Design and Operation of Aquaculture Facilities Workshop

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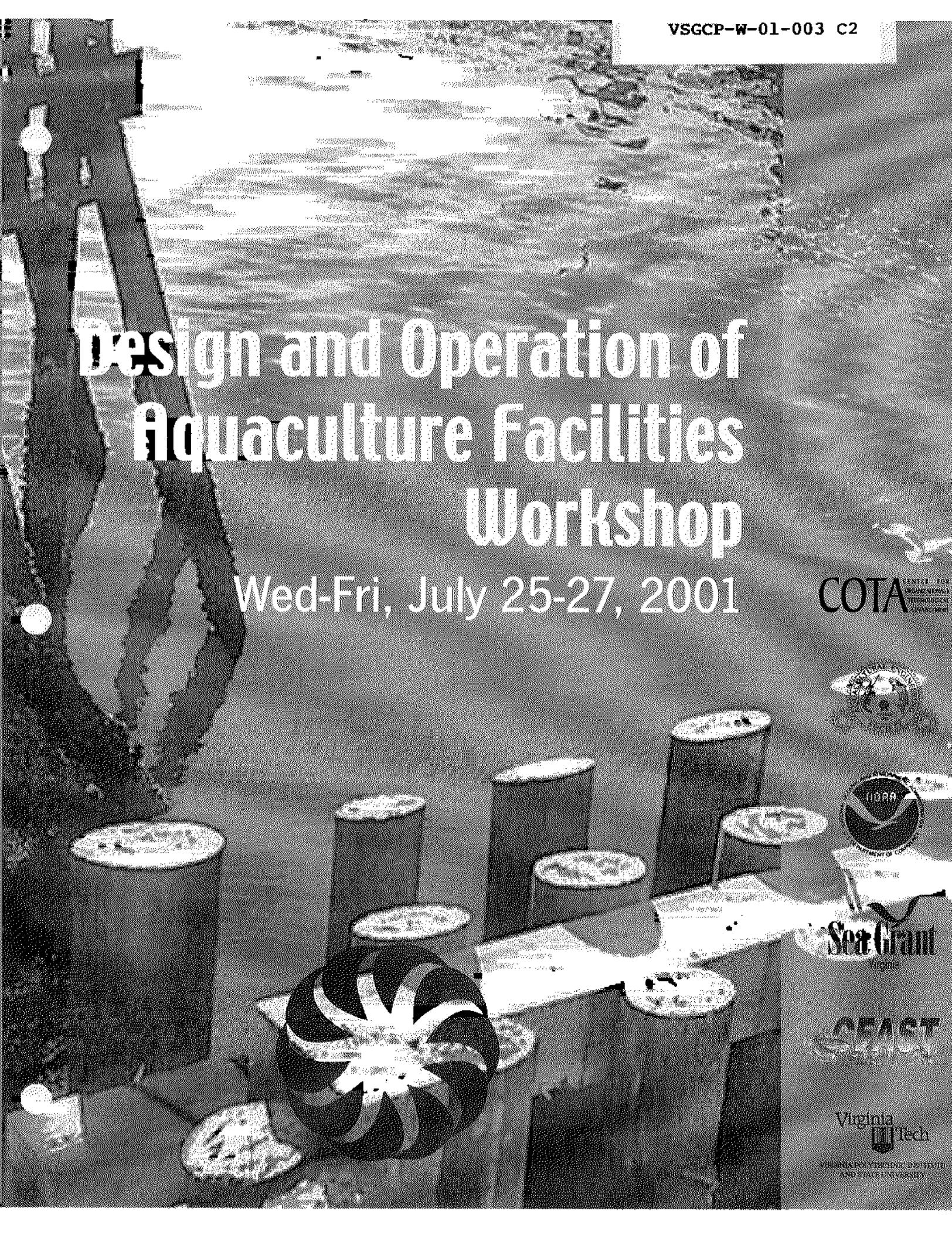
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Aquaculture Bioengineering

Principles of Intensive Fish Culture

A bioengineering approach to fish production facility design & operation

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I. APPLYING BIOENERGETICS

INTRODUCTION

Bioengineering, in the context of this workshop, is the use of bioenergetics and the known physiology of fish to rationally derive at production capacities, operational strategies, and design for intensive fish production systems.

More specifically, bioengineering occurs with the metabolic characteristics related to the feeding and growth of a certain species of fish (bioenergetics) is used to establish optimal production levels and rational design and operational parameters for intensive fish culture systems.

In true intensive fish production systems all bioengineering processes are driven by the food source of energy input. This principle will be illustrated during the course of this seminar.

Fish gain their energy from the consumption of food, retain some of it through growth, expend some of it through various metabolic processes, and lose a portion of it through excretion and heat production (Figure 1). Quantifying the various destinations of feed is necessary to determine the impacts the feed has on fish, rearing water quality, and the characteristics of the effluent.

Because feed is responsible for the degradation of the water quality, capacity of an intensive fish culture system must be rated on the basis of how much feed per day it can "process" without exceeding selected water quality parameters required for fish health.

A QUANTITATIVE APPROACH

A characteristic of life is variability. Because of this, the tolerances of a biological system cannot be calculated exactly. For instance, in fish culture, estimates and averages are used for mortality rates, growth rates, feed conversions, condition factors, metabolic rates, etc. These values are generally given as a range, but are nevertheless based on solid, rational, numbers and collected data. These data are needed to plan production programs, establish carrying capacities and, even more important, for design purposes, because engineers must use exact numbers, not ranges.

This means that fish culturists and biologists need to convert variable values into single values. This involves choice, and this choice must be as rational as possible, i.e., it should be supported by empirical data as much as possible. The more empirical data, the greater confidence we can have that the chosen value is a reasonable one or so it would seem. Unfortunately, this is not always the case, because of the complexities of biology. These complexities include differences in responses to environmental conditions, such as specific water quality characteristics. There are also differences based on species and their various life stages. Available data does not always adequately cover multiple factors, with the result that such reported data may show wide ranges in values. This can make it very difficult to zero in on a "rational" number.

For example, how do we select a safe value for ammonia (NH_3)? Meade (1985) reviewed the literature on sublethal, chronic effects of ammonia exposure to fish. Based on his findings, he concluded that safe, or acceptable, concentrations of ammonia suggested for fish culture are at best questionable, and at worst misleading. This is a reflection of how difficult it is to select a rational value. What to do about this? Meade's recommendation is that it is better to use a calculated estimate of NH_3 concentration to determine maximum safe production levels than the use of no quantitative guidelines. In other words, choose a number! Nevertheless, the likely

result is that the production level, based on that value, will nearly always be incorrect, neither maximum nor optimum, and therefore insufficient.

Considerable discussion about selecting a "rational" value for maximum allowable un-ionized ammonia (MUA) will be presented when we cover this important parameter. The issue of safe carbon dioxide concentrations is equally confusing with recommended maximum concentrations ranging from 10 to over 60 mg/l. More discussion will follow on this confounding water quality parameter as well.

INTENSIVE FISH CULTURE

Aquaculture, or fish culture, involves biological processes which are governed by two laws of thermodynamics:

1)   energy cannot be created nor destroyed, but can be changed into different forms ("what goes in must go out").

2)   in a system where energy is transformed, e.g. food to flesh, there is a loss of energy in the form of heat (no biological system is 100% efficient).

One key management feature of aquaculture systems is the intensity of production. Intensities can be described in terms of two variables:

1)   the amount of biological material harvested per unit of area (productivity).

2)   the degree of manipulation of natural processes (technology).

Using this criteria all aquaculture systems can be placed on a continuum from extensive to intensive. All systems characteristically have:

1)   inputs from outside the system;

2)   a processing function within it;

3)   outputs to the external environment.

Extensive systems are mostly driven internally. The processes occurring within the culture system are the primary determinants of water quality.

Natural, earthen ponds are associated with the extensive method, but they have their own level of intensity. Such extensive systems are dynamic ecosystems which respond to, and interact with, physical, chemical, and biological processes. Weather is a major external factor with its variations in temperature, sunshine, wind, and rainfall. But this external influence is entirely beyond the control of the fish culturist. All of these trigger complex internal responses, including actions by fish culturists, such as fertilization, feed introductions, etc. The more control the fish culturist exercises over the system the more intensive it becomes, eventually reaching a point where external influences predominantly determine the internal responses. We have now moved from extensive to intensive systems, which are primarily externally driven. These principles will be discussed in detail further down.

A flow-through system with a high water turnover rate should be considered an externally driven system because water quality factors are primarily determined by external factors under the control of the fish culturist: water turnover rate, aeration, feed input, fish biomass maintained, etc.

Intensive systems, as is true of extensive systems, have their own level of intensity (Figure 2).

CARRYING CAPACITY AND PRODUCTION

Predicting the carrying capacities of extensive, internally driven systems is difficult. Production often varies from year to year, from pond to pond.

It is very difficult for the fish culturist to make predictions concerning changes in pond water quality and biological activity in response to environmental/external factors. Besides, as

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was mentioned earlier, weather, which is unpredictable and uncontrollable, is one of the major external (environmental) factors causing internal responses.

The production of channel catfish in earthen ponds has evolved toward a more intensive production mode with the fish culturist exercising considerable control over water quality, aeration, water inflow/exchange rate, feed input, etc.

In this manual, only intensive "flow-through" production systems will be considered. Systems of this kind are capable of producing from 20,000 to 1,000,000 kg per ha, and support rearing densities from 5 to over 100 kg per m^3 (Figure 2). Flow-through water systems operate at varying water turnover rates. These systems offer much control over the rearing water quality. They include one-pass and serial reuse systems, partial and full scale recirculation systems. All of these have relatively fast water turnover rates through their rearing units.

In any aquaculture operation, it is the responsibility of the fish culturist to keep fish healthy. The culturist must manage the environment so that rearing water quality is maintained compatible with the physiological requirements of the fish. For the culturist to manage this water quality requires knowledge of the fish's requirements, but it also involves understanding the impact of the fish itself on its environment through its metabolic processes. Necessary too is knowledge about impacts from other sources, such as the effects that biofilters have on water quality. Armed with such knowledge, the fish culturist should be able to manage, and maintain, a healthy rearing environment for the fish, provided the facility meets the proper design criteria. All of these aspects will be covered in this course through the use of qualitative and quantitative applications.

In intensive, flow-through, aquaculture systems the rearing environment only serves to provide physical living space and *in itself* does not significantly contribute to any water quality modification as is true of extensive (pond) systems which are internally driven "eco-systems." There can be some nitrification of ammonia by nitrifying bacteria colonizing tank and pipe

surfaces, but most likely their effects are insignificant, unless we are dealing with recirculation systems. More about this later.

Loading (Ld) and Density (D)

Carrying capacity is expressed two ways, as unit of fish weight per unit of flow and unit of fish weight per unit of space. The first one, fish weight per unit flow, is termed loading. For metric equivalents, kg fish per liter per minute flow (kg/lpm) is used, for English equivalents, pounds per gallon per minute (lb/gpm) is used. The second one, weight of fish per unit of space, is termed kg per cubic meter (kg/m³). In the English system, density is measured in pounds per cubic foot (lb/ft³). It is important to understand that carrying capacity represents the system's one-time maximum carry capacity, while production represents the maximum possible annual output of the system. At times these two terms are used synonymously.

To summarize:

Loading (Ld): The weight of fish per unit of flow (kg/lpm or lb/gpm) maximum allowable loading is indicated with MLd.

Density (D): The weight of fish per unit of space (kg/m³ or lb/ft³). Maximum allowable density is designated as MD.

Production (AP): The annual output of fish in kg or lb. For maximum annual production we use MAP.

The relationship between loading (Ld) and density (D) can be expressed by using the number of water turnovers per hour (R), also called the exchange rate, as the variable with:

$$Ld = \frac{D \times 0.06}{R}; \quad D = \frac{Ld \times R}{0.06}; \quad R = \frac{D \times 0.06}{Ld} \quad (1)$$

The constant 0.06 represents 0.06 m³. A one lpm flowrate exchanges 60 l (0.06 m³) in one hour

(60 min). Rate of turnover (R) expresses number of turnovers per hour.

Flows, such as lpm or gpm, will be represented by the letter Q. Rearing volume, given in units, m^3 or ft^3, by RV. We can now express the relationship between exchange rate (R), flow rate (Q) and rearing volume (RV) by means of these equations:

$$R = \frac{Q \times 0.06}{RV}; \quad Q = \frac{RV \times R}{0.06}; \quad RV = \frac{Q \times 0.06}{R} \qquad (2)$$

For English equivalents:

$$Ld = \frac{D \times 8}{R}; \quad D = \frac{Ld \times R}{8}; \quad R = \frac{D \times 8}{Ld} \qquad (1a)$$

and

$$R = \frac{Q \times 8}{RV}; \quad Q = \frac{RV \times R}{8}; \quad and \ RV = \frac{Q \times 8}{R} \qquad (2a)$$

In metric: $Ld = kg/lpm$; $D = kg/m^3$; $Q = lpm$; $RV = m^3$
In English: $Ld = lb/gpm$; $D = lb/ft^3$; $Q = gpm$; $RV = ft^3$

The constant 8 in the "English" equations represent one gpm for one hour (60 gal), which is equivalent to 8.02 ft^3. The relationships expressed with equations 1 and 2 are very useful in establishing rational design and operational parameters for intensive, flow-through, fish production systems. For instance, if the maximum allowable loading (MLd) is 1.5 kg/lpm (12 lb/gpm) and the maximum density (MD) is 96 kg/m^3 (6 lb/ft^3), then the rearing unit should be operated at an exchange rate (R) of about 4 water turnovers per hour.

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$$R = \frac{96 \times 0.06}{1.5} = \frac{5.76}{1.5} = 3.84 \qquad (3)$$

For a rearing volume (RV) of 10 m^3 (353 ft^3) the maximum biomass (MBM) is 960 kg (2118 lb) and the required flowrate (Q) is 640 lpm (170 gpm). Equations 4 and 5:

$$\textbf{MBM} = \textbf{D x RV (96 x 10 = 960 kg)} \qquad (4)$$

$$\textbf{Q} = \frac{\textbf{MBM}}{\textbf{MLd}} \left(\frac{960}{1.5} = 640 \ \textbf{lpm} \right) \qquad (5)$$

In these three equations, loading, density, and exchange rate must balance once maximum allowable values for loading and density have been established and a desirable exchange rate has been determined. Once this has been accomplished, facility design and operational mode can follow. These factors are the driving force in facility design.

Maximum values for loading density can be selected for different phases of a production program. Phases can include various life stages and/or cohorts for sequential rearing strategies. Facility design must accommodate such phases. We will cover production phases and how these impact facility design and operations.

First we need to discuss how to establish "rational" maximum values for loading and density and how to "balance" such values along with exchange rates. Loading, as you may recall, relate to flowrate (Q), while density relates to rearing volume (RV).

Loading (Ld)

Loading represents carrying capacity as weight of fish per unit of flow; expressed in kg per lpm for metric and in lb per gpm for English equivalents.

The incoming flow of water into a rearing unit (RU) delivers oxygen while the effluent flow removes the metabolic waste products from the unit. Of these, waste products, suspended and dissolved solids, ammonia nitrogen, its products nitrite and nitrate nitrogen, and carbon dioxide are of primary importance to the quality of the rearing water. Solids, biological oxygen demand (BOD), nitrogenous compounds and phosphorus in the effluent may represent environmental concerns.

The more oxygen the flow delivers the more fish this flow can support. Therefore, adding oxygen can increase the carrying capacity. But as the biomass of fish increases, the demand for feed increases and the production of metabolic wastes increases. Eventually the biomass itself, density-wise, may become too great for the rearing space available.

Feed is responsible for negative changes in rearing water quality. The amount of feed that can be added per unit of flow depends on how much oxygen is required to metabolize this feed, and how much ammonia, carbon dioxide, and solid waste this feed generates, and at what point one or more of these components render the water quality unacceptable. **In other words, the carrying capacity of intensive aquaculture systems should be rated on how much feed they can "process" before predetermined water quality parameters are exceeded.**

Dissolved Oxygen (DO)

In most cases reduced dissolved oxygen is the first factor limiting water quality. Unless reaeration or oxygenation is applied, the fish will have used up the available oxygen well before concentrations of metabolic wastes have reached critical levels.

The oxygen required to metabolize one kg feed (designated as OF) ranges from 200 to 250 g for salmonids. This seems to be the range for many other species as well. Per pound of feed the range is 90 to 115 g (0.20 to 0.25 lb). This is true for non-recirculation flow-through

systems. For recirculation systems, some recommend that a one-to-one ratio be applied, i.e., one kg feed requires one kg oxygen. In recirculation systems, biofilters have a high demand for oxygen as they oxidize ammonia to nitrate. In addition, heterotrophs exert a demand for oxygen as well. Trickling and rotating biofilters also function as aeration and degassing devices. These obtain oxygen from the ambient air while simultaneously degassing some of the carbon dioxide from the water. Therefore, less oxygen needs to be added to systems using these types of biofilters. They can be rated on a 0.5 to 1.0 ratio, i.e. 0.5 kg oxygen per 1.0 kg feed (0.5 lb O_2 per 1.0 lb feed). Managing oxygen and carbon dioxide in recirculating aquaculture systems (RAS) is covered in Unit VIII.

The oxygen the fish require for respiration is removed from the water by the gills (Unit II). Not all of the dissolved oxygen contained in the water is available for respiration. To maintain a healthy, oxygenated environment, dissolved oxygen should not be depressed below a certain concentration. The difference between the incoming concentration and the minimum allowable concentration represents the oxygen that is available for the fish to use. This oxygen is designated as Available Oxygen (AO).

$$\textbf{AO} = \textbf{DO}_{In} - \textbf{DO}_{min} \qquad (6)$$

One liter per minute (1.0 lpm) delivers 1.44 g of oxygen per day for each mg/l dissolved oxygen (1.0 x 60 x 24 x 1.0 mg = 1440 mg = 1.44 g). One gallon per minute @ 1.0 mg/l delivers 5.45 g (3.785 x 1.44). Note: One gallon equals 3.785 liter.

If the oxygen demand is 250 g per kg food per day, then one can feed 0.00576 kg of feed per day per lpm per 1.0 mg/l DO (1.44 ÷ 250).

The greatest metabolic activity occurs during the "feeding day", assumed to be ~17 hours in length instead of the full 24 hours, and therefore available oxygen per lpm per 1.0 mg/l DO is 1 gram, rather than 1.44 g, while for one gpm @ 1.0 mg/l, 3.785 g of O_2 would be available.

Equations 7 and 7a can be used to determine the amount of feed that can be fed per unit of flow per mg/l DO. This is designated as "feed loading" (LdF) versus fish loading (Ld) shown earlier in equation 1.

$$LdF = \frac{AO}{OF} \text{ (kg feed / lpm)} \qquad (7)$$

$$LdF = \frac{3.8\,AO}{OF} \text{ (lb feed / gpm)} \qquad (7a)$$

Instead of 3.785 we will use 3.8. As mentioned earlier, biological parameters are "more-or-less" values.

For salmonids it is recommended to target minimum DO concentrations from 5.0 to 7.0 mg/l, respectively for temperatures from 15°C (58°F) to 5°C (41°F). These equate to a partial oxygen pressure (pO_2) of about 90 mmHg. Studies have shown that there is no measurable effect on growth if the partial oxygen pressure is maintained at or above 90 mmHg (about 60% of saturation). Nevertheless, maintaining oxygen concentrations at all times near saturation is beneficial to the fish especially when exposed to relatively high ammonia and/or carbon dioxide concentrations. This will be addressed when discussing these particular water quality parameters in more detail in the chapter covering the function of fish gills.

Feed loading equations (7 and 7a) can be changed into "fish loading" equations (Ld). For that we must consider the amount of feed the fish require, expressed in percent of their body weight, or biomass in the system. For one percent (%BW = 1.0), one hundred times as much fish weight can be supported as feed weight per unit of flow. At 10%BW it is ten-times the amount of feed. The fish loading equation is a modification of the feed loading equation (8 and 8a).

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$$Ld = \frac{AO}{OF} \times \frac{100}{\%BW} \qquad (8)$$

and

$$Ld = \frac{3.8\,AO}{OF} \times \frac{100}{\%BW} \qquad (8a)$$

The question we must ask now is how much oxygen can be made available (maximum AO) before toxic unionized ammonia and/or carbon dioxide buildup has rendered the water unacceptable. We can assume that one or the other of these parameters will be responsible for a decline in water quality before suspended solids, for instance, have reached damaging concentrations. However, in recirculation systems with adequate biofiltration and degassing of carbon dioxide, suspended solids can become the limiting factor unless they, in turn,.are well managed. In that case, nitrate (NO_3) becomes the limiting parameter. These issues will be discussed under recirculation technology and design (Unit VI).

Ammonia Nitrogen

From 60% to 90% of the waste nitrogen found in the system as ammonia (NH_3), is excreted primarily through the gill membranes. This is believed to be the most efficient route for nitrogen excretion, requiring less energy than the synthesis and excretion of urea.

Ammonia, in its unionized form (NH_3), moves readily across cell membranes. This is no problem as long as there is a positive gradient between the blood ammonia concentration and that of the rearing water, the ambient concentration. As the ambient concentration increases, the outward flow of NH_3 becomes more difficult , eventually stopping altogether, or even reversing itself.

As ammonia enters water it instantly reacts with it. Most of it ionizes into the relatively non-toxic ammonium ion (NH_4^+). This reaction is pH and temperature dependent (see Table 1). At a pH of 7.6 and a temperature of 15°C (59°F) about 1.0% of the total ammonia nitrogen (TAN) is in the toxic, unionized form. By the way, a measurement of ammonia includes both forms (NH_3 and NH_4^+), known as the total ammonia nitrogen (TAN). By knowing the temperature and pH, table 1 can be consulted to determine the percent of toxic unionized ammonia. A much more detailed and extensive table can be found in Piper, et al. 1982. An increase in pH by one full unit increases the percent toxic ammonia ten-fold!

While most of the ammonia in the body fluids of fishes is in the ionized form, only about 1.0% is in the gaseous, unionized form (NH_3) which readily diffuses out through the gill, and is then instantly replaced to maintain the equilibrium between the two forms.

The higher the pH of the rearing water, the sooner the unionized ammonia concentration reaches that of the blood, thus hindering the excretion due to lack of a gradient. But, there may be some relief. The gill also excretes carbon dioxide, and carbon dioxide acidifies the water, i.e., lowers the pH, thus changing the balance between unionized and ionized ammonia in favor of the ionized nontoxic form. This reaction too is basically instantaneous, and so a micro-water quality environment is created immediately adjacent to the gill, providing a "protected layer" of lower pH water around it. The ability to change the pH of this water near the gills depends on its alkalinity, i.e., ability to resist pH changes, and the overall concentration of CO_2 in the rearing water. These are good reasons to keep ambient carbon dioxide concentrations as low as possible. More discussion on CO_2 will follow when this water quality parameter is covered in Unit VII.

There appears to be yet another way to expedite ammonia removal; this is by means of an ion exchange mechanism. The base of the gill filaments contain chloride cells which are used to transport sodium (Na^+) and chloride ions (Cl^-) from the water into the blood of freshwater fish. These ions facilitate the excretion of ammonium (NH_4^+) and bicarbonate (HCO_3^-) ions respectively. This branchial Na^+/NH_4^+ and Cl^-/HCO_3^- ion exchange mechanism can lower the

ammonia and carbon dioxide concentrations in the blood. This mechanism functions importantly in osmoregulation. The chapter on fish gills covers this in greater detail (section 2).

In freshwater fish, the water surrounding the fish is lower in ions than the blood. This water diffuses by osmosis through the gills into the fish. To prevent edema, water must be continuously excreted. The influx of water can be as high as 1% of the body weight per hour. Water is excreted as a very dilute urine, but despite this, small amounts of electrolytes are steadily lost due to the large volume of urine discharged. These electrolytes are then replaced by the food and from the water by the gill chloride cells to prevent ionoregulatory disturbances. Very soft water, low in ions, makes it more difficult for fish to maintain homeostasis. Water low in sodium ions also interferes with ammonium excretion via the branchial ion exchange mechanism. Adding salt, (Na^+ Cl) to the water can help to lower the blood ammonia concentration and re-establish disturbed ionoregulatory functions caused either by a lack of available ions, or by stressful situations, such as handling and transporting.

For example, in a low-sodium, softwater salmon hatchery, steelhead experienced severe gill hyperplasia contributing to elevated blood ammonia levels. Increasing the Na^+ concentration to 20 mg/l brought about some relief.

In a personal study, coho salmon were exposed for periods up to 128 days to an average total ammonia concentration of 12 mg/l. Unionized ammonia averaged 0.5 mg/l, 20-fold higher than a routinely recommended concentration of 0.025 mg/l. The rearing water had concentrations of 476 mg/l sodium and 269 mg/l chloride. The fish showed no signs of ammonia toxicity, they fed and grew at a normal rate, and their overall health was excellent.

I believe that in the coho study the fish used the branchial ion exchange mechanism to maintain low blood ammonia concentrations against a very high ambient concentration, made possible by the relatively high environmental sodium concentration. I think this is a fertile area for further research because of the potential benefit to the practicing aquaculturist. After all, the

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buildup of ammonia is, frequently considered to be the second limiting factor, after depletion of dissolved oxygen. Oxygen concentrations can easily be controlled through aeration or oxygenation (Unit VI). If the ambient ammonia tolerance concentration could be doubled, carrying capacity might be doubled as well, or the growth limitations shifted to another water quality parameter, such as carbon dioxide, suspended solids, etc.

A concentration of 500 mg/l sodium, for instance, is far below that of seawater. Seawater with a salinity of 3.5% has a sodium concentration of 10,560 mg/l, a chloride concentration of 18,980 mg/l. These two represent 86% of all the ions in sea water.

The blood plasma of freshwater fish has an overall salinity of about 0.75% (7500 mg/l) with sodium ions comprising about 3,300 mg/l, chloride ions at 3,350 mg/l for a total of 89% of the 0.75% salinity (7,500 mg/l). Salmonid blood pH ranges from 7.5 to 7.8.

Now to return to the question of how much oxygen can be made available before toxic unionized ammonia has reached its maximum allowable concentration. To determine this we must quantify the following:

1.   how much total ammonia nitrogen (TAN) is generated per unit of food (TANF).

2.   what percent TAN remains as toxic unionized ammonia (UA).

3.   what is the safe, maximum unionized ammonia concentration (MUA).

The amount of TAN generated by the feed depends on the protein content of the diet, its protein-energy ratio, the species of fish reared and how well feeding is managed.

Generally the literature supports ranges of 25 to 30 g TAN per kg feed (11.4 to 13.6 g per lb). Studies have consistently shown that 50-60% of dietary nitrogen is lost to the environment, 80% of which is in the form of ammonia, and 20% is fecal nitrogen. Approximately, 16 percent of protein is nitrogen (N), ammonia (NH_3) has a weight 1.2 times that of nitrogen.

The following equation can be used to determine the grams of TAN generated per g of feed:

$$gTAN = gFd \times \%P \times \%N \times \%Ex \times \%TAN \times 1.2 \qquad (9)$$

For example, a 40% protein diet (%P = 0.40) has an environmental nitrogen loss of 45% (%Ex = 0.45), of which 80% is TAN (%TAN = 0.80), hence 27.6 g TAN per kg feed (1000 g) is generated:

$$gTAN = 1000 \times 0.40 \times 0.16 \times 0.45 \times 0.80 \times 1.2 = 27.6 \ gTAN$$

Per pound of feed (454 g) the value is 12.55 gTAN.

For a 50% protein diet these values are 34.6 and 15.7 g respectively, for a 30% protein diet 20.7 and 9.4 g. In the following examples to we will use 30g TAN per kg feed (13.6 g per lb). Thus TANF = 30 and 13.6, for metric and English equivalents respectively.

Next we need to know the percent unionized ammonia. For this we need to know the pH and the temperature of the water. In the examples to follow, a pH of 7.6 and a water temperature of 14°C (57°F) will be assumed. According to Table 1, the percent unionized ammonia is 1.0 (UA = 1.0).

Finally, we must decide on a value for a safe, maximum, unionized ammonia concentration. From the previous discussions it is clear that much is still unknown. The extensive literature review by Meade (1985) bears that out. He was unable to provide the fish culturist with a number, yet a number is required if we consider unionized ammonia a critical factor in the rearing environment of the fish. More research is critically needed to enable us to derive at a truly rational value. One important facet of such research should concentrate on the role of sodium ions (Na^+) in the rearing water, their function in a branchial ion-exchange

mechanism with blood ammonia (NH^+_4) and what would be an optimum concentration of sodium for such an exchange.

In the interim we need to select a value without having the benefit of such guidelines. For salmonids the literature supports values ranging from 0.0125 to 0.030 mg/l, more often than not we encounter the values 0.020 and 0.025 mg/l. I recommend 0.025 mg/l as a maximum safe value for salmonids, providing dissolved oxygen concentrations are maintained above 6.0 mg/l and carbon dioxide concentrations below 20 mg/l. The higher the DO and the lower the CO_2 the healthier the rearing environment. See Unit II.

For the following exercises, with respect to unionized ammonia as a second limiting factor (after dissolved oxygen), the following values will be used:

1.   gram TAN per kg feed is 30, per lb 13.6 (TANF = 30 or 13.6).

2.   % unionized ammonia is 1.0 (UA = 1.0).

3.   maximum safe unionized ammonia concentration is 0.025 mg/l (MUA = 0.025).

Equations 7 and 7a are used to determine the amount of feed that can be fed per unit of flow (kg/lpm and lb/gpm) as well as per unit available oxygen (mg/l AO). For OF values of 250 and 114 respectively one can feed 0.004 kg and 0.033 lb of feed per lpm and gpm respectively per mg/l available oxygen. For the assumed TAN production of 30 g per kg feed or 13.6 g per lb feed, 0.12 g and 0.45 g of TAN is generated respectively per 0.004 kg and 0.033 lb of feed per lpm and gpm, again per mg/l AO, according to equations 10 and 10a.

$$gTAN = \frac{AO}{OF} \times TANF \qquad (10)$$

and

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$$gTAN = \frac{3.8\ AO}{OF} \times TANF \qquad (10a)$$

Using the values indicated above:

$$gTAN = \frac{1.0}{250} \times 30 = 0.12\ g$$

and

$$gTAN = \frac{3.8}{114} \times 13.6 = 0.45g$$

In these equations TAN is expressed as weight (g) per day, it must be converted to concentration as mg/l because the maximum safe level of unionized ammonia is expressed in mg/l.

Earlier it was shown that one lpm @ one mg/l DO "delivers" 1440 mg (1.44 g) of oxygen in a 24-hour period. Per gpm one mg/l delivers 5450 mg (3.786 x 1,440). Based on these values, 0.12 g as well as 0.45 g TAN represent a concentration of 0.083 mg/l per 24-hour day if we assume an even distribution over that period of time.

Equations 11 and 11a can be used to determine the concentrations of TAN (TANC) per one AO.

$$TANC = \frac{1.0 \ (AO) \ x \ TANF}{OF \ x \ 1.44} \qquad (11)$$

$$TANC = \frac{3.8 \ x \ 1.0 \ (AO) \ x \ TANF}{OF \ x \ 5.45} \qquad (11a)$$

Using the assumed values:

$$TANC = \frac{1.0 \ x \ 30}{250 \ x \ 1.44} = 0.083 \ mg/l$$

$$TANC = \frac{3.8 \ x \ 1.0 \ x \ 13.6}{114 \ x \ 5.45} = 0.083 \ mg/l$$

This TAN concentration assumes even distribution of the excreted TAN over a 24-hour period. But in reality much of the TAN is excreted three to four hours after feeding. When feeding is spread somewhat evenly throughout the feeding day, the concentration of TAN shows little peaking, but most of it is still eliminated within a 24-hour day. It is therefore not unreasonable to use a concentration of 0.10 mg/l TAN generated per AO. Once again, we are dealing with a rational number, a number that is also easy to remember and work with.

$$TANC = 0.10 \ mg/l \ per \ AO$$

We must also determine how much of this total ammonia nitrogen (TAN) is unionized (NH_3). A pH of 7.6 and a temperature of 14°C (57°F) was assumed, so consequently the percent unionized ammonia (%UA) is 1.0 (Table 1).

We can now determine the concentration of unionized ammonia with equation 12.

$$UAC = \frac{TANC \times \%UA}{100}$$

(12)

Applying the previously determined values of TANC and %UA:

$$UAC = \frac{0.10 \times 1.0}{100} = 0.0010 \text{ mg}/l$$

It is important to be reminded that this value of 0.0010 mg/l is based on a "per AO" value. To determine the maximum available oxygen concentration (MAO) equation 13 is used:

$$MAO = \frac{MUA}{UAC}$$

(13)

We had decided on a maximum allowable ammonia concentration of 0.025 mg/l (MUA = 0.025). When the values for MUA and UAC are applied, the resulting maximum AO is 41 mg/l.

$$MAO = \frac{0.025}{0.0010} = 25 \text{ mg}/l$$

After having gone through the steps represented by equations 11, 12, and 13, we can combine these into a single equation for MAO. This is accomplished with equations 14 and 14a:

$$MAO = \frac{MUA \times OF \times 1.44 \times 100}{TANF \times \%UA}$$

(14)

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and:

$$MAO = \frac{MUA \times OF \times 5.45 \times 100}{TANF \times \%UA} \qquad (14a)$$

What must be realized here is that a value must be selected by the fish culturist for MUA, OF, and TANF, and that it can be difficult to select a "best" value, as discussed previously.

For a maximum AO of 25 mg/l, the maximum loading (MLd), according to equations 8 and 8a is 10.0 kg per lpm and 83.3 lb per gpm. These values are based on a feeding level of one percent body weight (%BW = 1.0).

$$MLd = \frac{25 \times 100}{250 \times 1.0} = 10.0 \, lg/lpm$$

$$MLde = \frac{3.8 \times 25 \times 100}{114 \times 1.0} = 83.3 \, lb/gpm$$

Equations 1 and 1a show the relationship between loading, density, and exchange rate. This relationship must balance, i.e., the loading and density values must result in an acceptable exchange rate. Alternatively if an optimum or preferable exchange rate has been selected for a particular rearing unit, the rearing density must be modified to accomplish the right hydraulics to make the unit self-cleaning.

To illustrate this with the maximum loading of 16.4 kg/m³and selected exchange rate of two per hour (R = 2.0), the rearing density, in order to balance the equation, must be an impossible 333 kg per m³ or 20.8 lb per ft³.

$$D = \frac{10.0 \times 2.0}{0.06} = 333 \ kg/m^3$$

$$D = \frac{83.3 \times 2.0}{8} = 20.8$$

Note: A density of 16 kg/m³ equates to 1.0 lb/ft³·

The other problem with the high value for a maximum available oxygen of 25 mg/l is the fact that the fish would have to have an incoming DO of 31 mg/l (DO_{in} = 31) if we want to maintain a minimum effluent DO of 6.0 mg/l (DO_{out} = 6.0).

This too is unacceptable, because this hyperconcentration of dissolved oxygen (hyperoxic) represents a supersaturation concentration of about 300% for the 10^0C water temperature.

The challenge with high MAO values will be addressed in Unit V. Table 2 shows values for MAO based on a one percent unionized ammonia value, and the previously selected numbers for OF (250 and 114) and TANF (30 and 13.6). The table shows MAO values for six different MUA values.

To obtain MAO values for different %UA values, the MAO numbers must be divided by the new %UA value.

Carbon Dioxide (CO_2)

Carbon dioxide is generated by the fish as a by-product of metabolism, and, as with ammonia, is excreted by the gills. For each gram of oxygen consumed, 1.375 g of carbon dioxide is produced (molecular weight of CO_2 is 44 g/mole, for O_2 this is 32 g/mole, a ratio of 1.375).

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In the previous discussion we concluded that, based on ammonia limits, up to 41 mg/l dissolved oxygen can be used by the fish in our example. Based on the ratio of 1.375 this would result in the production of 56 mg/l CO_2. How much can the fish tolerate? This question has no easy answer, as will be explained.

Carbon dioxide is very soluble in water and reacts with water in a complex, dynamic way. It establishes equilibrium concentrations of four types or "species" of carbon compounds, namely, free carbon dioxide gas (CO_2), carbonic acid (H_2CO_3), bicarbonate ion (HCO^-_3) and carbonate ion (CO^-_3). The toxic species is the free carbon dioxide (CO_2). The reactions are controlled primarily by pH and alkalinity. Carbonic acid remains present in very small amounts, releasing hydrogen ions (H^+) to produce the bicarbonate ion, some of which may further dissociate into H^+ ions and CO^-_3 ions.

$$CO_2 + H_2O = H_2CO_3 \leftrightarrow H^+_+HCO^-_3 \leftrightarrow H^+_+CO^-_3$$
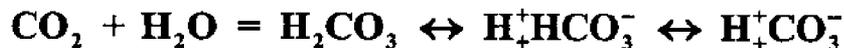
As hydrogen ions are released, the pH of the water is lowered.

As the pH is lowered, a new equilibrium is established. Calcium carbonate ($CaCO_3$), buffers the pH change, increasing the capacity of the water to neutralize acids.

High alkalinities generally result in relatively high but stable pH values, i.e. low free CO_2 concentrations. Waters that have a low alkalinity are subject to low pH values in the presence of carbon dioxide.

Alkalinity in the 100-200 mg/l range is desirable as it provides good buffering against pH fluctuations. Such levels also provide a carbon source for nitrifying bacteria in the biofilters used in recirculating aquaculture systems (Unit VI).

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Low pH favors problems with unionized ammonia toxicity, but works against free carbon dioxide toxicity. Generally, the literature indicates that 20 mg/l free CO_2 should be considered an upper limit, but one can find recommended maximum concentrations as low as 10 mg/l and as high as 60 mg/l. Fish do have some ability to acclimate to free carbon dioxide as long as the buildup occurs slowly over time. However, under certain water quality conditions, carbon dioxide may lead to nephrocalcinosis, the formation of calcareous deposits in the kidneys. This condition may even occur at relatively low levels of carbon dioxide. Under supersaturated dissolved oxygen conditions a maximum safe concentration of 20 mg/l CO_2 may be conservative. However, when CO_2 concentrations approach 30-40 mg/l, the oxygen carrying capacity of blood will be decreased to the point where even high concentrations of dissolved oxygen may be inadequate to prevent decreased blood oxygen levels. Under conditions of dissolved oxygen supersaturation, rates of ventilation by the fish may be reduced, less water is passed over the gills potentially reducing carbon dioxide exchange from the gills (Unit II).

Carbon dioxide moves from the tissues of the fish into the blood and from the blood into the water at the site of the gills. The main function of the gills is to take in oxygen from the water. To accomplish this, relatively large volumes of water must be "pumped" over the gills. The higher the dissolved oxygen concentration, the less water needs to be moved over the gills to satisfy the oxygen demand. This can be counter productive as far as CO_2 removal is concerned.

Most of the blood CO_2 is converted to HCO_3^- ion (blood pH is 7.5-7.8). To eliminate the carbon dioxide, the bicarbonate is converted to free carbon dioxide (gas) in the gills and, as such, diffuses into the surrounding mucous layer, where, it is again converted to HCO_3^- to maintain a positive gradient for CO_2 between the blood and the external surroundings. It is also believed that some of the bicarbonate ions can be exchanged directly at the gills for chloride ions (HCO_3^- − Cl^-).

Similar ion exchange mechanism has also been reported for the ammonia ion (NH_4^+) exchanging with the sodium ion (Na^+). When there is inadequate removal of CO_2 from the

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blood, either because of insufficient flow of water across the gills (ventilation rate too low) and/or a lack of gradient between the blood CO_2 and the rearing water CO_2 concentration, the CO_2 builds up in the blood (hypercapnia) the blood pH is lowered (acidosis) and the capacity of the hemoglobin to bind oxygen is impaired.

Obviously the buildup of carbon dioxide can become a limiting factor with respect to carrying capacity. This is especially true in recirculating systems. Whenever maximum allowable oxygen concentrations exceed 15-20 mg/l (MAO = 15-20), carbon dioxide should be managed or controlled.

By controlling carbon dioxide, it no longer needs to be considered a limiting factor in our deliberations about carrying capacities. Techniques to manage carbon dioxide will be covered in Unit VII.

Table 1. Percent of total ammonia that will be in the toxic form over the range of pH and temperature listed.

pH	Water temperature (°C)			
	5	10	15	20
6.0	0.01	0.02	0.03	0.04
6.2	0.02	0.03	0.04	0.06
6.4	0.03	0.05	0.07	0.10
6.6	0.05	0.07	0.11	0.16
6.8	0.08	0.12	0.17	0.25
7.0	0.13	0.18	0.27	0.40
7.2	0.20	0.29	0.43	0.63
7.4	0.32	0.47	0.69	1.0
7.6	0.50	0.74	1.08	1.60
7.8	0.79	1.16	1.71	2.45
8.0	1.24	1.83	2.68	3.83
8.2	1.96	2.87	4.18	5.93
8.4	3.07	4.47	6.47	9.09
8.6	4.78	6.90	9.88	13.68
8.8	7.36	10.51	14.80	20.07
9.0	11.18	15.70	21.59	28.47

SOURCE: G.A. Wedemeyer, 1996. Physiology of Fish in Intensive Culture. pp 232

Chapman and Hall, New York (A HIGHLY RECOMMENDED RESOURCE!)

Table 2. MAO values for six MUA values, based on UA = 1.0%; OF = 250 (114) and TANF = 30 (13.6).

		MUA			
0.015	0.020	0.025	0.030	0.035	0.040
15	20	25	30	35	40

Note: Shortcut: <u>MAO = MUA x 1000</u>

This is on the basis of an unionized percentage of one (UA = 1.0) and generating 0.10 mg/l TAN per AO. For other %UA values, divide the MAO values of the table by the new %UA values. For instance, for %UA = 0.5, the table values are doubled, for %UA = 2.0, the values are halved!

Table 3 presents approximate values for free carbon dioxide in mg/l for ten pH values and six alkalinities.

pH	Alkalinity in mg/l (15^0C)					
	50	100	150	200	250	300
6.4	46	92	138	184	230	276
6.6	29	58	87	116	145	174
6.8	18	37	55	73	92	111
7.0	12	23	35	46	58	70
7.2	7	15	22	29	36	44
7.4	5	9	14	18	23	28
7.6	3	6	9	12	15	18
7.8	2	4	6	7	9	11
8.0	1	2	3	5	6	7
8.2	.075	1.5	2.3	3.0	3.7	4.5

For practical purposes, CO_2 concentrations are negligible above pH 8.4.

Fish Culture Workshop

"*Bio-Engineering*" – A qualitative, quantitative approach to "*Rationally*" determine production and facility design concepts for *Intensive* fish production systems.

Fish Culturists/Biologists use variable numbers (Life).......

Engineers work with exact numbers...... Therefore "*variable*" numbers must become "*exact*" numbers.....

A Choice Must Be Made!

This is what Plato said about fish: *"Senseless beings......which have received the most remote habitation as a punishment for their extreme ignorance."*

But consider this: Fish have been very "successful" – about half of all vertebrates are fish.

$\pm$ 45,000 species

Also: Assertions creating doubt and suspicion are considered **"Fishy"** in the English language.

We all have our biases! And: Our biases have us!

Fish Culture Workshop

"**Bio-Engineering**" – A qualitative, quantitative approach to **Rationally** determine production and facility design concepts for Intensive fish production systems.

Fish Culturists/Biologists use variable numbers (Life)...

Engineers work with exact numbers... Therefore **variable** numbers must become **exact** numbers...

<u>A Choice Must Be Made!</u>

Quantitative Approach

Biologists (Life) Deal with Variability.

In Aquaculture: Mortality rates; Growth rates; Feed conversions; Condition factors; Metabolic rates, etc.

"More or Less" Values

Engineers use exact values: Rearing unit dimensions, Pipe sizes, Pumps, Pressure, etc.

Fish Culturists must select the "best" number (based on empirical data; experience; tradition; personal preferences; etc.) Must be as rational as possible.

"The person with experience is never at the mercy of a person with a theory."

Intensive Fish Culture

Biological Processes governed by two laws of thermodynamics:

1. **Energy** cannot be created nor destroyed but... can be changed into different forms.

2. In the **transformation** – such as food to flesh, there is a "loss" of energy in the form of heat.

(Figure 1-1)

Intensity of production; two variables:

1. **Productivity:** Harvest per unit area.

2. **Technology:** Degree of manipulation.

Systems: Extensive $\longrightarrow$ Intensive

1. Inputs from the outside.

2. Processing within.

3. Outputs to the external environment.

Extensive : Internal Control

Intensive : External Control

Carrying Capacity and Production

Difficult (to determine) with internally driven systems (such as ponds).

Intensive systems are **externally driven**...by the actions of the culturist!

Extensive systems:

Production in units per area

kg/ha or lb/acre

Intensive systems:

1. Production (carrying capacity) per unit of flow: **kg/lpm** or **lb/gpm**.

2. Production per unit of volume:

   kg/m^3 or **lb/ft^3**

1.0 kg/lpm = 8.33 lb/gpm (**3.0** kg/lpm = **25** lb/gpm)

1.0 lb/ft^3 = 16 kg/m^3

(1.0 m^3 = 35.3 ft^3)   (1.0 kg = 2.2 lb)

Loading (Ld) And Density

Loading (Ld): Capacity per unit of Flow (Q)

As: $Ld = kg/lpm$ lb/gpm

Density (D): Capacity per unit of Volume (RV)

As: $D = kg/m^3$ lb/ft^3

DO NOT USE THE TERM "LOADING DENSITY"

Relationships **Ld; D; R**

$$Ld = (D \times 0.06)/R \quad \text{and} \quad (D \times 8)/R$$

$$D = (Ld \times R)/0.06 \quad \text{and} \quad (Ld \times R)/8$$

$$R = (D \times 0.06)/Ld \quad \text{and} \quad (D \times 8)/Ld$$

R: Water turnover rates in #/hr

Example: **R = 2 = Every 30 minutes.**

"Nothing is ever as bad as it first appears."

$0.06 = 1.0 \text{ lpm} \times 60\text{min} = 60\text{l} = 0.06\text{m}^3$

$8 = 1.0 \text{ gpm} \times 60\text{min} = 60\text{gal} = 8\text{ft}^3$

R is turnover rate in #/h (60min) and rearing volume (RV) is expressed in m³ or ft³

An Exercise (Application)

Assume loading is 1.5 kg/lpm (12.5 lb)

Density is 96 kg/m^3 (6 lb)

What is R ?

R = (D $\times$ 0.06)/Ld $\longrightarrow$ (96 $\times$ 0.06)/1.5 = **3.84**

and: (6 $\times$ 8)/12.5 = **3.84** (For English)

Assume rearing volume (RV) = $10m^3$ ($353ft^3$)

Maximum Biomass (MBM) is:

MBM = D × RV $\longrightarrow$ 96 × 10 = **960kg**

English: MBM = 6 × 353 $\longrightarrow$ **2118 lb**

Q = MBM/Ld $\longrightarrow$ 960/1.5 = **640 lpm**

Q = 2118/12.5 = **169.4 gpm**

Equations:

$Ld = (D \times 0.06)/R$ $\qquad$ $(D \times 8)/R$

$D = (Ld \times R)/0.06$ $\qquad$ $(Ld \times R)/8$

$R = (D \times 0.06)/Ld$ $\qquad$ $(D \times 8)Ld$

$MBM = (D \times RV)$

$Q = MBM/Ld$ $\qquad$ $Q = (RV \times R)/0.06 \text{ or } 8$

Loading relates to flow rate (Q)

Density to rearing volume (**space**) (RV)

Ld, **D** and **R** Must Balance

These three are facility design driving forces.

"What you are driving is not important. What's important is what's driving you."

Establishing Loading Values

Dissolved Oxygen (DO) First limiting carrying capacity factor.

Demand for oxygen best expressed in terms of feed! (OF)

OF = Gram O_2 per **kg** feed

g O_2/lb

Per kg: 200 to 250g

Per lb: 91 to 114g

These are "Rational" values for salmonids, and seem to fit many other species as well.

But still somewhat controversial and... does not fit RAS! (More Later)

Must select a value

Will use **250 per kg** and **114 per lb**

Loading Values (II) (Oxygen)

Maximum loading values (MLd) depend on the fish's tolerance to the quality of the rearing water as it undergoes changes caused by the metabolic actions of the fish – Bioenergetics – (See again Figure 1)

1. **Removing** dissolved oxygen.

2. **Adding** ammonia; carbon dioxide; suspended solids; nitrates.

First Limiting Factor:

Dissolved oxygen depletion – but can correct (**can remove as limiting factor**) by aeration or oxygenation.

Loading based on oxygen required per unit of feed

(250g/kg; 114g/lb)

LdF = kg feed/lpm

LdF = lb feed/gpm

Loading Values – (Oxygen) III

Available Oxygen (AO)

1.0 lpm @ 1.0 mg/1 DO delivers 1440mg

(**144g**) O_2 Per day

($1.0 \times 1.0 \times 60 \times 24 = 1440$)

1.0 gpm @ 1.0 mg/1 (ppm):

$1.44 \times 3.785 = 5.45g$ O_2/day

$LdF = (1.44 \ AO)/ OF \ (5.45 \ AO) \longrightarrow$ English

Use: $\mathbf{LdF = AO/OF * (3.8 \ AO)} \longrightarrow$ English

$AO = DO_{in} - DO_{out} \ (DO_{out}$ is min. DO)

$DO_{in} = 10 \qquad DO_{out} = 6 \qquad AO = 4.0$

*Greatest metabolic activity during

"**Feeding Day**" — use 16.7 h.

$1.0 \times 1.0 \times 60 \times 16.7 = 1000 = \mathbf{1.0 \ g}$ (Instead of 1.44)

$English \longrightarrow \mathbf{3.8 \ g}$ (Instead of 5.45)

Loading Values – (Oxygen) IV

$LdF = AO/OF$ and 3.8 AO/OF

For OF $= 250$ $LdF = {}^{1}\!/_{250} = 0.004$ kg/lpm

For OF $= 114$ $LdF = {}^{3.8}\!/_{114} = 0.033$ lb/gpm

NOTE: Per AO !

Per AO can feed **0.004 kg/lpm**

0.033 lb/gpm

To change to fish loading (Ld) must know how much feed they require (% BW)

$$Ld = (AO \times 100)/(OF \times \% \ BW)$$

$$Ld = (3.8 \ AO \times 100)/(OF \times \% \ BW)$$

$\% \ BW = 1.0$ Ld is $100 \times LdF$

$\% \ BW = 10$ Ld is $10 \times LdF$, etc.

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Loading Values — (Oxygen) V

$DO_{in} = 10$ $DO_{min} = 6$ $AO = 4.0$ $\%\ BW = 1.0$

$Ld = (4 \times 100)/(250 \times 1.0) = \mathbf{1.6\ kg/lpm}$

$Ld = (3.8 \times 4 \times 100)/(114 \times 1.0) = \mathbf{13.3\ lb/gpm}$

The Question: How much oxygen can be made available before ammonia becomes the limiting water quality factor?

How high can AO be?

Feed "consumes" oxygen ($OF = \ldots ? \ldots$)

Feed generates ammonia as total ammonia nitrogen ($TANF = \ldots ? \ldots$)

(TAN)

Loading Values – (Ammonia) I

What is the value (the number) for TANF?

TANF: g TAN per unit food (kg or lb)

A "Rational" number, supported by the literature:

$\underline{30}$ g/kg Food

$\underline{13.6}$ g/lb Food

Range : 20-35g (11.4-13.6)

Depends on protein content: Quantity; Quality;
Ratio-(Energy-Protein)

$$gTAN = g F \times \% P_T \times \% N \times \% Ex \times \% TAN \times 1.2$$

Diet: 40% P_T N = 16%   Environment

Nitrogen loss (Ex) = 45% of which 80% is TAN.
Per kg (1000g) feed:

$$gTAN = 1000 \times 0.16 \times 0.45 \times 0.80 \times 1.2 = 27.4 \text{ g}$$

30% Protein: **20.7**   50% Protein: **34.6**

Loading Values (Ammonia) II

We "collectively" selected a number for

TAN*F*:   30 and 13.6 for English.

How much TAN is **Toxic Unionized Ammonia** (NH_3)?

This is **pH and Temperature** dependent (Table 1)

Will use in our deliberations a pH = 7.6 and

Temperature = 14°C (57°F) Resulting in a

% UA of 1.0

Next

Must select a number for a safe (healthy) concentration of unionized ammonia, a maximum allowable concentration (MUA)

No matter how thin you you slice it, there are always two sides.
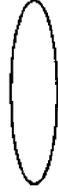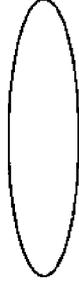
Loading Values – (Ammonia) III

Recommendations for maximum unionized ammonia (MUA): Ranges 0.010 to 0.035 **mg/l**

For salmonids – 0.0125 – 0.025

Still controversial Meade's Review ('85)

<u>Discussion</u> . . . .

For our exercise "we" select MUA = **0.025**

Provided: High **DO**; Low CO_2; High Alk (Na$^+$)

Now Recall:

$LdF = 0.004$ and 0.033 For English

$\boxed{kg/lpm}$ $\boxed{lb/gpm}$

$$\boxed{gTAN = LdF \times TANF}$$

$gTAN = 0.004 \times 30 = \mathbf{0.12g}$

and: $0.033 \times 13.6 = \mathbf{0.45g}$

This is **gTAN/d.**

We need to know what the concentration is!!

Loading Values – (Ammonia) IV

Remember: 1.0 lpm @ 1.0 mg/l = 1.44g/d

and 1.0 gpm @ 1.0 mg/l = **5.45g/d**

Therefore: 0.12g/1.44 = **0.083 mg/l**

and

For English:0.45g/5.45 = **0.083mg/l**

Will use a general rule, and that is that for each AO used we can expect **0.1 mg/l TAN**

This equates to a TANF of **36** (**16.3** English)

Also: The production of TAN peaks 2 to 4 hours after feeding …and… 0.1 can be considered a

Rational number.

Therefore, in our deliberation/examples or exercises, we will use **0.1 mg/l TAN** for each **AO** used.

Loading Values – (Ammonia) V

$$TANC = (AO \times TANF)/(1.44 \times OF)$$

English

$$TANC = (3.8\ AO \times TANF)/(5.45 \times OF)$$

We now need to determine the concentration of toxic

Unionized Ammonia (UA)

$$UAC = (TANC \times \%\ UA)/100$$

When we use "our" numbers:

$$UAC = (0.083 \times 1.0)/100$$

But: We decided **0.083** is **0.1**

Therefore:

$$UAC = (0.1 \times 1.0)/100$$

$$UAC = \mathbf{0.001 \ mg/l}$$

For TANC = 0.1   and   %UA = 1.0 (per AO)!

