IV. FISH REARING UNITS

INTRODUCTION

Flow-through fish units come in many shapes, depths and operational modes. Two flow patterns are commonly used: plug-flow and circular flow (Figure 1). In plug-flow mode, water enters at one end and travels in a direct line, at a uniform velocity, to outflow at the opposite end. The rectangular raceway is the most common example of this, while an upflow silo is another. In a circulating mode, water enters a unit at a selected location and travels in a circular motion towards a central outlet. The circular or round tank is the most common representative of this design. A second popular version of a circular-flow unit is the square Swedish tank with rounded corners. This latter system was specifically developed for rearing Atlantic Salmon, and for that reason is shallow to provide this species a two dimensional rather than three dimensional space based on the belief that Atlantic salmon do not tolerate stacking.

A hybrid rearing unit is the Burrows pond (Figure 2). This type of pond was designed to incorporate the advantages of both rectangular plug-flow and circular units into a single pond. Water is introduced through a series of nozzles at different depths into one or two opposite corners of the pond. Curved vanes radiate from the center wall towards each corner to reduce turbulence and maintain an even water flow. Velocities diminish as flow approaches the center wall, allowing solids to settle and be carried out by floor drains positioned on either side of the center wall, but in opposite locations (Burrows and Cheneveth 1970). For a time, this system was very popular with public agencies producing Pacific salmon. Few, if any, are constructed today because of high cost and poor self-cleaning properties.

A more recent attempt to combine the advantages of plug-flow and circulating rearing units (Watten and Johnson, 1991) was the cross-flow rearing unit. Water is introduced through a series of inlet ports near the bottom along the longitudinal axis, and exits through a perforated
drain line opposite the intake line (Figure 3). The tank can be converted to a plug-flow mode of operation for cleaning and fish handling.

Circular or round ponds enclose the largest volume of water per unit wall area (Figure 4). Depending on dimensions, a raceway requires 1.5 to 3.0 times as much wall area to enclose a given volume of water compared to a round tank. However, rectangular shapes are more economical with respect to floor space.

FLOW VELOCITY

There are interesting differences between plug-flow and circulating rearing units with respect to the rearing environment. From here on the term raceway will be used when referring to plug-flow units and the round tank will be representative of the circulating rearing unit. Raceways create a distinct gradient in water quality from inflow to outflow. Dissolved oxygen (DO) levels decrease downstream, while metabolic byproducts, such as ammonia and carbon dioxide, increase. Water velocities are generally very low, from 1.0 to 3.0 cm per second (0.033-0.1 ft/s). Feces and excess feed settle quickly and accumulate on the bottom. This is a distinct disadvantage since fish activity resuspends these materials, breaking them into finer fractions which take longer to settle out. As a result, some solids move out of the rearing unit, but overall, raceways are not self-cleaning.

The poor handling of solids is a serious drawback of raceways for the following reasons:
1. solids settle and are broken up by fish activity;
2. solids re-enter the water column as finer particles and so pollute the rearing environment;
3. broken or fragmented solids take longer to resettle and, therefore, require a larger settling basin;
4. smaller particles, which have larger surface to volume ratio; leach nutrients faster into the water;
5. A portion of fractured solids continuously leaves the rearing unit and, were serial reuse is applied, degrade water quality in lower rearing unit.

Fish in raceways often concentrate themselves in the upper one-third of the system and sparsely occupy the lower two-thirds. Since the fish themselves select this higher rearing density, it seems logical to shorten the raceway to one-third without altering flow. This would increase water exchange rate threefold, generally resulting in an exchange rate of around four per hour. The next logical step would be to utilize the raceway in its entirety by increasing flow to affect an exchange rate of four per hour for the entire raceway, rather than shortening the tank. Even this relatively high exchange rate does not create water velocities exceeding 5 cm/s (0.016 ft/s) unless the unit is extremely long.

Flow velocity in a raceway can be calculated as:

\[ v = \frac{L_m \cdot R}{36} \]  \hspace{1cm} (1)

and

\[ v = \frac{L_f \times R}{3600} \]  \hspace{1cm} (1a)

Where \( v \) is velocity in cm/s, \( L_m \) raceway length in meter and \( R \) the familiar exchange rate as water turnover rates per hour.

The value of 36 represents seconds per hour (3600) divided by 100 (to convert meters to cm). To accomplish a velocity of 10 cm/s at an \( R \) of 4 would require a raceway length of 90 m (nearly 300 feet). Commonly raceways range from 18 to 35 m (60 to 120 feet), which would
give velocities from 2.0 to 4.0 cm/s (0.067 - 0.133 ¹/s) at an exchange rate of 4. This is 
considerably below a cleaning velocity of 10 to 20 cm/s, and also below recommended velocity 
for fish conditioning which range from 0.5 to 2.0 body lengths per second (BL/s) (Poston et al 
1969; Besner and Smith 1983; Woodward and Smith 1985; Leon 1986; Totland et al. 1987; 

Youngs and Timmons (1991) pointed out these deficiencies and stated that in practice 
raceways can be managed much closer to their design requirements for oxygen supply than for 
cleaning requirements: in other words, raceways are designed to function below required 
cleaning velocities. To overcome this deficiency, it is necessary to either design very long 
raceways, or raceways with very small cross-sectional areas. To at least partially overcome these 
shortcomings with standard size raceways, Boersen and Westers (1986) propose the use of 
baffles spaced at equal distances. Such baffles are solid barriers, forcing all water through a 
narrow gap between the lower edge of the baffle and the bottom of the tank (Figure 5). The 
width of this gap determines water velocity through the gap. With a gap one-tenth of the water 
depth, water velocity under the baffle is approximately ten times average raceway velocity. In 
the above examples, water velocity under the gap would be 20 and 40 cm/s. Generally, optimum 
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velocities is to make the tank self-cleaning, removing solid waste as it is generated, thereby 
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small end section of the raceway dedicated to settling (Figure 6). As a rule of thumb, the settling 
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The use of baffles in raceways does not completely overcome the shortcoming of 
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over a small area along the bottom. Fish may utilize this high velocity zone, but there is room for
only a relatively small proportion of the total population in that zone. Fish probably will exchange positions and select different areas in the tank over time.

Youngs and Timmons (1991) recommend that safe velocities for salmonids should be one half the critical speed based on data provided by Beamish (1978). Safe velocity can be calculated as:

\[ v_s = (0.5) \cdot (10.5/L^{0.37}) \]  

(2)

Thus, for a 10 cm fish, raceway velocity should not exceed 2.2 BL/s or 22 cm/s, while for a 20 cm fish, this is 1.73 BL/s or 35 cm/s.

Velocity, Benefits to Fish

Totland et al. (1987) exercised large Atlantic salmon Salmo salar; (56.3 cm and 2,038 g) during culture at velocities of 0.45 BL/s. They found improved survival of exercised fish over caged fish except during the initial two week adjustment period when losses were 1.2 percent, much greater than the reference group. Final losses were 4.4 percent for exercised fish and 8.8 percent for reference fish. Weight gain was nearly 40 percent greater in exercised fish, and by industry standards, quality was rated 9.2 percent higher. Based on equation 2., the recommended velocity for 56-cm fish would be 1.3 BL/s, but favorable results were obtained at the lower velocity of 0.45 BL/s. Neenham (1988) recommended velocities between 0.5 to 1.0 BL/s for Atlantic salmon, which he considers a riffle species in contrast to trout and coho salmon Oncorhynchus kisutch which tend to live in pools. Besner and Smith (1983) exposed coho salmon to velocities of 0.2 BL/s (control) and 1.0, 1.5, and 2.0 BL/s. Endurance in test groups improved over the control group. They concluded that long-term velocity regimes before release may be profitable for survival, because this early training allowed energy conservation during migration. Woodward and Smith (1985) exercised rainbow trout O. mykiss at velocities of 1.5 BL/s for 42 days. This improved fish quality in terms of better stress resistance; indeed sustained
swimming exercise has been shown to improve disease resistance. Leon (1986) found improved disease resistance, growth rates and feed conversions when brook trout Salvelinus fontinalis were reared in velocities of 1.5 to 2.0 BL/s.

