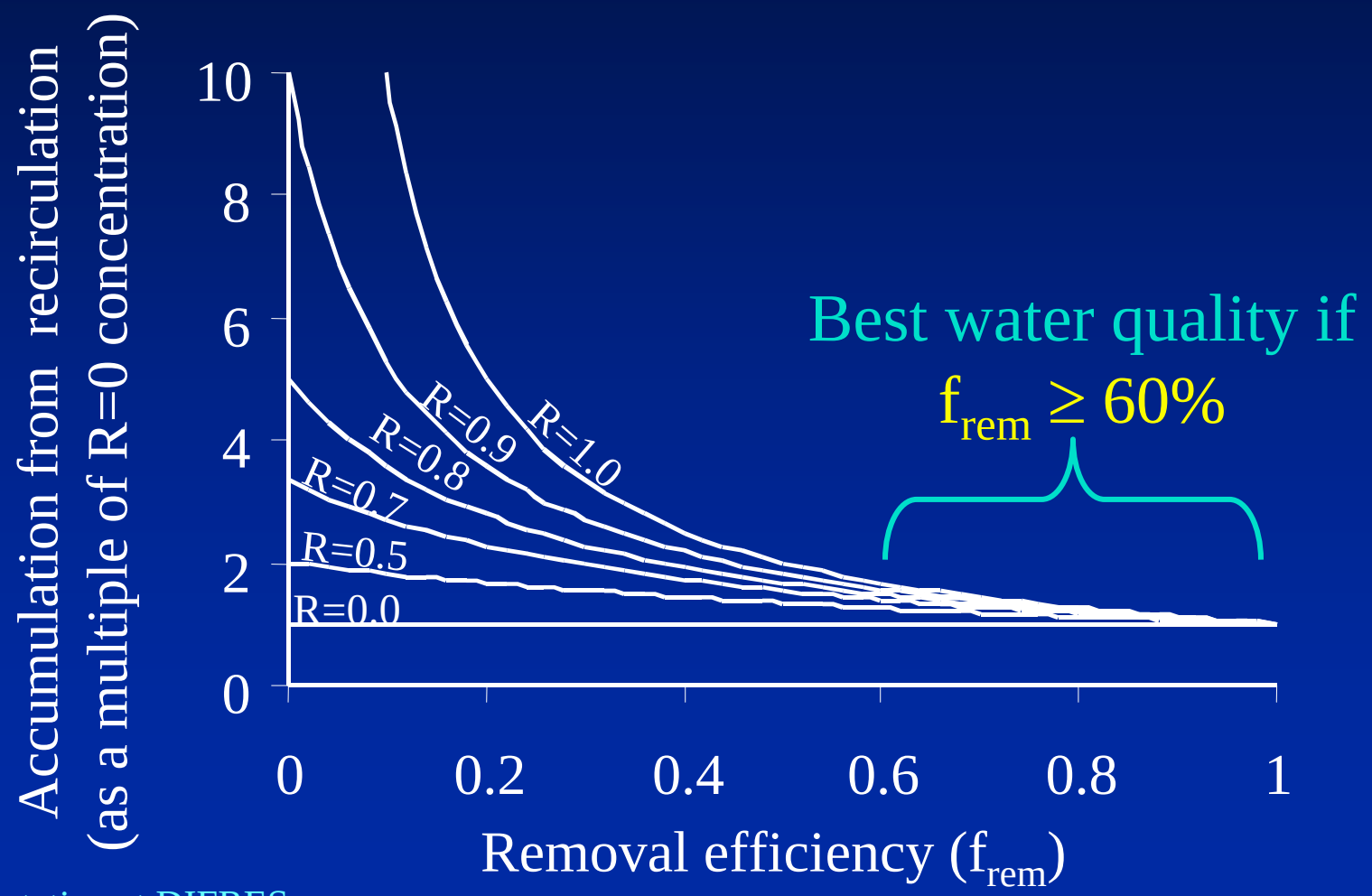
<u>EXAMPLE</u>: @ f_{rem}=0.8, R=0.8 to 0.99

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

$$= \{1.19 \text{ to } 1.25\} \cdot \{\text{single pass outlet conc.}\}$$

Water Quality Within RAS

- Treatment efficiency (f_{rem}) controls water quality!



Water Quality Within RAS

BMP #1:

select unit processes that provide high waste removal efficiencies within coldwater RAS!

- Treatment efficiency (f_{rem}) ≥ 0.6

Water Quality Within RAS

BMP #1.2:

select *fluidized-sand biofilters* to remove ≥ 80% of TAN each pass through coldwater RAS

Design, Management, and Applications of Fluidized Sand Biofilters

Steven Summerfelt

Freshwater Institute, Shepherdstown, WV

Outline

- Introduction
- Mechanisms for Flow Injection
- Fluidization Fundamentals
  - ✓ Sand selection guidelines
  - ✓ Calculating pressure drop
  - ✓ Calculating bed expansion
  - ✓ Experimental technique to measure bed expansion
  - ✓ Effect Of biofilm growth on fluidization

Outline

- FSB Design and Performance Criteria
  - ✓Nitrification rate and ammonia removal efficiency
  - ✓CO_2 production and O_2 consumption
- FSB Operation and Management Practices
  - ✓Managing bed growth
  - ✓Managing flow & avoiding air bubbles
  - ✓Mechanisms to unplug the flow distribution manifold
- Applications for salmonids

Introduction to FSBs

- FSBs treat dissolved wastes.
- FSBs appear cost effective for some large RAS:
  - ✓ specific surface area of sand is high
    - 4,000-20,000 m^2/m^3
  - ✓ cost of sand is low
    - \$70-200 per m^3 delivered
  - ✓ cost for surface area is low
    - \$0.05-0.004/m^2

Introduction to FSBs

- FSBs are compact.
- FSBs can treat small or large flows.
  - 3 to 190 L/s
  - 50 to 3,000 gal/min

FSB Can Be More Cost Effective

- FSB are about 5 times less expensive than comparable trickling filters

(Summerfelt & Wade, 1998, *Recirc Today*)	***Fluidized-sand biofilter #1***	***Fluidized-sand biofilter #2***	***Plastic media trickling filter***
Flow capacity, L/min	1,520	2,280	2,000
Design feed load[d], kg/day	58	64	59
Media specific surface area, m^2/m^3	11,300	11,300	180
Design TAN removal rate, $g/d/m^2$	0.06	0.06	0.2
Media volume, m^3	2.5	2.7	49.0
Cost of media, $	380	415	20,600
Total biofilter cost, $	**$6,000**	**$5,500**	**$28,000**

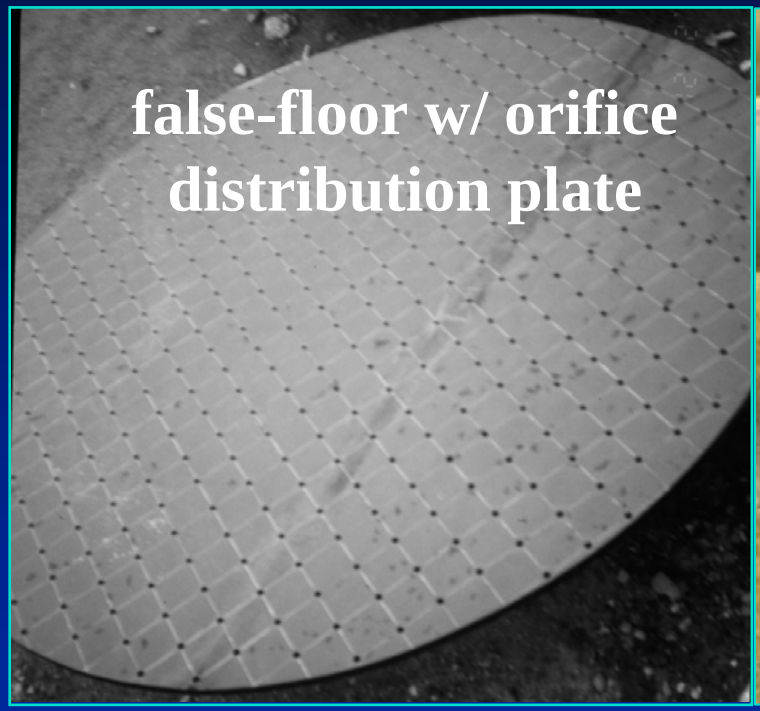
FSB Appear to be Cost Effective at Large Scales

- Capital cost estimates associated with biofilter choice for a 454 ton/yr tilapia farm.

(Timmons et al., 2000)	***Farm Cost***	***Cost, $/kg/yr***
RBC	$668,000	$1.5
Trickling Biofilter	$620,000	$1.36
Pressurized Bead Filter	$296,000	$0.66
Conventional FSB	$124,000	$0.26
Cyclo Bio FSB	$76,000	$0.18

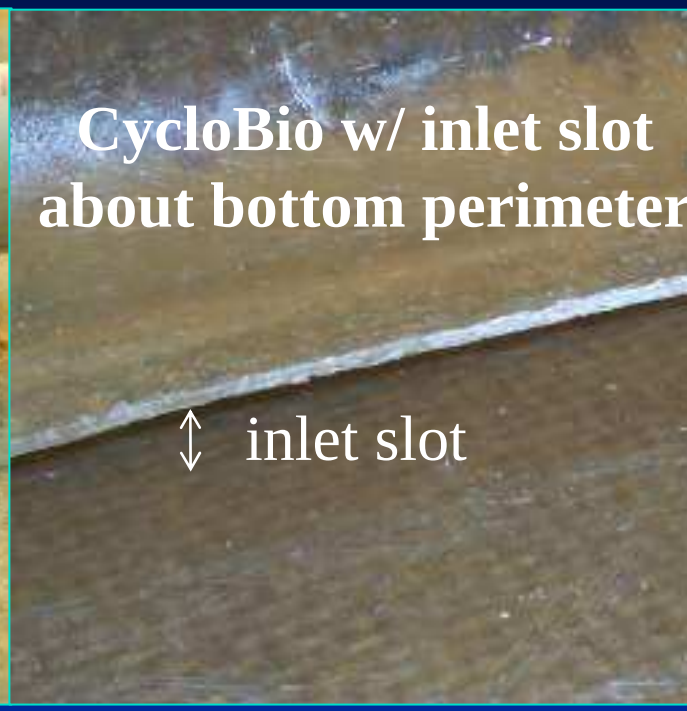
Flow Distribution Mechanisms

- Flow distribution methods vary, but are all important!



orifices distributed
across false-floor
(controlling ΔP)

