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Chapter 11

Engineering Design of a Water Reuse System

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Introduction

Recirculating aquaculture systems are a type of flowing water (intensive) fish culture technology in which a high percentage of the water is reused after treatment. The recirculating system consists of interacting unit processes that form a complex whole. Such a system implies an organized set of complementary parts. A deficiency in one component, e.g., the clarifier, will affect performance of the other components and the entire system.

Water quality criteria required to maintain a healthy and fast growing fish (Table 1) are the basis for designing water reuse processes for closed-systems. The parameters of primary concern are dissolved ammonia, nitrite, oxygen, carbon dioxide, nitrogen and solids. These parameters are important because their production or reduction (Table 2) can lead to concentrations that affect fish growth and health. Further, it is not only the individual components, but the aggregate of all the water quality components, which affect fish growth and health (Meade 1989).

The reused water must be sufficient in both quantity and quality to maintain acceptable growth and health of the cultured organism. Most often, treatment systems utilized to prepare water for reuse are designed to reduce fish metabolites, such as suspended and settleable solids, dissolved nitrogen compounds (ammonia and ammonium), and BOD, as well as processes for controlling dissolved gases, pH, and pathogens.

Recirculating aquaculture systems typically use clarifiers or filters to remove particulate solids, biological filters to reduce dissolved wastes, strippers/aerators to add oxygen and decrease carbon dioxide levels, and oxygenation units to increase oxygen concentrations above saturation (Table 3). Processes to provide advanced oxidation and pH control may also be required.

The purpose of this chapter is to present engineering criteria to construct a recirculating system to culture walleye. The system design presented here is not unique and consists of components common to many commercial and research recirculating systems. All components have been researched as individual unit processes, but not in combination as a functional system.

It should be noted that a variety of commercially viable designs and technologies exist, and that a randomly selected group of experts will have different preferences on what constitutes the most effective combination of components. Different technologies used in recirculating aquaculture systems will not be reviewed because of the availability of several reviews (Liao and Mayo 1972, 1974; Lucchetti and Gray 1988; Mayo 1991; Rosenthal and Black 1993; Losordo 1993; Timmons and Losordo 1994).

Design guidelines

Generally, a fish production system is designed to meet a predetermined production capacity, expressed as pounds (kg) fish produced per year. To maximize its efficiency, the production system must be operated at or near its maximum carrying capacity defined by the maximum pounds that can be supported by the system. Therefore, the starting point for a rigorous design of a recirculating aquaculture system begins by determining the system's carrying capacity. Procedures for calculating carrying capacity based upon limiting water quality

criteria have been reviewed by Meade (1988), Colt (1991), Losordo and Westers (1994), Soderberg (1995), and others. Determination of yearly production capacity, on the other hand, is much more complex because it depends upon both the characteristics of the fish (health, growth, etc.) and on the production strategies (i.e., frequencies and rates of stocking and harvesting and fish size when stocked and harvested) used to maintain the culture facility near maximum carrying capacity. Rigorous determination of a system's yearly production capacity has been reviewed elsewhere (Summerfelt et al. 1993).

Table 1. Water quality standards for fish culture. Unless otherwise stated, units are in mg/L (Meade 1989).

Parameter	Desirable range	Maximum
Alkalinity (as calcium carbonate)	10-400	
Aluminum		0.01
Ammonia		**0.02**
Arsenic		*0.05*
Barium		*5.0*
Cadmium		
Alkalinity < 100 mg/L		0.0005
Alkalinity > 100 mg/L		0.005
Calcium	*4-160*	
Carbon dioxide	0-10	
Copper		
Alkalinity < 100 mg/L		0.006
Alkalinity > 100 mg/L		0.03
Dissolved oxygen	5 mg/L to saturation	
Hardness, (as calcium carbonate)	10-400	
Iron		0.01
Lead		0.02
Magnesium		15.0
Manganese		0.01
Mercury		0.2
Nitrogen		110% (total gas pressure)
		103% (as nitrogen gas)
Nitrate	0-3.0	
Nitrite		0.1 in soft water
PCB (polychlorinated biphenyls)		0.002
pH	*6.5-8.0*	
Potassium		5.0
Salinity		5%
Selenium		0.01
Sodium		75
Sulfate		50.0
Sulfur		1.0
Total dissolved solids		400.0
Total suspended solids		*80.0*
Zinc		0.005

It is difficult to define the optimum size of a recirculating system used to produce food-size fish. To protect against a ruinous loss from system malfunction or disease, a large scale production operation should use a number of independent recirculating system modules rather than one gigantic system with common treatment units. Adding more recirculating system modules is also a simple method to increase the overall facility production capacity. Decsions on the size of the recirculating system modules must consider benefits to be obtained from economies of scale (i.e., lower cost per unit flow treated for larger systems) against difficulties that could arise from distributing flow and removing solids within the culture tank, grading and harvesting fish, removing mortalities, or isolating the biofilter while treating the fish with a chemotherapeutant; and other criteria. There is a definite trend, however, towards large recirculating system modules for food-fish production. Further commercial experience is needed to help define the optimal size of these systems

The principle components of the recirculating system design described here include: a microscreen filter for solids removal; a fluidized-sand reactor for biofiltration; a cascade column for both aeration and carbon dioxide stripping; a unit for purified oxygen injection (e.g., multi-stage low head oxygenator or U-tube); and a circular tank for fish culture. The recirculating aquaculture system design also requires methods to add ozone and manage pH. Each of these components is discussed

Table 2. Metabolite production and consumption.

Metabolite	Species	lb metabolite per lb feed fed	Reference
Oxygen demand	Walleye	0.2	Yager and Summerfelt (1994)
	Trout	0.22	Willoughby (1968)
	Salmon	0.54	Liao and Mayo (1974)
Total ammonia nitrogen produced	Walleye	0.027	Forsberg and Summerfelt (1994)
	Nonspecific	0.032	Piper et al. (1982)
	Trout	0.031	Speece (1973)
	Salmon	0.029	Liao and Mayo (1974)
Nitrate produced	Nonspecific	0.087	Piper et al. (1982)
	Salmon	0.024	Liao and Mayo (1974)
Phosphate produced	Nonspecific	0.005	Piper et al. (1982)
	Salmon	0.016	Liao and Mayo (1974)
Settleable solids produced	Nonspecific	0.3	Piper et al. (1982)
	Salmon	0.52	Liao and Mayo (1974)
Total solids produced	Catfish	0.4	Speece (1973)
cBOD produced (5-day, 20°C)	Catfish	0.4	Speece (1973)
	Salmon	0.60	Liao and Mayo (1974)
COD produced	Salmon	1.60	Liao and Mayo (1974)
Carbon dioxide produced	Coho salmon	0.285	Liao and Mayo (1974)
	Steelhead	0.43	Liao and Mayo (1974)

separately below. In addition, each section below includes an example illustrating the design or sizing of the component described when used within a moderately-large system with a design recirculating flow rate of 1,000 gpm (3,800 Lpm).

Solids removal by microscreen filtration

Solids removal is the most critical process to manage in recirculating aquaculture systems, because solids influence the efficiency of all the other component functions as well as the potential for disease (Chen et al. 1994). Solids production is proportional to feed input (Seymour **and** Bergheim 1991; Chen et al. 1994).

Table 3. Summary of the unit processes typically used within recirculating aquaculture systems.

Unit process	Effect	Example types
Clarification	removes settleable and/or suspended solids	• microscreen filters (drum, Triangel™, and disk) • settling basins • tube/plate settlers • roughing filters (packed with random rock or plastic, and with structured plastic) • swirl separators • pressurized filters (sand and plastic bead) • gravity filters (high rate sand and slow sand) • flotation/foam fractionation
Biofiltration	removes dissolved organics and ammonia	• fluidized-media reactors (sand and plastic bead) • rotating biological contactors • trickling filters • submerged large media reactors • pressurized bead filters
Stripping/aeration	shifts concentrations of dissolved carbon dioxide, nitrogen, and oxygen towards equilibrium values	• mechanical-surface mixers • diffusers • columns (open to atmosphere, and enclosed with forced ventillation) a. packed or tray b. spray • shallow air-lifts • corrugated inclined plane • stair-type drops
Oxygenation	adds dissolved oxygen to levels generally greater than equilibrium	• U-tubes • columns (atmospheric pressure and pressurized) a. multi-staged (e.g., low head oxygenators) b. packed or tray c. spray • oxygenation cones • oxygen aspirators • diffusers • enclosed mechanical-surface mixers

Particulate matter (feces, feed fines, uneaten feed and sloughed biofilm) is the major source of carbonaceous oxygen demand and nutrient input into the water, especially if it degrades within the system. The best solids removal practice, therefore, removes solids from the system as soon as possible and it exposes the solids to the least turbulence and mechanical shear. Conventional solids removal processes generally remove solids larger than 100 μm but, with few exceptions, they do not remove colloidal solids smaller than 20 μm or dissolved solids (Chen et al. 1994).

Microscreen filters are commonly used within commercial recirculating aquaculture systems for removing solids. They are commonly used by producers with large recirculating systems, because they are modular, not permanently fixed to one spot, and relatively easy to install. They also have a high hydraulic capacity, a low space requirement, and an acceptable headloss. Microscreen filters also perform well within recirculating systems because they remove a large proportion of the solids produced during each pass and because they do not store the solids they have removed.

Microscreen filters are sieves. They strain water-bound particles larger than the filter screen (mesh) openings. **A** cleaning mechanism is necessary to remove solids from the filter. Depending on the type of microscreen filter, the filter is cleaned by either hydraulic flushing, pneumatic suction, mechanical vibration, or ralung. Cleaning of the sieve can occur continuously, periodically, or on demand. The drum, Triangel™, and disk microscreen filters are the three main variations used in the United States. Drum filters are now used by many commercial facilities because they cost less than Triangel™ filters per unit flow treated. Drum filters are also desirable because they can be plumbed so that if ever the filter screen wash mechanism breaks down (allowing solids to accumulate and plug the microscreen panels), water overflows to the pumping sump and not out of the system through the solids collection trough.

Drum filters (Figure 1) use fine mesh screens to remove solids from high volume flows. The filter screen is supported on a grid, which in turn is attached to the outer circumference of the drum. Each drum contains several grid-supported screens. Flow is usually passed from the inside to the outside of the drum during solids removal. When the drum rotates, solids trapped on the filter screen in the cells of the supporting grid are gently lifted out of the water. When the drum filter is operated without rinsing, however, the particulates begin to clog the screens, which causes the water level within the drum to increase. To maintain flow, solids are washed from the filter with a high pressure spray during drum rotation. Some drum filters have used air suction to remove solids from the surface of the screens. These vacuum cleaned drum filters generally operate with the flow passing from the outside to the inside of the drum. Drum rotation can be either continuous or intermittent, when automatically controlled with a level switch located within the drum. During automatic control, the drum is not rotated until the difference in water level between the inside and outside of the drum reaches a predetermined upper level. The drum rotates 180° or more each wash cycle. In either mode, pressure sprays rinse the solids off the screens into collection troughs where they are piped away for disposal. Because microscreen filters are washed frequently (Libey 1993; Summerfelt et al. 1994), trapped solids are not stored for a significant time within the recirculating aquaculture system.

Microscreen filters have been shown to effectively remove solids from recirculating aquaculture systems (Libey 1993; Summerfelt et al. 1994), and from the influents (Liltvedt and Hansen 1990) and effluents from

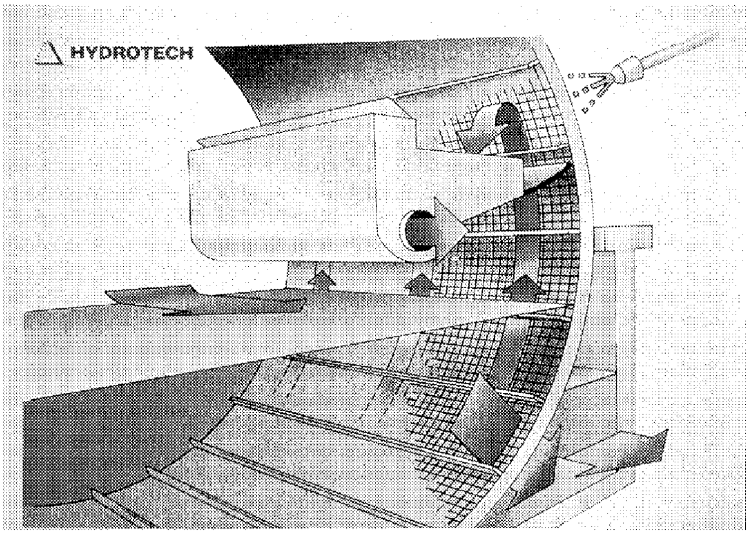

Figure 1. Working mechanism of a drum filter (Courtesy of HydroTech). Arrows indicate the paths taken by the treated flow and the filterable solids as they pass through the unit.

single-pass systems (Mäkinen et al. 1988; and Bergheim et al. 1993). Studies within a recirculating system at the Freshwater Institute indicated that microscreen filters, with sieve panels containing 80 µm openings, removed a large portion of the net solids produced each pass (Summerfelt et al. 1994), particularly when ozone was added to the system. The fine particles that were not removed accumulated within the recirculating system. Particles that accumulate within a recirculating system using microscreen filters are smaller than 20-40 µm and constitute 50% (by mass) or more of the particles approaching the filter in the recirculating flow (Heinen et al. 1996).