Josse et al. (1989) maintained rainbow trout at sustained velocities of about 2.5 BL/s with bursts of 3.8 BL/s for a few minutes daily, the latter velocity specifically aimed at developing white musculature without exhausting fish. Continuous swimming also had a positive effect on tail muscle developmental. Red muscle area increased by 27%, the white by 9% over controls maintained in still water. Furthermore, muscle fibers increased 75% and 39% in number, respectively, resulting in denser muscle as well. Josse et al. (1989) concluded that permanent rotary water movement ensured perfect homogenization of the medium, optimal distribution of fish, and inhibition of territorial behavior which, in turn, resulted in 100% increase in rearing density over the control group (68.35 kg/m³ versus 35.98 kg/m³). Mortalities during early rearing were significantly less in the high velocity environment, and experimental fish grew as well as controls, despite sustained swimming action. They also concluded that experimental fish were most likely better prepared for survival in nature.

Earlier studies by Poston et al. (1969) pointed out similar benefits to rearing at high velocity. Brook trout, exposed to velocities in excess of 2.0 BL/s had increased stamina, more efficient feed conversion ratio, and faster replacement of muscle glycogen after exposure to strenuous exercise in a stamina tunnel, compared to unconditioned fish. Those authors recommended physical conditioning of hatchery trout before stocking.

Forced exercise, contrary to common expectations, seems to result in reduced O₂ consumption compared to non-exercised fish. This reduction has been attributed to physiological adaptations, such as increased white muscle activity (Nahhas et al. 1982), improved cardiac output, and enhanced oxygen carrying capability of blood (Woodward and Smith 1985). There may also be reduction in energetic costs of ventilation. Fish that maintain position in fast flowing water need only to open their mouths to ventilate their gills. This has been termed "ram"
ventilation. Ram ventilation can contribute to saving energy in two ways: (1) passive movement of water over the gills which, in turn, results in (2) a more streamlined flow of water over the body. This latter hydrodynamic advantage results in small, but measurable, reductions in oxygen consumption (Randall and Daxboeck 1984). However, cost of active ventilation in a dense media such as water can be substantial; reports indicate from 10 to 30 percent of total oxygen uptake is required for active ventilation (Shelton 1970; Jones and Randall 1978).

Watten and Johnson (1990) offer yet another theory for the better performance of fish in high water velocities. The elevated surface velocities in their cross-flow tank, along with a homogenous DO concentration, may accelerate diffusion of oxygen at the air-water interface. This would make more oxygen available than that added initially with inflow water.

Sustained velocities for small salmonids (< 0.5 kg) should be maintained, if at all practical, between 1.0 to 1.5 BL/s. These are well below those expressed with equation 2 or those used by Josse et al (1989) and Poston et al. (1969).

Plug-flow rearing units do have physical, i.e., flow rate, limitations based on the maximum practical flow rate per cross-sectional area. Plug-flow rearing units use foot screens to keep the fish confined. The screens, basically, represent the cross-sectional area of the rearing unit. The volume of water they can "process" without frequent plugging, depends on the water quality (debris load) and screen type (percent openings) and size of openings.

Raceways for large fish can accommodate flow rates of 1000 to 2000 lpm per square meter (25-50 gpm 1 ft²), tanks for median-sized fish 750 to 1250 lpm per m² and troughs for small fish from 500 to 1000 lpm per m². Table 1 shows flowrates for raceways, tanks, and troughs based on averages for the above values (1500, 1000, and 750 lpm).

Also shown are required flow rates to meet the specific selected velocities for these units, namely 3.0, 2.0, and 1.0 cm/s respectively. Furthermore, we show the loading values based on
5.0 mg/l available oxygen (AO = 5.0) and feeding levels in %BW of 1.0, 2.0, and 4.0 respectively. The results are too high rearing densities. If there are to be 60, 40, and 25 respectively for raceway, tank, and trough, then these units should be placed in series of 2, 3, and 5 respectively.

**ROUND TANKS, WATER QUALITY CHARACTERISTICS**

Round tanks do not have a distinct water quality gradient and frequently the rearing environment is homogeneous. Colt and Watten (1988) described the ideal round tank as a continuous-flow, stirred-tank reactor where dissolved gas concentrations are well mixed and equal to concentration in the effluent. However, Tvinne and Skybakmoen (1989) pointed out that in a complete mixed flow reactor, the maximum possible water exchange will be 63.2 percent during the theoretical mean retention time. High concentrations of oxygen entering round tanks are rapidly diluted with lower DO water. This is very different from raceways. If incoming water from a raceway has 10.0 mg/l DO, available oxygen to the fish might be 4.0 mg/l (10.0 - 6.0). Dissolved oxygen levels gradually decline from upper to lower portion of the tank, while the opposite is true of waste products in solution. In a hydraulically ideal round tank, with near homogeneous water quality, the rearing environment has the same DO level as effluent water. If the same oxygen consumption is allowed as in the raceway example above (same level of fish production per unit of flow), the rearing environment will be degraded to a uniform 6.0 mg/l, and the production capacity per unit of flow would have to be reduced by 25 percent (from 10.0 to 7.0 makes only 3.0 mg/l DO available rather than 4.0 mg/l). When water is sprayed forcefully onto the surface, some aeration is accomplished. This could make the round tank as productive as a raceway or, where outflow DO levels are maintained equal to those of raceways, the round tank actually may have a higher production potential.

Round tanks are very popular, especially for production of Atlantic salmon in Norway, Scotland, and New England. Whenever low rearing densities are practiced, round tanks seemed to be preferred over raceways. One advantage round tanks have over raceways is that water
velocities are, to a large extent, controllable. This most critical factor in water velocity control is 
design of inlet and outlet arrangements. Tvinneirn and Skybakmoen (1989) tested three 
submerged inlet systems: a horizontal spray bar, a multilevel vertical slot, and a point source 
inlet. The vertical slot inlet provided stable and uniform flow patterns at all flow rates, along 
with stable bottom current towards the outlet. The horizontal inlet accomplished better mixing 
and water exchange, but created weaker and less stable bottom current, and was therefore poorer 
in self-cleaning. The single point source inlet gave an unstable flow and insufficient water 
exchange. It also created very high velocities along the edge, driving fish to the center of the 
tank where mixing may be inadequate. Tanks were tested without fish and at exchange rates 
from 0.5 to 1.2 per hour and inlet velocities ranged from 20 to 235 cm/s. The tests were 
conducted in tanks with non-sloping bottoms. Tanks with bottom sloping toward the center are 
easier to manage as far as the self-cleaning characteristics are concerned, because bottom water 
velocities are not as critical in solid removal.

Circular tanks can function as "swirl settlers." For this they need a relatively swift 
velocity in excess of 15 to 30 cm/s, a velocity that is strong enough to move settleable solids 
along the tank bottom to a center drain.

Distributing the inlet flow with both vertical and horizontal perforated pipes can achieve 
uniform mixing and effectively transport waste solids along the tank bottom to the center drain 
(Summerfelt 2000). See Figure 7.

When a circular tank is managed as a "swirl settler", the bulk flow is discharged from a 
location distant from the settleable solids concentrated at the bottom and center of the tank. The 
majority of the settleable solids should then leave the tank through the bottom center drain with 
only 5-20% of the total flow. The bulk of the flow, withdrawn from an elevated drain is 
relatively free of settleable solids. There are a number of dual-drain designs, some are patented. 
A recent, non-patented, design is the "Cornell-type" dual-drain tank with an elevated drain 
partway up the tank sidewall (Figure 8).
Removing settleable solids from the bulk flow has many advantages. Less water needs to be treated intensively, higher concentrations of settleable solids (20 mg/l or more) make micro-screening more effective. The quality of the bulk flow relatively free of solids, can be reused again. Dual-drain tanks are of excellent design for partial or semi-reuse systems, to be discussed later.

Round tanks are more difficult to manage for fish handling, since fish cannot be cornered as in raceways. This difficulty can be overcome with specially designed fish crowders (Figure 9). Removing dead fish is also more labor intensive. On the other hand, round tanks lend themselves more readily to automatic feeding systems, requiring fewer feeding stations than raceways to distribute feed throughout the rearing unit, since water currents will distribute the feed more uniformly. Major differences between raceways and round tanks, with respect to design and operation, are summarized in Table 1.
Table 1. Flow rate limits for plug-flow rearing units (raceway, tank and trough) based on maximum flowrate capacity per cross-sectional area ($M_{Q_{c/s}}$) in lpm/m², and minimum selected operational velocity ($v$) in cm/s. Raceway (RW): $M_{Q_{c/s}} = 1500$; Tank (TK): $M_{Q_{c/s}} = 1000$; and Trough (TR): $M_{Q_{c/s}} = 750$. Velocities are 3.0, 2.0, and 1.0 cm/s respectively.