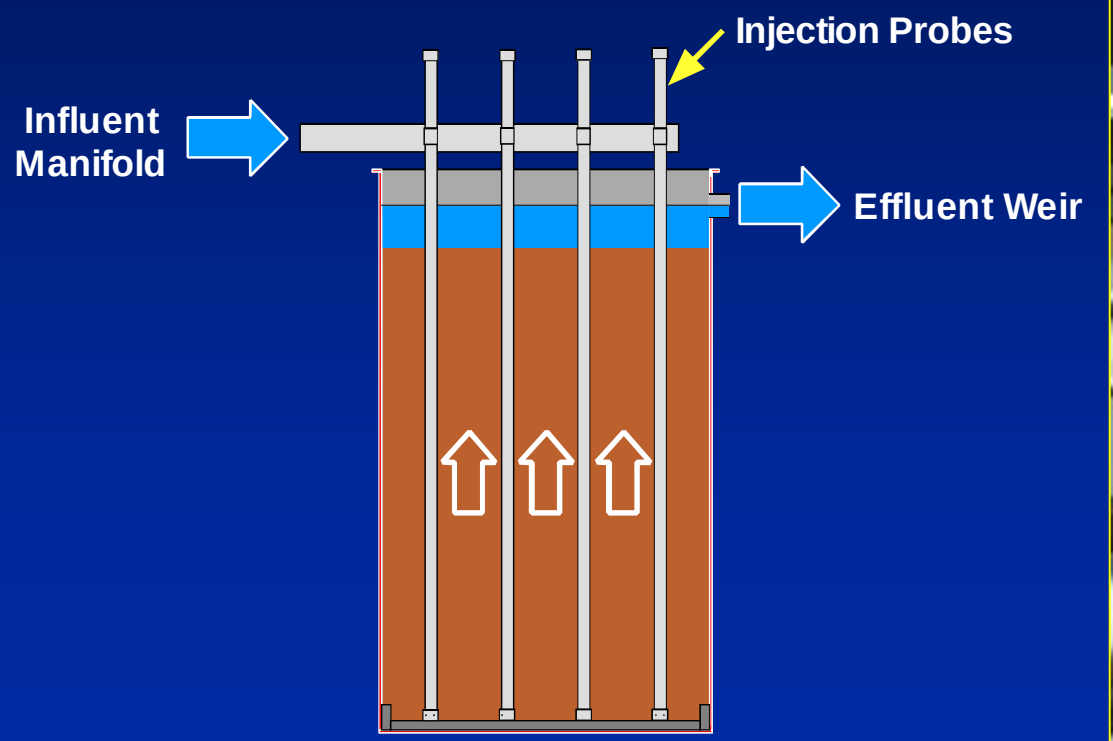
orifices distributed
across pipe-manifold
(controlling ΔP)



slotted inlet
about circumference
(NO controlling ΔP)

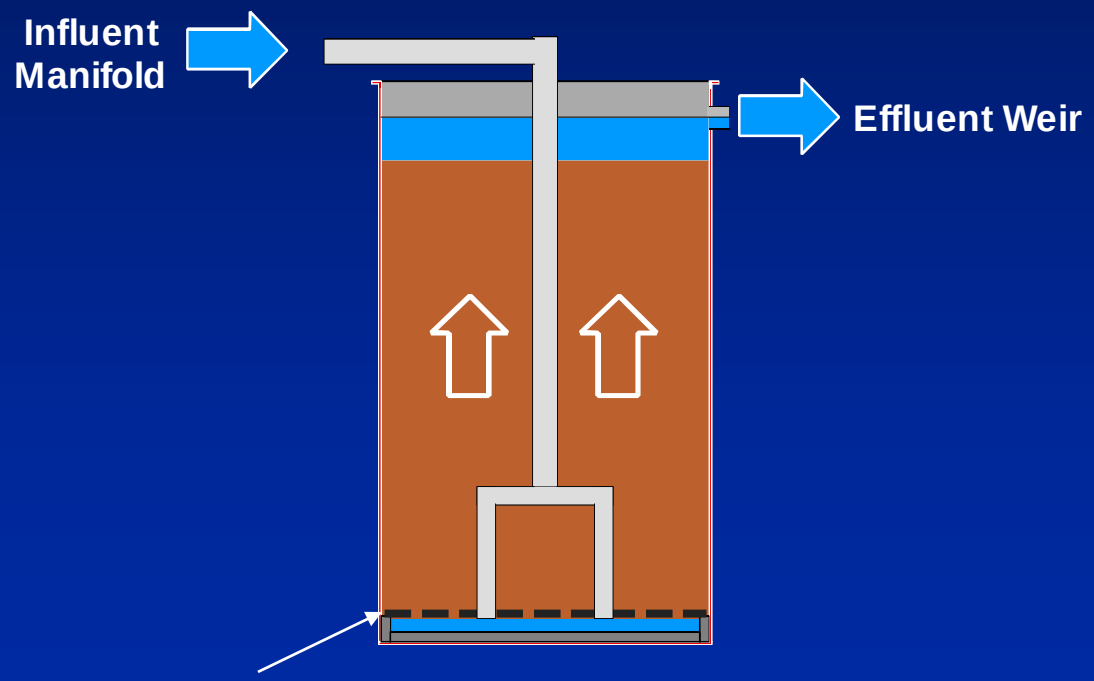
Flow Distribution by Vertical Probes

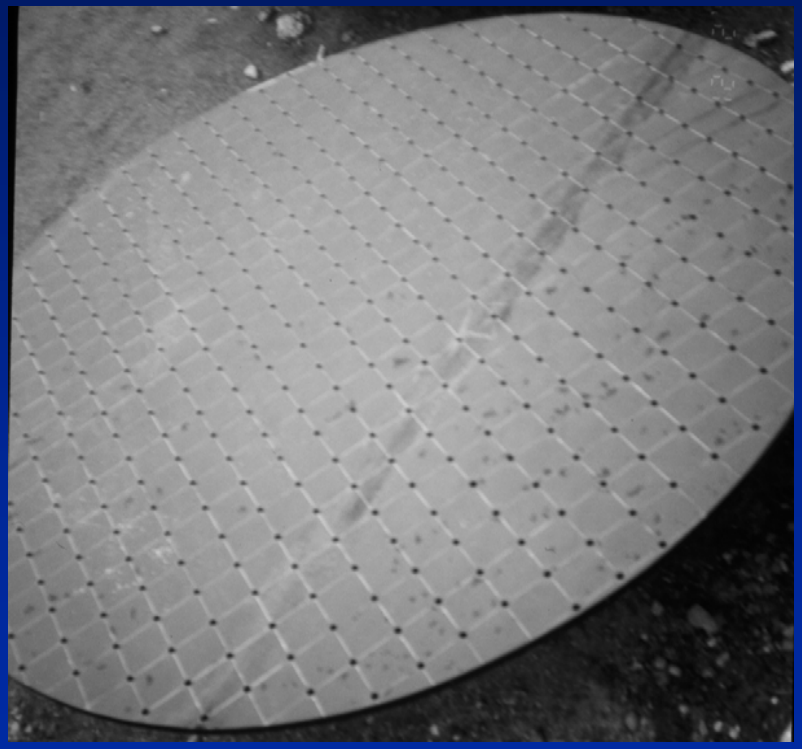
- Widely applied in many RASs.
- FI purchased this FSB in 1989 from Dallas Weaver



Distribution Through False Floor

- Eric Swanson reported (Aqua Expo, 1992) flow injection underneath a false floor.

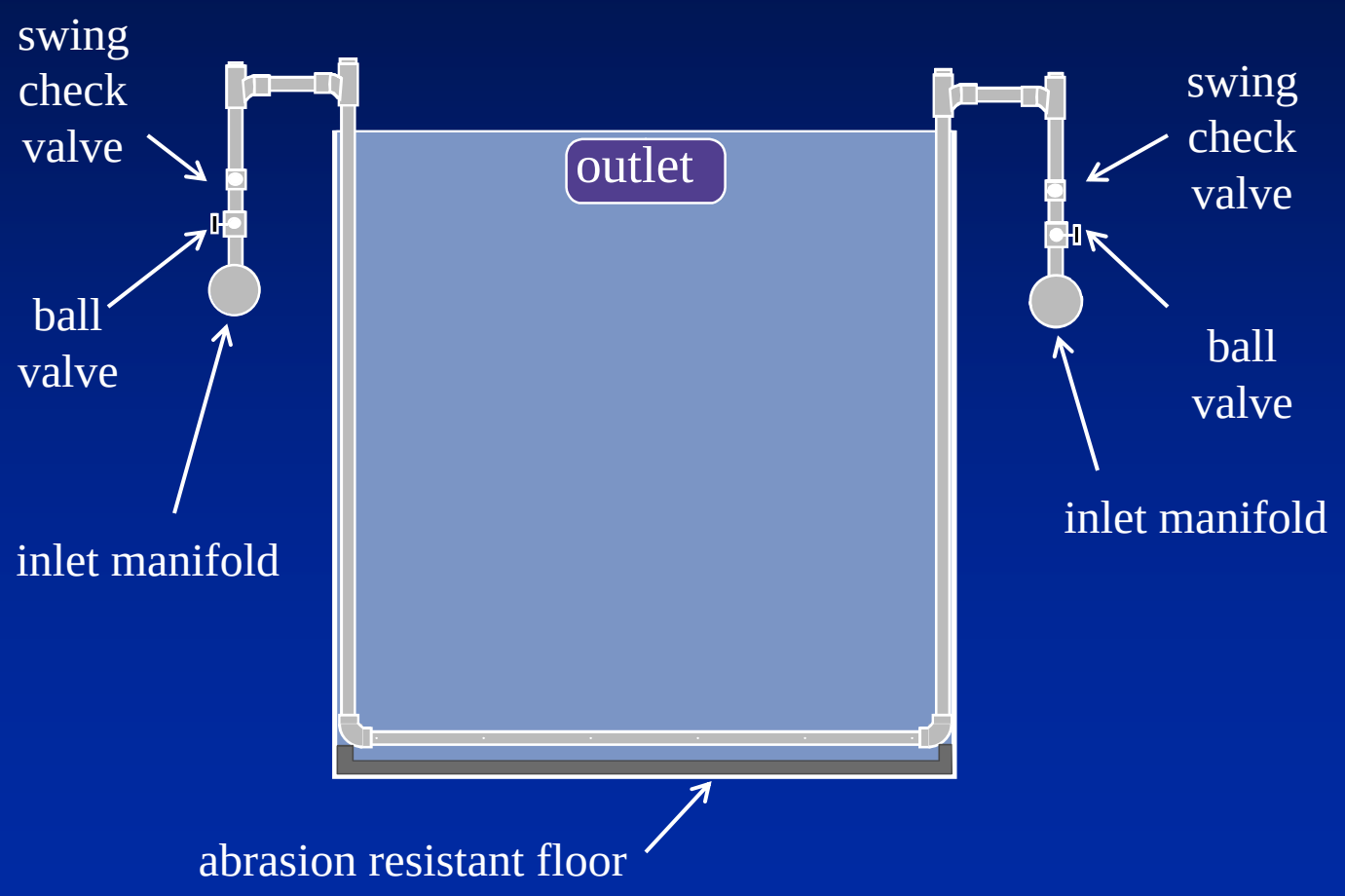




false-floor distribution plate

Pipe-Lateral Distribution

- Modified pipe-lateral distribution manifold.



Pipe-Lateral Distribution

- Modified pipe-lateral distribution manifold above abrasion resistant floor

Pipe-Lateral Distribution

- Example FSB in salmon smolt RASs at Marine Harvests Big Tree Creek Hatchery (BC)

(system designed by PRAqua Tech.)