Size of the microscreen mesh also affects the filter's hydraulic capacity, total solids removal, sludge water production rate and concentration, and filter wash frequency. Summerfelt et al. (1994) demonstrated that microscreen filters with panels of small openings removed more TSS but also required much more frequent washings than filters with panels having larger openings. More frequent washings resulted in more sludge effluent and less concentrated sludge. Conversely, microscreen filters installed with panels containing larger sieve openings did not capture as large a proportion of the suspended solids from the recirculating flow each pass, but required fewer washes and produced less volume, but more concentrated sludge water effluent.

Microscreen filters require relatively large capital investment and operating expenses. Operating costs included electricity for the pumps, labor to periodically clean the sieve panels, and labor and parts to restore worn-out pressure pumps. Pressure pumps cycle on and off several hundred to several thousand times per day (Libey 1993; Summerfelt et al. 1994). **As** a result, pressure pumps can fail and are often the most likely items within the entire recirculating system to cause problems, When pressure pumps fail, sieve panels plug and water overflows past the filter unit. When selecting and installing microscreen filters, attention should be given to planning for water overflow when plugged sieve panels cause flow to bypasses the filter unit.

Microscreen filters are available from distributors in capacities ranging from under 80 to over 13,000 gpm (under 300 to over 50,000 Lpm). Larger models can generally be purchased at a large economy of scale. Fully equipped drum filters using 60 µm microscreen panels, for example, range from $1,000 to 4,000 for every 100 gpm (380 Lpm) of flow capacity. Commercial distributors of microscreen filters may often be of assistance when selecting a microscreen filter based on the system flow rate, fish loading, and desired microscreen opening size.

Example design: drum *filter*

Microscreen drum filters are usually purchased from manufacturers because they are difficult to fabricate locally (unlike fluidized-sand biofilters, aeration/stripping towers, or U-tubes). Several companies manufacture microscreen drum filters. In late 1995, the price for a drum filter with panels containing 60 µm sized openings capable of treating more than 1,000 gpm (3,800 Lpm), and equipped with pressure pumps and solids-flushing control mechanism costs about $17,000.

Biofiltration by fluidized-sand biofilters

Fluidized-sand biofilters are used to treat dissolved wastes within recirculating aquaculture systems (Cooley 1979; Burden 1988; Owsley et al. 1988; Paller and Lewis 1988; Wimberly 1990; Thomasson 1991; Weaver 1991; Bullock et al. 1993; Heinen et al. 1996; Summerfelt and Cleasby 1996). Microbes attached to the surface of the sand oxidize ammonia to nitrate and oxidize or metabolize and incorporate organic compounds. Attachment of the microbe population to the sand, which has a density 2.65 times that of water, keeps the microbes from being flushed out of the filter and provides the biosolids retention time required for biological oxidation of ammonia to nitrates, The fine sands used in fluidized beds make a good support for microbial attachment because they have very high specific surface areas (i.e., available surface area per unit volume). Adhtionally, filter sands are relatively inexpensive, inert, non-compressible, non-biologically degradable, and environmentally friendly (compared with plastic beads).

Fluidization requires relatively high water velocities to tumble the sand in the water and transport ammonia, nitrite, organic compounds, and oxygen in close contact with the biofilm-coated sand. The high velocities improve transfer of dissolved compounds into the biofilm by exposing all portion of the biofilm surface to the solution and by replacing and decreasing the thickness of the stagnant boundary layer surrounding the biofilm. The high velocities also produce forces

(both hydraulic and the physical particle-particle or particle-wall interactions that occur in the region of water distribution under the fluidized bed) that continuously shear the growing biofilm. Some control over the biofilm thickness can be maintained by selecting a given sand size, by manipulating shear forces, and by replacing sand.

Fluidized-sand biological filters have been used by commercial aquaculture producers with large recirculating systems. Relative to other large scale biofilters, fluidized-sand biofilters are compact, reliable, efficient at removing ammonia, and are cost competitive ($0.002-0.0001/ft^2 sand surface area, depending upon characteristics of the sand).

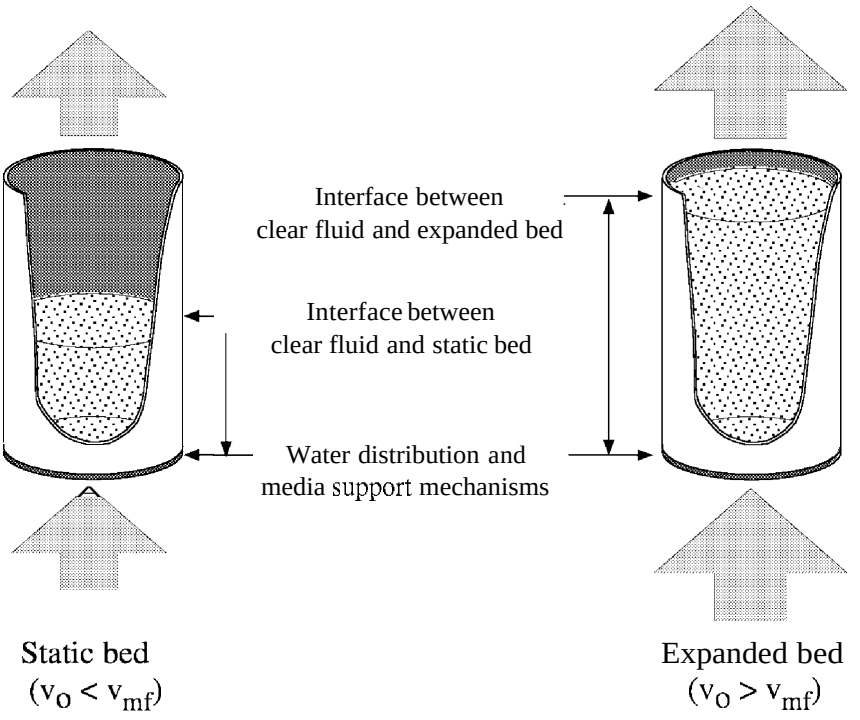

Figure 2. Mechanics of flow through a granular bed at velocities (v_o) above and below the minimum fluidization velocity (v_{mf}).

Design considerations

Fluidized-sand beds operate by injecting an equal distribution of water across the biofilter's cross-section at the bottom of the sand (Figure 2). Water flows up through void spaces between sand grains in the bed. Viscous and inertial forces resist the water passing through the static bed, causing the pressure loss (static bed) to increase with increasing superficial velocity[1] (Figure 3). The bed expands, becoming fluidized, when the velocity of water through the bed is sufficiently large to result in a pressure loss greater than the apparent weight (actual weight less buoyancy) per unit cross-sectional area of the bed. The relative amount of bed expansion is dependent upon the shape and diameter of the sand and the velocity and temperature of the water. Once the bed has been fluidized, the pressure drop across the bed remains constant at all bed expansions (Figure 3).

If oxygen is not limiting, design of most nitrifying biofilters is based on the amount of surface area

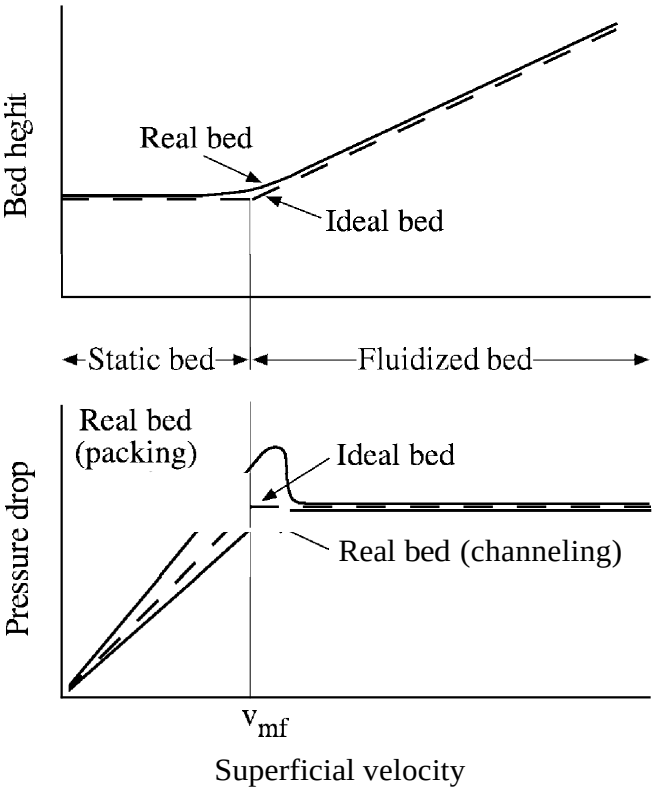

Figure 3. Hydraulics of flow through a bed of granular media at velocities above and below the minimum fluidization velocity (v_{mf}) (after Fan [1978]).

[1] Superficial velocity is a term used for calculating hydraulics within granular media. The superficial velocity is the velocity of the flow that would be measured if no media were present. It can be calculated by dividing the average volumetric flow rate by the cross-sectional area of the reactor that is perpendicular to the flow. In the remainder of the chapter, superficial velocity is referred to simply as velocity.

required to daily convert a given amount ammonia to nitrate. For most types of biofilters, capital costs increase roughly in proportion to increased requirements for surface area. In fluidized-sand biofilters, however, the total available surface area can be increased relatively inexpensively due to the super high specific bed surface areas (ranging from 1,000-14,000 ft^2/ft^3 [4,000-45,000 m^2/m^3]) and relative low cost of the media (around \$1-2/ft^3 [40-70/m^3] of graded sand). Although the cost per unit surface area is low compared to other biofilter types, the total head pressure required across the fluidized-sand biofilter is moderate (generally < 6 psi [4 m of water head]). The head pressure required to fluidize a given sand depth does not change with sand diameter; only the water velocity required changes with the sand size selected and the desired bed expansion (Table 4). Therefore, the design of a fluidized-sand biofilter is based on both hydraulic and nitrification considerations. The first step in designing a fluidzed-sand biofilter is to select a sand and a bed expansion. Assuming that the flow rate to be treated by the fluidized-sand biofilter withm the recirculating aquaculture system was previously set, selection of these two criteria sets the velocity needed to fluidize the sand to the desired expansion. The velocity, flow rate, sand size, and depth of sand controls the size (e.g., diameter) and oxidation capacity of the biofilter. When selecting sand size, bed expansion, and bed depth, you must ensure that the biofilter has excess capacity for nitrification and sufficient oxygen loading to maintain an aerobic effluent. Completing the fluidized bed requires design of a distribution mechanism for injecting flow at the bottom of the sand bed and uniformly fluidizing the sand.

Sand selection & bed expansion

Summerfelt and Cleasby (1996) reviewed the hydraulic design of fluidized-beds. Fluidization hydraulics depends on characteristics of the sand. Density, sphericity, and porosity can be approximated for the

Table 4. Velocity (v_o) required to fluidize a uniformly sized sand of equivalent diameter (De_q) to a given bed expansion, assuming a temperature of 25°C and characteristics of typical sands* (Summerfelt and Cleasby 1996). Bed specific surface area (S_b) and minimum fluidization velocity (v_{mf}) are also shown for each diameter.

			v_o (gpm/ft²)†		
De_q (mm)	S_b (ft²/ft³)‡	v_{mf} (gpm/ft²)†	at 50% Expansion	at 100% Expansion	at 150% Expansion
0.05	26,800	0.04	0.2	0.5	0.8
0.1	13,400	0.16	1.0	1.9	2.9
0.15	8,900	0.36	2.2	3.8	6.0
0.2	6,700	0.64	3.4	6.9	10.6
0.25	5,400	1.00	5.1	10.6	15.4
0.3	4,500	1.44	7.6	14.4	20.0
0.35	3,800	1.95	10.1	18.2	25.0
0.4	3,400	2.54	12.8	22.1	29.5
0.45	3,000	3.19	15.4	25.7	34.1
0.5	2,700	3.92	18.1	29.4	38.4
0.6	2,200	5.56	23.2	36.6	46.9
0.7	1,900	7.42	28.4	43.4	54.8
0.8	1,700	9.46	33.2	50.0	62.5
0.9	1,500	11.62	38.1	56.2	69.7
1.0	1,300	13.88	42.6	62.2	76.6

*i.e., a sand density of 2.65 g/cm³, a loose-bed porosity of 0.45, a sphericity of 0.45, and a water temperature of 25°C. Variations in sand characteristics from different quarries can result in significantly different expansion velocities requirements than those reported here, particularly as the diameter of the sand increases. Therefore, the numbers in Table 4 should only be used for preliminary design estimates; a hydraulic test on a sample of the sand selected should be completed to determine the actual expansion velocities on a case by case basis; ‡ 1 cm^{-1} = 100 m^2/m^3 = 30.48 ft^2/ft^3; † 1 cm/s = 14.7 gpm/ft^2.

Table 5. Example particle size analysis provided by a sand distributor (data for FilterSil™ filtration sand from Unimin Corporation's facility in Oregon, Illinois).