<table>
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<th>Type</th>
<th>$l$ m</th>
<th>$w$ m</th>
<th>$d$ m</th>
<th>$RV$ m³</th>
<th>$c/s$ m²</th>
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<td>3600</td>
<td>3.0</td>
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<td>0.6</td>
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<td>1.0</td>
<td>120</td>
<td>100</td>
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<td>125</td>
<td>150</td>
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\[
Q_{c/s} = M_{Q_{c/s}} \times C/S
\]
\[
R_{c/s} = \frac{(Q_{c/s} \times 0.06)}{RV}
\]
\[
Q_v = \frac{(RV \times R_{c/s})}{0.06}
\]
\[
R_{c/s} = \frac{(v \times 36)}{l}
\]
\[
L_d = \frac{(5.0 \times 100)}{(250 \times \%BW)}
\]
\[
D = \frac{(L_d \times R_v)}{0.06}
\]

Recommended Rearing Densities:

- RW = 60; TK = 40; TR = 25

Series:
- RW = 2; TK = 3.0; TR = 5.0

- AO = 5.0
- $\%BW = 1.0$ (RW)
- 2.0 (TK)
- 4.0 (TR)
INTENSIVE FISH PRODUCTION:
(1) DESIGN, OPERATION AND CARRYING CAPACITY
OF RACEWAY (PLUG-FLOW) AND ROUND TANK
(CIRCULATING) FISH REARING UNITS

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Abstract.—Two basic types of fish rearing units: plug-flow (raceway) and circulating (round tank), are compared with respect to their physical, hydraulic, water quality and fish production characteristics.

Raceways require 1.5 to 2.0 times as much wall area as do round tanks. Also, less wall thickness is required for round tanks. Raceways are operated far below recommended water velocities of 0.5 to 1.0 body lengths of the fish per second. Even with relatively high water exchange rates of 4 to 6 per hour, generally velocities do not exceed 5.0 cm/s. Round tanks can create optimum velocities through proper design of the inlet and outlet structures, and velocities are largely independent of intake volume.

Raceways have a distinct water quality gradient from intake to outlet, while round tanks have a more or less homogeneous water quality environment. Raceways, due to their capability to operate at high water exchange rates, can support fish at high rearing density. The homogeneous water quality environment and relatively low exchange rate in round tanks does not allow for high density rearing. In round tanks, water quality equals effluent quality and this can create a condition of continuous low level un-ionized ammonia in the presence of relatively low dissolved oxygen levels, a major disadvantage. The application of pure oxygen can overcome this disadvantage, since the homogeneous rearing environment can be maintained at saturated DO level making high density rearing possible without exposing fish to hypoxic conditions.

These facts make it worthwhile to consider round tanks for high density fish production, since they can also provide optimum water velocities for fish health conditioning, while simultaneously they can be self-cleaning. This combination is difficult, if not impossible, to accomplish with standard size raceways.

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The present trend in fish production appears to follow that of chickens, hogs and other meat producing industries, i.e., an evolution towards increased intensity, or greater production per unit of space. This requires greater reliance on controlled environments, through mechanization and automation, and less on human action. Today's technology makes this approach possible. Properly controlled rearing environments also permit high rearing density for most species of fish. Such environmental controls start with source water which must be free of specific pathogens, have the right chemical and physical characteristics and a relatively stable temperature regime within the desired range for the cultured species. This may require some form of pre-treatment of water such as disinfecting, degassing, aerating, buffering, filtering and heating or cooling.

Since water quality is impacted by fish metabolism, proper rearing water quality parameters must be known for the species reared, such as tolerance for accumulation of metabolic byproducts and dissolved gas concentrations. Of immediate interest and concern are dissolved oxygen, ammonia, carbon dioxide and suspended solid (feces and waste food). As these variables are related directly to quantity of feed added to the system (Haskell 1955), carrying capacity is in direct proportion to amount of feed applied. Feeding rates are influenced primarily by water temperature and fish size.

High density rearing requires large flows of water to deliver oxygen and remove metabolic waste products, just as power ventilation (air exchange) as well as liquid and solid waste removal are required in intensive chicken and hog production. This paper will discuss intensive fish culture in two types of flow-through rearing units, the plug-flow linear raceway and the circulating round tank. This comparison will be followed by a general review of limits to intensive fish culture, then a design of several raceway and round-tank systems to optimize production under different constraints.

Comparing Round Tanks and Raceways

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Flow velocity in a raceway can be calculated as

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with symbols given in Appendix Table 1. The value of 36 equals seconds per hour (3600) divided by 100 (to convert meters to cm). To accomplish a velocity of 10 cm/s at an R of 4 would require a raceway length of 90 m (nearly 300 feet). Common raceways range from 18 to 35 m (60 to 120 feet), which would give velocities from 2.0 to 4.0 cm/s at an exchange rate of 4. This is considerably below a cleaning velocity of 10 to 20 cm/s, and also below recommended velocity for fish conditioning which range from 0.5 to 2.0 body lengths per second (BL/s) (Poston et al. 1969; Besner and Smith 1983; Woodward and Smith 1985; Leon 1986; Totland et al. 1987; Needham 1988; Josse et al. 1989; Youngs and Timmons 1991).

Young and Timmons (1991) pointed out these deficiencies and stated that in practice raceways can be managed much closer to their design requirements for oxygen supply than for cleaning requirements: in other words, raceways are designed to function below required cleaning velocities. To overcome this deficiency, it is necessary to either design very long raceways, or raceways with very small cross-sectional area. To at least partially
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The use of baffles in raceways does not completely overcome the shortcoming of providing ideal velocities for fish health and conditioning. Baffles increase velocities, but only over a small area along the bottom. Fish may utilize this high velocity zone, but there is room for only a relatively small proportion of the total population in that zone. Fish probably will exchange positions and select different areas in the tank over time.

Youngs and Timmons (1991) recommend that safe velocities for salmonids should be one half the critical speed based on data provided by Beamish (1978). Safe velocity can be calculated as

$$V_s = (0.5) \cdot (10.5/L^{0.37})$$  \hspace{1cm} (2)

Thus, for a 10 cm fish, raceway velocity should not exceed 2.2 BL/s or 22 cm/s, while for a 20 cm fish, this is 1.73 BL/s or 35 cm/s. Totland et al. (1987) exercised large Atlantic salmon Salmo salar, (56.3 cm and 2,038 g) during culture at velocities of 0.45 BL/s. They found improved survival of exercised fish over caged fish except during the initial two week adjustment period when losses were 1.2 percent, much greater than the reference group. Final losses were 4.4 percent for exercised fish and 8.8 percent for reference fish. Weight gain was nearly 40 percent greater in exercised fish, and by industry standards, quality was rated 9.2 percent higher. Based on equation 2, the recommended velocity for 56-cm fish would be 1.2 BL/s, but favorable results were obtained at lower velocities of 0.45 BL/s. Needham (1988) recommended velocities between 0.5 to 1.0 BL/s for Atlantic salmon, which he considers a riffle species in contrast to trout and coho salmon Oncorhynchus kisutch which tend to live in pools. Besner and Smith (1983) exposed coho salmon to velocities of 0.2 BL/s (control) and 1.0, 1.5 and 2.0 BL/s. Endurance in test groups improved over the control group. They concluded that long term velocity regimes before release may be profitable for survival, because this early training allowed energy conservation during migration. Woodward and Smith (1985) exercised rainbow trout O. mykiss at velocities of 1.5 BL/s for 42 days. This improved fish quality in terms of better stress resistance; indeed sustained swimming exercise has been shown to improve disease resistance. Leon (1986) found improved disease resistance, growth rates and feed conversions when brook trout Salvelinus fontinalis were reared in velocities of 1.5 to 2.0 BL/s.

Josse et al. (1989) maintained rainbow trout at sustained velocities of about 2.5 BL/s with bursts of 3.8 BL/s for a few minutes daily, the latter velocity specifically aimed at developing white musculature. The continuous cruising speed served to develop red musculature, but it was also sufficient to stimulate the white musculature without exhausting fish. Continuous swimming also had a positive effect on tail muscle development. Red muscle area increased by 27%, the white by 9% over controls maintained in still
water. Furthermore, muscle fibers increased 75% and 39% in number, respectively, resulting in denser muscle as well. Jossé et al. (1989) concluded that permanent rotary water movement ensured perfect homogenization of the medium, optimal distribution of fish, and inhibition of territorial behavior which, in turn, resulted in a 100% increase in rearing density over the control group (68.35 kg/m³ versus 35.98 kg/m³). Mortalities during early rearing were significantly less in the high velocity environment, and experimental fish grew as well as controls, despite sustained swimming action. They also concluded that experimental fish were most likely better prepared for survival in nature.