Pipe-Lateral Distribution

- To create uniform flow distribution:
  - ✓ Pressure drop (ΔP) across orifice should be ≥ headloss through the sand bed (i.e., ≥ depth of static sand):

$$\Delta P_{orif} = \left[\frac{Q_{orif}}{C \cdot A_{orif}}\right]^2 \cdot \frac{1}{2 \cdot g}$$

Q_{orif} = flowrate in m^3/s
A_{orif}= orifice area in m^2
$C = 0.6$ and $g = 9.81\ m/s^2$

Cyclo Biofilter™

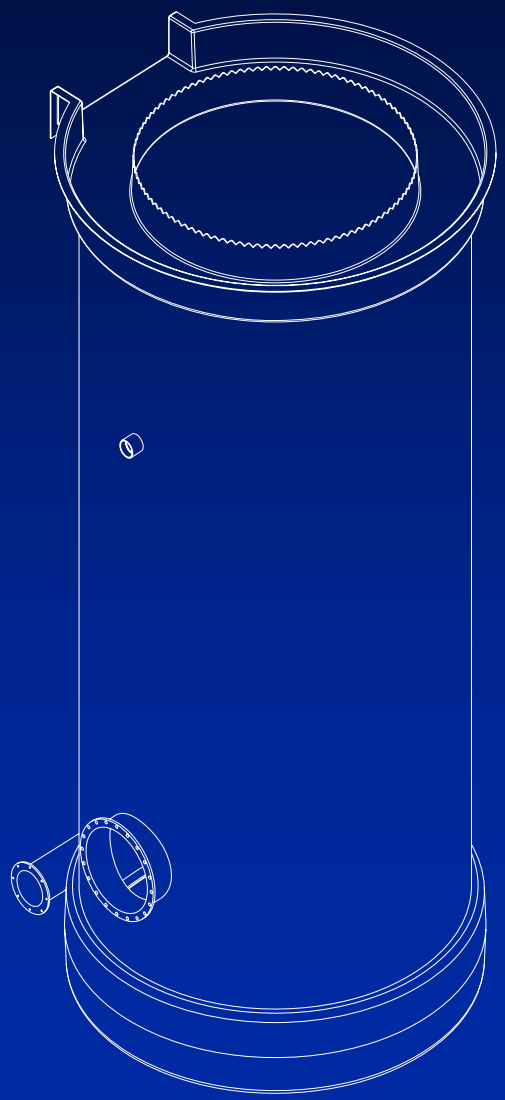
- Water injected tangentially into circular plenum and through slotted inlet about its base.
  - ✓Developed by Marine Biotech Inc. (Beverly, MA)

Cyclo Biofilter™

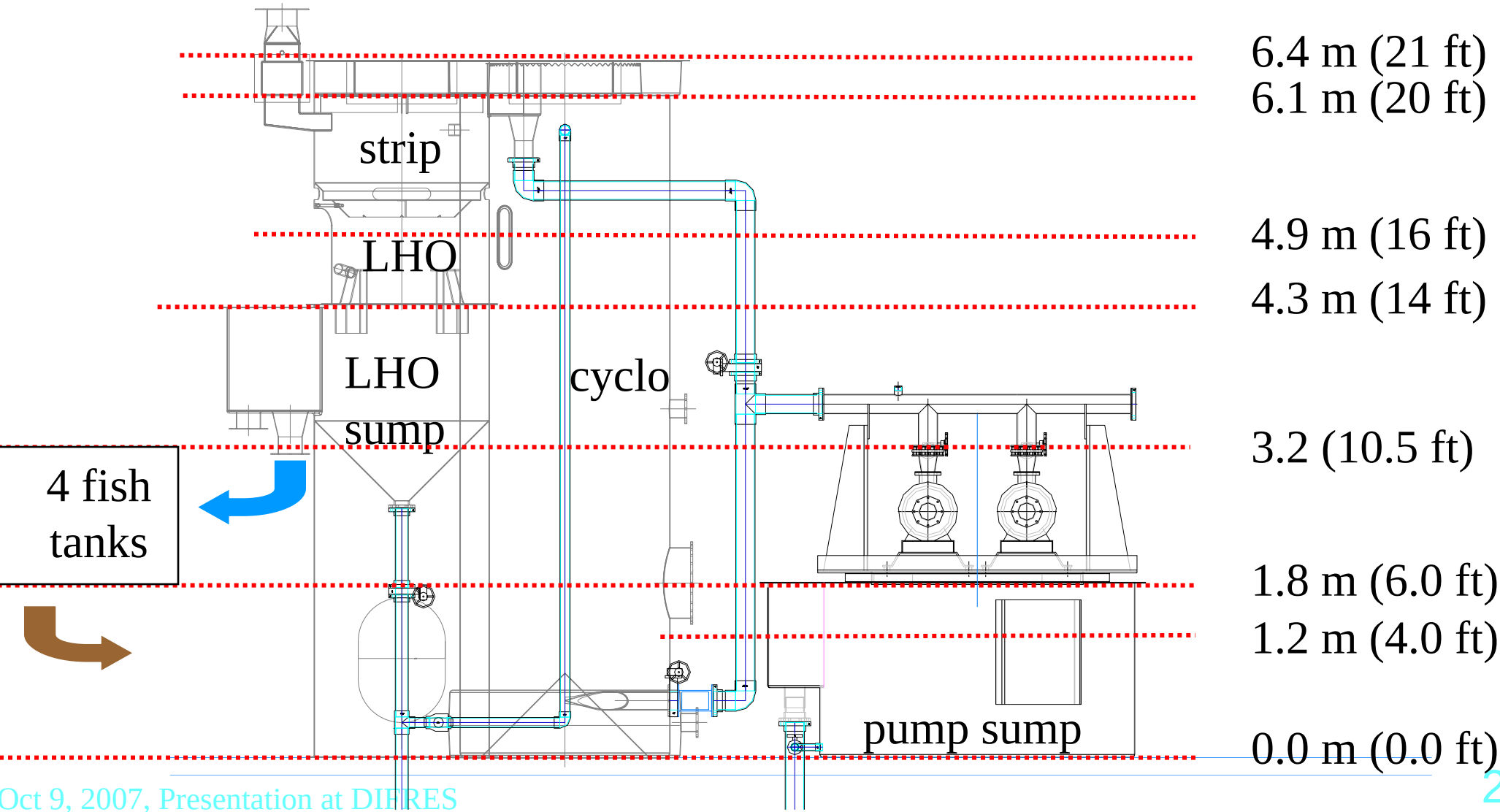
- USDA ARS National Cold Water Marine Aquaculture Center, Franklin, ME
  - ✓ compact trt system
    - 2.74 m dia x 6.4 m tall
  - ✓ 101 kg feed/day sustained capacity
    - lightly loaded
    - 5000 L/min RAS flow

Cyclobio FSB @ NCWMAC

- Height of Cyclobio was set at 6.4 m (21 ft) :
  - ✓ Elevation required to gravity flow
    - from top of cyclobio,
    - through CO2 stripper,
    - through LHO unit,
    - through LHO head tank,
    - through fish culture tanks,
    - through drum filter, and
    - back to pump sump



Process Elevations @ NCWMAC

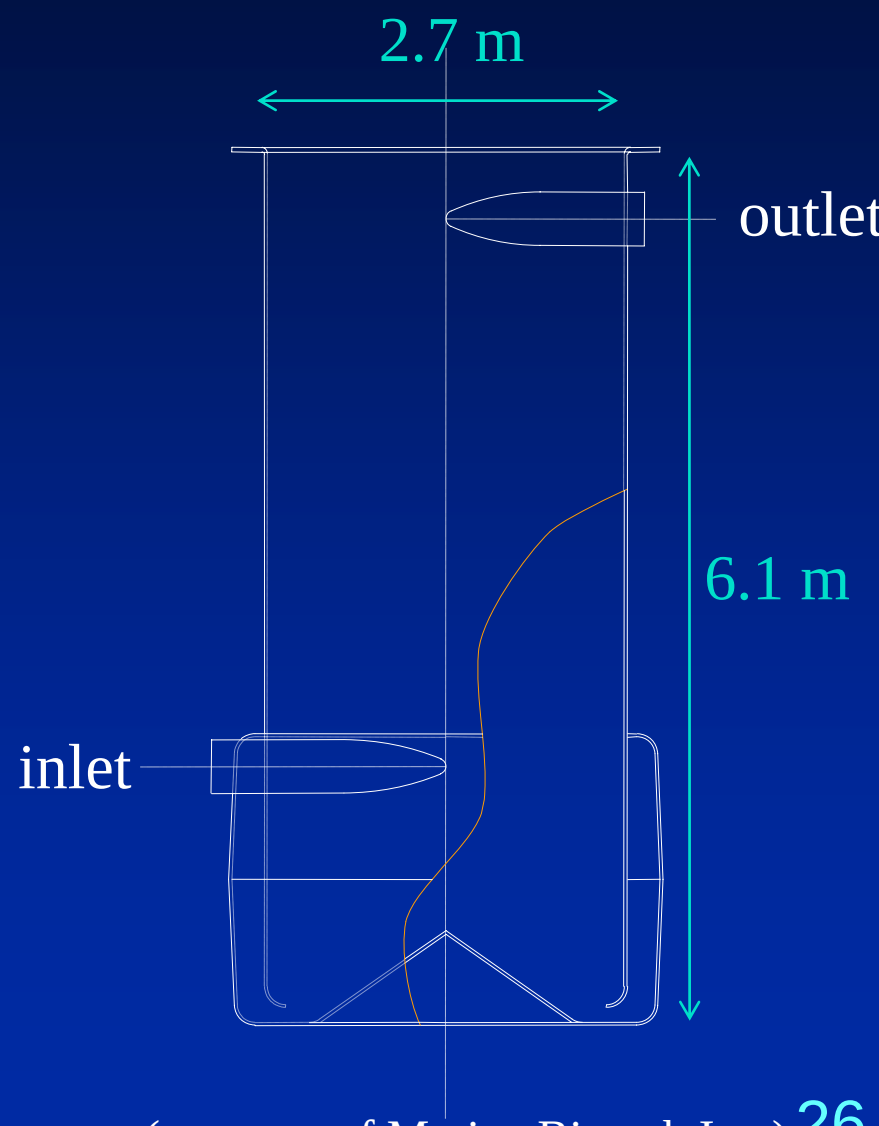


Cyclobio FSB @ NCWMAC

- Requirement to provide height > 2*Dia of cyclobio
  - ✓Static sand depth of 1.8-2.4 m (6-8 ft)
  - ✓Total expanded bed depth of 4.3-5.5 m (14-18 ft)
  - ✓Minimizes turbulence in bed of cyclobio
  - ✓Pump Total Dynamic Head of 7.6 m (25 ft)
    - Two 7.5 HP pumps
    - 5.0 m^3/min RAS Flow

Cyclobio FSB @ Freshwater Inst.

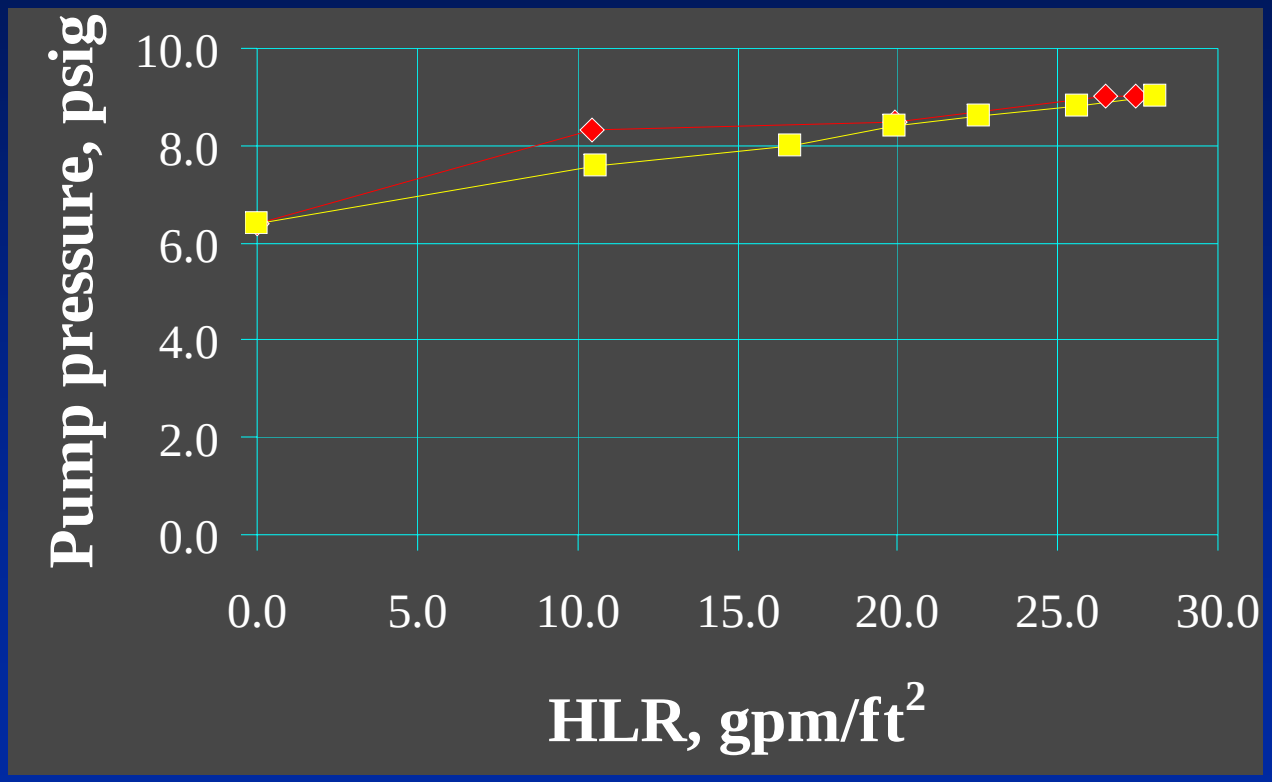
- Dimensions:
  - ✓ 2.7 m (9 ft) dia
  - ✓ 6.1 m (20 ft) tall
- Static sand capacity:
  - ✓ 1.5 m (5 ft) depth
  - ✓ 8.5 m^3 (300 ft^3) volume
  - ✓ assimilates TAN from 160 kg feed/day
  - ✓ $1000-1500 for sand
- 4700 L/min RAS flow
  - ✓ Two 5-HP pumps