Mesh (ASTM E-11)	Sieve analysis Typical mean % retained on individual sieves				
20	1.5	—	—	—	—
30	45.0	15.0	3.0	1.0	—
40	45.0	60.0	36.0	20.0	1.0
50	5.0	20.0	40.0	34.0	15.0
70	2.0	3.0	13.0	24.0	47.5
100	1.0	1.0	6.0	15.0	30.0
140	0.4	0.4	1.4	5.0	6.0
200	—	0.1	0.1	1.0	0.5
270	—	—	trace	0.1	trace
pan	—	—	—	—	—
Size designation	0.45	0.35	0.25	0.15	0.10
Effective size (mm)	0.45	0.34	0.23	0.16	0.13
Uniformity Coefficient	1.4	1.4	1.8	2.0	1.7

purpose of design (Summerfelt and Cleasby 1996). Diameter and uniformity of the sand can be determined from a sieve analysis provided by the supplier. The characteristics for a given sand are used to estimate the velocity required to achieve a given bed expansion. Equations to determine the hydraulics of flow through expanded beds of sand and the typical values used in these calculations are summarized by Summerfelt and Cleasby (1996). Estimates of the velocities required to fluidize a given diameter sand to a given expansion are presented in Table 4.

Suppliers of silica filter sand are listed in the AWWA (1994) Buyer's Guide. Fluidized-sand biofilters in aquaculture typically use an extremely hard, whole grain crystalline silica sand, which is finely graded and has a mean effective diameter of 0.1-1.0 mm, and a uniformity coefficient between 1.3 to 1.8. Average bed expansions are often between 20 and 100%. Because sands are not perfectly uniform, larger sands move to the bottom of the fluidized beds where they expand less than the smaller sands that have migrated to the top of the bed. The average expansion of a bed at a given velocity depends upon the size gradation within the bed (i.e., uniformity coefficient), which makes it important to predict expansion of both the largest and smallest fractions of sand (Cleasby and Fan 1981). In particular, the largest fraction of sand must expand at the velocity selected.

The following example illustrates why expansion of the entire bed must be considered when selecting a sand. A supplier provides a particle size analysis (Table 5) for several sizes of sand. Assume the sand selected is the one with an effective diameter of 0.34 mm and a uniformity coefficient of 1.4 (Table 5). To design a fluidized bed using this sand, the first step is to determine how much expansion would be obtained within the largest and smallest size fractions. Examination of the sieve analysis (Table 5) indicates that the largest 15% of the sand was retained on the 30 mesh sieve, but passed through the 20 mesh sieve, and that the smallest 4.5% of the sand passed through a 50 mesh screen. Table **6** can be used to convert sieve size to approximate sand diameter. Roughly, the largest 15% of the sand has a diameter > 0.595 mm and < 0.841 mm, and the smallest 4.5% of the sand has a diameter < 0.297 mm. The relationship between sand size, velocity, and bed expansion can be estimated from Table 4. Sand with a mean effective size of 0.34 mm requires a velocity of around 17-18 gpm/ft^2 (1.20 cm/s) to expand 100%. The largest 15% of the sand has a diameter > 0.60 mm (but < 0.841 mm). It would fluidize to some extent at a velocity of 17.6 gpm/ft^2, but expansion would be less than 50%. Most of the smallest 4.5% of the sand would expand slightly less than 150% at a velocity of 17.6 gpm/ft^2. Accordingly, the 0.34 mm sand would com-

Table 6. Size of opening corresponding to the U.S. sieve series designation number (Perry and Chilton 1973).

Sieve designation number†	Size of opening (mm)	Sieve designation number†	Size of opening (mm)
16	1.19	60	0.250
18	1.00	70	0.210
20	0.841	80	0.177
25	0.707	100	0.149
30	0.595	120	0.125
35	0.500	140	0.105
40	0.420	170	0.088
45	0.354	200	0.074
50	0.297	230	0.063

† Number of meshes per inch.

pletely fluidize at a velocity of 17.6 gpm/ft^2 and would have a mean expansion of about 100%.

Biofilm growth on the sand increases expansion as it decreases the effective density of the sand. Increased expansion due to biofilm growth can be of special significance with fine sands (< 0.5 mm), as the biofilm thickness may become greater than the Qameter of the sand.

Biofilter geometry

The design of the recirculating aquaculture system described in this chapter assumes that the biofilter will treat the full flow of reused water. With this flow rate (Q) and with a velocity (v,) that was set when the sand and overall bed expansion were selected, the cross-sectional area (A_b) requirements for the biofilter can be calculated:

$$A_b = \frac{Q}{v_o} \quad (1)$$

Due to practical considerations based on biofilter geometry, pressure drop, and reactor oxygen demand, the depth of sand in aerobic fluidized-sand biofilters is generally designed to be 3-6 ft (1-2 m), unexpanded. After setting the depth of sand within the bed, the total available surface area (SA_{avail}) should be checked to ensure that there is more surface area available than surface area required (SA_{reqd}) to remove the total ammonia nitrogen (TAN) produced by the fish:

$$SA_{avail} = S_b \cdot V_{bf} \quad (2)$$

$$SA_{reqd} = \frac{P_{TAN}}{R_{TAN}} \quad (3)$$

where:

SA_{avail} = surface area available in biofilter for nitrification (ft^2);

SA_{reqd} = surface area required for nitrifying all of the TAN produced (ft^2);

S_b = specific surface area of the bed of sand (ft^2/ft^3);

V_{bf} = volume of sand within the biofilter (ft^3);

P_{TAN} = TAN generation rate (lb TAN produced per day);

R_{TAN} = area specific nitrification rate (lb TAN removed per day per ft^2 of surface area).

The rate that TAN is produced (P_{TAN}) within the system is proportional to the product of the culture biomass and the feeding rate:

$$P_{TAN} = a_{TAN} \cdot \rho_{fish} \cdot V_{ct} \cdot r_{feed} \quad (4)$$

where:

ρ_{fish} = density of fish in the culture tank (lb fish per ft^3 culture volume);

V_{ct} = volume of water contained within culture unit (ft^3 culture volume);

r_{feed} = feeding rate (lb feed per lb fish per day);

a_{TAN} = TAN produced as a proportion of feed fed (lb TAN per lb feed).

The fluidized-sand biofilter design should have excess available surface area. Generally spealung, the expense of the excess sand and slightly larger biofilter tank is relatively low, and the excess is necessary to ensure stable operation. Excess capacity is important to ensure complete nitrification (prevent accumulation of nitrite) and to prevent gelling of the biofilm. The latter problem may result in channelization and media wash-out, which has been reported to occur when sands of less than approximately 1.0 mm diameter were used within fluidized beds operated under high substrate loading rates (approximately 6.0×10^{-5} lb TAN removed per day per ft^2 of surface area, as calculated from data presented by Burden [1988]). Burden (1988) did not report gelling in fluidized beds of sand larger than approximately 1.5 mm. Research on nitrification in fluidized-sand biofilters at the Freshwater Institute indicated that area specific removal rates ranged from 0.45×10^{-5} to 2.0×10^{-5} lb TAN removed per day per square foot of surface area (20-100 $mg/d/m^2$), depending upon the amount of excess sand present (unpublished data). However, nitrification rates on sands are highly dependent upon the sand size, water temperature, and ammonia and organic loading rates. In addition, because sands have such high specific surface areas, it can be argued that the nitrification capacity of the filters would be more accurately represented by the total sand volume, rather than the total sand surface area. More applied research is needed in this area.

Large fluidized beds can be circular or rectangular, constructed withn plastic, fiberglass, concrete, or enamel-coated steel tanks, and can generally be constructed on site. If necessary, the design can be modified by adjusting tank dameter, sand diameter, or recirculating sytem flow rate to provide a tank of convenient size, or to allow the use of a graded sand which is available locally.

Flow distribution

A reliable flow distribution mechanism is critical to effectively operate a fluidized-sand biofilter. The flow distribution system must deliver an equal amount of flow across the base of the bed, prevent loss of media, operate without detrimental fouling (or have a fouling prevention system) and, in some cases, support the bed. There are a wide variety of distribution mechanisms used to inject water into the bottom of large fluidized-sand biological filters. Each mechanism differs in how flow is transported and distributed. However, most mechanisms used in recirculating aquaculture systems transport the flow through a manifold, starting at the top of the biofilter, that runs down the inside of the reactor to the base of the sand. Bringing the flow into the biofilters from above avoids distribution pipes piercing the biofilter wall. A check valve to stop siphoning, installed after the pump and before the dstribution manifold above the biofilter, prevents the hydraulic head of water in the tank from producing back flow into the distribution system when normal flow is lost. Backflow can carry sand into the distribution pipes and plug them, which in turn can cause uneven fluidization of the bed.

A flow distribution mechanism is described below that is a simple modification of the pipe-manifold system used in wastewater treatment filters. This distribution mechanism introduces the flow through a manifold structure located at the top of the biofilter (Figures 4 and *5)*. The overhead manifold branches to equally spaced pipe laterals that transport the flow down an inside wall to the reactor base. At the base, each lateral elbows 90" and runs across the floor to the far wall where they elbow 90" up from the reactor bottom and

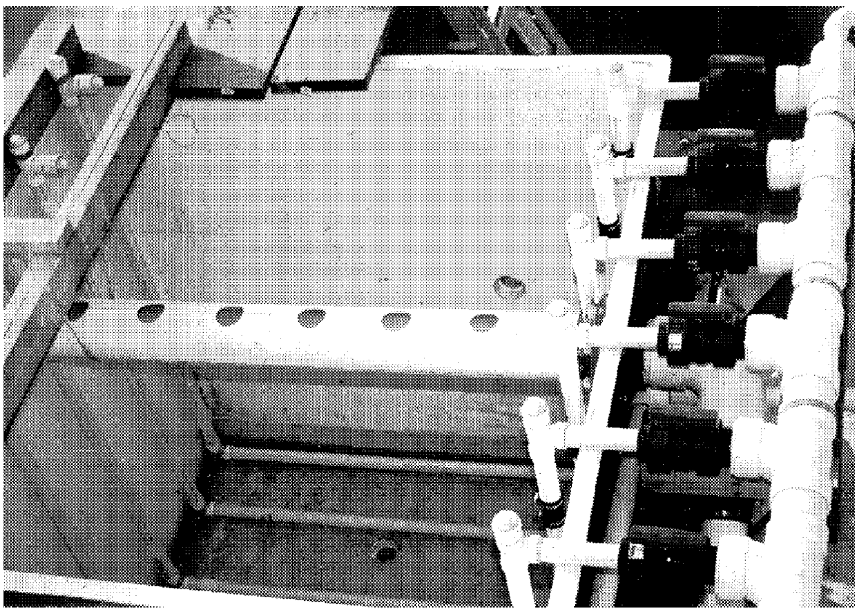

Figure 4. A modified pipe-lateral distribution system before sand was added.

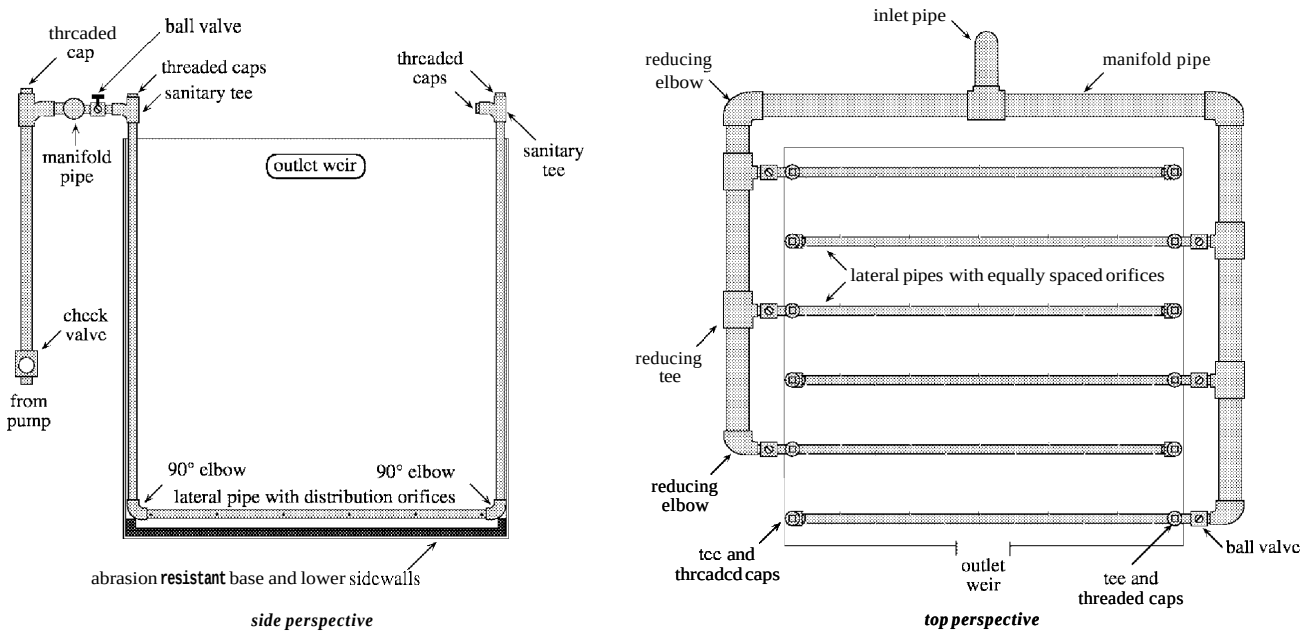

Figure 5. A modified pipe-lateral distribution system for fluidized-sand biofilters (side and top perspectives).

run the length of the wall to the top of the reactor (Figures 4 and **5).** Flow distribution orifices are located on each section of pipe running along the vessel floor (Figures 4 and *5).* Tees fitted with screw caps are located at the end of each manifold pipe. This configuration allows for installation of control valves on individual pipe laterals, and provides a mechanism for unplugging individual pipes by flushing water, sand, or other debris by temporarily removing the threaded cap on the side-tee at the top and end of the plugged pipe-lateral (Figure **6).**

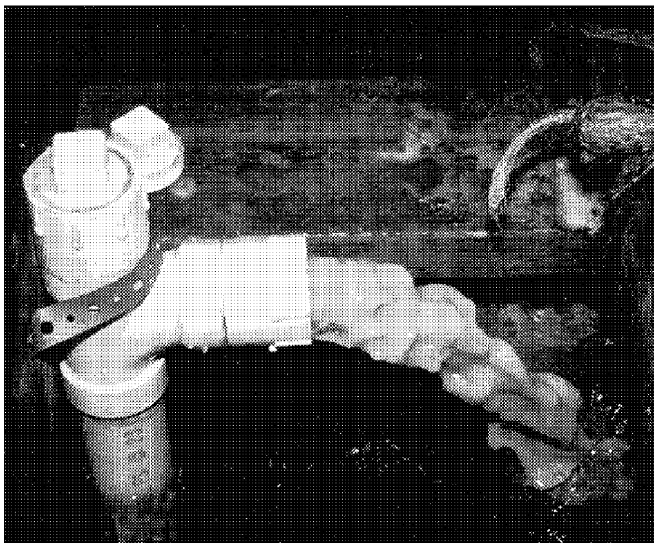

Figure 6. A plugged lateral was cleared by removing the screw cap from the overhead tee at the lateral end and flushing with water.