Loading Values – (Ammonia) VI

Now to determine the maximum AO value (MAO)

Recall: UAC of **0.001 mg/l** represents concentration
per AO

The question then: **How many AO's?**

$$MAO = \frac{MUA}{UAC} = \frac{0.025}{0.001} = 25 \text{ mg/l}$$

An equation:

$$\boxed{MAO = (MUA \times OF \times 1.44 \times 100)/(TANF \times \%UA)}$$

"Our" numbers:

$MAO = 0.025 \times 250 \times 1.44 \times 100)/(36 \times 1.0)$

Based on

$UAC = 0.1$ per AO

$MAO = 900/36$

$\boxed{MAO = 25}$

Maximum Loading (MLd) I

Conclusion: Can use **AO = 25**

$$\boxed{MLd = (MAO \times 100)/(OF \times \%BW)}$$

$$MLd = (25 \times 100)/(250 \times 1.0)$$

$$MLd = 10 \text{ kg/lpm} \quad (For \%BW = 1.0)$$

English: $MLd = (3.8 \times 25 \times 100)/(114 \times 1.0)$

$$MLd = 83.3 \text{ lbs/gpm} \quad (Use 83)$$

Discussion: What density to select?

$Ld = (D \times 0.06)/R \quad D = (Ld \times R)/0.06$

English: $Ld = (D \times 8)/R \quad D = (Ld \times R)/8$

Maximum Loading – (*MLd*) II

Must balance the **Ld, D, R** Equation.

$$D = (Ld \times R)/0.06 \quad \text{or} \quad 8$$

$$D = (10 \times 1.0)/0.06 = 167 \text{ kg/m}^3$$

$$D = (83 \times 1.0)/(8) = 10.4 \text{ lb/ft}^3$$

This is per **R** value of 1.

$R = 2$ **D** = **334 kg/m**^{3} English: **20.8 lb/ft**^{3}

R 2 Ok for circular units but plug flow (raceways) should have **4 or more. Later!**

Density Discussion

D.I. ?

Position: See Table 2

Keen Buss:> 500 kg/m^3 (31 lb/ft^3)

More fish than water.

Need A Number!!

Will return later for more discussion.

Ld – D – R Relationship

Ld = 10 kg/l   83 lb/gpm

What we saw – Too High Densities

For R = 2 → D = 334 kg/m^3 20.8 lb/ft^3

For R = 4 → D = 668 kg/m^3 41.6 lb/ft^3

These exchange values are needed for good hydraulics.

This will be discussed under **Rearing Units**

Conclusion:

$$D = (Ld \times R)/0.06 \qquad \text{or } 8 \qquad \text{Does Not Fit}$$

Does Not Balance

Will return to this when discussing facility design processes.

For now: Assumed DO not limiting rather unionized ammonia is limiting.

But: What about <u>Carbon Dioxide?</u>

Carbon Dioxide – (CO_2) I

For each AO used about 1.4 mg/1 CO_2 is generated.

For MAO = 25 MCO_2 = 35 mg/1

Maximum CO_2 (MCO) Concentrations

Range from 10 to 60 mg/1

Discussion: pH, Alkalinity, Temp.

$$CO_2 + H_2O = H_2CO_3 \longleftrightarrow HCO_3 \longleftrightarrow CO_3$$
$$H^+ \qquad\qquad H^+$$

Lowers **pH** – Alkalinity Resists

A Dynamic Equilibrium

Free CO_2 (Gaseous) Is Toxic

How much free CO_2?   Table I-3

May have to control CO_2:

1. Degas
2. Chemical (pH control)

Unit VII

Carbon Dioxide – (CO_2) II

Colt: When COC (cumulative oxygen consumption) is 20, CO_2 must be managed. (COC same as MAO)

Table I-4 shows impact of pH, temperature and alkalinity on free CO_2.

More discussion about CO_2 later.

Gas Management (Unit VII)

Recirculation (Unit VI)

Low **pH** favors unionized ammonia

High **pH** favors gaseous CO_2 problem

Discussion?

See Figures

Equations Used

1. $Ld = (D^{\times} 0.06)/R \quad D = (Ld^{\times} R)/0.06$

   $R = (D^{\times} 0.06)/Ld$

   1a. For English: 0.06 is 8

2. $MBM = D^{\times} RV$

3. $Q = MBM/Ld$ and $\boldsymbol{Q} = (RV^{\times} R)/0.06$ or 8

4. $LdF = AO/OF$

   4a. $LdF = 3.8\ AO/OF$

5. $AO = DO_{in} - DO_{out} \qquad DO_{out} = DO_{min}$

6. $TAN\,g = LdF^{\times} TANF$

Equations Used

7. $TANC = (AO \times TANF)/(1.44 \times OF)$

7a. $TANC = (3.8\ AO \times TANF)/(5.45 \times OF)$

8. $UAC = (TANC \times \%UA)/100$

9. $MAO = (MUA)/(UAC)$

10. $MAO = (MUA \times OF \times 1.44 \times 100)/(TANF \times \%UA)$

11. $MCO_2 = MAO \times 1.4$

Recall: $MAO = \dfrac{0.025}{0.001} = 25$

Equations Used

This is for: 1) % UA = 1.0 and

2) 0.1 mg/1 TAN per AO

Other *MAO* Values: 25 / % UA

$0.0125 \times 1000 = 12.5$ and

$0.035 \times 1000 = 35.0$ etc.

$$MAO = \frac{MUA \times 1000}{\%UA}$$

See Table – MAO Values

Energy In; Lost; Used; Stored.

Feed

1000 g @ 10% H_2O = 900 g

Fish

80% H_2O

Ingest. G.E.

Digest

Digest Energy

Food Utilization

Waste Feed

3-5%
30-50 g

Fecal Matter

25%
250 g

Excert. Products

NH_3 = 3%
(30g)

F-1
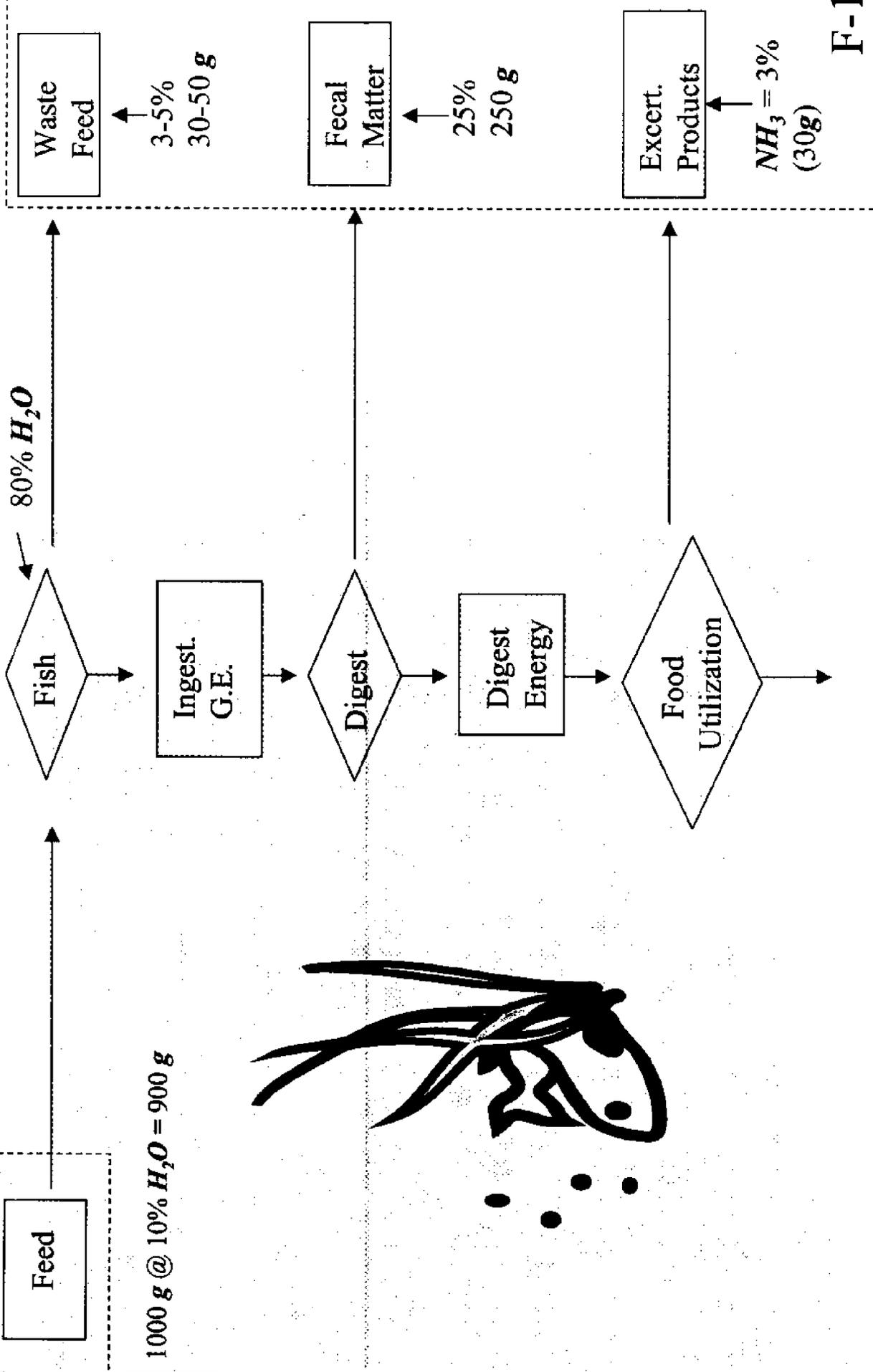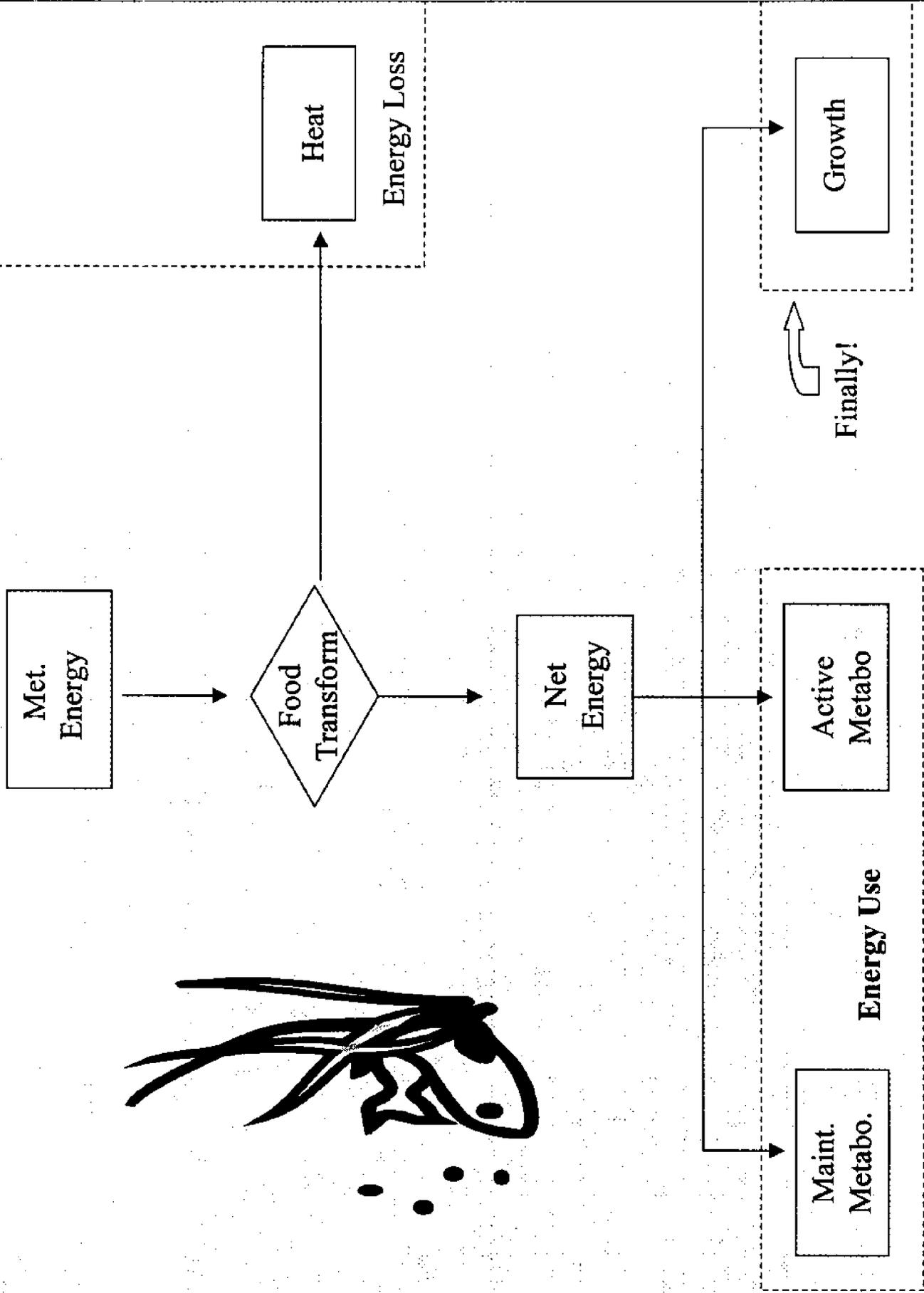
Flow diagram of Fish Bioenergetics modified after Ernst (2000)

F-1a

Table 1 Percent of total ammonia as toxic unionized over the range of pH and temperature.

	Water Temperature			
pH	5(41)	10(50)	15(59)	20(68)
6.0	0.01	0.02	0.03	0.04
6.2	0.02	0.03	0.04	0.06
6.4	0.03	0.05	0.07	0.10
6.6	0.05	0.07	0.11	0.16
6.8	0.08	0.12	0.17	0.25
7.0	0.13	0.18	0.27	0.40
7.2	0.20	0.29	0.43	0.63
7.4	0.32	0.47	0.69	1.00
7.6	0.50	0.74	1.08	1.60
7.8	0.79	1.16	1.71	2.45
8.0	1.24	1.83	2.68	3.83
8.2	1.96	2.87	4.18	5.93

Source: G.A. Wedemeyer. 1996. Physiology of Fish in Intensive Culture. Chapman and Hall, New York   **Highly Recommended!**

T-1

Table 2 MAO values for six MUA values, based on UA=1%; OF=250; (114); TANF=30; (13.6) and OF=350 (159); OF=450 (205)

	- MUA –(mg/l)				
OF	0.015	0.020	0.025	0.030	0.035
250	18	24	30	36	42
350	25	34	42	50	59
450	32	43	54	65	76

Must select a number for:

MUA

OF

TANF

(% UA – pH and Temp)

T-2

Table 3   Approximate Values for free CO_2

(In mg/l)

pH	**Alkalinity in mg/l (15° C)**					
	50	**100**	**150**	**200**	**250**	
6.4	46	92	138	184	230	
6.6	29	58	87	116	145	
6.8	18	37	55	73	92	
7.0	12	23	35	46	58	
7.2	7	15	22	29	36	
7.4	5	9	14	18	23	
7.6	3	6	9	12	15	
7.8	2	4	6	7	9	
8.0	1	2	3	5	6	
8.2	.75	1.5	2.3	3.0	3.7	

For practical purposes, CO_2 concentration are negligible above pH 8.4.

T-3

Problem Solving Unit I

1. What will be the Rearing Density in kg/m^3 ; lb/ft^3 ?

   a) $DF = 250 \, g \, O_2/kg$ feed $114/lb$

   b) $AD = 5.0 \, mg/l$

   c) $\% \, BW = 2.0$

   d) $R = 4.0$

2. Determine the Maximum Possible mg/l DO (MAO) under the following Conditions:

   a) $TANC = 0.1 \, mg/l$ per AO

   b) $\% \, UA = 0.80$

   c) $MAUA = 0.020 \, mg/l$

PROBLEM SOLVING UNIT-I

1. ANSWER:

$$Ld = \frac{100 \times AO}{OF \times \%BW} = \frac{100 \times 5.0}{250 \times 2.0} = \underline{1.0 \ kg/\ell pm}$$

$$Ld = \frac{3.8 \times 100 \times AO}{114 \times 2.0} = \underline{8.33 \ lb/gpm}$$

$$D = \frac{Ld \times R}{0.06} = \frac{1.0 \times 4.0}{0.06} = \underline{66.7 \ kg/m^3}$$

$$D = \frac{8.33 \times 4}{8} = \underline{4.16 \ lb/ft^3}$$

CONVERSIONS:

$1.0 \ lb/ft^3 = 16 \ kg/m^3$

$1.0 \ kg/\ell pm = 8.33 \ lb/gpm$

$1.0 \ gal = 3.785 \ \ell$ and: $1.0 \ \ell = 1.057 \ quart$

$1.0 \ \ell pm = 0.264 \ gpm$ $1.0 \ gpm = 3.785 \ \ell pm$

PROBLEM SOLVING UNIT I

2. ANSWER:

a) $MAO = \dfrac{MUA \times OF \times 1.44 \times 100}{TANF \times \% UA}$

b) $MAO = \dfrac{0.020 \times 200 \times 1.44 \times 100}{36 \times 0.80} = \underline{20.0 \, mg/\ell}$

FOR OTHER OF VALUES:

$OF = 250 \quad MAO = 25$

$OF = 300 \quad MAO = 30$

$OF = 500 \quad MAO = 50$

etc.

II. RESPIRATION AND OSMOREGULATION

INTRODUCTION

The gills of fish are in intimate contact with the surrounding water, the rearing environment. It is imperative that the quality of this water not only protects the fish gill against physical damage, but also allows the gill to carry out its multiple tasks; gas exchange, ion transport, acid base balance, and nitrogenous waste excretion. To accomplish these varied functions, the gill epithelium consists of a variety of cells. Because its foremost function is gas exchange, respiratory or pavement cells may represent up to 90% of all epithelial cells contained in the gill..

Mitochondria rich (MR) chloride cells, are sometimes referred to as "ionocytes" to reflect their function in ion transport. Freshwater fish live in a hypo-osmotic environment, which means that their internal (plasma) salt content, which ranges from 0.75 to 1.2%, is greater than that of the environment. To maintain osmoregulatory balance, these fish must constantly replenish ions (electrolytes), the primary ones being sodium (Na^+) and chloride (Cl^-). Under the hypo-osmotic conditions, water continuously diffuses into the fish, and consequently they generate large volumes of dilute urine, but still lose ions which must be replaced by diet and from the water. Saltwater fish live in a hyper-osmotic environment, and continuously lose water, which is replaced by drinking seawater. These fish must rid themselves of excess ions in order to maintain osmotic balance. Their salt content may vary from 1.2 to 1.5%. In both cases (freshwater and saltwater fish), the gills play an important role in maintaining osmotic balance (Figure 1).

Gills can also take up "bad" ions such as heavy metals. In intensive culture nitrite ions can be present. It is readily taken up across the gills and concentrated in the blood, whereby even low concentrations in the ambient water can result in significant methemoglobinemia (Met Hb), the so-called brown blood disease. During nitrite exposure, a large decrease in blood O_2 affinity

1

occurs, mainly due to RBC shrinkage. Another interference with blood O_2 affinity is known as the Bohr effect. It is caused by a decrease of blood pH, the result of carbon dioxide buildup (acidosis). This same condition also effects the oxygen carrying capacity of the hemoglobin, known as the Root effect. When this (acidosis) happens, even supersaturated dissolved oxygen concentrations cannot bring relief!

Under normal conditions of blood pH (±7.6) only 5% of the carbon dioxide is free CO_2, and > 90% as HCO_3^- in the plasma. The blood can carry much HCO_3^-.

THE UPTAKE OF OXYGEN

To extract oxygen from the water, it must flow over the gills in one direction (Figure 2). This is accomplished by the action of muscular "pumps," which create the breathing movements observable in fish. This breathing in water has a significant energetic cost associated with it. Routine ventilation cost is around 10% of the oxygen consumed, but can be as high as 70% with ventilation rates three-fold the routine. In resting humans this cost is about 2%.

Compared to air, water has a viscosity 800 x that of air and a density 60 x as great. Additionally, oxygen saturated water has only about 1/20 the O_2 content of air and the rate of diffusion is but 1/10,000 that of air!

With each inspiration, much of the water moved across the gills does not come in contact with the secondary lamellae, the site where the gas exchange takes place. This water bypass can be as high as 60%, and, of the water that does come in contact with the secondary lamellae, only 60 to 80% of the dissolved oxygen in the water is taken up. Under unfavorable low-oxygen conditions the uptake rate is even worse. As the fish increases the rate of inspiration, the result is reduced contact time of the water on the lamellae, and in addition, the gradient between blood and water oxygen content is less!

2

The secondary lamellae are extremely thin, from 1 to 5 μm depending on species. It is the total surface area that determines the efficiency of oxygen uptake. Active fish generally have a larger gill area than sluggish ones. Also, small fish of the same species have a larger gill area per unit of weight than large fish. Small fish, under conditions of the same temperature, have higher metabolic rates than large ones.

Data compiled from 31 species show the average area of gills to be 4.9 cm^2/g body weight (4900 cm^2/kg). There is considerable variation around this value. Active fish, such as mackerels and tunas have a gill area of 12 cm^2/g, while air-breathing fish, such as climbing perch, have a gill area of only 1.44 cm^2/g. In these latter fish, the respiratory epithelium has a thickness of about 20 μm, while generally the thickness falls between 1 and 5 μm.

To help in visualizing these numbers, an area of 4.9 cm^2/g represents 8 standard 8-1/2 x 11 sheets per kg fish, and the maximum of 12 cm^2/g equals 20 sheets per kg.

As mentioned, each inspiration delivers more water than is exposed to the lamellae, and of the water contacting these, only a portion of the oxygen content is transferred to the blood. If we know the water bypass percentage and percent oxygen removed, the efficiency of oxygen extraction can be determined. For instance, for a water bypass of 60% and an oxygen uptake of 80%, this efficiency is 32% [(80/100) x (100 - 60)]. Because of this relatively low efficiency, the fish must pump a significant amount of water across the gills to satisfy the demand for oxygen.

For example, a one kg trout with a metabolic rate of 300 mg O_2 per hour in water with dissolved oxygen concentration of 9.0 mg/l must pump 104 l (27.5 gal) of water per hour over the gills (Oxygen uptake efficiency is 32% of 9.0 mg/l = 2.88 mg/l; water pumped is 300/2.88 = 104 l per kg per hr). Dissolved oxygen is lowered from 9.0 to 6.12 mg/l by 1.0 kg trout per lpm flow.

3

If we apply this to the loading equation I-8 using the AO value of 2.88 and OF of 250, the fish can be fed 1.152 %BW [(2.88/250) x (100)] = 1.152. For OF of 350, %BW = 0.82. Depletion of oxygen results in increased ventilation volumes as does exercise. When exposed to hypoxic conditions, volumes as high as 420 to 720 l per hour have been reported.

Table 1 shows respiratory volumes in lpm for different DO concentrations and oxygen demands (metabolic rates in mg O_2 per kg fish per hour).

Fish may save some "respiration energy" when they switch to ram ventilation. With ram ventilation, the fish either position themselves in a fast current or they swim at a high speed. By simply opening their mouth, water flows in over the gills and out of the opercular cavities. Ram ventilation can reduce the energy demand for some fish species. For instance, when brook trout were reared in water velocities 1.5 to 2.0 times their body length per second they exhibited better growth rates and feed conversions. Velocities exceeding these may be counter productive. Unexercised salmonids can, indefinitely, sustain velocities from 1 to 2 body lengths per second. Safe velocities (v_s), expressed in body length per second (BL/s) for salmonids should be one half the critical speed, these can be calculated with equation 1, as suggested by Youngs and Timmons (1991):

$$v_S = (0.5) \, X \, (10.5 \, / \, L^{0.37}$$

(1)

For a 10 cm fish this is 2.2 BL/s, for a 20 cm fish 1.73 BL/s.

LOW OXYGEN STRESS

Low dissolved oxygen concentrations can affect fish in several ways, such as reduced growth rates, increased feed conversions, changed behavior, accelerated ventilation and, ultimately disease and reduced survival.

What are the lowest safe limits for DO? This is highly species specific. For salmonids, recommendations vary from 5 to 7 mg/l. For tilapia it may be only 2.0 mg/l. Concentration can be expressed by partial pressure (pO_2). Oxygen constitutes 21% of the total atmosphere, thus at an atmospheric pressure of 760 mmHg, the pO_2 is 159.6 mmHg (0.21 x 760). Atmospheric pressure is standardized at sea level and is equivalent to 760 mmHg (based on this, the following discussion).

According to some studies optimum oxygen transfer across gill membranes requires a pO_2 of 118 mmHg for rainbow trout. Other investigations found that rainbow trout maintain near 100% saturation with oxygen as long as pO_2 is above 80 mmHg (50% saturation), Downey and Klontz (1981) recommend 90 mmHg pO_2 for rainbow trout (56.4% saturation).

Both temperature and elevation affect oxygen solubility (Table 2). However, temperature has little effect on oxygen partial pressure. For instance, an increase in temperature from 0 to 20°C results in a decrease in dissolved oxygen of 38%, but a reduced pO_2 of only 2%.

With respect to elevation, a linear relationship exists between dissolved oxygen content and partial pressure exerted at constant temperature. Air saturated water at 5000 feet elevation has 17% less dissolved oxygen and 17% less pO_2 than water with the same temperature at sea level.

Because efficiency of oxygen uptake depends on partial pressure, not dissolved oxygen content, a minimum partial pressure of 90 mmHg is recommended for salmonids. The gradient between oxygen in the water and blood determines the ease of transfer from one fluid to the other. Elevation, although it affects partial pressure in water, it also, simultaneously affects the partial pressure within the fish itself. Based on a minimum pO_2 of 90 mmHg, the minimum oxygen concentrations, as a general rule, should be about 7.5 mg/l above 15°C.; 6.5 mg/l from 6 to 10°C; 6.0 mg/l from 11 to 15°C abdomen 5.5 mg/l above 15°C. A general formula to calculate the equilibrium oxygen concentration is:

$$SO = \frac{129.5}{T_F^{0.625}} \qquad (2)$$

To correct for elevation:

$$SO = \frac{129.5}{T_F^{0.625}} \times \frac{760}{760 = \dfrac{E}{32.8}} \qquad (3)$$

Where T_F is temperature F and E represents elevation in feet above sea level (Soderberg, 1986).

Rainbow trout reared at 130% saturation showed decreased blood hemoglobin, hematocrit, and red blood cell count. Rearing at 150% O_2 saturation increased suseptibility to enteric redmouth disease. Growth, generally, is not increased under hyperoxic conditions.

ION EXCHANGE MECHANISM

The mechanisms for Na^+ and Cl^- uptake by the gills are independent and counter ions for these, presumably, H^+ (NH_4^+) and HCO_3^- respectively are excreted to the water simultaneously. These electroneutral ion-exchange pathways have been suggested to be involved in acid-base regulation and a portion of carbon dioxide and ammonia excretion. The direct excretion of HCO_3^- via Cl^-/HCO_3^- exchange mechanism, though important for ionic and acid-base regulation, likely accounts for less than 5% of total carbon dioxide excretion.

Fish can excrete acid into water which has a pH of 6 while maintaining gill epithelium pH at around 7.4. With a low pH boundary layer nearly all of the ammonia is in the ionized form. Thus a significant gradient between blood level ammonia (pH 7.4) and environmental ammonia within the gill boundary layer (pH 6) exists. This expedites the passive diffusion of NH_3 into this

6

boundary layer. Exchanging NH_4^+ ions with Na^+ ions can potentially be a significant mechanism for ammonia excretion, but at this time it is still a controversial issue. It seems desirable to investigate its potential as an ammonia excretion mechanism, and the role sodium ion concentrations may play in this.

Ionic regulation in fish is covered extensively in "Cellular and Molecular Approaches to Fish Ionic Regulation" by C.M. Wood and T.J. Shuttleworth, Academic Press 1995.

Table 1. Lpm fish must pump across their gills based on five DO concentrations and six metabolic rates, assuming an oxygen uptake efficiency of 32%.

DO mg/l	Metabolic Rates (mg O_2/kg/hr)					
	100	200	300	400	500	1000
20 (s)	0.26	0.51	0.78	1.05	1.30	2.60
16 (s)	0.33	0.65	0.98	1.31	1.62	3.24
12	0.44	0.86	1.30	1.74	2.16	4.32
10	0.53	1.03	1.56	2.10	2.60	5.20
8	0.67	1.29	1.95	2.62	3.24	6.48

Table 2. Dissolved oxygen at saturation (*SO*), minimum effluent dissolved oxygen (*EO*) and available dissolved oxygen (AO in mg/L) for four temperatures (in C) and four elevations, based on a minimum pO_2 of 90 mmHg (56.4% of saturation).

Temperature	Sea level			1,000 m			2,000 m			3,000 m		
	SO	*EO*	AO	*SO*	*EO*	AO	*SO*	*EO*	AO	*SO*	*EO*	AO
5	12.7	7.1	5.6	11.3	6.4	4.9	10.1	5.7	4.4	9.0	5.1	3.9
10	11.3	6.3	5.0	10.0	5.6	4.4	8.9	5.0	3.9	7.9	4.5	3.4
15	10.1	5.7	4.4	8.9	5.0	3.9	7.9	4.5	3.4	7.0	3.9	3.1
20	9.1	5.1	4.0	8.1	4.6	3.5	7.1	4.0	3.1	6.3	3.6	2.7

TABLE 2.1 Composition of Seawater

Constituent	Concentration (ppm)		Constituent	Concentration (ppm)
Chloride	18,980 } 86%ₑ		Lead	0.004–0.005
Sodium	10,560		Selenium	0.004
Sulfate	2560		Arsenic	0.003–0.024
Magnesium	1272 } 13%		Copper	0.001–0.09
Calcium	400		Tin	0.003
Potassium	380		Iron	0.002–0.02
Bicarbonate	142		Cesium	~0.002
Bromide	65		Manganese	0.001
Strontium	13		Phosphorous	0.001–0.10
Boron	4.6		Thorium	$\leqslant 0.0005$
Fluoride	1.4		Mercury	0.0003
Rubidium	0.2		Uranium	0.0015–0.0
Aluminum	0.16–1.9		Cobalt	0.0001
Lithium	0.1		Nickel	0.0001–0.0
Barium	0.05		Radium	8×10^{-11}
Iodide	0.05		Beryllium	.
Silicate	0.04–8.6		Cadmium	.
Nitrogen	0.03–0.9		Chromium	.
Zinc	0.005–0.014		Titanium	Trace

Source: Spotte, 1973.

FRESHWATER FISH BLOOD PLASMA: $Na^{+} \doteq 0.31\%$ (3100 mg/l)

$Cl^{-} \doteq 0.315\%$ (3130 mg/l)

OVERAL SALINITY OF FISH BLOOD: 0.7 – 0.9%

Respiration and **Osmoregulation**

How about stirring up a little sympathy
and respect for our fish

Aquatic versus Terrestrial Environment

Water:

Viscosity	$800 \times$ Air
Density	$60 \times$ Air
DO SAT	$\pm \frac{1}{30}$ of air

$21\%\ O_2$ $=$ **210,000 mg/l**

Air:

Many substances in solution

The Gill: A Multifunctional organ

Absorption - Intake (O_2; Na^+; CI^-; CA^{2+}, etc)

Excretion - Output (CO_2; NH_3)

Respiration = Uptake of oxygen is the main function of the gill

Water (Heavy Media) must be "pumped" across the gills. High energy cost associated with this - 10 to 30% of oxygen taken in. Can be as high as 70%.

Respiration – I

1. Bypass can be 60% (shunt)

2. 40% of water "pumped" in contact with the filaments.

3. Of this 80% of the oxygen is taken up by the filaments.

4. This results in an efficiency of 32% oxygen absorption from the water "pumped"

$$\% \ O_2 \ ABS = [(80/100) \times (100 - 60)] = 32$$

Bypass 60% of H_2O

40% of H_2O and 80% of DO

H_2O + DO
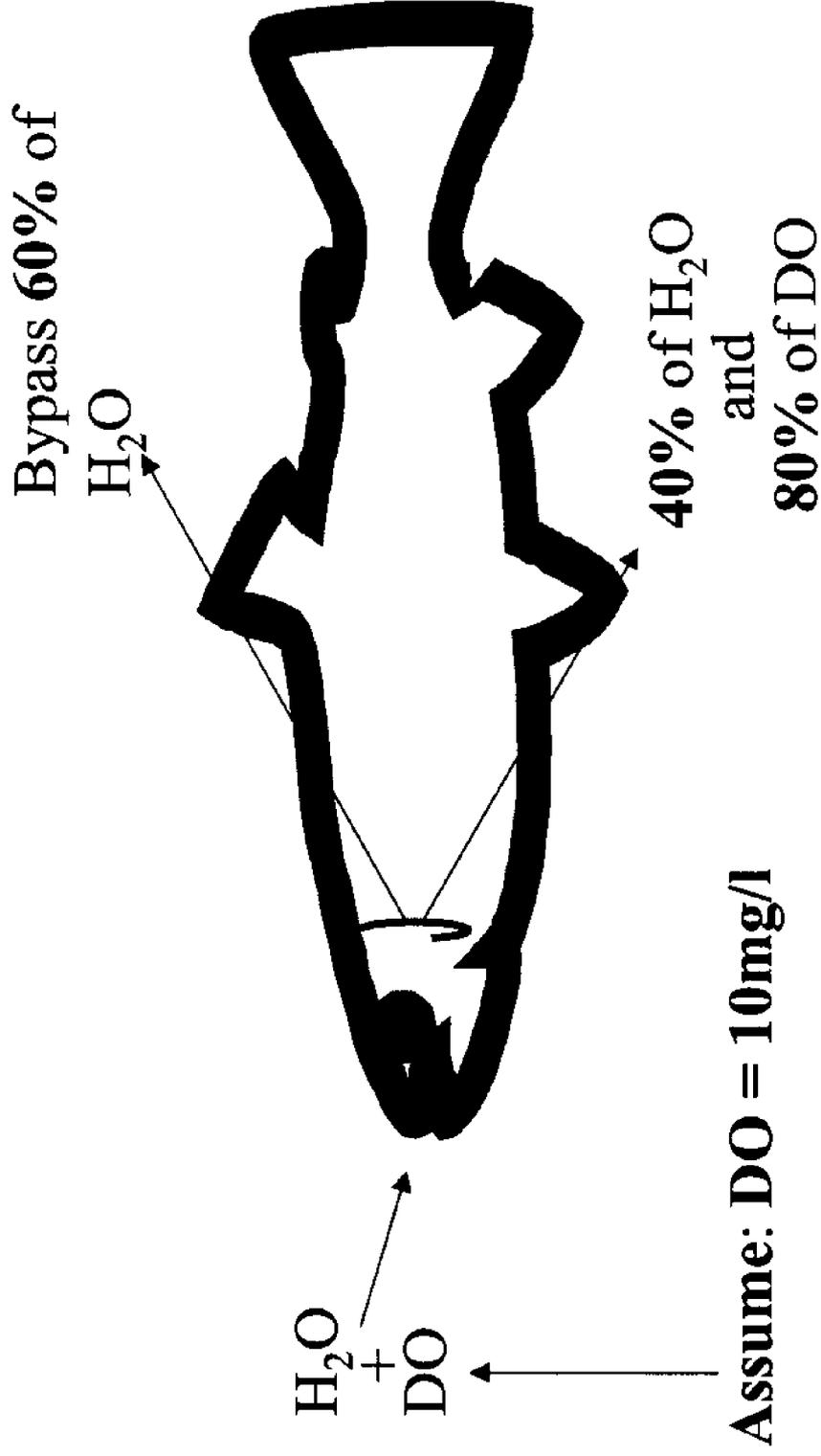
Assume: DO = 10mg/l

Discussion: Ram Ventilation

Respiration – II

Assume **DO = 10 mg/l**

Metabolic rate is **300 mg O_2 / kg/h**

$$\boxed{MR = 300}$$

At "Respiration Efficiency" of 32% the fish (one kg) must pump **93.75 l/h**

32% of 10 mg/l = **3.2 mg/l** taken up

Need 300 mg/h   300/3.2 = **93.75 l/h**

lpm Fish must pump across their gills based on 5 DO's and 6 MR's for an uptake efficiency of 32%

Metabolic Rate (mg/kg/h)

DO mg/l	100	200	300	400	500	1000
20(s)	0.26	0.51	0.78	1.05	1.30	2.60
16(s)	0.33	0.65	0.98	1.31	1.62	3.24
12	0.44	0.86	1.30	1.74	2.16	4.32
10	0.53	1.03	(1.56)	2.10	2.60	5.20
8	0.67	1.29	1.95	2.62	3.24	6.48

l/h = 60 × l/min

× 60 = **93.6 l/h**

Respiration – III

O_2 Transfer across membranes is most efficient when:

1. There is a large gradient differential

  -Partial oxygen pressure (pO_2)

$O_2 - 21\%$ ATM. 760 mmHg

21% $=$ pO_2 of **159 mmHg**

Minimum (Rainbow Trout) $pO_2 =$ **90 mmHg**

  About 60% saturation DO.

O$_2$ Solubility

1. **Temperature Effect** – Little on pO$_2$

2. **Elevation:** Linear Relationship.

Air saturated water at 5000 feet elevation has 17% less DO and 17% less pO$_2$ than saturated water at sea level.

Fish at high elevation also have reduced pO$_2$ in blood – It is the gradient that is important.

Respiration – IV

The problem with very **high DO's:**

(>200% Super saturation)

1. Fish "pump" **less water** and this can interfere (reduce) CO_2 excretion – less water contact.

2. Fish **reduce hemoglobin** – reduction can create problems.

The problem with **Low DO's:**

1. Fish must "pump" greater volume of water. Energy demand, reduced growth.

2. Magnifies problem with elevated NH_3 and CO_2 levels (stress).

CO_2: Bohr and Root effects, Hypercapnia and Acidosis

See Figure 3

Osmoregulation – 1

Absorption of ions (electrolytes) and
Excretion of ions.
To maintain Homeostasis = Balance

Freshwater: Hypo Osmotic
Fish blood (plasma) 0.75-1.0%

Saltwater: Hyper Osmotic

Freshwater: H_2O moves into the fish – must
get rid of – copious volume of
diluted urine.

And: Must **replace ions** lost (Na^+; Cl^-; Ca^{++}; K)

Gill takes in ions

Ion – Exchange: Na^+ with NH_4^+ Cl^- with HCO_3^-

Saltwater: H_2O moves out of the fish must

replace H_2O by drinking saltwater…

And: Must **Excrete Ions** – Function of Gill.

Osmoregulation –II

Need Research:

$$Na^+ \longrightarrow NH_4^+ \text{ Exchange Mechanism}$$

Discussion: Na^+ has mediating effect

1. Steelhead Study – Dworstak NFH

2. Personal Study – (Coho Salmon)
   500 mg/l Na^+

   MUA at 0.2 mg/l = 10 – Fold

   Recommended Concentration (0.0125 – 0.030 mg/l)

Note: 1.0% equals 10,000 mg/l

$$500 \text{ mg/l} = \underline{0.05\%}$$

Seawater: 3.5% salt, mostly NaCI

Na^+: > 10,000 mg/l

Fish blood: $\pm$ 1.0%

Table 2
Dissolved oxygen at saturation (DOs), minimum effluent DO (DO_{min}) and available dissolved oxygen (AO) for four temperatures and four elevations, based on minimum pO_2 of 90 mmHg (56.4% sat)

Temp.	Sea Level			1000m			3000m		
	Do_s	DO_{min}	AO	DO_s	DO_{min}	AO	Do_s	DO_{min}	AO
5 (41)	12.7	7.1	5.6	11.3	6.4	4.9	9.0	5.1	3.9
10 (50)	11.3	6.3	5.0	10.0	5.6	4.4	7.9	4.5	3.4
15 (59)	10.1	5.7	4.4	8.9	5.0	3.9	7.0	3.9	3.1
20 (68)	9.1	5.1	4.0	8.1	4.6	3.5	6.3	3.6	2.7

Low temperature, More AO, But higher DO_{min}

II-T2

Figure 1

Water In

Na^+, Cl⁻, K

Water, some ions lost

Freshwater Fish

Drink Water

Water Out

$Na^+ + Cl^-$ Out

Ca^{++} Mg^{++} $SO_4^=$ + Water Out
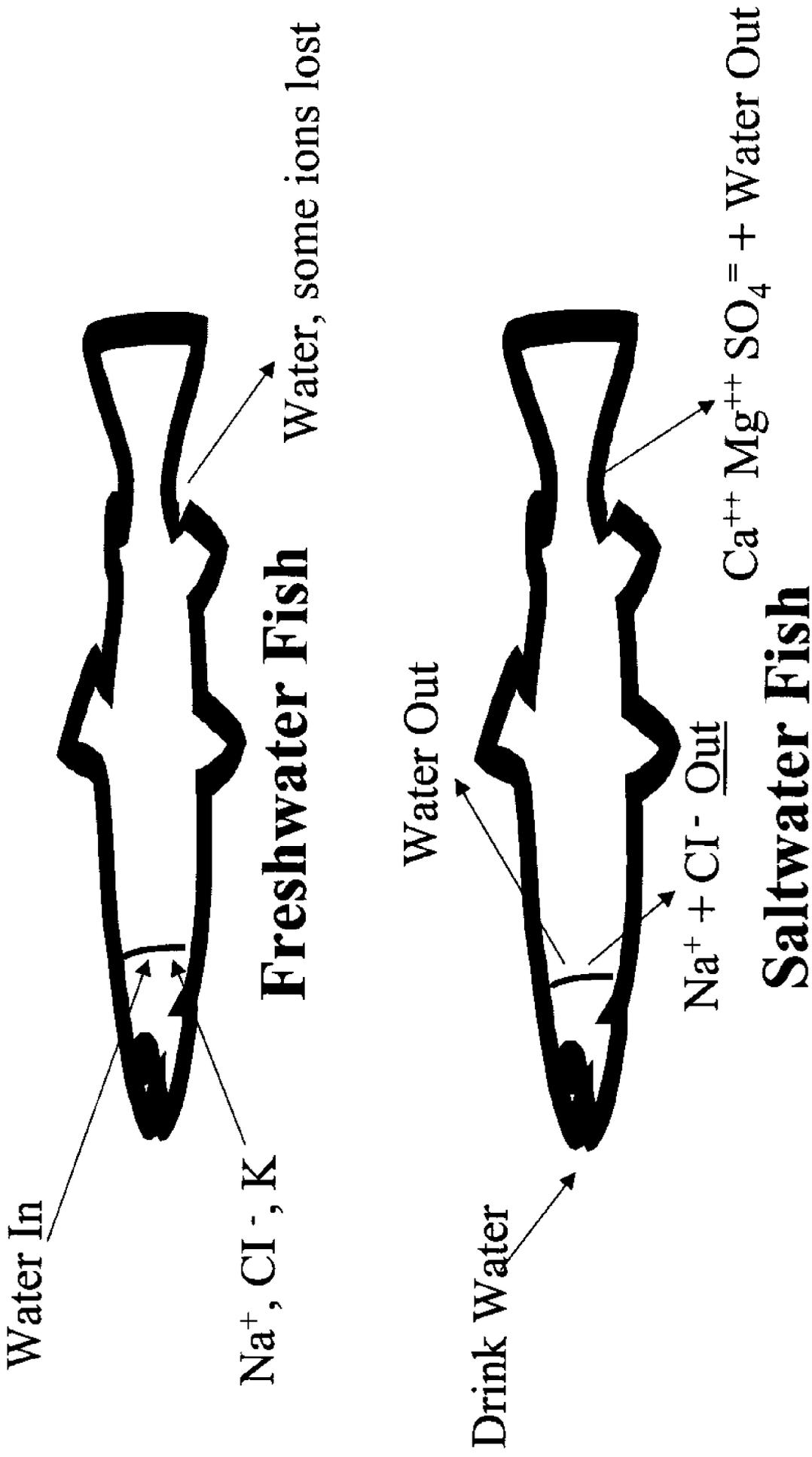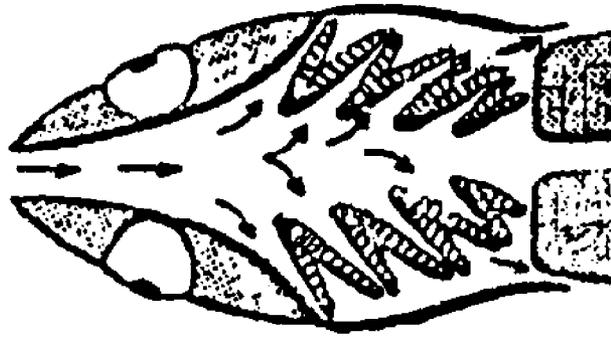
Saltwater Fish

Maintaining Osmoregulatory Balance:
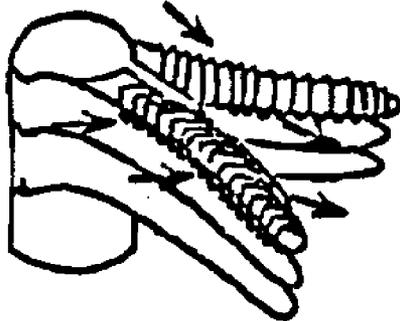Freshwater versus Saltwater Fish

II-F1

Figure 2.

A
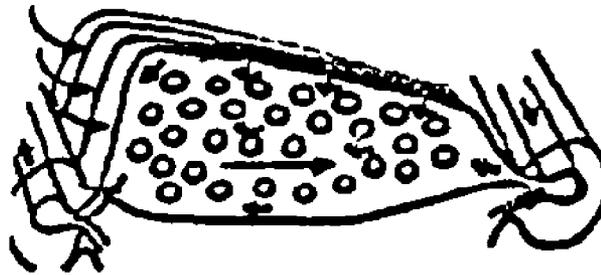

Fish Gill - Arrows indicate direction of water flow.

B

Single gill arch with two rows
of filaments

C

A lanella in side view

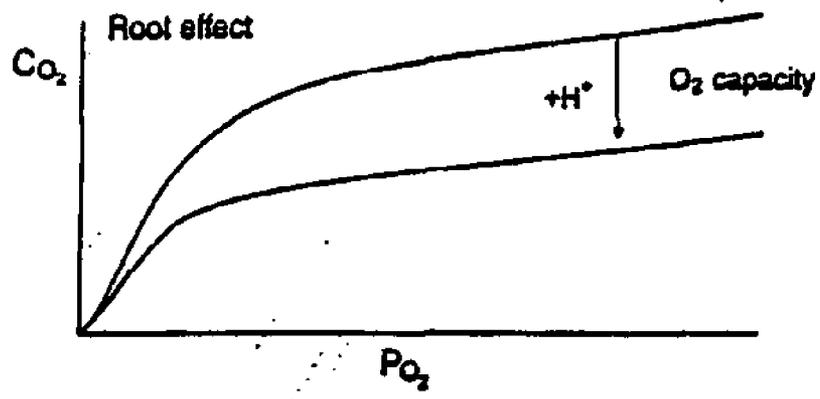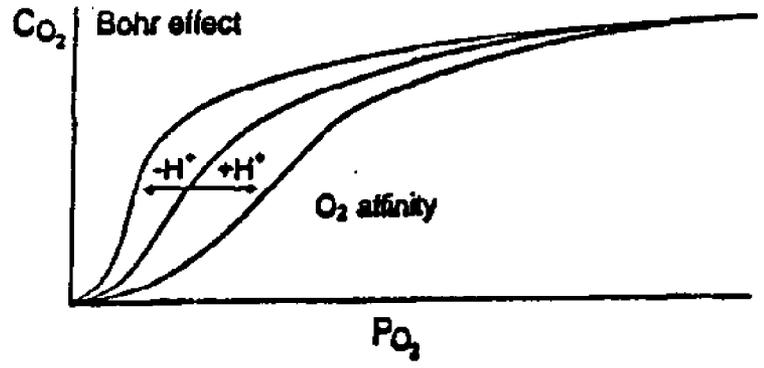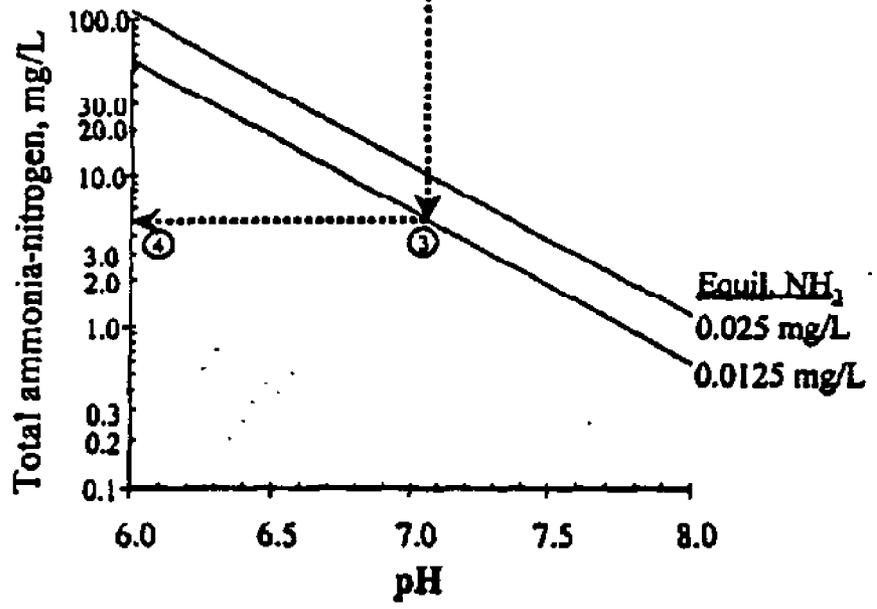Source: D.H. Evans (ed) The Physiology of Fishes. CRC Press 1993

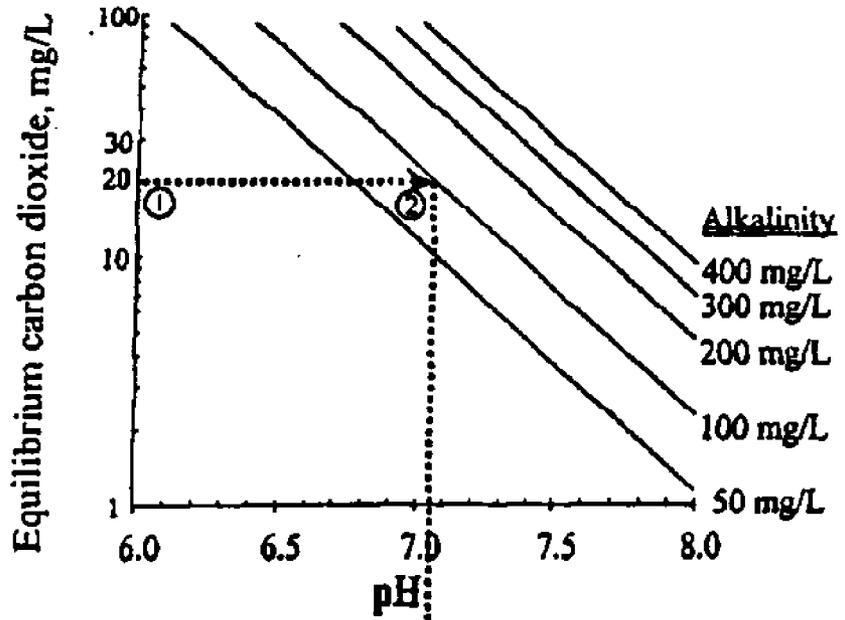Co$_2$ | Bohr effect

−H$^+$ +H$^+$

O$_2$ affinity

P$_{O_2}$

Root effect

Co$_2$

+H$^+$ O$_2$ capacity

P$_{O_2}$

Figure 3. Effect of CO$_2$ on blood's oxygen affinity and capacity

pH dependence of CO_2 and NH_3 (15°C)
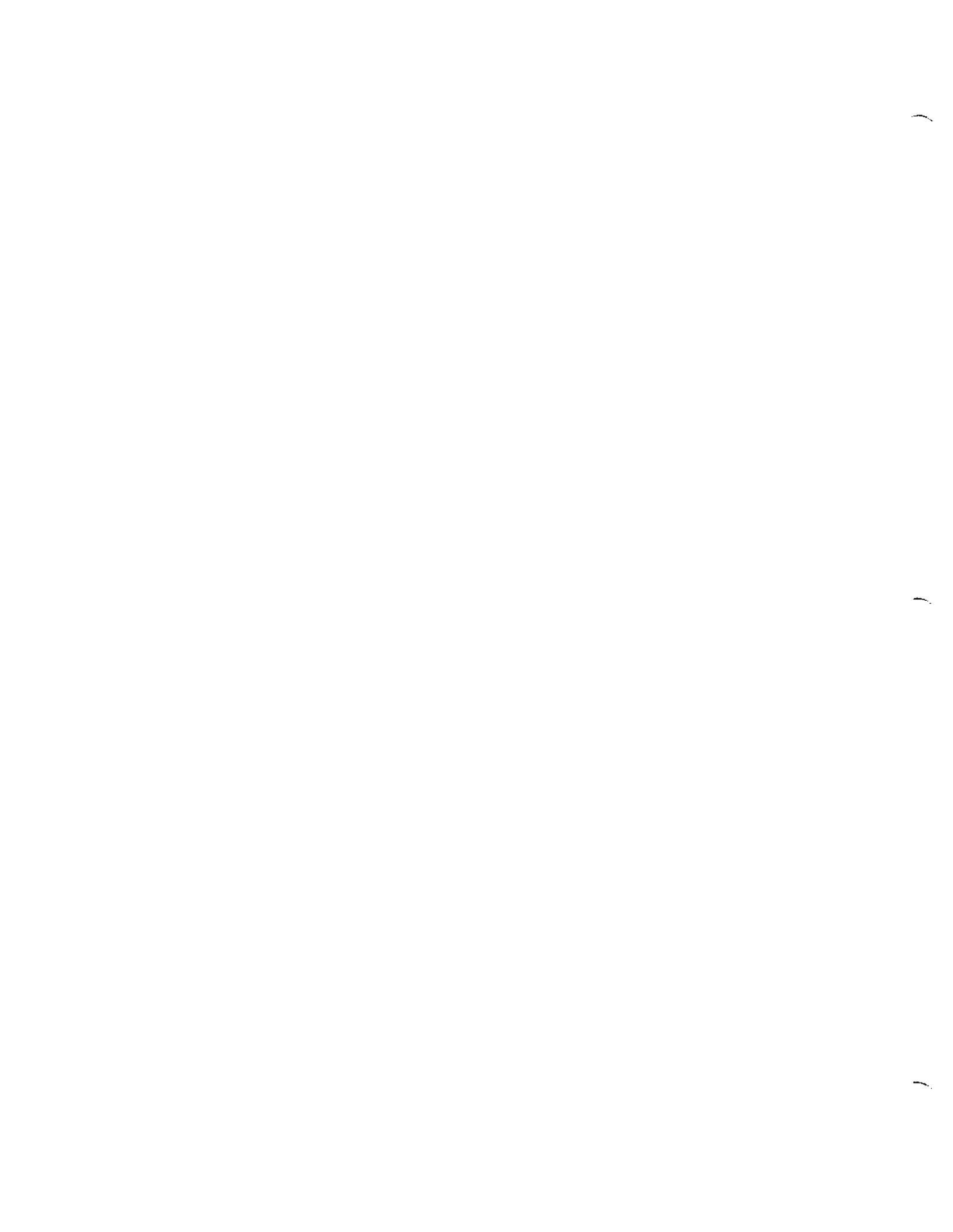
Optimum pH = ± 7.06   MTAN = ±5.0 mg/l

ASSUMPTIONS:

MCO = 20

MUA = 0.0125

ALK = 100

Source: Summerfelt (2000)

PROBLEM - UNIT II

1. How much water must 1.0 kg fish pump accross their gills. Express in ℓ per h and ℓpm.
   Also: What can be the loading value?