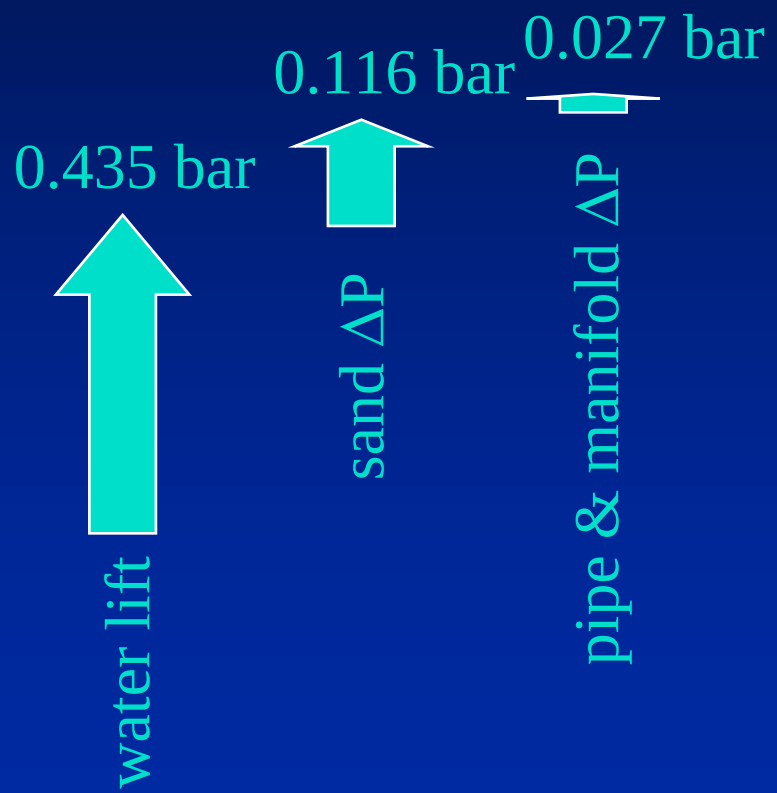


(courtesy of Marine Biotech Inc.)

Cyclo Biofilter™

- Pressure drop across the piping, sand, & cyclo bio





(Summerfelt et al., 2004)

(1 cm/s = 14.7 gpm/ft2)

Cyclo Biofilter™ Advantage

- Cyclo Bio requires less pressure to operate.
  - ✓ 0.1-0.3 bar (2-4 psig) less pressure was required to operate a cyclo bio compared to a modified-pipe manifold FSB.
    - assuming a similar fluidized-sand biofilter height.
  - ✓ CycloBio has lower ΔP of piping and inlet orifice

Cyclo Biofilter™

- Effluent collection launder

To stripping column

Sand Selection Guidelines

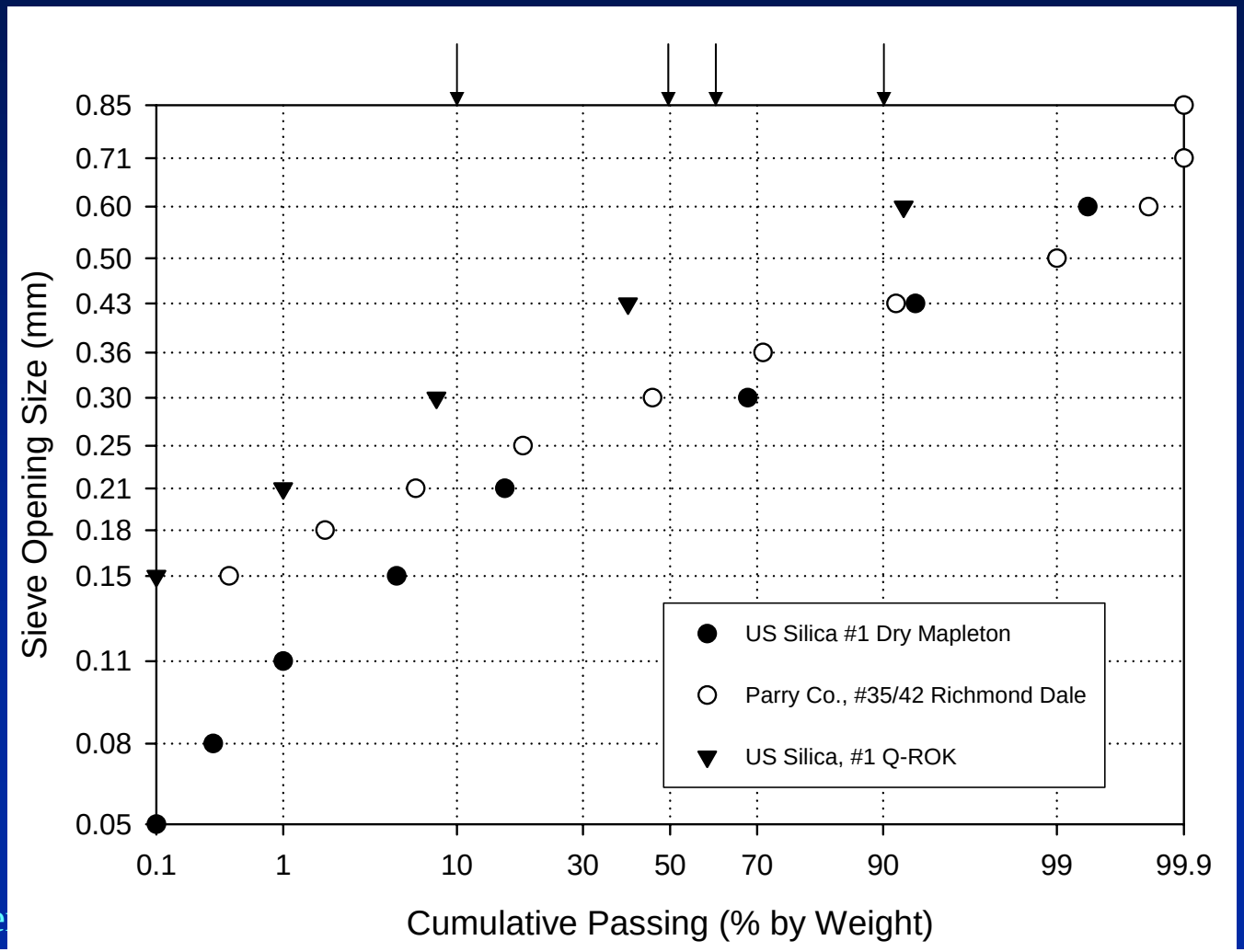
- Purchase silica filter sand from supplier listed by American Water Works Association Sourcebook (AWWA)

Sand Selection Guidelines

- Filter sand is characterized by a sieve analysis
  - ✓ Effective size (D_{10}) is size where 10% of sand is finer
  - ✓ Also need to estimate D_{50}, D_{60}, and D_{90}
    - D_{50} is mean size of sand
    - D_{90} is largest 10% of sand, which must expand at design velocity
  - ✓ Sand uniformity coefficient, $UC = D_{60}/D_{10}$
- Sieve analysis is plotted on log-probability axis.

Sand Selection Guidelines

- Determine D_{10}, D_{50}, D_{60}, D_{90}, and UC from sieve analysis



Characterizing Sand: D_{10}

- The "*effective size*" (D_{10}) is defined as the opening size which will pass only the smallest 10%, by weight, of the granular sample.
- D_{10} provides an estimate of the smallest sand in the sample and is the size used to estimate the maximum expansion at a given superficial velocity.

Characterizing Sand: D_{90}

- D_{90} provides an estimate of the largest sand in the sample and is the size to estimate the minimum expansion at a given velocity.
- D_{90} can be estimated from the D_{10} and the UC:

$$D_{90} = D_{10} \cdot \left(10^{1.67 \cdot \log(UC)}\right)$$

Characterizing Sand: D_{50}

- The "*mean size*" (D_{50}) is the sieve size for which approximately 50% of the grains by weight are smaller.
- D_{50} provides an estimate of the average size of the sand in the sample and is the value used during design to estimate the average bed expansion at a given superficial velocity:

$$D_{50} = D_{10} \cdot \left(10^{0.83 \cdot \log(UC)}\right)$$

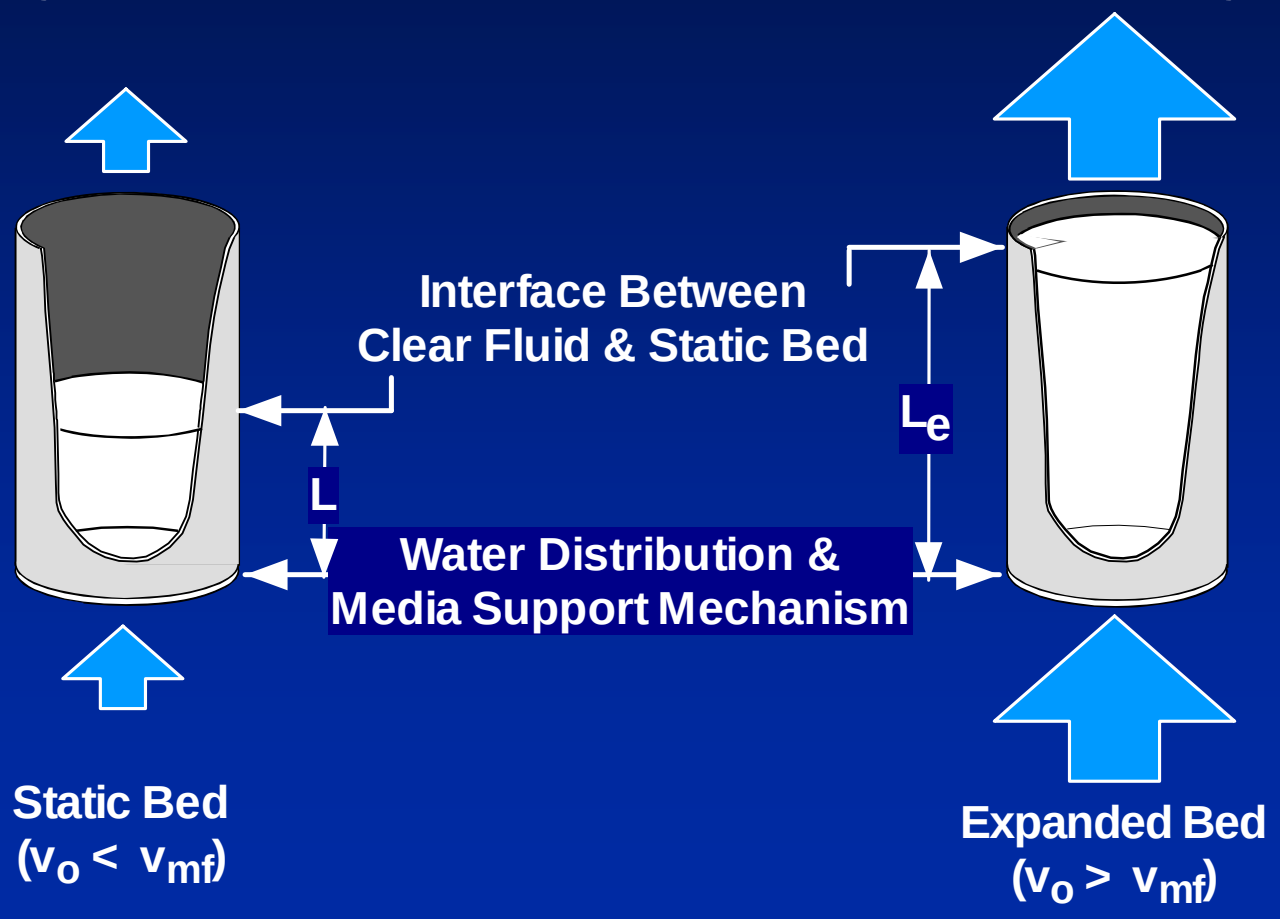
Characterizing Sand: S_b

- The "*bed specific surface area*" is the specific surface area available per unit of bed volume (S_b); this can can be estimated using estimates for the static bed void fraction ($\varepsilon \approx 0.45$) and sand sphericity ($\Psi \approx 0.75$):