Criteria for spacing of the pipe-laterals, and the spacing and diameter of orifices, are provided in several engineering texts (Weber 1972; AWWA 1990). Water is distributed from the pipe-laterals along the floor of the vessel through two rows of 0.25 to 0.5 in (6.4 to 12.7 mm) diameter orifices that are "directed downward (on each side of a lateral pipe) so as to dissipate the energy of the water jets" (Weber 1972). Laterals and orifices are normally spaced at roughly the same interval, between 3 to 12 in (7.5 to 30 cm) apart. Additional guidelines given for lateral design includes the following ratios:

Total area of orifices: cross-sectional area of bed 0.0015 to 0.005:1 (5)

Cross-sectional area of pipe-lateral: total area of orifices served 2 to 4:1 (6)

Cross-sectional area of manifold: total area of pipe-laterals served 1.5 to 3:1 (7)

Conformation to these ratios will assist with the basic approach used to obtain uniform flow distribution (Montgomery 1985): to size the orifices small enough to introduce a controlling headloss, and to scale the distribution pipes so that the flow velocity within the pipes are reasonably low and uniform throughout the entire filter area. Orifices of pipe-lateral systems generally create a headloss of at least 2 ft (0.6 m) of water (Montgomery 1985). It is rationale to size the orifices to create a headloss greater than or equal to the head required to fluidize the bed. Much larger orifice headloss would produce much stronger jetting actions

that are more likely to damage the vessel or distribution pipes and are more likely to scour the biofilm from the sand in the jetting zone. Much smaller orifice headloss would not maintain proper distribution of flow under the sand bed.

The following equation can be used to estimate the headloss for a given orifice diameter and flow rate:

$$HL_{orif} = \left[\frac{Q_{orif}}{C \cdot A_{orif}}\right]^2 \cdot \frac{1}{2 \cdot g} \qquad (8)$$

where:

HL_{orif} = headloss due to flow through orifice (ft of water);
Q_{orif} = flow rate of water through orifice (ft^3/s);
A_{orif} = area of orifice (ft^2);
g = gravity constant (32.2 ft/s^2);
C = orifice discharge coefficient for sharp-edged, submerged orifices (0.6).

The pressure loss across a fluidized bed is constant at all bed expansions (Figure 3) (i.e., velocities > than the minimum fluidization velocity), and is equal to the buoyant weight of the media per cross sectional area of the bed. The head required to fluidize sand is between 0.9-1.0 ft of water for every 1.0 ft of sand in the loosely packed bed.

When the modified pipe-lateral distribution mechanism was evaluated within a cubical **6 x** 6 **x 6** ft (1.8 **x** 1.8 **x** 1.8 m) tank at the Freshwater Institute (Figure 4). The orifices were oriented at an angle 45" below horizontal. Water jets emitting from the downward facing orifices sand blasted holes through the 0.25 in (6 mm) thick fiberglass floor of the biofilter vessel in 7 d (Figure 7). The AWWA (1971) has also reported on jet action producing problems at the base of filter beds. We modified the design to prevent the jet action from "sand-blasting" through the tank wall by pouring a concrete pad on the biofilter floor (4 in thick pad with side walls **3** in thick by 4 in high), after first removing the sand and distribution pipe-laterals. After about one year of operation the sand was removed and the concrete pad showed little erosion from the water jets.

During evaluation, this distribution system maintained uniform sand expansion (30% expansion) throughout the bed (3 ft deep, unexpanded) with no maintenance, even though flow was interrupted several hundred cycles (30 min flow followed by 30 min no flow). Flow

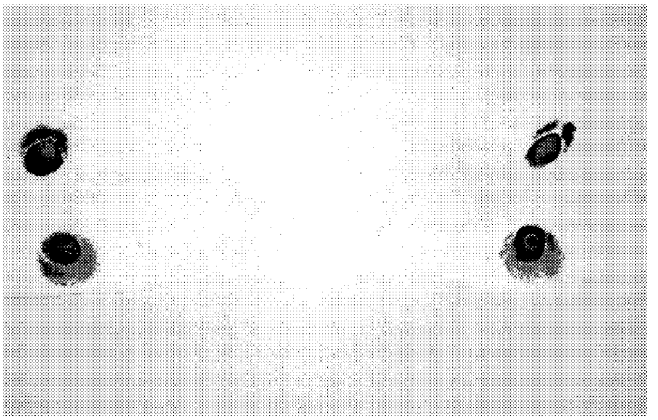

Figure 7. Water jets emitting from distribution orifices sand-blasted holes through the bottom of an unshielded fiberglass vessel. The vessel floor was later shielded with 4 in (10 cm) of concrete to prevent tank damage.

interruption did not plug the pipe laterals. However, when sand was initially loaded into the bed with a front end loader, plant stalks, leaves, and roots that had grown on the sand pile entered the pipe manifold with the recirculated, unfiltered flow and blocked flow through the orifices at the end of two pipe-laterals. Pipe-laterals were unplugged by flushing water down the pipe after the screw caps were removed from the overhead tees at the end of each plugged lateral (Figure **6).** If more vigorous action had been required to unplug a lateral, a garden hose or wire-rooter could have been run down through the top of the tee fittings (after temporarily removing the threaded cap). **A** similar distribution manifold has been successfully used to treat 200 gpm in a fluidized-sand biofilter withn a recirculating system at the Freshwater Institute.

Example design: fluidized-sandbiofilfer

Fluidized-sand biofilters are complex devices, but they are easily fabricated locally using a vessel and PVC pipe/fittings and concrete. The most critical design factor for a fluidized-sand biofilter is the water distribution manifold. Assuming that the 0.34 mm diameter filter sand (Table 5*)* described earlier was selected, a velocity of 17.6 gpm/ft^2 would be required to obtain an average bed expansion of 100%. Equation 1 can be used to calculate the biofilter's cross-sectional area based upon the desired velocity (17.6 gpm/ft^2) and system flow (1,000 gpm):

$$A_b = \frac{Q}{v_0} = \frac{1{,}000 \text{ gpm}}{17.6 \text{ gpm/ft}^2} = 57 \text{ ft}^2 \ (5.3 \text{ m}^2) \qquad (1)$$

Either a circular or rectangular vessel can be selected to provide the biofilter's cross-sectional area requirement. A circular vessel would be 8.5 ft (2.6 m) in diameter or a rectangular vessel could be 6.5 ft (2 m) wide by 8.7 ft (2.65 m) long. For this example, a rectangular vessel was selected because it could be fabricated out of concrete. Nine distribution pipe-laterals, spaced on 0.75 ft (0.23 m) centers, would fit within the vessel parallel to the long walls. Their would be 23 orifices through the underside of each lateral (placed 15-45" below lateral center). Twelve of the orifices would be located on one side of each lateral and 11 orifices located on the opposite side. The distribution mechanism would contain a total of 207 orifices and each orifice would distribute roughly 4.83 gpm (18.4 Lpm). The orifice diameter can be selected using equation 8 to provide a controlling headloss greater than the head required to expand the sand. If the biofilter had 6.6 ft (2 m) of sand (static), it would require about 6.6 ft (2 m) of water head to expand. An orifice of 6/16 in (9.53 mm) diameter would create a controlling head loss of 8.4 ft (2.6 m). The laterals and manifold should be scaled to minimize pressure losses within the distribution system. Each distribution lateral should have an inside diameter from 3 to 4 in (7.6 to 10.2 cm), according to the criteria in equation 6. The distribution manifold at the top of the vessel should have an inside diameter anywhere from 8 - 12 in (20 - 30 cm), according to the criteria in equation 7.

The 0.34 mm sand in the fluidized bed would have a specific surface area of about 4,000 ft^2/ft^3 (13,000 m^2/m^3)(from Table 4). The total volume of sand in the biofilter, 376 ft^3 (10.6 m^3), would likely cost about $800, excluding shipping. This fluidized bed would have about 1,500,000 ft^2 (140,000 m^2) of surface area available for microbial growth (using Equation 2). If we assume a conservative area specific nitrification rate (1.0×10^{-5} lb TAN removed per day per ft^2 of surface area), then the biofilter could be expected to remove 15 lb (6.8 kg) TAN per day. Assuming that 0.03 lb TAN are produced for every lb of feed eaten (Table 2), then at maximum loading this biofilter could treat the ammonia produced from feeding about 500 lb (230 kg) per day.

Aeration/stripping by cascade column

Commercial oxygen is widely used to supplement oxygen levels and boost fish production in intensive aquaculture systems. However, accumulation of high levels of carbon dioxide can become a limiting toxicity factor with high fish densities and inadequate water exchange; i.e., high fish loadings (Colt and Tchobanoglous 1981; and Colt et al. 1991). Carbon dioxide toxicity is more likely to occur in intensive aquaculture systems which inject pure oxygen because oxygen injection unit processes use insufficient gas exchange to strip much carbon dioxide (Watten et al. 1991). Additionally, more carbon dioxide is usually produced in systems which inject pure oxygen because these systems have the oxygen to support higher fish loadmg rates. When aeration is used to supply oxygen to aquaculture systems, however, fish loadmg levels are lower than can be obtained with pure oxygen and enough air-water contact is generally provided to keep carbon dioxide from accumulating to toxic levels (Speece 1973).

Air stripping and aeration are mass transfer processes that occur together when water is contacted with air to bring its concentration of dissolved gases (such as nitrogen, carbon dioxide and oxygen) into equilibrium with the partial pressures of these gases in the surrounding atmosphere. The rate of mass transfer (J), as defined by Fick's Law, is equal to the product of the overall mass transfer coefficient (K_L), the total interfacial contact area (A) per unit system volume (V) and the concentration gradient $\left(X^{eq} - X\right)$ (Treybal 1980):

$$J = K_L \cdot \frac{A}{V}\left(X^{eq} - X\right) \qquad (9)$$

The concentration gradient is the driving force for mass transfer. In the expression for the concentration gradient, X^{eq} is the limiting molar concentration of Qssolved gas defined by Henry's Law and **X** is the actual molar concentration of dissolved gas in the water. The term $\frac{A}{V}$, represents the specific interfacial area.

Carbon dioxide can be transferred from water with any of the non-closed aeration systems that Boyd and Watten (1989), Colt and Orwicz (1991) and others have described. However, because carbon dioxide has a Henry's Law constant 200 to 300 times that of oxygen, it is more difficult to strip carbon dioxide than to add oxygen to water; consequently, bubbles formed from diffused aeration readily become saturated with carbon dioxide, requiring enormous quantities of air to achieve substantial carbon dioxide transfer rates when compared with the air-flow rates required for oxygen transfer alone. Passing water through air provides the

larger ratio of air to water volume needed for carbon &oxide exchange. This makes it more effective to strip carbon dioxide by moving water through air, as is done with surface aerators and air strippers, than by moving air through water, as is done with subsurface aerators (Colt and Orwicz 1991). Also, when water droplets are formed while passing through air, the shortened diffusion distance (a function of droplet diameter) enhances mass transfer out of the liquid phase.

The obvious way to let water fall through air is by a gravity drop, which can be: over a weir, onto a splash-board, through plastic media or stacked splash screens, down an inclined corrugated sheet (with or without holes), or down a stair-stepped surface. Because carbon dioxide stripping requires such a large volume of air per unit volume of water, it is most effective when large volumes of air can be forced through cascading water within enclosed columns. Increasing the air-water contact area by packing the columns with high voidage plastic media or stacked screens improves both carbon dioxide stripping and aeration (Figure 8). Air stripping in forced ventilation columns has been described by Onda et al. (1968) and reviewed extensively in the waste water treatment field by Kavanaugh and Trussell (1980), Cornwell (1990), Haarhoff and Cleasby (1990), and Thom and Byers (1993). Design of air-stripping columns requires selection of the following parameters:

- liquid loading rate;
- air to water volumetric loading ratio (this selection determines the air loading rate);
- packing depth;
- packing material (size and type);

Sherwood and Holloway (1940) and Piedrahita and Grace (1989) have measured $K_L a$ values for packed CO_2-stripping chambers. Summerfelt (1993) reviewed and reported criteria for carbon &oxide stripper design within aquaculture systems, they are:

a hydraulic fall of 3-5 ft (1-1.5 m), (10)

a hydraulic loading of 25-35 gpm/ft^2 (1.0-1.4 m^3/min/m^2), (11)

a volumetric air:water ratio of 6:1 to 10:1. (12)

High porosity packing or splash screens are needed to avoid flooding or gas hold-up. If high solids loadings are expected, a stripping tower with screens or trays is easier to maintain than a packed tower. Also, the air blown through the air stripper should be vented out of the building to prevent carbon dioxide from accumulating inside the building that contains the recirculating aquaculture system. In a cold climate, heat can be conserved by venting the air through an air-air heat exchanger.