Parameters:
   a) $MR = 400$ $(400\ mg\ O_2/kg/hr)$.
   b) % water in contact with filaments is 40% (Bypass is 60%)
   c) % O_2 taken up by the gills is 80%
   d) $DO = 12.0\ mg/\ell$.
   e) $DO_{out} = 6.0\ mg/\ell$.

PROBLEM SOLVING UNIT-II

1. ANSWER:

$\%\ abs. = 0.80 \times 0.40 = \underline{0.32}$

$mg\ O_2\ uptake : 0.32 \times 12.0 = \underline{3.84\ mg}$

$\ell ph : \dfrac{400}{3.84} = 104\ \ell \quad \left(\dfrac{MR}{O_2\ uptake} \right)$

$\ell pm : \dfrac{104}{60} = \underline{1.73\ \ell pm} \qquad \mu\ 3.84\ mg\ O_2 / kg\ fish$

$Ld = 1.0/1.73 = \underline{0.578\ kg/\ell pm}$

$DO_{IN} = \underline{12.0} \quad DO_{used} = \underline{3.84} \quad DO_{out} = \underline{8.16}$

$DO_{out}\ at\ \underline{6.0\ Ok}$

$\dfrac{8.16}{6.0} \times 0.578\ kg/\ell pm = \underline{0.786\ kg/\ell pm}$

III. GROWTH RATES AND FEEDING LEVELS

CONDITION FACTOR

Growth rates can be measured as weight and/or length increases. Most often they are measured in terms of weight gains, however, both concepts are important. Generally, weight gains show an exponential pattern, length increase a linear one. This is shown in Figure 1.

The relationship of weight and length can be expressed by means of what is known as the condition factor (k for metric, c for English), which reflects the shape of the fish. For metric measurements we use grams for weight and cm for length (g/cm^3) for English, pounds and inches (lb/inch^3). The condition factor in metric uses the letter k, English the letter c, both in lower case.

$$k = \frac{W_g}{L_{CM}^3}; \quad C = \frac{W_{lb}}{L_{inch}^3} \tag{1}$$

The nice thing about the metric condition factor is that there is a good relationship between length (cm) and weight (g). For instance, it is reasonable to assume that the specific weight of fish is the same as for water itself, namely one. This means that one cubic cm of fish (water) weighs one gram. In other words, a perfectly "cubed" fish has a condition factor of one:

$$k = \frac{1.0_g}{1.0_{cm}^3} = 1.0$$

A 10 cm x 10 cm x 10 cm "cube" fish, with a specific weight of one, would weight 1000 g (1.0 kg), again showing the k-value of 1.0.

1

$$k = \frac{1000}{10^3} = 1.0$$

For English equivalents, a "cube" fish has a condition factor of 0.0361, and therefore a one inch "cube" fish weighs 0.0361 lb.

To illustrate: 1.0 inch equals 2.54 cm and 2.54^3 is 16.387 cm^3, thus the weight is also 16.387 g (specific weight - 1.0) which is the same as 0.0361 lb (one pound equals 454 g).

To convert therefore from k to c and vice versa:

$$c = k = 0.0361 \quad \text{and} \quad k = \frac{c}{0.0361} \qquad (2)$$

Note: The metric condition factor is much more "elegant" and easier to use, it is also easier to use grams for weight, rather than pounds, especially for small fish. It also makes good sense to use cm for length, instead of inches. In metric, every measurement can either be divided or multiplied by 10. One tenth of a cm is a millimeter, a cm multiplied by 10 is a decimeter (dm). For gram, we have milligram (1/1000 of a gram), and kilogram (1000 g), etc. In metric we work with decimals, 5.4 cm equals 54 mm, 40 g equals 0.04 kg, etc. Fish culturists should become proficient with the use of the metric system (SI system). In this unit on of Fish Growth, we will primarily use metric equivalents for weight and length.

Returning to the topic of fish shape, as reflected by the condition factor. Fish do not have a cuboid shape, far from it. Therefore, condition factors are much less than one, more in the range of 0.020 to 0.005, which means that the weight of a fish with a length of one cm ranges from 0.020 to 0.005 g (0.000044 to 0.000011 lb).

2

$$W = kL^3; \quad L = \sqrt[3]{\frac{W}{k}} \text{ or } \left(\frac{W}{k}\right)^{1/3} \tag{3}$$

Fish 10 cm long would weight 20 and 5 g respectively (23 and 91 per pound).

$$\#lb = 454 / W_g \tag{4}$$

Although most fish probably fall within this range of condition factor, there certainly are many exceptions, such as the eel, which is snake-like. On the other extreme, there actually is a fish with the scientific name "cubicus." Its common name is box fish (Gold Striped Grouper, *Ostracion cubicus*). This particular fish looks like it lives in a box with its head and tail sticking out. Not a very aquadynamic shape! Table 1 shows length and weight relationships for four condition factors.

Northern pike and muskellunge have condition factors around 0.005 salmonids and percids around 0.010 sunfish near 0.015 and Tilapia have k-values around 0.020!

Throughout this chapter a condition factor of 0.010 will be used. It not only fits many salmonids, whose k-values range from 0.009 to 0.012, but it also makes it easy to convert this value to any other condition factor. For instance, a fish with a condition factor of 0.009 requires that the 0.010 weight values of Table 1 are multiplied by 0.9, etc.

FEEDING LEVELS

Fish, as cold-blooded animals (poikilotherms), take on the temperature of their environment; i.e. the water. They perform best at their species specific, standard environmental temperature (SET). At this temperature, the best growth rate and food utilization can be realized.

3

Feed utilization is measured by feed conversion ratios (FC) or feed efficiencies (FE). The first represents food fed divided by weight gain. The latter is its reciprocal, i.e. weight gain over feed fed, and it is expressed as percent. For example, a feed conversion of 1.4 is the same as a feed efficiency of 71 percent (1.0/1.4), a conversion of 1.0 represents a feed efficiency of 100%.

This 100% efficiency is misleading. We know that biological systems, nor any other system, can ever be 100% efficient. Indeed, efforts ("dreams") to create the perpetual motion machine have always failed for that very reason.

A feed conversion ratio of one, is in reality a conversion of three or greater. This is why. Fish feed may have a moisture content of 10%, so the dry matter is 90%. Fish flesh has a moisture content of around 75%, so its dry matter is only 25%. For a feed conversion of one, the dry to dry conversion is 3.6!

The following equation can be used to reflect the "true" feed conversion ratio:

$$\textbf{TFC} = \frac{\textbf{\%DF}}{\textbf{Df}} \textbf{ x FC} \qquad (5)$$

Where: TFC is true feed conversion, %DF is percent dry matter in feed and %Df is percent dry matter in fish.

For a feed conversion of 1.4, a 12% moisture diet and 70% moisture of fish flesh, the "true" conversion is:

$$\textbf{TFC} = \frac{\textbf{88}}{\textbf{30}} \textbf{ x 1.4} = \textbf{4.1}$$

4

Temperature regulates the metabolic rate, it is the main factor responsible for feed intake (appetite).

Depending on temperature, daily length increases can be as little as 0.01 cm or as great as 0.10 cm. Table 2 shows percent weight gains for 1.0 cm fish (L = 1.0) and daily length increases (ΔL) from 0.01 to 0.10 cm (ΔL = 0.01 to 0.10).

The percent gain in weight is independent of the condition factor (k). The percent gain is the new weight (W_t) less the starting weight (W_1) divided by the starting weight times one hundred:

$$\%\mathbf{GAIN} \; = \; [(\mathbf{W_t} \; - \; \mathbf{W_1}) \,/\, \mathbf{W_1}] \; \mathbf{x} \; \mathbf{100} \qquad (6)$$

The percent gain, multiplied by the feed conversion, represents the feed fed as a percent of the original weight (W_1). Feeding levels are commonly expressed in percent body weight or biomass (%BW). The percent gain values of Table 2 are also the feeding levels as percent body weight for feed conversions of one. For feed conversions below one, feeding levels are less, while they are greater for feed conversions over one for the corresponding length and weight gains of the table. Recall that values of Table 2 are based on a starting length (L_1) of 1.0 cm.

To determine % gain values for other lengths, these values must be divided by those respective lengths. For example, for 5.0 cm fish the listed percent gains of Table 2 must be divided by 5.0. The larger the fish the smaller the percent gains realized. Also: The larger the fish the lower the %BW feeding levels and metabolic rates! (Figure 2).

Another characteristic of the percent gain values is the fact that for each 0.01 cm length increase, the values increase by 3.0. In other words, the percent gain is three times the daily length increase, times 100 for 1.0 cm fish (for weight determinations, length is cubed $W = kL^3$).

5

$$\%\text{Gain} = 3.0 \times DL \times 100 \qquad (7)$$

For other lengths (L)

$$\% \text{ Gain} = (3.0 \times DL \times 100) / L \qquad (8)$$

Because %BW equals % gain times the feed conversion, the equation for %BW is:

$$\%\text{BW} = (3.0 \times DL \times 100 \times FC) / L \qquad (9)$$

The two unknowns in the equation are ΔL and FC.

Daily length gain is equal to the temperature unit growth rate (TUG) multiplied by the temperature (^{0}C). There is evidence that TUG is greatest at SET (Standard Environmental Temperature). Under these conditions the best feed utilization is realized, i.e. the lowest feed conversion and highest feed efficiency.

The product TUG x FC appears to be relatively constant, independent of temperature (Westers, 1987). Such values may range from 0.004 to 0.008 depending on species, quality of the rearing environment, feed quality as well as other factors impacting fish growth.

Where TUG x FC equals 0.004, the feeding equation is:

$$\%\text{BW} = (^0\text{C} \times 1.2) / L \qquad (10)$$

For 0.008 it is:

$$\%\text{BW} = (^0\text{C} \times 2.4) / L \qquad (11)$$

6

As discussed under condition factors, the length (L) can be converted to weight (see equation 12:

$$L = (W / k)^{1/3} \qquad (12)$$

The feeding equation now becomes:

$$\%BW = (^{0}C \times 1.2 \text{ to } 2.4) / (W / k)^{1/3} \qquad (13)$$

The greatest difficulty is in determining the proper value for TUG x FC. High quality diets have performed extremely well, accomplishing feed conversions as low as 0.6. These diets must be fed at lower levels, they generate less waste and are therefore more environmentally compatible. For instance, when a diet with a protein level of 45% and a lipid level of 10% has the lipid level increased to 30%, the fish will reduce their feed intake but maintain the same growth rate. Nitrogen excretion decreases, indicating that the fish are making better use of the available protein. In addition, there appears to be a reduction in oxygen demand by the fish, as well as in the system itself (because less NH_3 needs to be oxydized). It is, of course, extremely important to avoid feed waste!

All fish have a maximum growth potential which is observable within a population ("runts" versus "hogs"). Through selective breeding (domestication) and other manipulations, growth rates of certain species, such as channel catfish, rainbow trout, and Atlantic salmon, have been accelerated. This sort of domesticated stock requires high feeding levels, i.e. product TUG x FC x 300 will be greater.

As for new species entering aquaculture, such fish are still far from being domesticated. They are still "wild" fish. Little data on growth rates and feed conversion are available. An example is yellow perch, a species of considerable interest.

7

At this time it appears that, based on limited data, a TUG of 0.0025 for a rearing temperature of 20^0C and a feed conversion of 1.4 is reasonable. The resulting feeding level is:

$$\%BW = (20 \times 0.0025 \times 300 \times 1.4) / (W / k)^{1/3} \quad (14)$$

and for a condition factor of 0.01:

$$\%BW = 21 / (W / 0.010)^{1/3} \quad (15)$$

For a fish weighing 10 g the %BW = 2.1.

Greater TUG values, feed conversions and condition factors, singly or combined, result in greater feeding levels. An elevated rearing temperature might also yield greater TUG values. Some research has shown a SET of 22^0C for yellow perch. Unfortunately, at this time, not much data is available for yellow perch.

Another potential problem with yellow perch, in addition to its undomesticated status is the finding that males may grow considerably slower than females. Add to this the lack of knowledge of species nutritional requirements (optimal diets), and it becomes obvious that much research and genetic selection is still required before this fish species can be as successfully reared as channel catfish and salmon and trout.

However, yellow perch is a very popular food fish in the Great Lakes region, it commands a high price, making it an attractive candidate for recirculation aquaculture systems (RAS), especially in light of the fact that the Great Lakes, the traditional source of yellow perch, no longer delivers a catch sufficient to meet the demand. The market weight for yellow perch is only 150 g (0.33 lb).

I believe it is but a matter of time before this species will make an important contribution as a "farmed" product. Table 3 presents feeding levels for yellow perch for three different temperature unit growth rates.

GROWTH MODELS

Without the ability to predict growth rates one cannot manage a fish production facility efficiently. Without information on expected growth, it would be impossible to predict feed requirements for specific time periods, or the approximate date when the fish are ready for harvest (or release).

Several growth models have been developed for predictive purposes, but these tend to be relatively complex. We need models that are easy to use yet provide a high degree of accuracy in making growth projections. Because length increase is linear, it is less complicated to use in a growth model versus weight increase, which is exponential. On the other hand, fish samples are routinely taken in weight instead of length.

But, as pointed out earlier, length can be converted to weight, and vise versa, by means of the condition factor (k).

$$L = (W/k)^{1/3} \quad \text{and} \quad W = kL^3$$

One model can be written as:

$$W_t = k [(W/k)^{1/3} + (TUG \times {}^{\circ}C \times t)]^3 \qquad (16)$$

W_1 is beginning weight in g.

W_t is final weight.

t is time in days.

9

Iwama (1996) proposes the following growth model:

$$W_t^{1/3} = W_j^{1/3} + {}^{\circ}C / 1000 \times t \qquad (17)$$

The model is based on the same two assumptions as the previous model; that the cube root of weight increases linearly over time and that the effect of temperature on growth is also linear (for salmonids between 5° and 15°C).

From the model one can calculate the growth coefficient (Gc) which compares the actual growth rate (Gs) with the theoretical growth rate (Gs'). The growth rate coefficient is their ratio:

$$Gc = Gs / Gs^1 \qquad (18)$$

Thus the model becomes:

$$W_t^{1/3} = w_j^{1/3} = ({}^{\circ}C / 1000 \times Gc) \times t \qquad (19)$$

Growth coefficients for various species and stocks may range from 0.899 to 1.089 for steelhead and 0.930 to 0.984 for chinook salmon.

But, chinook salmon grown on commercial farms in seawater show coefficients ranging from 1.081 to as high as 2.292 over a 12 month period. The average was 1.757, the average for coho salmon grown in seawater over a similar period was 1.849 (Iwama, 1996)

In other words, these fish grew at nearly twice the rate of those reared in land-based, fresh-water facilities. To compare the two models, the following values are used:

$W_1 = 15$ g; $t = 50$; $^{\circ}C = 12$; TUG 0.005; $k = 0.01$; Gc = 1.000

10

Model 1:

$$W_t = [(15/0.01)^{1/3} + (0.005 \times 12 \times 50)]^3$$

$$W_t = 0.01 (11.44 + 3.0)^3$$

$$W_t = 30.11g$$

Model 2:

$$W_t^{1/3} = 15^{1/3} + (12/1000 \times 50)$$

$$W_t^{1/3} = 2.466 = 0.6$$

$$W_t^{1/3} = 3.066 \quad W_t = 3.066^3 \quad W_t = 28.82$$

By rearranging the growth models, one can determine the temperature required to arrive at a specific weight within a predetermined time period or the time required to reach a given weight at a particular temperature.

$$°C = [(W_t/k)^{1/3} - (W_1/k)^{1/3}]/(TUG \times t) \qquad (20)$$

and

$$t = [(W_t/k)^{1/3} - (W_1/k)^{1/3}]/TUG \times °C) \qquad (21)$$

Another common way to measure growth performance is by means of the specific growth rate in % per day (SGR).

$$SGR = 100 [(LnW_t - LnW_1)/t] \qquad (22)$$

Where Ln is the natural logarithm, and using previous values: $W_1 = 15$; $W_t = 30.11$ and $T = 50$

$$\text{SGR} = 100\ [(\text{Ln } 30.11) - (\text{Ln } 15.0) / 50]$$

$$\text{SGR} = 100\ [(3.405 - 2.708) / 50] = 1.394\% \text{ per day}$$

Recall equation 7:

$$\%\text{Gain} = (3.0 \times \text{DL} \times 100) / \text{L}$$

For the average length of the fish during the time period (t):

$$\overline{x}\text{L} = (\text{L}_1 + \text{L}_t) / 2 \quad \text{or} \quad (11.44 + 14.44) / 2 = 12.94$$

$$\%\text{Gain} = (3.0 \times 0.06 \times 100) / 12.94$$

$$\%\text{Gain} = 1.39$$

See Figure 2 for the effect of fish weight on the specific growth rate (SGR)!

Table 1. Length to weight relationship for three condition factors: k = 0.005; 0.010; 0.015 (c = 0.00018; 0.00036 and 0.00054).

Length	Weight		
cm (inch)	g (lb) 0.005	g (lb) 0.010	g (lb) 0.020
5 (2.0)	0.625 (000144)	1.25 (0.0028)	2.50 (0.0056)
10 (4.0)	5.00 (0.011)	10.00 (0.022)	20 (0.044)
15 (6.0)	16.8 (0.037)	33.7 (0.074)	67.4 (0.148)
20 (8.0)	40.0 (0.088)	80.0 (0.18)	160 (0.36)
25 (10.0)	78 (0.17)	156 (0.34)	312 (0.68)
30 (12.0)	135 (0.30)	270 (0.59)	540 (1.18)
35 (14.0)	214 (0.47)	428 (0.94)	856 (1.88)
40 (16.0)	320 (0.70)	640 (1.41)	1280 (2.82)

English values in parentheses.

Table 2. Percent gain for 1.0 cm fish realizing daily length increases from 0.01 to 0.10 cm, for two condition factors: 0.010 ($W_1 = 0.010$) and 0.015 ($W_1 = 0.015$).

ΔL	L_t	$k = W_1 = 0.010$		$k = W_1 = 0.015$	
		W_t	% Gain	W_t	% Gain
.01	1.01	.0103	3.0	.01545	3.0
.02	1.02	.0106	6.0	.01592	6.0
.03	1.03	.0109	9.0	.01639	9.0
.04	1.04	.0112	12.0	.01680	12.0
.05	1.05	.0115	15.0	.01725	15.0
.06	1.06	.0118	18.0	.01770	18.0
.07	1.07	.0121	21.0	.01815	21.0
.08	1.08	.0124	24.0	.01860	24.0
.09	1.09	.0127	27.0	.01905	27.0
.10	1.10	.0130	30.0	.01950	30.0

14

Table 3. Recommended feeding levels for yellow perch, reared at 22°C. A condition factor of 0.012 is assumed and a feed conversion of 1.4. Three TUG's are used: 0.0025, 0.0035, and 0.0045, the resulting nominator values are 23, 32, and 42.

W_g	L_{cm}	%BW TUG .0025	%BW TUG .0035	%BW TUG .0045
10				
10	9.4	2.4	3.3	4.4
20	11.8	1.9	2.6	3.5
30	13.6	1.7	2.3	3.0
40	14.9	1.5	2.1	2.7
50	16.1	1.4	1.9	2.6
60	17.1	1.3	1.8	2.4
70	18.0	1.3	1.7	2.3
80	18.8	1.2	1.7	2.2
90	19.6	1.2	1.6	2.1
100	20.3	1.1	1.5	2.0
110	20.9	1.1	1.5	2.0
120	21.5	1.1	1.5	1.9
130	22.1	1.0	1.4	1.9
140	22.7	1.0	1.4	1.8
150	23.2	1.0	1.3	1.8

Fish Growth and Feeding

Condition Factor (k or c)
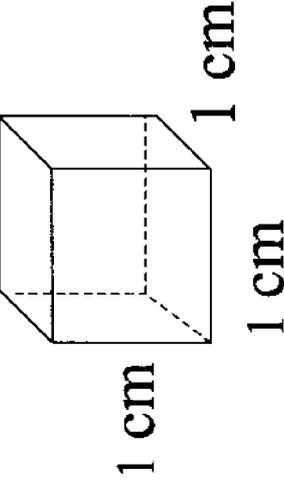
Shape of the Fish

<u>Metric (k):</u> Weight in Grams (W)

Length in cm (L)

$$k = W/L^3 \qquad W = kL^3 \qquad L = (W/k)^{1/3}$$

$1.0 \text{ cm} \times 1.0 \text{ cm} \times 1.0 \text{ cm} = 1.0 \text{ cm}^3$

$1.0 \text{ cm}^3 = 1.0 \text{g} \ (H_2O - \text{specific}$ weight is one)

Fish as H_2O

1 cm

1 cm

1 cm

Fish-1

A "cube-shaped" fish has a k value of 1.0

$$k = 1.0/1.0^3 = 1.0$$

Fish are not shaped like a cube.

Trout and Salmon   -   k = 0.0080 – 0.0120
Pike and Muskie   -   k = 0.0045 – 0.0060
Sunfish   -   k = 0.0125 - 0.0135
Tilapia   -   k = 0.0150 - 0.0250

0.0050   0.0100   0.0150   0.0200

Condition Factor

English (c) $W = lb$ $L = Inch$

1" = 2.54 cm

$2.54^3 = 16.387\ cm^3 = 16.387g$

and: $16.387g = 0.0361\ lb$
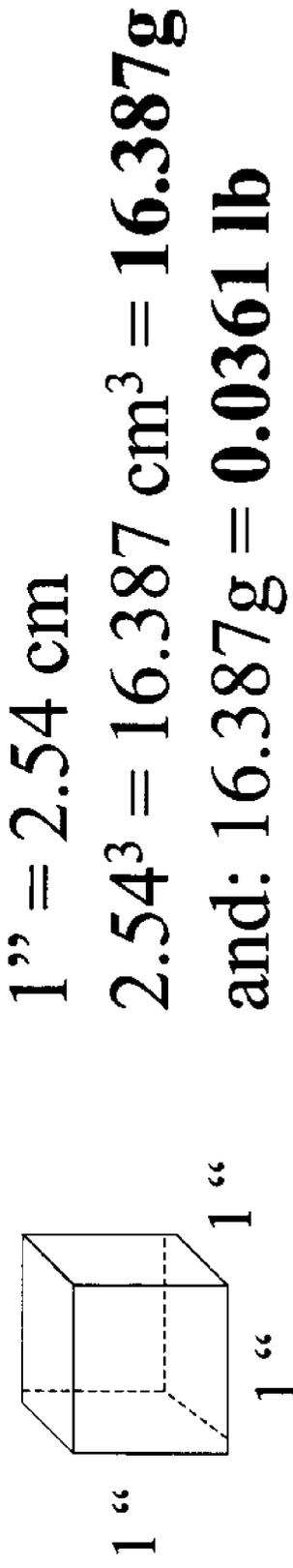
"Cube" Fish 1" – 0.0361 lb

$c = 0.0361 \longrightarrow k = 1.0$ $c = 0.000361$

For $k = 0.0100$

Metric is more "Elegant"

g and cm – Good Relationship

lb and inch – Poor Relationship

"Problem" with English measurement for Fish Culture:

1. No small weight measures (lb = 454 g)

2. Length measures in fractions ($^3/_{32}$ etc.)

3. No relationships **Inch–Yards–Mile**

Gallon –Feet^3

Volume and Weight

Metric: Greatest <u>danger</u> is the decimal point misplacement.

Note: $c = k \times 0.0361$ $k = c / 0.0361$

Growth Rates and Feeding

Growth Measured As:

1. Length Gain (cm)or inches
2. Weight Gain (g) or lbs

Under constant temperature, length gain is *linear* but weight gain is *exponential* – ($\mathbf{W = kL^3}$)

Depending on temperature, *Daily* length gain ($\triangle$L) may be as small as 0.01 cm (0.004") or *Monthly* 0.3 cm (0.12") to as much as 0.10 cm (0.04") or *Monthly* 3 cm (1.2")

<u>Note</u>: Netpen (salt water) growth rates can be as much as twice this maximum for salmoids studied.

The Table: % gain for 1.0 *cm* (0.4") fish realizing daily gains from
0.01 to 0.10 *cm* for two *k*-values (0.01 and 0.015)

III-F1
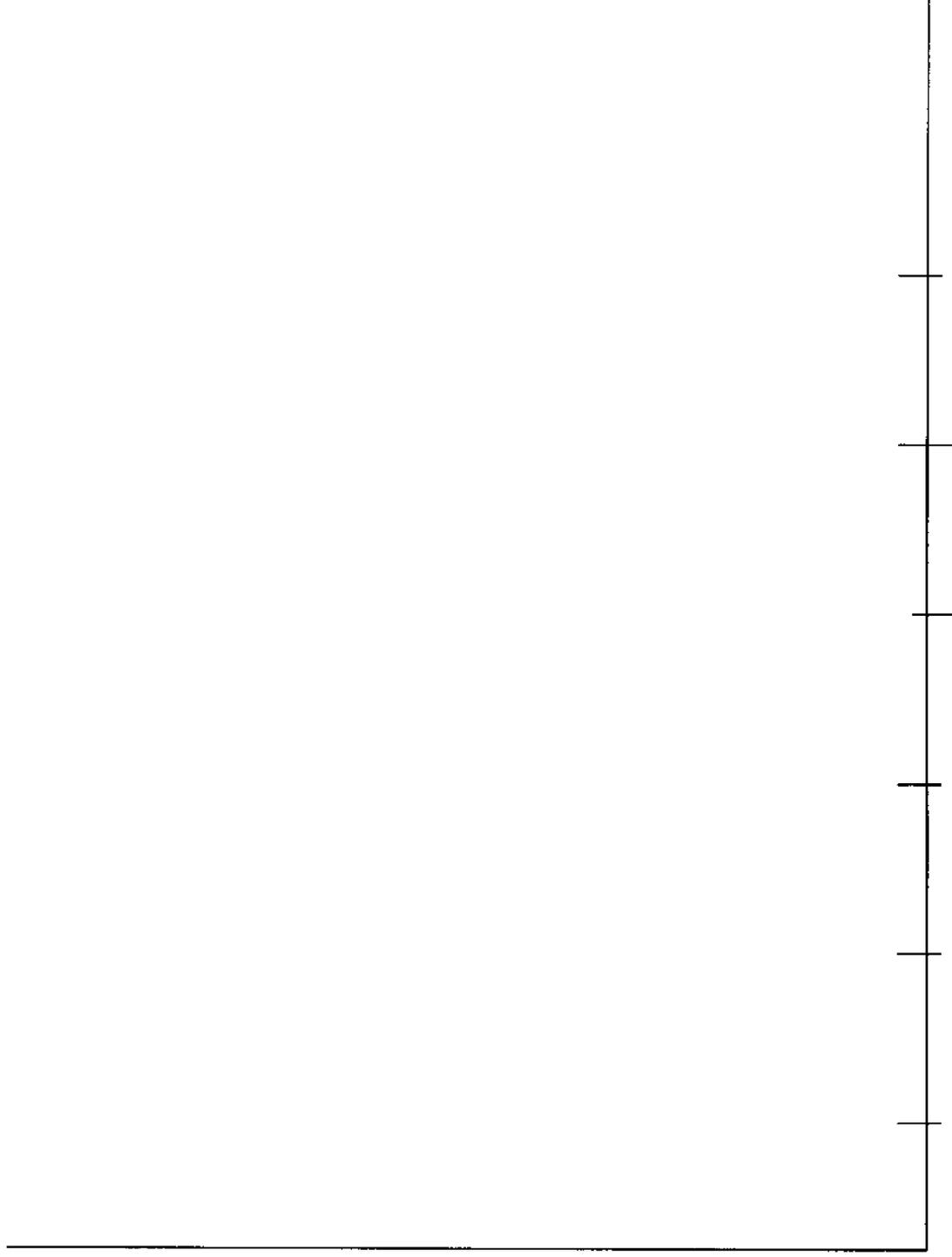
Feeding Levels – I

Fish are <u>Poikilotherm</u>
(Cold-blooded)

Both temperature and size affect metabolic rate (MR)
Small fish have higher MR.

Best performance (Growth rate and Feed conversion
at SET = Standard Environmental Temperature).

Feed utilization is measured by Feed Conversion
Ratio (FC) or Feed Efficiency (FE).

FC = Feed Fed/Weight Gain

FE = Weight Gain/Feed Fed (Expressed as %)

Assume FC = 1.4 $\qquad$ FE = 71% (1.0/1.4) × 100

$\qquad$ FC = 1.0 $\qquad$ FE = 100%

But, as mentioned in the introduction, no system is (can be) 100% efficient. We have not, as yet, invented the perpetual motion machine, but we have certainly tried.

(Would give us infinite mileage "per gallon")

Feed Conversion – Feed Efficiency

$$FC = 1.0 \qquad FE = 100\%$$

In reality, a feed conversion of one is more like a FC of 3 to 4, a FE of 33 to 25%.

This is why:

- Feed may have a moisture content of 10% – dry matter is 90%.

- Fish may have a moisture content of 75% – dry matter is 25%.

- For a recorded FC = 1.0, the dry to dry FC = 3.60 (True FC = 3.6)

$$TFC = \frac{\%DF}{\%Df} \times FC$$

TFC = True FC;   %DF = % Dry in Feed

    %Df = % Dry in Fish

Example: FC = 1.4   Feed 12.5% H_2O,

    Fish 70% H_2O

$$TFC = \frac{87.5}{30} \times 1.4 = \underline{4.1}$$

Feeding Level – II

Main Factors: Temperature and Fish Size (L or W)

See Feeding Chart

A Step by Step Process:

1. %Gain $\triangle$ ($\triangle L = 0.09$ cm)

    %Gain $= [(W_2 - W_1)/W_1] \times 100$

    $L_1 = 5.0$ cm $L_2 = 5.09$ cm

    $W_1 = 1.25$ g

    $W_2 = 1.31872$ g

    $k = 0.01$

    % Gain $= [(1.31872 - 1.25)/1.25] \times 100$

    % Gain $= 5.497$ (5.5)

    % Gain × FC Represents feeding level in

    percent of the original weight (W_1)

Fish Growth & Feeding – II

Recall condition Factor (k or c)

$k = W/L^3$ $L = (W/k)^{0.333}$ $W = kL^3$

$W_1 = 0.010$ $W_1 = 0.015$

$W_1 = 0.010$ $W_1 = 0.015$

ΔL	L_1	k = 0.010		k = 0.015	
		W_1	% G	W_1	% G
0.01	1.01	0.0103	3.0	0.01545	3.0
0.02	1.02	0.0106	6.0	0.01592	6.0
0.03	1.03	0.0109	9.0	0.01639	9.0
0.04	1.04	0.0112	12.0	0.01680	12.0
0.05	1.05	0.0115	15.0	0.01725	15.0
0.06	1.06	0.0118	18.0	0.01770	18.0
0.07	1.07	0.0121	21.0	0.01815	21.0
0.08	1.08	0.0124	24.0	0.01860	24.0
0.09	1.09	0.0127	27.0	0.01905	27.0
0.10	1.10	0.0130	30.0	0.01950	30.0

% Gain = $[(W_t - W_1)/W_1] \times 100$

W_1 : Starting weight of 1.0 cm for 2 k's

2.

$$\%BW = \% \text{ Gain} \times FC$$

The percent gain values on the table are also the feeding levels in % BW for feed conversions of one. For FC < 1.0; Feeding levels are less and greater for FC > 1.0. Table values are based on a starting length (L_1) of 1.0 cm. To determine % gain for other lengths, these values must be divided by those lengths.

Example: For 5 cm length the % gains of the table must be divided by 5. The larger the fish, the smaller the % gain; the lower the metabolic rate; the lower the % BW.

See Figure 3

Another interesting fact:

For each 0.01 *cm* increase, values increase by 3.

Feeding Level (Table) – III

3. % Gain = $3.0 \times \triangle L \times 100$

For other lengths:

% Gain = $(3 \times \triangle L \times 100)/L$

And: Because % BW equals % gain × FC:

4. $\boxed{\% BW = (3 \times \triangle L \times 100 \times FC)/L}$

The variables (unknown values)

$\triangle L$ and FC

Temperature Unit Growth Rate (TUG)

There is evidence that **TUG** is greatest at SET (standard environ. temp.) under those conditions the best growth rates and lowest feed conv. are realized.

$\triangle L = TUG \times {}^\circ C$

III-13

Feeding Levels – IV

The product TUG × FC appears to be relatively constant. The values may range from 0.004 to 0.008. This depends on species, rearing water quality, feed quality, species domestication, etc.

For Salmonids: 0.0065   (0.006–0.007)

For Yellow Perch: 0.0040   ?

For this latter value: (0.004)

$$\% \, BW = (°C × 300 × 0.004)/L$$

$$\% \, BW = (1.2 ×°C)/L$$

For Salmonids:

(0.0065)

$\%BW = (°C \times 300 \times 0.0065)/L$

$\%BW = \dfrac{(1.95 \times °C)}{L}$ or $\dfrac{(2 \times °C)}{L}$

In our Deliberations/Examples we will use:

$$\% BW = (2 \times °C)/(W/k)^{0.333}$$

In Seawater: NetPen Culture

$$3 \text{ to } 4 \times °C$$

(Growth Models)

Growth Models

1. $W_t = k \, [((W/k)^{1/3} + (TUG \times {}^\circ C \times t)]^3$

2. $W_t{}^{1/3} = W_1{}^{1/3} + {}^\circ C / 1000 \times t$ [Iwama 1996]

Assumptions:

The cube root of weight increases linearly over time, and that the effect of temperature on growth is linear (TUG $\times$ $^\circ$C). true for salmonids between 5° and 15° C.

Model 2 incorporates a growth coefficient (Gc) which compares the actual growth rate (Gs) with the theoretical growth rate (Gs[1])

$$\mathbf{Gc = Gs/Gs^1}$$

Growth Models

Model 2 becomes:

$$W_t^{1/3} = W_1^{1/3} + (°C/1000 \times Gc) \times t$$

Gc values: 0.899 – 1.089 Steelhead

0.930 – 0.984 Chinook

But Chinook (in NetPen)

Gc = 1.810 to 2.292 over 12 months (avg. was 1.757)

Coho Salmon: Gc = 1.849

In other words, these fish had a growth rate about twice of those in fresh water (early life).

Comparing the two models: $W_1 = 15g$; $t = 50d$;

$°C = 12$; TUG = 0.005; k= 0.01; Gc = 0.9

III-17

Growth Models
Comparison

#1 $W_t = 0.01 \, [(15/0.01)^{1/3} + (0.005 \times 12 \times 50)]^3$

$W_t = 0.01 \, (11.44 + 3.0)^3$

$W_t = 30.11g$

#2 $W_t^{1/3} = 15^{1/3} + (12/1000 \times 0.9) \times 50$

$W_t^{1/3} = 2.466 + 0.54$

$W_t^{1/3} = 3.006$

$W_t = 3.006^3$

$\mathbf{W_t} = 27.16g$

For Gc = 1.1

#1 30.11g

#2 27.16 to 30.54g

$W_t = 30.54g$

Growth Models

Rearranging #1 we can isolate either the temperature required for a particular weight goal, or the required time period in days:

1a) $^{\circ}C = [(W_t/k)^{1/3} - (W_1/k)^{1/3}]/(TUG \times t)$

1b) $t = [(W_t/k)^{1/3} - (W_1/k)^{1/3}]/(TUG \times {}^{\circ}C)$

3. **SGR** (specific growth rate)

A common way to measure growth performance over time in % per day.

$SGR = 100[(LnW_t - LnW_1)/t]$

Ln is the natural logarithm

(found on scientific calculators)

SGR – Using previous values:

$W_t = 15;$ $\qquad W_t = 30.11$ $\qquad t = 50$

$SGR = 100[(Ln\ 30.11) - (Ln\ 15.0)/50]$

$SGR = 100[(3.405 - 2.708)/50]$

$SGR = 1.394\%$ per day

Recall: % Gain = $(3 \times \triangle L \times 100)/L$

For the average length ($\bar{x}\,L$) during the time period ($t = 50$)

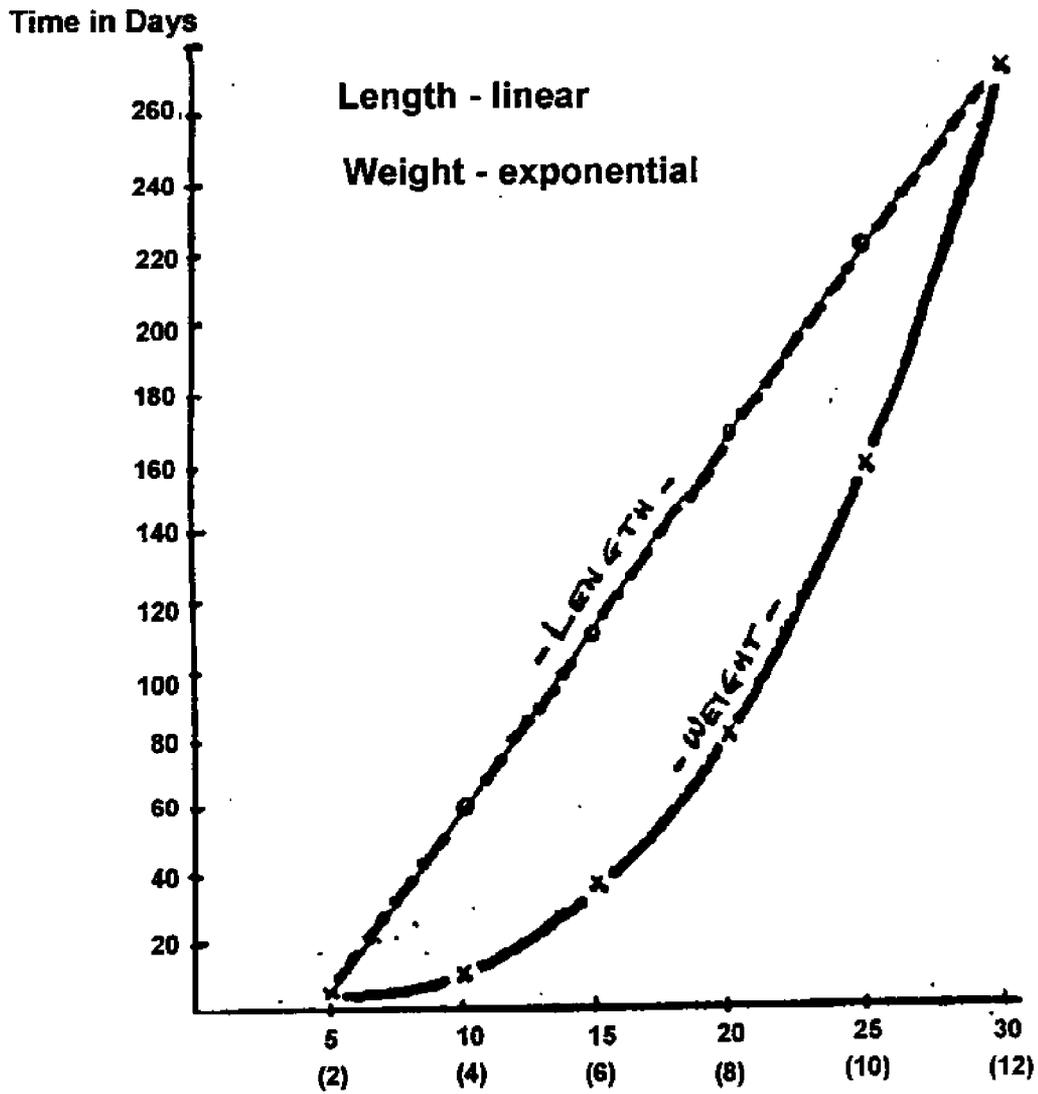$\bar{x}\,L = (L_1 + L_t)/2$

$\bar{x}\,L = (11.44 + 14.44)2 = 12.94$

% Gain = $(3 \times 0.06 \times 100)/12.94$

% Gain = 1.39

Same as SGR (1.394)
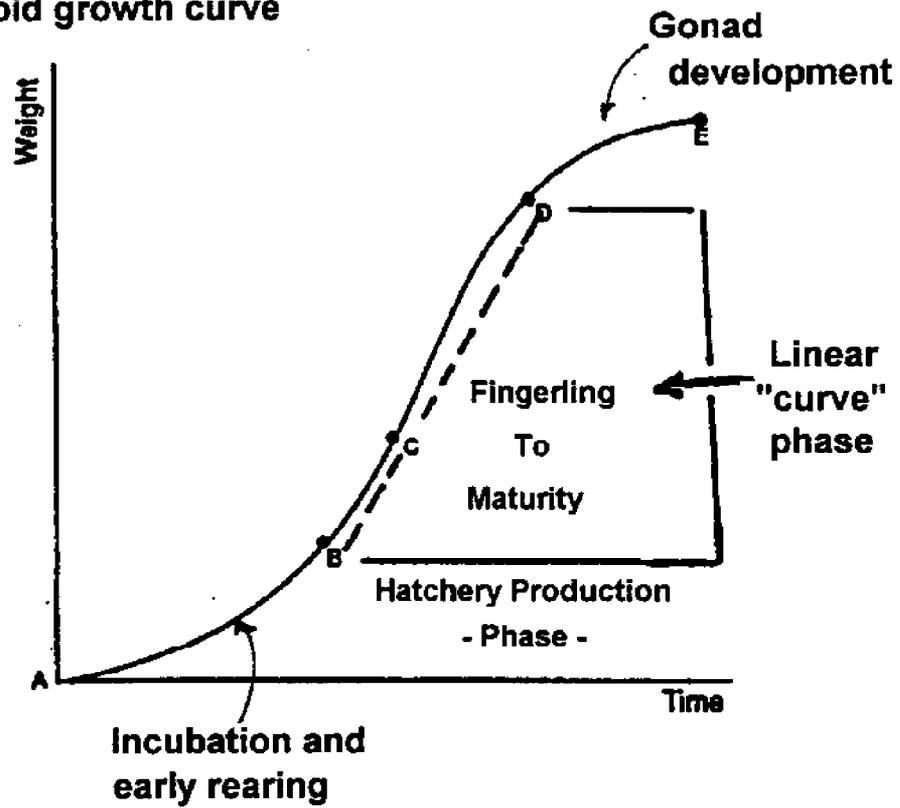
Problem Solving Unit III

1. What is the loading value (kg/lpm or lb/gpm) for fish based on the following:

   a) W = 25g
   b) K = 0.0100
   c) TUG = 0.0055cm
   d) FC = 1.2
   e) Temp. = 15°C (59°F)
   f) AO = 5.0 mg/l
   g) OF = 250

2. For a maximum density of 80 kg/m^3 (D = 80) or 5.0 lb/ft^3, what will be the water turnover rate? The R value?

Time in Days

260
240
220
200
180
160
140
120
100
80
60
40
20

Length - linear

Weight - exponential

- LENGTH -

- WEIGHT -

5   10   15   20   25   30
(2)   (4)   (6)   (8)   (10) (12)
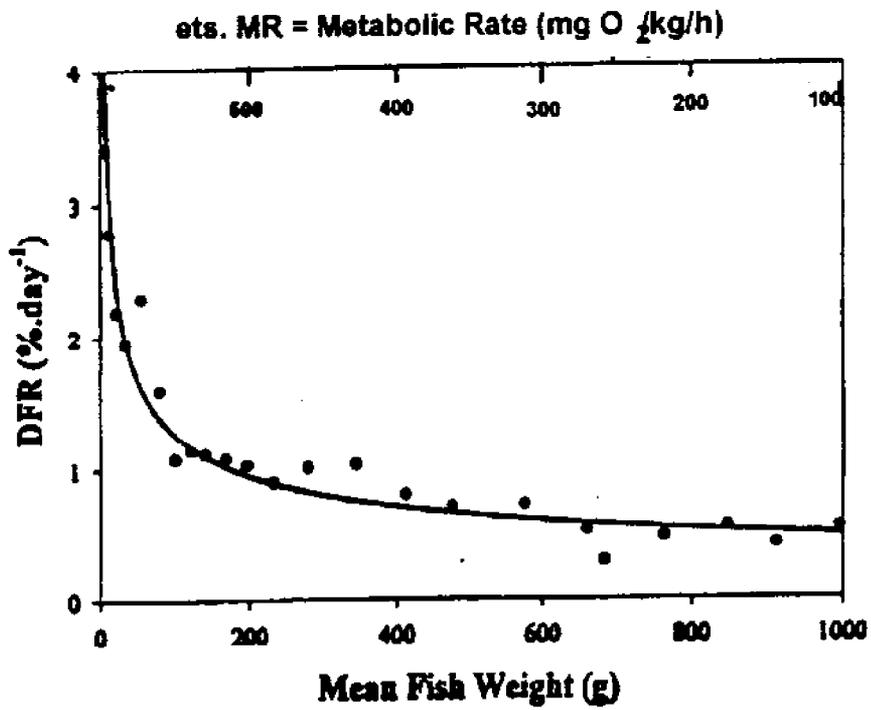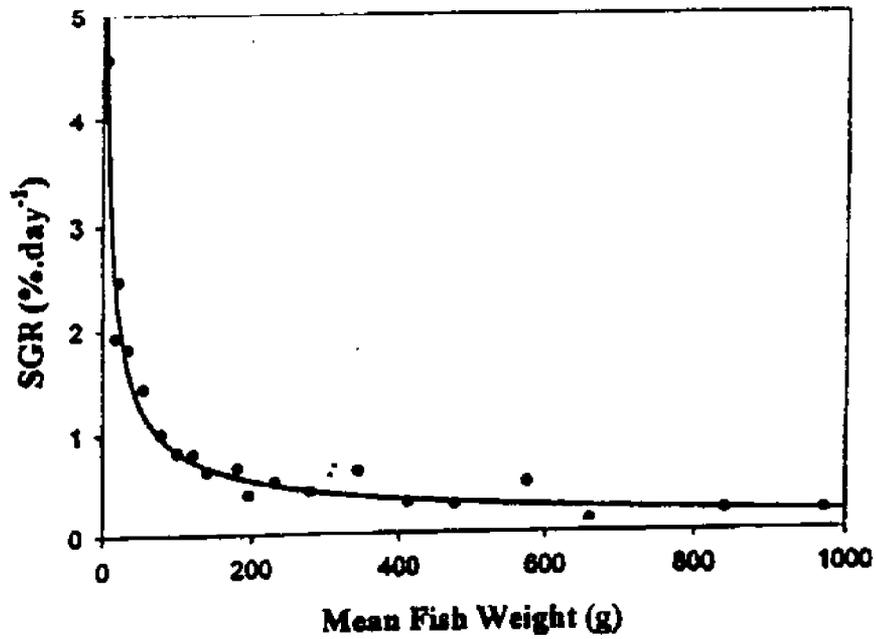
Figure 1. Length and weight growth - salmonids
Based on: TUG 0.006   T = 15.4^{0}C   k = 0.0100

A sigmoid growth curve

Gonad development

Linear "curve" phase

Fingerling To Maturity

Hatchery Production - Phase -

Incubation and early rearing

Figure 2. Typical growth curve.

Figure 3. Effect of fish weight on SGR, feeding level and MR.

PROBLEM SOLVING UNIT III

ANSWER:

1. a) $Ld = \dfrac{100 \times AO}{OF \times \% BW}$ $AO = 5.0$
   $OF = 250$

   b) $\% BW = \dfrac{{}^\circ C \times 300 \times TUG \times FC}{W/k^{1/3}}$

   $LD = \dfrac{(5 \times 100)}{250 \times \% BW}$

   ${}^\circ C = 15 \; ; \; TUG = 0.0055$
   $FC = 1.2 \; ; \; W = 25 g$
   $k = 0.0100$

   $\% BW = \dfrac{(1 \times \Delta L \times 100 \times 1.2)}{L} = 2.5$

   c) $\% BW = \dfrac{15 \times 300 \times 0.0055 \times 1.2}{(25/0.01)^{1/3}}$

   $\Delta L = TUG \times {}^\circ C$
   $\Delta L = (0.0055)(15) = .0825$

   $\left(\dfrac{25}{.0100}\right)^{1/3} = .00$

   $\% BW = \dfrac{29.7}{13.6} = \underline{2.18}$ (2.2)

   d) $Ld = \dfrac{100 \times 5.0}{250 \times 2.2} = \underline{0.91 \; kg/lpm}$

2. a) $R = \dfrac{D \times 0.06}{Ld}$ $R = \dfrac{D \times 8}{Ld}$

   b) $R = \dfrac{80 \times 0.06}{0.91} = \underline{5.27}$ $R = \dfrac{5 \times 8}{0.91 \times 8.33} = \underline{5.27}$

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 Cheneweth 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

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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;

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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 ^{1}/s) unless the unit is extremely long.

Flow velocity in a raceway can be calculated as:

$$v = \frac{Lm \bullet R}{36} \qquad (1)$$

and

$$v = \frac{Lf \times R}{3600} \qquad (1a)$$

Where v is velocity in cm/s, Lm 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

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give velocities from 2.0 to 4.0 cm/s (0.067' - 0.133 '/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).

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 velocity varies from 15 to 25 cm/s, depending on fish size. The major objective of such velocities is to make the tank self-cleaning, removing solid waste as it is generated, thereby preventing its build- up and resuspension by fish activity. Intact solids can settle quickly in a small end section of the raceway dedicated to settling (Figure 6). As a rule of thumb, the settling zone should be as long as the tank is wide. This same ratio can be applied to spacing of the baffles. This simple modification provides an effective solids management approach. The interception and removal of solids in intensive fish culture operations cannot be stressed enough, as aquaculture faces increasingly tighter restrictions on effluents.

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

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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:

$$v_s = (0.5) \bullet (10.5/L^{0.37})$$ (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. Neeham (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

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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/m^3 versus 35.98 kg/m^3). 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 O_2 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"

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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 ($\leq$ 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, dependes 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 ft^3), tanks for median-sized fish 750 to 1250 lpm per m^2 and troughs for small fish from 500 to 1000 lpm per m^2. 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

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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, 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 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. Tvinnereim 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).

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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 ($MQ_{c/s}$) in lpm/m², and minimum selected operational velocity (v) in cm/s. Raceway (RW): $MQ_{c/s}$ = 1500; Tank (TK): $MQ_{c/s}$ = 1000; and Trough (TR): $MQ_{c/s}$ = 750. Velocities are 3.0, 2.0, and 1.0 cm/s respectively.

Type	l m	w m	d m	RV m³	c/s m²	$Q_{c/s}$ lpm	$R_{c/s}$ #/h	R_v #/h	Q_v lpm	Ld kg/lpm	D_v kg/m³	$D_{c/s}$ kg/m³
RW	30	3.0	0.8	72	2.4	3600	3.0	3.6	4320	2.0	120	100
TK	10	1.0	0.6	6.0	0.6	600	6.0	7.2	720	1.0	120	100
TR	3	0.3	0.4	0.36	0.12	90	15.0	18.0	108	.05	125	150

$$Q_{c/s} = MQ_{c/s} \times C/S$$

$$R_{c/s} = (Q_{c/s} \times 0.06) / RV$$

$$R_v = (v \times 36)/l$$

$$Q_v = (RV \times R_v) / 0.06$$

$$Ld = (5.0 \times 100)/(250 \times \%BW)$$

$$D = (Ld \times R_v) / 0.06$$

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 hyperoxic 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

Flow-through fish rearing units come in many shapes, depths and operational modes. Two flow patterns are commonly used: plug-flow and circular flow (Figure 1). In a 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 in common use is the Burrows ponds (Figure 2). This type of pond was designed to capture 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 Cheneweth 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.

In a more recent attempt to combine the advantages of plug-flow and circulating rearing units, Watten and Johnson (1991) developed the cross-flow rearing unit. Water is introduced through a series of inlet ports located 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 square meter of 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 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. 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:

    a. solids settle and are broken up by fish activity;

    b. solids re-enter the water column as finer particles and so pollute the rearing environment;

    c. broken or fragmented solids take longer to resettle and, therefore, require a larger settling basin;

    d. smaller particles, which have larger surface to volume ratio, leach nutrients faster into the water;

    e. a portion of fractured solids continuously leaves the rearing unit and,

where serial reuse is applied, degrade water quality in the 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 4 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 unless the unit is extremely long.

Flow velocity in a raceway can be calculated as

$$V = \frac{Lm \cdot R}{36} \qquad (1)$$

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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overcome these defects with standard size raceways, Boersen and Westers (1986) proposed 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 in the gap would be 20 and 40 cm/s. Generally, optimum velocity varies from 15 to 25 cm/s, depending on fish size. The major objective of such velocities is to make the tank self-cleaning, removing solid waste as it is generated, thereby preventing its build up and resuspension by fish activity. Intact solids can settle quickly in a small end section of the raceway dedicated to settling (Figure 6). As a rule of thumb, the settling zone should be as long as the tank is wide. This same ratio can be applied to spacing of the baffles. This simple modification provides an effective solids management approach. The interception and removal of solids in intensive fish culture operations cannot be stressed enough, as aquaculture faces increasingly tighter restrictions on effluents (Westers 1994b).

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

$$V_S = (0.5) \cdot (10.5/L^{0.37}) \qquad (2)$$

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. 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 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 O_2 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 ($\leq$ 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).