$$S_b = \frac{6 \cdot (1 - \varepsilon)}{\Psi \cdot D_{50}}$$

Calculating Bed Expansion

- Buoyant force of rising water lifts sand bed when velocity exceeds minimum fluidization velocity (v_{mf}).



Calculating Bed Expansion

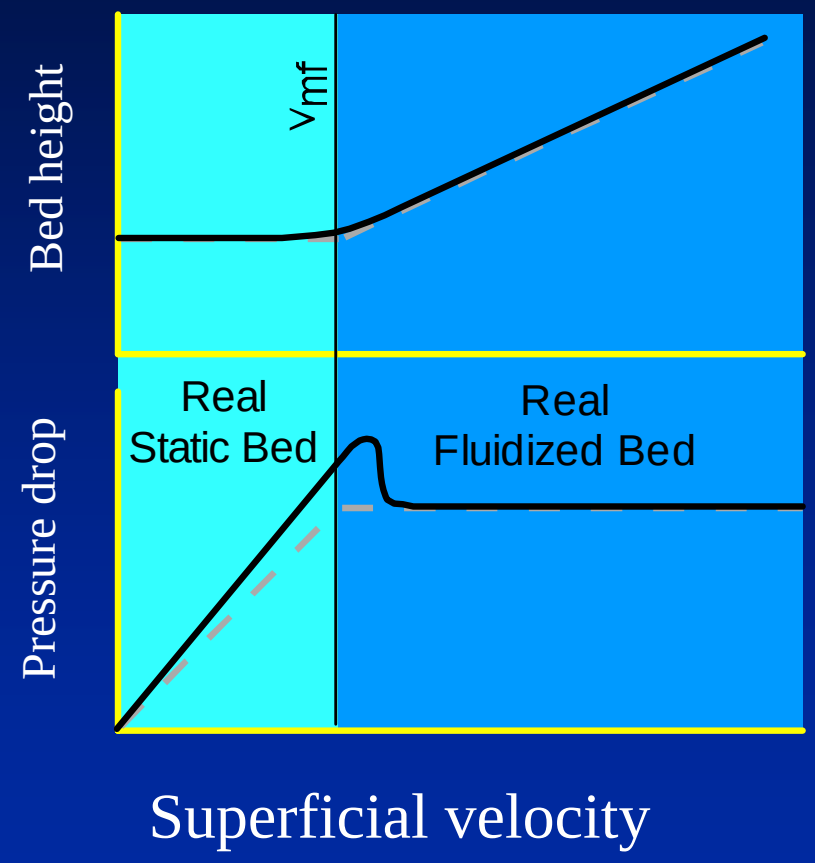
- Bed expansion terminology:
  - ✓ 50% expansion , e.g., 1 m of static sand depth expands to 1.5 m
  - ✓ 100% expansion , e.g., 1 m of static sand depth expands to 2.0 m
  - ✓ 200% expansion , e.g., 1 m of static sand depth expands to 3.0 m

Calculating Pressure Drop

- Pressure drop across a sand bed
  - ✓ increases according to Ergun's equation until bed begins to expand.
  - ✓ remains constant at all water velocities after the expansion begins.
  - ✓ remains constant for all sand sizes,
    - 1 m of static sand requires about 1 m of water head to expand.

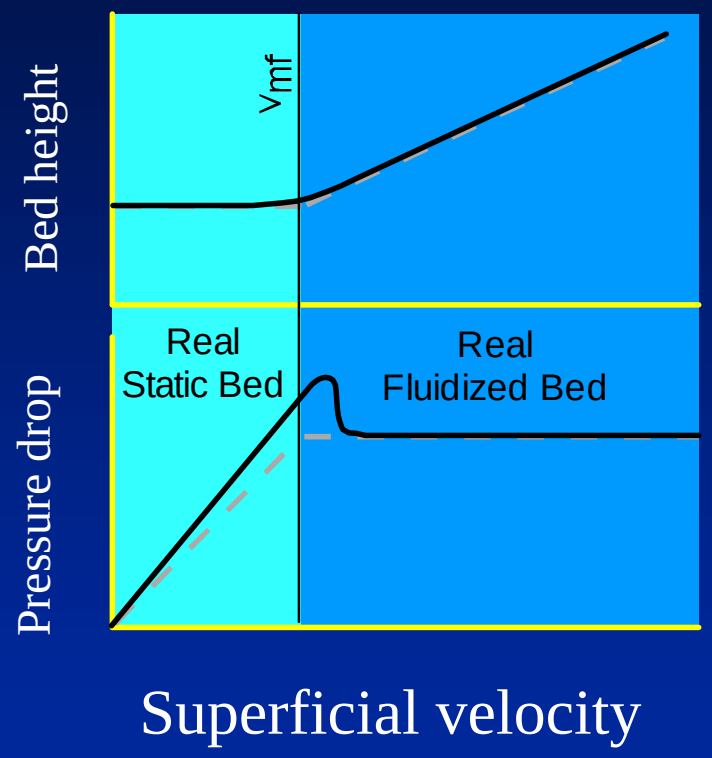
$$\frac{h}{L} = \left(SG_p - SG_w\right)\cdot\left(1-\varepsilon\right)$$

- see Summerfelt and Cleasby (1996)



Calculating Bed Expansion

- Estimate bed expansion for a given sand as a function of water velocity, using:
  - ✓ water viscosity and density
  - ✓ sand size, sphericity
  - ✓ void space of the loose static bed
- see Dharmarajah and Cleasby (1986)

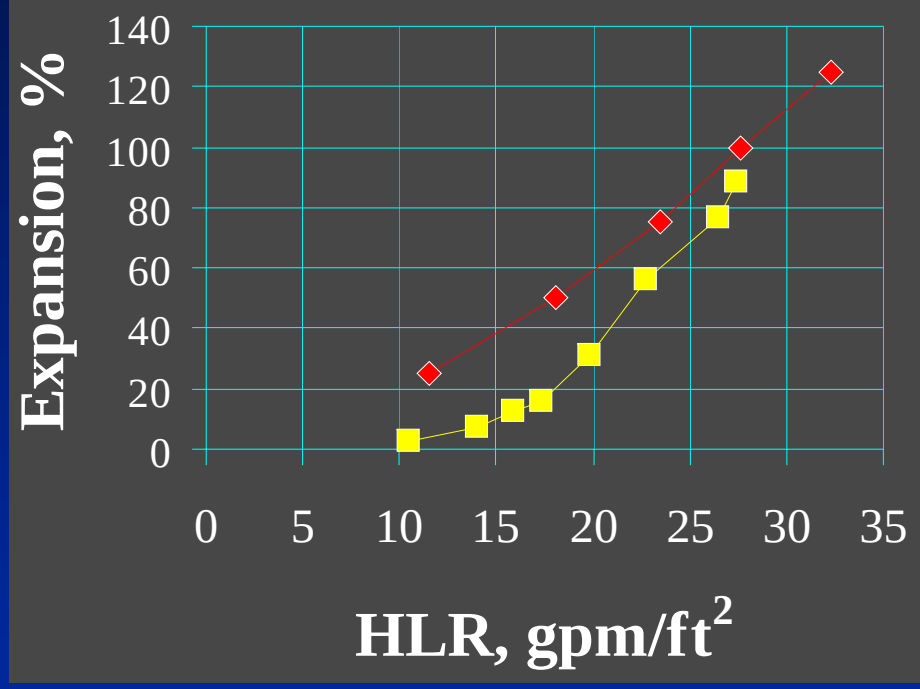


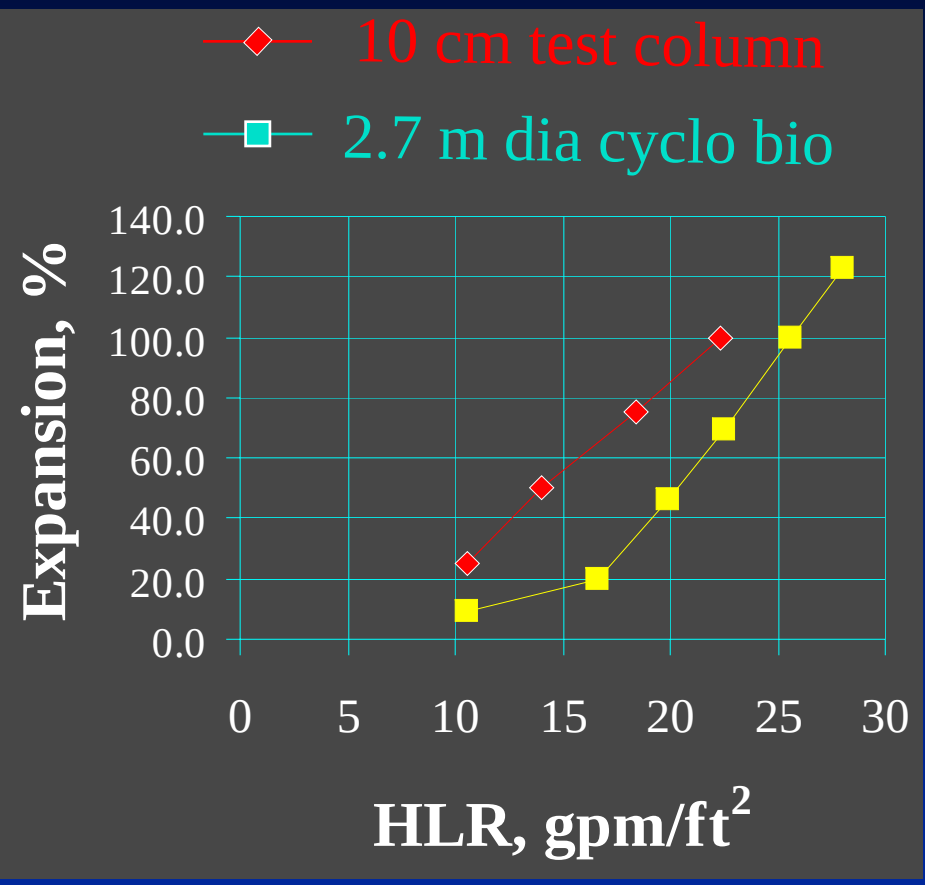
Experimental Measurement of Sand Expansion