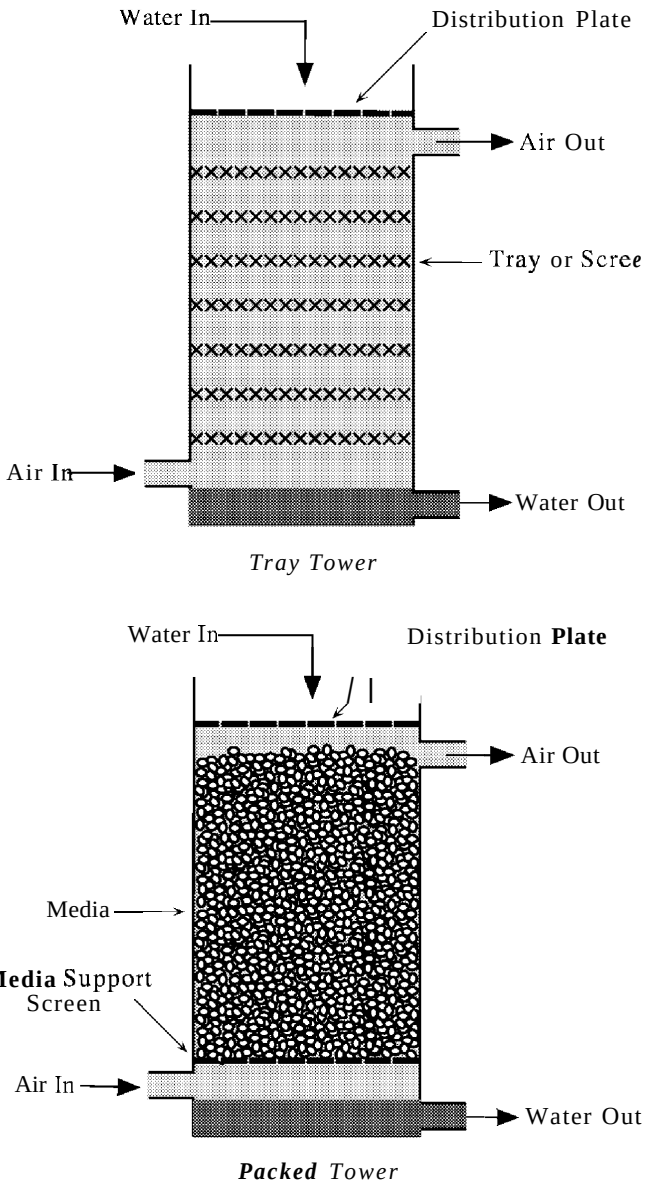

Figure 8. Two common types of air stripping columns.

As an alternative to air stripping, carbon dioxide can be treated by chemical addition as described in the pH Control section. Chemical addition is already required to maintain alkalinity in closed recirculating aquaculture systems.

Example design: aeration/stripping column

Aeration/stripping columns (Figure 8) are relatively simple devices that can be locally fabricated in a sheet metal shop. For a flow of 1,000 gpm (3,800 Wmin) the air stripper should provide a drop of 4.0 ft (1.2 m, Equation 10), across a cross-sectional area of 33 ft^2 (3.2 m^2, Equation 11), and force 1,300 scfm (38 m^3/min, Equation 12) of air flow counter-current to the water. Water is distributed across the cross-section of the column with an orifice plate located at the top (similar to that used on a LHO™, as shown in Figure 9). Flow will be equally distributed to all of the orifices in the distribution plate and a water seal will be formed above the distribution plate by selecting the number and size of orifices to create a 4-6 in (10-15 cm) head loss (Equation 8). The column can operate with or without splash media, but more carbon dioxide will be stripped using media. Several expanded metal panels (0.75-1.0 in openings) that are placed perpendicular to the flow work well to break the falling water and also resist fouling better than some plastic media (Figure 8). Air exhausted from the stripper should be vented outside of the building and through an air-to-air heat exchanger in cold climates.

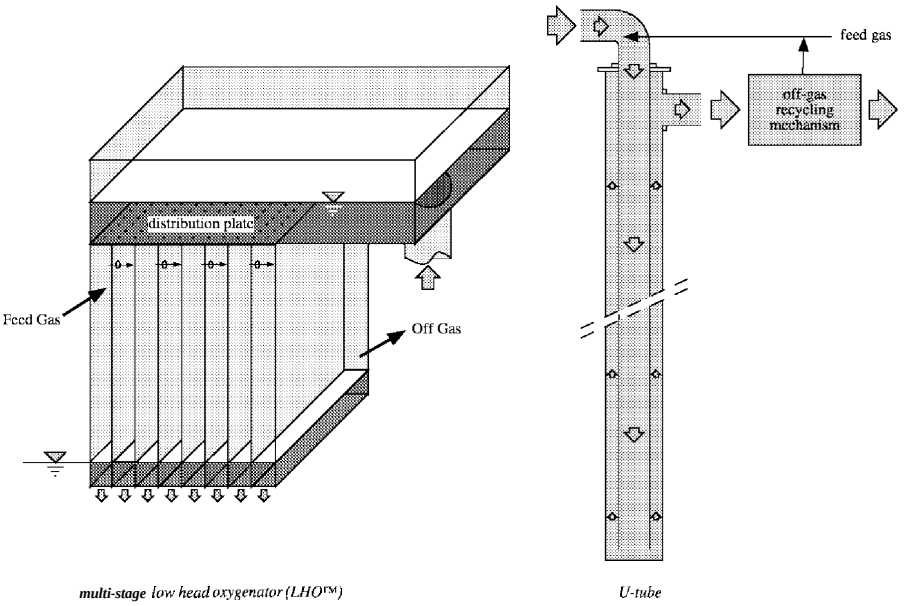

Figure 9. An LHO™ or U-tube can be used for tansferring pure oxygen into water.

Oxygen injection with low head oxygenators or U-tubes

Aeration and oxygenation are processes used to maintain adequate levels of oxygen within recirculating fish culture systems. Fortunately several outstanding reviews on aeration and oxygenation have been written by Speece (1981), Visscher and Godby (1987), Colt and Watten (1988), Speece et al. (1988), Boyd and Watten (1989), Visscher and Dwyer (1990), and Watten (1994). In the aeration process described above, air is brought into contact with water so oxygen transfers from the air into the water. The aeration unit also serves as the carbon dioxide stripping unit. In the oxygenation unit process, pure oxygen gas is used (instead of air) to achieve oxygen levels in the water flow that are above standard atmospheric saturation levels. Increasing oxygen in the flow increases the system's carrying capacity, resulting in an economical means of boosting system production (Collins et al. 1984).

Oxygen can be produced on site using pressure swing adsorption (PSA) equipment or purchased from commercial sources as a bulk liquid or gas (Speece 1981; Boyd and Watten 1989; Watten 1994). Producing oxygen on site requires a source of dry air at pressures of 90 to 150 psi as well as the PSA unit, which amounts to a considerable capital investment. The cost of generating oxygen using **PSA** units, which varies with electric rates, is about 0.5 kwh of electricity per pound of oxygen produced. The cost of liquid oxygen varies with location. At the Freshwater Institute, the operating and capital costs (using net present value over a ten year period) of using liquid oxygen versus on site generation were compared; we found that liquid oxygen costs about three times more annually than would oxygen generated on site. However, the capital investment and risk of system failure would be lower if liquid oxygen were used (Boyd and Watten 1989).

Oxygen is not an insignificant cost, it may represent about 15% of feed costs if generated on site (E. Wade, Freshwater Institute, unpublished data), and thus the transfer of oxygen into the fish culture water must be efficient. Gas absorption equipment is designed to take advantage of the factors governing the rate of mass transfer. Gas absorption is dependent on the area of the

gas-liquid interface and the thickness and rate of surface film renewal (both dependent upon the energy transfer in the gas-liquid contactor) and also on the gradient between the saturation and existing concentrations of the gas in the water. When pure oxygen rather than air is transferred into water, the water's saturation concentration for oxygen is increased nearly 5-fold over the saturation concentration obtained when air is used. The saturation concentration can also be increased by increasing the total pressure in which the transfer occurs (e.g., via a pump or hydrostatic head). Increasing the pressure during oxygen transfer from 1 to 2 atmospheres nearly doubles the saturation concentration of oxygen in water. Increasing the absorption pressure to increase the oxygen transfer, however, may also increase the operating costs, and this must be considered when selecting an oxygenation unit. Additionally, mechanisms for stripping/venting nitrogen and argon gas released during oxygen absorption are important both to reduce the total gas pressure of the water and to increase the efficiency of oxygen transfer.

Many types of oxygen transfer equipment have been described: U-tubes, multi-staged low head oxygenation units, packed columns, spray columns, pressurized columns, oxygenation cones, oxygen aspirators, bubble diffusers, and enclosed mechanical-surface mixers. Two methods are particularly well suited to transferring oxygen to water within large recirculating systems: U-tubes and multi-staged low head oxygenation units (Figure 9). Both methods can be readily scaled-up, are easy to control, and require only a modest hydraulic head. Performance and design criteria for each are given below.

Multi-stage low head oxygenators

A multi-stage low head oxygenation unit (LHO™) was patented by Watten (1989) and described by Watten and Boyd (1990). They maximize oxygen transfer efficiency by reusing the oxygen feed gas though a series of contact chambers. Water flow is typically distributed equally to each chamber at the top of the LHO™ via head-controlling orifices. Water flowing through the orifices typically drops anywhere from 1 to 4 ft (0.3 to 1.2 m) into a plunge pool which seals the lower portion of each LHO™ chamber (Figure 9). The chambers typically do not contain packing, but can be packed with plastic media to improve mass transfer (Weber et al. 1995).

Most evaluations of LHO™ units (Dwyer and Peterson 1993; Wagner et al. 1995; Weber et al. 1995), have been in cold water (12-17°C), where the saturation of oxygen is higher than at the temperature used to raise walleye (20-25°C). These studies demonstrated that LHO™ units provide excellent (60 to 90%) oxygen transfer efficiencies, when operated at gas to liquid ratios of less than 1 volume of oxygen feed gas for every 100 volumes of water flow (G:L = 0.01:1). However, the low oxygen loading rates (G:L < 0.01:1), which are good for maximizing oxygen transfer, limit the increase in dissolved oxygen concentrations within the flow to generally < 8 mg/L above saturation. Weber et al. (1995) found that to produce dissolved oxygen concentrations of approximately 25 mg/L in 12°C water required increasing the G:L to around 0.02:1. The oxygen transfer efficiency dropped to 50 to 60% at the increased G:L, even though plastic packing was used within the LHO™ chambers. Results from these studies make it clear that oxygen off-gas recycling is necessary to conserve oxygen when trying to double (or more) the saturation concentration of dissolved oxygen within the flow leaving an LHO™ unit. The studies also demonstrated that LHO™ units remove nitrogen gas when they add oxygen, which helps prevent large total gas supersaturations, even when large oxygen supersaturations are obtained.

U-tube

A U-tube maximizes oxygen transfer by using hydrostatic pressure to temporarily increase the saturation concentration of oxygen as the flow passes through the depth of the vertical, U-shaped conduit (Figure 9). U-tubes operate by continuously diffusing pure oxygen into the water entering the top of the conduit and by then entraining the oxygen bubbles in the flow passing down one side of the conduit and up through the other. Bubbles are entrained by designing the cross-sectional area of the first conduit to create a velocity greater than the buoyant velocity of the bubbles. Watten and Beck (1985) developed an equation to predict the dissolved oxygen concentration in the effluent of a U-tube (DO_0) for a given conduit depth (D in m), water temperature (T in °C), influent dissolved oxygen saturation (S in %), and volumetric gas to liquid ratio (G:L in %), assuming that the diffuser is placed at the beginning of the downward conduit:

$$DO_0 = \left\{ \begin{array}{l} -3.77 + 12.198 \cdot \ln\left(\frac{G}{L}\right) \\ +0.9069 \cdot D - 0.1405 \cdot T \\ +0.0575 \cdot \%S \end{array} \right\} \quad (13)$$

Boyd and Watten (1989) show data indicating that U-tube systems without off-gas recycle provided oxygen transfer efficiencies of only 30-50%, but that when off-gas recycling was used, U-tubes could increase their oxygen transfer efficiencies to 55-80%. Watten and Beck (1985) provide an equation to correct for the effects of off-gas recycling:

$$(DO_0)_{\text{recycling}} = DOCF \cdot (DO_0)_{\text{no recycling}} \quad (14)$$

where

$$DOCF = \exp\left\{ \begin{array}{l} 0.16347 - 0.0922 \cdot \ln\left(\frac{G}{L}\right) \\ +0.00279 \cdot D \\ -0.00143 \cdot T \\ -0.00078 \cdot \%S \\ +0.00393 \cdot \%R \end{array} \right\} \quad (15)$$

and

$$\%R = \frac{\text{off gas recycled}}{\text{off gas recycled} + \text{new gas}} \cdot 100 \quad (16)$$

The pump pressure required for a given U-tube, generally from 4-15 ft of water head, can be estimated by adding the head losses resulting from pipe friction, velocity, and two-phase flow. The head loss resulting from two-phase flow can be estimated with an equation provided by Watten and Beck (1985):

$$DHL = \exp\left\{ \begin{array}{l} (0.888 + 0.0758 \cdot D) \\ +1.021 \cdot \ln\left(\frac{G}{L}\right) \end{array} \right\} \quad (17)$$

At a constant pipe velocity, large diameter U-tubes used to oxygenate high volume flows have less total head loss than do correspondingly small U-tubes that oxygenate low volume flows.