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. Tvinnereim 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 capa-city can be expressed in two ways; in production per unit of flow 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

$$Ld = (D \cdot 0.06)/R \qquad (3)$$

$$D = (Ld \cdot R)/0.06 \qquad (4)$$

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

$$R = (D \times 0.06)/Ld \qquad (5)$$

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 (pO_2) appears to be a more valid way to determine the lower limits than concentration. A pO_2 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 pO_2 represents $(90/159.6) \cdot 9.0 = 5.1$ mg/L, and at 5 C when saturation is 12.5 mg/L DO, 90 mm pO_2 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 (*FL*) is expressed in percent of the biomass of

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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

$$LdF = AO/OF \qquad (6)$$

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

$$LdO = AO/OF \cdot 100/FL \qquad (7)$$

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

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

$$TAN = (AO/OF) \cdot (TANF/1.44) \qquad (8)$$

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

$$UA = TAN \cdot (\%UA/100) \qquad (9)$$

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

$$UA = (AO/OF) \cdot (TANF/1.44)$$
$$\cdot (\%UA/100) \qquad (10)$$

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

$$MAO = AUA \cdot OF \cdot 1.44 \cdot (100/TANF) \cdot \%UA \quad (11)$$

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

$$LdA = AUA \cdot 1.44 \cdot 100 \cdot (100/TANF) \cdot \%UA \cdot FL \quad (12)$$

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

$$LdA = 12/(\%UA \cdot FL) \quad (13)$$

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 $LdO = 4.0/2.5 = 1.6$, and $LdA = 12/\%AU = 8.8$, 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), salmonids 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 (Colt 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 (Colt 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 CO_2 concentration is $0.065 \cdot 200$ 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 (Westers 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 ($16 \text{ g} \cdot \text{L}^{-1} \cdot \text{min}^{-1} \cdot 0.3 = 3.8 \text{ g solids} \cdot \text{L}^{-1} \cdot \text{min}^{-1}/1.44 = 3.33$ 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 m^3 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 ($4000 \cdot 0.016$), 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 (Westers 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 $1.6 \text{ kg} \cdot \text{L}^{-1} \cdot \text{min}^{-1}$ (equation 7); based on un-ionized ammonia it is $8.8 \text{ kg} \cdot \text{L}^{-1} \cdot \text{min}^{-1}$ (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 $\cdot L^{-1} \cdot min^{-1}$ · 30,000 L/min).

Many species of salmonids can be kept healthy at densities exceeding 100 kg/m³. In this exercise, 100 kg/m³ will be used as a maximum density. According to equation 5, this results in an R value of 3.0 (R = (100 · 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 · 3.6 m · 1.0 m equals 129.6 m³. To realize an exchange rate of 3, this pond should receive 6,480 L/min ((129.6/0.06) · 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 m³ to retain the R value of 3, and the velocity at 3.0 cm/s ((6,000 · 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 · 2700 · 0.70 · 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/m³. A maximum loading of 2.0 kg · $L^{-1} \cdot min^{-1}$ results in a maximum biomass of 20,000 kg per series, 60,000 kg for a three-pass system. At 80 kg/m³ this translates into 750 m³ rearing volume, 250 m³ per series. To provide for flexibility, a minimum of 12 rearing units are desired at 62.5 m³ 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 · 3)/2.4). For a rearing volume of 62.5 m³ 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/m^3, 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/m^3, 1500 m^3 of rearing space must be provided or 500 m^3 per series. If a minimum of 12 units are required, each series consists of 4 units at 125 m^3. 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/m^3 and a maximum loading of 2.0 kg · L^{-1} · min^{-1}, 250 m^3 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 m^3. To provide the 250 m^3 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/m^3 ((2.0 · 2.5)/0.06). For 18 tanks the R value would be 2.2, maximum rearing density 73

kg/m^3. A two-pass design would reduce the maximum incoming DO level to 17.1 mg/L.

At maximum rearing density of 40 kg/m^3, 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. Tvinnereim and Skybakmoen (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 1.—Major differences between raceways and round tanks.

Criteria	Raceways	Round Tank
Velocity	Inflow dependent	Independent of inflow
	Inadequate for solid removal unless equipped with baffles	Self-cleaning
	Inadequate for fish exercise	Can meet fish requirements of 1.0 to 1.5 BL/s
Water Quality	Distinct gradient	Uniform
	Passes peak metabolites out	Mixes metabolites and allows some to remain
Wall Area	Requires 1.5 to 3.0 times as much wall per water volume	Most efficient shape in water volume to wall area
Management	Easy to crowd and harvest fish	Difficult to crowd fish
	Easy to collect dead fish	Difficult to collect dead fish
	Difficult to equip with feeders	Easy to equip with feeders
	Difficult to mix disease treatments	Easy to mix disease treatment compound

Table 2.—Multiplication factors to determine carbon dioxide from pH, temperature, and total alkalinity.*

pH	41 F 5 C	50 F 10 C	59 F 15 C	68 F 20 C	77 F 25 C	86 F 30 C	95 F 35 C
6.0	2.915	2.539	2.315	2.112	1.970	1.882	1.839
6.2	1.839	1.602	1.460	1.333	1.244	1.187	1.160
6.4	1.160	1.010	0.921	0.841	0.784	0.749	0.732
6.6	0.732	0.637	0.582	0.531	0.493	0.473	0.462
6:8	0.462	0.402	0.367	0.335	0.313	0.298	0.291
7.0	0.291	0.254	0.232	0.211	0.197	0.188	0.184
7.2	0.184	0.160	0.146	0.133	0.124	0.119	0.116
7.4	0.116	0.101	0.092	0.084	0.078	0.075	0.073
7.6	0.073	0.064	0.058	0.053	0.050	0.047	0.046
7.8	0.046	0.040	0.037	0.034	0.031	0.030	0.030
8.0	0.029	0.025	0.023	0.021	0.020	0.019	0.018
8.2	0.018	0.016	0.015	0.013	0.012	0.012	0.011
8.4	0.012	0.010	0.009	0.008	0.008	0.008	0.007

* For practical purposes CO_2 concentrations are negligible above pH 8.4.

Table 3.—Design driving forces for raceway complexes A, B and C of Figure 5.

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

*See text for explanation

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

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

Figure 1. Linear raceway (a) and round tank (b) flow pattern and dissolved oxygen characteristics.

a)

b)
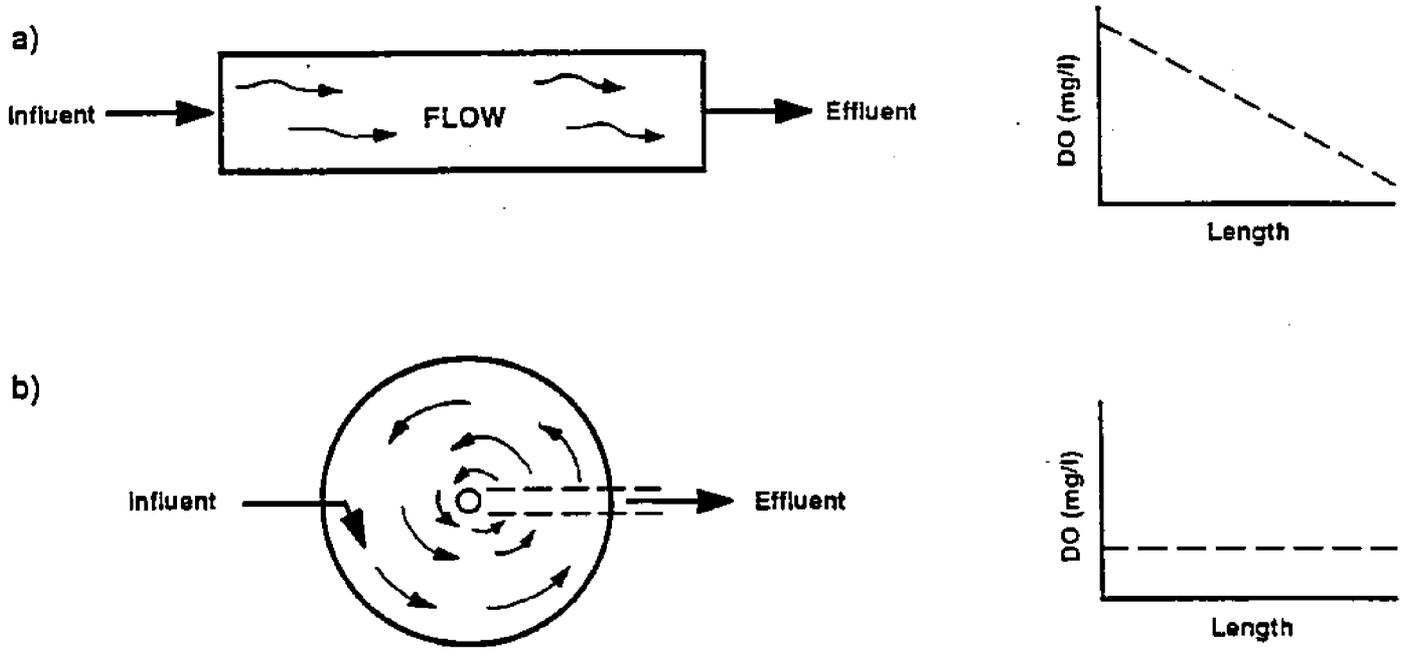
Figure 2. Burrows Pond design.

5
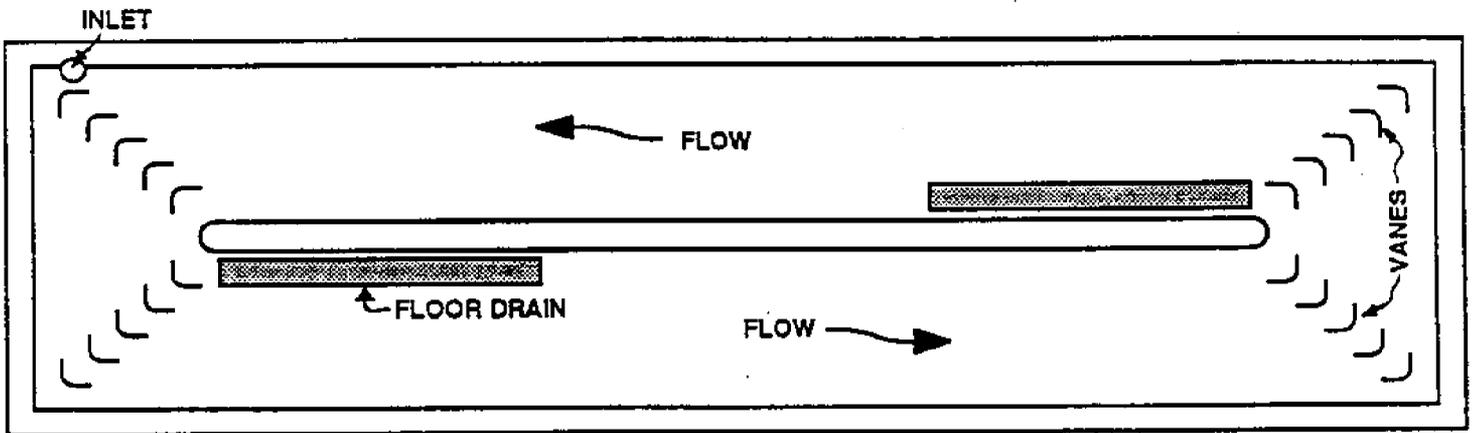
Figure 3.   Diagrams of the cross-flow fish rearing tank.
          a)   Longitudinal view   b)   Cross-sectional view

a)

IN

OUT

b)

IN   OUT

6
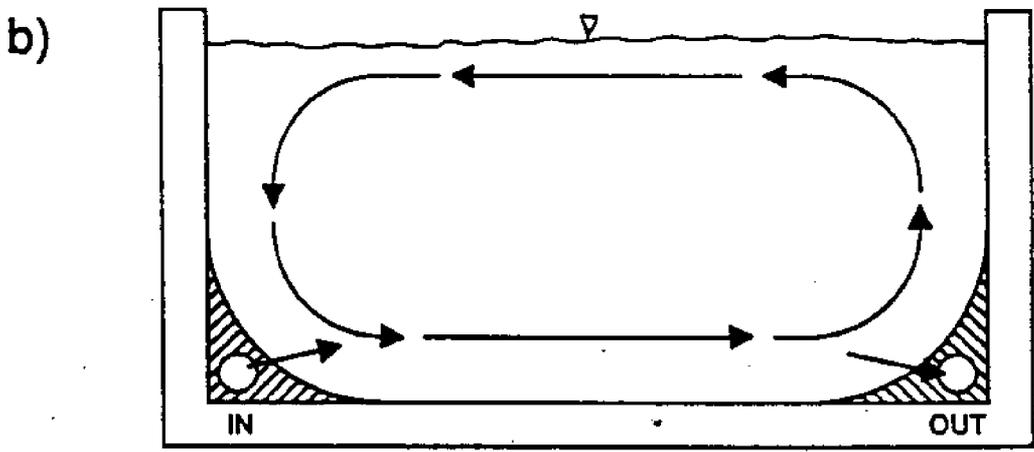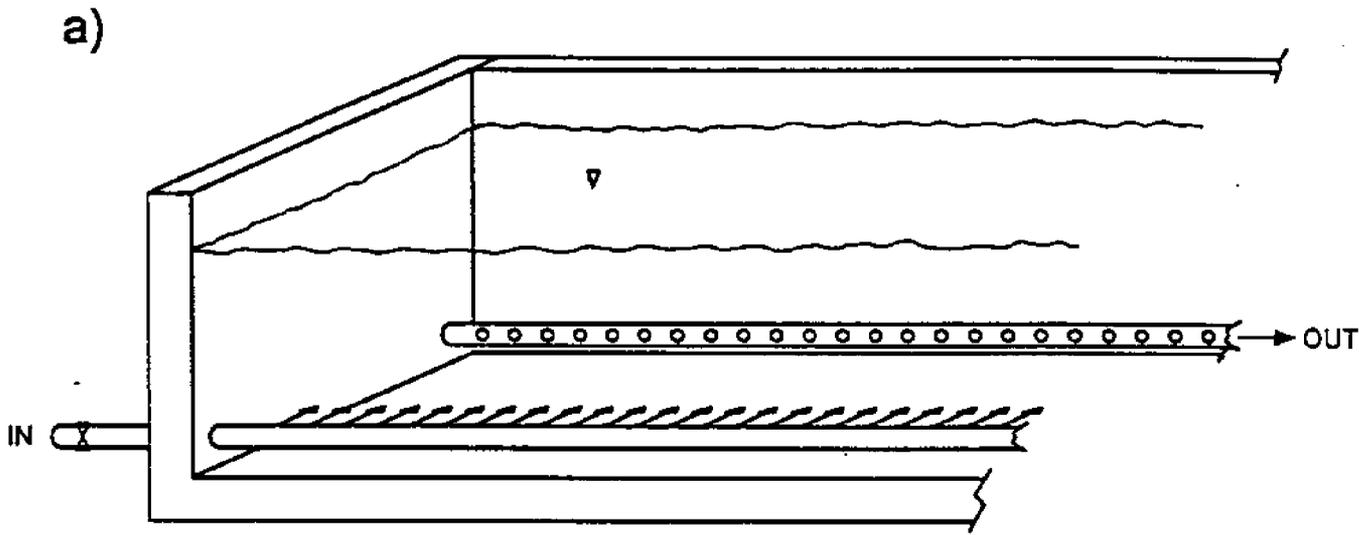
Figure 4. Enclosure area (wall space) comparison between different types of fish rearing units.
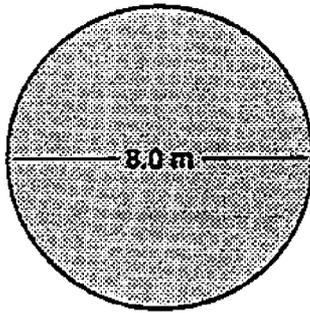
Diameter is 8.0 m
Operating depth is 1.2 m
Free-board is .3 m
Rearing volume is 60 m³
Wall area is 37.7 m²

ROUND TANK
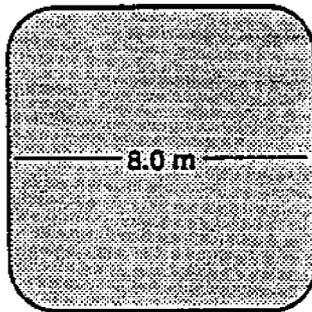
Dimensions are 8.0 x 8.0 m
Operating depth is .94 m
Free-board is .3 m
Rearing volume is 60 m³
Wall area is 39.7 m²

SQUARE TANK
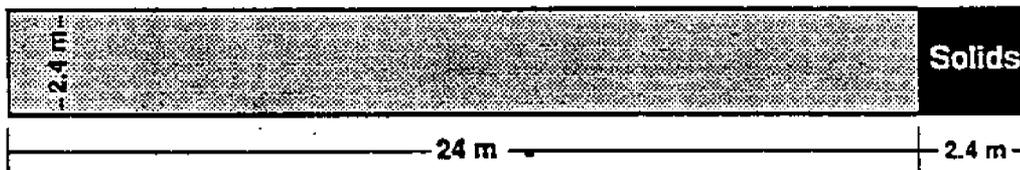
Dimensions are 24 x 2.4 m
Operating depth is 1.05 m
Free-board is .3 m
Rearing volume is 60 m³
Wall area is 77.7 m²

RECTANGULAR RACEWAY

Ratio of round to square to raceway = 1.0 to 1.05 to 2.06.

Figure 5.   Raceway equipped with baffles.
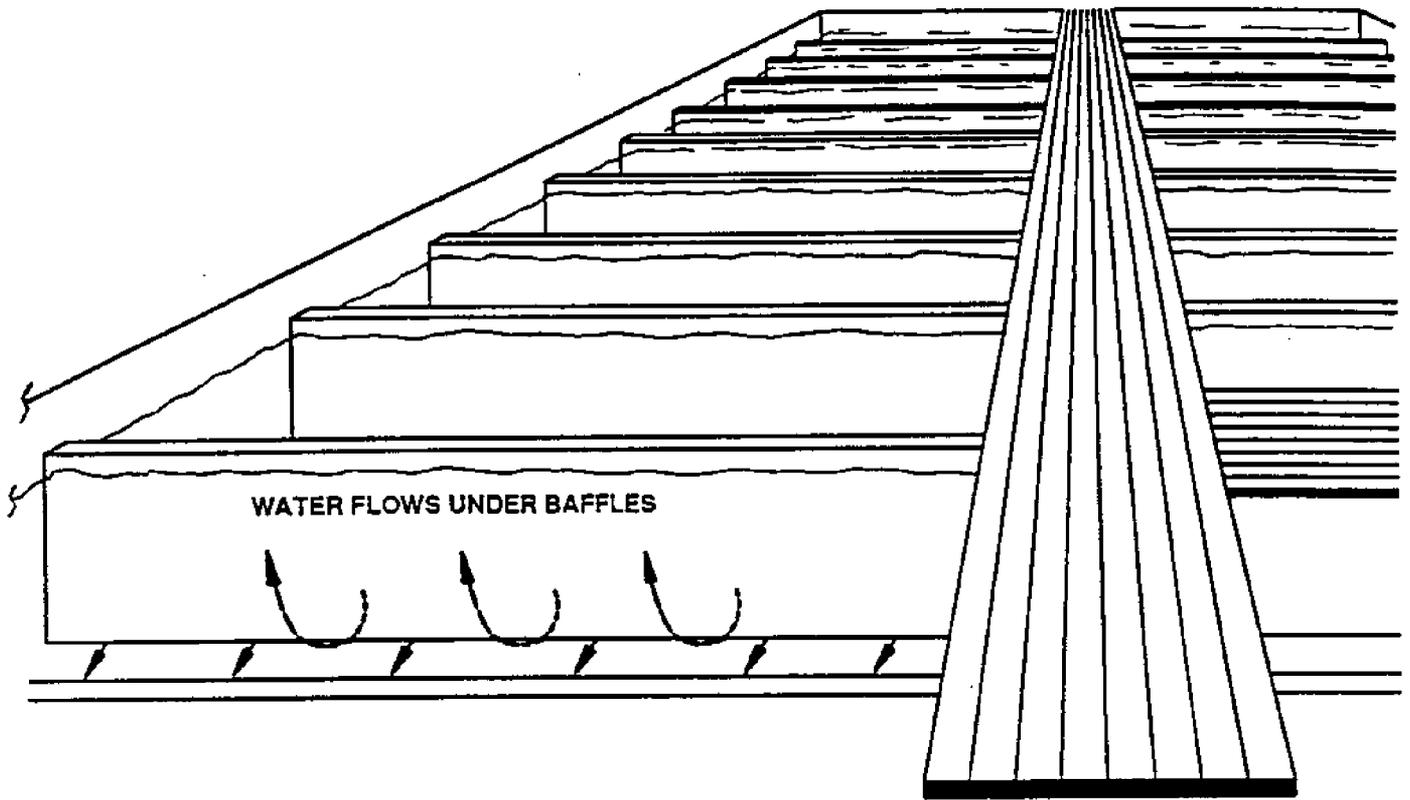
WATER FLOWS UNDER BAFFLES

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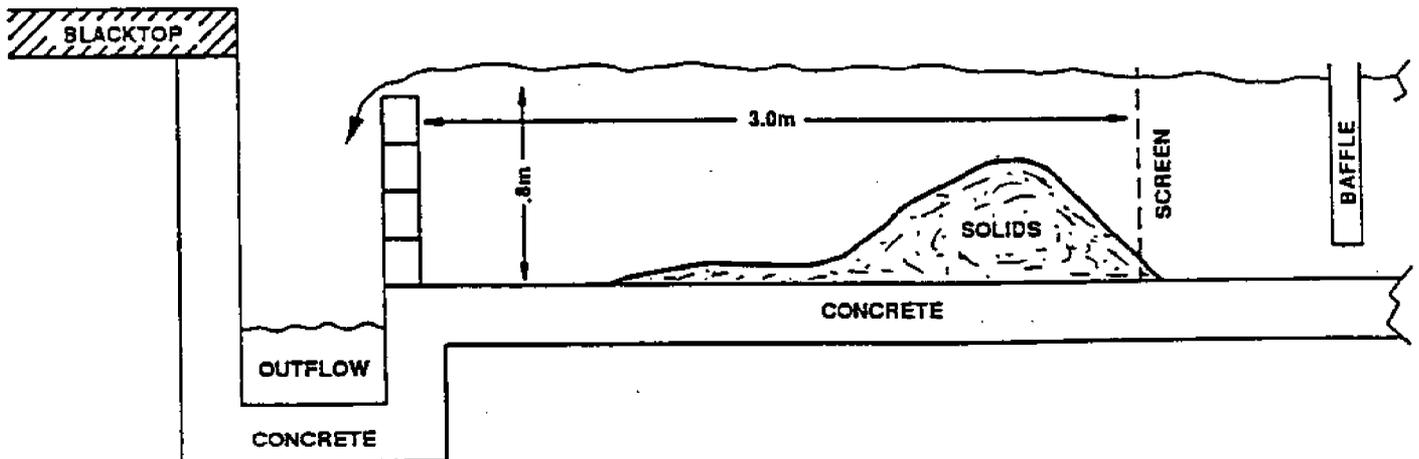
Figure 7.   Water level and solids management system for a
circulating, round tank.
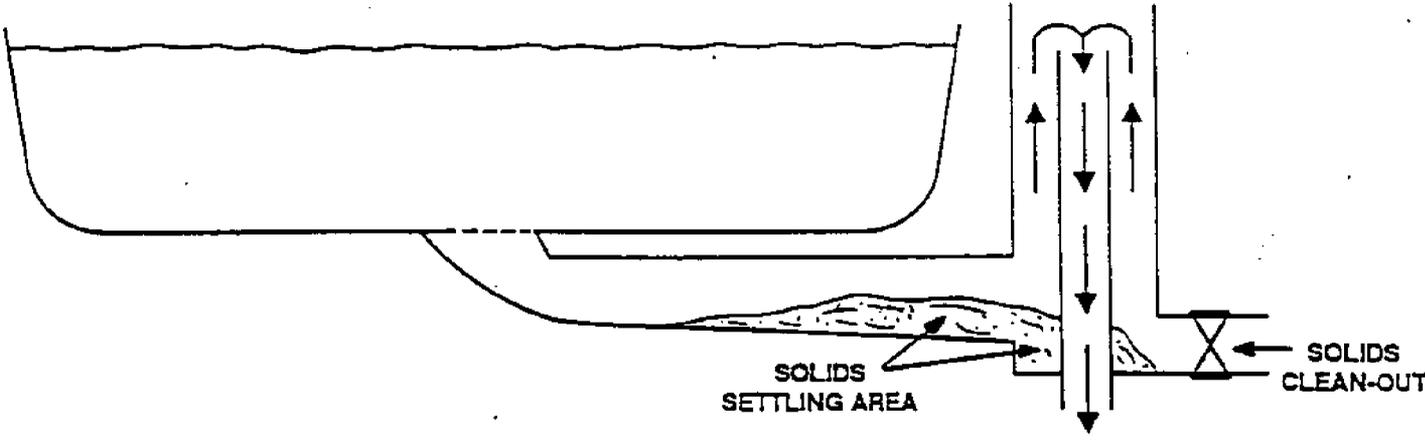
Figure 8A. Raceway complex on 80,000 L/min flow. Selected design driving forces: D = 80;   Ld = 1.6; AO = 4.0;   COC = 10.0;   V = 3.0;   OD = 1.0 .

TV = 1600 m³

44.4 m

2ⁿᵈ - pass

36 m

Add 4.0 mg/L DO

| #1   UV = 133.2 m³ |
| #2 |
| #3 |
| #4 |
| #5 |
| #6 |
| #7 |
| #8 |
| #9 |
| #10 |
| #11 |
| #12 |

3.7 m

| #1 |
| #2 |
| #3 |
| #4 |
| #5 |
| #6 |
| #7 |
| #8 |
| #9 |
| #10 |
| #11 |
| #12 |

2ⁿᵈ pass
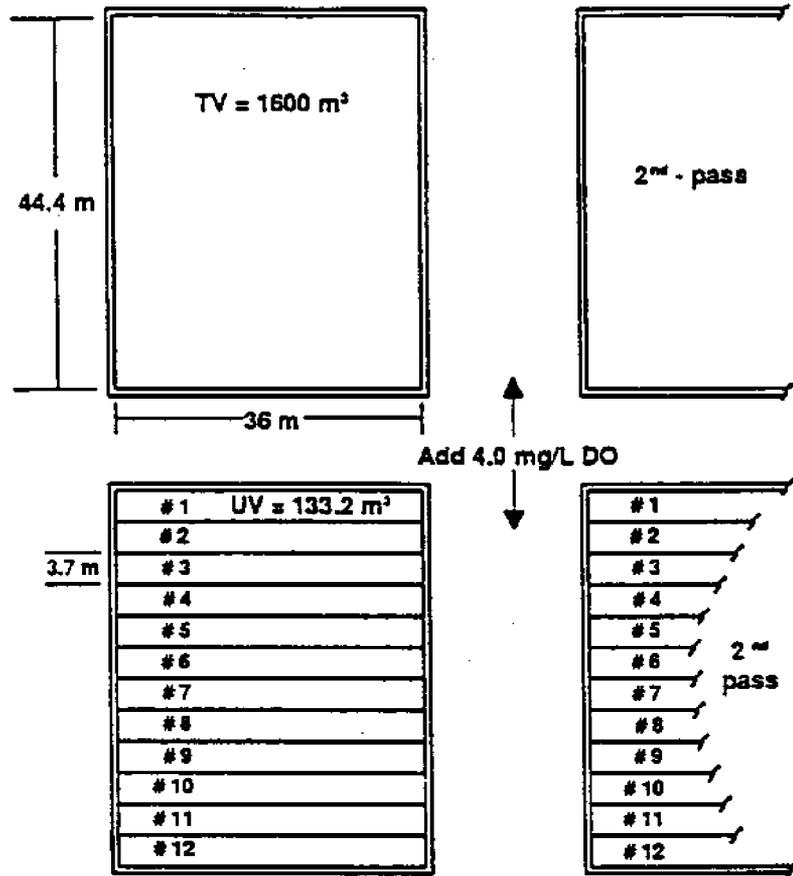
Figure 8B. Raceway complex on 20,000 L/min flow. Selected design driving forces: D = 80; Ld = 1.6; AO = 4.0; COC = 10.0; V = 3.0; OD = 1.0 .
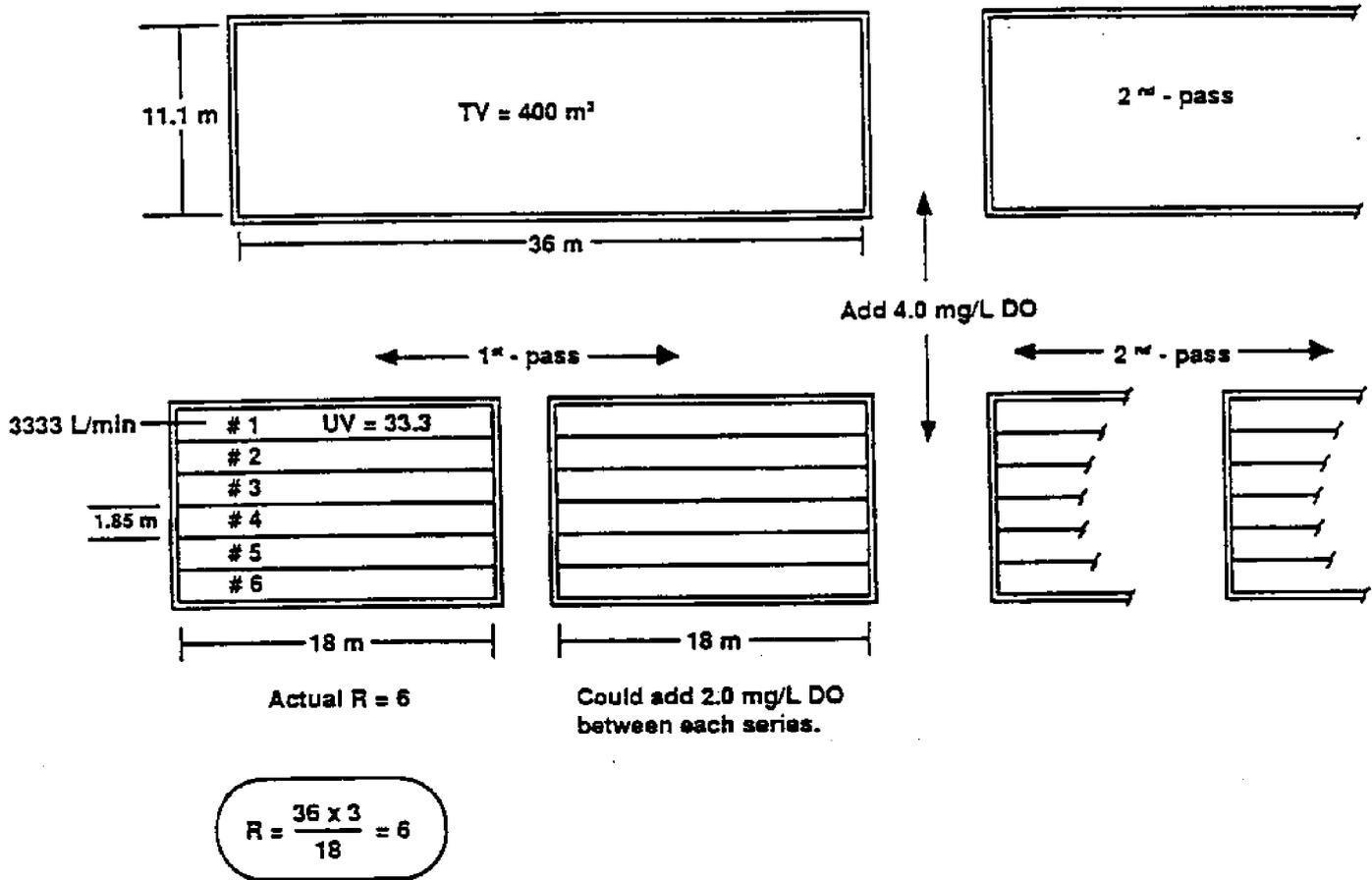
Figure 8C. Raceway complex on 20,000 L/min flow. Selected design driving forces: D = 40; Ld = 1.6; AO = 4.0; COC = 10.0; V = 3.0; OD = 1.0 .

11.1 m

TV = 800 m³

2 ⁿᵈ - pass

72 m

Add 4.0 mg/L DO

1ˢᵗ - pass

2 ⁿᵈ - pass

5000 L/min

#1   UV = 66.6

#2

2.8 m   #3

#4

24 m   24 m   24 m
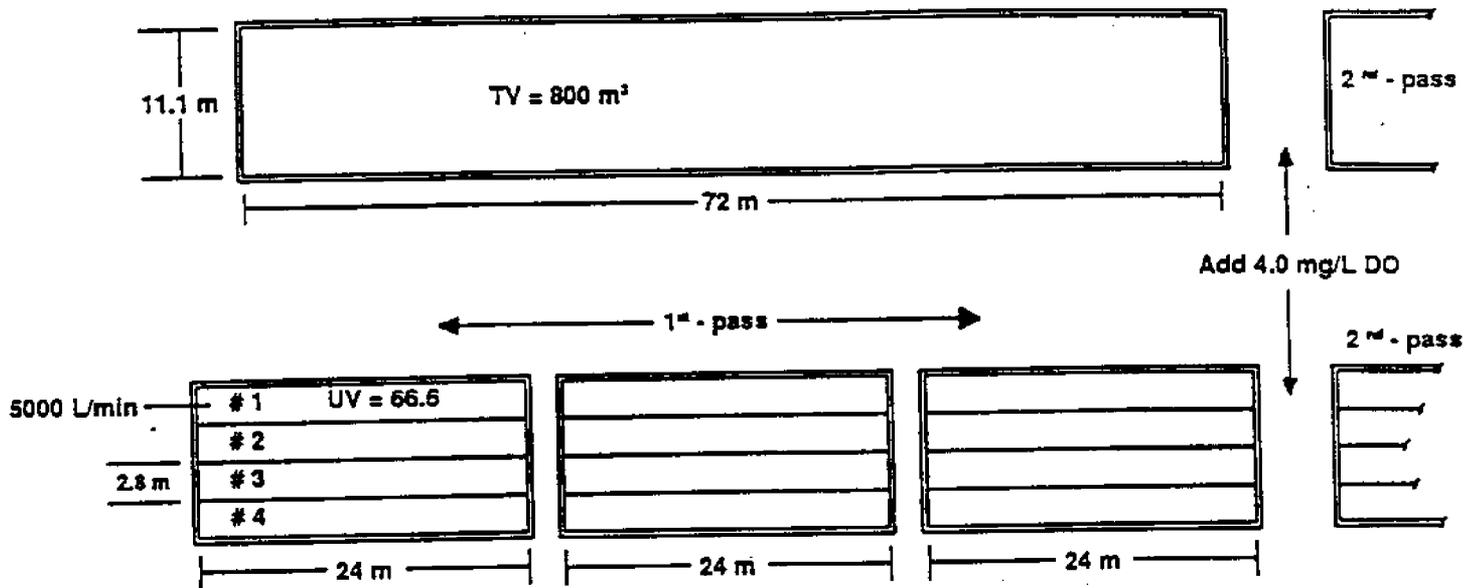
Actual R = 4.5

$$R = \frac{36 \times 3}{24} = 4.5$$

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.

INTAKE AT 20,000 L/MIN

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

1250 L/MIN

| #1 80 KG/M³ | #2 | #3 | #4 | #6 |

SOLIDS → WATER →

| #7 | #8 | #9 | #10 | #16 |

FIRST PASS (OR ONLY PASS)

REUSE

ADD O$_2$ TO 16 MG/L

| #24 40 KG/M³ | #20 | #19 | #18 | #17 |

SOLIDS WATER DISCHARGE ← SOLIDS ← WATER

| #32 | #28 | #27 | #26 | #25 |

SECOND PASS
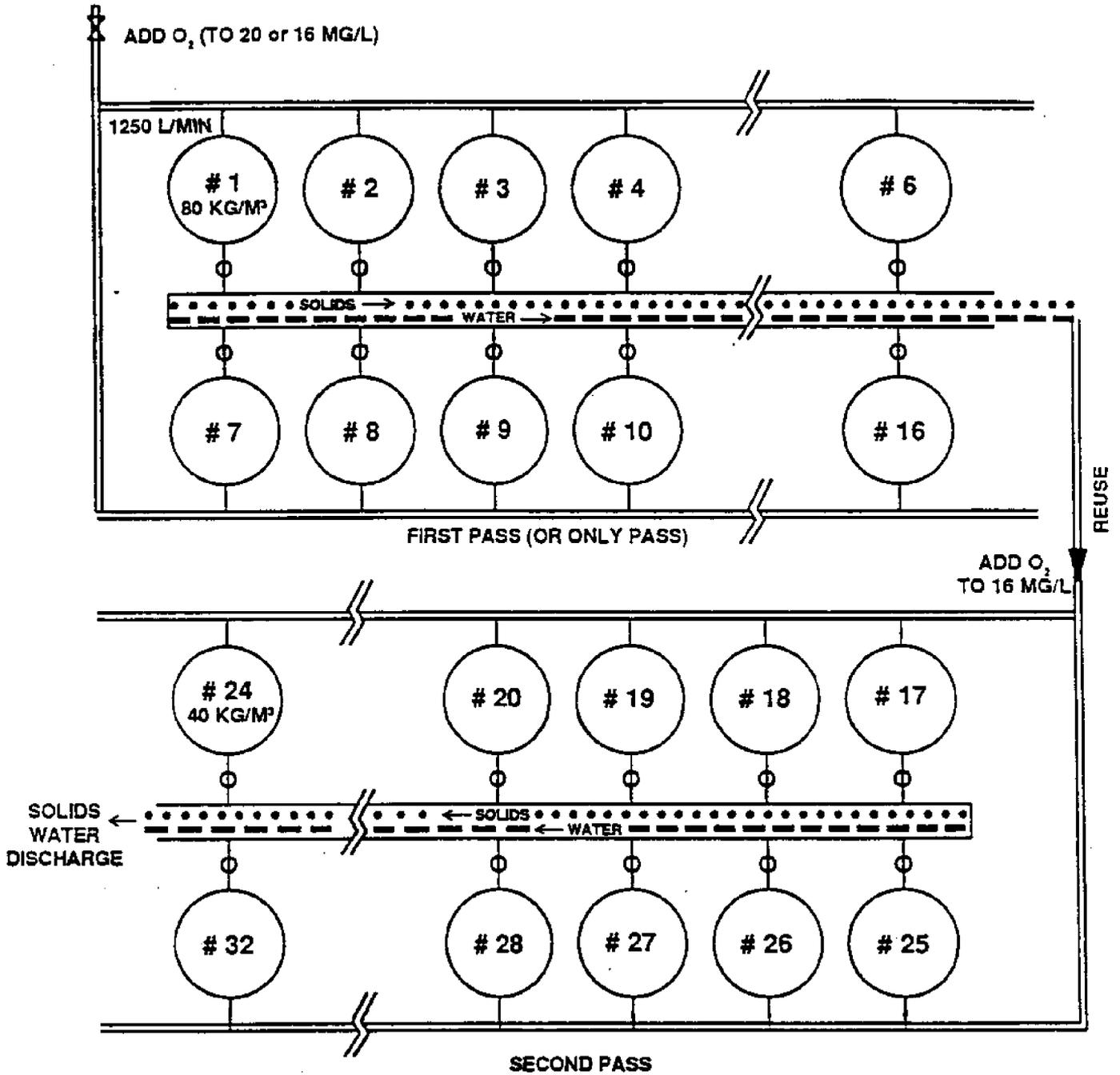
Fish Rearing Units

The obvious (1)

1) All fish must be grown in one kind of container or other. It must be able to hold water.

2) Containers come in many shapes, sizes and dimensions.

3) **Primary Shapes:**
   A. Round and Oval
   B. Rectangular

4) **Two Main Flow Patterns:**
   A. Circular (mixing)
   B. Plug flow (gradient)
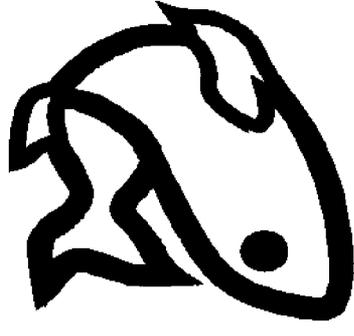
5) **Representatives**
   A. Round Tank
   B. Raceway

"Examine what is said, not him who speaks"

A Comparison

Raceway	Round
1. Requires 1.5 – 3.0 x Wall Area	Largest Volume To Wall Ratio
2. Water Quality Gradient	Homogeneous = Mixing
3. Uniform Velocity	Variable Velocity
4. Low Velocity	Can Be High or Low
5. Velocity Flow Rate Dependent	Velocity Independent of Flow Rate

IV-3

A Comparison (Cont'd)

Raceway	Round
6. Not Self-Cleaning	Can Be Self-Cleaning
7. Can Operate at Very High Exchange Rate (R value)	Limited Water Exchange Rates
8. Poor Fish Distribution	More Even Distribution
9. Easy to Corner Fish	Difficult to Harvest Fish

IV-4

A Comparison (Cont'd)

	Raceway	Round
10.	Difficult Feed Distribution	Easy Feed Distribution
11.	Can Compare Water Quality "In" with "Out"	Mixing of Water Quality = Homogeneous
12.	Hyperoxic Possible With Use of Pure O_2	Immediate Mixing of O_2
13.	Complete Water Replacement (100%)	Partial (65%) Replacement

A Comparison (Cont')

14. Raceways require less floor space than round tanks

15. Other? (Discussion)

"When you have to make a choice and don't make it, that in itself is making a choice."

Further Discussion

Selecting the type of rearing unit a very significant decision! This will come back to "haunt" us.

A Few Diagrams:

I. Circular
    Swedish
    Raceway   } Wall Area

II. Self-Cleaning Raceway

III. Circular with double drain
     (Good for partial recirc.)

Rearing tanks should incorporate excellent features for solid waste management = "gently" dispersing it..... But:

"Everything should be made as simple as possible, but not simpler" (Einstein)

(KISS Principle)

The Linear Raceway

Has Low Velocity (v):

1. Not Self-Cleaning
2. In-Pond Pollution – Solids settle, are resuspended, break down, leach.
3. Low v – No Conditioning of Fish

$$v = \frac{lm \times R}{36} \quad \text{or} \quad \frac{lf \times R}{3600}$$

$$= cm/s \qquad\qquad = ft/s$$

Example: Raceway 100' × 10' × 2.5'

$$RV = 2500 \text{ ft}^3$$

For $\underline{R = 2}$

$$v = \frac{100 \times 2}{3600} = 0.056'/s$$

$$Q = \frac{RV \times R}{8} = \frac{2500 \times 2}{8} = 625 \text{ gpm}$$

For $\underline{R = 4}$ $v = 0.112'/s$

$$Q = 1250 \text{ gpm}$$

Recommend Minimum Velocity: 0.1'/s

The Linear Raceway

$$v = 0.1\text{'}/s \quad \text{or} \quad 3.0 \text{ cm/s}$$

$$\text{For } R = 4.0 \qquad L = \frac{v \times 3600}{4} = 90\text{'} \quad (27 \text{ m})$$

Need velocity of 3.0 cm/s (0.1'/s) for "Good" hydraulics, but this is far too low for channel cleaning. Almost all raceways function as settling chambers! For cleaning, need velocities 10 – Fold.

Very Important: Fecal matter must not be destroyed! It's specific gravity is only 1.19. A particle of **100 um (0.004")** requires **+ 50** min to settle a depth of **2.5' (0.76 *m*)** It will drift out of the raceway.

The Linear Raceway

Example of High Flow Rate (High R Value) and Low Velocity:

Raceway (Tank): $30' \times 3' \times 2'$ (180 ft^3)

For R = 10

$$Q = \frac{180}{8} \times 10 = \textbf{225 gpm}$$

$$v = \frac{30 \times 10}{3600} = 0.083'/s \quad (\textbf{<0.1'/s})$$

For MAO = 25   And   R = 4

$$Ld = \frac{3.8 \times 25 \times 100}{114 \times 1.0 \ (\%BW)} = \textbf{83 lb/gpm}$$

$$D = \frac{Ld \times R}{8} = \frac{83 \times 4}{8} = \textbf{41 lb/ft}^3$$

The balance between Ld, D and R is not appropriate.

Need to design Multi-Pass Serial Reuse

Fix D at 5 $\longrightarrow \frac{41}{5} = 8$ series   * $\boxed{AO = 3.1}$

Fix D at 10 $\longrightarrow \frac{41}{10} = 4$ series   * $\boxed{AO = 6.25}$

*AO per series = $\dfrac{MAO}{\# \ series}$

Table 1. Flow rate limits for plug-flow rearing units (raceway, tank and trough) based on maximum flowrate capacity per cross-sectional area ($MQ_{c/s}$) in lpm/m², and minimum selected operational velocity (v) in cm/s. Raceway (RW): $MQ_{c/s}$ = 1500; Tank (TK): $MQ_{c/s}$ = 1000; and Trough (TR): $MQ_{c/s}$ = 750. Velocities are 3.0, 2.0, and 1.0 cm/s respectively.

Type	l m	w m	d m	RV m³	c/s m²	$Q_{c/s}$ lpm	$R_{c/s}$ #/h	R_v #/h	Q_v lpm	Ld kg/lpm	D_v kg/m³	$D_{c/s}$ kg/m³
RW	30	3.0	0.8	72	2.4	3600	3.0	3.6	4320	2.0	120	100
TK	10	1.0	0.6	6.0	0.6	600	6.0	7.2	720	1.0	120	100
TR	3	0.3	0.4	0.36	0.12	90	15.0	18.0	108	.05	125	150

$$Q_{c/s} = MQ_{c/s} \times C/S$$

$$R_{c/s} = (Q_{c/s} \times 0.06) / RV$$

$$R_v = (v \times 36)/l$$

$$Q_v = (RV \times R_v) / 0.06$$

$$Ld = (5.0 \times 100)/(250 \times \%BW)$$

$$D = (Ld \times R_v) / 0.06$$

Recommended Rearing Denities:

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)

Figure 1. Enclosure area (wall space) comparison between different types of fish rearing units.
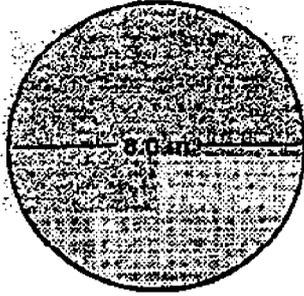
Diameter is 8.0 m
Operating depth is 1.2 m
Free-board is .3 m
Rearing volume is 60 m³
Wall area is 37.7 m²

ROUND TANK

Dimensions are 8.0 x 8.0 m
Operating depth is .94 m
Free-board is .3 m
Rearing volume is 60 m³
Wall area is 39.7 m²

SQUARE TANK

Dimensions are 24 x 2.4 m
Operating depth is 1.05 m
Free-board is .3 m
Rearing volume is 60 m³
Wall area is 77.7 m²

Solids

24 m — 2.4 m
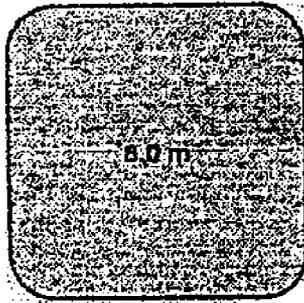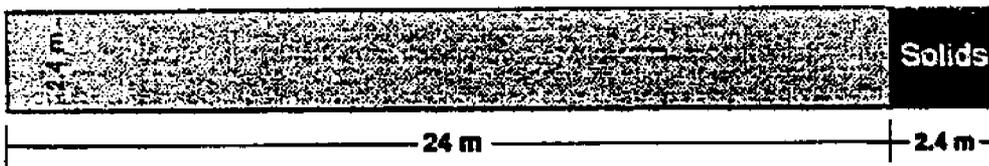
RECTANGULAR RACEWAY

Ratio of round to square to raceway = 1.0 to 1.05 to 2.06.

Figure 2.   Linear raceway (a) and round tank (b) flow pattern
and dissolved oxygen characteristics.

a)

b)
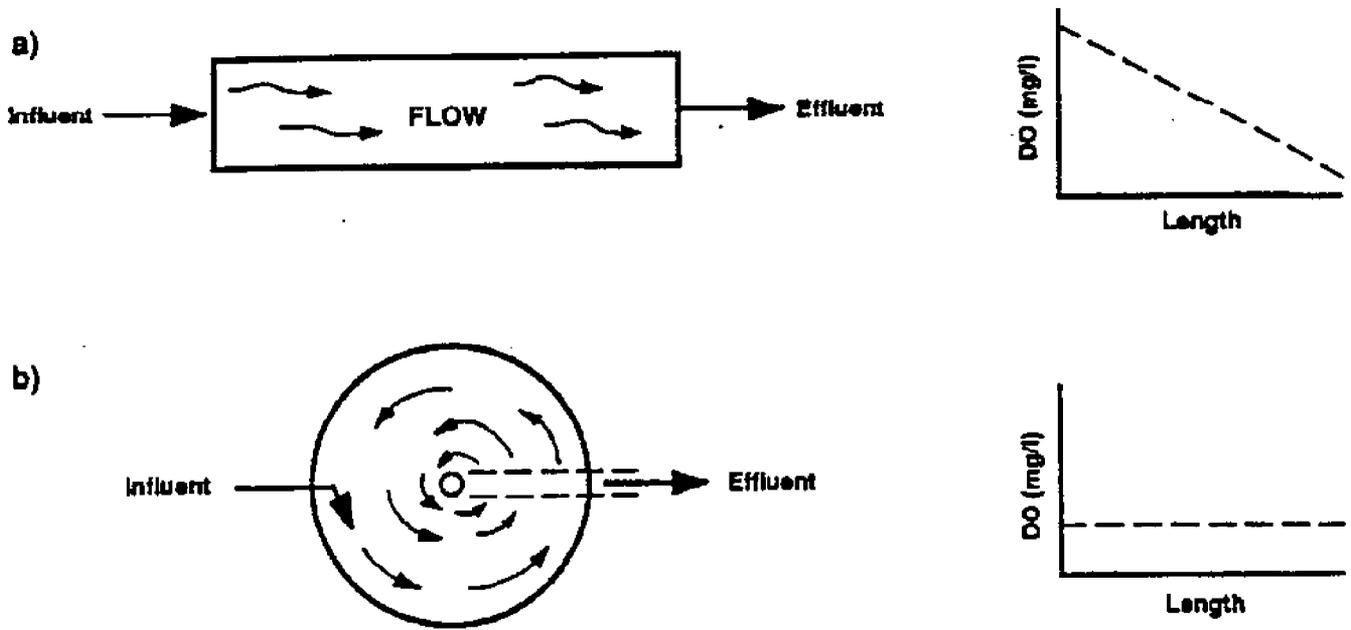
Figure 3.   Burrows Pond design.
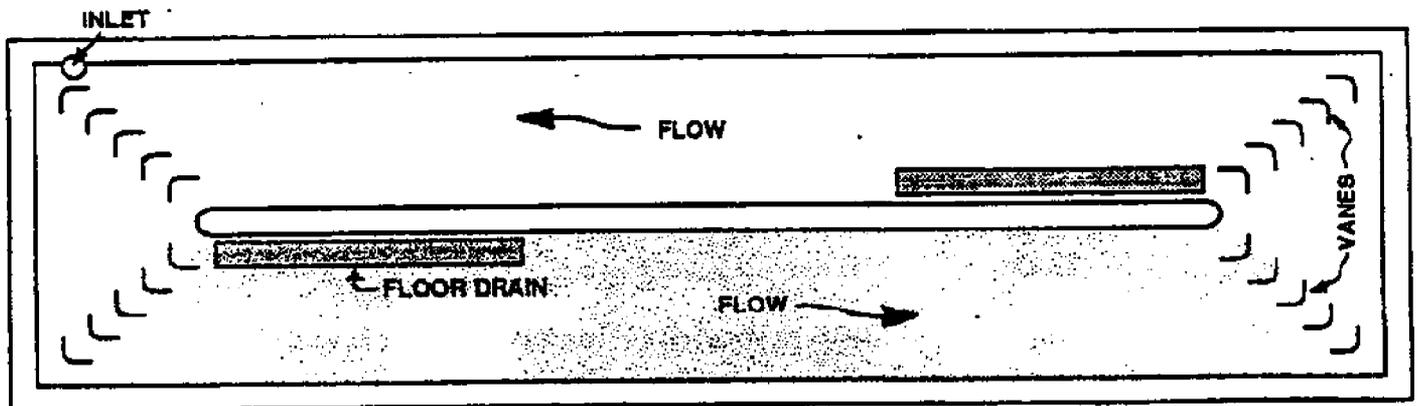
Figure 4. Diagrams of the cross-flow fish rearing tank.
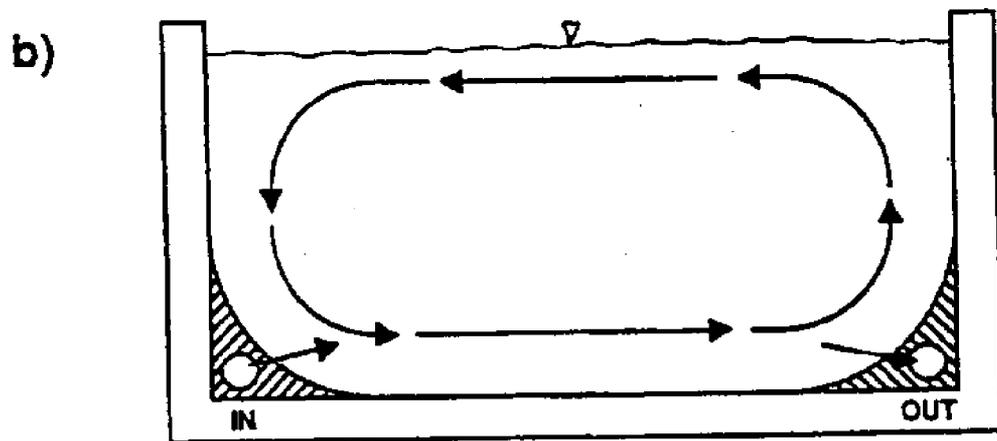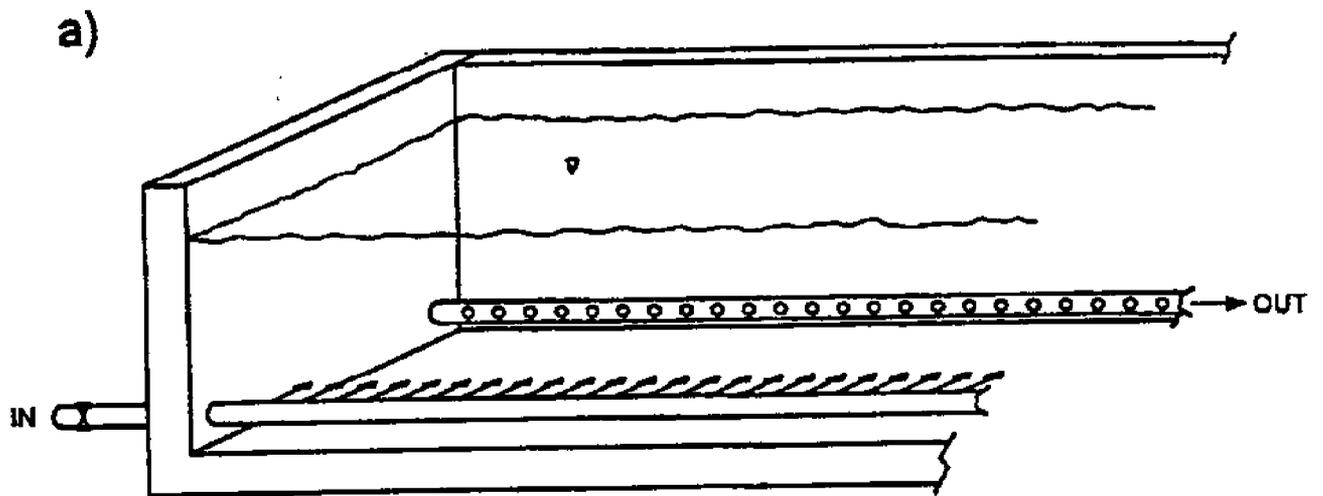
a) Longitudinal view   b) Cross-sectional view

Figure 5. Raceway equipped with baffles.
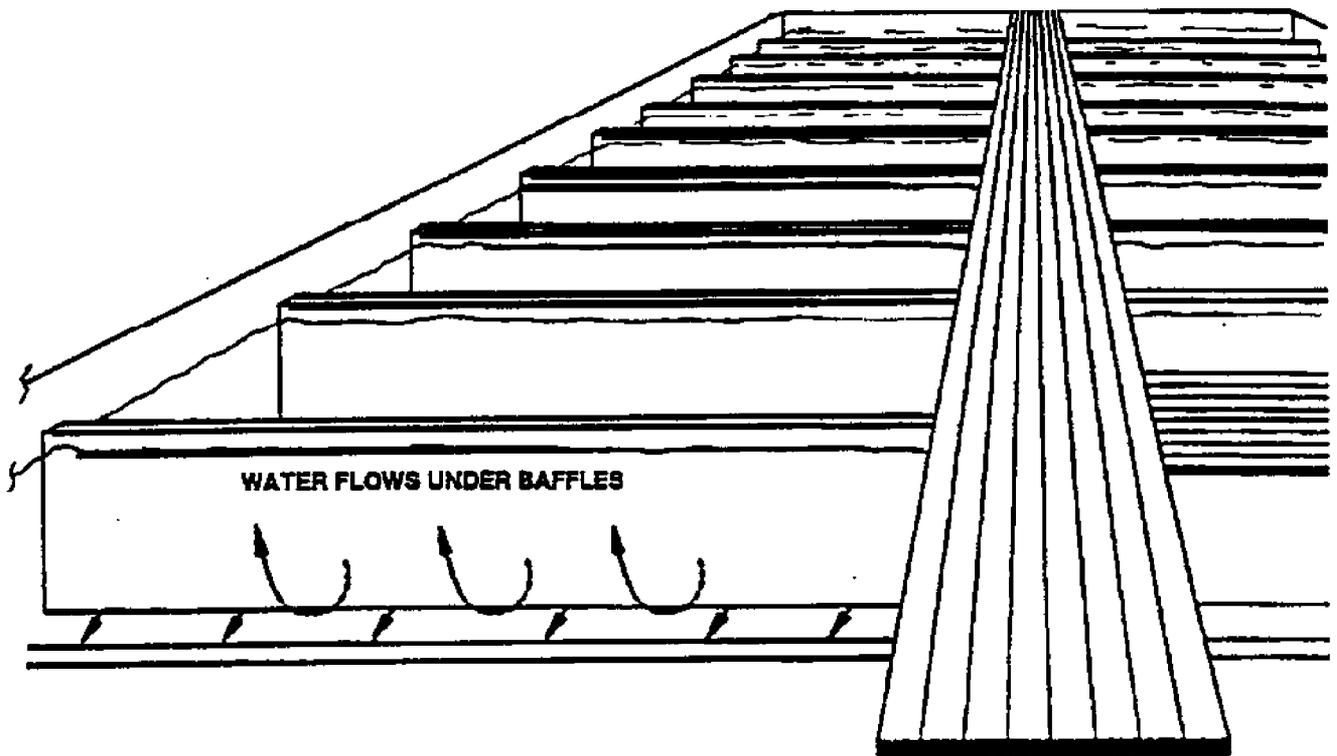
WATER FLOWS UNDER BAFFLES

Figure 6. Solids settling characteristics in raceway solids settling section behind fish retaining barrier.