- Filter sand sample should be obtained & tested in a 10-cm dia column
  - ✓ validate relationship between sand bed expansion and superficial water velocity
  - ✓ conduct this test before completing design of FSB

Bed Expansion in Test Columns vs. Full-Scale FSBs

- Sand Expansion Tests



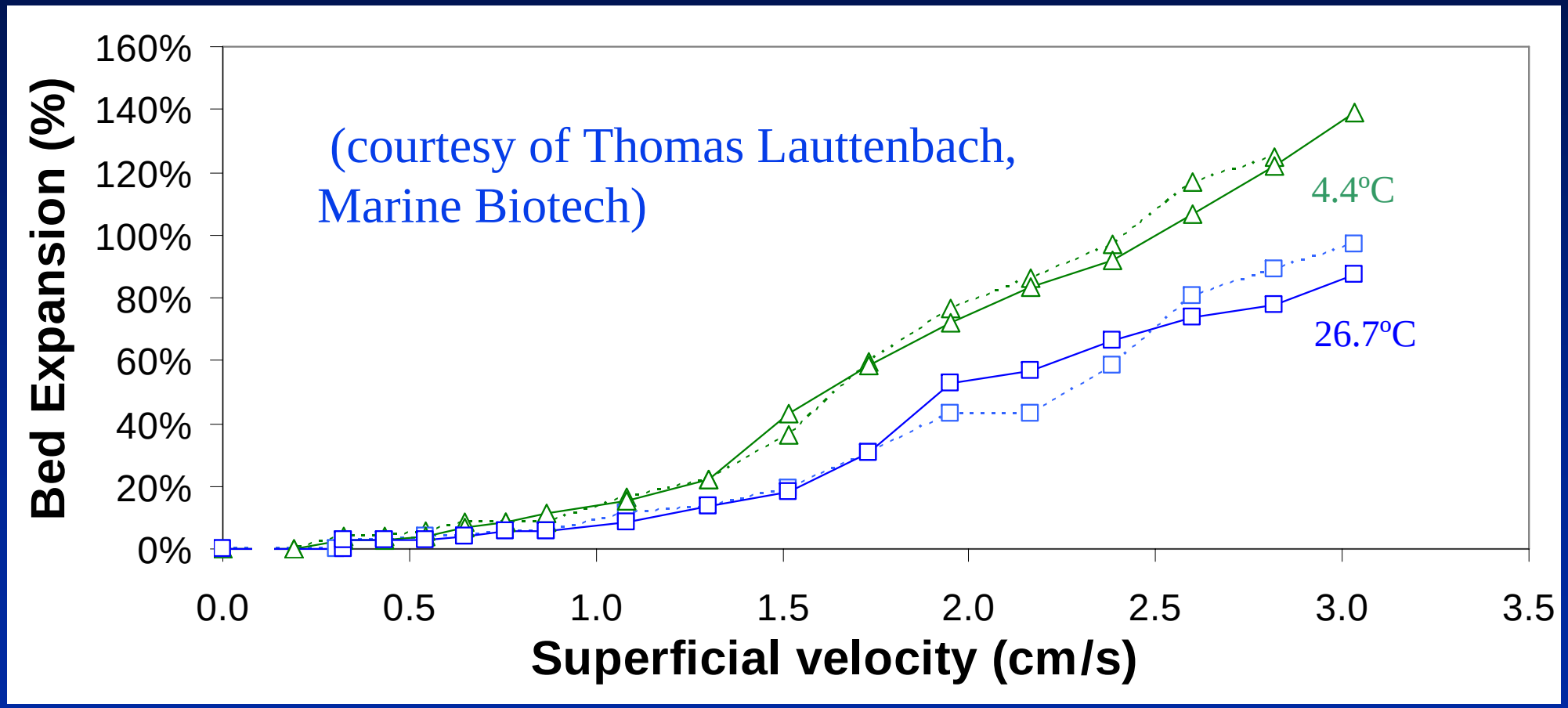


US Silica sand
D_{10} = 0.275 mm

Parry Company sand
D_{10} = 0.23 mm

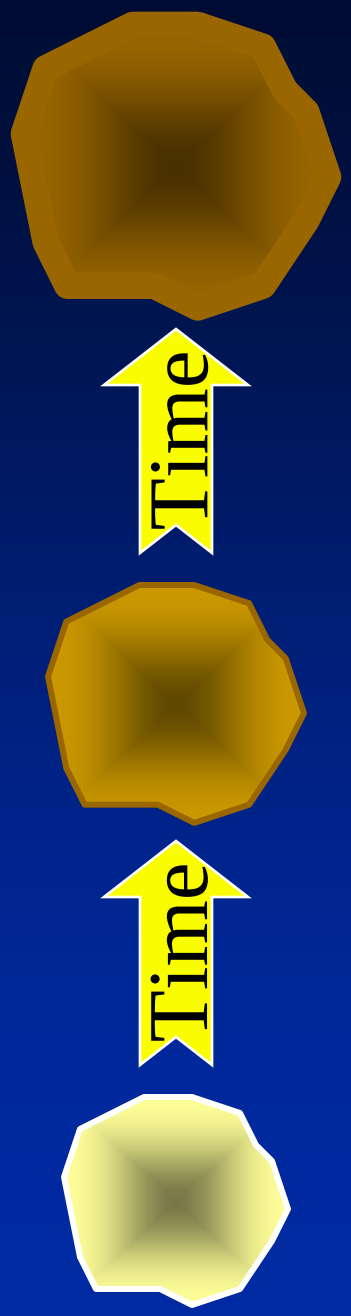
Bed Expansion

- Seawater vs freshwater at 4.4ºC and 26.7ºC



Biofilm in Fine Sand Biofilters

- biofilms grow on the expanded sand

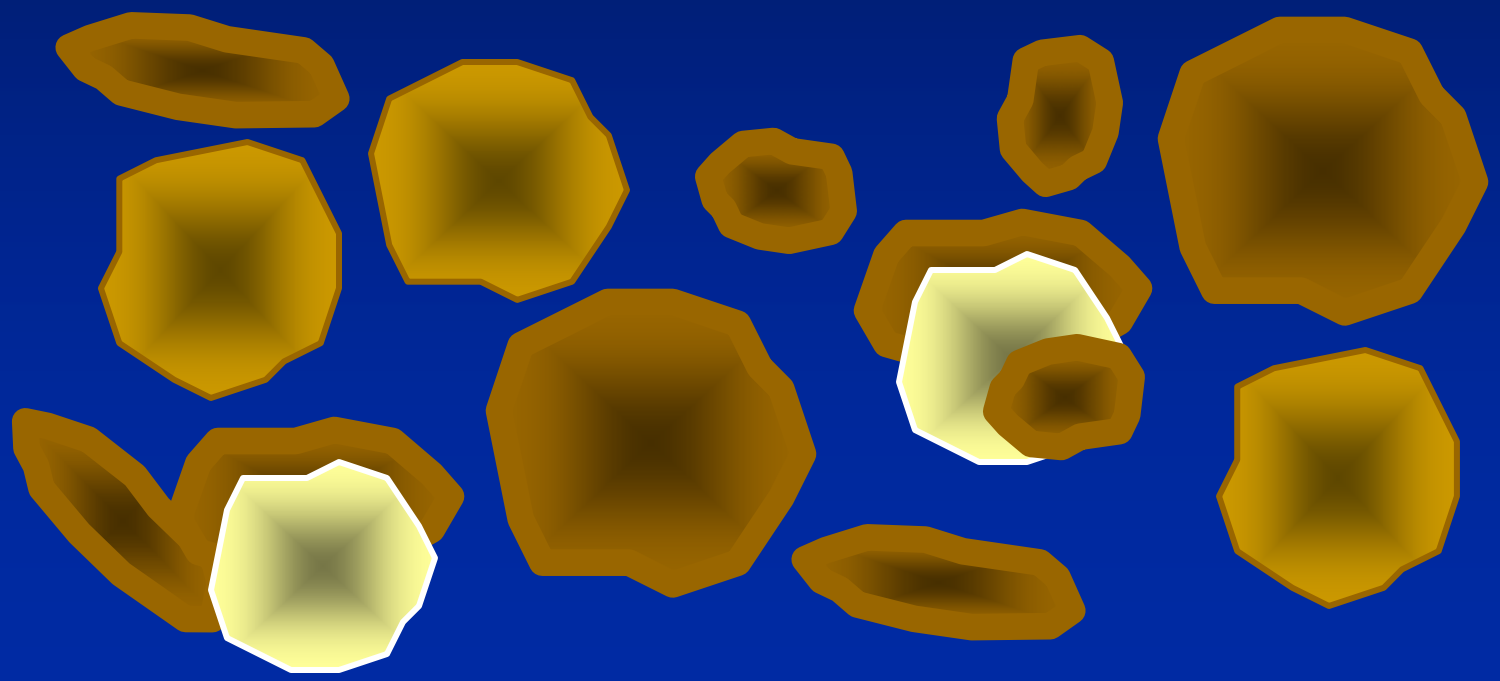


Biofilm Development in Fine Sand Biofilters

- biofilms thicken with time:
  - ✓ decreasing particle density,
  - ✓ increasing bed expansion,
  - ✓ migrating to top of bed.

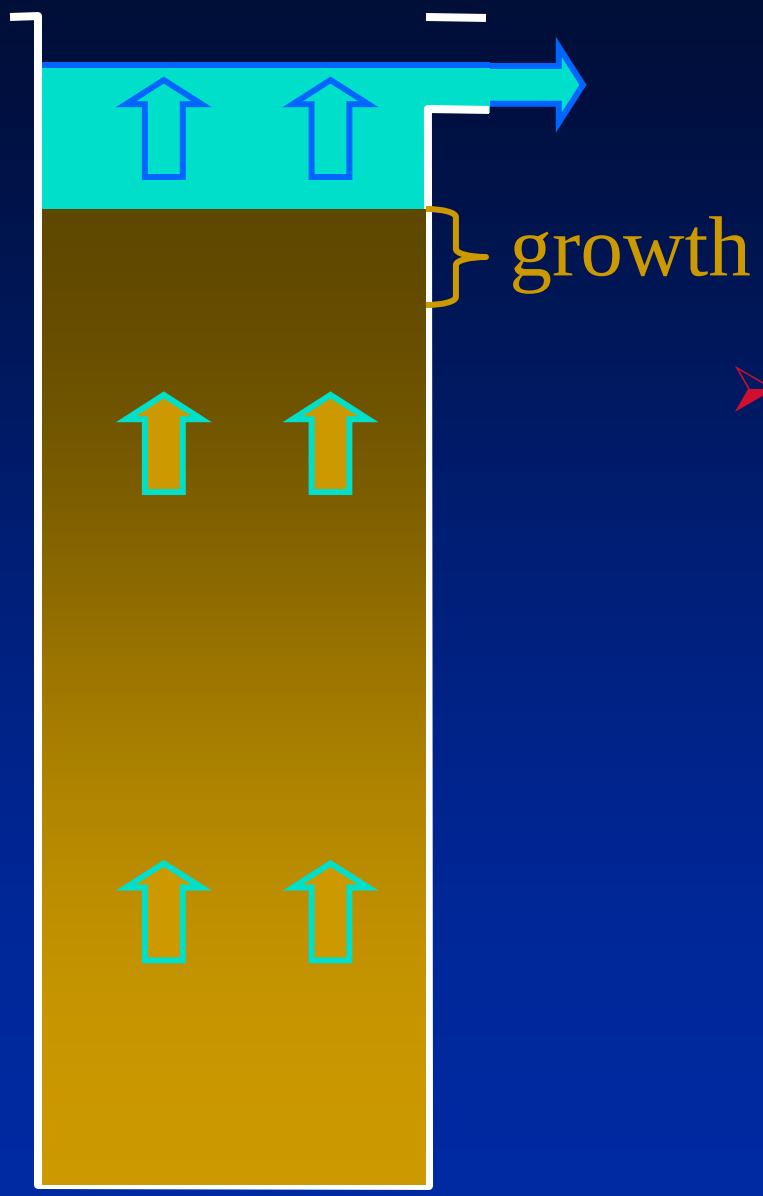
Biofilm in Fine Sand Biofilters

- Water velocities (0.7-1.4 cm/s) do not flush larger sheared pieces from the bed;
  - ✓ such pieces accumulate & continue to grow.