Earlier studies by Poston et al. (1969) pointed out similar benefits to rearing at high velocity. Brook trout, exposed to velocities in excess of 2.0 BL/s had increased stamina, more efficient feed conversion ratio, and faster replacement of muscle glycogen after exposure to strenuous exercise in a stamina tunnel, compared to unconditioned fish. Those authors recommended physical conditioning of hatchery trout before stocking.

Forced exercise, contrary to common expectations, seems to result in reduced O₂ consumption compared to non-exercised fish. This reduction has been attributed to physiological adaptations, such as increased white muscle activity (Nahhas et al. 1982), improved cardiac output, and enhanced oxygen carrying capability of blood (Woodward and Smith 1985). There may also be reduction in energetic costs of ventilation. Fish that can maintain position in fast flowing water need only to open their mouths to ventilate their gills. This has been termed "ram" ventilation. Ram ventilation can contribute to saving energy in two ways: (1) passive movement of water over the gills which, in turn, results in (2) a more streamlined flow of water over the body. This latter hydrodynamic advantage results in small, but measurable, reductions in oxygen consumption (Randall and Daxboeck 1984). However, cost of active ventilation in a dense media such as water can be substantial; reports indicate from 10 to 30 percent of total oxygen uptake is required for active ventilation (Shelton 1970; Jones and Randall 1978).

Watten and Johnson (1990) offer yet another theory for the better performance of fish in high water velocities. The elevated surface velocities in their cross-flow tank, along with a homogeneous DO concentration, may accelerate diffusion of oxygen at the air-water interface. This would make more oxygen available than that added initially with inflow water.

Sustained velocities for small salmonids (≤ 0.5 kg) should be maintained, if at all practical, between 1.0 to 1.5 BL/s. These are well below those expressed with equation 2 or those used by Jossé et al. (1989) and Poston et al. (1969).

Round tanks do not have a distinct water quality gradient and frequently the rearing environment is homogeneous. Colt and Watten (1988) described the ideal round tank as a continuous-flow, stirred-tank reactor where dissolved gas concentrations are well mixed and equal to concentration in the effluent. However, Tvinnereim and Skybakmoen (1989) pointed out that in a complete mixed flow reactor, the maximum possible water exchange will be 63.2 percent during the theoretical mean retention time. High concentrations of oxygen entering round tanks are rapidly diluted with lower DO water. This is very different from raceways. If incoming water in a raceway has 10.0 mg/L DO, available oxygen to the fish might be 4.0 mg/L (10.0 - 6.0). Dissolved oxygen levels gradually decline from upper to lower portion of the tank, while the opposite is true of waste products in solution. In a hydraulically ideal round tank, with near homogeneous water quality, the rearing environment has the same DO level as effluent water. If the same oxygen consumption is allowed as in the raceway example above (same level of fish production per unit of flow), the rearing environment will be degraded to a uniform 6.0 mg/L, and the production capacity per unit of flow would have to be reduced by 25 percent (from 10.0 to 7.0 makes only 3.0 mg/L DO available rather than 4.0 mg/L). When water is sprayed forcefully onto the surface, some aeration is accomplished. This could make the round tank as productive as a
raceway or, where outflow DO levels are maintained equal to those of raceways, the round tank actually may have a higher production potential.

Since a round tank has no gradient, ammonia and carbon dioxide are also mixed into the rearing environment. This results in continuous exposure to at least some level of ammonia. Burrows (1964) found that fish can tolerate relatively high levels of ammonia on a short term basis, but continuous exposure to low levels can cause gill problems. Other investigators have found that chronic exposure to low levels of ammonia, in the presence of relatively low DO levels, causes gill lesions (Smith and Piper 1975). Low oxygen concentrations may increase toxicity of ammonia significantly (Lloyd 1961). Round tanks, therefore, may be more prone to problems with ammonia, under equal production levels, than are raceway environments.

Notwithstanding the above considerations, round tanks are very popular, especially for production of Atlantic salmon in Norway, Scotland and New England. Whenever low rearing densities are practiced, round tanks seemed to be preferred over raceways. One advantage round tanks have over raceways is that water velocities are, to a large extent, controllable. The most critical factor in water velocity control is design of inlet and outlet arrangements. Tvinneirem and Skybakmoen (1989) tested three submerged inlet systems: a horizontal spray bar, a multilevel vertical slot, and a point source inlet. The vertical slot inlet provided stable and uniform flow patterns at all flow rates, along with stable bottom current towards the outlet. The horizontal inlet accomplished better mixing and water exchange, but created weaker and less stable bottom current, and was therefore poorer in self-cleaning. The single point source inlet gave an unstable flow and insufficient water exchange. It also created very high velocities along the edge, driving fish to the center of the tank where mixing may be inadequate. Tanks were tested without fish and at exchange rates from 0.5 to 1.2 per hour. Inlet velocities ranged from 20 to 235 cm/s. The tests were conducted in tanks with non-sloping bottoms. Tanks with bottom sloping towards the center are easier to manage as far as the self-cleaning characteristics are concerned, because bottom water velocities are not as critical in solid removal.

Water level in round tanks can be controlled with an adjustable stand pipe located outside the tank (Figure 7). In this design, the center drain in the tank is covered with mesh screen. Solids are swept into the center drain, but few are carried out through the stand pipe. Instead, they settle near the center of the tank, on the screen, and in a trap beneath the tank. The trap is a properly-sized drain pipe leading to an outer double stand pipe. By briefly removing or lowering the stand pipe which controls water level, hydraulic pressure of tank water will force solids through the clean-out drain, directing water and solids into a solid collection basin.

Round tanks are more difficult to manage for fish handling, since fish cannot be cornered as in raceways. This difficulty must be overcome with fish crowders. Removing dead fish is also more labor intensive. On the other hand, round tanks lend themselves more readily to automatic feeding systems, requiring fewer feeding stations than raceways to distribute feed throughout the rearing unit, since water currents will distribute the feed more uniformly. Major differences between raceways and round tanks, with respect to design and operation, are summarized in Table 1.

Limits To Intensive Fish Production

Loading and Density

Intensive fish culture requires a high quality rearing environment which starts with proper water quality characteristics, but also involves rearing unit design, operational modes and management practices. Production capacity can be expressed in two ways; in production per unit of flow per or per unit of space. In this discussion, loading (LD) will be used for capacity expressed in kg fish per liter per minute flow (kg · L⁻¹ · min⁻¹), while density (D)
will be used to express capacity as kg fish per cubic meter of space (kg/m³). The relationship between these two can be expressed with the following formulas

\[ Ld = (D \times 0.06)/R \]  
(3)

\[ D = (Ld \times R)/0.06 \]  
(4)

(0.06 is 60 liters or 0.06 m³ which equals 1 L/min for one hour). Isolating \( R \) gives

\[ R = (D \times 0.06)/Ld \]  
(5)

The loading capacity depends primarily on source water quality, particularly dissolved oxygen, temperature, total alkalinity, and pH, but also on fish size and species. Density is a function of fish size, species and characteristics of the rearing environment. At one time it was believed that Atlantic salmon could not be "stacked"; in other words, they could not successfully utilize three dimensional space. However, when sufficient depth is provided under conditions of diffuse light, these fish will tolerate stacking. Even under these conditions, Needham (1988) recommended maximum densities not to exceed 30 kg/m³ for yearling smolts and only 15 to 20 kg/m³ for two-year-old smolts. Maximum allowable densities are much more difficult to ascertain than maximum loadings because of behavioral responses of fish. It is still a very subjective process and holds much controversy. This is unfortunate since density determines space requirements, frequently the most capital intensive component of a fish production system.

Maximum allowable loading can be established on the basis of dissolved oxygen available to fish, water temperature, pH, fish size and species, as species concerns relate to their metabolic characteristics and their responses to water quality variables, such as un-ionized ammonia, carbon dioxide, suspended solids, and other environmental factors including light, water velocities, or handling.

For the rest of this paper, near optimum conditions are assumed with respect to source water quality, overall rearing environment, rearing unit design, and modes of operation. The objective is to obtain maximum fish production from water in as little space as possible, while maintaining environmental quality conducive to production of healthy fish displaying near optimum growth rates and favorable feed conversions. After discussing methods to establish maximum loading on the basis of available oxygen and metabolic waste build-up, the information will be applied to the two types of rearing units discussed in the previous section: the plug-flow raceway and the circulating round tank.