BLACKTOP

3.0m

SCREEN

BAFFLE

SOLIDS

CONCRETE

OUTFLOW

CONCRETE

Figure 7.

horzontal and vertical influent
injection pipes awith orifices

outlet flow   inlet flow
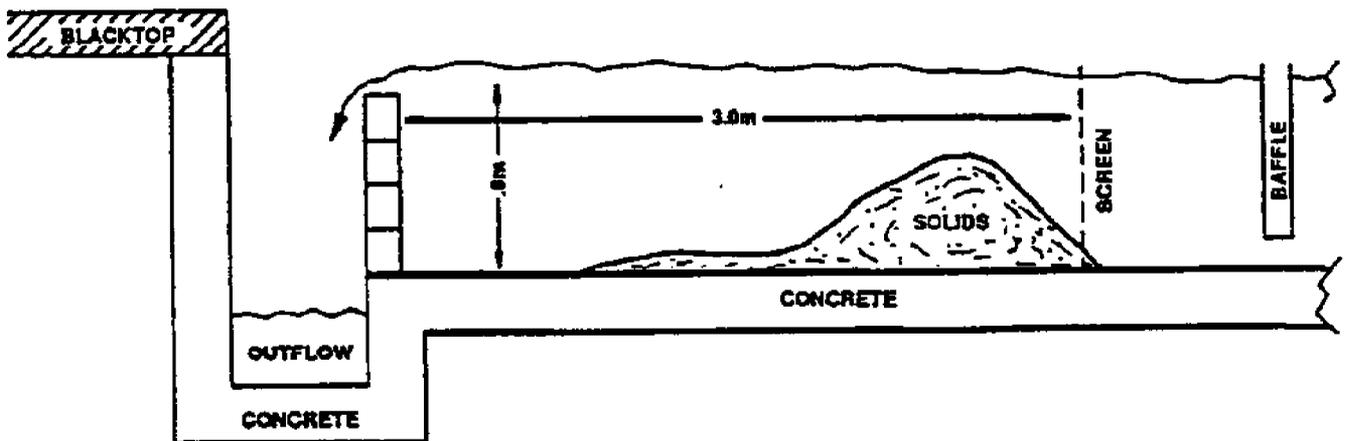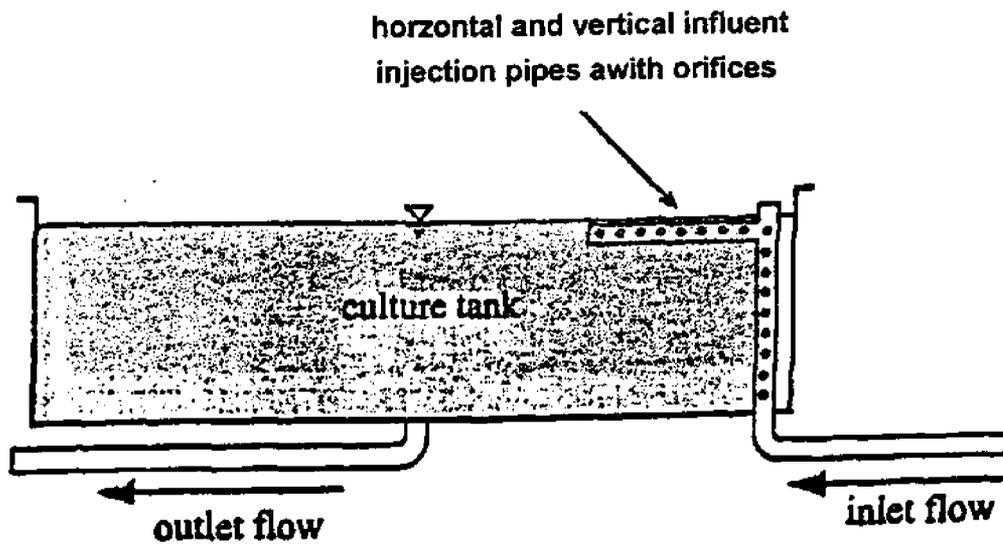
'Cornell-type' dual-drain tank

Figure 8.
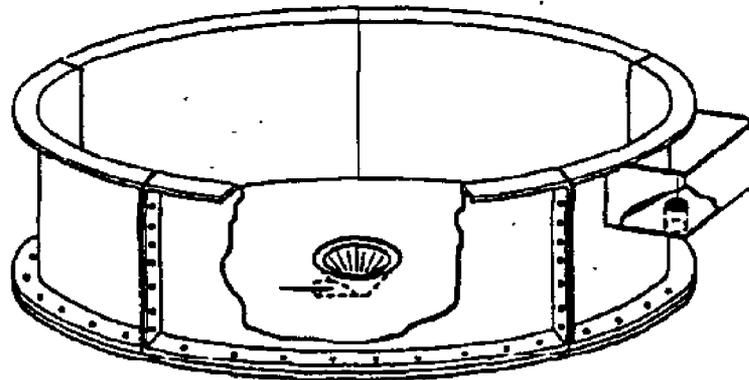
Courtesy of Red Ewald, Inc. (TX)

Source: Timmons and Summerfelt (1997), Advances in Circular Culture Tank Engineering
to Enhance Hydraulics, Solids Removal, and Fish Management. In: Advances in
Aquaculture Emgomeering - Timmons & Losordo, ED's

Plan   Section
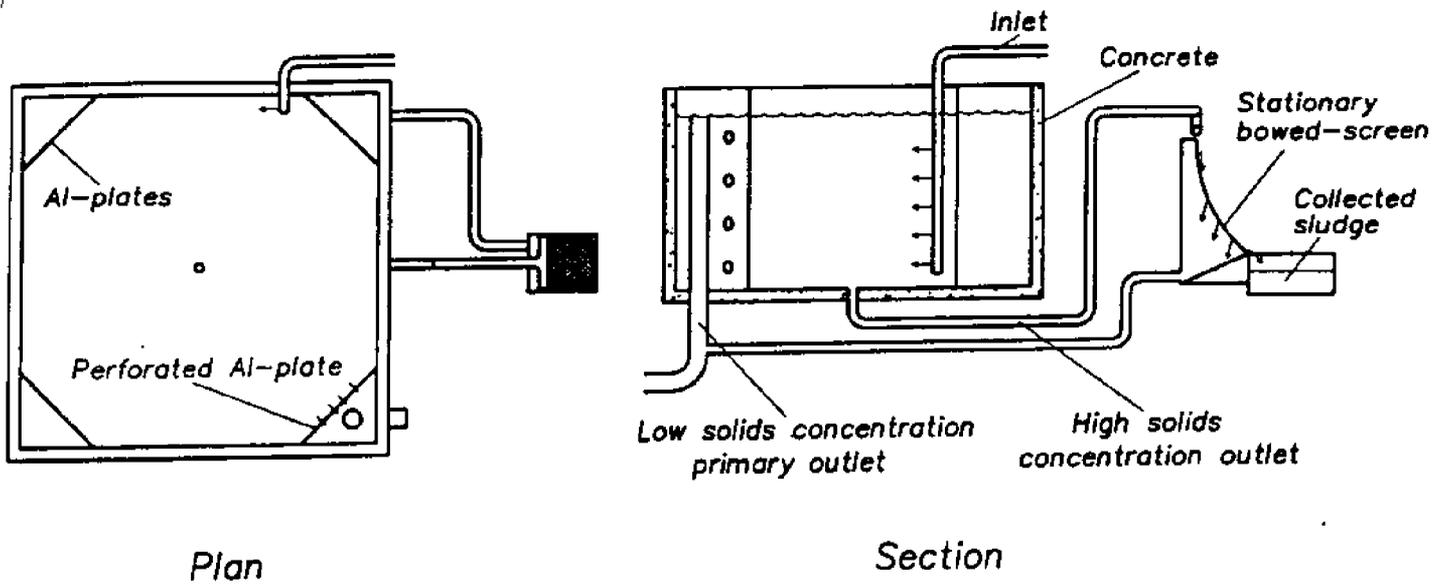
Fig. 1. Sketch of the wastewater treatment system i.e. the newly developed tank and the REKO static bowed screen.
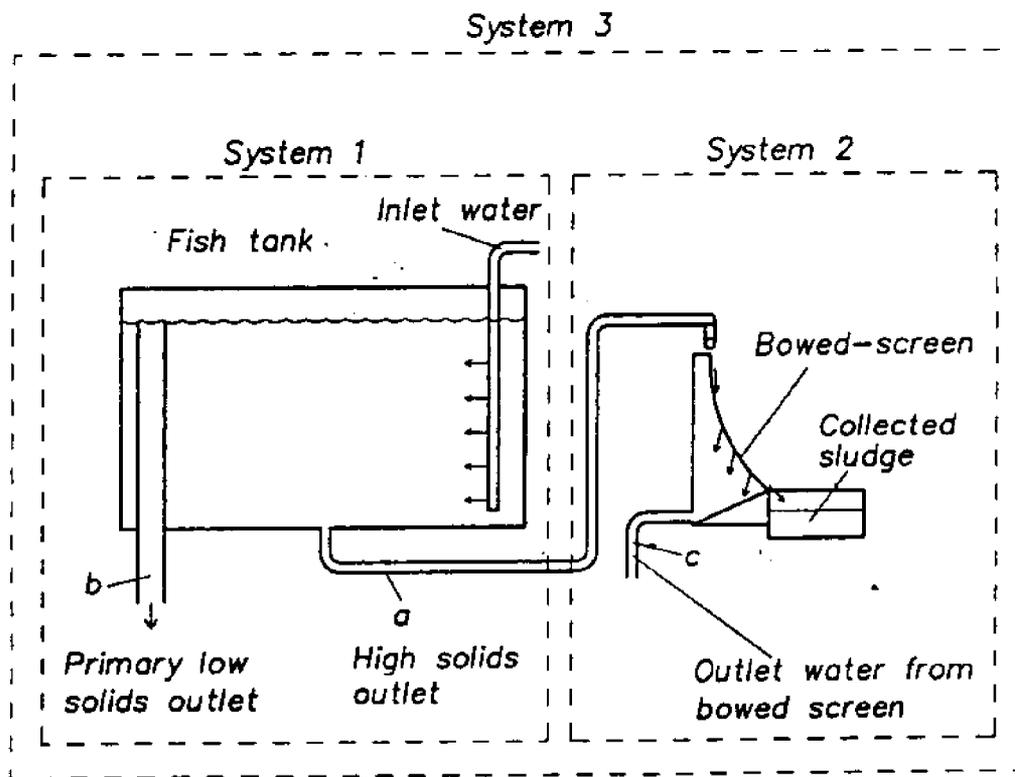
Fig. 2. Sketch of the system in which the removal efficiency was determined.

V. FACILITY DESIGN PROCESS

A. INTRODUCTION

Designing an intensive fish production facility involves much input and requires many decisions.

I. Of primary importance.
1.   Quantity and quality of the water source.
2.   Desired production: species, numbers, and purpose.

II. Questions to consider.
1.   Does the source water require pre-treatment? Should it be specific pathogen free?
2.   Is some level of re-circulation acceptable?
3.   Do we need bio-security measures?
4.   What is to be the level of monitoring, alarms, back-up, and automation?
5.   What level and kind of rearing water treatment is desired?
6.   What level of effluent treatment is required? (Regulations, available technology).

III. Numbers (values) must be selected relative to specific production and design parameters.
1.   Maximum permissible rearing densities (MD).
2.   Oxygen requirement per unit of food (OF).
3.   Ammonia generated per unit of food (TANF).
4.   Maximum permissible, safe, concentration of unionized ammonia (MUA).

IV. Other choices.

1. Type of rearing unit desired (plug-flow or circulating).

2. Minimum/maximum size and number of rearing units.

3. Indoor or outdoor rearing (biosecurity, predation).

V. Consider the fish culturist (worker).

1. Pleasant work environment (light, noise, smell, break room, etc.).

2. Manageability

   a) Feed handling (storage, moving, feeders, etc.).

   b) Fish handling (sorting, moving, harvesting, treating, etc.).

   c) Sanitation (hosing, floor drains, wash basins, etc.).

   d) Rearing tank (depth, diameter, equipment, etc.).

   e) Overall equipment need (identify with input from fish culturist).

3. Laboratory space (proper equipment).

4. Heavy equipment storage and maintenance space.

VI. Visitor/educational facility (managing visitors).

1. Especially appropriate for public fish hatcheries.

2. Important public relations function. "Aquaculture is agriculture," a concept not well understood by the general public. Ignorance never serves society well!

Obviously there are many components and details to consider when designing a "complete" aquaculture facility. This workshop's focus is on production capacity and rearing space requirements based on water quantity, quality, and production program/goals.

A step-by-step process is used to arrive at a rational design concept. Major driving forces are parameter values selected by the "client." Probably the most significant concept is the flow, space, and operational relationship expressed as loading (Ld), density (D), and rearing unit water turn-over or exchange rate (R) presented in unit I:

$$Ld = (D \times 0.06)/R; \quad D = (Ld \times R)/\ 0.06; \quad R = (D \times 0.06)/Ld$$

B. DESIGN PROCESS

The following sample scenario utilizes a set of arbitrarily selected parameters.

I. The water (a somewhat ideal source to keep things simple).

The source water is a 10, 000 lpm (2642 gpm) spring. It has a constant temperature of 14°C (57°F), a pH of 7.6. These two, pH and temperature result in an ammonia fraction of 1.0% of the total ammonia nitrogen.

The water has no fish in it, it is specific pathogen-free. The dissolved oxygen concentration is 10.0 mg/l. The water does not require pre-treatment (no gas supersaturation).

II. The production program.

Rainbow trout are to be reared to 500 g (1.1 lb) each for the food market. The production program starts with feed trained fingerlings at a size of 1.25 g (W = 1.25). Their condition factor (k) is 0.010 resulting in a length of 5.0 cm $[L = (W/k)^{1/3}]$.

The fish will be reared indoors to a length of 15 cm, a weight of 34 g (6" and 13.4/lb). This is phase I of the rearing program. Their temperature unit growth rate is 0.0055 cm, the daily length increase is 0.077 cm [ΔL = TUG x °C].

The feed conversion during the indoor rearing period is 1.0. After phase I rearing is complete, the fish are moved to the outdoor rearing system for grow-out to 500 g. This is phase II. During phase II, the k-factor is 0.012 and the feed conversion is 1.2. The TUG value is

0.0050, the $\Delta L = 0.070$. Phase I spans a period of 130 days ($t = 130$), phase II 281 days ($t = 281$) [$t = (L_t - L_1)/\Delta L$]. For a final weight of 500 g, the length is 34.7. It requires 411 days to complete the full rearing cycle(RC). Because a new group of fingerlings enters the facility once a year, the system supports two cohorts simultaneously for a 46-day period each rearing cycle. It will be assumed that a new cohort enters the facility on March 1st each year.

Phase I fish move outdoors on July 10 (March 1 + 281 d). From April 18 through July 9 there are no phase II fish in the system (82d). Facility is used inefficiently.

III. Design.

1. ***Selected parameters***

    a)   Oxygen required per kg food per "day" is 250 g (OF = 250).

    b)   TAN generated per kg food per "day" is 30 g (TANF = 30).

    c)   TAN concentration per AO used is 0.1 mg/l (TANC = 0.1).

    d)   Maximum allowable unionized ammonia concentration is 0.025 mg/l (MUA = 0.025). Recall: %UA = 1.0.

    e)   Maximum rearing densities are 60 kg/m³ for phase I, 96 kg/m³ for phase II (MD = 60 and 96).

    f)   The %BW feeding level is $(2 \times °C)/(W/k)^{1/3}$.

2. ***Values derived from 1: a through f "choices."***

    a)   Maximum available oxygen is 25 mg/l [MAO = (MUA x 1000)/%UA].

    b)   Feeding level in %BW for phase I, at end of rearing period, is 1.87% [(2 x 14)/15].

    c)   Maximum loading for phase I, at end of rearing period, is 5.38 kg/lpm [MLd = (MAO x 100)/(OF x %BW)].

    d)   Feeding level in %BW for phase II, at end of rearing period, is 0.81% [(2 x 14)/34.7].

e) Maximum loading for phase II, at end of rearing period, is 12.4 kg/lpm.

f) Phase I maximum weight per fish to maximum loading ratio is 34 to 5.4 or 6.3 to 1.0.

g) Phase II W to Ld ratio is 500 to 12.3 or 40.6 to 1.0.

h) The ratio's 6.3 to 40.6 (1.0 to 6.4), represent the ratios of maximum flowrates (MQ) required for phase I and phase II at the end of their rearing period.

i) Maximum flowrate required for phase I is 1351 lpm [MQ = TQ/(sum of ratio)] and in our case this is: [MQ = 10,000/(1 + 6.4)]. This leaves 10,000 lpm - 1351 lpm for phase II. It's maximum flowrate is 8649 lpm.

j) Maximum biomass for phase I is 7268 kg [MBM = (MQ x MLd)] or: MBM = 1351 x 5.38.

k) Maximum biomass for phase II is 106,383 kg [MBM = 8649 x 12.3].

l). These respective biomasses represent 213,765 and 212,765 fish [# Fish = (MBM/Wg) x 1000].

Note: The differences in numbers are the result of rounding values.

m) Rearing volume required for phase I is 121 m³, for phase II 1108 m³ [MBM/MD].

3. *Rearing volume to rearing unit design and operation.*

Recall: [(Ld = D x 0.06)/R] and [D = (Ld x R)/0.06].

a) The exchange rates (R values) for phase I and phase II, based on flowrate and rearing volume, are 0.67 and 0.47 respectively [R = (Q x 0.06)/RV]. Important: These flow rates are to provide a maximum available oxygen of 25 mg/l, the incoming DO must therefore be as high as 31 mg/l if a minimum residual DO of 6.0 mg/l is required.

Recall the MLd for phase I is 5.38 and the MD is 60 [R = (96 x 0.06)/5.38 = 0.67]. For phase II: [R = (96 x 0.06)/12.3 = 0.47].

b) Too high AO! Assume AO of 5.0 DO_{in} = 11.0. Requires a serial reuse of

five passes: 5+5+5+5+5. Total rearing volume per rearing unit (RV_t) for phase I is 24.3 m^3 (121/5). For phase II it is 221.6 m^3 (1108/5).

c) The resulting exchange rates are 3.35 and 2.35 respectively for phases I and II [R = (Q x 0.06)/RV]. The new loadings are: 1.076 and 2.46 [Ld = (5 x 100)/(250 x %BW]   [R = (60 x 0.06)/1.076) = 3.35] [R = (96 x 0.06)/2.46) = 2.35].

4. *Select plug-flow rearing unit*

Criteria: For phase I, velocity must be 2.0 cm/s or greater (v = ≥ 2.0), for phase II 3.0 cm/s or greater (v = ≥ 3.0). Also the length to width ratio must be 10 (or more) to 1 (≥ 10 to 1.0).

a) Plug-flow rearing unit design for a ratio of l to w of 10 to 1.0 is: w = √(RV)/(10 x d) For a depth of 0.8 m (d = 0.8) and a rearing volume of 24.3 m^3 for phase I, the l x w x d is 17.4 m x 1.74 m x 0.8 m.

b) The resulting velocity is 1.62 cm/s [v = (l x R)/36] [v = (17.4 x 3.35)/36 = 1.62].

c) Velocity does not meet the criterion of 2.0 or more cm/s. Must either increase l or R (see equation above). Cannot change the rearing volume (RV) because of maximum density criterion of 60 kg/m^3. Cannot change the flow rate either because of the loading value. Since D, Ld, and R must balance, cannot change the R value.

d) Change the length (but not the RV) to 21.49 m [l = (v x 36)/R] [l = (2 x 36) / 3.35 = 21.49]. The new width is now 1.41 m [w = (RV)/(l x d)]. The l to w ratio is 13.5 to 1.0. This makes the total linear distance of the four sides 1.2 times as long. From a total of 38.2 m to 45.7 m. The cost will be greater, but hydraulically better, more channel-like design.

e) Phase II dimensions are 52.6 m x 5.26 m x 0.8 m. The velocity is 3.4 cm/s [v = (52.6 x 2.34)/36 = 3.4]. Meets the velocity criterion of 3.0 or more cm/s. Good hydraulics, but not self-cleaning.

6

5.   *Select circular rearing units*

Criteria: Exchange rates from 1.5 to 2.5; diameter not to exceed 9 m (±30'). Can introduce super-saturated dissolved oxygen concentrations up to 150% saturation. Saturation is 11.0 mg/l, 150% of saturation is 16.5 mg/l.

The velocity is independent of the flowrate, but to accomplish proper hydraulics for self-cleaning requires the right designs for intake and outlet (Unit IV).

a)   Use a three-pass serial design. The AO value is 8.3 mg/l (25/3), the DO_{in} is 14.3 mg/l (± 135% sat.).

b)   Phase I rearing unit volume is 40.3 m³ (121/3) for an operating depth of 1.5 m, the diameter is 5.85 m (19.1') [diameter = 2 $\sqrt{RV/(\P \times d)}$]. The R value is 2.0.

c)   If six units are desired (split the flow) the diameter is 4.1 m (13.5'). No change in R value.

d)   The new loading is 1.78 [Ld = 8.3 × 100)/(250 × 1.87)] Check: [R = 60 × 0.06)/(1.78) = 2.0] Balance!

e)   Phase II rearing unit volume is 369.3 m³ (1108/3). For an operating depth of 1.5 m, the diameter is 17.9 m (58'). Tank is too large! For six units the diameter is 12.5'.

f)   Options: Six units with a depth of 2.85; diameter is 9.0 m. Want to keep depth at 1.5 m or less. Consider 12 units (either 4 × 3 for AO or 8.3 or 3 × 4 for AO of 6.25). Diameter for d = 1.5 is 8.85 m. This is acceptable.

IV. There are other options.

1.   *Design:* Partial Recirculation (Unit VI).

2.   *Program:* Sequential Rearing Strategy (Unit VIII).

The designed production program for feeding fingerlings of 1.25 g to harvest size of 500 g once per year represents the batch culture approach. This occurs commonly in "conservation" hatcheries that mimic the natural life cycle of the species reared. The result is inefficient use of the facility, because much of the time the biomass is far below the maximum carrying capacity.

This facility, theoretically, can "process" a maximum of 1000 kg feed per day. This number is derived from the maximum AO value of 25 mg/l and the maximum available flowrate of 10,000 lpm:

$$[MF/d = (MAO \times Q_T) / (OF)]$$

At the end of phase II, the maximum biomass is 106,383 kg, the feeding level is 0.81% BW. Daily feed fed is 862 kg. By this time phase II fish (213,000) have been reared for 45 d. At a daily length increase of 0.077 cm these fish gained 3.46 cm in length, which makes them 8.46 cm long. The weight for this length is 6.05 g and their obvious biomass is 1290 kg (213,000 fish @ 6.05 g) for a total daily feed requirement of 60 kg. The maximum daily feed requirementis 922 kg (862 kg + 60 kg), which is near the maximum of 1000 kg. Let us assume that we can feed 1000 kg per day every day throughout the year. To do so would require the removal of the daily gain each day, namely 800 kg for a feed conversion of 1.25. To do this 365 days per year would result in an annual output of 292,000 k. How close can we come to the 1000 kg feed per day on a year-around basis? This will be discussed in the next unit which addresses sequential rearing strategies.

Facility Design Process

Requires Input and Decisions (Choices)

I. **Water Source : Quantity; Quality**

II. **Production : Species ; Goals**

III. Discussion:

   1. Need pre-treatment? N_2; O_2; O_3; etc.

   2. Specific pathogen free?

   3. Bio-Security?

   4. Recirculation?

   5. Monitoring, Alarms, Automation, etc.

   6. Effluent/Regulations

IV. Numbers (Values) to Select

1. Max. Permissible Rearing Densities (MD)
2. Oxygen Required Per Unit Food (OF)
3. TAN Generated Per Unit Food (TANF)
4. Maximum Acceptable Unionized Ammonia Concentration (MUA)

V. Other Choices

1. Type of Rearing Unit (Plug-flow versus Circulating)
2. Minimum/Maximum Size and Number of Rearing Units
3. Indoors/Outdoors (Biosecurity;Predation)

VI. Consider the Fish Culturist (Worker)

1. Pleasant work environment (light, noise, smell, breakroom, temp., etc.)

2. Manageability

   a) Feed handling (storage, moving, feeders, etc.)

   b) Fish handling (sorting, harvesting, treating, etc.)

   c) Sanitation (hosing, floor drains, wash basins, etc.)

   d) Rearing tank management (depth, diameter, equipment, etc.)

   e) Overall equipment need (identify needs)

3.   Laboratory space (equipment)
4.   Storage; garages, workshop

VII. **Visitor/Educational**

1.   Public Fish Hatcheries
2.   Visitor Control
3.   Public Relations

Many details, components, to designing a "complete" aquaculture facility. This workshop's focus is on production capacity and rearing space requirements, and uses a step-by-step process to derive at a rational design.

The Process (An Exercise)

The Most Significant Concept:

Flow-Space-Operational Mode Relationship

$$Ld = (D \times 0.06)/R; \quad D = (Ld \times R)/0.06; \quad R = (D \times 0.06)/Ld$$

The Exercise (Process)

Assumption I

Water: 10,000 lpm (2642 gpm)

Temp. Constant: $14°C$ ($57°F$)

pH 7.6 ($\%UA = 1.0$)

Alk. 200 mg ($CaCO_3$)

No Fish: S.P.F NO:N_2 Supersaturation

$DO = 10.0$ mg/l

Production: Rainbow Trout

$$W_1 = 1.25g \quad L_1 = 5.0cm \quad (k = 0.010)$$
$$W_H = 500g \quad L_H = 34.6cm \quad (k = 0.012)$$

Phase I (Indoors):

1. $1.25g - 34.0g \quad (5.0 - 15cm)$
2. $TUG = 0.0055cm$
3. $\triangle\, L = 0.077cm \quad (14^{\circ}C)$
4. $FC = 1.0$
5. $MD = 60\ kg/m^3 \quad (3.75lb/ft^3)$

Rearing Cycle Phase I:

$$(15cm - 5cm)/0.077cm = 130d$$

Phase II (Outdoors):

1. 34g —— 500g   k = 0.012
2. 15cm —— 34.6cm   TUG = 0.005cm
3. $\triangle$ L = 0.070cm
4. FC = 1.2
5. MD = 96kg/m³   (6 lb/ft³)

Note: 1.0 lb/ft³ = 16 kg/m³

Rearing Cycle Phase II: (34.6 – 15)/0.070 = 280d

Complete RC: 130 + 280 = **410d**   (RC = 410)

Program Specifics:

1. New Batch Enters March 1
2. Move Outdoors July 10 (3/1 + 130d)
3. Harvest April 16 (7/10 + 280d)
*4. 4/17 – 7/9 No Phase II Fish (81d)
5. Phase I + II Overlap 45d (410 – 365)

Note: *Facility is Used Inefficiently.

Discussion: Batch versus Sequential

Selected Parameters/Values

1. $OF = 250g$

2. $TANF = 30g$

3. $TANC/AO = 0.1 \, mg/1$

4. $MUA = 0.025 \quad (\%UA = 1.0)$

5. $MD \quad Phase \, I = 60 \, kg/m^3$

6. $MD \quad Phase \, II = 96 \, kg/m^3$

7. $\%BW = (2 \times {}^{\circ}C)/(W/k)^{1/3} \quad 2 \times 14^{\circ} = 28$
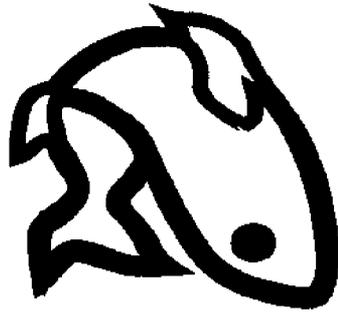
Values Derived From Previous "Choices"

1. $MAO = 25$ $\left(\dfrac{MUA \times 1000}{\%UA}\right)$

2. $\%BW$ End Phase I $= 1.87\%$ $\left(\dfrac{2 \times 14}{15}\right)$

3. MLd End Phase I $= 5.38$ kg/lpm $\left(\dfrac{MAO \times 100}{OF \times \%BW}\right)$

4. $\%BW$ End Phase II $= 0.81\%$ $\left(\dfrac{2 \times 14}{34.6}\right)$

5. MLd End Phase II $= 12.3$ kg/lpm

6. Phase I W to Ld $= 34$ to $5.4 = 6.3$ to 1.0

7. Phase II W to Ld $= 500$ to $12.3 = 40.6$ to 1.0

8. Phase I to Phase II Ratio's: 6.3 to 40.6

   1.0 to 6.4

9. Ratio 1.0 to 6.4 Are Maximum Flow Rate
   Ratio's for Phase I to Phase II (MQ – I to
   MQ – II)

10. $MQ - I = 1351 \ lpm$ $= \dfrac{\underset{(Total \ Q)}{TQ}}{Sum \ Ratios} = \dfrac{10,000}{1.0 + 6.4}$

11. $MQ - II - 10,000 - 1351 = 8649 \ lpm$

12. $MBM - I = 7268 \ kg$ $(MQ \times MLd)$

13. $MBM - II = 106,383 \ kg$ (8649×12.3)

   (1351×5.4)

14. # Fish – I = 213,765 $\left(\dfrac{MBM \times 1000}{Wg}\right)$

15. # Fish – II = 212,765 $\left(\dfrac{MBM \times 1000}{Wg}\right)$

16. RV – I = 121 m³ $\left(\dfrac{MBM}{MD}\right)$

17. RV – II = 1108 m³

Rearing Volume Relative To
Rearing Unit Design and Operation

Recall:

$$Ld = \frac{D \times 0.06}{R} \qquad D = \frac{Ld \times R}{0.06} \qquad R = \frac{D \times 0.06}{Ld}$$

1. R – Values (exchange rate)

Phase I $= 0.67$

Phase II $= 0.47$

From: $\quad R = \dfrac{Q \times 0.06}{RV}$

$Q =$ flow rate

$RV =$ rearing volume

Note: These flow rates must deliver a MAO of 25

$$DO_{in} = 25 + 6 = 31 \text{ mg/l}$$

Recall: MLd – I = 5.38   MD – 1 = 60

$$R = \frac{60 \times 0.06}{5.38} = 0.67 \quad \text{(Balance)}$$

MLd – II = 12.3   MD – II = 96

$$R = \frac{96 \times 0.06}{12.3} = 0.47 \quad \text{(Balance)}$$

2. Above value for $DO_{in\_}$ too high. (31 mg/l)

Next: Select Rearing Unit Type

A. Plugflow (Raceway)
Criteria:

1. $v - I = \geq 2.0$ cm/s

2. $v - II = \geq 3.0$ cm/s

3. $DO_{in} = 11.0 \ (AO = 5)$

4. L to W Ratio $= \geq 10$ to 1.0

Design Formula:

$$W = \sqrt{\dfrac{RV}{10 \times d}}$$

$RV = L \times W \times d$

$L = 10W$

$RV = 10W \times W \times d$

$RV = 10W^2 \times d$

$W = \sqrt{\dfrac{RV}{10 \times d}}$

RV – I = 24.3 m³
(per raceway)

5 – Pass Series From

$$\frac{MAO}{AO} = \frac{25}{5} = 5$$

Select d = 0.8 m (2.6')

Raceway: $L \times W \times d = 17.4\ m \times 1.74\ m \times 0.8\ m$

From: $W = \sqrt{\dfrac{24.3}{10 \times 0.8}} = \underline{1.74}$

v = 1.62 cm/s
(needs 2.0 cm/s or more)

(Does not meet criterium.)

$$v = \frac{(L \times R)}{36} = \frac{17.4 \times 3.35}{36} = \underline{1.62}$$

$$R = \frac{Q \times 0.06}{RV} = \frac{1351 \times 0.06}{24.3} = 3.35$$

$v = 1.62$ Must be minimum 2.0

1. **Either Increase L or R**

$$\left[v = \frac{L \times R}{36} \right.$$

Can't change RV (D = 60), Can't change Q (Ld), Can't change R (These 3 must balance.)

2. Change L to 21.49 m (**NO** changing **RV!**)

$$L = \frac{v \times 36}{R} = \frac{2 \times 36}{3.35} = 21.49$$

The New Width: **1.41 m**

$$W = \frac{RV}{L \times d} = \frac{24.3}{21.49 \times 0.8} = 1.41 \text{ m}$$

L to W Ratio: **15.35 to 1.0**

Linear distance of 4 sides is greater.

Increase from **38.2 m** to **45.7 m** (1.2 $\times$)

Higher cost but Good Hydraulics – Channel Shape.

$$RV - II = 221.6 \ m^3 \quad (1108/5)$$

$$W = \sqrt{\frac{221.6}{10 \times 0.8}} = 5.26$$

$$\boxed{L \text{ to } W \text{ to } d = 52.6 \times 5.26 \times 0.8}$$

$$\boxed{R = \frac{Q \times 0.06}{RV} = \frac{8649 \times 0.06}{221.6} = \underline{2.34}}$$

$$\boxed{v = \frac{L \times R}{36} = \frac{52.6 \times 2.34}{36} = 3.4 \ cm/s}$$

Meets velocity criterium of 3.0 cm/s or more.
Good Hydraulics. Not Self-Cleaning.

V -19

B. **Circular Units**

Criteria: R Values: 1.5 – 2.5

DIA: 9 m or Less (Up to 30')

DO Super Sat. Up to 150%

(Sat. DO = 11.0 mg/1 – 150% = 16.5 mg/1)

d = 1.5 m (Approximate)

Velocity Independent of Flow Rate

Intake – Outlet Design – Self-Cleaning

Design:

1. Three-Pass Serial   AO = 8.3 (25/3)

    $DO_{in} = 14.3$ %SAT = $\pm$ 135

Phase I: RV = 40.3 m^3 (121/3)

$$DIA = 2\sqrt{\dfrac{RV}{\pi \times d}} = \underline{5.85\ \boldsymbol{m}}\ (19')$$

For d = 1.5

R = 2.0 $\left(\dfrac{1351 \times 0.06}{40.3} = 2.0 \right)$

Six Units: DIA = 4.1 m (13.5')
Must Split The Flow. R the Same!

Phase II: RV = 369.3 m^3 (1108/3)

For d = 1.5   DIA = 17.9 m   (58')

Too Large Diameter

For Six Units:

DIA = 12.5 m (41')   Still Too Large!

Desire to Keep Depth at 1.5 m.

Options:

   a) 12 Units   4 × 3 (AO = 8.3)

   b) 12 Units   3 × 4 (AO = 6.25)

DIA = 8.85 m (29')   Acceptable

   Other Options?   Other Ideas?

Different Approaches (Techniques/Programs)

1. Partial Recirculation (Unit VI)

2. Sequential Rearing (Unit VIII)

Introduction to Sequential Rearing

1.25 g – 500 g Batch Culture – Once-A-Year

Practiced in "Conservation" Hatcheries.

Inefficient Facility Use.

The described facility can "Process" a maximum of 1000 kg feed per day.

$$MF/d = \frac{(MAO \times Q_T)}{OF} = \frac{25 \times 10{,}000}{250} = 1000 kg/d$$

Feed 1000 kg/d   FC = 12.5   FE = 80%

Daily gain in fish flesh: 800 kg

365 d/yr x 800 kg = 292,000 kg/yr.

Must remove the daily gain daily.

Not practical – But.... how close can we come to

1000 kg feed per day every day of the year.

Requires sequential rearing strategy- new cohort

(Batch, Group) enters the facility frequently –

How many times?   What is practical, manageable?

What are the facility requirements?

Will Discuss in Unit 8.

PRODUCTION CAPACITY OF AQUACULTURE SYSTEMS
(INCLUDING RECYCLE SYSTEMS)

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There are several ways to express and determine production capacities of aquaculture systems. This has caused some confusion relative to terminology. For instance, the term "loading density" is an example of a poorly selected expression for production or carrying capacity. This will become clear in the discussion to follow.

Production capacity or capability can be expressed in four ways. They are all valid and integrate with each other.

1. **Production expressed as maximum weight of fish per unit of flow.**
   For this I recommend the term <u>LOADING</u> (Ld) either as kg/lpm or lbs/gpm.

2. **Production expressed as maximum weight of fish per unit of rearing space.**
   For this I recommend the term <u>DENSITY</u> (D) either as kg/m^3 or lbs/ft^3

3. **Production expressed as maximum carrying capacity.**
   This is the one time maximum biomass a facility can support (MBM), either in kg or lbs.

4. **Production expressed as maximum annual output.**
   This is the maximum annual production a facility can deliver (AP), either as kg or lbs.

LOADING (Ld)

Production in terms of weight per unit of flow should be designated <u>LOADING</u> (Ld) and is expressed either as kg fish per lpm (kg/lpm) or as lbs per gpm (lbs/gpm). The maximum allowable loading that can be realized depends on many factors, the most important ones are:

a) Species and its weight.

b) Fish size

c) Source water quality characteristics - of special importance are dissolved oxygen; temperature; pH and alkalinity.

d) Tolerance towards metabolic waste product build-up in the rearing water - of special importance are ammonia nitrogen; carbon dioxide; and particulate and dissolved solids.

Because feed is responsible for all water quality changes, production capability can be related to feed can be added to the system. How much feed can be added (fed) per unit of flow depends on how much oxygen it requires and how much ammonia, carbon dioxide and solid waste it generates and at what point these components impact the quality of the rearing water to such an extent that it is no longer acceptable for the species reared.

Dissolved Oxygen

The amount of oxygen a unit of feed requires is relatively constant for a particular species and independent of fish size and water temperature. For many species this seems to range from 200 to 280 g per kg feed (*91 to 127 g per lb*).

In the examples presented 250 g/kg (*114 g/lb*) will be used, and designate O_F, thus $O_F = 250$ or $O_F = 114$ for English equivalents. The loading equations for feed per unit of flow (Ld_F) are:

$$\mathbf{Ld_F = AO/O_F} \quad \text{and} \quad \mathit{3.8\, AO/O_F} \tag{1}$$

AO is available oxygen for the fish. This is the difference between the incoming dissolved oxygen concentration (DO_{IN}) and the minimum allowable effluent concentration (DO_{OUT}).

$$\mathbf{AO = DO_{IN} - DO_{OUT}}$$

One lpm @ 1.0 mg/l delivers 1440 mg per day or 1.44 g, because there are 1440 minutes in a day (60 x 24). If a 16.7 hour day is used instead of a 24 hour day, 1.0 lpm @ 1.0 mg/l delivers 1002 mg or 1.0 g per "day". This I consider a feeding day, a period of greatest activity. The result is a more conservative approach because, instead of 1.44 g oxygen, only 1.0 g is considered available. In above equations, AO represents one, from 1.0 mg/l DO available, per gpm (3.785 l) this is 3.8. For values O_F is 250 (*114*), the following amounts of feed can be fed per lpm (gpm) per one AO:

$$\mathbf{Ld_F = 1.0/250 = 0.004 \ kg/lpm} \tag{2}$$

and

$$\mathit{Ld_F = 3.8/114 = 0.033 \ lbs/gpm} \tag{3}$$

Note: 1.0 kg/ lpm equates to 8.3 lbs/gpm.

To convert the "feed loading" equation to a fish loading equation we must know how much feed the fish require. Most often this is expressed as percent body weight (%BW). If they require 1.0% BW, than the loading for fish is 100 times the loading for feed.

The loading equation for fish is:

$$\mathbf{Ld = (AO/O_F) \ x \ (100/\%BW)} \tag{4}$$

$$\mathit{Ld = (3.8\, AO \, / \, O_F) \, x \, (100/\%BW)} \tag{5}$$

For one AO and one %BW the values are 0.4 kg/lpm and *3.3 lbs/gpm.*

How much oxygen can be made available before metabolic waste build-up makes the rearing water unsuitable?

Only ammonia build-up will be considered. First of all this waste component is usually the first limiting factor (after oxygen) and secondly, design and operational modes should allow for managing, i.e. removal, of carbon dioxide and solids.

Unless recycle technology is used, ammonia build-up becomes the limiting factor. In recycle technology it may be suspended/dissolved solids or nitrates. This will be discussed shortly.

Ammonia is primarily toxic in the un-ionized form (NH_3). Fish excrete NH_3 which reacts with the water to form NH^+_4 ions. Not all of the NH_3 becomes NH^+_4, the less toxic form, but, fortunately in most culture waters by far the largest percentage changes to the ammonium ion. The two forms together are known as total ammonia nitrogen (TAN) and all ammonia is measured as TAN. In most culture water the un-ionized portion of TAN ranges from 0.2 to 3.0 percent, it is pH and temperature dependent.

The amount of TAN generated per kg feed (TAN_F) depends on the protein content, on diet composition, i.e. protein - energy ratio and species of fish. Generally it ranges from 25 to 30 g per kg feed (*11 to 16 g per lb*).

In the following examples, 30 g TAN per kg feed will be assumed (*13.6 g/lb*).

Equation 2 shows that per one AO and O_F of 250, 0.004 kg feed can be fed per lpm. This, at TAN_F = 30, generates 0.12 g of TAN (*English equation 3; .033 x 13.5 g is 0.45 g TAN*).

In both cases, the concentration of TAN is 0.12 mg/l (0.12/1.0 and .45/3.8). Again, this is based on a "feeding day" of 16.7 hours. Peak TAN production occurs about 4 hours after feeding.

The equation for TAN as mg/l (TAN_C) is:

$$TAN_C = (AO/O_F) \times TAN_F / 1.0 \tag{6}$$

$$TAN_C = (3.8\, AO/O_F) \times TAN_F / 3.8 \tag{7}$$

Simplified:

$$TAN_C = (TAN_F) / (O_F) \tag{8}$$

For metric:

$$TAN_C = (30) / (250) = 0.12 \text{ mg/l} \tag{9}$$

For English:

$$TAN_C = (13.6) / (114) = 0.119 \text{ mg/l} \tag{10}$$

Recall, this is per one AO. These values must be multiplied by the AO values. Thus the equations should be:

$$TAN_C = (AO \times TAN_F) / (O_F) \tag{11}$$

The concentration of un-ionized ammonia (UA_C) is the concentration of TAN times the percent un-ionized ammonia divided by 100.

3

$$UA_C = [(AO \times TAN_F) / (O_F)] \times [(\%UA) / 100] \quad (12)$$

Simplified:

$$UA_C = (AO \times TAN_F \times \%UA) / (100 \times O_F) \quad (13)$$

For our examples UA is 1.0% (and AO = 1.0)

$$UA_C = (1.0 \times 30 \times 1.0) / (100 \times 250) = 0.0012 \text{ mg/l} \quad (14)$$

$$UA_C = (1.0 \times 13.6 \times 1.0) / (100 \times 114) = 0.00119 \quad (15)$$

Finally it is necessary to decide the maximum concentration of un-ionized ammonia acceptable for the fish (the particular species). This is designated as AUA.

For our example, a concentration of 0.02 mg/l will be used (AUA = 0.02).

It was shown that, per one AO, and the values used in the examples, the UA_c is 0.0012. For an AO value of 2.0 this concentration would be 0.0024 (2 x 0.0012) etc.

Therefore the maximum oxygen that can be made available (MAO) is 16.7 mg/l (0.02/0.0012).

$$\textbf{MOA} = \underline{\textbf{(AUA)}} / \textbf{(UA}_c\textbf{)}$$

Recall that it is based on a one percent un-ionized ammonia value (%UA = 1.0). Should this value be 0.5%, twice as much oxygen can be made available, at 2.0% only half the amount.

The loading for AO of 16.7 and at 1.0% BW, is:

$$\textbf{Ld} = \textbf{(16.7 x 100)} / \textbf{(250 x 1.0)} \quad \textbf{or} \quad \textbf{6.6 kg/lpm} \quad (16)$$

and

$$Ld = (3.8 \times 16.7 \times 100) / (114 \times 1.0) \quad or \quad 55.6 \text{ lbs/gpm} \quad (17)$$

For recycle systems

In recycle systems the ammonia nitrogen is converted, via nitrite nitrogen (NO_2) to nitrate nitrogen (NO_3) by nitrifying bacteria (biofilters).

At steady state the daily removal rate of ammonia (TAN) has to be equal to the input.

The concentration of TAN, at steady state, must be in balance with the allowable un-ionized ammonia (AUA) concentration.

$$\textbf{TAN}_c = \textbf{(AUA x 100)} / \textbf{(\%UA)} \quad (18)$$

As TAN is converted to NO_3, nitrates continue to accumulate in the rearing environment, eventually reaching the allowable nitrate concentration (ANO_3). Once this has been reached, any daily addition must be removed. This is accomplished by flushing it out of the system with the proper volume of water, which must then be replaced with new make-up water.

For instance, at a loading of 1.0 kg/lpm and a feeding level of 1.0% BW, 0.01 kg feed is introduced per day, generating 0.3 g of TAN per day (0.01 x 30 g).

Stoichiometrically, one gram of TAN equals 4.2 g of NO_3, therefore 0.3 g of TAN generates 1.26 g of NO_3.

If the maximum allowable concentration of NO_3 can be 200 mg/l (ANO_3 = 200), then, once this concentration is reached at steady state, any daily input of NO_3 must be removed. For the above example, this is 1.26 g. One liter of 200 mg/l NO_3 contains 200 mg NO_3 or 0.2 g. If 1.26 g must be removed, then we must remove 6.3 l of water having a concentration of 200 mg/l NO_3. This represents a certain percentage of the rearing volume. Per one exchange per hour (R = 1), one lpm exchanges 60 l per hour, a rearing volume of 60 l (RV = 60 or 0.06 m³). Sixty liter @ 200 mg/l NO_3 represents 12,000 mg NO_3 or 12.0 g. To this is added 1.26 g or NO_3 per day and this represents 10.5 percent of the 12.0 g (10.5% of the RV). To maintain steady state at 200 mg/l, 10.5% of the rearing volume must be removed daily and replaced with make-up water. This makes the recycle system 89.0 percent efficient.

The daily percent rearing volume (% RV) replacement can be determined with this equation:

$$\% \ RV = (Ld \ x \ \%BW \ x \ TAN_F \ x \ 4.2 \ x \ R \ x \ 100) \ / \ (6 \ x \ ANO_3) \qquad (19)$$

and:

$$\% \ RV = (Ld \ x \ \%BW \ x \ TAN_F \ x \ 4.2 \ x \ R \ x \ 100) \ / \ (22.7 \ x \ ANO_3) \qquad (20)$$

In this latter equation 22.7 is from 6 x 3.785 (one gallon equals 3.785 l).

For example, for a maximum loading of 1.5 kg/lpm, a feeding level of 1.0 percent, TAN_F is 30, R is 2.5 and ANO_3 is 500, the percent daily replacement is 15.7%!

The above equations can be converted to loading equations.

$$Ld = (\%RV \ x \ 6 \ x \ ANO_3) \ / \ (\%BW \ x \ TAN_F \ x \ 4.2 \ x \ R \ x \ 100) \qquad (21)$$

and:

$$Ld = (\%RV \ x \ 22.7 \ x \ ANO_3) \ / \ (\%BW \ x \ TAN_F \ x \ 4.2 \ x \ R \ x \ 100) \qquad (22)$$

For instance if I want the recycle system to be 80% efficient (20% RV); ANO_3 at 250; an exchange rate of 3.0 and the required feeding rate is 1.5 percent (%BW = 1.5), the maximum loading is:

$$Ld = (20 \ x \ 60 \ x \ 250) \ / \ (1.5 \ x \ 30 \ x \ 4.2 \ x \ 3.0 \ x \ 1000) = 0.53 \ kg/lpm$$

The next expression for carrying capacity is related to rearing volume requirements.

DENSITY (D)

Carrying capacity, as it relates to rearing space, is expressed as kg fish per cubic meter rearing volume or as pounds per cubic foot.

The maximum allowable, or safe, rearing density depends on many factors, but the species and its size, are the primary ones. Determining the optimum density is still a rather subjective decision driven by personal convictions and/or experiences, traditions and/or reports in the literature. Even the terminology of "low" and "high" rearing density is an uncertain one, because what someone might consider a low density someone else may consider high.

To bring some uniformity into this rather arbitrary situation the use of a density index (DI) has been proposed. This index relates the length of the fish directly proportional to an allowable, or optimum, rearing density. The longer the fish, the greater the density it can tolerate, thus the DI multiplied with the length of the fish provides the density.

For metric equivalents, a density index of 3.2 means that a 10 cm fish can be reared at a density of 32 kg/m³. For English equivalents the DI is 0.5, thus a 4" fish (10 cm) can be reared at 2 lbs/ft³. One pound per cubic foot equates with 16 kg per cubic meter.

The more commonly used DI's are shown in table 1.

Table 1. Commonly used density indices are those listed in the midrange. The low and high ranges are the conservative and extreme values. Values in parentheses represent the number of fish based on a condition factor of 0.01.

Metric (kg/m³ ; #/m³) Length in cm					English (lbs/ft³ ; #/ft³) Length in inches				
DI	10	15	20	30	DI	4	6	8	12
1.6	16 (1600)	24 (711)	32 (400)	48 (178)	.25	1.0	1.5	2.0	3.0
3.2	32 (3200)	48 (1422)	64 (800)	96 (356)	.50	2.0	3.0	4.0	6.0
4.8	48 (4800)	72 (2133)	96 (1200)	144 (534)	.75	3.0	4.5	6.0	9.0
6.4	64 (6400)	96 (2844)	128 (1600)	192 (712)	1.00	4.0	6.0	8.0	12.0

The ratio's of weights are: 1.0 to 1.5 to 2.0 to 3.0
Versus those of numbers: 1.0 to 0.44 to 0.25 to 0.11

Low rearing densities require much rearing space (expensive) and often this results in low water turnover rates, low R values.