Because U-tubes operate at higher pressures than LHO™ units, it is possible to add more oxygen to a flow with a U-tube than could be achieved by using a LHO™. However, U-tubes do not strip nitrogen as readily as LHO™ units, and a U-tube would produce higher total gas pressures per unit of oxygen transferred than an LHO™ unit,

Example design: LHO™

LHO™ units are relatively simple devices that are patented and licensed to Ziegler Brothers (Gardners, **PA).** For this example, the oxygen transfer unit should be expected to raise oxygen concentrations to at least 17 mg/L within the recirculating flow, **A** LHO™ unit can easily add 7-10 mg/L to the flow at a transfer efficiency of 50-70%. Ziegler Brothers will manufacture and sell LHO™ units to oxygenate 1,000 gpm (3,800 Lpm). They will also manufacture an aeration/stripping column that can stack on top of an LHO™ unit. This requires that both units use about the same hydraulic loadmg rate, which presents no problem because a hydraulic loadmg rate of 25-35 gpm per ft^2 cross sectional area works well for both LHO™ units (Weber et al. 1995) and cascade columns (Summerfelt 1993). Stacking the two gas transfer processes saves on space, tanks, and plumbing. **(A** U-tube would also have worked in this example).

Culture within circular tanks

Tanks for the intensive culture of fish are of varied shape and flow pattern (Piper et al. 1982). They are designed with considerations for production cost, space utilization, water quality maintenance, and fish management. Geometry, water velocity, and flow patterns are particularly important design considerations. The rationales for several common tank designs are reviewed by Piper et al. (1982), Watten and Beck (1987), Young and Timmons (1991), and Timmons and Young (1991).

Circular tanks are good for culturing walleye, because the tanks are relatively easy to maintain and provide a healthy and uniform culture environment. The main reason circular tanks are advantageous is because they operate with a rotating flow about the center drain. Rotational velocity can be controlled with properly

designed water inlet and outlet structures (Klapsis and Burley 1984; Tvinnereim and Skybakmoen 1989). Rotational velocity should be swift enough to carry solids and make the tank self cleaning, yet not faster than required to avoid over-exercising the fish. Water velocities of 0.5-2.0 times fish body length per second were reported in a recent review (Losordo and Westers 1994) to be optimal to maintain fish health, muscle tone, and respiration. To generate centrifugal forces capable of driving settleable solids to the tank's center drain, velocities should be greater than approximately 15 to 30 cm/s (Burrows and Chenoweth 1970; Mäkinen et al. 1988).

Circular fish culture tanks can be managed as "swirl settlers" because the rotational flow concentrates solids at their bottom and center (Goldsmith and Wang 1993). Concentrated solids can be removed in a small flow stream (as low as 5-10% of the total flow leaving the tank) by using a bottom-drawing center drain as part of a double-drain system (Makinen et al. 1988; Lunde and Skybakmoen 1993; Losordo et al. 1995). The remainder of the flow leaving the tank (roughly 90-95% of the total) is withdrawn through a fish-excluding port located above the bottom-drawing drain or part-way up the tank's side wall (M. Timmons, Cornel1University, personal communication; **S.** Summerfelt, unpublished data). According to Losordo et al. (1995), removing solids with a double-drain system has the potential to improve solids removal withn recirculating aquaculture systems.

Circular tanks provide about complete mixing, which maintains uniform water quality throughout the tank. Complete mixing means that the concentration of a constituent in the water flowing into the tank changes instantaneously to the concentration that exists throughout the tank. Complete mixing also means that the concentration of the constituent in the tank will be the same as in the water leaving the tank through the center drain. Thus, if good mixing can be achieved, all fish within the tank are exposed to the same water quality. The tank water exchange rate can be set to maintain the water quality throughout the tank.

The importance of homogeneous mixing can be illustrated by looking at how the concentrations of dissolved oxygen and carbon dioxide, and the total gas pressure change within circular tanks with high densities of fish. It is not uncommon for tanks with high densities of fish to receive influents with, for example, dissolved oxygen and carbon dioxide concentrations of 22 mg/L and 10 mg/l, respectively, and a total gas saturation of 108%. Within a well mixed tank, however, fish respiration (oxygen uptake and carbon dioxide excretion) can bring the concentration of oxygen and carbon dioxide throughout the tank to 8 mg/L and 30 mg/L, respectively, and bring the total gas pressure to less than 100% saturation. As this example illustrates, homogeneous mixing and hydraulic exchange within circular tanks can be used to maintain water quality.

Example design: culture tank

Circular culture tanks can be manufactured from many materials: fiberglass, concrete, enamel coated steel, and supported plastic liners. The circular tank is best sized based upon its exchange rate. An exchange rate of at least 1.0/hr is a good rule of thumb. Exchange rates of > 2.0/hr are not that uncommon in ultra-intensive systems using complete mixed tanks. Accordingly, a circular tank scaled for 1-2 exchange/hr with a flow of 1,000 gpm (3,800 Lpm) would range in size from roughly 60,000 to 30,000 gal (230 to 115 m^3), respectively. Tank geometry is set by considering the flow distribution necessary to achieving homogeneous mixing and solids flushing, the head required to gravity flow through the drum filter, and the strategies designed to manage the fish. A 40 ft (12.2 m) diameter tank with 5 ft (1.52 m) of water **(6** ft side wall) is one option for providmg 47,000 gal (180 m^3). At 1,000 gpm flow the water volume in this tank would be exchange 1.3 times every hour. Price of this tank would depend upon construction material. Fiberglass tanks of these dimensions cost about $16,000.

An oxygen balance on the flow indicates that 120 lb *(55* kg) of dissolved oxygen would be available for fish consumption, assuming that the oxygen entering the tank was I7 mg/L and that a minimum of 7 mg/L were maintained within the tank. Assuming that fish require 0.25 lb of oxygen for every lb of feed fed (Table 3), then there would be enough oxygen available to support fish consuming 480 lb (220 kg) of feed per day. The example fluidized-bed biofilter can support this feed rate. If a daily feeding rate of 1.5% of body rate were fed to grow out food-size walleye, then the tank could support a maximum biomass of roughly 36,700 lb (14,700 kg), equating to a maximum density of 0.78 lb/gal (82 kg/m^3) of tank volume.

Advanced oxidation with ozone

Ozone is a powerful oxidizing agent that can be put to numerous beneficial uses within aquaculture (Rosenthal 1981; Hochheimer and Wheaton 1995). Because many contaminants in water used for aquaculture are oxidizable, ozone can be used in applications ranging from disinfection to general water quality control. Ozone is particularly well suited to aquaculture because it is a strong disinfectant, capable of a wide range of oxidizing uses, with a rapid reaction rate, few harmful reaction by-products, and oxygen is produced as a reaction end product. Ozone has been used within recirculating aquaculture systems to reduce fish disease (Owsley 1991; G. L. Bullock, Freshwater Institute, personal communication); but most often ozone has been added to recirculating systems to oxidize nitrite, dissolved non-biodegradable organic material, and/or organic particulate matter (Otte et al. 1977; Otte and Rosenthal 1979; Rosenthal and Otte 1980; Rosenthal 1981; Williams et al. 1982; Sutterlin et al. 1984; Rosenthal and Kruner 1985; Paller and Lewis 1988; Poston and Williams 1988; Reid and Arnold 1992). Oxidation of organic material can produce microflocculation (Maier 1984; Chang and Singer 1991) and improve solids removal via sedimentation and foam fractionation (Sander and Rosenthal 1975; Otte and Rosenthal 1979; Williams et al. 1982), granular filtration (Wilczak et al. 1992; Rueter and Johnson 1995), or microscreen filtration **(S.T.** Summerfelt, unpublished data). Ammonia, unfortunately, is not readily oxidized by ozone except at pH values > 9 (Rice et al. 1981).

Proper application of ozone requires consideration of four unit processes: ozone gas generation, gas to liquid absorption, contact time for reaction, and ozone residual removal.

Generation

Ozone is most commonly generated in large quantities by passing relatively pure oxygen gas through a corona discharge where a portion of the oxygen **(O,)**molecules are excited to form ozone **(O,)**molecules (Bablon et al. 1991).

$$O_2 + \text{energy} \rightarrow O + O \quad (18)$$

$$O + O, \rightarrow O, \quad (19)$$

The corona discharge is produced when electric current is made to jump between two parallel electrode surfaces. In situations were only small amounts of ozone are required, ozone can also be generated by exposing oxygen gas to ultraviolet light at wavelengths less than 200 nm (Dohan and Masschelein 1983). However, producing ozone with ultraviolet light requires 6-30 times more energy than corona discharge systems (Bablon et al. 1991).

Ozone can be produced using a feed gas of air or of purified oxygen. In corona-type systems, 2-3 times less energy is required to generate ozone using concentrated oxygen gas rather than air (Bablon et al. 1991; Dimitriou 1990). Using pure oxygen instead of air also increases the amount of ozone produced from about 1-3% to 2-6% by weight (Dimitriou 1990). Because oxygen is also typically being used to maximize carrying capacity in intensive aquaculture systems where ozone would be a candidate, purified oxygen is the logical choice for generating ozone.

Ozone generation requires a low moisture feed gas (dew point temperature < -65°C), without particulates and coalescible oil mists (Dimitriou 1990). Moisture, particulates and oil mists can all greatly reduce ozone production by fouling the dielectrics within the corona discharge cells. Efficient ozone production also requires adequate cooling of the feed gas while it passes through the corona discharge to prevent elevated temperatures that would decompose a large portion of the ozone produced (Carlins 1982). Typically, heat is transferred to water or air flowing outside the &electric cell as a single-pass, straight, shell and tube heat exchanger. Ozone generation capacity can also be greatly reduced if the dielectrics within the ozone generator's corona discharge cells are fouled by hydrocarbon contamination of the oxygen feed gas. Oxygen feed gas used to generate ozone should have hydrocarbon concentrations less than 5 ppm (Dirnitriou 1990) or they can combust within the corona discharge, depositing a layer of carbon upon the dielectric surfaces that reduces both ozone production efficiency and concentration of ozone output. At the Freshwater Institute, hydrocarbon contamination was blamed for fouling the &electric cell in the ozone generator about every 3-6 months. According to engineers at PCI Corporation (West Caldwell, New Jersey), hydrocarbon concentrations > 20 ppm within the oxygen feed gas can occasionally occur in systems using industrial grade liquid oxygen. This results because hydrocarbons with vapor pressures similar to oxygen are retained when liquid oxygen is distilled. Hospital grade liquid oxygen, though more

expensive, must meet strict limits on contaminants and will not produced fouled dielectric panels. Oxygen produced with pressure swing absorption systems is also low in hydrocarbons, because hydrocarbons are largely absorbed by the molecular sieves used to strip nitrogen out of air (Dimitriou 1990).

Rice and Netzer (1982) recommend that ozone generators be operated at 50-75% of their rated production capacity (kg/d). They claim that operating at below rated ozone production capacity reduces dielectric wear and also provides excess capacity that can be used during surges in ozone demand or when another generator (plumbed in parallel) is serviced. Additionally, when feed gas rates through the ozone generator are reduced, higher concentrations of ozone can be generated within the feed gas. Energetically it is less efficient to produce these higher ozone concentrations (Rice and Netzer 1982). However, when higher concentrations of ozone are generated, the same daily amount of ozone can be met with less oxygen requirements. Thus, the ozone concentration produced can be adjusted so that the aquaculture system's ozone requirements can be met at the same time that the system's oxygen requirements are met.

Ozone has a half-life in the ambient atmosphere of about 12 hours (Rice et al. 1981). Ozone's relative stability in air is such that it cannot be stored and must be generated on site. However, ozone can be piped considerable &stances with little decomposition (Rice et al. 1981).

Absorption

The relatively high costs of ozone and oxygen make their efficient transfer into water important. Because ozone can be co-transferred with oxygen, similar transfer units can be used (see earlier section on oxygen transfer for more details). Adding ozone to a recirculating system that is already using purified oxygen only requires installation of an ozone generator and the accompanying ozone distribution, monitoring, and control mechanisms. All of the other necessary equipment (oxygen supply and dstribution system, gas transfer units, and control mechanisms) are already in place.

When ozone is transferred to water, the overall rate of ozone disappearance from the gas phase depends upon the rate it reacts with constituents within the water and the type of contacting system used. The type and quantity of constituents withn the water sets the rate that ozone reacts. Rapid reaction with oxidizable inorganics and organics will maintain a low apparent equilibrium concentration of ozone within the liquid film and increase the rate of ozone transfer. As mass transfer and reaction occur in series, either one can become rate limiting.