**Dissolved Oxygen**

Maximum allowable loading can be determined on the basis of oxygen available to fish. This is the amount of oxygen the incoming water delivers less the amount that should leave the rearing unit. Understandably, oxygen should not go below a level (species specific) where stress begins. For salmonids as a group, effluent should contain from 5.0 to 7.0 mg/L DO. This variation is included because partial oxygen pressure (pO₂) appears to be a more valid way to determine the lower limits than concentration. A pO₂ of 90 mm Hg seems to be a reasonable target (Downey and Klontz 1981). Since the atmosphere contains 21% oxygen, at standard pressure of 760 mm Hg this represents a partial oxygen pressure of 0.21 x 760 or 159.6 mm Hg. At 20 C dissolved oxygen saturation is 9.0 mg/L, 90 mm pO₂ represents (90/159.6) \times 9.0 = 5.1 mg/L, and at 5 C when saturation is 12.5 mg/L DO, 90 mm pO₂ is 7.0 mg/L. I recommend that pure oxygen should be used wherever practical to elevate DO levels to saturation or above (Westers 1994a). In the following discussion, incoming oxygen levels are assumed to be at saturation, thus in all cases 4.0 mg/L DO is available to fish for metabolism.

To derive a practical loading equation, the following criteria are used:

a) One kg feed to salmonids requires from 200 to 250 g of oxygen to metabolize (OF; Westers 1984).

b) Optimum feeding level (FZL) is expressed in percent of the biomass of
the fish. As any feeding chart shows, this is directly related to fish size and water temperature, two major factors affecting carrying capacity.

c) A 16.7-hour day (1000 min) rather than a 24-hour day. I assume that the greater metabolic activity takes place during this 16 hour plus "feeding day", followed by a period of reduced metabolic activity.

The maximum feed per unit of flow (LdF) can be calculated as

$$LdF = AO/OF$$

(6)

To convert this to kg of fish per liter per minute based on available oxygen (LdO)

$$LdO = AO/OF \cdot 100/FL$$

(7)

By using optimum feeding level in the loading equation, both water temperature and fish size are taken into account, and these are the two main factors which affect metabolic rate. It is obvious from equation 7 that more oxygen available gives a greater production potential. It is therefore imperative to determine the maximum available oxygen (MAO) before water quality is degraded to a degree that it is no longer suitable for fish culture.

**Ammonia**

The MAO issue brings us to the second concern, that is ammonia build-up. Ammonia nitrogen, specifically un-ionized ammonia, is very toxic to fish. Meade (1985) reviewed published literature on the effects of ammonia on fish. Two of his conclusions are quoted below:

1. "A truly safe, maximum acceptable concentration of un-ionized, or total ammonia, for fish culture systems is not known."
2. "The apparent toxicity of ammonia is extremely variable and depends on more than the mean or maximum concentration of ammonia."

What, then, should a production manager do? To this Meade responds that use of a calculated estimate of NH$_3$ concentration to determine maximum, or optimum, safe production levels is far better than no quantitative guidelines. Consequently, I select 0.025 mg/L as the maximum allowable un-ionized ammonia (UA) level for salmonid culture, according to recommendations by the European Inland Fishery Advisory Commission of FAO (Solbe 1988), provided that dissolved oxygen levels are not below a pO$_2$ of 90 mm Hg, water temperature is above 5°C, and pH does not exceed 8.0.

For the calculations leading to maximum loading level based on un-ionized ammonia, the following factors will be used:

a) One kg of feed requires 250 g of oxygen for metabolism (OF).

b) One kg of feed generates 30 g of total ammonia nitrogen (TANP).

c) The maximum allowable un-ionized ammonia (UA) is 0.025 mg/L (UA).

The equation to determine the TAN (mg/L) is

$$TAN = (AO/OF) \cdot (TANP/1.44)$$

(8)

where 1.44 equals the total TAN (g) for 1.0 mg/L TAN per 24 hour day (1440 min). The first part of this equation represents kg feed that can be fed per liter per minute flow, and is the same as equation 6.

When the previously selected values are used in this equation the TAN is 0.33 mg/L. But since the concentration of the toxic un-ionized ammonia (UA) is of primary importance, this can be calculated as

$$UA = TAN \cdot (%UA/100)$$

(9)

The %UA is a function of water temperature and pH (Piper et al. 1982). For a pH of 7.9 and temperature of 9°C, %UA is 1.35. Applying all of the previously used values, the UA is 0.0045 mg/L.

The generic equation for un-ionized ammonia combines equation 8 and 9, or

$$UA = (AO/OF) \cdot (TANP/1.44) \cdot (%UA/100)$$

(10)
For the values suggested, $UA$ (mg/L) per $AO$ equals 0.00125 mg/L. $MAO$, then, is equal to $AUA/UA$, or

$$MAO = AUA \cdot OF \cdot 1.44 \\
\cdot (100/TANF) \cdot %UA$$

(11)

Based on selection of $AUA = 0.025$ mg/L and the other selected values, $MAO$ is 22.2 mg/L.

The maximum loading, based on un-ionized ammonia ($LdA$) is $LdA = (MAO/OF) \times (100/FL)$. The generic equation, incorporating Equation 7, is

$$LdA = AUA \cdot 1.44 \cdot 100 \cdot (100/TANF) \cdot %UA \cdot FL$$

(12)

For the values used ($AUA = 0.025$ and $TANF = 30$) $LdA$ is

$$LdA = 12/(UA \cdot FL)$$

(13)

The value 12 can range from a conservatively low of 6 to a liberal high of 18.

The ratio of loading based on available oxygen without supplementation is $LO = 4.0/2.5 = 1.6$, and $LdA = 12/UA = 8.8$, which means that 5.5 times the original $AO$ of 4.0 mg/L can be provided. This is the same value encountered in Equation 11 ($MAO 22.2$). This oxygen can be distributed by means of serial reuse design or single pass, and these options will be discussed under Production Systems.

**Carbon Dioxide**

Another metabolic by-product to be considered as a limiting factor in fish production is carbon dioxide or free CO$_2$. For each mg/L of O$_2$ utilized by fish, 1.1 mg/L CO$_2$ is generated (Needham 1988), but according to Colt and Watten (1988), salmonoids produce 1.375 mg/L CO$_2$ for every mg/L O$_2$ consumed. These latter authors also recommend that the maximum concentration of CO$_2$ should not exceed 20 mg/L, while Needham recommends the maximum not exceed 10 mg/L. Because of the many complex reactions of CO$_2$ with other water quality characteristics, such as temperature, pH, alkalinity, carbonate, and DO levels, it is difficult to settle on a specific value. For instance, Alabaster et al. (1957) mentioned that in well-aerated water, toxic levels of CO$_2$ are usually above 100 mg/L for rainbow trout. Contrastingly, 10 mg/L caused mortalities at pH of 4.5, and at 20 mg/L CO$_2$ mortalities occurred at pH of 5.7 (Lloyd and Jordan 1964). Piper et al. (1982) stated that 40 mg/L CO$_2$ had little effect on juvenile coho salmon, but they also mentioned that CO$_2$ in excess of 20 mg/L may be harmful to fish. Further, they proposed that where DO levels drop to 3-5 mg/L, lower concentrations of CO$_2$ may be detrimental, and long term exposure of one year or more should not exceed 12 mg/L. Smart (1981) suggested that fish are able to acclimate to elevated levels of CO$_2$. His data show that rainbow trout performance was equal when exposed to 12 or 24 mg/L of CO$_2$. At 55 mg/L, growth rate was poor during the first 28 days, but subsequently there was a marked improvement. He also observed that increased CO$_2$ concentrations were correlated with increased incidence of a condition known as nephrocalcinosis, the presence of white calcareous deposits in the kidney. The severity of this condition appeared to vary greatly according to diet and environmental factors as well.

Carbon dioxide is very soluble in water, but since CO$_2$ concentration in air is only 0.03 percent (compared to 21% for O$_2$), equilibrium concentrations in water are less than 1.0 mg/L for temperatures above 5 C (Cott and Orwicz 1991). Once CO$_2$ reaches a state of supersaturation in water, some can be driven off through aeration using open systems such as packed columns or other conventional aeration devices. However, pure O$_2$ aeration will not lower CO$_2$ concentration due to the low gas to liquid ratio (Cott and Watten 1988).

The relationship between CO$_2$, pH, temperature and alkalinity can be used to determine the concentration of free CO$_2$, the gas of concern. Table 2 provides the multiplication factors to determine carbon dioxide from pH, temperature and alkalinity. In our example, for a temperature of 9 C, pH of 7.6 and assuming a total alkalinity of 200 mg/L,
the free CO₂ concentration is 0.065 · 200 or 13 mg/L.