Ideally there should be a balance between loading, density and exchange rates. This balance is expressed with these equations:

$$Ld = (D \times .06) / R \quad \text{and} \quad D = (Ld \times R) / .06 \quad \text{and} \quad R = (D \times .06) / Ld \qquad (23)$$
and:
$$Ld = (D \times 8) / R \quad \text{and} \quad D = (Ld \times R) / 8 \quad \text{and} \quad R = (D \times 8) / Ld \qquad (24)$$

where 0.06 represents m^3 from 1.0 lpm x 60 min = 0.06 m^3 and 8 represents ft^3 from 1.0 gpm x 60 min = 60 gal. = 8 ft^3.

Loading can be determined rationally (see equations 4 and 5).

The selection of density is subjective, but a choice must be made. Once this is accomplished, the exchange rate (R) follows.

Equations 19 and 21 are used to determine the efficiency of a recycle system based on a number of parameters, including a maximum allowable rearing environment concentration of nitrate (ANO_3).

Both equations include loading and exchange rate, and, once these have been determined, the rearing density is fixed (equations 23 and 24).

It now becomes a matter of selecting the best values for loading and exchange rates (density) to accomplish an acceptable recycle system efficiency.

For flow-through systems design driving forces also include loading and exchange rates (density) which may include the need for serial reuse design to efficiently balance loadings, densities and exchange rates according to equations 23 and 24.

The third and forth way to express production capability is by means of determining the maximum biomass a system can support (MBM) and how this relates to a maximum annual production capability (AP).

MAXIMUM ONE-TIME, BIOMASS (MBM)

The maximum biomass a system can support is expressed in kg or lbs. Once this biomass has been reached fish must be removed at the daily rate of weight gain. A facility is used most efficiently if it can maintain this maximum biomass continuously by daily harvesting the addition of weight. For instance, if the maximum biomass is 1000 kg and the daily feed level is one percent, 10 kg of feed is added daily. For a feed efficiency of 70 percent (feed conversion of 1.4), the daily gain in fish weight is 7.0 kg. If this was possible to do throughout a year (365 d) the annual output would be 2555 kg, which is 2.55 times the maximum biomass of 1000 kg.

PRAS Pilot Study - 10% and 20% Flow Replacement

distribution
aeration of new
water
(was zeolite unit in RAS)

Recirculated (96 - 104 lpm)
(aeration/degassing)

aerated new water 12-24 lpm

10 or 20% new

new

12 - 24 lpm

discharge

Settling tank 1.0 m^3

120 lpm (recirc. + new)

Rearing unit 1.3 m^3

12 - 224 lpm

96 - 104 lpm

48 - 54 lpm

Rearing unit 1.3 m^3

6 - 12 lpm

Rearing unit 1.3 m^3
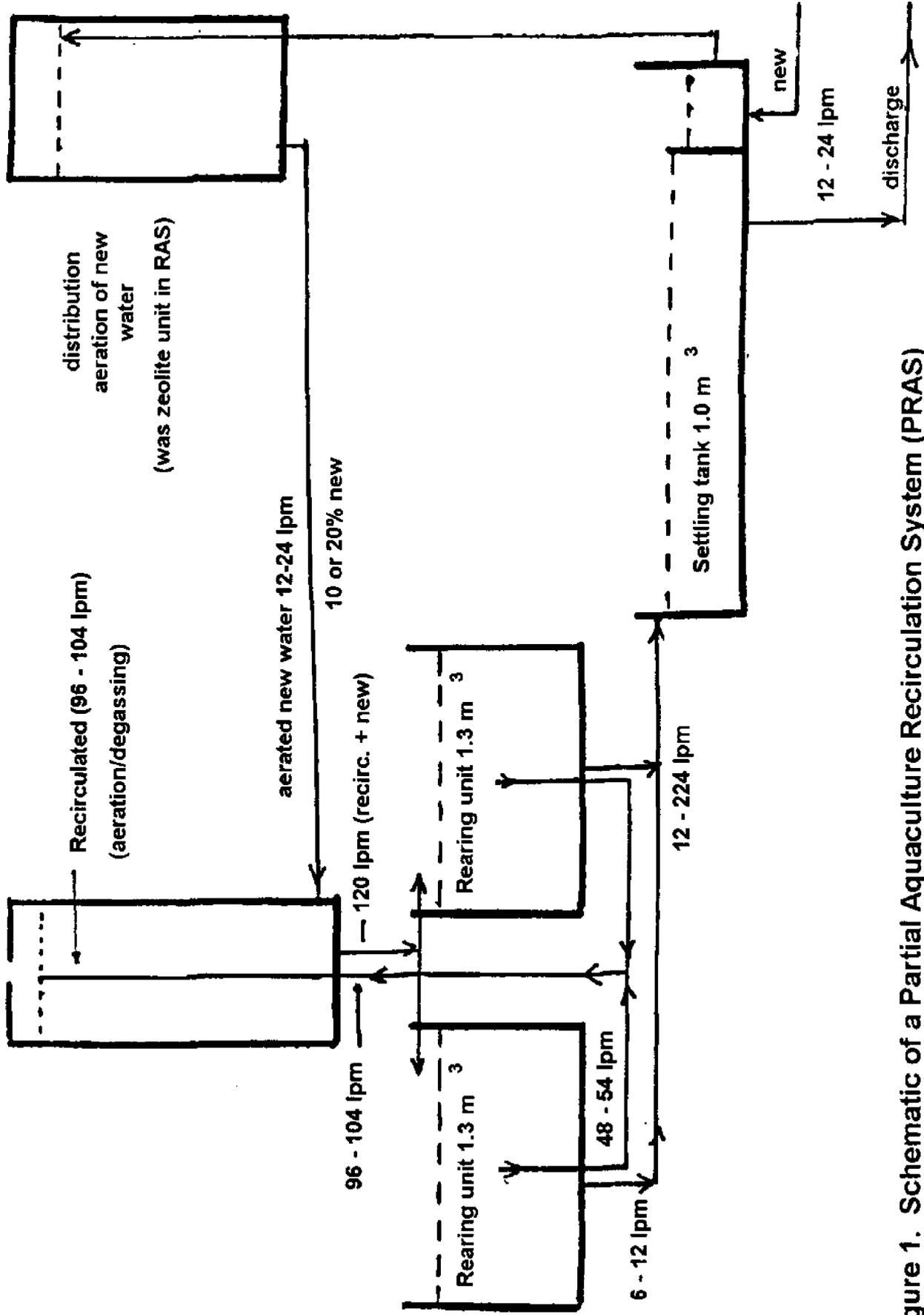
Figure 1. Schematic of a Partial Aquaculture Recirculation System (PRAS)

Recirculation Aquaculture Systems (PRAS & RAS)

Partial RAS

1. Reduced water requirements
2. Less discharge (Less in)
3. Increased biosecurity
4. No biofiltration

NH_3 controlled thru dilution

NH_3 control through pH (and Na^+?)

Full RAS

1. Greatly reduced water needs
   (Can heat or chill)
2. Biofilter (or ion-exchange) required
3. Excellent biosecurity
4. Excellent waste control
5. Independent of climate (indoors)

PRAS Efficiency

Assume: **85% Efficient**

This Means: 15% of Total Flow Rate Replaced

For Example: RV = 100 m³ (3530 ft³)

Exchange Rate: 2 (R = 2)

Q = 3333 lpm (880 gpm) $\xrightarrow{\text{From:}} \dfrac{RV}{0.06} \times R \quad \dfrac{100}{0.06} \times 2$ $\dfrac{100}{0.06}$

15% = 500 lpm (132 gpm)

RAS Efficiency

85% Efficient

This Means:
    15% of total system
    volume replaced per day

Total System Volume: 100 m^3 (3530 ft^3)

    $15\% = 15\text{m}^3$ (530 ft^3; 3961 gal)

    $15 \text{ m}^3/\text{day} = 15000$ l/d

    $15{,}000$ l/d / $1440 = 10.4$ lpm (2.75 gpm)

    10.4 versus 500 lpm!

Serial Reuse

1. $MAO = 25$

2. 5-Pass $(5.0 + 6.0 = Do_{in} = 11.0)$

3. $Q_t = 4000$ lpm (1057 gpm)

4. MLd @ 1.0%BW = **10 kg/lpm = 40,000 kg**

$$Ld = \frac{100 \text{ AO}}{250}$$

5. $MD = 80$ kg/m^3

6. $RV_t = 40,000/80 = 500$ m^3

7. $RV_{ru} = 500/5 = 100$ m^3 (5-Pass)

8. Plugflow Design: 0.1 ft/s (3.0 cm/s)

9. % Recirc. $100 - \dfrac{100}{5} = 100 - 20 = 80\%$

10. % new: $100 - 80 = 20\%$

11. Dimension: $l = 10w$ or more $w = \sqrt{\dfrac{RV}{10 \times d}}$

   $d = 0.80$ m $w = 3.5$ m $l = 35$ m

12. $R = 2.4$ $\left[\dfrac{Q \times 0.06}{RV}\right] = \dfrac{4000 \times 0.06}{100} = 2.4$

13. $V = \dfrac{l \times R}{36} = \dfrac{35 \times 2.4}{36} = 2.3$ cm/s   Need 3.0 cm/s

14. $l = \dfrac{v \times 36}{R} = \dfrac{3 \times 36}{2.4} = 45$ m

For $RV = 100$ m^3 $w = \dfrac{100}{45 \times 0.8} = 2.8$ m

$Do_{in} = 11.0$
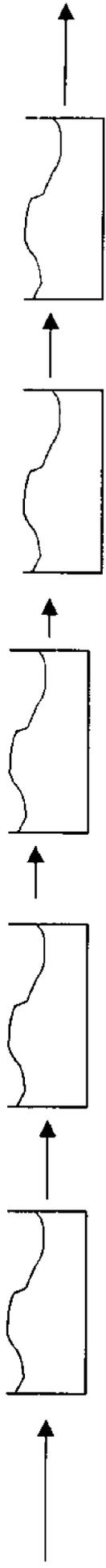
$Q = 4000$

$Do_{out} = 6.0$

Option: Make it a 3-Pass ($AO_{ru} = 25/3 = 8.33$)

1. $Do_{in} = 8.33 + 6.0 = 14.33$

$$RV_t = \frac{500}{3} = 167 \text{ m}^3$$

2. No change in RV_t but RV_{ru}

3. $v = 3.0$ cm/s or more.

4. Dimension RU→W $= \sqrt{\dfrac{RV}{10 \times d}} = \sqrt{\dfrac{167}{8}} = 4.57$ m

$l = 45.7$ m

$$R = \frac{Q \times 0.06}{RV} = \frac{4000 \times 0.06}{167} = 1.437 \ (1.44)$$

5.

$$v = \frac{45.7 \times 1.44}{36} = 1.8 \text{ cm/s}$$

$$1 = \frac{v \times 36}{R} = \frac{3 \times 36}{1.44} = 75 \text{ m } (w = 2.78 \text{ m})$$

$$1 : w \text{ ratio} = 27 \text{ to } 1.0 \quad \text{(expensive)}$$

Exercise: 3-Pass to PRAS

1. $RV_t = 500 \text{ m}^3$

2. $MD = 80 \text{ kg/m}^3$

3. $MBM = 40,000 \text{ kg } (80 \times 500)$

4. $MLd = 10 \text{ kg/lpm } (1.0\% BW)$ $MQ = 40,000/10$
    $= 4000 \text{ lpm}$

5. $MAO = 25 \text{ mg/l}$

6. %Reuse: 66% = 2640 lpm

7. %New: 33% = 1360 lpm   Out

8. MFd/d: 1% of 40,000 kg = 400 kg

9. MTAN/d: 30 g/kg = 12,000g (TANF = 30)

10. $MTANC = \dfrac{TANC}{MQ \times 1.44} = \dfrac{12{,}000}{4000 \times 1.44g} = 2.08\ mg/l$

11. $Do_{in} = 25/3 + 6.0 = 8.33 + 6.0 = 14.33\ mg/l$ 12.

    MUA = 0.025 mg/l %UA =1.0 MTAN =2.5mg/l   13.

    Each 1.0 mg/l AO used generates 0.1 mg/l TAN,

    therefore: MAO = 25 results in 2.5 mg/l TAN.   14.

    $RV_{ru} = 500/3 = 167\ m^3$

15. Circular design - DIA $= 2\sqrt{\dfrac{RV}{\| \times d}}$

For d = 15 DIA = 11.89 m   (39')

16. Q_t = 4000 lpm (represents "new" water) = 33%

17. Q_{rec} = 66% = 8000 lpm

18. Q_{ru} = 4000 lpm

19. $R = \dfrac{4000 \times 0.06}{RV} = \dfrac{240}{167} = 1.44$

20. Ld, D, R relationship: $Ld = \dfrac{D \times 0.06}{1.44} = \dfrac{80 \times 0.06}{1.44}$
$= 3.3$ kg/lpm

21. $Ld = \dfrac{8.33 \times 100}{250} = \dfrac{833}{250 \,(\times 1.0\%BW)} = 3.33$ kg/lpm
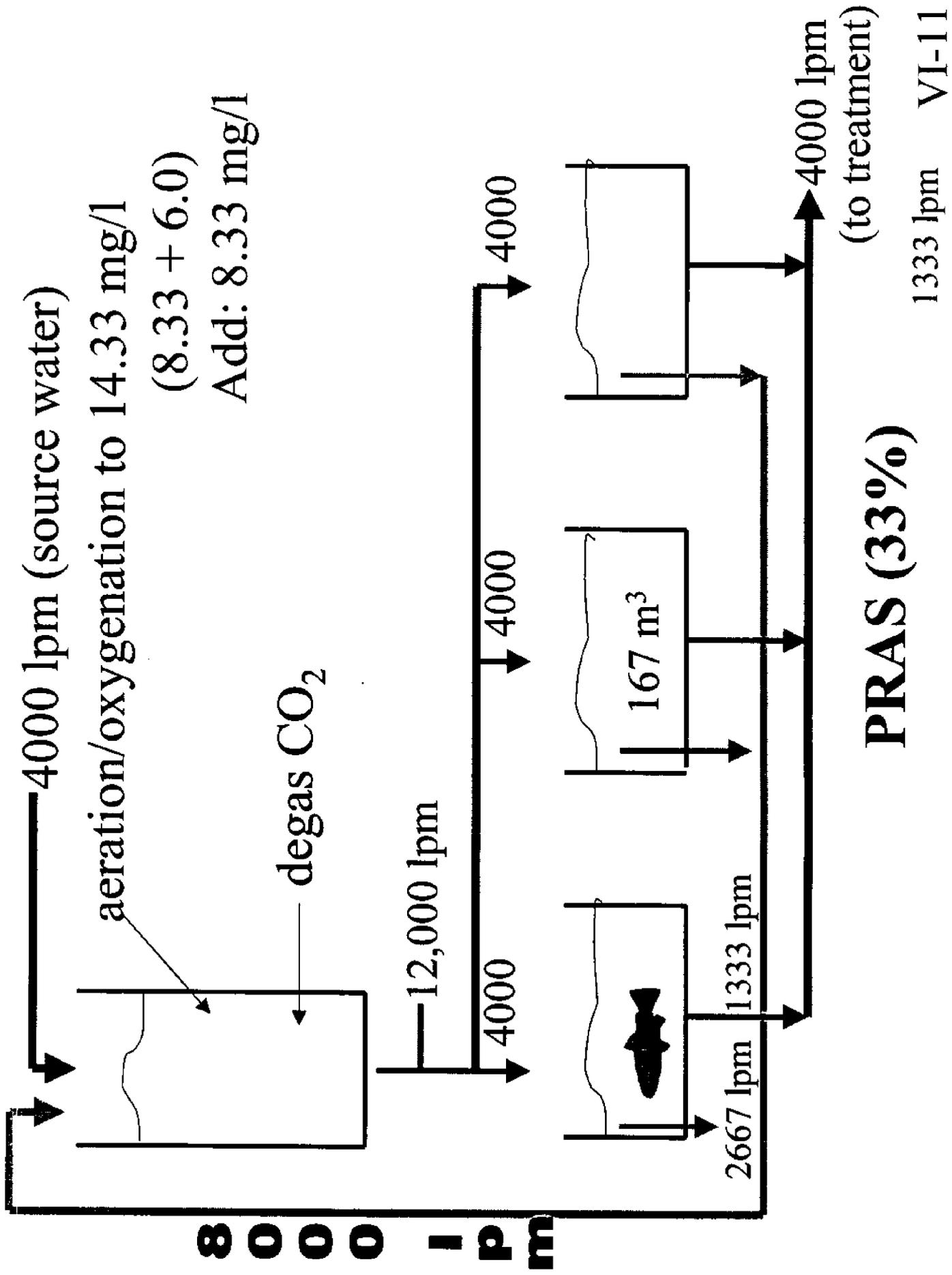
4000 lpm (source water)

aeration/oxygenation to 14.33 mg/1

(8.33 + 6.0)

Add: 8.33 mg/1

degas CO_2

12,000 lpm

4000

4000

4000

167 m^3

2667 lpm

1333 lpm

1333 lpm

4000 lpm

(to treatment)

1333 lpm   VI-11

PRAS (33%)

8000 lpm

Design & Production

PRAS: Basically a variant of serial use.

    Example: 8-Pass (87.5% Recirc.)

        12.5% new water

Figure 1 Schematic flow diagram

1. $RV_{ru} = 63 \text{ m}^3 \ (2224 \text{ ft}^3)$

2. $R = 4 \, Q_{ru} = 4 \times \dfrac{63}{0.06} = 4200 \text{ lpm } (1110 \text{ gpm})$

3. New H_2O – 4200 lpm

4. $Q_T = 8 \times 4200 = 33600 \text{ lpm } (8876 \text{ gpm})$

5. $Q_{re} = 29,400 \text{ lpm } (87.5\% \text{ of } 33,600)$

6. $Q_{new} = 4200 \text{ lpm } (12.5\% \text{ of } 33,600)$

Dual Drain Tank (Fig. 2)

1. Bottom drain: 75-85% ss (15-20 mg/l)

2. Side wall discharge: Tss = 2 to 3 mg/l.

Exercise: 8-Pass to PRAS

$RV_T = 500 \text{ m}^3 \ (17,650 \text{ ft}^3)$

$MD = 100 \ (6.25)$

$MBM = 50,000 \text{ kg} \ (100 \times 500)$

$\%BW = 1.2$

$MFd/d = 600 \text{ kg} \ \dfrac{1.2 \times 50,000}{100}$

$MTAN/d = 18,000 \text{ g} \ (TANF = 30)$

$MTANC = 2.5 \text{ mg/l} \ \dfrac{MUA \times 100}{\%UA} \ (TANF = 30)$

$MUA = 0.025 \quad \%UA = 1.0$

$\%RE = 100 - [(Ld \times \%BW \times TANF)/(1.44 \times MTANC)]$

$\%RE = 100 - [(1.5 \times 1.2 \times 30)/(1.44 \times 2.5) = \mathbf{85\%}$

See Values of Table 3 – Start with MAO = 30

RAS:

$$NH_3 \longrightarrow NO_2 \longrightarrow NO_3$$

How High NO_3? (MNO_3)

Steady state at MNO_3 - NO_3 produced must be removed daily by flushing – and replacement of new water (make-up water)

Assume:

$Ld = 1.0 \text{ kg/lpm}$ $\%BW = 1.0$

Fed: 0.01 kg per lpm per day.

Generate: 0.3 g TAN/lpm/day (0.1×30)

One g TAN = 4.2 NO_3

    0.3 g TAN = 1.26 g NO_3

MNO_3 = 200 mg/1

Once steady state is reached, any daily input must be removed. (1.26g)

One Liter@ 200 mg/1 NO_3 = 0.2 g NO_3

Need to Remove 1.26 g NO_3
    and: 1.26/0.2 = 6.311 1

Remove 6.311 1 @ 200 mg/1 NO_3.

What is this total in terms of percent rearing volume?
          (%RV)

RAS: (cont.)

One exchange per hour 1.0 lpm (R=1) = 60 l/h =

$$0.06 m^3 \ (RV = 0.06)$$

60 l @ 200 mg/1 NO_3 = 12,000 mg NO_3 (12 g)

Add: 1.26 g NO_3 = 10.5% of 12.0 g = 10.5% of RV

Efficiency: 100-10.5% = **89.5%**

$$\%RV = \frac{MLd \times \%BW \times TANF \times 4.2 \times R \times 1000}{60 \times MNO_3}$$

Using Values (PRAS and MNO_3 = 500)

$$\% \text{ RV} = \frac{(1.5 \times 1.2 \times 30.0 \times 4.2 \times 4 \times 1000)}{60 \times MNO_3 = 500} = \mathbf{30.24\%}$$

RAS Efficiency: 100-30.24 = **69.76%**

The faster the turnover rate (R Value) the greater the need for make-up water

(When biomass (D) is greater, feed input must be greater!)

RAS

Greater R, greater D for same Ld.

$$Ld = (D \times 0.06)/R$$

$$D = (Ld \times R)/0.06$$

$$R = (D \times 0.06)/Ld$$

Greater D (biomass) means more feed, more TAN, and more NO_3!

The 30.24% new water, for a 500 m³ RAS volume represents 151 m³ (151,000 l) or 104 lpm new water.

Unknowns:

Max. NO_3
100-1000 mg/l

Water Conservation in Intensive Aquaculture

1. Aquaculture **uses** water

2. Aquaculture does **not** consume water

3. Aquaculture **modifies water quality**

   a) Effluent must be treated

   b) Small flow cheaper than large flow

   c) Concentrated waste easier to manage than very diluted waste stream

4. High quality water sources, such as **wells** (Artesian), **springs** and **groundwater** are limited – Intensive Aquaculture maximizes output of each unit of water used

Water Conservation In Intensive Aquaculture (cont.)

5. **Surface water (public water)** such as **creeks, streams, rivers, lakes** are generally, not available for private aquaculture

6. **Therefore:** We must make the most of what we have, that is, we must realize the greatest possible production per unit of flow (gpm)

Loading as lbs per gpm

$$Ld = lbs/gpm$$

Four Basic Intensive Production Systems

I. One-Pass Flow-Thru

In $\longrightarrow$ $\boxed{}$ $\longrightarrow$ Out
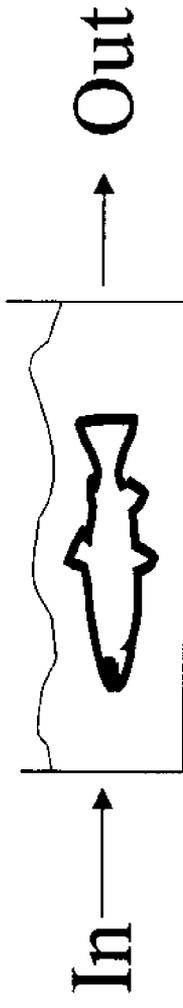
Dissolved Oxygen Limiting

$DO_{in} = 11$ $\longrightarrow$ $\boxed{}$ $\longrightarrow$ $DO_{out} = 6$
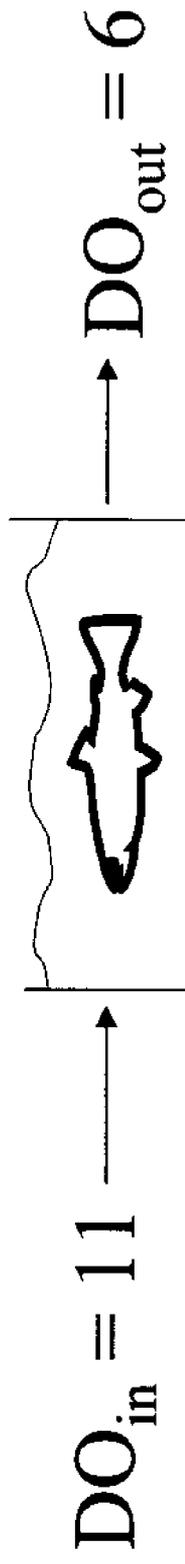
Available DO for Fish to Use is DO_{in} Less DO_{out}

$$AO = 11 - 6 = 5$$

1.0 gpm delivers 4.0 g (0.0088 lbs) of oxygen per 1.0

ppm (1.0 mg/l)

$$\underline{\text{x 17 hrs} = 3.8 \text{ bg}} \text{ (Pick a number!)}$$

$$*1.0\ \textit{gpm} \times 60\ \text{min} \times (18)\ \text{hrs} \times 3.785 \times 1.0\ \text{mg/l} = 4{,}088\text{mg}$$

$$= 4.088\ \text{g} (4.0\ \text{g})$$

The water quality – once through – is most likely still good enough for additional production. All we need to do is aerate or oxygenate it and reuse it.

II Serial Reuse

DO = 11

Add 5 mg/l
DO

AO = 5

AO = 5

Add 5 mg/l
DO

AO = 5

DO = 6
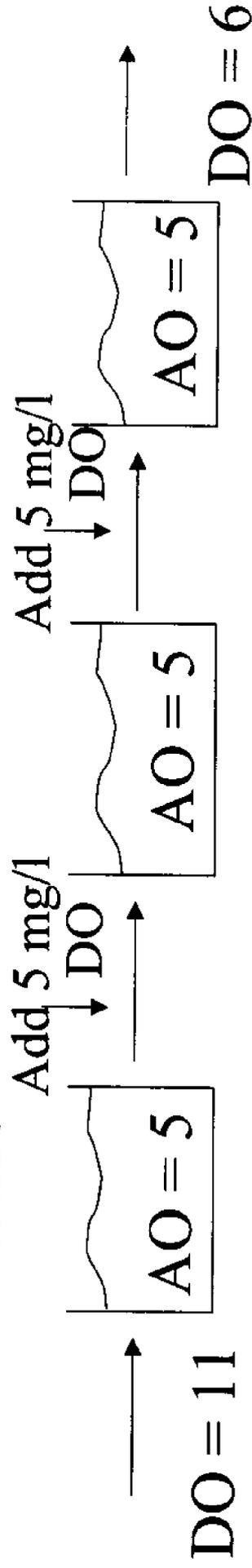
Total or Maximum AO = $3 \times 5 = 15$ mg/l

Triple Production Potential

But what about water quality?
next limiting factor: **Ammonia** (TAN)
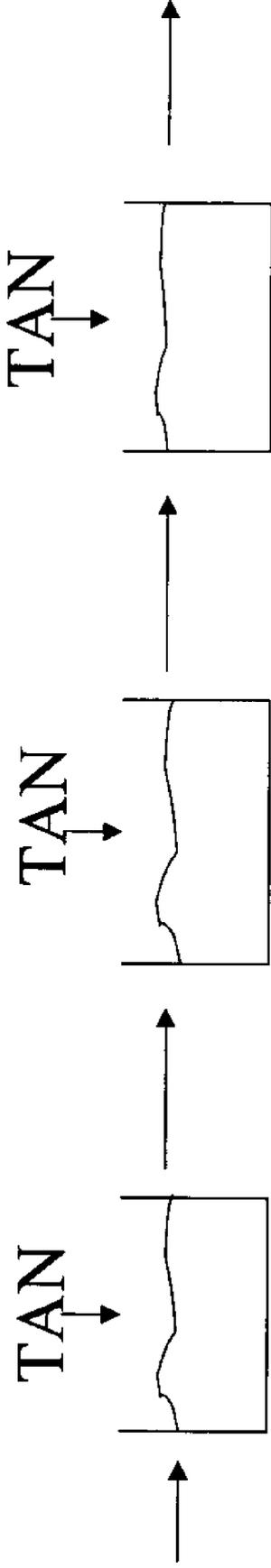
Source of TAN

$NH_3 + NH_4$)

(Total Ammonia Nitrogen as

is the feed

Oxygen required and **carbon dioxide** production, and solids are all qualifiable.

We can assign values, **numbers.**

Feed is responsible for water quality degradation.

Aquaculture systems should be rated in terms of how much feed they can "process" (per day) without exceeding critical water quality parameters.

Each Unit of Feed – (**One Pound**)

Requires	100 g of oxygen (220 g/kg)
Generates	13 g of TAN (30 g/kg)
Generates	130 g of CO_2 (286 g/kg)
Generates	136 g of suspended solids (300 g/kg)
Generates	150 g of BOD (330 g/kg)

Please bear with me – It is getting interesting now...

Remember that we determined that 1 gpm @ 1.0 mg/1 DO delivers 4.0 g O_2 per 18 hour "feeding day"? This means that if one pound of feed requires 100 g O_2 we can feed 0.04 lb feed per gpm per each AO.

The loading based on feed (Ld_F) can be expressed as:

$$Ld_f = \frac{4.0 \times AO}{O_f}$$

Where O_f is the oxygen (g) required per lb of feed (= 100) per AO Ld_f is:

$$Ld_f = \frac{4.0 \times 1.0}{100} = \mathbf{0.04\ lbs/gpm}$$

Now Watch This.........

1.0 gpm @ 1.0 AO Can Support 0.04 lbs of Feed.

This 0.04 lbs of Feed Generates:

1. $0.04 \times 13g \times TAN = 0.544 \ g \ TAN$
2. $0.04 \times 130 \ g \ CO_2 = 5.2 \ g \ CO_2$ ⎫
3. $0.04 \times 136 \ g \ SS = 5.44 \ g \ SS$ ⎬ Per Day
4. $0.04 \times 150 \ g \ BOD = 6.00 \ g \ BOD$ ⎭

The average concentration over a 24 hour period is then expressed per AO!

1. $TAN_C = 0.10 \ mg/1 \ (ppm) \ (0.1)$
2. $CO_2 = 0.96 \ mg/1 \ (ppm) \ (1.0)$
3. $SS = 1.00 \ mg/1 \ (ppm) \ (1.0)$
4. $BOD = 1.13 \ mg/1 \ (ppm) \ (1.13)$

Simply stated: Each AO (mg/1) used theoretically generates 0.1 mg/1 TAN; 1.0 mg/1 CO_2 and 1.0 mg/1 solids and 1.13 mg/1 BOD based on the values used (rational numbers!)

VI-9

This is pretty easy to remember, but how do we use this information?

$$TAN = NH_3 + NH_4^+$$

1.

NH_3 is the most toxic, unionized form – A Gas

NH_4^+ is in the ionized form, and is relatively non-toxic

Percent of TAN remaining as the toxic form depends
on pH and temperature

% Unionized (% UA)

pH	10°C(50°F)	15°C(59°F)	20°C(68°F)
7.0	0.18	0.27	0.40
7.2	0.29	0.43	0.63
7.4	0.47	0.69	1.00
7.6	0.74	1.08	1.60
7.8	1.16	1.71	2.45
8.0	1.83	2.68	3.83

pH 7.0 to pH 8.0 $\longrightarrow$ 10-fold increase!

For TAN_C (Concentration of TAN)

Recall: Per AO = 0.10 mg/1

For pH 7.4 and 10°C (50°) %UA = 0.47%

Thus the concentration of UA is:

$$UA_c = \frac{0.10 \times 0.47}{100} = 0.00047 \text{ mg/1}$$

$$\boxed{UA_c = \frac{0.1 \times \%UA}{100}} \quad \text{Per AO!}$$

$$\boxed{UA_c = \frac{0.1 \times \%UA \times AO}{100}}$$

Now, if we say that the concentration of unionized ammonia must not exceed **0.025 mg/l**

(A rational number)

MUA = 0.025

Than the maximum AO value (**MAO**) can be:

$$MAO = \frac{0.025}{0.00047} = 53 \text{ mg/l}$$

A very high value

$$MAO = \frac{MUA_c}{UA_c}$$

MUA$_c$ is Selected!
UA$_c$ Depends on pH and temperature. (%UA)

$$UA_c = \frac{0.1 \times \%UA}{100}$$

MAO = 53 mg/l For a pH 7.4 and a temperature 10°C

For temperature 15° : MAO = 36 mg/l

For temperature 20° : MAO = 25 mg/l

For pH:

pH 7.6	-	10° C (%UA = 0.74)	34 mg/l
pH 7.6	-	15° C (%UA = 1.08)	23 mg/l
pH 7.8	-	10° C (%UA = 1.16)	22 mg/l
pH 7.8	-	15° C (%UA = 1.71)	15 mg/l

Recall: 3-Pass: 3 × 5 AO = **15**

Simplified:

For MUA = 0.025 (x 1000) = 25

For UAC = 0.00074 [(0.1x%UA)/100]x1000 = 0.74 (same as %UA)

25/0.74 = 34; 25/1.08 = 23; 251.16 = 22; 251.71 = 15

VI-15

Maximum available oxygen, i.e. "safe AO", based on pH, temperature and maximum (safe) unionized ammonia concentration (MUA) of 0.025 mg/1

pH	10°C(50°F) MAO	TAN_c	15°C(59°F) MAO	TAN_c	20°C(68°F) MAO	TAN_c
7.0	140	14.0	92	9.2	62	6.2
7.2	86	8.6	58	5.8	40	4.0
7.4	53	5.3	36	3.6	25	2.5
7.6	30	3.0	23	2.3	16	1.6
7.8	22	2.2	15	1.5	10	1.0
8.0	14	1.4	9	0.9	6.5	0.7

$$TAN_C = 0.1 \times MAO$$

Maximum allowable unionized ammonia – controversial and unclear/confusing*

$MUA = 0.0125 - 0.0300$ mg/l

Literature - Salmonids

Na^+ - Sodium ion seems to play a role.

Carbon Dioxide – CO_2

$$CO_2 \longrightarrow H_2CO_3 \longrightarrow HCO_3^- \longrightarrow CO_3^{-2}$$

Gaseous
"Toxic"

Carbonic
Acid

Lowers pH

Bicarbonate
Ion

Non-Toxic

Carbonate
Ion

Non-Toxic

Dynamic equilibrium reaction controled by
pH and alkalinity

VI-18

Free Gaseous CO_2 (approximate)

- Alkalinity in mg/l -

pH	100	150	200	250
7.0	25	38	50	62
7.2	16	24	32	40
7.4	10	15	20	25
7.6	6	9	13	16
7.8	4	6	8	10
8.0	2.5	3.8	5.0	6.3

Low pH allows for high TAN (less toxic NH_3, more NH_4^+)
High pH allows for high CO_2 (less toxic CO_2, more HCO_3^-)

VI-19

$$CO_2 = ALK \times 10 (6.4 - pH)$$

Maximum allowable CO_2 (free) = 20 mg/l

$$MCO_2 = 20$$

Per *AO* 1.0 *mg/l*

Recall:

	MAO		Temp.		CO$_2$
pH 7.4	MAO = 53	-	10°	-	53 mg/l
	MAO = 36	-	15°	-	36 mg/l
	MAO = 25	-	20°	-	25 mg/l
	Need to degas CO_2		>20 mg/1		

pH 7.4

Free CO_2	=	10	- 100 mg/l Alk
Free CO_2	=	15	- 150 mg/l Alk
Max Ok	Free CO_2	= 20	- 200 mg/l Alk
Too High	Free CO_2	= 25	- 250 mg/l Alk

Need to degas!

But: CO_2 (which converts to carbonic acid) lowers the pH. This favors (lowers) unionized ammonia %, but increases free CO_2.

Recommendation: MAO > 20 degas CO_2!

/(Colt 2000)

Example:

$pH = 7.6$ Temp. $= 10°$ $(50°F)$ MAO $= 30$

$DO_{in} = 11.0$ mg/l

add O_2 add O_2 add O_2

5.0 AO

DO_{out}
6.0 mg/l
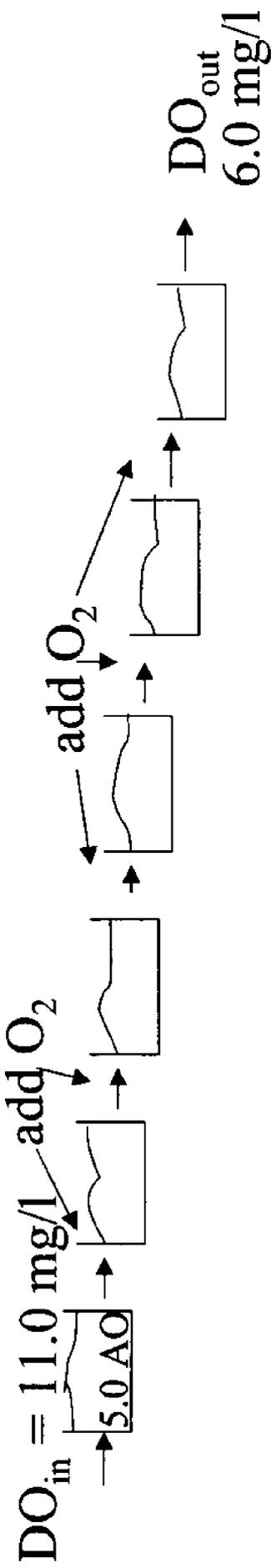
Six Pass: $6 \times 5AO = 30$ AO

30×0.1 TAN $= 3$ mg/l TAN

30×1.4 $CO_2 = 42$ mg/l CO_2

Problem with this design is managing the solids. Raceways are not self-cleaning- they function as settling chambers ... but fish stir waste back into suspension – breaking it up into finer particles which are carried to the raceway below it, causing water quality problems.

Potential solution:

Partial recirculation without the need for biofiltration, because we stay within safe parameters (MUA = 0.025) for **unionized ammonia.**

Six Pass

100 gpm × 6 = 600 gpm

100 gpm represents 1/6 of 600 gpm or 16.66% (17%)

For design we will use **17%**

Total rearing volume is determined by the maximum allowable rearing density. At 100 gpm raceway rearing volume should be 200 ft^3. Exchange rate is 4.0. Circular rearing units are recommended for the partial recirculation system. These will be operated at an exchange rate of 2.0 per hour, accomplishing good hydraulics to make them self-cleaning is the key.

Solids generated are removed instantly along with 17% of the flow - This is then treated and discharged, while 83% of the flow is

Recirculated .... **Oxygenated and CO_2 degassed!**

Required special design, incorp. dual drain system!

Partial Recirculation

Per 100 gpm available water

$5\% + 95\% = 100 + 1900 = 2000$ gpm

$10\% + 90\% = 100 + 900 = 1000$ gpm

$15\% + 85\% = 100 + 566 = 666$ gpm

$20\% + 80\% = 100 + 400 = 500$ gpm

$25\% + 75\% = 100 + 300 = 400$ gpm

$30\% + 70\% = 100 + 230 = 330$ gpm

$$\text{Max. } Q = \left[\left(\frac{\% \text{ Recirc.}}{\% \text{ Loss}} \times Q \right) + Q \right]$$

Example: % Recirc. = 80   Q = 100

% Loss   = 20

$$Max.\ Q = \left[\left(\frac{80}{20} \times 100\right) + 100\right]$$

$$MQ = 400 + 100 = 500$$

Partial Recirculation System (PRAS)
versus
Recirculation System (RAS)

PRAS: No biofiltration

RAS: Biofiltration

Water Use:

Assume PRAS at 80% (20% new)

Rearing volume: **2000 ft^3**

14,960 gal

$Q = 100$ $MQ = 500$ gpm

Per Day: 100 gpm × 60 × 24 = 144,000 gal

For RAS: 80% efficient

RV = 2000 ft^3 System volume: 3000 ft^3

                                    22,440 gal

20% Volume replacement:

          0.20 × 22,440 = 4488 gal

PRAS: 144,000 gal   **RAS:** 4488 gal

          Ratio: 1.0 to 32!

Six Pass

Q = 100 gpm

DO = 11

RV = 200 ft³

MRV = 6 × 200 = 1200 ft³   DO = 6
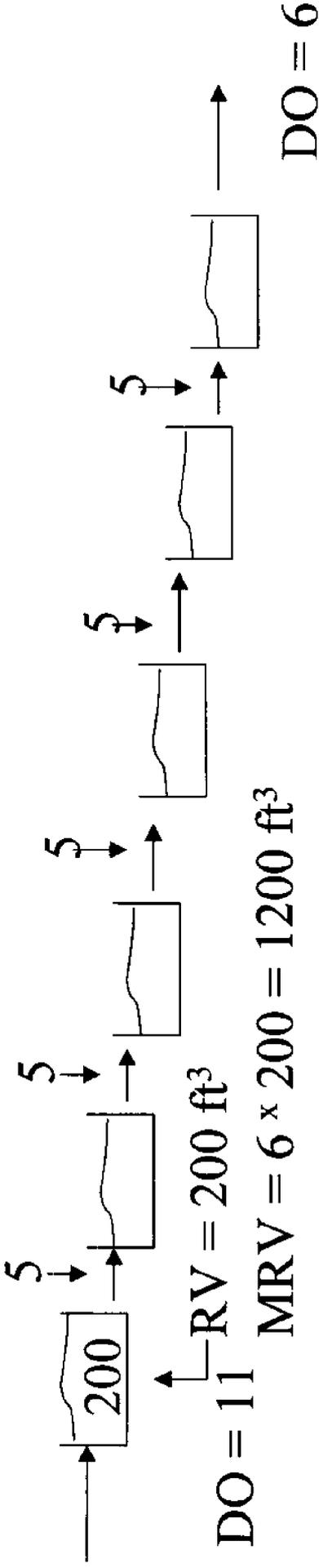
Q = 100 gpm   Exchange Rate (R) = 4.0

MAO = 6 × 5 = 30 mg/1

Three Pass

Q 100

DO = 16   DO = 6

MRV = 1200ft³ (3 × 400)

MAO = 30 (3 × 10)

Q = 100 gpm – R = 2 (Too Low)
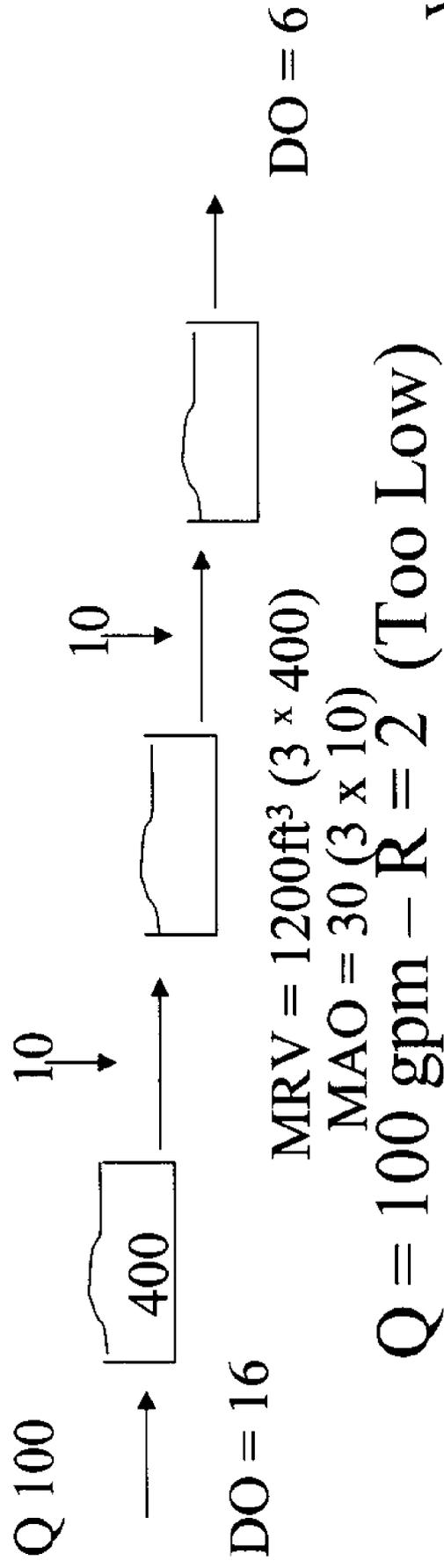
6-pass: 6×100 gpm = 600

$100 = 1/6 = $ **16.6%**

3-Pass: 3×100 gpm = 300

$100 = 1/3 = $ **33.3%**

R = 4 to R = 2

MQ = 600 to 300

MRV = No change!

MAO = No change!

Q = No change!

VII. GAS MANAGEMENT IN INTENSIVE AQUACULTURE

INTRODUCTION

The following gases may have to be managed or controlled in intensive aquaculture; oxygen, ozone, nitrogen, hydrogen sulfide, and carbon dioxide. Oxygen (O_2)must be added to the water in the culture tank and, either is taken from the ambient air (aeration) or from a pure or high purity source (oxygenation). If ozone (O_3) is used, it too is either produced from air or from pure oxygen. Because ozone is toxic to fish, it may have to be removed from the water as well. Nitrogen gas (N_2) can cause the bends in fish, i.e., create gas bubbles in the blood, when present in rearing water under supersaturated conditions. Nitrogen supersaturation is not uncommon in groundwater; it can occur when water temperature is increased, and sometimes is caused by air leaks in pumps. Low level supersaturation can cause chronic gas bubble disease (gas bubble trauma) while high concentrations can lead to high mortalities in a very short period of time.

Carbon dioxide too, can be present in groundwater. Limestone, for instance, can be a reservoir of carbon dioxide. As has been discussed, living organisms that use oxygen (fish and nitrifying bacteria on biofilters) also generate carbon dioxide in large amounts. Because much oxygen is utilized in intensive fish culture, carbon dioxide must be managed in such systems.

OXYGENATION

Because air contains only 21% oxygen and about 78% nitrogen, the maximum safe limit of aeration is to 100% saturation. Going beyond this will result in supersaturated nitrogen levels and may result in gas bubble disease, potentially causing acute mortalities. Continuous exposure to a total gas pressure (TGP) even slightly over 100% saturation can cause gas trauma. Dissolved oxygen can be above 100% saturation without exceeding 100% TGP, provided nitrogen is below saturation and at increasingly lower levels as oxygen increases.

1

With the use of high purity oxygen, it appears that one can safely exceed dissolved oxygen supersaturation without creating conditions leading to gas bubble disease. Oxygen toxicity can occur when partial pressure exceeds 300 mmHg. This is equivalent to 21 mg/l DO at 12^0 C, 16 mg/l at 25^0 C.

What is important is that, as more and more oxygen is dissolved into the water, nitrogen gas must be displaced to avoid exceeding TGP over 100%, especially critical where source water is supersaturated with nitrogen gas to begin with.

To accomplish that a non-pressurized oxygen contractor is required, such as a sealed column. On the other hand, pressurized systems have limitations because they can increase the TGP above 100% saturation. These systems are more suitable for side-stream aeration, where a relatively small portion (10-25%) of the total flow is supersaturated with oxygen (200-400%) then blended into the main flow. This technique can only be used if there is no initial nitrogen gas supersaturation. Since most groundwater sources are naturally supersaturated with nitrogen gas, pressurized systems should not be installed on such sources. Application of high purity oxygen offers an effective means to control nitrogen gas supersaturation. Oxygen introduced into water flowing through a negative pressure system, such as the Michigan spray column, will effectively displace the nitrogen gas with oxygen, while maintaining a total gas pressure near 100%, even when dissolved oxygen levels are elevated to 200% saturation or more (Figure 1). Michigan spray columns, due to their dual function, are only moderately efficient. Figure 2 shows a variety of oxygen contactors, including the Michigan spray column.

Design and Operational Characteristics of the Michigan Sealed Column

The column consists of an airtight chamber into which water and oxygen are introduced while preventing outside air from entering (Fig. 1). Whenever clean, nutrient-free water is used, a sealed column such as this can contain packing material, such as pall rings, tri-pack, or other materials to break up the flow of water and create the maximum possible gas-water interface.

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In case of nutrient rich water, as in a serial reuse design, packing media quickly biofouls, plugging the systems. In this case, the Michigan sealed column becomes a sealed spray column, equipped with a non-plugging sprayer device. Oxygen can be introduced into the water delivery line at the top of the column, or into the column itself, near the bottom to create a counter current gas flow with the downward flow of the water.

Some studies have shown that at higher water flow rates a better absorption is realized when oxygen is introduced at the top rather than the bottom of the column. A unique feature of the sealed column is that it operates under a partial vacuum, created through venturi action.

One design (Figure 1) shows that the column outlet is reduced to half the diameter of the column proper. This causes the water to back up higher into the column. This height is directly proportional to the water flow rate (hydraulic loading). Because of this, the column can also serve as a flow metering device. By installing a viewing window, water level in the column can be observed. After making a series of flow measurements, the column or sight glass can be marked off to indicate specific flow rates. Table 1 provides operational and performance characteristics. The partial vacuum occurs naturally (law of physics) and varies with flow rate. It is this feature that makes sealed columns an excellent device to control and/or prevent TGP over 100%. Oxygen absorption efficiency is of considerable importance in the economics of using pure oxygen.

However, high absorption efficiencies do not necessarily result in less expensive oxygen injection. The cost per unit of O_2 absorption is a function of amortization, energy cost, O_2 cost, water flow, and DO increase. Excellent absorption efficiencies can be achieved at low oxygen flow rate relative to water flow rate, but this occurs at a higher cost because only a small amount of oxygen is added relative to capital expenditure for the system. In cases like these, mechanical aerators may be more economical. The percent oxygen absorption efficiency (AE) of sealed columns can be determined with equation 1.

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$$AE = (Q_w \times 100 \times DDO) / (1.43 \times 1000 \times Q_o) \qquad (1)$$

Where Q_w is water flow rate and Q_o is oxygen flow rate in lpm, ΔDO is DO increase in mg/l, 1.43 is the weight (g) of one liter of oxygen at STP, and 1000 converts mg O_2 to g. To mathematically simplify the equation:

$$AE = (Q_w \times DDO) / (14.3 \times Q_o) \qquad (2)$$

$$AE = (Q_w \times DDO) / (3.8 \times Q_o) \qquad (2a)$$

The equation must be adjusted based on % oxygen purity. The absorption efficiency or performance optimization of a sealed column depends on many variables. Certain combinations of such variables can result in the same DO gain, but not necessarily at the same cost. Through trial and error it was determined that a sealed column functions well with a cross-sectional area of 1.0 to 2.0 cm^2 per lpm (244 to 122 gpm per square foot).

The column diameter can be determined with equation 3:

$$DIA = (2\sqrt{aQ \times Q_w}) / p \qquad (3)$$

where aQ is area per unit flow (cm^2/lpm).

Initial dissolved oxygen concentrations near saturation contribute to relatively poor absorption efficiencies, while initial low DO concentrations can result in high absorption efficiencies. These observations, of course, follow a typical law of diminishing returns."

Reducing the height of a column while maintaining the same level of dissolved oxygen requires an increase in the gas to liquid ratio, hence a reduction in absorption efficiency. Overall, the effect of column height is not as important a design parameter for pure oxygen systems as it is for atmospheric packed columns.

How Much Oxygen?

The potential benefits of increased dissolved oxygen levels can be very significant. Generally, these benefits are two-fold, namely improved quality of the rearing water and increased fish production potential.

In situations where the objective is to increase dissolved oxygen level of source and/or rearing water only moderately, mechanical aeration might be the most economical method. Although a low oxygen to water ratio can produce good aeration efficiency, the benefits from a costly oxygenation system make this economically problematic.

In general, any increase in dissolved oxygen makes that much more oxygen available to the fish. An increase of as little as 1.0 mg/l can represent a 20 to 25% increase in carrying capacity. In cases where incoming dissolved oxygen levels already approach saturation, less than 50% of the oxygen will be available to salmonids, evidenced by the fact that the effluent should contain anywhere from 5.5 to 7.5 mg/l DO. When supplemental oxygen is used to increase production, one has to determine to what extent additional production can be accomplished before unionized ammonia reaches the maximum acceptable level (I). As more and more oxygen is made available, carbon dioxide concentrations will continue to rise.

In a previous discussion, we assumed a maximum available oxygen of 30 mg/l (Table 3-V). At maximum biomass, or carrying capacity, the daily requirement is for 30 mg/l DO, the loading is 12 kg/lpm, the rearing volume is 500 m³, the maximum density 100 kg/m³, the resulting maximum biomass 50,000 kg, and the required flow rate is 4167 lpm. To determine the

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flow rate of oxygen required (Q_o) to provide 30 mg/l in a flow rate of 4167 lpm (Q_w), equation 4 can be used:

$$Q_o = (Q_w \times AO) / (14.3 \times \%abs) \qquad (4)$$

For our values (assuming a 50% absorption efficiency):

$$Q_o = (4167 \times 30) / (14.3 \times 50)$$

$$Q_o = 175 \text{ lpm}$$

To determine the minimum capacity of an PSA oxygen system which are rated on volume generated per hour (ft^3 or m^3) the 175 lpm O_2 equals 10490 l/h or 370 ft^3/h (one ft^3 = 28.3 l). In the case of LOX we must decide on the size of the storage tank. One gallon liquid oxygen equates to 115 ft^3 gaseous. Assume that for each 100 ft^3/h requirement, 720 gallons of liquid are needed per month. For a 6-month supply, a 4,320-gallon tank is needed per 100 ft^3/h. For 370 ft^3/h a 15,984-gallon tank is required.

It is important to maintain a steady biomass of fish in the system, and a biomass less than the maximum, yet one that approaches it as much as is practical. This will be covered when discussing maximizing production through sequential rearing (VII).

Oxygen Source and Cost

High purity oxygen for aquaculture can be supplied in three basic forms:

1. Bottled oxygen under high pressure (2550 psi). The cost is high, from $8 to $10 per 100 ft^3. Cylinders are sized from 100 to 250 ft^3. Oxygen purity is high, from 98 to 99%.

2. Liquid oxygen (LOX) under pressure of 150 to 200 psi. To maintain the low temperature (-182.96°C; -297.3°F), 0.25% is vented daily due to pressure increase. Storage tanks ranging in size from "portable" of 100 l to over 40,000 l (10,000 gals.) Tanks are often rented along with the required evaporator and regulator. The cost of oxygen varies from $0.25 to $3.00 per 100 ft^3, depending on distance and company.

Liquid oxygen may be the best choice when:
- an inexpensive, nearby supplier is available.
- the culture site is remote and has very limited and/or unreliable electrical power.
- oxygenation requirements are very large (6 to 10 tons per day or 5,000 to 9,500 ft^3/h).

3. The pressure swing adsorption (PSA) oxygen generator can provide on-site oxygen production as needed. The generators are available in a wide range of capacities, from less than 15 to over 400 ft^3/h. Very large systems can be custom designed and assembled on site. PSA systems require dry, filtered air under pressure of 90 to 150 psi. Air compressors of the proper capacity are an integral part of a PSA oxygen generator. Although air contains 21% oxygen, or approximately 1.0 ft^3 per 5 ft^3 of air, a PSA may require 13 to 15 units of air to generate one unit of O_2. Even then, its purity is only 85 to 95%. The cost of oxygen ranges from $0.30 to $0.70 per 100 ft^3, depending on the electric cost.

Recently, a low-pressure PSA has been marketed, although not as yet field tested. This system uses a low pressure, high volume regenerating blower to supply air. Energy costs are significantly reduced because the high pressure air compressor is eliminated. One serious drawback is that the oxygen generated in this manner is only slightly pressurized (<5 psi). An additional component may be needed to pressurize the O_2 so it can be delivered to the oxygen contactor in adequate volumes.

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Carbon dioxide is very soluble in water and reacts with it in a complex, dynamic, acid-base equilibrium. The lower the pH the more free CO_2 (gaseous); the greater the pH the more CO_2 is present as bicarbonate (HCO_3^-) and/or carbonate ion (CO_3^-).