There are a wide range of devices that can be used for transferring ozone within air or purified oxygen into water (AWWA Research Foundation 1991; Rosenthal 1981). Units that have a continuous gas-phase (i.e., units that disperse liquid drops and films within a gas) – such as spray columns, packed columns, and multi-stage low head oxygenators (LHO™ units) – provide transfer but very little time for reaction. Units that have a continuous liquid phase (i.e., units that disperse gas bubbles within a liquid) – such as U-tubes, Speece cones, aspirators, bubble diffusers, and enclosed mechanical surface or subsurface mixers – provide both ozone transfer and some reaction time. Because they do not provide contact time for reaction, transfer units where the gas phase is continuous are generally smaller and are sometimes less costly than units where the liquid phase is continuous. Additionally, systems that pass water through air can be designed for much higher transfer efficiencies than systems designed to pass air through water. Higher transfer efficiencies are achieved by the high interfacial area provided by the packed systems and the more efficient counter-current plug flow contacting in both phases in the continuous gas phase systems (Montgomery 1985). When using units based upon absorption within a continuous gas phase, however, a separate contact chamber may be required for reaction (as described in the reaction section next).

Ozone transfer within continuous gas phase units, though not well published, can be quite good. Ozone transfer efficiency was 100% in the LHO™ units evaluated in the recirculating system at the Freshwater Institute (S.T. Summerfelt, unpublished data). In this system, complete ozone transfer occurred because: ozone is 13 times more soluble than oxygen in water according to Henry's law; gas residence times within the LHO™ chambers were approximately 45 minutes; and, there were nitrite and dissolved and suspended organic material in the water that rapidly reacted away the ozone.

Contacting and reaction

Ozone is relatively unstable in water. In a solution of pure water, the half-life of ozone is ~165 min at 20°C (Rice et al. 1981). In real systems containing organic carbon (TOC), the half life of ozone may be less than a few minutes (Glaze 1990). The levels of TOC in a high density recirculating aquaculture systems produced typical ozone half-lives that were ≤ 15 s (G. L. Bullock, Freshwater Institute, personal communication).

Although ozone is reactive, it is fairly selective in what it reacts with (Pankow and Morgan 1981). Ozone is capable of oxidizing a great many organic and inorganic substances. When ozone reacts with organic carbon, the reaction often takes place at many of the bonds which can not be readily oxidized through biological metabolism and makes the partially oxidized organic compounds biologically degradable at a faster rate (Rice et al. 1981). Rice et al. (1981) explained that the increased biodegradation rate is partially due to formation of smaller molecules and partially due to fewer higher order covalent bonds. Additionally, ozone oxidation can cause dissolved organic molecules to precipitate and colloidal organic solids to microflocculate (Maier 1984). These reactions enhance the removal of organic matter from process flow streams.

The desired end results produced by adding ozone (e.g., microflocculation, nitrite and/or color oxidation, disinfection, etc.) can be controlled by either mass transfer or lunetic limitations. Microbial reductions, in particular, are largely controlled by lunetic limitations. This means that for microbial reductions to occur, a certain dissolved ozone concentration must be maintained for a given amount of time. For disinfection, the required residual ozone concentration is usually between 0.1-1.0 mg/L and the hydraulic retention times are any where from 0.5 to 20 minutes (AWWA Research Foundation 1991).

Waters within recirculating aquaculture system contain high levels of organic matter and nitrite, and these compounds (particularly nitrite) will react with ozone in approximately stoichiometric amounts (Rosenthal 1981; Sutterlin et al., 1984; Rosenthal and Kruner, 1985; Bablon et al. 1991). However, under most conditions ozone does not convert organic molecules to carbon dioxide, but only fragments organic molecules into smaller pieces. When ozone is used only to remove color, nitrite, and microflocculate organic matter, it is not as important to maintain a measurable ozone residual as when microbial reductions are desired. To improve water quality it is often satisfactory to just add sufficient ozone. Microflocculation, however, will require time after the ozone has reacted away.

The high ozone demand of water in a recirculating aquaculture system makes maintaining an ozone residual difficult, particularly when gas-phase ozone transfer units are used. Therefore, achieving large microbial reductions in recirculating systems requires much more ozone than would be needed to disinfect the influent of typical single-pass aquaculture systems (G. L. Bullock, Freshwater Institute, personal communication). Because liquid-phase ozone contact units allow ozone gas to be transferred into water for longer periods than gas-phase units, liquid-phase units are more often used to achieve microbial reduction than gas-phase units (AWWA Research Foundation 1991).

Until recently, criteria on how much ozone should be added to recirculating aquaculture systems to produce perceptible benefits were not available. Recent research at the Freshwater Institute has shown that ozone addtion at a rate of 0.025 lbs ozone per lb feed improved water quality and microscreen filtration (S.T. Summerfelt, unpublished data), and reduced BGD associated mortalities and chemical treatments required to control BGD epizootics (G.L. Bullock, Freshwater Institute, personal communication), in a recirculating system used to culture rainbow trout. Adding ozone at a higher rate (0.036-0.039 lb ozone per lb feed) produced similar results but was much more likely to produce fish mortality when on occasion ozone accumulated to toxic levels. Although ozonation reduced BGD mortality, it failed in nearly all cases to produce even a 1 log,, reduction (i.e., 90% reduction) in numbers of heterotrophic bacteria in the system water or on gill tissue (G. L. Bullock, Freshwater Institute, personnel communication). Failure of the ozone to lower numbers of heterotrophic bacteria or to prevent the causative BGD bacterium from occurring on gills was attributed to the short exposure time to ozone residual (35 s contact chamber) and rapid loss of oxidation (ozone half-life ≤1-15 s) caused by levels of nitrite and dissolved and particulate organic material. Since ozonation equipment is expensive, it is rational to add ozone at the lowest effective rate necessary to achieve the desired results. Adding ozone at the lower rate is also justified to reduce potential for fish to be exposed to ozone,

particularly when little hydraulic retention time is available between the fish culture tank and the ozone transfer point.

The economy of using ozone within recirculating aquaculture systems is sometimes questioned, because it requires large capital and operating costs. However, if the oxygen feed gas required for increasing fish loadmg rates is used to generate ozone (assuming that 4.5 kwh/lb ozone are required to produce 6% ozone in the feed gas) and if only electric costs are considered, then it would cost less to generate ozone in the oxygen feed gas (about 0.27 kwh/lb oxygen used) than it would cost to generate the oxygen feed gas (about 0,5 kwh/lb oxygen generated). We should also note that although ozone improves recirculating aquaculture system performance, these systems can function at a somewhat lower carrying capacity without ozone.

Residual removal

Ozone may be present in the water after the contact chamber, depending upon the applied ozone dose, the ozone demand of the water, and the contact time. There are four methods to eliminate dissolved ozone: use greatly extended contact times; pass the flow through a biofilter or bed of activated carbon; strip the ozone into air with either a bubble chamber or a packed bed aeration column; or destroy the dissolved ozone with high intensity ultraviolet light (AWWA Research Foundation 1991).

No ozone gas should escape. All residual gases should be collected and vented to an ozone destruction process that will destroy the ozone before releasing the gas to the atmosphere. Ozone gas destruction can be catalyzed by heat, media (such as granular activated carbon or a manganese dioxide or other coated media), or a combination of both (AWWA Research Foundation 1991). It is possible that ozone gas can escape from ozone transfer units, particularly those that are characterized by a continuous gas phase, because often these transfer units use an orifice plate to distribute the water flow across the top of the transfer unit. The layer of water covering the distribution plate and the water surface at the bottom of the unit are the barriers that prevent ozone containing gas from escaping the unit. If water flow to this type of unit is interrupted, however, the water barrier above the orifice distribution plate disappears and ozone gas within the unit escapes directly into the surroundings. To safely use a unit with a continuous gas phase for ozone addition, an automatic method must be provided to shut off the ozone when flow to the unit ceases. It is possible that a similar problem could result within units that pass air through water if, after water flow stopped, gas pressure overcame static water head and forced an exit out either the water influent of effluent paths.

Ozone toxicity

Ozone can be harmful to humans and highly toxic to aquatic organisms at low concentration levels. Ozone is capable of oxidizing many biochemical compounds present in living organisms, including amino acids, pyrimidine nucleotides, fatty acids, flavins, and proteins containing sulfhydryl groups (Carmichael et al. 1982). The most severe oxidation of living tissue is the production of short-lived free radicals that are highly reactive and damage membrane-bound enzymes and lipids.

Table 7. Toxicity of dissolved ozone to fish.

Effect	Ozone concentration (mg/L)	Species	Reference
96-hr LC50	0.0093	rainbow trout	Wedemeyer et al. (1979)
lethal	0.01-0.06	rainbow trout	Roselund (1975)
60% mortality after 4 wks	0.01	bluegill	Paller and Heidenger (1979)
lethal	0.2-0.3	fat head minnows	Arthur and Mount (1975)
24-h LC50	0.38	white perch	Richardson et al. (1983)
24-h LC50	0.06	bluegill	Paller and Heidenger (1979)
96-h LC50	0.08	striped bass larvae	Hall et al. (1981)

Fish

Ozone destroys epithelium covering the gill lamella which results in a rapid drop in serum osmolality (Paller and Heidinger 1979: Wedemeyer et al. 1979) and, if mortality does not occur immediately, can leave the fish highly susceptible to microbial infections (Paller and Heidinger 1979). The minimum ozone concentration lethal to fish is about 0.01 mg/l, but it depends upon species and life stage (Table 7).

Technology does not exist to continuously monitor the concentrations of dissolved ozone that can be lethal to fish. Oxidation reduction potential (ORP) has been used by many, with varying degrees of success, as an indirect means to monitor and control ozone addition.

Humans

Exposure to ozone in air is hazardous to humans as ozone attacks the respiratory tract, producing inflammation, pulmonary edema accompanied by capillary hemorrhage and, with prolonged exposure, ozone has been shown to cross over into the bloodstream and attack blood cells and serum proteins (Carmichael et al. 1982). OSHA standard allows for a permissible exposure level of less than 0.1 ppm on a time weighted average for an 8-hour work period and a maximum single exposure level of 0.3 ppm for less than 10 minutes duration.

Example design: ozonafiun

Based on current research, the optimum effects of ozonation within recirculating aquaculture systems are obtained at doses of about 0.025 lb ozone per lb of feed fed. It is recommended that the ozone generation capacity be around 1.5-2.0 times the ozone demand. In this example, a single modular recirculating aquaculture system would require an ozone generator with the production capacity of roughly 25 lb (11 kg) of ozone per day. An industrial grade ozone generator of this capacity would cost around $25,000, making ozonation the most expensive unit process within the recirculating system.

As discussed above, ozone is most efficiently generated within an oxygen feed gas. Because oxygen is already required within the recirculating aquaculture system, it is most efficient to co-transfer ozone with the oxygen feed going into the system's oxygen transfer unit (i.e., LHO™ in this example). A draw-back of addmg ozone within the LHO™ unit is the potential to accumulate residual ozone within the fish culture tank (placed just downstream of the LHO™ unit). An ozone reaction chamber below the LHO™ unit (i.e., LHO™ sump tank) that provided several minutes of water retention time would provide additional time to expend the ozone's oxidative power prior to the fish culture tank. A 5,000 gal (19 m^3) tank would provide 5 min retention time for 1,000 gpm (3,800 Lpm) flow.

Dissolved ozone cannot be measured continuously at the levels required to protect fish (<0.01 mg/l). An indirect measure of ozone residual is the water's oxidation reduction potential (ORP), which is a measure of a water's potential to oxidize and thus a measure of the waters toxicity to fish. The ORP can be monitored within the fish culture tank and can be used to control ozone addition such that ozone residual is not present within the fish culture tank. A safe ORP for freshwater is around 300 mv, dependmg upon pH.

pH control

Alkalinity and pH play an important role in aquaculture. The pH is a measure of the hydrogen ion concentration and controls acid/base chemistry. Alkalinity, a measure of the acid neutralizing capacity of a solution, depends on the concentrations of the bicarbonate, carbonate, hydroxide, and hydrogen ions. An alkalinity of at least 50 mg/L as calcium carbonate should be maintained during nitrification to prevent pH instability (Gujer and Boller 1984). Malone et al. (1993) recommends an alkalinity of at least 100 mg/L as calcium carbonate.

The equilibrium of many of the chemical species important in aquaculture is controlled by pH. Of great importance is the influence of pH on the equilibrium of the ammonia and carbonic acid systems. Taking the equilibrium of ammonia and ammonium for example:

$$NH_3 + H_20 \Leftrightarrow NH_4^+ + OH- \qquad (20)$$

Because the ammonia (NH_3) associates with water (H_2O) to form hydroxide (OH-) and ammonium (NH_4^+), the resulting equilibrium is a function of pH:

$$\frac{\left[NH_3\right]^1}{\left[NH_4^+\right]} = 10^{(pH-pK_a)} \qquad (21)$$

and temperature (at 25°C, $pK_a = 9.245$):

$$pK_a = 0.09018 + 2729.92/T,°K \quad (22)$$

such that increasing pH or temperature shifts the equilibrium to form more ammonia. The location of equilibrium is important because ammonia (unionized) is much more toxic to aquatic organisms than ammonium (Meade 1985).