Vertical Stratification

- The beds are vertically stratified in:
  - ✓ sand size
  - ✓ bed expansion
  - ✓ biofilm thickness and biofloc size
  - ✓ nitrification rate



Fine Sand Biofilters

- Biofilter bed depth increases with time (about 8 cm/wk @ FI):
  - ✓bio-particles accumulate;
  - ✓bed expansion increases,
    - as thickening biofilm reduces particle densities.

TAN Removal Rate & Efficiency

- Warm-water & cold-water FSB applications:

	g TAN removed per day		TAN Removal Efficiency
	per m^2 surface area	per m^3 expand bed volume	
COLD-WATER BIOFILTER fine sand, ~11,500 m^2/m^3 D_{10} = 0.18-0.24 mm	0.06	170	70-90%
WARM-WATER BIOFILTER coarse sand, ~5,000 m^2/m^3 D_{10} = 0.5-0.7 mm	0.2	600-1000	10-30%

Nitrification in Coldwater Applications

- Fine sands (D_{10} = 0.18-0.24 mm) are used:
  - ✓ controls nitrite-nitrogen at very low levels
    - generally < 0.1-0.2 mg/L
  - ✓ produce higher TAN removal efficiencies
    - 80-95% TAN removal each pass
  - ✓ provide excess nitrification capacity
    - 200% excess can be achieved

Tank Water Quality in 6 Replicate Trout RAS with out Ozone

Parameters	**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

Results: Biofilter Nitrification

- #1 Mapleton Sand, D_{10}=0.19 mm
- 2,700 L/min flow through CycloBio (60% of total)

	6.4% Makeup DOC = 2.7 mg/L		1.1% Makeup DOC = 7.4 mg/L	
	TAN (mg/L)	NO_2-N (mg/L)	TAN (mg/L)	NO_2-N (mg/L)
Biofilter inlet	1.18 ± 0.04	0.06 ± 0.00	1.49 ± 0.04	0.28 ± 0.03
Biofilter outlet	0.09 ± 0.01	0.02 ± 0.00	0.25 ± 0.01	0.25 ± 0.07
Change	-1.09 ± 0.10		-1.24 ± 0.03	
Removal Eff.	92%		83%	

Results: Biofilter Respiration

- #1 Mapleton Sand, D_{10}=0.18 mm
- 2,700 L/min flow through CycloBio (60% of total)

	6.4% Makeup DOC = 2.7 mg/L		1.1% Makeup DOC = 7.4 mg/L	
	CO_2 (mg/L)	O_2 (mg/L)	CO_2 (mg/L)	O_2 (mg/L)
Biofilter inlet	20 ± 2	10.9 ± 0.4	25 ± 0	9.4 ± 0.1
Biofilter outlet	28 ± 2	4.6 ± 0.1	28.5 ± 2	2.5 ± 0.0
Change	8 ± 1	-6.4 ± 0.3	4 ± 1	-6.9 ± 0.3

CBOD Removal in FSB's Treating Intensive Fish Farm Effluent

Sand D_{10} (mm)	**Bed Management**	**Inlet CBOD (mg/L)**	**Outlet CBOD (mg/L)**	**CBOD Removal Efficiency (%)**
0.11	siphon	**11.5 ± 2.7**	**4.1 ± 1.0**	**64**
0.11	siphon	**11.0 ± 2.6**	**4.2 ± 1.3**	**62**
0.19	siphon	**8.7 ± 2.3**	**3.4 ± 1.2**	**60**
0.11	shear	**6.8 ± 1.0**	**1.2 ± 0.3**	**82**
0.11	shear	**6.7 ± 1.1**	**1.5 ± 0.4**	**77**
0.19	shear	**7.1 ± 1.2**	**2.4 ± 0.5**	**66**

TAN Removal in FSB's Treating Intensive Fish Farm Effluent

Sand D_{10} (mm)	Bed Management	Inlet TAN (mg/L)	Outlet TAN (mg/L)	TAN Removal (%)	Outlet Nitrite (mg/L)
0.11	siphon	1.01 ± 0.16	0.37 ± 0.10	63	0.17 ± 0.02
0.11	siphon	0.99 ± 0.13	0.38 ± 0.11	62	0.17 ± 0.02
0.19	siphon	0.94 ± 0.14	0.66 ± 0.11	30	0.20 ± 0.04
0.11	shear	0.83 ± 0.06	0.10 ± 0.04	88	0.07 ± 0.02
0.11	shear	0.82 ± 0.06	0.11 ± 0.04	87	0.09 ± 0.02
0.19	shear	0.81 ± 0.06	0.11 ± 0.04	86	0.15 ± 0.03

Total Coliform Removal in FSB Treating Intensive Fish Farm Effluent

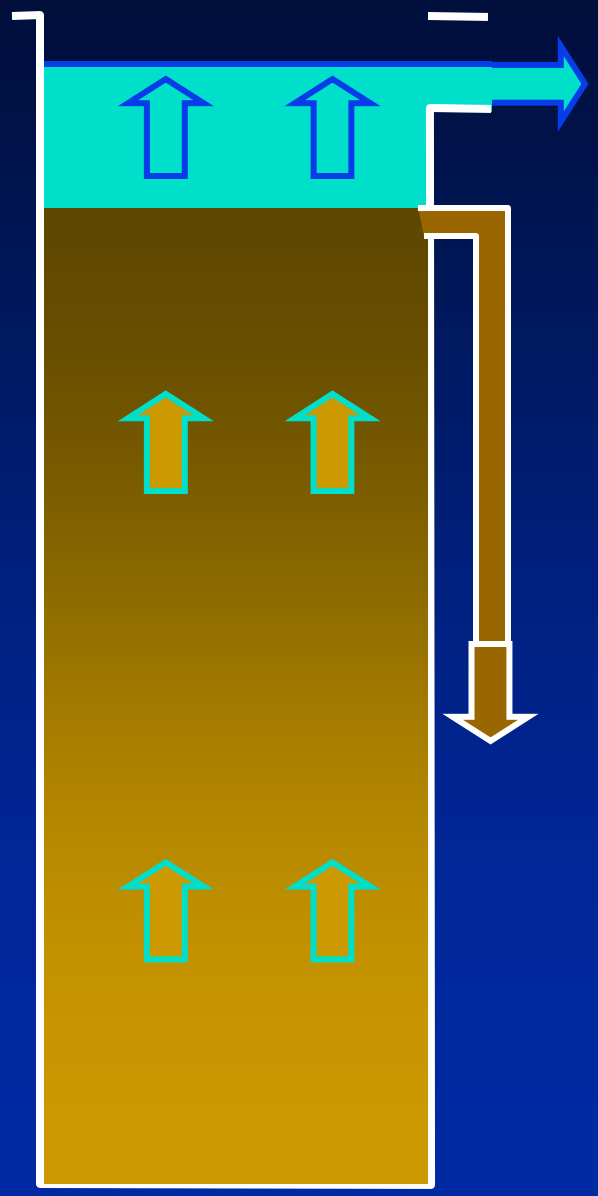
Sand D_{10} (mm)	Bed Management	Inlet Total Coliform (counts/100 mL)	Outlet Total Coliform (counts/100mL)	Total Coliform Removal Efficiency (%)
0.11	shear	4.7×10^5	1.3×10^4	97
0.11	shear	4.2×10^5	6.5×10^3	98
0.19	shear	1.8×10^5	1.1×10^4	94

O_2 demand due to Nitrification

- Approximately 60% of O_2 consumed across FSB goes towards nitrification;
- Every 1 mg/L of TAN removed requires approximately 7.7 mg/L (= 4.6 mg/L DO ÷ 0.6) of dissolved O_2
- O_2 limitations can become a problem when the desired removal of TAN is high
  - i.e., ≥ 1.2 mg/L of TAN removed per pass

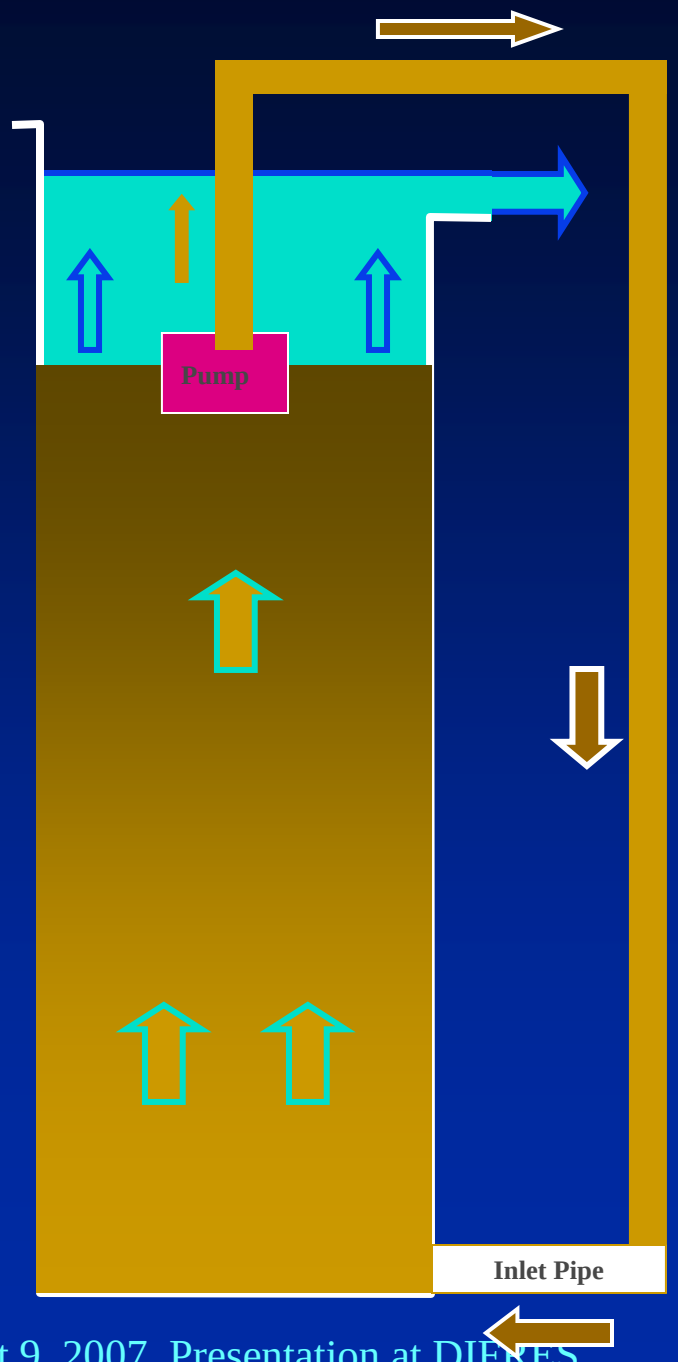
Managing Bed Growth

- Siphon biosolids bed as needed to prevent them from overtopping biofilter.



Managing Bed Growth

- Siphon biosolids from the bed:
  - ✓ maintain a maximum bed depth;
  - ✓ remove biosolids from the top,
    - removes thickest and oldest biofilm;
  - ✓ also remove some sand,
    - lost sand must be replaced on occasion.