When removing gaseous (toxic) CO_2 it is replaced from the HCO_3 or CO_3 sink to maintain equilibrium. Below pH 5, almost all CO_2 exists as free CO_2, between pH 7 and 9, it is converted to non-toxic bicarbonate at about pH 11 it exists mostly as carbonate. From a practical viewpoint, there is no free CO_2 above pH 8.4.

Stripping CO_2 from the water requires large quantities of air. The gas-liquid ratio (G/L) must be 5:1 and 10:1. Aeration typically uses a < 3:1 ratio, oxygenation only requires between 0.05:1 and 0.3:1.

The best way to strip CO_2 is to expose the water to the air. The air concentration of CO_2 is low, only about 350 mg/l (0.035%) versus oxygen at 21% has a concentration of 210,000 mg/l. The saturation concentration in water is at 0.69 mg/l for CO_2 versus 10.1 mg/l for DO at 15^0C.

A packed column degasser can be used to strip CO_2 from the water. Summerfelt (2000) states that the high gas/liquid ratio is accomplished by forcing air through a 1.0-1.5 m tall cascade column, sized to treat 1000 to 1400 lpm water flows per square meter (1.0 lpm per 10 to 7 cm²) (one square meter is equal to 10.76 ft²). Hydraulic loading rates as high as 1667 to 4167 lpm per m² have been suggested (41 to 102 ft²/gpm).

Air discharged from stripping columns should be vented from buildings to prevent carbon dioxide from accumulating in the building space. The Occupational Safety and Health Administration (OSHA) limits the allowable time-weighted average exposure over an eight-hour

workday to concentrations less than 5000 mg/l (Vinci et al, 1998) A concentration of 50,000 mg/l is considered immediately dangerous to life.

Because pH controls the relative concentrations of each species of CO_2 in the inorganic carbon system, methods to increase the pH will lower the proportion of free CO_2. Adding lime, caustic soda, soda ash, or sodium bicarbonate to the water will increase the water's pH.

When stripping CO_2 the equilibrium is shifted as bicarbonates release carbonate ions. This shifts the pH to a higher value. Within minutes carbonic acid will have dehydrated to establish a new equilibrium replenishing (replacing) some of the carbon dioxide that was removed. This dynamic makes it difficult to strip a large fraction of carbon dioxide from well-buffered waters. Because pH also controls the acid-base equilibrium between ammonia (NH_3) and ammonium (NH^+), increasing the pH to reduce free CO_2 concomittantly increases the proportion of unionized ammonia, a toxic component. This limits the pH range available for CO_2 control (See Figure 3).

OZONE IN INTENSIVE AQUACULTURE

Introduction

Ozone is a triatomic oxygen gas (O_3). It is unstable and highly reactive, and is thus a very powerful oxidizing agent. These properties make it a better disinfection agent than ultraviolet radiation (UV) and chlorine. It has a pungent odor, which is sometimes noticeable after a violent thunderstorm, when lightening through the atmosphere causes some of the oxygen molecules to change into ozone.

Ozone generators apply this principle by creating an electrical arc (lightening) between two high voltage electrodes (Figure 4). As oxygen, the feed gas, flows between the electrodes some of the oxygen (4 to 6% by weight) is changed to ozone. Much heat is produced as well,

which can represent 90% of the energy applied, with only 10% going toward the production of ozone. Because heat destroys ozone, the units must be either air-or-water cooled.

Although some units can convert 10 to 15% of the oxygen to ozone, generating these higher percentages makes them less efficient, and the cost of ozone produced will be greater.

Where atmospheric air is used (21% O_2) only 1-3% of the oxygen is converted to ozone. It is much more advantageous to use pure oxygen, especially in aquaculture situations where oxygen is used to oxygenate the rearing water. Whether air or oxygen is used, the gas must be dry, free of water vapor.

Ozone can also be produced by means of UV radiation, but this requires 6 to 30 times more energy than the corona discharge method. Application of ozone is costly in terms of capital expenditure and energy required. The capacity of ozone generators is rated in weight of O_3 produced over time; kg/hr or lb/hr. John Colt (2000) reports that it requires 6-7 kwh/kg O_3 produced.

There are four unit processes required for ozone use in an aquaculture application: 1) O_3 gas generation (corona discharge method); 2) gas-to-liquid absorption; 3) contact time and concentration for reaction; 4) O_3 removal and destruction.

Gas-to-Liquid Absorption

The high cost of ozone makes its efficient transfer into the water important. Because it can be co-transferred with oxygen, the same device can be used. The rate of ozone transfer into water is a function of the concentration of ozone in the gas, the contact area, the thickness and rate of exchange of the two stagnant layers, and the rate of ozone reaction. Increasing mass-transfer efficiency can be accomplished with the use of media that that creates a large surface area of a thin film of either gas or liquid or by reducing bubble or droplet size.

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Increased turbulence decreases the thickness of the stagnant layers. This decreases the resistance to the transfer of ozone across it. It also keeps water and gas mixed.

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, LHO's, provide efficient transfer but very little time for reaction. In this case a separate contact chamber may be required for reaction. Most ozone contactors rely on continuous liquid phase units that bubble ozone into the liquid. These units are best suited to situations where reaction is rate limited and an ozone residual must be maintained for a specific length of time, such as during disinfection. Their absorption efficiency is not as good as the continuous gas phase technique. Systems that pass water through air can be designed for much higher transfer efficiencies than systems designed to pass air through water.

Contact Time and Concentration Necessary for Reaction

The most common method to provide adequate contact time is by means of a deep basin, separated into three to five chambers by means of baffles (Figure 5). The ozone is introduced by diffusers, venturi eductors or static mixers. The length of contact and strength of the concentration depend on the quality of the water and the objectives. For disinfection, the longer the exposure the greater the kill, but, in theory, ozone requires infinite contact times to reduce microbial populations to zero (sterilization), as shown with the equation:

$$\log \frac{N_t}{N_0} = -k't$$

where N_t = number of organisms at time t

N_0 = number of organisms at time = o

t = time in minutes

k' = constant (1/minute)

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For instance, a concentration of 1,000,000 bacteria/mL is equal to 6 log units (10^6). It takes the same contact time to reduce the concentration from 6 to 3 log units (1,000,000 to 1000/mL) as it takes to reduce the concentration from 2 to -1 log units (100 to 0.1/mL). The greater the concentration the less contact time is required as shown:

$$Ct = constant$$

where C = concentration of ozone.

t = time required to achieve a given kill.

Ozone is rather unstable in water. In pure water the half-life of O_3 is about 165 min at 20^0C. In aquaculture systems the half-life may be less than a few minutes because of an abundance of organic compounds. It can be worse in high-density, water-recirculation systems where half-life can be as short as 15 seconds.

Microbial reductions (disinfection) are largely limited by the ability to maintain a certain dissolved ozone concentration for a given time period. For disinfection, the required residual O_3 concentration is usually between 0.1 - 1.0 mg/l with a hydraulic retention time anywhere from 0.5 to 20 minutes (Langlais et al. 1991).

Obviously these are rather wide ranges, the result of the target organisms and the quality of the water (organic load).

The high ozone demand of recirculated water, caused by accumulated nitrite and organic matter, makes maintaining an adequate ozone residual difficult. In order to achieve large microbial reductions in RAS or PRAS, much more ozone would be needed to disinfect, for instance, most influent waters of a typical, flow-through aquaculture system.

Studies have shown that adding ozone at the rate of 0.025 kg/feed improved water quality and reduced mortality associated with bacterial gill disease, but failed to produce even a one log

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reduction (i.e., 90% reduction) in the numbers of heterotrophic bacteria in the water or on the gill tissue (Summerfelt, et al. 1997, and Bullock et al. 1997).

To achieve a large bacterial reduction in recirculation systems requires more ozone than has been reported in the literature. This increases the cost of ozonation, and in addition the contact time must be increased as well. Because the capital costs for adding ozone are large, the economy of using ozone within recirculation systems is questionable.

Ozone Removal and Destruction

Increasing the ozone concentration to accomplish some measure of disinfection requires the incorporation of a mechanism to remove ozone residual from the water before it enters the culture tanks.

Either the contact time must be extended until the ozone is fully "used up" or other treatments must be applied, such as activated charcoal, stripping, or UV destruction. Residual gases from a contact chamber must be collected and vented to an ozone destruction device before entering the atmosphere.

Ozone is harmful to humans as well as aquatic organisms. It is important that there are no leaks within the ozone delivery system. Only ozone compatible materials should be used, such as stainless steel, Teflon®, special fiberglass, and cement.

At low concentrations in the air, ozone has a very distinctive odor, and can be detected well below the daily safety criteria limits of 0.1 p.m. by volume determined as a time-weighted average over a full working day (8-hour maximum) or 0.2 ppm by volume as a maximum 10-minute exposure. For fish, lethal levels can be as low as 9.3 $\mu g/l$ (0.0093 mg/l). However, production conditions concentrations in the range of 10-20 $\mu g/l$ (0.01 - 0.02 mg/l) have been found to have no impact on salmonid eggs and fry. The chemical ozone demand from uneaten

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feed and waste products will quickly reduce the ozone residual to near zero. Ozone has attracted a great deal of interest. Improvements in water quality and solids removal have resulted from applied doses in the range of 0.025 to 0.045 kg O_3/kg feed.

In an earlier presentation (I) it was concluded that, based on O_2 demand by feed of 250 g/kg, one can feed 0.004 kg feed per lpm for every mg/l DO available.

If ozone is applied at the rate of 0.025 kg per kg feed, 0.004 feed requires 0.001 kg of ozone per lpm or 0.1 g/lpm/mg DO/day.

Because one lpm @ 1.0 mg/l delivers 1.44 g/day, the 0.1 g/day O_3 represents a concentration of 0.07 mg/l (0.1 ÷ 1.44) or 70 μg/l.

Using the range of 0.025 to 0.045 kg O_3/kg feed for water quality improvements is rather risky with respect to potential toxicity problems relative to the fish. Accordingly, Colt (2000) recommends that a more focused research is needed to rationally develop the design parameters and operational strategies for the use of ozone in aquaculture systems.

Colt, John, 2000. Ozone. In Encyclopedia of Aquaculture, ed R.R. Stickney pp 622-628. John Wiley and Sons Inc. New York.

Langlais, B., D.A. Reckhow, and D.R. Brink. 1991. Ozone in water treatment - application and engineering. American Water Works Association Research Foundation, Denver.

Summerfelt, S.T., and J.N. Hockheimer. 1997. Review of ozone processes and applications as an oxidizing agent in aquaculture. The Progressive Fish-Culturist 59:94-105.

Summerfelt, S.T., J.A. Hankins, A.L. Weber, M.D. Durant. 1997. Ozonation in a recirculating rainbow trout culture system. II. Effects on microscreen filtration and water quality. Aquaculture 158: 57-67. Elsevier Science, Amsterdam, Holland

TABLE 1.—Operation and performance characteristics of a sealed packed column at the Harrietta State Fish Hatchery (Figure 1). Column diameter is 30.5 cm and discharge pipe diameter is 15.25 cm. Water characteristics: temperature, 8.2°C; dissolved oxygen (DO), 10.7 mg/L; O_2 saturation, 92%; N_2 saturation, 101–105%.

Measure	Water flow in L/min			
	200	400	600	800
Cross-sectional area-to-flow relationship (cm^2/[L/min])	3.65	1.80	1.20	0.91
DO gain in mg/L for O_2 inflows of				
1.0 L/min	2.5	1.5	1.0	0.9
1.5 L/min	3.9	2.3	·1.8	1.3
2.0 L/min	4.7	3.7	2.1	1.8
O_2 absorption efficiency in percent for O_2 inflows of				
1.0 L/min	35	42	42	50
1.5 L/min	36	43	50	48
2.0 L/min	33	52	44	50
% gas:liquid ratios for O_2 inflows of				
1.0 L/min	0.50	0.25	0.17	0.13
1.5 l/min	0.75	0.37	0.25	0.19
2.0 L/min	1.00	0.50	0.33	0.25
Vacuum in mm Hg	36	54	74	91
%O_2 saturation for O_2 inflow of 1.5 L/min^2	121	108	104	103
%N_2 saturation for O_2 inflow of 1.5 L/min^2	94	98	99	99.5

Gas Management in Aquaculture

Gases of Concern:

Oxygen (DO)
Carbon Dioxide (CO_2)
Nitrogen (N_2)
Hydrogen Sulfide (H_2S)

Also of Interest:

Ozone (O_3)

Oxygen Required

Salmonids: 250 g – 17 hr. Day
(Per kg Feed)   350 g – 24 hr. Day

Biofilter: 1.0 g TAN – 4.4 g O_2

$(TAN \longrightarrow NO_3)$

Also Heterotrophs Exert an O_2 Demand

RAS: 500 to 1000 g/kg Feed

½ to 1.0 lb/lb Feed

How Much Oxygen Do Fish Require?

Depends on their metabolic rate, which depends on fish size (W_t) & **water temperature** - And - ...these same criteria determine the feeding level!

Therefore: Oxygen required per unit of feed is independent of these criteria – It is a constant.

For Salmonids: 200 – 250 g/kg feed/day (17hrs)

OF = 200 to 250

$$MR = \frac{\%BW \times OF}{0.1 \times 17 \ (hrs)}$$

MR (OF 250) = % BW × 147

MR (OF 200) = % BW × 118

But to determine O_2 required use food required.

Per kg: 250 g O_2/Day

However in recirculation the biofilter consumes

Oxygen as well!

O_2 Required for a RAS

Biofilter: Nitrifiers Oxidate TAN

1.0 g TAN – 4.4 g O_2

Feed generate 30 g TAN/kg food

O_2/kg feed: 30×4.4 g $= 132$ g O_2

*Heterotrophic bacteria consume oxygen too. Much depends on solids control

Total O_2/kg feed for RAS

Fish	250 g
Nitrifiers	132 g
Heterotrophs	118 g (More or Less)
	500 g O_2/kg Feed

Many Variables:

1. Feed Quality (Fines, etc.)

2. Feed Protein Level

3. Feeding Strategy

4. RAS Intensity (%)

5. Biofilter Type

6. Rearing Tank Design

7. Rearing Tank Operation (H_2O Turnover Rate) Etc.

An Exercise (Method)

1. RAS – System Volume: $10,000$ m^3
    a) Fish Rearing Volume: $8,000$ m^3

2. Intensity 80% (20% Volume Replacement Per Day) = 200 m^3/Day) = 1400 lpm

3. Final Rearing Density 80 kg/m^3
    a) Max. Biomass: $80 \times 8000 = 64,000$ kg
    b) Final Feeding Level: 1.5% BW

4. Max. DO$_{in}$ = 20 mg/l
    Min. DO$_{out}$ = 4.0 mg/l (Out of Biofilter)
    AO = $20 - 4 = 16$ mg/l

5. Circular Rearing Unit

6. OF = 250 (fish) + 250 (biofilt.) = 500 g/kg Feed

$$Ld(\text{kg Fish/lpm}) = \frac{16(AO) \times 100}{500(OF) \times 1.5} = 2.1 \text{ kg/lpm}$$

Rearing Unit Flowrate (Q_{ru}):

$$Q_{ru} = \frac{640,000}{2.1} = 304,762 \text{ lpm}$$

Exchange Rate (R) :

$$R = \frac{Q_{ru} \times 0.06}{RV} = \frac{18,286}{8,000} = \frac{2.3/\text{hr}}{(26 \text{ min})}$$

How Much Oxygen Per Day (O_d)

$$Q_{dg} = Q \times AO \times 1.44 \text{ g} = \text{g O}_2/\text{d}$$

$$Q_{dl} = Q \times AO = \text{L O}_2/\text{d}$$

In Our Example:

Q_{dl} $= 304{,}762 \times 16 = 487{,}619 \text{ L/d}$

$= 487.6 \text{ m}^3/\text{d} = 20.3 \text{ m}^3/\text{h}$

$= 717 \text{ ft}^3/\text{h}$

At 80% Efficiency (%E = 80)

$$717 \times \frac{100}{80} = 896 \text{ ft}^3/\text{h}$$

Introduce the Oxygen

1. Aeration: Take O_2 from Air (21% O_2)

    A. Exposing Water to Air

        a) Columns

        b) Surface Aerators

        c) Gravity (Steps, etc.)

    B. Exposing Air to Water

        a) Diffusers

        b) Sparges

        c) Jets

Water to Air More Efficient.

In general, aeration not effective for oxygenation in RAS, but does have the advantage that it also can dispel some of the carbon dioxide.

Trickling and rotating biological filters combine some aeration/degassing. They are high volume biofilters with a "low" surface to volume ratio (150-300 m^2/m^3) versus granular filters, i.e., sand and micro beads (5000-10,000 m^2/m^3).

In RAS: **Oxygenate**, i.e., use pure or high purity oxygen.

LOX or PSA Source.

Controlling Carbon Dioxide in RAS

In Previous Example: 16 mg/1 DO
Needed to support maximum biomass.

Carbon Dioxide exists in four forms (species)
kept in an acid-base (dynamic) equilibrium:

$$CO_2 + H_2O = H_2CO_3 \longrightarrow H^+ + HCO_3 \rightleftharpoons H^+ + CO_3$$

VII-12

Carbonic Acid (H_2CO_3) instantly releases H^+ ions, lowering the pH.

Result: More (Toxic) Free CO_2 (Gas).

Free CO_2 Must be kept below 20 mg/l

Hypercapnia (High CO_2)

Acidosis: Blood pH lowered due to CO_2 build-up.

Interferes with O_2 **uptake and transport** in the blood!

Acid-Base (pH and Alkalinity) Equilibrium

Concentrations of Free CO_2 in mg/l

Alkalinity ($CaCO_3$)

pH	30	50	70	90	100
6.5	18.9	31.6	44.3	56.9	69.9
7.0	6.0	10.0	14.0	18.0	22.0
7.5	1.9	3.2	4.4	5.8	6.9
8.0	0.6	1.0	1.4	1.8	2.2

Alkalinity:

Buffering Capacity

Resisting pH Change

In RAS, **Nitrifiers Use Up Alkalinity** and

Generate CO_2 Which Lowers the pH.

Should Maintain Alkalinity > 50 mg/l

And pH 7.2 – 7.4

Low pH: Favors Unionized Ammonia (Less NH_3)

But More Free CO_2!

CO_2 Control in RAS

1. Air Stripping
2. pH Control (Alkalinity = Buffer)

Air Stripping: Need a **high** gas to liquid ratio

g/l from 5 to 10/1.0

Aeration: 3 to 1 (inadequate for CO_2)

Oxygenation: 0.05 to 1.0 (No CO_2 stripping)

Stripping accomplished with packed column and forced air.
In a building — CO_2 must be vented out to prevent build-up — health concerns.

Vinci et al. (1998) Developed Software Program for Air Stripping CO_2

Summary:

Guidelines for O_2 and CO_2 control

1. Strip CO_2 after it reaches its highest level and before O_2 supersaturations are created:

   a)   After biofilter

   b)   Before oxygenation

Note: Airstripping CO_2 elevates DO to $\pm$ 90% saturation – Therefore pure oxygen should only be used to create supersaturation! And...produce DO supersaturation just before the water enters the rearing tanks.

Four Unit Process

1. O_3 Generation
2. Gas to Liquid
3. Contact Time / Concentration
4. Removal / Destruction

O_3 Generation:

a) Expensive – 6 – 7 kwh/kg O_3 *
b) Air Feed Gas (21% O_2) – 1 –3% O_3
c) O_2 Feed Gas: 4-6% O_3 (10-15%)
d) Energy: 90% as Heat
e) Cooling Required – Heat Destroys Ozone.
f) Rating in g/hr!

Note: $1.0 \text{ mg/l per 1 l/min} = 1.44 \text{ g/day}$

$(1.0 \text{ mg} \times 1.0 \times 60 \text{ min} \times 24 \text{ hr} = 1440 \text{ mg} = 1.44 \text{ g})$
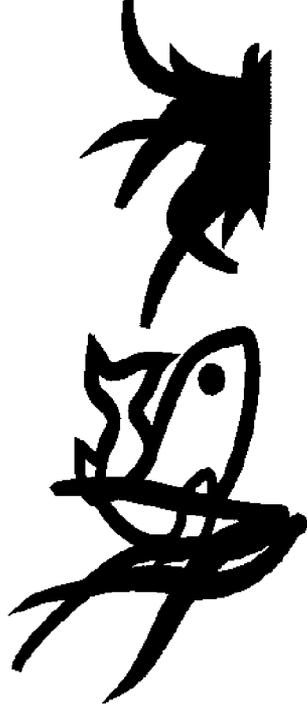
* 6-7 kwh/kg O_3 About \$0.50/kg O_3

   O_2 \$0.50/100 ft^3 = \$0.50/4.0 kg O_2

   O_2 \$0.50/100 ft^3 = 0.1254/kg O_2

Contact Time and Concentration

Need Deep Basin (Large Volume)

Length of contact time and strength of O_3 concentration needed depends on quality of the water and objectives.

In theory, ozone requires infinite contact time to reduce a microbial population to zero (sterilization)

$$\log = \frac{N_t}{N_o} = k^1 t$$

N_t = Number of organisms at time t

N_o = Number of organisms at time o

t = Time in minutes

k^1 = Constant (1/minute)

For instance, a concentration of 1,000,000 bacteria/ml is equal to 6 LOG units (10^6)

Ozone (*Lack of*) Stability

1. In pure water ½ life $\pm$ 165 min.

2. In aquaculture water ½ life maybe less than a few minutes (organics)

3. In RAS, ½ life as short as 15 seconds

RAS: Disinfection is limited by the ability to maintain a certain O_3 concentration for a given time period.

Required: 0.1 – 1.0 mg/l
               0.5 – 20 min.
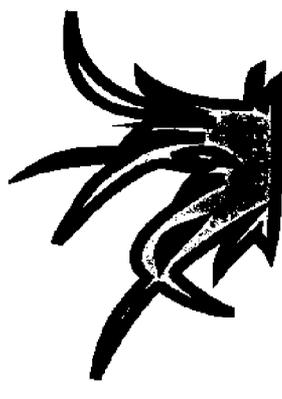
Depends on the target organism and water quality.

In RAS: Difficult to disinfect due to:

a) $O_3 + NO_2 \longrightarrow NO_3 + O_2$

b) Organic Load

Ozone relative to feed (source of NO_2 and organics)

Rate: 0.025 kg O_3 (25 g)/kg feed.

$0.025\ kg\ (25\ g)\ O_3/kg$ Feed

1. Improved water quality
2. Reduced mortality due to
    Bacterial Gill Disease
3. Failed to reduce bacteria significantly
    (heterotrophic as well as gills)

To achieve a large bacterial reduction in a RAS
requires more ozone than the literature reports
(Summerfelt et al. 1997, and Bullock et al. 1997)

Water Quality Improvements – Yes.

1. **Solids Coagulation** – Better removal with microscreening.

2. **Removes Color** (Recent study by Christensen et al. 2000) reports: 0.007 kg (7 g) to 0.015 kg (15 g) O_3 per kg feed removes color from RAS

3. Also: COD (chemical oxygen demand) Reduced from 50 mg/1 to 15 mg/1

Assume 0.025 kg O_3/kg Feed

Earlier Discussion:

RAS: 500 g O_2/kg feed

Can feed: 0.02 kg feed/1pm/AO/day

$$LdF = \frac{AO}{OF} = \frac{1}{500} = 0.002$$

Ozone: 0.025 kg × 0.002 = 0.00005 kg O^3

Or: 0.05 g/1pm/AO/day

For 16 AO: 0.8 g O_3/1pm/day

0.8 g/1pm/day = 0.56 mg/1

$$\frac{0.8}{1.44}$$

Previous discussion:

RAS @ 300,000 lpm flow

Need to generate

$0.8 \text{ g} \times 300,000 = 240,000 \text{ O}_3 = 240 \text{ kg O}_3/\text{day}$

@ $0.50/kg = $120/day

But need to consider absorption efficiency at:

50% : $240/day

At 15%: $\dfrac{100}{15} \times 120 = \$1,333/\text{day}$

Final comments

1. Use O$_3$ Compatible Materials

a) Stainless Steel (AISI 316;316l)

b) Teflon

c) PVC (?)

d) Concrete (Type 2 or Type 5 Portl. Cem)

e) Fiberglass (Depends on Resin Used)

2. Disinfection: 0.5 to 1.5 mg/l

C$_t$ = Concentration × Exposure Time

0.5 × 30 min. = 1.5

1.5 × 1.0 min = 1.5

Same Result

3. **Water Quality:** 0.025 to 0.045 kg O_3 per kg feed

0.025 kg O_3/kg feed:

    Assume requires 500 g O_2/kg feed

$$LdF = \frac{AO(1)}{500} = 0.02 \text{ kg feed/lpm}$$

And: 0.02 (kg feed) × 0.025 kg O^3 = 0.00005 kg O_3

    Per lpm, per one AO

    For 16 AO: 0.0008 kg O_3/lpm (0.8 g/lpm)

    0.8 g O_3/lpm = 0.56 mg/l (0.8/1.44)

    At rate Of 0.045 O_3/kg feed: 1.0 mg/1 O_3

Ozone Toxicity to Fish

Under Production Conditions

10 to 20 ug/l (0.01 – 0.02 mg/l)

Recall: Rate of 0.025 kg O_3 /kg feed

Concentration is 0.035 mg/l per AO per lpm.

For AO = 16 $\longrightarrow$ 0.56 mg/l (560 ug/l)

O_3 Removal

a)   Detention Time (Short Half Life)
b)   Air Stripping
c)   Activated Carbon
d)   UV Radiation

Gas Phase: Thermal or Catalytic Unit.

Human Toxicity

0.1 ppm (By Volume) – 8 hour
0.2 ppm (By Volume) – 10 min.

NOTE: Smell of O_3 can be detected well before it
reaches these concentrations.

Monitoring O$_3$

Difficult to measure, especially in liquid phase.

Gas Phase: UV Absorption Technique.

Liquid Phase:

Indigo Trisulfonate Potentiometric - Probe

Final Comment

Ozone is Expensive

Ozone is Risky

But: Can improve water quality in RAS (solids & clarity)

Can disinfect – but difficult to accomplish the proper combination of concentration and exposure time.

RAS: Heavy Organic Load

(C_t)

Need more research:

a) **RAS** improvements (esp. solids)

b) O_3 application, control
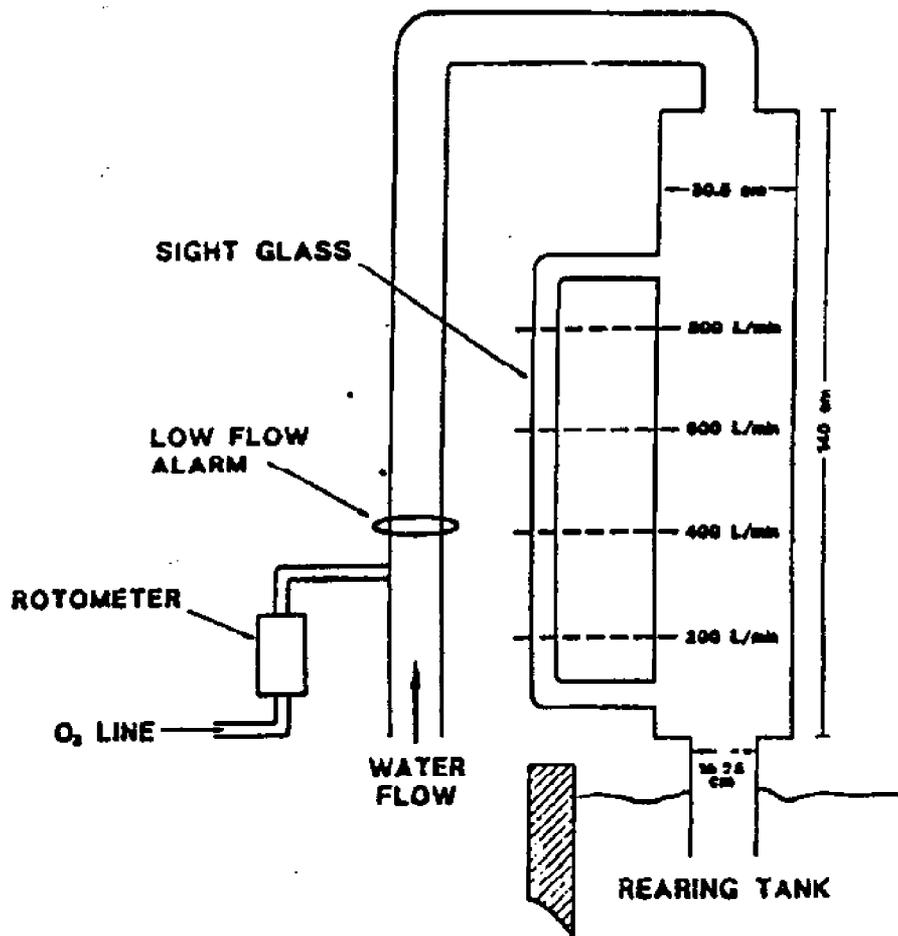
Figure 1. Design of a sealed column

Source: Westers et al. 1991. Design and operation of sealed
columns to remove nitrogen and add oxygen.
AFS symposium 10: 445-449, 1991

O$_2$ Application

1. Packed columns
2. Screened columns
3. Lowhead oxygenators (LHO)
4. U-tube design (hydrostatic pressure)
5. Bubble contactor
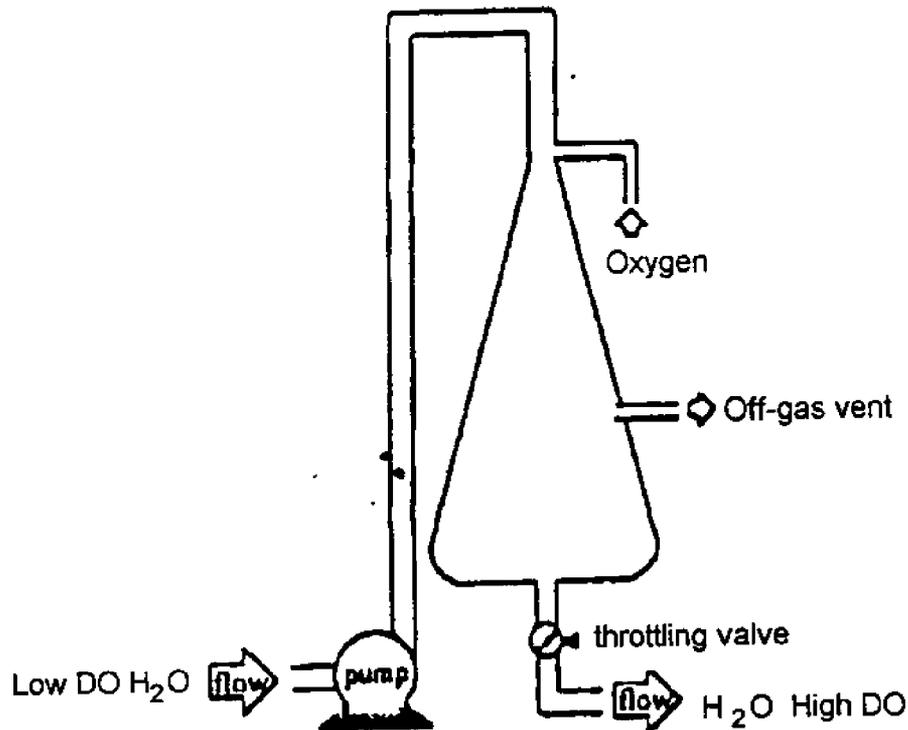
Downflow bubble contactor
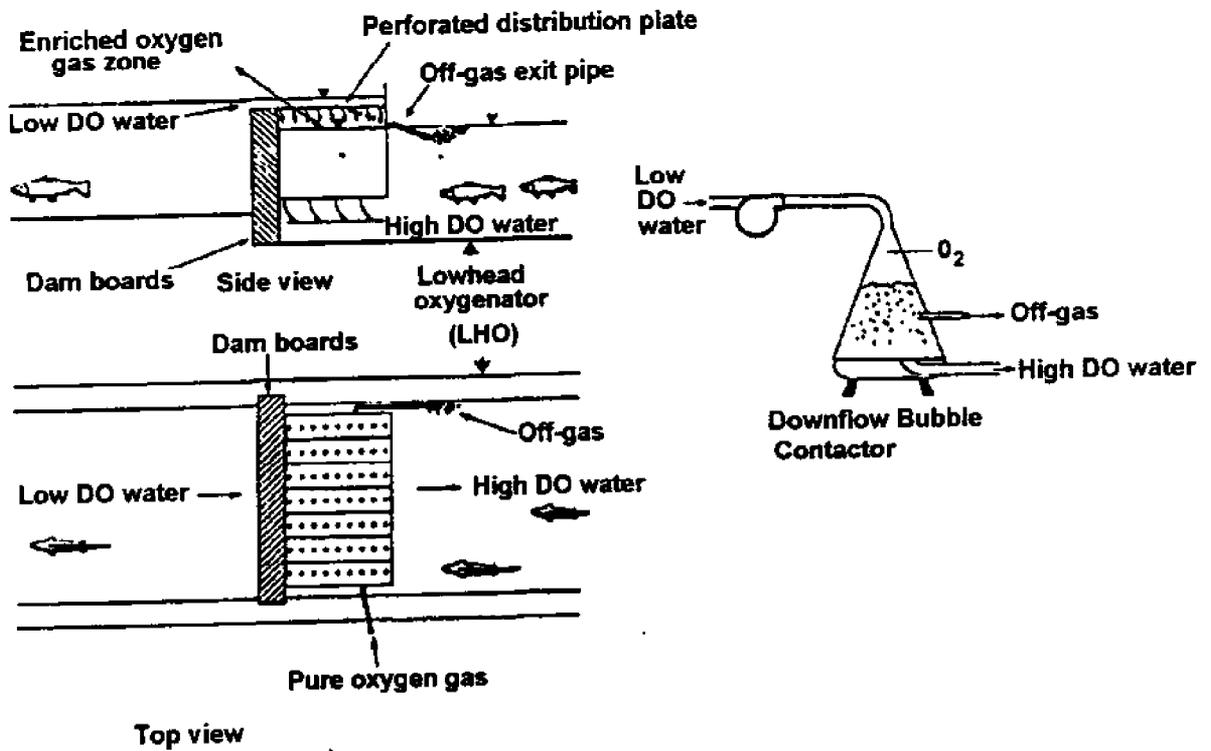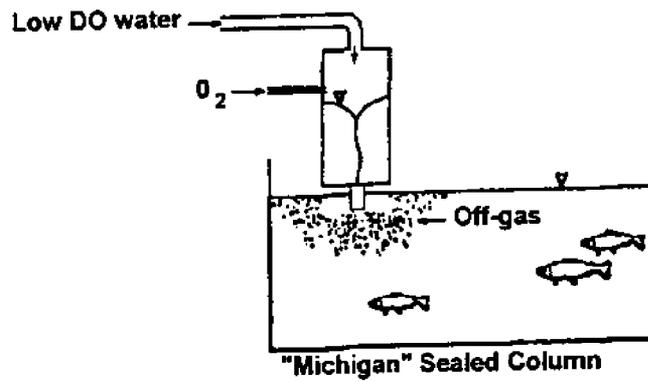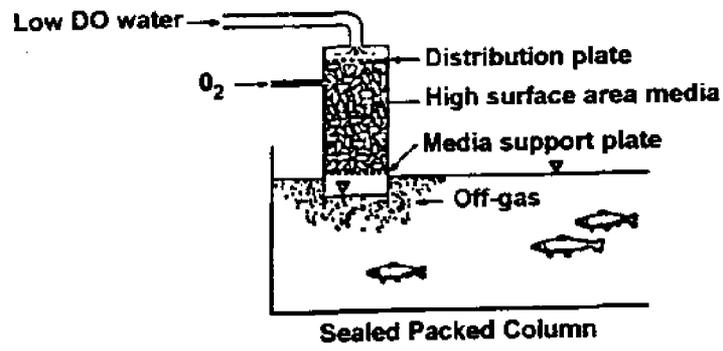
Low DO water → Distribution plate

O_2 → High surface area media

Media support plate

Off-gas

Sealed Packed Column

Low DO water →

O_2 →

Off-gas

"Michigan" Sealed Column

Enriched oxygen gas zone

Perforated distribution plate

Off-gas exit pipe

Low DO water

High DO water

Dam boards   Side view

Lowhead oxygenator (LHO)

Low DO → water

O_2

Off-gas

High DO water

Downflow Bubble Contactor

Dam boards

Off-gas

Low DO water →   → High DO water

Pure oxygen gas

Top view

Technologies used in aquaculture to oxygenate fish rearing water

U-tubes

Multistage Lowhead oxygenator (LHO)

Packed column

Screened column
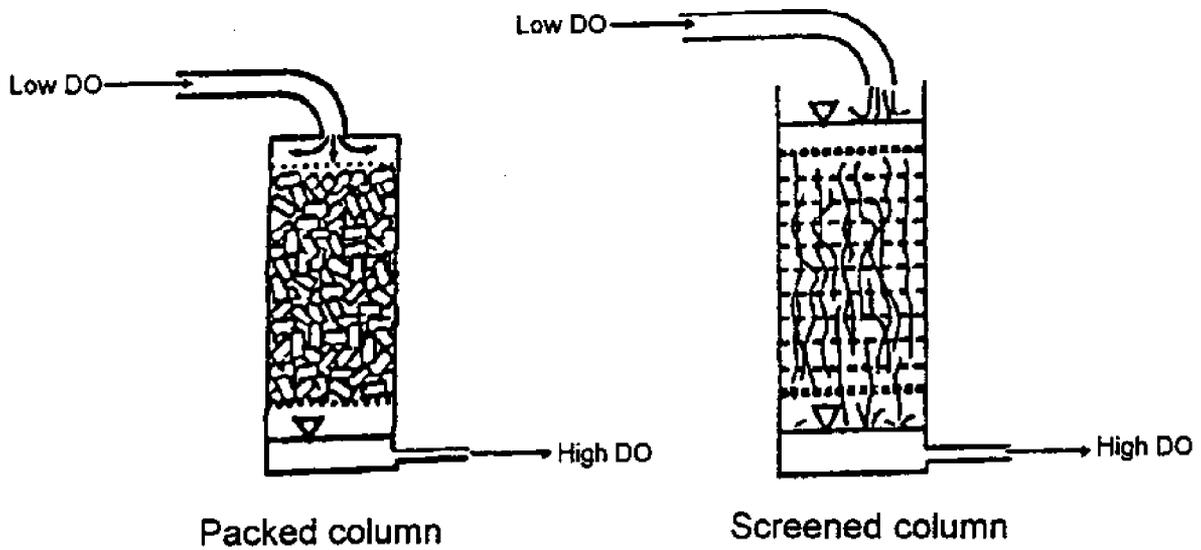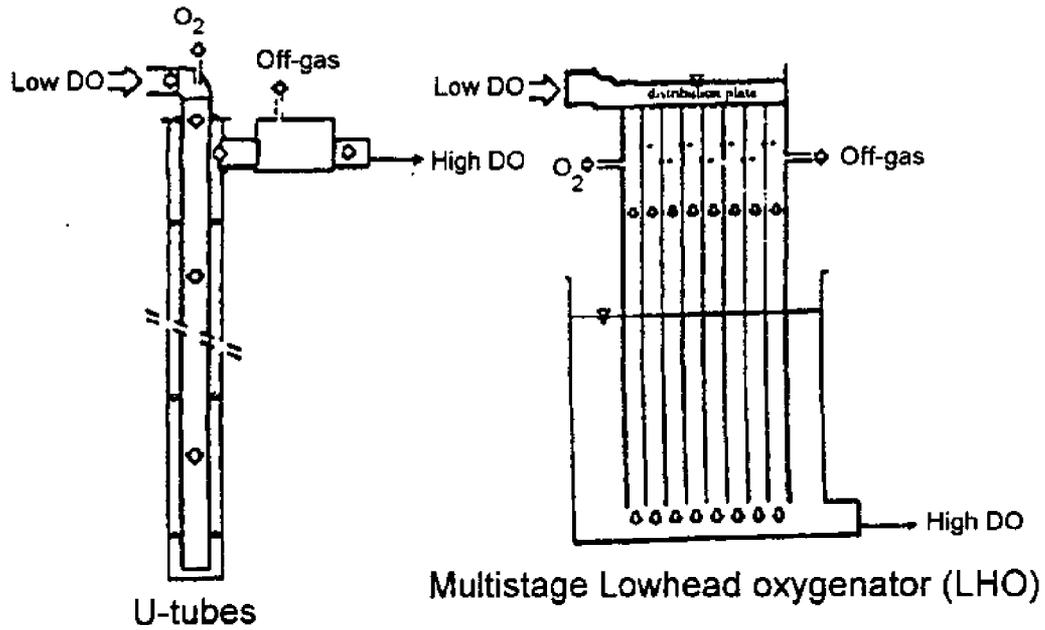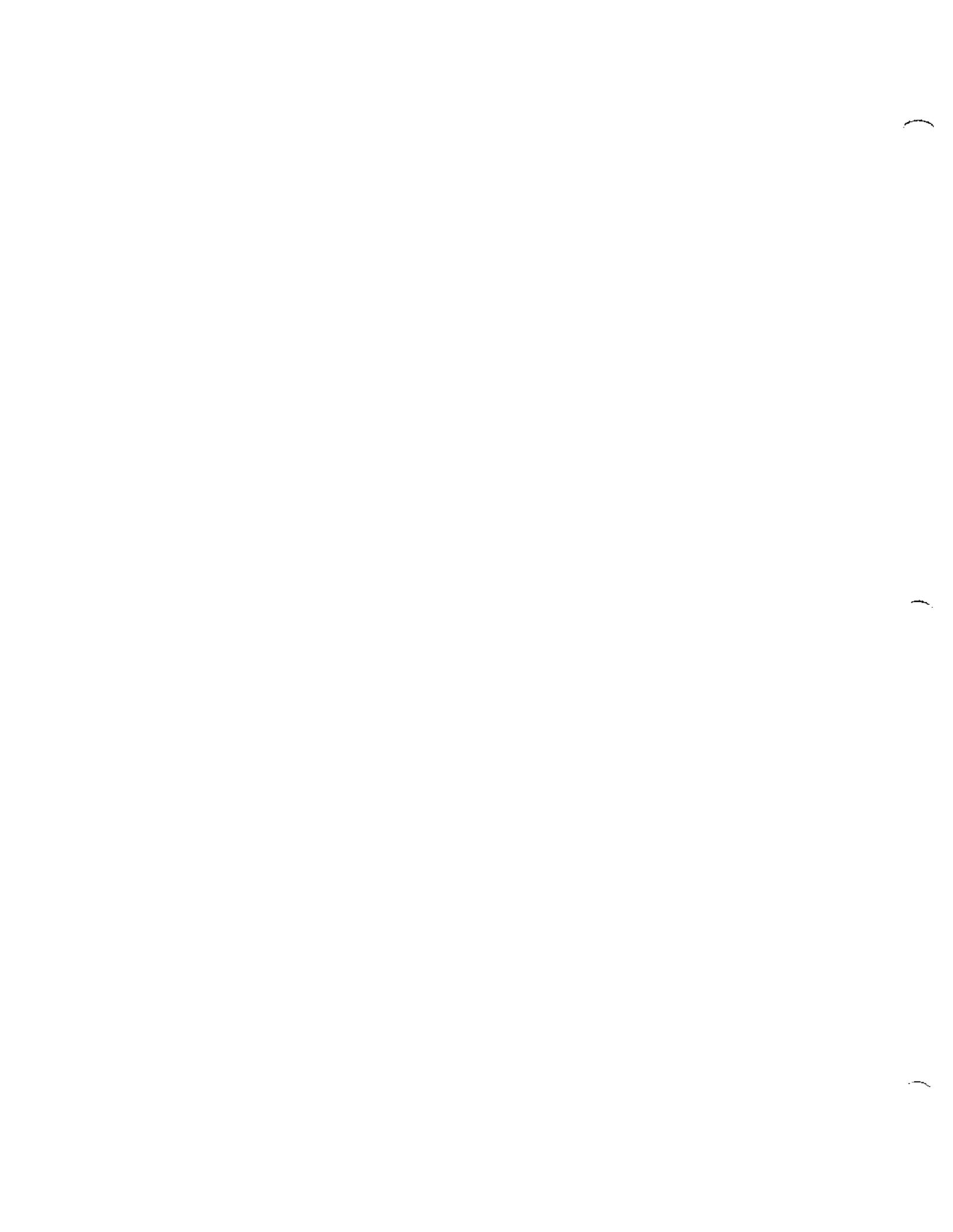
VIII. MAXIMIZING PRODUCTION THROUGH SEQUENTIAL REARING STRATEGIES

INTRODUCTION

The production potential of intensive fish culture systems, whether flow-through or recirculating, should be rated on the basis of how much feed they can "process" per day without exceeding specific, predetermined, water quality parameters such as ammonia nitrogen and its derivatives: nitrite and nitrate nitrogen, and carbon dioxide, suspended solids, and dissolved oxygen.

To realize optimum, i.e. maximum, annual production the daily feed allotment should be as close to the maximum as practical at all times. For example, if a system can "process" 120 kg of feed per day, the daily gain in biomass would be 120 kg for a feed conversion of one. For a feed conversion of 1.25, the daily gain would be 96 kg. Annual production would be 43,800 kg and 35,040 kg respectively if a steady state of maximum daily feed allotment could be maintained throughout the year and gains in production were removed daily. This is not practical, but the goal is to come as close to this maximum as possible. To accomplish this requires a sequential rearing strategy, where a new group of fish, a new cohort, is introduced into the system at regular time intervals.

Summerfelt et al. (1993) describe and model a sequential rearing strategy where market-size fish are selectively harvested from the entire system, irrespective of their location within the system. This approach is used by catfish farmers to accomplish year round production through "cull" harvesting. The per area output can be more than doubled compared to traditional batch culture, where an entire pond is harvested at the end of the growing cycle, and is then restocked with a new batch of fingerlings. The annual output for a one-year batch culture production cycle is basically equal to the carrying capacity.

1

Most public hatcheries use the batch culture strategy as they mimic the natural spawning cycle of fish intended for release into the natural environment.

The model presented here uses routine fish cultural data, such as growth rates, feed conversions, feeding levels, condition factors, and mortality rates. These data are species and facility specific and often show some variation from growing season to growing season. However, established fish farms should have reliable information for these parameters.

METHODS

Five different culture strategies are presented. They are (1) single cohort or batch culture, (2) two cohort, (3) four cohort, (4) six cohort, and (5) twelve cohort sequential rearing culture. The model is based on the following assumptions:

(a) The system can "process" a maximum of 120 kg of feed per day (MFd = 120).

(b) The Feed Conversion is 1.25 (FC = 1.25), the Feed Efficiency is 80% (FE = 80).

(c) The rearing water Temperature is a constant $15\,^{0}C$ (T = 15).

(d) The Temperature Unit Growth rate is 0.006 cm/d (TUG = 0.006). The daily growth rate equals the average daily temperature times the temperature unit growth rate.

(e) The daily growth rate is 0.09 cm ($\Delta L = 0.09$).

(f) The condition factor is 0.0100 (k = 0.0100). It is assumed to remain constant throughout the rearing cycle.

(g) The beginning weight is 2.75 g ($W_1 = 2.75$).

(h) The harvest weight is 500 g ($W_H = 500$).

(I) The beginning length is 6.5 cm ($L_1 = 6.50$).

(j) The harvest length is 36.84 cm ($L_H = 36.84$).

(k) The length of the rearing cycle is 337 days (RC = 337).

(l) Cohorts are introduced at equal time intervals during a rearing cycle.

(m) For multi-cohort rearing the number of fish are the same for each cohort.

2

If a fish is stocked at an initial length (L_I) and grown until harvested at a final length (L_H), then the length of the rearing cycle (RC) can be estimated by dividing the length gain during the rearing cycle ($L_H - L_I$) by the constant daily increase in length (ΔL).

$$RC[day] = \frac{L_H - L_I}{\Delta L} \qquad (1)$$

The feeding level is determined with the formula developed by Westers (1987) and is expressed in percent body weight or biomass (%BW).

$$\%BW = \frac{(T \times 300 \times TUG \times FC)}{(W/k)^{1/3}} \qquad (2)$$

The value of the numerator is a constant because the values for temperature, temperature unit growth rate, and feed conversion are assumed to remain constant throughout the rearing cycle. This value is 33.75. The denominator represents the length of the fish, but because samples are measured as weight, rather than length, the equation uses weight and the condition factor, k.

Single Cohort, Batch Culture

Fish are stocked into the facility only once per year, and grow through one rearing cycle to a maximum weight of 500 g and length of 36.84 cm. Their final feed requirement, according to equation 2, is 0.91%BW/d. The maximum permissible biomass (MBM) can be estimated by:

$$MBM = \frac{MFd \times 100}{\%BW} \qquad (3)$$

The maximum number of fish (N) can now be determined by:

$$N = \frac{MBM \times 1000 \ (g/kg)}{W_H} \qquad (4)$$

where 1000 represents g per kg.

or by:

$$N = \frac{MFd \times 1000}{Fd/Fs} \qquad (5)$$

Where Fd/Fs equals gram of feed per fish per day, and is calculated with:

$$Fd/Fs = \frac{\%BW \times W}{100} \qquad (6)$$

When only one batch is produced annually, the maximum annual production (MAP) is equal to the maximum biomass the system can support. Thus, MAP also equals the carrying capacity for batch culture. One common assumption with this type of model is that the growth rate is constant over time for the entire cohort of fish.

Multi-cohort, Sequential Rearing Culture

A sequential rearing strategy has a dual benefit: increased production and steady, continuous output over time. The model presented here only requires estimates of fish lengths, weights, and feeding levels for each cohort at an instantaneous point in the rearing cycle, i.e, the

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point at which maximum loading occurs. Lengths and weights for each cohort are obtained by:

$$L_t = L_1 + \Delta L_t \qquad (7)$$

$$W_t = kL_t^3 \qquad (8)$$

Where t is the age of the cohort in days. For the multi-cohort examples that follow, maximum loading occurs on day-337, just prior to harvesting the first cohort of the rearing cycle.

The feeding level for individual cohorts is determined by equation (2). Based on initial parameters, and equations (6-8), a simple table can be constructed giving values of L, W, %BW. and Fd/Fs for each cohort at the point of maximum loading.

An equation for estimating the number of fish in each cohort (N) can be derived from the maximum amount of feed (MFd) the system can process, and feeding levels of all cohorts in the system. Complexity is reduced through the assumption that all cohorts contain the same number of fish ($N = N_{cohort-1} = N_{cohort-2}$, etc...).

$$MFd = \sum_{i=1}^{c} feed_i$$

$$= \sum_{i=1}^{c} N_i x (Fd / Fs)_i$$

$$N = \frac{MFd \times 1000}{\sum_{i=1}^{c} (Fd / Fs)_i} \qquad (9)$$

5

The value of 1000 in equation (9) converts grams to kilograms.

The maximum annual production (MAP) for a selected sequential rearing strategy can then be estimated by:

$$MAP = \frac{N x W_H x C}{1000} \times \frac{365}{RC} \tag{10}$$

where C is equal to the number of cohorts in the rearing cycle.

Equations 7 -10 define the basic mathematical concepts behind the simplified sequential rearing model. In later sections we present results from 2, 4, 6, and 12 cohorts per rearing cycle based on historical data, and demonstrate how fish producers might use this model to help optimize the production potential for their individual systems.

Effects of Growth Rates On Production

To examine the effect of growth rate on production we used slower growing fish in a six-cohort rearing strategy.
The parameters of slower growing fish are as follows:

    (a) The rearing Temperature is 10^0C (T=10)

    (b) The Temperature Unit Growth rate is 0.005 cm (TUG = 0.005)

    (c) The daily growth rate is 0.05 cm ($\Delta L = 0.05$)

    (d) The length of the Rearing Cycle is 607 days (RC = 607)

    (e) A new cohort is introduced every 101 days (t = 101)

    (f) The %BW is 18.75/L (300 x 10 x 0.005 x 1.25/L)

Mortality

Seasoned fish farmers know nearly all cohorts of fish experience mortality losses throughout the rearing cycle. Often mortality rates vary between cohorts and between life stages within cohorts. Based on past experience or historical data, a fish farmer can estimate annual and/or age specific mortality rates in the form of percentages of fish expected to survive from one stage to the next. To examine effects of mortality on the model we assumed constant mortality from year to year, but higher mortality for younger fish than older fish. This can easily be demonstrated for the 2-cohort model.

Assumptions:

(a) Mortality rate for the first 168 days is 8 percent ($m_I = 0.08$).

(b) Mortality rate for days 169-337 is 5 percent ($m_{II} = 0.05$).

(c) Numbers of fish at age are equal between cohorts.

As in the case of the multi-cohort model, length, weight, and feed levels can be estimated from equations (7), (8), and (2).

The number of fish on day 337 equals the number of fish on day 168 less five percent. This can be shown with equation 11.

$$N_{t=337} = N_{t=168} \times (1 - m_{II})$$

(11)

Maximum loading occurs just prior to harvest, which is on day-337 for the examples presented here. The maximum amount of feed that the system can handle must be distributed between the number of cohorts in the system. For a two-cohort rearing strategy:

$$MFd = Feed_{cohort-1} + Feed_{cohort-2}$$

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On day-337, the age of cohort-1 is 337 d, and the age of cohort-2 is 168 d. The maximum amount of feed can be then related to the number and age of individual cohorts:

$$MFd = N_{t=337} x Fd / Fs_{cohort-1} + N_{t=165} x Fd / Fs_{cohort-2}$$

Through substitution of equation (11) into the above equation, and after rearranging to solve for $MN_{t=168}$, the number of fish at the midpoint of the rearing cycle can be obtained:

$$N_{t-168} = \frac{MFd \times 1000}{Fd/Fs_{cohort-1} \times (1-m_{II}) = Fd/Fs_{cohort-2}} \qquad (12)$$

Finally, the initial stocking numbers for each cohort entering the system can be estimated by:

$$N_{t=1} \frac{N_{t=168}}{(1 - m_I)} \qquad (13)$$

RESULTS

Single Cohort, Batch Culture

A single cohort of fish enters the system on day 1; the fish grow through one rearing cycle in 337 d to a harvest size of 500g. From equation (3) the maximum biomass is determined to be 13,187 kg, and the maximum number of fish that should be stocked into the system is 26,374 fish (equation 4).

Batch culture normally requires a full rearing cycle, sometimes a full year, to achieve maximum biomass and to harvest the fish. Feed input to the system approaches the maximum feed allotment the system can process only once per rearing cycle. Thus, through batch culture strategies, the fish farmer is not optimizing the biological efficiency of the culture system.