The pH-equilibrium relation between carbon dioxide and the species in the carbonic acid system is equally important, though more complex. Dissolved carbon dioxide can combine with water in a hydrolysis reaction to form carbonic acid:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \quad (23)$$

However, there is about 633 times as much carbon dioxide in water as carbonic acid under equilibrium conditions. Depending upon pH, carbonic acid dissociates, releasing hydrogen ions and bicarbonate ions. Similarly, bicarbonate ions dissociate, releasing additional hydrogen ions and carbonate ions:

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \quad (24)$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^= \quad (25)$$

When pH is 6.5-9.5, the equilibrium carbon dioxide concentration can be approximated using pH and alkalinity (Summerfelt 1993):

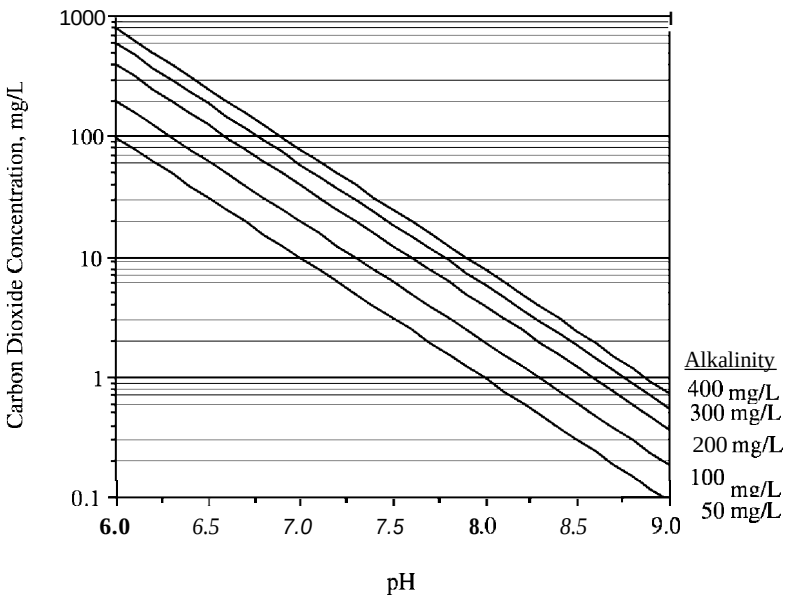

Figure 10. Carbon dioxide equilibrium with the carbonic acid system as a function of pH and alkalinity (at 25°C).

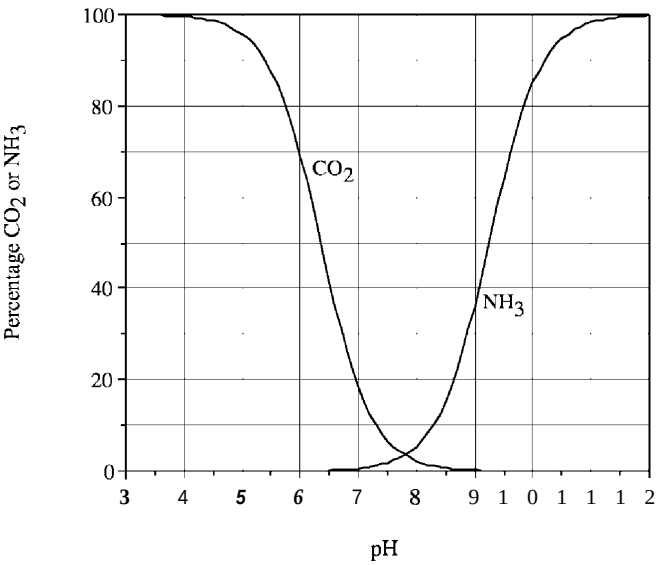

Figure 11. Percentage of carbon dioxide and ammonia as a function of pH (at 25°C).

$$C_{CO_2} = \mathbf{Alk} \cdot 10^{(6.3-pH)} \quad (26)$$

where C_{CO_2} is the concentration of carbon dioxide in mg/L (Figure 10).

Comparing the range of pH values where ammonia and carbon dioxide coexist indicates that the smallest fractions of both carbon dioxide and ammonia coexist at a pH of 7.5-8.2 (Figure 11). Changing the system pH only 1 unit changes the corresponding equilibrium carbon dioxide or ammonia concentration 10 fold.

Chemical treatment can be used to maintain a pH that will minimize the potentially toxic effects of ammonia and carbon dioxide in recirculating aquaculture systems. The treatment process consists of adding a supplemental source of alkalinity such as lime, caustic soda, soda ash, or sodium bicarbonate to the water (Bisogni and Timmons 1991). Lime, caustic soda, and soda ash react with carbon dioxide to produce bicarbonate alkalinity. Adding sodium bicarbonate is simply a source of bicarbonate alkalinity and a means to increase pH. An alternate way to maintain pH with lower chemical additive costs would be to increase make-up water exchange rate if the make-up water con-

tained medium to high levels of alkalinity. Make-up water may require heating and the costs saved in chemical additives may not be justified due to increased heating costs.

Lime may be purchased as calcium oxide (CaO), which is also known as "burned lime," "quick lime," or "unslaked lime." When calcium oxide is added to water it hydrates, forming calcium hydroxide ($Ca(OH)_2$) which is also known as "slaked lime." Although calcium hydroxide is very soluble in water, the dosages that are normally used produce a slurry that is called "milk of lime" because of its chalky appearance. When calcium hydroxide dissolves in water, it produces hydroxide ions that react with carbon dioxide forming bicarbonate ions:

$$OH^- + CO_2 \Leftrightarrow HCO_3^- \qquad (27)$$

Caustic soda. Sodium hydroxide (NaOH), is more expensive than lime. It is very soluble in water. When sodium hydroxide dissolves in water, it dissociates and releases hydroxide ions into solution that react with carbon dioxide to form bicarbonate ions.

Soda ash. Sodium carbonate (Na_2CO_3), is also a more expensive source of alkalinity than lime. It, too, is very soluble in water. When soda ash dissolves in water it dissociates, releasing carbonate ions into solution that react with carbon dioxide to form bicarbonate ions:

$$CO_3^= + CO_2 \Leftrightarrow 2HCO_3^- \qquad (28)$$

Sodium bicarbonate ($NaHCO_3$) is a popular chemical additive for maintaining alkalinity in a recirculating aquaculture system (Bisogni and Timmons 1991). It is very soluble and dissociates in water to release bicarbonate ions. Bicarbonate ions do not react with carbon dioxide, but they can shift the equilibrium of the carbonic acid system through a shift in pH.

The rate of interconversion of various carbonate forms affects the buildup of carbon dioxide in water. The rate of ionization of carbonic acid into bicarbonate and carbonate ions is nearly instantaneous, but the rate of hydration of carbon dioxide into carbonic acid is relatively slow (Kern 1960).

$$CO, + H_2O \Leftrightarrow H_2CO_3 \qquad (29)$$

Accumulation of carbon dioxide occurs when the rate of production of carbon dioxide by the fish exceeds the rate at which carbon dioxide is lost to water replacement and to the atmosphere. Carbon dioxide will then build up the carbonic acid concentration. **As** it does, the concentration of bicarbonate will increase and the concentration of carbonate will go down. These changes in the relative amounts of carbonic acid and its ion products will lower pH. If carbon dioxide is removed from solution, carbonic acid will slowly dehydrate to reestablish the equilibrium. As this happens, bicarbonate will disproportionately release carbonic acid and carbonate ions into solution.

Conclusions

T h e technology described here consists of some of the most cost and technologically effective unit processes available to recirculating systems. The descriptions provided here can be used by an engineer to design a recirculating aquaculture system capable of treating from as little as 100 gpm to as much as several thousand gpm (or more). The system scale is primarily limited to the amount of risk one is willing to place in a single recirculating production module and the ability to manage the fish and the hydraulics in the fish culture tank.

Although recycle aquaculture systems have many advantages, the systems have large capital investments and high operating expenses relative to other production technologies. To date, few U.S. fish producers have found it economically viable to culture fish where large amounts of energy must be expended for pumping or heating water. As a result, many recirculating systems used to culture fish commercially have not been technically or economically effective and have failed. Recirculating systems that have attained profitability rely on technologies that minimize capital and operating costs for water treatment. Marketing and production management, however, may play an even larger role in the economic success of the recirculating system (Hanluns et al. 1995).

The economics of fish production are the controlling criteria for determining whether-or-not to construct the facility. However, the economics of walleye production within a recirculating system were not presented in this chapter. Wade et al. (1996) reported the economics of

fish production at several scales are currently being evaluated within a system as described here.

Example design: system integration and layout

General guidelines for integrating and laying out a recirculating aquaculture system follow:

- Solids should be removed from the recirculating flow immediately after they leave the culture tank, before any pumping occurs and before biofiltration.
- Solids should not be stored in the recirculating system or they will begin to degrade and leach nutrients.
- Pumping should occur only once each pass.
- Carbon dioxide should be air stripped after reaching its highest concentration before oxygen supersaturations are produced, and before returning to the fish culture tank (i.e., just after the biofilter and just before the oxygenation unit).
- Alkalinity is best added for pH control after carbon dioxide has been stripped and just before the fish culture tank (i.e., within the sump tank of the air stripper).
- Air stripping should occur before the oxygen transfer unit, because the aeration it produces brings the oxygen levels in the flow up to near saturation. Bringing an oxygen saturated flow to the oxygenation unit allows all of the oxygen added to go towards supersaturating the water.
- Oxygen should be added to supersaturate the flow just before the fish culture tank. The water should be kept from significant contact with the atmosphere after the oxygen supersaturation has been obtained.
- Ozone should be generated in the oxygen feed gas used to supersaturate the flow.

The recirculating system designer must also consider the hydraulics that are encountered when transporting water from unit to unit. In this example, water is

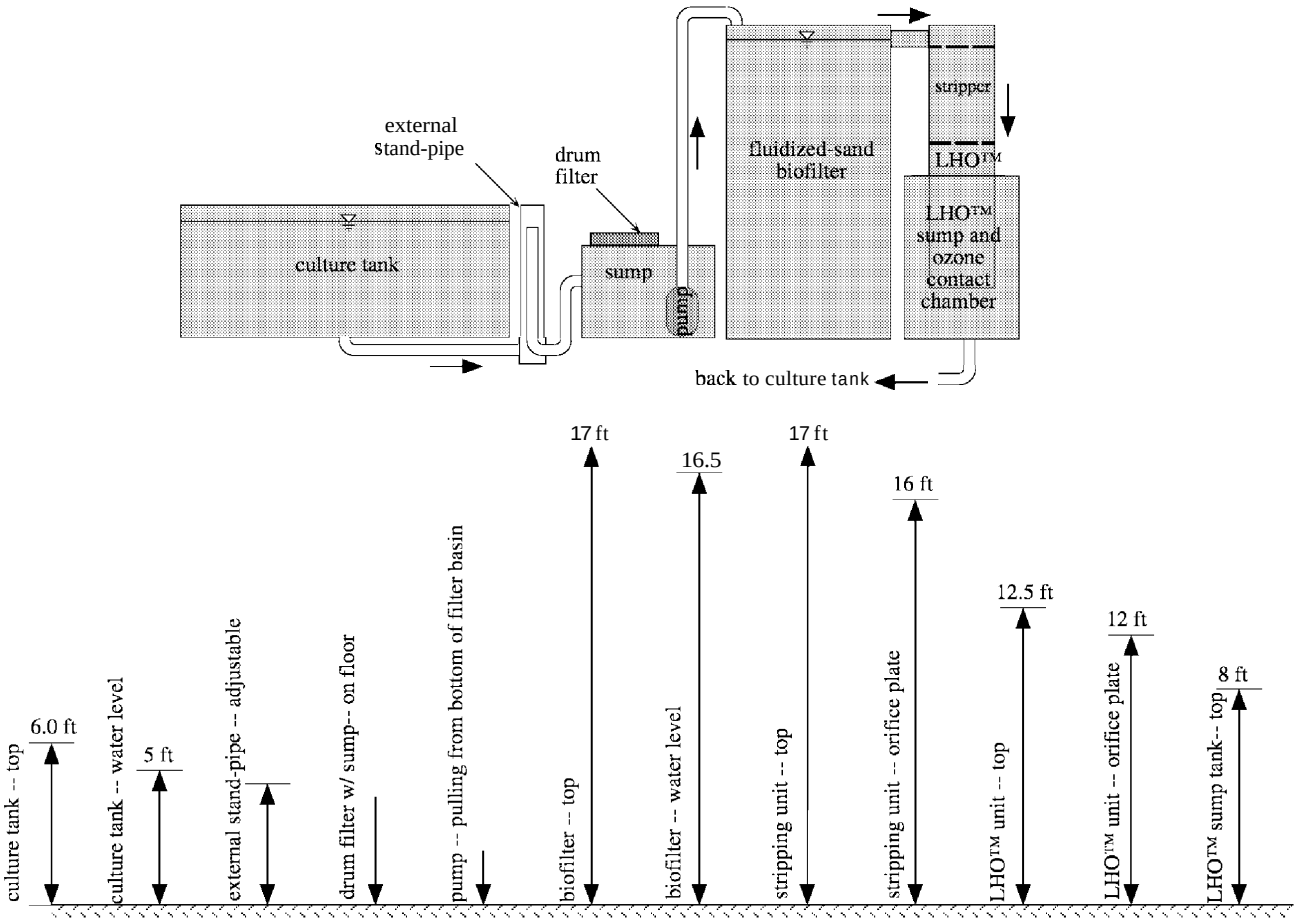

Figure 12. Layout of example recirculating aquaculture system.

pumped only once. Gravity must be used to move water in all other places. Elevations suggested to integrate and create gravity flow through the example recirculating system are presented in Figure 12.

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