Carbon dioxide can easily become a limiting factor under conditions of low pH and poor aeration capabilities, and indeed, has been found quite damaging under such conditions (Lloyd and Jordan 1964).

**Solids**

Whenever water is reused, as in serial reuse, this water must not pass solid waste (feces and lost feed) to the next rearing unit. Approximately 300 g of solid waste (in the form of feces) can be generated per kg of food (Wester 1994b). At a loading level of 0.016 kg (16 g) feed per L per min (equation 6), the suspended and settleable solids generated would amount to 3.33 mg/L if evenly distributed in the water over a 24-hour period (16 g · L⁻¹ · min⁻¹ · 0.3 = 3.8 g solids · L⁻¹ · min⁻¹/1.44 = 3.33 mg/L). However, most solids settle out quite rapidly and accumulate in the rearing unit, from which they must be removed frequently to prevent in-tank pollution. For instance, a raceway with a rearing volume of 60 m³ and an hourly exchange rate of 4 operates on 4,000 L/min. At the maximum feeding potential of 0.016 kg feed per liter per minute flow, a total of 64 kg of feed could be added to the pond daily (4000 · 0.016), generating 19.2 kg of solid waste. Even if half of the solids would remain, the potential for pollution would be great. This one day accumulation, if evenly distributed throughout water in the tank, would represent over 100 mg/L of suspended solids. This clearly illustrates the importance of self-cleaning rearing units, but also the need to separate solids from outflow to prevent solids from entering a lower rearing unit or receiving water.

Effective solids management, therefore, has two important objectives: firstly to prevent within rearing unit water quality degradation; and secondly to prevent polluting the natural water receiving the effluent. Since solids can contain a significant portion of phosphorus, it is also important to separate solid waste from outflow as frequently as possible to prevent this nutrient from leaching, leaving the facility as soluble phosphorus with the effluents (Wester 1994b).

**Production Systems**

Production capacity is self-limiting through fish metabolism, such as the rate of oxygen consumption and accumulation of waste products. Other factors conducive to fish health are proper water velocities and light intensities, absence of disturbances, rearing unit design, modes of operation and management practices.

It is possible to determine the maximum production potential on the basis of flow, as shown earlier. Based on water quality characteristics and tolerances of salmonids to un-ionized ammonia, it was shown that, with 4.0 mg/L available oxygen and a feeding level of 1.0 %BW, the maximum production potential is 1.6 kg · L⁻¹ · min⁻¹ (equation 7); based on un-ionized ammonia it is 8.8 kg · L⁻¹ · min⁻¹ (equation 13). Dissolved oxygen is clearly the first limiting factor, which can be corrected through oxygen supplementation. The example used shows that available oxygen can be increased 5.5 fold, from 4.0 mg/L to 22.2 mg/L.

The parameters used above to determine maximum loadings on the basis of oxygen are quite conservative. Those for un-ionized ammonia are considered safe under favorable dissolved oxygen conditions, while those suggested for carbon dioxide are still problematic for reasons discussed earlier.

**Raceways**

The following exercise assumes that 30,000 L/min water is available. The average feeding level (FL) at the time of maximum biomass is 1.5. All other parameters are those used previously.

The maximum available oxygen (MAO) is 22.2 mg/L. If the effluent dissolved oxygen level is 6.0 mg/L, the incoming oxygen level
should be 28.2 mg/L. At a temperature of 9 C and an assumed elevation of 400 m, the saturation level is 11.0 mg/L. A single pass design would receive a dissolved oxygen level in excess of 250 percent saturation. For raceways this presents two problems: extremely hyperoxic conditions at the inlet area and an oxygen loss at the air-water interface as the water travels the distance from intake to outlet. In addition, adding high levels of oxygen reduces the absorption efficiency.

A two-pass design would result in an incoming DO of 11.1 + 6.0 = 17.1 mg/L per series or 155 percent saturation, which is still quite high. The choice is for a three-pass design, each series supplied at maximum biomass with 7.4 + 6.0 = 13.4 mg/L DO or 122 percent saturation.

At maximum biomass the total oxygen requirement for 30,000 L/min is 959 kg/day (30,000 - 1.44 g - 22.2). At an absorption efficiency of 50 percent, some 2,000 kg of oxygen must be made available per day. This requires an oxygen generating capacity of 2,000 cubic feet per hour, if a PSA system is used. A liquid oxygen system (LOX) must provide about 18 gallons per day at maximum biomass. At 7.4 mg/L AO, the maximum biomass per series is about 60,000 kg (1.97 kg \cdot L^{-1} \cdot min^{-1} \cdot 30,000 L/min).

Many species of salmonids can be kept healthy at densities exceeding 100 kg/m^3. In this exercise, 100 kg/m^3 will be used as a maximum density. According to equation 5, this results in an R value of 3.0 (R = (100 \cdot 0.06)/2). To accomplish a velocity of 3.0 cm/s, the raceway length, according to equation 1, is 36 m. This is an acceptable length.

Westers (1984) recommends the width of a raceway to be equal to about 1/10 the length. This would give the raceway a width of 3.6 m. This is not bad, but a somewhat narrower pond is easier to equip with baffles. The water depth should range from 0.8 m to 1.2 m, depending on personal preferences.

A raceway 36 m \cdot 3.6 m \cdot 1.0 m equals 129.6 m^3. To realize an exchange rate of 3, this pond should receive 6,480 L/min ((129.6/0.06) \cdot 3). With a total flow of 30,000 L/min, it seems reasonable to divide the water over five units, each receiving 6,000 L/min. This reduces the raceway volume to 120 m^3 to retain the R value of 3, and the velocity at 3.0 cm/s ((6,000 \cdot 0.06)/3). If an operating depth of 1.0 m is preferred, the width of the pond must be reduced to 3.3 m, a more desirable dimension. An additional 3.3 m must be added for solids settling, resulting in an overall raceway length of 39.3 m. This design realizes a proper balance between maximum loading (2.0) and maximum density (100) as expressed with equation 3.

The maximum biomass per raceway can reach 12,000 kg. Five ponds in the upper series, five in the middle series and five in the lower series together can support, theoretically, 180,000 kg of fish, fed an average of 1.5 percent body weight per day or 2,700 kg. At a feed conversion of 1.4 or feed efficiency of 70 percent, the daily gain in weight, is 1,890 kg, this would be 689,850 kg per year or 3.8 times the maximum allowable biomass. This annual output is more theoretical than real. However, an annual output can exceed the maximum biomass two to four fold, depending on growth rates. In the above example, a more realistic production strategy would be to maintain an average maximum biomass of 80% and a 300 day annual feeding program. This would result in an annual production of 0.80 \cdot 2700 \cdot 0.70 \cdot 300 = 453,600 kg which is some 2.5 times the maximum possible biomass of 180,000 kg! This raceway design for 30,000 L/min is depicted in Figure 8a.

A similar exercise uses 10,000 L/min available water and a maximum rearing density of 80 kg/m^3. A maximum loading of 2.0 kg \cdot L^{-1} \cdot min^{-1} results in a maximum biomass of 20,000 kg per series, 60,000 kg for a three-pass system. At 80 kg/m^3 this translates into 750 m^3 rearing volume, 250 m^2 per series. To provide for flexibility, a minimum of 12 rearing units are desired at 62.5 m^3 per unit. Twelve units results in four per series, receiving 2,500 L/min per unit, and this results in an exchange rate of 2.4 per hour. To realize a velocity of 3.0 cm/s the length of the raceway is 45.0 m ((36 \cdot 3)/2.4). For a rearing volume of 62.5 m^3 and an operational depth of 1.0 m, the width of the unit is only 1.39 m. To
overcome this problem, rearing units could be arranged as two parallel instead of four. This increases the flow to 5,000 L/min, reduces the length to 22.5 m and increases the series from 3 to 6. The width of units would be 2.8 m. Depending on site specifics, such as area and topography, it may be possible to place the rearing units parallel and direct the water in a serpentine fashion through the system (Figure 8b).

Finally, if raceways are used for low density rearing, for instance not to exceed 40 kg/m³, it is important to not sacrifice important hydraulic characteristics such as minimum velocities (3.0 cm/s). For the above example, twice the rearing space must be provided. To maintain the proper velocities, each series must consist of 12 units 22.5 m · 2.8 m · 1.0 m, preferably arranged parallel (Figure 8c). Placing these linearly would require a length of 270 m (12 · 22.5) not counting space between these units.