Managing Bed Growth

- Biofilm Shearing with Pump
  - Top of bed pumped back into inlet.
  - Creates shearing effect on biofilm
  - Sand bed maintains constant height
  - Minimal sand loss

Management Practices: Water Flow

- To maintain proper bed expansion, a FSB must operate within a fairly narrow water flow range,
  - ✓ i.e., within about ± 10-30% of its design flow.
- Water flow cannot cease for more than approximately 6-24 hrs, to prevent anaerobic conditions and resulting loss in the nitrification capacity of the FSB.

Management Practices: Prevent Air Bubbles

- Prevent air bubbles from being pumped into fluidized-sand biofilters. Bubbles washout sand!

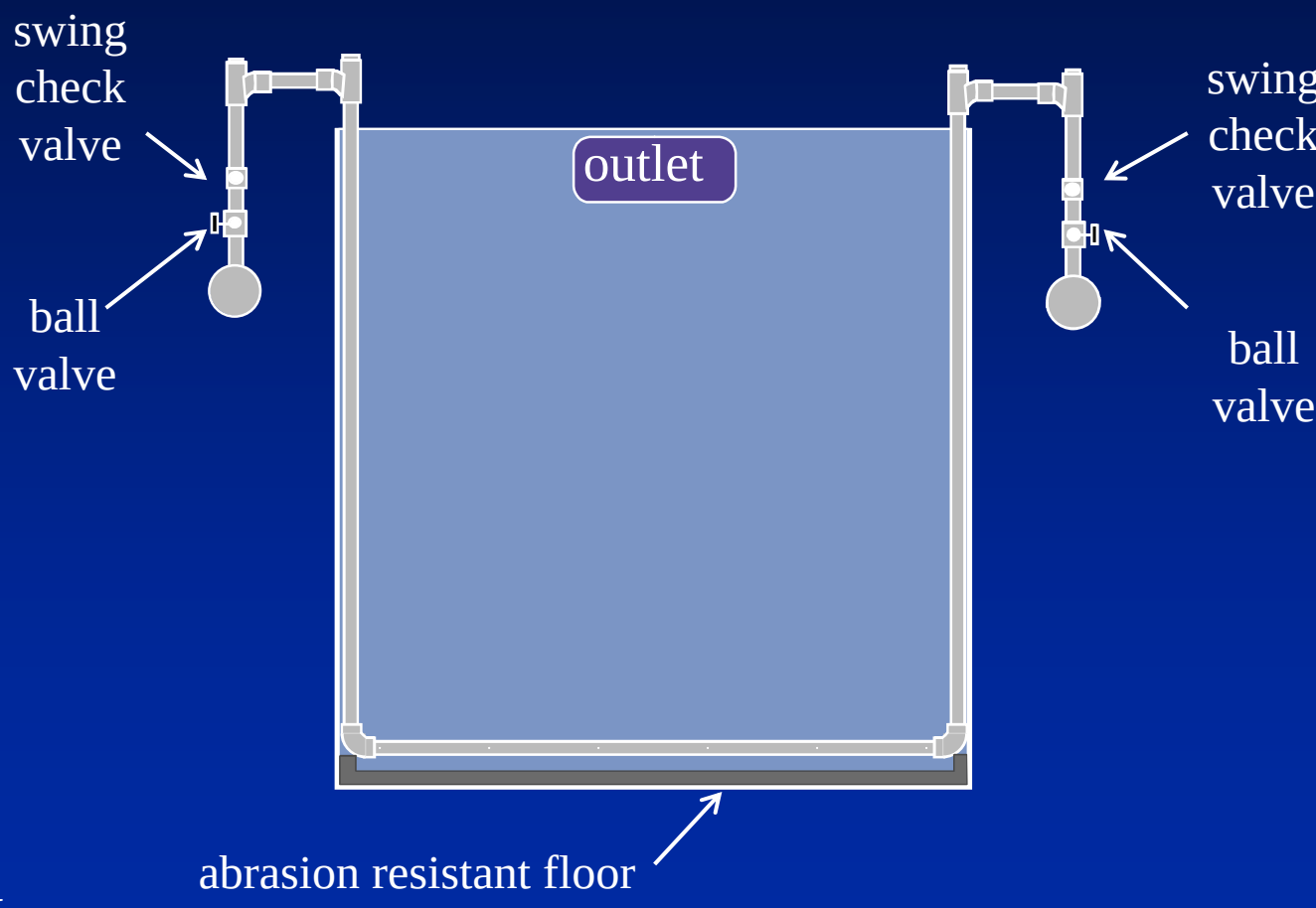
Bubbles from leaky pipe fittings or entrained air at pump intake.

Management Practices: Clean Outs

- Clean-outs must be provided to remove debris that could plug the flow distribution manifold.

Practical Considerations: Check Valves

- Reliable swing check valves (or foot valves) are critical to prevent backflow!



swing-flex foot valves @ FI

Practical Considerations: Sand Blasting

- Installation of an abrasion resistant floor is critical.

Practical Considerations: Installing New Sand

- Load sand pneumatically (14 m^3 in 2-3 hrs)
- Wash fine clay found in new sand out of system before recirculating water to fish.

Applications of FSB's

- Used widely in N. America for salmonid RAS.
  - ✓ some in Chile.

Nutreco's Big Tree Creek Hatchery (BC)

- Fluidized-sand biofilters used in many salmonid RAS's.
  - ✓Remove TAN & cBOD efficiently & do not generate NO_2,
  - ✓Low cost, compact, and robust.

(designed by PRAqua Tech

Nutreco's Big Tree Creek Hatchery (BC)

- Three recirc systems (~12 m^3/min/system) for chinook salmon smolt production.

(designed by PRAqua Techn.)

Nutreco's Big Tree Creek Hatchery (BC)

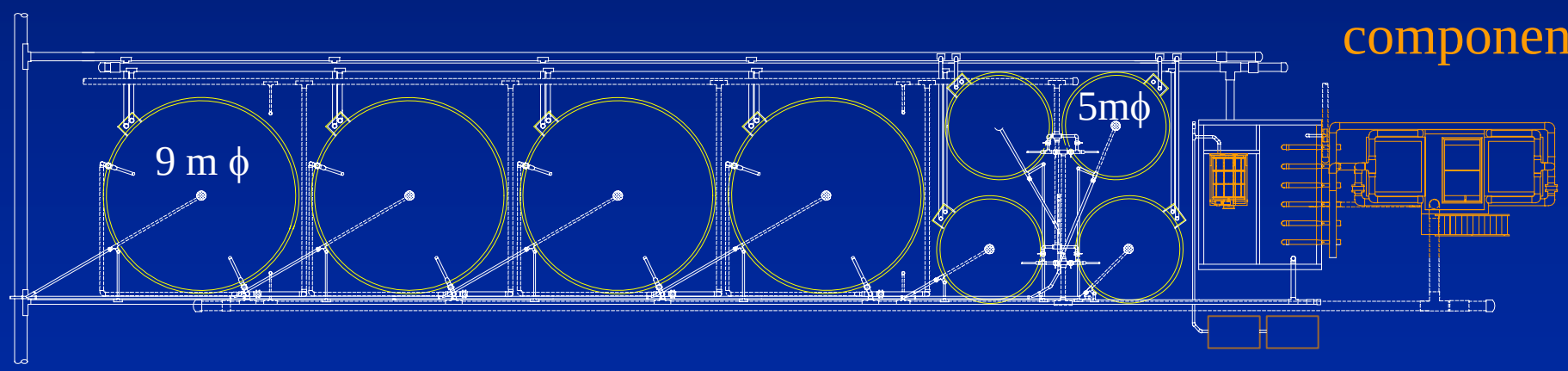
- Chinook salmon fry RAS (~4,000 L/min)

Target Marine Hatcheries

- Two recirc modules for coho salmon smolt production (Sechelt, BC)

Target Marine Hatcheries

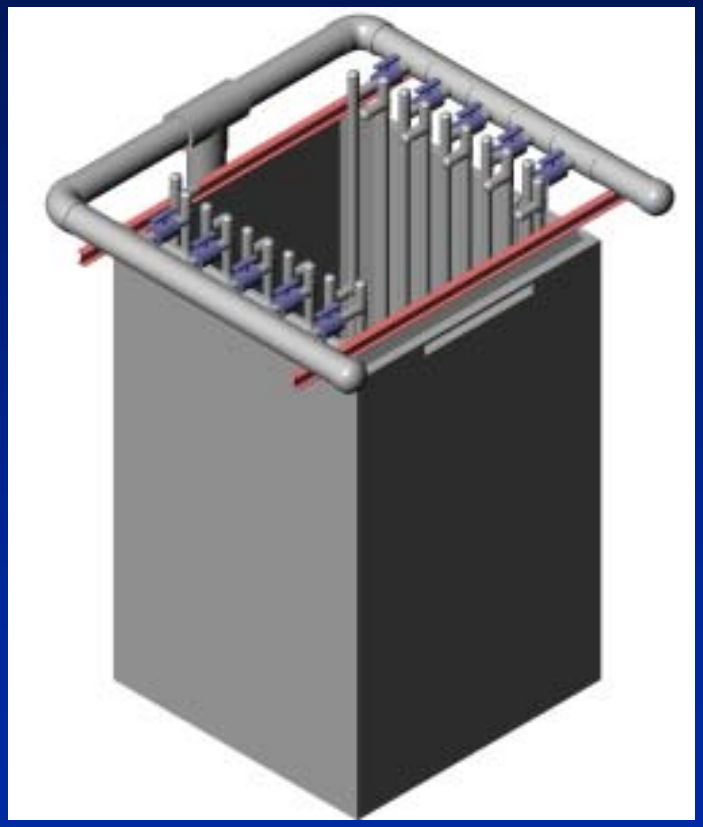
- Compact layout of a RAS module.



(designed by PRAqua Technologies)

Target Marine Hatchery (BC)

- Salmon smolt



(systemdesigned by PRAqua Tech.) Courtesy of PRAqua Technologies (BC)

Target Marine Hatcheries (BC)

- Salmon smolt

(system designed by PRAqua Tech.)

USDA ARS, Franklin, ME

- Temporary 1200 L/min RAS for Atlantic salmon fry,
  - ✓ used for 3 yrs before new facility was ready
- 7 new RAS's for broodstock development program.

Penobscot Smolt Hatchery

- Currently *Center for Cooperative Aquaculture Research* (Franklin, ME)

(Designed by Eric Swanson)

Oak Bay Hatchery, Cooke Aquaculture (NB)

- Atlantic salmon smolt
- Distribution through false floor

(Swanson-type design)

WV Aqua (West Virginia)

- Arctic char grow-out farm
  - ✓12 m^3/min in each of three RAS

(system designed by PRAqua Tech.)

CONCLUSIONS

- Fine sand fluidized biofilters are used in many large-scale recycle systems, because they:
  - ✓ can be scaled to treat flows > 10,000 L/min
  - ✓ provide high TAN removal efficiencies
  - ✓ maintain low nitrite-nitrogen levels
  - ✓ are compact
  - ✓ are capital cost efficient
    - high specific surface areas (4,000-45,000 m^2/m^3)
    - low media cost ($40-70/$m^3$ of sand)
  - ✓ are reliable if well designed, non-plugging.

CONCLUSIONS

- Disadvantages:
  - ✓ design not well understood until recently
  - ✓ moderate operating pressure (0.34-0.68 bar; 5-10 psig)
    - elevation at top of biofilter usually designed to provide gravity flow back through remaining treatment processes
  - ✓ must be operated at +/- 20% of design flow
  - ✓ cannot be shut-down for ~ 6 hrs w/o losing nitrification
  - ✓ biofilm on the sand may require management

Thank you for your attention!