However, there are other options for low density rearing. For instance, the entire available flow of 10,000 L/min could be directed through a single unit. For a maximum biomass of 60,000 kg at 40 kg/m³, 1500 m³ of rearing space must be provided or 500 m³ per series. If a minimum of 12 units are required, each series consists of 4 units at 125 m³. At 10,000 L/min R is 4.8. For a minimum velocity of 3.0 cm/s, the length is only 22.5 m, the width would be 5.55 m for a depth of 1.0 m, which is not a good ratio. Since 3.0 cm/s is a minimum desirable velocity, 5.0 cm/s might even be more desirable. This would bring the length of the unit to 37.5 m, the width to 3.3 m—a much better ratio. Even better might be a depth of 1.2 m and a width of 2.8 m. The four units per series are, in effect, also placed in series. The total available oxygen per series is 7.4 mg/L. This can now be distributed over four units or 1.85 mg/L per unit. Each of these raceways could be equipped with low head oxygenators, but a better option is to equip every other one with a LHO and have the capability to add 3.7 mg/L DO.

As is obvious from the above exercises, there are various options of choice, but, at the same time, design is also driven by critical biological and physical parameters.

Round Tanks

The same basic process is applied to this type of tank as was used for raceways. The major differences relate to the fact that round tanks can be effectively operated at low water exchange rates (low R-values). Relatively high velocities can be realized to benefit fish health and self-cleaning characteristics.

Since round tanks mix rapidly, high input DO levels can quickly be reduced to normal levels, thus preventing hyperoxic conditions. High rearing densities can thus be realized with round tanks at low water exchange rates, in contrast with raceways. Although the same amount of rearing space must be provided, based on a selected maximum density, serial reuse can be reduced or even eliminated.

The example of 10,000 L/min will be applied to round tanks. At a density of 80 kg/m³ and a maximum loading of 2.0 kg · L⁻¹ · min⁻¹, 250 m³ rearing space must be provided. For a single pass use, i.e. the water is used only once, the full complement of oxygen must be added to source water, which is 22.2 mg/L as available oxygen and 6.0 mg/L as effluent DO for a total of 28.2 mg/L DO at the time of maximum biomass. Although this creates a supersaturation of 250 percent, the biomass of fish continuously consumes the oxygen provided, while new water carrying supersaturated oxygen immediately mixes with depleted water. In theory, one can establish some degree of in-pond equilibrium at or near DO saturation.

A round tank with a diameter of 4.0 m and water depth of 1.2 m has a rearing volume of 15 m³. To provide the 250 m³ needed, 16.7 tanks are required. Either 16 or 18 tanks should be provided. For 16 tanks, each tank would receive 625 L/min for an R value of 2.5. This is a reasonable operating strategy. The maximum rearing density will reach 83 kg/m³ ((2.0 · 2.5)/0.06). For 18 tanks the R value would be 2.2, maximum rearing density 73
A two-pass design would reduce the maximum incoming DO level to 17.1 mg/L.

At maximum rearing density of 40 kg/m³, twice the number of units are required. A single-pass design would provide 312.5 L/min per tank for an exchange rate of 1.25 per hour. At this low R value, round tanks can still function very satisfactorily. However, single-pass design requires that maximum available oxygen is provided within a single rearing unit. Adding very high DO levels to the water reduces absorption efficiency.

Figure 9 illustrates design options for round tanks. Maintaining a near DO saturation rearing environment in round tanks will ameliorate the toxic effects of un-ionized ammonia and carbon dioxide.

Unfortunately, there seems to be a lack of information with respect to optimum flow rates, water intake designs and pressures to accomplish the desired hydraulic characteristics for round tanks. This is further complicated as it relates to size variations and diameter to depth relationships. Larmoyeux et al. (1973) stated that, to a large degree, flow patterns are a function of depth, diameter, and the manner of introducing water. Where the depth-diameter ratio becomes too great, a large dead or viscous area may be formed. Flow patterns in tanks with diameters five to ten times the water depth do not differ drastically from those of small, relatively deep tanks (i.e. diameters three to five times the depth). Josse et al. (1989) operated their small 0.6 m diameter tank, which they termed an ichthyodrome, at a R value of over 10!

However, Rosenthal and Murray (1981) warned against using small scale experimental parameters for upscaling to large production units. Flow distribution, mixing, residence time distribution, and volume to area ratios can create many unforeseen scale-up problems.

The objective of round tank systems is to achieve an optimum water quality throughout the rearing unit in order to grow healthy fish successfully. Tveinnereim and Skybåtemoen (1989) intend further studies on factors responsible for hydraulic properties of fish rearing units. In their first studies, fish were excluded from the system. High density rearing in a round tank could add to a more complete mixing with fish acting as an active stirrer. High density rearing is possible in round tanks provided high purity oxygen is used.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Raceways</th>
<th>Round Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>Inflow dependent</td>
<td>Independent of inflow</td>
</tr>
<tr>
<td></td>
<td>Inadequate for solid removal unless equipped with baffles</td>
<td>Self-cleaning</td>
</tr>
<tr>
<td></td>
<td>Inadequate for fish exercise</td>
<td>Can meet fish requirements of 1.0 to 1.5 BL/s</td>
</tr>
<tr>
<td>Water Quality</td>
<td>Distinct gradient</td>
<td>Uniform</td>
</tr>
<tr>
<td></td>
<td>Passes peak metabolites out</td>
<td>Mixes metabolites and allows some to remain</td>
</tr>
<tr>
<td>Wall Area</td>
<td>Requires 1.5 to 3.0 times as much wall per water volume</td>
<td>Most efficient shape in water volume to wall area</td>
</tr>
<tr>
<td>Management</td>
<td>Easy to crowd and harvest fish</td>
<td>Difficult to crowd fish</td>
</tr>
<tr>
<td></td>
<td>Easy to collect dead fish</td>
<td>Difficult to collect dead fish</td>
</tr>
<tr>
<td></td>
<td>Difficult to equip with feeders</td>
<td>Easy to equip with feeders</td>
</tr>
<tr>
<td></td>
<td>Difficult to mix disease treatments</td>
<td>Easy to mix disease treatment compound</td>
</tr>
</tbody>
</table>
Table 2.—Multiplication factors to determine carbon dioxide from pH, temperature, and total alkalinity.*

<table>
<thead>
<tr>
<th>pH</th>
<th>41 F</th>
<th>50 F</th>
<th>59 F</th>
<th>68 F</th>
<th>77 F</th>
<th>86 F</th>
<th>95 F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 C</td>
<td>10 C</td>
<td>15 C</td>
<td>20 C</td>
<td>25 C</td>
<td>30 C</td>
<td>35 C</td>
</tr>
<tr>
<td>6.0</td>
<td>2.915</td>
<td>2.539</td>
<td>2.315</td>
<td>2.112</td>
<td>1.970</td>
<td>1.882</td>
<td>1.839</td>
</tr>
<tr>
<td>6.2</td>
<td>1.839</td>
<td>1.602</td>
<td>1.460</td>
<td>1.333</td>
<td>1.244</td>
<td>1.187</td>
<td>1.160</td>
</tr>
<tr>
<td>6.4</td>
<td>1.160</td>
<td>1.010</td>
<td>0.921</td>
<td>0.841</td>
<td>0.784</td>
<td>0.749</td>
<td>0.732</td>
</tr>
<tr>
<td>6.6</td>
<td>0.732</td>
<td>0.637</td>
<td>0.582</td>
<td>0.531</td>
<td>0.493</td>
<td>0.473</td>
<td>0.462</td>
</tr>
<tr>
<td>6.8</td>
<td>0.462</td>
<td>0.402</td>
<td>0.367</td>
<td>0.335</td>
<td>0.313</td>
<td>0.298</td>
<td>0.291</td>
</tr>
<tr>
<td>7.0</td>
<td>0.291</td>
<td>0.254</td>
<td>0.232</td>
<td>0.211</td>
<td>0.197</td>
<td>0.188</td>
<td>0.184</td>
</tr>
<tr>
<td>7.2</td>
<td>0.184</td>
<td>0.160</td>
<td>0.146</td>
<td>0.133</td>
<td>0.124</td>
<td>0.119</td>
<td>0.116</td>
</tr>
<tr>
<td>7.4</td>
<td>0.116</td>
<td>0.101</td>
<td>0.092</td>
<td>0.084</td>
<td>0.078</td>
<td>0.075</td>
<td>0.073</td>
</tr>
<tr>
<td>7.6</td>
<td>0.073</td>
<td>0.064</td>
<td>0.058</td>
<td>0.053</td>
<td>0.050</td>
<td>0.047</td>
<td>0.046</td>
</tr>
<tr>
<td>7.8</td>
<td>0.046</td>
<td>0.040</td>
<td>0.037</td>
<td>0.034</td>
<td>0.031</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>8.0</td>
<td>0.029</td>
<td>0.025</td>
<td>0.023</td>
<td>0.021</td>
<td>0.020</td>
<td>0.019</td>
<td>0.018</td>
</tr>
<tr>
<td>8.2</td>
<td>0.018</td>
<td>0.016</td>
<td>0.015</td>
<td>0.013</td>
<td>0.012</td>
<td>0.012</td>
<td>0.011</td>
</tr>
<tr>
<td>8.4</td>
<td>0.012</td>
<td>0.010</td>
<td>0.009</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.007</td>
</tr>
</tbody>
</table>

* For practical purposes CO₂ concentrations are negligible above pH 8.4.
Table 3.—Design driving forces for raceway complexes A, B and C of Figure 5.

<table>
<thead>
<tr>
<th>Design Driving Forces</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF (L/min)</td>
<td>80,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>D (kg/m³)</td>
<td>80</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Ld (kg/L/min)</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>AO (mg/L)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>MAO (mg/L)</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>S</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>V (cm/s)</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>R: (D · 0.06)/Ld</td>
<td>3.0</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Lm: (R · 36/V)</td>
<td>36</td>
<td>36 (2 · 18)</td>
<td>72 (3 · 24)</td>
</tr>
<tr>
<td>Total Volume (TV): (0.06 · TF)/R</td>
<td>1,600</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>Total width (TW): [TV/(Lm x OD)]</td>
<td>44.4</td>
<td>11.1</td>
<td>11.1</td>
</tr>
<tr>
<td># units: TW/(1 · Lm) (per pass)</td>
<td>12.34</td>
<td>3.08</td>
<td>12.34</td>
</tr>
<tr>
<td>3 units selected (per pass)</td>
<td>12.0</td>
<td>6 · 2*</td>
<td>4 · 3*</td>
</tr>
<tr>
<td>Unit width (UW): TW/# units</td>
<td>3.7</td>
<td>1.85</td>
<td>2.78</td>
</tr>
<tr>
<td>Unit volume (UV): TV/# units</td>
<td>133.2</td>
<td>33.3</td>
<td>66.6</td>
</tr>
<tr>
<td>Unit flow (UF): (UV · R)/0.06</td>
<td>6,660</td>
<td>3,333</td>
<td>5,000</td>
</tr>
</tbody>
</table>

*See text for explanation
Literature Cited

Alabaster, J.S., D.W.M. Herbert, and J. Memens. 1957. The survival of rainbow trout (Salmo gairdneri Richardson) and perch (Perca fluviatilis L.) at various concentrations of dissolved oxygen and carbon dioxide. Annals of Applied Biology 45:177-188.


Appendix Table 1.—Symbols used in various equations in the text.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>$V$</td>
<td>Water velocity in rearing unit (cm/s)</td>
</tr>
<tr>
<td>(1)</td>
<td>$Lm$</td>
<td>Length of the rearing unit (m)</td>
</tr>
<tr>
<td>(1)</td>
<td>$R$</td>
<td>Number of water turnovers per hour</td>
</tr>
<tr>
<td>(2)</td>
<td>$V_s$</td>
<td>Safe water velocity for continuous fish swimming</td>
</tr>
<tr>
<td>(3)</td>
<td>$Ld$</td>
<td>Loading as kg fish per liter flow per minute</td>
</tr>
<tr>
<td>(3)</td>
<td>$D$</td>
<td>Density as kg fish per cubic meter</td>
</tr>
<tr>
<td>(6)</td>
<td>$LdF$</td>
<td>Maximum kg feed per liter flow per minute</td>
</tr>
<tr>
<td>(6)</td>
<td>$AO$</td>
<td>Available oxygen</td>
</tr>
<tr>
<td>(6)</td>
<td>$OF$</td>
<td>Gram of oxygen required per kg of feed</td>
</tr>
<tr>
<td>(7)</td>
<td>$LdO$</td>
<td>Maximum loading based on available oxygen</td>
</tr>
<tr>
<td>(7)</td>
<td>$FL$</td>
<td>Optimum feeding level as percent body weight per day</td>
</tr>
<tr>
<td>(8)</td>
<td>$TAN$</td>
<td>Total ammonia nitrogen in mg/L</td>
</tr>
<tr>
<td>(8)</td>
<td>$TANF$</td>
<td>Total ammonia nitrogen generated in g per kg feed</td>
</tr>
<tr>
<td>(9)</td>
<td>$UA$</td>
<td>Un-ionized ammonia in mg/L or in %</td>
</tr>
<tr>
<td>(11)</td>
<td>$AUA$</td>
<td>Maximum allowable level of un-ionized ammonia in mg/L</td>
</tr>
<tr>
<td>(11)</td>
<td>$MAO$</td>
<td>Maximum available oxygen in mg/L</td>
</tr>
<tr>
<td>(12)</td>
<td>$LdA$</td>
<td>Maximum loading based on allowable ammonia level</td>
</tr>
</tbody>
</table>
Figure 1. Linear raceway (a) and round tank (b) flow pattern and dissolved oxygen characteristics.

Figure 2. Burrows Pond design.
Figure 3. Diagrams of the cross-flow fish rearing tank.

a) Longitudinal view b) Cross-sectional view
Figure 4. Enclosure area (wall space) comparison between different types of fish-rearing units.

ROUND TANK

- Diameter is 8.0 m
- Operating depth is 1.2 m
- Free-board is .3 m
- Rearing volume is 60 m$^3$
- Wall area is 37.7 m$^2$

SQUARE TANK

- Dimensions are 8.0 x 8.0 m
- Operating depth is .94 m
- Free-board is .3 m
- Rearing volume is 60 m$^3$
- Wall area is 39.7 m$^2$

RECTANGULAR RACEWAY

- Dimensions are 24 x 2.4 m
- Operating depth is 1.05 m
- Free-board is .3 m
- Rearing volume is 60 m$^3$
- Wall area is 77.7 m$^2$

Ratio of round to square to raceway = 1.0 to 1.05 to 2.06.
Figure 5. Raceway equipped with baffles.

Figure 6. Solids settling characteristics in raceway solids settling section behind fish retaining barrier.
Figure 7. Water level and solids management system for a circulating, round tank.
Figure 8A. Raceway complex on 80,000 L/min flow. Selected design driving forces: \( D = 80 \); \( Ld = 1.6 \); \( AO = 4.0 \); \( COC = 10.0 \); \( V = 3.0 \); \( OD = 1.0 \).
Figure 8B. Raceway complex on 20,000 L/min flow. Selected design driving forces: \( D = 80; \quad Ld = 1.6; \)
\( AO = 4.0; \quad COC = 10.0; \quad V = 3.0; \quad OD = 1.0. \)

\[ TV = 400 \text{ m}^2 \]

1st pass

Add 4.0 mg/L DO

2nd pass

3333 L/min

<table>
<thead>
<tr>
<th>#1</th>
<th>UV = 33.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td></td>
</tr>
<tr>
<td>#4</td>
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</tr>
<tr>
<td>#5</td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td></td>
</tr>
</tbody>
</table>

1.85 m

18 m

Actual \( R = 6 \)

Could add 2.0 mg/L DO between each series.

\[ R = \frac{36 \times 3}{18} = 6 \]
Figure 8C. Raceway complex on 20,000 L/min flow. Selected design driving forces: \( D = 40; \) \( L_d = 1.6; \)
\( A_0 = 4.0; \) \( C_O = 10.0; \) \( V = 3.0; \) \( O_D = 1.0. \)

TV = 800 m³

Add 4.0 mg/L DO

Actual \( R = 4.5 \)

\[
R = \frac{36 \times 3}{24} = 4.5
\]
INTAKE AT 20,000 L/MIN

ADD O$_2$ (TO 20 or 16 MG/L)

1250 L/MIN

# 1
80 KG/MP

# 2
# 3
# 4
# 6

SOLIDS
WATER

# 7
# 8
# 9
# 10
# 16

FIRST PASS (OR ONLY PASS)

ADD O$_2$ TO 15 MG/L

# 24
40 KG/MP

# 20
# 19
# 18
# 17

SOLIDS
WATER

# 32
# 28
# 27
# 26
# 25

SECOND PASS

Figure 9. Round tank complex on 20,000 L/min flow.

D = 80 (D = 40 for two-pass system);  Ld = 1.6;
AO = 4.0;  COC = 10.0;  OD = 1.2;  DIA = 8.0.