Multi-cohort, Sequential Rearing Culture

Model estimates for a 2-cohort rearing strategy is shown in Table 1. One assumption of this model is that the number of fish per cohort (MN) is the same for each cohort. Maximum feed input to the system should occur when fish are ready for harvest (i.e., at maximum biomass). Equation (9) states that at the time of maximum daily feed (120 kg or 120, 000 g feed), the feed requirements of all cohorts in the system should equal this maximum. Assuming $MN_I = MN_{II}$ and cohort II starting at 168 we can write:

$$1.57 \text{ MN} + 4.55 \text{ MN} = 120,000$$

$$6.13 \text{ MN} = 120,000$$

$$\text{MN} = 19,576$$

All critical information for two or more cohorts is summarized in tabular form (Tables 1 through 4) and graphically presented in Figures 1 through 4.

The results of the five rearing strategies are summarized in Table 5. Column 3, "ratio" gives the ratios between the maximum annual production realized with the different rearing strategies and the maximum biomass the system can support, i.e., the carrying capacity. In the single cohort, batch culture strategy, the maximum annual production equals the carrying capacity, thus its ratio is 1.0. The two-cohort program accomplishes an annual output that is 1.6 times as great as the one-time maximum biomass, (i.e., the system's maximum carrying capacity).

Column 5 (of Table 5), "kg/ch," lists the increase in production per cohort. As the number of cohorts increases, the gain per cohort decreases. Column 6 "%TMAP" shows the maximum, i.e. 100% efficiency. This theoretical maximum is realized if 120 kg feed could be

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fed 365 d of the year. For a feed conversion of 1.25 (feed efficiency of 80%), the theoretical maximum annual production equals 35,040 kg (120 x 0.80 x 365).

Column 7, "mean Fd/d" records the maximum average daily amount of feed realized at time of maximum biomass. The closer this is to the 120 kg, the more efficient the production.

Effects of Growth Rates on Production

Figure 5 graphically illustrates how diminishing returns on production are realized as the number of cohorts added to the rearing cycle increases. The maximum number per cohort (N) and maximum annual production (MAP) for the slower growing fish were determined using equations 9 and 10.

N = 120,000/7.37 = 16,290

MAP = (16,290 x 500 x 6 x 365)/(1000 x 607) = 29,386

Notice that this group requires an 80% increase in fingerlings, 7247 fish, over the faster growing fish (Table 3), but the maximum annual production remains the same. The maximum biomass for the slower growing fish under steady state conditions is 1.21 times the one of the faster growing species in Table 3. Thus, for equal rearing densities the rearing volume must be 1.21 times greater.

Mortality

Mortality effects were incorporated in the model for a 2-cohort system. Equations (11)-(13) were used to estimate numbers of fish in the system over time. Taking mortality into account, initial stocking levels were estimated to be 22,108 in order to achieve the same MAP estimated for the basic two-cohort model. Thus, the basic model, without mortality, underestimated initial stocking levels by 12.9% as compared to the mortality incorporated model.

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DISCUSSION

Contrary to what one might expect, faster growth rates do not result in greater annual production than slower growth rates, providing there is no difference in feed conversions. Once the maximum biomass has been attained, i.e., the steady biomass of a specific amount of daily feed allowance, the daily gain in fish flesh is the same, as long as feed conversions are identical. However, there are distinct disadvantages with slower growth rates. Slower growing fish require longer time periods and more fish per cohort to achieve steady state. As a result, more space is required, resulting in higher capital costs.

Non-mixed cohort rearing is preferred over mixed rearing in intensive aquaculture. Uniform size fish populations greatly expedite good feed management by producing less feed waste. This is an important environmental issue and a critical economic factor (Midlen and Redding 1998). Table 5 and Figure 5 clearly show diminishing returns with each additional cohort added to the program. The most significant increase per cohort added to a production program is to move from batch culture to two cohorts. The results show that this change in strategy increases production by 61%. The overall increase in production is 104% for four cohorts (26% per cohort), 123% for six cohorts (20.5% per cohort) and 145.5% for twelve cohorts (12% per cohort).

For a non-mixed sequential rearing strategy it appears from the above data that a program of two to six cohorts may be optimal. Much depends on the availability of eggs or fingerlings throughout a year, as well as species' domestication, broodstock programs, number of rearing units, and economics. At the very least, fish culturists should attempt to go from batch culture to one of two cohorts.

Routine fish culture data has been used in this simplified method for sequential rearing strategies. Values have been rounded to simplify hand calculations. Constant values have been

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used throughout the rearing cycle for temperature, feed conversion, growth rate, and condition factor. This is not realistic, but it makes the presentation less complicated, less confusing. The mechanism presented is valid and can be applied where these parameters change during the production cycle. It is of great importance for production managers to establish a reliable data base for these fish culture parameters. Today's computers can readily deal with the variables, including mortalities.

Table 1. Projected fish length, weight, feed percent body weight (%BW), feed per fish (Fd/Fs), biomass per cohort (BM/ch) and maximum feed per cohort (MFd/ch) for a two-cohort rearing strategy at the end, day-337, of the first cohort's rearing cycle.

Cohort	Age (d)	Length (cm)	Weight (g)	%BW	Fd/Fs (g)	BM/ch (kg)	MFd/ch (kg)
2	168	21.62	101	1.56	1.57	1,980	30.9
1	337	36.84	500	0.91	4.55	9,804	89.1
				Total	6.12	11,784	120

Table 2. Length, weight, feed percent body weight (%BW), feed per fish (Fd/Fs), biomass per cohort (BM/ch) and maximum feed per cohort (MFd/ch) for a four-cohort rearing strategy.

Cohort	Age (d)	Length (cm)	Weight (g)	%BW	Fd/Fs (g)	BM/ch (kg)	MFd/ch (kg)
4	84	14.06	27.8	2.4	0.67	345	8.3
3	168	21.62	101	1.56	1.57	1,254	19.5
2	525	29.18	248	1.16	2.88	3,080	35.7
1	337	36.84	500	0.9	4.55	6,210	56.5
				Total	9.67	10,889	120

Table 3. Length, weight, feed percent body weight (%BW), feed per fish (Fd/Fs), biomass per cohort (BM/ch) and maximum feed per cohort (MFd/ch) for a six-cohort rearing strategy.

Cohort	Age (d)	Length (cm)	Weight (g)	%BW	Fd/Fs (g)	BM/ch (kg)	MFd/ch (kg)
6	56	11.54	15.4	2.92	0.45	139	4.1
5	112	16.58	45.6	2.04	0.93	412	8.4
4	168	21.62	101	1.56	1.57	913	14.2
3	224	26.66	189	1.27	2.40	1,709	21.7
2	280	31.70	318	1.06	3.37	2,876	30.5
1	337	36.84	500	0.91	4.55	4,522	41.2
				Total	13.27	10,571	120.1

Table 4. Length, weight, feed percent body weight (%BW), feed per fish (Fd/Fs), biomass per cohort (BM/ch) and maximum feed per cohort (MFd/ch) for a twelve-cohort rearing strategy.

Cohort	Age (d)	Length (cm)	Weight (g)	%BW	Fd/Fs (g)	BM/ch (kg)	MFd/ch (kg)
12	28	9.02	7.3	3.74	0.27	36	1.4
11	56	11.54	15.4	2.92	0.45	77	2.2
10	84	14.06	27.1	2.4	0.67	139	3.3
9	112	16.58	45.6	2.04	0.93	227	4.5
8	140	19.10	69.6	1.77	1.23	347	6.1
7	168	21.62	101	1.56	1.57	5.03	7.7
6	196	24.14	141	1.39	1.96	703	9.7
5	224	26.66	189	1.27	2.40	942	12.0
4	252	29.18	248	1.16	2.88	1,236	14.2
3	280	31.70	318	1.06	3.37	1,585	16.7
2	308	34.22	401	0.98	3.92	1,998	19.5
1	337	36.84	500	0.91	4.55	2,492	22.7
				Total	24.20	10,283	120.0

Table 5. Number of cohorts in a rearing strategy, maximum annual production (MAP), ratio of MAP to the maximum biomass for a one-cohort strategy, initial stocking levels (MN), increase in production per cohort (kg/ch), MAP as a percentage of the theoretical maximum annual production (%TMAP), and mean daily feed per fish (Mean Fd/d).

Cohorts	MAP (kg)	Ratio	MN	kg/ch	%TMAP	Mean Fd/d (kg)
1	13,187	1.00	26,374	-	38	45.6
2	21,237	1.60	19,608	8,050	61	73.2
4	26,902	2.04	12,419	4,572	77	92.4
6	29,383	2.23	9,043	3,239	84	100.8
12	32,381	2.46	4,984	1,745	92	110.4

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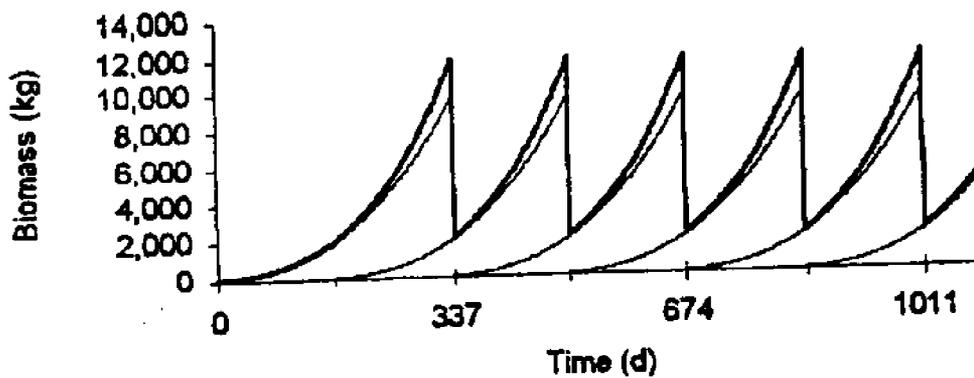
Figure 1. Total production (heavy line) and individual cohort production (thin line) in biomass for a two-cohort rearing strategy based on a 337-day rearing cycle.
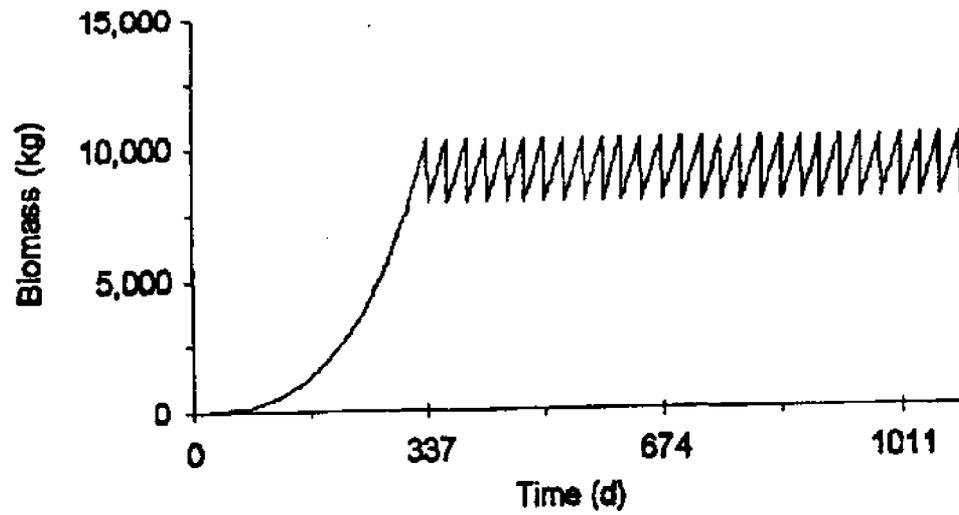
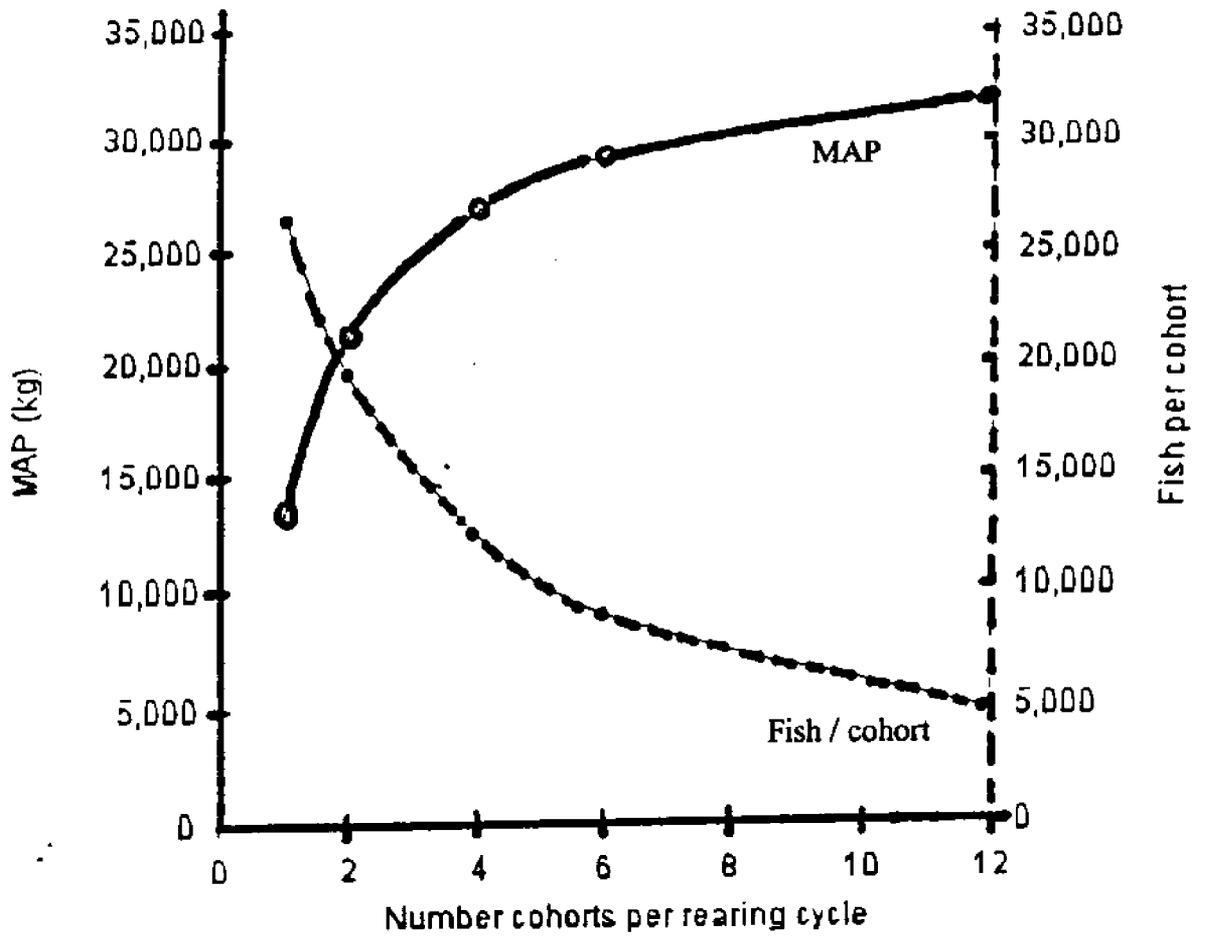**Figure 2.** Production in biomass for a twelve-cohort rearing strategy based on a 337-day rearing cycle.

Figure 3. Maximum Annual Production (MAP), and number of fish per cohort from sequential rearing strategies altering the number of cohorts per rearing cycle.

Maximizing Production

The capacity of a fish production system should be rated on how much **feed per day** it can "process" without exceeding pre-determined water quality parameters.

Assume: Can "process" 120 kg feed per day (264lb)

1. $FC = 1.0 \longrightarrow$ Daily gain = 120 kg
2. Remove the gain daily
3. $365 \times 120 \text{ kg} = 43,800 \text{ kg}$ (96,360 lb)

   1. $FC = 1.25$ (FE = 80%) Gain = 96 kg
   2. $MAP = 365 \times 96 = 35,040 \text{ kg}$ (77.088)

This scenario is not practical – but....

How close can we come to it?

Maximizing Facility Output

Through a sequential rearing program.

a) MFd = 120 kg (264 lb)

b) FC = 1.25   FE = 80%

c) T = 15°C (59°F)

d) TUG = 0.006 cm

e) $\triangle$L = 0.09 cm (0.006 × 15°C)

f) k = 0.0100

g) W_1 = 2.75 g   (165/lb)

h) W_H = 500 g   (1.1 lb)

i) L_1 = 6.5 cm (2.6")

j) L_H = 36.84 cm (14.5")

k) $RC = 337d \left(\dfrac{L_H - L_1}{\triangle L} \right)$

l) New cohort at equal time periods.

m) Same number of fish per cohort.

These are Assumptions

Will apply to: (1) Batch culture (conserv. hatcheries)
(2) Two cohort
(3) Four cohort
(4) Six cohort
(5) Twelve cohort strategies

Sequential Rearing Strategies

$$\%BW = (T \times 300 \times TUG \times FC)/(W/k)^{1/3}$$

$$\%BW = (300 \times \triangle L \times FC)/L$$

$$\%BW = 33.75/L$$

Batch as practiced in conservation hatcheries as they mimic the natural rearing cycles of the fish (but it can depend on their programs)

At final weight and length (500g & 36.84 cm) the %BW = 0.91%

Possible maximum biomass (MBM) based on maximum feed per day (MFd) is:

$$MBM = (MFd \times 100) / \%BW$$

$$MBM = 12,000 / 0.91 = \mathbf{13,187 \ kg}$$

The maximum number of fish (N):

$$N = (MBM \times 1000) / WH$$

$$N = 13,186,800g / 500g/fish = \mathbf{26,373 \ fish}$$

Batch Culture (Cont.)

English: MFd = 264 lb W_h = 1.1 lb

MBM = (264 × 100)/0.91 = **29,010 lb**

N = (29,010)/1.0 = **26,373**

(N = MBM/W_h)

MAP (Maximum Annual Production) is the same as the maximum carrying capacity.

(Fd/Fs): Feed per fish per day is:

Fd/Fs = (%BW × W)/100

For 500g fish: (0.91 x 500)/100 = **4.55g**

(0.91 x 1.1)/100 = **0.01 lb**

Because of the small values when expressed as lb Fd/Fs will be expressed in gram (g).

$$N = (MFd \times 1000g/kg)/Fd/Fs$$

N = 120,000/4.55 = **26,373 fish in system**

Two Cohort Strategy

Table shows fish length, weight, %BW, Fd/Fs, BM/ch, Max. feed per cohort (MFd/ch)   RC = 337

Cohort #	Age d	L cm	W g	%BW	Fd/Fs g	BM/ch kg	MFd/ch kg
2	168	21.6	101	1.56	1.57	1,980	30.9
1	337	36.8	500	0.91	4.55	9,804	89.1
			Totals:	6.12		11,784	120

$$\%BW = 33.75/L$$

$$W = kL^3$$

$$Fd/Fs = (\%BW \times W)/100 \qquad BM/ch = (N \times W)/1000$$

Four Cohort Strategy

CH #	Age d	L cm	W g	%BW	Fd/Fs g	BM/ch kg	MFd/ch kg
4	84	14.1	27.8	2.4	0.67	345	8.3
3	168	21.6	101	1.56	1.57	1,254	19.5
2	252	29.2	248	1.16	2.88	3,080	35.7
1	337	36.8	500	0.91	4.55	6,210	56.5
				Total:	9.67	10,889	120

$N = (120,000)/9.67 = \mathbf{12,410}$

$MAP = (12,410 \times 500 \times 4 \times 365)/(1000 \times 337)$

$MAP = \mathbf{26,882\ kg}$

Batch: **13,187 kg** (**29,011 lb**)

2-Cohort: **21,237 kg** (**46,722 lb**)

Six Cohort Strategy

CH #	d	L cm	W g	%BW	Fd/Fs g	BM/ch kg	MFd/ch kg
6	56	11.5	15.4	2.9	0.45	139	4.1
5	112	16.6	45.6	2.1	0.93	412	8.4
4	168	21.6	101	1.6	1.57	913	14.2
3	224	26.7	189	1.3	2.40	1,709	21.7
2	280	31.7	318	1.1	3.37	2,876	30.5
1	337	36.8	500	0.9	4.55	4,522	41.2
				Totals:	13.27	10,571	120.1

N = 120,000/13.27 = **9,043**

MAP = (9,043 × 500 × 6 × 365)/(1000 × 337)

MAP = **29,383 kg**   **(64,642 lb)**

Next: Comparing 5 production strategies.

A Comparison of Five Rearing Strategies

C	MAP kg	Ratio	N	kg/ch	%TMAP	Fd/d
1	13,187	1.00	26,374	-	38	45.6
2	21,237	1.60	19,608	8,050	61	73.2
4	26,902	2.04	12,419	4,572	77	92.4
6	29,383	2.23	9,043	3,239	84	100.8
12	32,381	2.46	4,959	1,745	92	110.4

Ratio: Ratio of MAP to maximum biomass for batch culture, or maximum carrying capacity.

kg/ch: Increase in production per cohort.

%TMAP: MAP as a percentage of the theoretical MAP

(96 kg/d × 365d = 35,040 kg)

Finally – *Figure 1.*

VIII-12

$N = (MFd \times 1000)/Fd/Fs$

$N = 120,000/6.12 = \mathbf{19,608}$

$MAP = (N \times W_H \times C \times 365)/(1000 \times RC)$

$MAP = 19,608 \times 500 \times 2 \times 365)/(1000 \times 337)$

$MAP = \mathbf{21,237\ kg\ (46,722\ lb)}$

A WHITE PAPER

ON THE STATUS AND CONCERNS OF

AQUACULTURE EFFLUENTS

IN THE NORTH CENTRAL REGION

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for the

North Central Regional Aquaculture Center

Current Draft as of December 1999

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INTRODUCTION AND JUSTIFICATION OF THE DOCUMENT

U.S. aquaculture has shown significant growth during the last two decades. During the 80s, the production of food fish tripled. This average 30% annual increase was primarily the result of a 700% increase in catfish production and a doubling of the trout output. These two species represent over half the food fish production in the U.S., grown primarily in industry scale farms in the states of Mississippi and Idaho. Expansion of the catfish industry is in jeopardy due to drawdowns of the once abundant groundwater sources in the Delta Region (Tucker 1996) and expansion of the Idaho trout industry is on hold as it must meet a 40% reduction in phosphorous discharges (Goldberg and Triplett 1997).

The growth during the 1990s was reduced to an annual average of about 15%. It is rather interesting to note that this more modest growth is mostly the result of new, non-traditional, species entering U.S. commercial aquaculture. These are the netpen operations for salmon in the states of Maine and Washington, the production of hybrid striped bass and tilapia in recirculation systems, and, even more recently, we are witnessing serious efforts to raise newcomers such as yellow perch and walleye as food fish.

This change to new species clearly reflects an increased interest in commercial aquaculture, prompted by the promotional efforts by several organizations and government agencies to counter projected declines in captive fisheries and increases in seafood consumption and imports.

Authors have addressed issues of expansion of aquaculture to convey ideas on how to integrate aquaculture into society. Growth of aquaculture must proceed in a sustainable manner, meaning that it must meet economic, social, and environmental goals simultaneously (Bardach 1997). Boyd (1999) considers the term sustainability, when used in environmental context, as a worthless word because there are many definitions, and no one knows what it means. Boyd suggests that sustainability, where used in the environmental context, should be replaced with the term environmental management. Both Bardach and Boyd have valid points, mainly, aquaculture must be economically viable, socially acceptable, and strive to reduce negative environmental impacts, i.e., it must be sustainable on all fronts.

The Food and Agricultural Organization has defined sustainable development as the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant, and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable, and socially acceptable. These are major challenges the growing aquaculture industry faces, challenges it can neither ignore nor circumvent, nor can a fledgling industry support the needed research and development efforts to accomplish all of these goals.

The U.S. government has acknowledged that a healthy aquaculture development is in the best interest of the nation, and modest research and extension dollars have been channeled through the U.S. Department of Agriculture (USDA) to five Regional Aquaculture Centers.

Since 1989 the North Central Regional Aquaculture Center (NCRAC), encompassing twelve states, has funded a variety of major projects in extension, improved culture technology of a number of species (e.g., yellow perch, hybrid striped bass, walleye, etc.), economics and marketing, wastes/effluents, and several drug-related projects.

Each year, priority areas are identified by the Center and the Industry Advisory Council in consultation with the Technical Committee. These are then presented to the NCRAC Board of Directors (BOD). Each year focuses may change, interrupting continuity.

At their 1998 annual meeting the BOD decided, after consultation with the various committees, that a series of white papers should be developed, addressing the most urgent areas for research and extension activities. Each white paper is to identify the current status, the critical factors limiting sustainable development, and recommendations as to the research and extension agenda that should be considered in future work plans.

Two white papers, one on tilapia and one covering yellow perch, have been completed. Seven additional papers have been approved by the Board, including this one on effluents and the environment.

The Board has recognized that the image of the industry and its future may be in jeopardy unless it deals effectively with environmental issues. Environmentalists are already in an attack mode in the U.S. as evidenced by the 1997 Environment Defense Fund publication of "Murky Waters: Environmental Effects of Aquaculture in the United States" (Goldberg and Triplett 1997). Also, the U.S. Environmental Protection Agency (USEPA) has decided that aquaculture must comply with the Clean Water Act.

The Joint Subcommittee on Aquaculture (JSA) has identified these "challenges" and states: "As U.S. aquaculture continues to expand, it must be sustainable and environmentally compatible. We need substantially better knowledge about possible interactions between aquaculture and natural environments to minimize the potential for habitat degradation, disease transmission, genetic dilution of wild stocks through interbreeding with cultivated strains, introduction of non-indigenous species into natural waters, and discharges of wastes, toxins, and excess nutrients."

CURRENT STATUS ON EFFLUENT AND THE ENVIRONMENT

Concerns and controversies about potential environmental degradation by aquaculture have gone hand in hand with its phenomenal growth and promotion.

A BRIEF HISTORICAL PERSPECTIVE

Prior to 1970, there were no articles of any significance concerning aquaculture as a source of pollution in the U.S., but Earth Day 1970 was a wake-up call. It spurred an awareness about a broad range of environmental issues, including pollution of our surface waters.

Consequently, in 1972, the Environmental Protection Branch of Michigan's Department of Natural Resources (MDNR) became proactive by conducting an extensive evaluation of the water quality downstream from nine state fish production facilities. Results of 41 water quality surveys showed that the fish culture activities generally resulted in increased concentrations of biochemical oxygen demand, suspended solids, organic nitrogen, ammonia nitrogen, orthophosphate phosphorus, and total phosphorus. None of the facilities had any form of waste treatment incorporated in their design (MDNR 1973).

No evaluation was made as to the real impacts on the receiving waters, but shortly after three facilities were completely renovated and designed with solids treatment features, some were discontinued while the remaining facilities were outfitted with simple solids settling ponds.

In 1975, Caufield (1975) reported on the water chemistry of five Columbia River Basin hatcheries and concluded that the variance within a data parameter was so high that the analyses were inadequate to provide reliable quantitative information. This problem is still with us today (Cho et al. 1991).

In 1974 the USEPA drafted regulations entitled "Development document for proposed effluent limitations and standards of performance for fish hatcheries and farms." Final regulations were not promulgated and where regulations have been established, they have been inconsistent due to the lack of a properly prepared guidance document, along with the fact that fish culture methodology was not adequate to predict the time at which effluent limits would exceed in any fish culture situation.

During the 1980s and early 1990s many additional studies to characterize aquaculture effluents and their environmental impacts have been conducted and reported on, both in the U.S. and Europe (DePauw and Joyce 1991; Cowey and Cho 1991; Rosenthal et al. 1993; SRAC 1998).

Most of the ensuing literature shows great variability in reported waste loadings and their environmental effects. This variability is a reflection of the difficulty to develop a uniformly clear picture of aquaculture effluents and environmental impacts. This difficulty stems from differences in culture systems, production rates and timing, quantity and quality of source and recipient waters, hydraulic retention time, fish species and age, feed types and feeding rates, and management procedures such as cleaning and effluent treatment. Bardach (1997) points out that impacts of low dilution, high volume, aquaculture discharges are extremely difficult to determine due to insufficient knowledge about very complex ecological relationships among members of the aquatic community.

Impacts can be beneficial where primarily aquaculture generated dissolved nutrients are added to relatively sterile waters, enhancing its productivity in a positive way. For instance, in the 1950s there were attempts in Michigan to fertilize sterile, unproductive streams with phosphorus. These attempts failed because the phosphorus quickly became unavailable as it bound with the substrate.

Hatchery effluents, on the other hand, function as "drip treatment" systems, continuously adding phosphorus at very low concentrations, allowing most of it to be assimilated by the biota of the receiving water. In other situations impacts are hardly noticeable as they are within the limits of natural fluctuations. In few situations there have been reports of undesirable, damaging water quality degradations where receiving waters are overburdened by aquaculture waste in the form of settleable and suspended solids and dissolved nutrients. Net pen operations in particular have the capability to cause localized degradation due to poor siting, or, when placed in confined bodies of water they can cause hyper-eutrophication. An example for the North Central Region (NCR) is represented by the net pen culture in Minnesota mine pits. These operations were, in essence, shut down by the state's Pollution Control Agency as they were unable to intercept and remove solids and nutrients to prevent excessive eutrophication and solids deposition (Axler et al. 1996; Hora 1999). Other cases may involve industrial-size operations, such as Idaho's trout industry's impact on the Snake River. Overall, the majority of aquaculture operations in the NCR are small, they show no measurable negative impacts, while larger operations appear to be well managed, causing minimal water quality impacts (GLFC 1999).

PRESENT SITUATION

There is a movement afoot by environmentalists to alert the public, the environmental regulatory agencies, and politicians that the projected development of a major U.S. aquaculture industry threatens the environment in multiple ways, and proper safeguards need to be put in place. As a result, regulatory constraints may become even more restrictive and, as such, may actually become the major impediment to the growth of aquaculture into the next decade. To counter this the government (USEPA) and industry must establish and maintain open channels of communication to negotiate practical and sound resolutions to these various environmental issues.

To that end, the JSA has been discussing this need with the EPA and an agreement has been reached to establish an Aquaculture Effluent Task Force under the direction of the JSA. This task force will consist of subgroups composed of persons with practical and research expertise relative to the various types of culture systems; flow-through, recirculation, pond, net pen, etc. (G. Jensen, USDA, personal communication).

Aquaculture must be environmentally responsible, but it should not be subject to excessive and unnecessary environmental regulations (Boyd 1999).

CRITICAL LIMITING FACTORS AND RESEARCH/OUTREACH NEEDS

The rapid growth of aquaculture, in response to the projected shortage of seafood and the promotional efforts by the government, created a climate of excitement resulting in unrealistic optimism causing a "running-before-walking" response. As a result, social, economic, and environmental problems have plagued aquaculture as a new and rapidly growing industry for which technology and management methods are being developed (Boyd 1999). For example, investments made on "turn-key" systems have often failed due to unrealistic, if not outright false, claims about production and performance capabilities.

Aquaculture, eventually, will reach the required performance as the technology pushes itself, but in this process there will be failures (Bardach 1997). Indeed, we have witnessed some failures, including a number of relatively large, high tech operations, making it more difficult to obtain capital for new ventures.

Technology is the critical factor as it must accomplish multiple goals of biological, economic, social and environmental requirements simultaneously.

In a nutshell, according to Midlen and Redding (1998), design and management of aquaculture systems are the critical factor leading to reduced waste output...but unless these functions are affordable, economic failures will occur. In other words, the applied technology must be cost effective. Midlen and Redding (1998) suggest that an incremental approach regarding regulations, combined with improvements in technology, can result in processes more harmonious and sensitive to the economic status of the industry. At the same time it is important to protect traditional small-scale operations from unrealistic or over-burdensome regulations.

The existing, traditional "industry" in the NCR consists mostly of a great diversity of small-scale, low-tech operations. It is pointless to insist on rigid controls for such traditional, relatively small and localized aquaculture facilities where the impacts are low or non-existent (Pillay 1992). Even where there are some adverse impacts recognized, be it minimal, such impacts are not irreversible and can often be avoided with simple measures (Boyd 1999; Collon, personal communication). Unfortunately, in some cases, small aquaculture facilities are subject to the same costly permit fee, monitoring, and discharge requirements applied to large industrial facilities (Rubino and Wilson 1993). It seems most reasonable, in such cases, that permits are negotiated on a case by case basis with as important considerations available treatment methods and the ability of the receiving water to assimilate the effluent. It is clear that this "cottage-type" industry cannot supply the future demand of food fish, but they can fulfill an important role by serving limited niche markets.

As has been true for farming of the land, farming of the water must be intensified to reduce environmental effects and to improve efficiency (Boyd 1999). Intensive aquaculture can be classified as concentrated feed-lot operations, which are subject to water quality regulations under the Clean Water Act. The operations must be as efficient in feed utilization as possible to reduce solid and dissolved wastes.

According to Nijhof (1992) a thorough knowledge on relationships between feed intake and growth should be applied in effluent assessment. Water quality monitoring should be interpreted in close conjunction with basic knowledge on growth and production data to avoid unrealistic estimations.

Cho et al. (1991) address this same concern. The accuracy of effluent analyses suffers from changes in production efficiency or management activities at the moment of sampling. They have shown that modeling the theoretical effects of feeding, based on diet composition and feed conversions, is simple, relatively inexpensive, and more accurate than sampling the effluent.

The development of nutrient dense, high energy, low phosphorus diets have made it possible to reduce waste output. But Nijhof (1992) points out that as the proportion of dietary lipids increase, at the expense of protein, the total waste discharge increases when expressed as biochemical oxygen demand, although the nitrogen discharge is reduced. The most significant waste contribution can come from spilled feed according Nijhof's model. This often is a problem at fish farms and can be as much as 30% of the ration fed (Verdegem et al. 1999). To eliminate this potential waste, fish farmers in Denmark must accomplish a feed conversion of one or less.

No matter how efficient the diet is, there still will be waste and, as a minimum, solids should be intercepted and removed from the waste stream. Removing solids relatively intact and removing them from the waste stream also reduces the discharge of phosphorus and nitrogen. The new technology of micro-screening has worked well in recirculation systems, but shows relatively low efficiency where solids concentrations are very dilute. This is the case with flow-through systems. For example, at a loading of 8.3 lb/gpm (1.0 kg fish/Lpm) and a feeding level of 1.0% body weight, 0.4 oz (10 g) of feed is fed per day per Lpm. If this feed generates 0.1 oz (2.5 g) of solid waste, its average concentration in the effluent is 1.75 mg/L.

For flow-through systems, suspended solids concentrations generally range from 2.0–6.0 mg/L. The large discharge volumes in flow-through systems also result in very dilute concentrations of nitrogen and phosphorus. Warren-Hansen (1982) reports concentrations of total nitrogen in the range of 0.5–4.0 mg/L and total phosphorus from 0.05–0.15 mg/L.

Still, low concentrations in high flow rates can exceed established total daily maximum loads (TDML). For example, 1.0 mg/L in a flow of just 264 gpm (1,000 Lpm) represents 3.2 lb/day (1.45 kg/day), 95.2 lb/month (43.2 kg/month), and 1,142 lb/year (518 kg/year).

Flow-through systems export most, if not all, of the burden for water treatment to the receiving water. These systems have a greater environmental impact than either pond or recirculation systems (Verdegem et al. 1999). Instead of traditional flow-through systems, facilities can be designed and operated as partial recirculation systems. Recent advances in solid waste management have been accomplished through the use of a double drain design in circular rearing units. A bottom drain continuously removes up to 90% of the solids by means of the self-cleaning action created by as little as 10% of the operating flow rate (Summerfelt 1998). Before discharging this effluent it can be treated with micro-screens because solids concentrations are now ten-fold the "normal" 2.0–6.0 mg/L. Also, this flow, if sufficiently small, can be treated further by means of constructed wetlands or "polishing" ponds to remove nutrients. The 90% clean water exits the tank through a drain placed near the surface or at mid-depth and is recirculated with 10% "virgin" water added to it.

Partial recirculation systems such as this require minimal or no biofiltration. A 10% flow-rate replacement greatly exceeds a daily 10% volume replacement a conventional recirculation aquaculture system may have. For instance, a 3.28-ft (1.00-m) diameter circular rearing unit which operates at a depth of 4.20 ft (1.28 m), has a rearing volume of 35.67 ft^3 (1.01 m^3). If operated at a water exchange rate of 1.5 exchanges/hour (40 min retention time) the incoming flow is 6.6 gpm (25 Lpm), the 10% cleaning flow 0.7 gpm (2.5 Lpm). This 0.7 gpm (2.5 Lpm)

represents a daily volume of 951.0 gal (3,600 L). On the other hand, if operated as a true recirculation aquaculture system at 90% efficiency, the 10% daily replacement would be 26.4 gal (100 L) for the rearing volume plus an additional 13.2 gal (50 L) for the rest of the system which may include the biofilter, for a total of 39.6 gal (150 L) versus 951.0 gal (3,600 L) for the partial recirculation system, a ratio of 1:24.

Designing "future" flow-through systems as partial recirculation systems can alleviate many of the concerns expressed by environmentalists. They use less water, effluents can be treated effectively, fish escapes can be prevented to a large extent, antibiotics, of which there are few, are mostly intercepted with the solids and, over time, are neutralized. Many federal and state culture operations are of flow-through design. Future renovation plans of existing flow-through hatcheries should consider partial recirculation system designs.

Additional potential advantages of these systems are application of wetland construction and utilization of solids as fertilizers (Yeo and Binkowski 1999). Also, without biofiltration, it will be easier and safer to treat the recirculation flow with ozone or pretreat the new water if needed.

Unless free heat (waste heat) is available, it is not economically feasible to heat water for a partial recirculation system because of the high, daily, water requirement relative to a recirculation aquaculture system. This "new" technology should be tested along with continuing research and development on traditional recirculation technology.

As future rearing systems move toward solids recovery through partial recirculation systems or recirculation aquaculture system designs, and dilution is increasingly abandoned as a waste disposal solution, aquaculturists will have to deal with the disposal and potential reuse of lowered volumes of more concentrated wastes. Aquaculture waste sludges have high water content and can present costly storage, odor and transportation problems. Like other agricultural manures they may need further stabilization and remineralization of their organic content. Following which they can provide a supplemental source of slow-release nitrogen and have beneficial soil conditioning properties.

The challenge will be to find environmentally appropriate, cost effective, and properly scaled means of disposing and/or beneficially reusing these by-products. In spite of being more concentrated and recoverable, the quantity produced by a typical operation may still be relatively too small to meet the needs of large scaled field agriculture. Transportation costs for hauling waste to reuse or municipal disposal sites may be prohibitively high. Aquaculturists may need innovative strategies for dealing with on-site disposal of these concentrated wastes that can no longer be discharged through dilution into public waters (Yeo and Binkowski 1999).

Existing and developing technologies for nutrient recovery and solid waste disposal (Adler et al. 1996) will have to be adapted to aquaculture facility needs. Improved land application, constructed wetland and septic system designs that are appropriately scaled to aquaculture waste production are needed.

Pioneering efforts by investigators attempting to integrate recirculation aquaculture systems nutrient recovery and solids utilization for producing plant crops have highlighted the difficulties

of matching the scale of waste production with the requirements of the plant crop. Further investigation of these types of strategies will take on increased significance as rearing systems move toward greater water recirculation and waste recovery (Adler et al. 1996).

RESEARCH/EXTENSION PRIORITIES
(not ranked by order)

RESEARCH

Nutrition
- Develop low-polluting diets requiring little fish meal and producing stable fecal pellets for non-traditional species.
- Develop predictive models of nutrient retention by the fish and excretion of solids and dissolved wastes for these diets (Cho et al. 1991; Nijhof 1992; Westers 1995)

Technology
- Test the performance of partial (semi) recirculation systems by evaluating critical water quality parameters, especially ammonia, under different production and water use intensities (Summerfelt 1998; Westers 1999).
- Evaluate commercial scale recirculation aquaculture systems: rearing water quality parameters, production capabilities, water demand, waste management, and economics.
- Evaluate appropriately scaled management strategies and technologies for recovery of nutrients and solids concentrated from partial and full recirculating aquaculture systems.

EXTENSION

- Keep abreast of the technological developments in aquaculture in the U.S. and Europe.

- Conduct workshops on best management practices for environmental management and effluent control.

ACKNOWLEDGMENTS

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A WHITE PAPER ON
THE **STATUS** AND **CONCERNS** OF
AQUACULTURE EFFLUENTS IN
THE NORTH CENTRAL REGION

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NORTH CENTRAL REGIONAL
AQUACULTURE CENTER

DECEMBER 1999

THIS ISSUE:

SUSTAINABILITY

1. ECONOMICALLY
2. SOCIALLY
3. ENVIRONMENTALLY

ALL MUST BE ME SIMILTANEOUSLY

BOYD – 1999   WAS METTING
KEYNOTE ADDRESS:

USE THE TERM

ENVIRONMENTAL MANAGEMENT

KEY: **TECHNOLOGY!**

SUSTAINABILITY

FAO:

1. CONSERVES LAND
2. CONSERVES WATER ⎫
3. CONSERVES PLANTS ⎬ GENETIC
4. CONSERVES ANIMALS
5. NON-DEGRADING ENVIRONMENTALLY
6. TECHNICALLY APPROPRIATE
7. ECONOMICALLY VIABLE
8. SOCIALLY ACCEPTABLE

1 THROUGH 5

ENVIRONMENTALLY

A TALL ORDER FOR THE

AQUACULTURE INDUSTRY

REQUIRES RESEARCH AND DEVELOPMENT

BUT…A FLEDGLING INDUSTRY IS NOT

IN A POSITION TO SUPPORT THE COST

OF THIS NEED – IT NEEDS HELP

JUSTIFICATION:
NATIONAL AQUACULTURE PLAN

"THE DEVELOPMENT OF A
SUSTAINABLE
AQUACULTURE INDUSTRY
IS OF
NATIONAL INTEREST"

ENVIRONMENTAL CONCERNS
(EDF – "MURKY" WATERS)

1. WATER QUALITY DEGRADATION (DIFFICULT TO ESTABLISH)

2. DISEASE (PATHOGEN) TRANSMISSION (WHILRING DISEASE)

3. EXOTICS (ANS)

4. GENETIC DILUTION

5. TOXINS/CHEMICALS

6. ANTIBIOTICS

PUBLIC PERCEPTION

POLICTICAL AGENDAS

POLICTICAL ACTION

HISTORICAL

1970'S

BEEN TRYING TO GET A "HANDLE" ON

EFFLUENT CHARACTERISTICS

YES ⟶ P, N, SOLDIS, BOD

BUT: GREAT VARIABILITY

IMPACTS: ? EVEN MORE DIFFICULT
(PLATTE LAKE, MICHIGAN)

"IMPACTS OF LOW CONCENTRATIONS,

HIGH VOLUMES OF AQUACULTURE

DISCHARGES ARE DIFFICULT TO

DETERMINE DUE TO INSUFFICIENT

KNOWLEDGE ABOUT VERY COMPLEX

ECOLOGICAL RELATIONSHIPS."

BARDACH, 1997

SOME POSITIVE!

EPA 1974

"DEVELOPMENT DOCUMENT FOR PROPOSED EFFLUENT LIMITATIONS AND STANDARDS OF PERFORMANCE FOR FISH HATCHERIES."

FINAL REGULATIONS WERE NOT PROMULGATED

EPA – JAS 2000

AQUACULTURE TASK FORCE
(GARY JENSEN)

FACILITIES
POND,
FLOW-THROUGH,
RECIRCULATION,
ETC.

SPECIES
COMMONLY GROWN
TROUT, SALMON,
CATFISH,
STRIPED BASS,
ETC.

MONITORING OF EFFLUENT WATER
QUALITY!

PROBLEM:

GREAT VARIABILITY
1. TIMING
2. SYSTEMS
3. MANAGEMENT PRACTICES
4. DYNAMICS, ETC.

FEED: SOURCE OF P, N, SS, ETC.

CAN BE QUANTIFIED.

MORE RELIABLE, LESS COSTLY
(CHO, et at.)

DENMARK (FEED LIMITS)

- FEED CONVERSIONS -

TECHNOLOGY

"THE DRIVING FORCE"
ECONOMICS

"THE FRICTION FORCE"
RESISTANCE

WE NEED HIGH QUALITY, LOW COST

"LUBRICATION" TO OVERCOME

THE ECONOMIC DRAG

NUTRITION

SYSTEMS (SRAS, RAS)

WASTE UTILIZATION (RESOURCE)

EXTENSION - BMP - WORSHOPS

Aquaculture – Environmental Concerns & Issues

Can Stir the Emotions. We are all human…

The following statements were actually made by people in leadership positions…statements, no doubt, made when facing challenging situations. The speaker likely felt a strong need to defend personal convictions of one kind or another – in other words, the statements are driven by emotions rather than objectivity.

"I desire what is good. Therefore anyone who does not agree with me is a traitor."

Such logic…
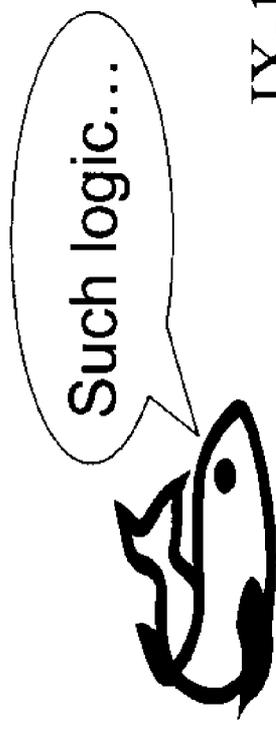
Truth

"I don't want to tell you any half truths, unless they're completely accurate."

And:

"There are two kinds of truths, real truths and made up truths."

Facts

"Some of the facts are true, some are distorted, and some are untrue."

"Don't confuse me with the facts, I've got a closed mind."

Free Speech

"When I want your opinion, I'll give it to you."

Facts are facts, but perception is reality.
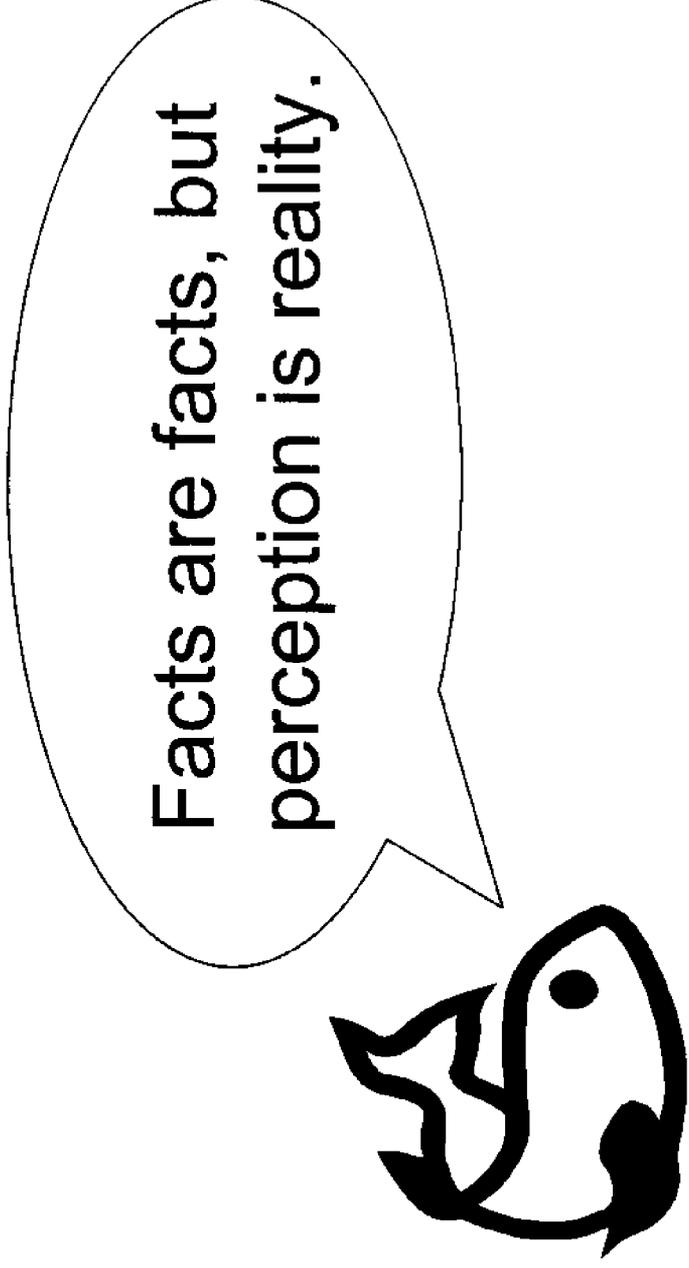
Environmental Issues

1. **Feed Related**

   a) Eutrophication (Nitrogen and Phosphorus)

   b) Sedimentation (BOD)

2. **Disease Related**

   a) Pathogens (example: whirling disease)

   b) Chemicals/Therapeutans

3. **ANS-Exotics = Biological Pollution**

4. **Genetic = Stock Pollution**

5. **Habitat Destruction (Mangroves)**

6. **User conflict = Limited resources**

7. **Predation (birds, seals, etc.)**

8. **Aesthetics (Nimby's)**

9. **Fish meal use**

10. Others?
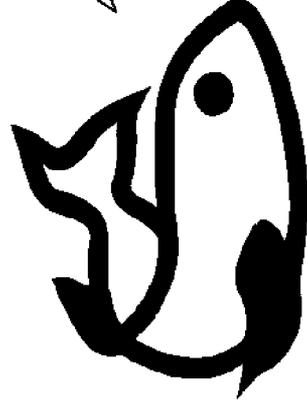
Are these real or perceived?

Concerns

TMDL's (Total Maximum Daily Load)
Watershed Basis

EPA Re-interpretation of clean water act.

EDF Murky Waters
Aquaculture is Agriculture

Agriculture (contribution)
41% to Rivers
23% to Lakes
81% to Wetlands

TMDL contribution versus concentration
Dilution (No Longer) the Solution

Solution

EPA in the process of developing guidelines (effluent) for fish farms.

EPA Wants Input

Committee under Gary Jensen, USDA.

Many Sub-Committees, Many Members,

<u>A Very Large Task</u>

They need **scientific** information, data is available but shows

Much Variation -

Many types of aquaculture systems.

*Also: Many types of receiving waters (environmment)

Examples: Platte Lake, Michigan

               Cherry Creek, Michigan

Feed (Simple Math)

Maximum Total Daily Load – kg or lb/day

Not as mg/1 or ppm

But:

1.0 mg/1 (ppm) @ 1.0 gpm= 5.45 g/d = 0.012 lb/d   @

@ 100 gpm = 1.2 lb/d

1000 gpm = 12 lb/d = 4,380 lb/y

Typical for feed: (salmonids)

Compound	Conc. mg/1	Per 100 gpm lb/d
Suspended Solids	14	16.8
Phosphorus	0.125	0.15
Nitrogen	1.4	1.68
BOD	8.0	9.6

Source: Cripps, 1994

Effluent

Waste Quantification

   1.   Biological (nutritional)

   2.   Chemical (limnological)

Problem with Chemical:

   1.   Effluent variations (time of day, etc.)

   2.   No homogeneous mixing

   3.   Many samples required (costly)

Advantage of Biological:

1. Predictable (diet composition, FC, etc.)

2. Inexpensive (no sampling, analysis)

Case Study (CHO et al. 1991)

Harwood Fish Culture Station

Ontario Ministry of Natural Resources

Result: See Table.

Effluent Characteristics (Salmonids)

Table shows a comparison of wastes using biological (B) and chemical (C) methods.

	Solids		Nitrogen		Phosphorus	
	B	C	B	C	B	C
kg	54	149	12.2	11.6	1.50	2.74
mg/l	1.31	6.17	0.47	0.48	0.042	0.11
% Loss	21	59	66	63	61	112

Intake (kg)	252	18.5	2.45
Gain (kg)	65	6.2	0.92

Only N Match Well

CHO et al. 1991

IX-11

Effluent Characteristics

Fish manure to beef, poultry and swine, presented as ranges on a dry-weight basis.

Element	Fish	Beef	Poultry	Swine
N	2.04-3.94	1.90-7.8	1.3-14.5	0.6-10.0
P	0.56-4.67	0.41-2.6	0.15-4.0	0.45-6.5
K	0.06-0.23	0.44-4.2	0.55-5.4	0.45-6.3
Ca	3.0-11.2	0.53-5.0	0.71-14.9	0.4-6.4
Mg	0.04-1.93	0.29-0.56	0.3-1.3	0.09-1.34

All Show Wide Ranges

Effluent

Feed Related

1. **Dissolved Nutrients (P & N)**
2. **Solids (Particulate & BOD)**

Review:

Agriculture: #1 Source of Water Pollution

Rivers: 41% NPS

Lakes: 31% NPS

Wetlands: 81% NPS

Aquaculture:

Finland Study: P only 2% versus 40%   from

Aqua. N only 1% versus 24% from Agric.

Lake Huron Netpen: 3000 Ton Trout P-15 Ton =

0.3% of Total P (4,360 Ton)

Effluent

Notice: In fish culture, the ratio of water to "pollutants" is very great compared with industrial and municipal waste effluents. This means more samples must be collected and analyzed, but at the same time there is less accuracy in prediction. Fortunately there is only one source of organic fish culture waste, namely feed. (CHO et al. 1991)

Now let's look at feed and feeding strategies to reduce aquaculture waste.

    a) Diet constituents

    b) From feed to fish

    c) From fish to waste

    d) Waste reduction strategies

Effluent

Diet Constituents

1. **Protein** – For Growth (Energy)

    30 – 50%

    Carbon (C) – 50-55%
    Oxygen (O) – 21.5-23.5%
    Hydrogen (H) – 6.5-7.5%
    Nitrogen (N) - $\pm$ 16%

Waste Concerns: Nitrogen & Solids

2. **Carbohydrates** – (starches)

    For energy & heat

    20 – 30%

    Waste concerns: solids, BOD

3. **Lipids** (fat & oils) for:

    Growth & Energy

    10 – 30%

    Waste concerns: COD

4. **Vitamins & Minerals** for:

    Health-Functions

    >2.0%

    Waste concern: Phosphorus

Eutrophication Fresh water: limiting nutrient

Effluent

Feed —→ To —→ Fish

Feed Conversion (FC) and Feed Efficiency (FE)

$$FE = \frac{1}{FC} \times 100$$

$$FC = <1.0 -> 2.0$$

$$FE = > 100\% - <50\%$$

Assume: FC = 1.0   FE = 100%

Feed Fed = 100 Units   Gain = 100 Units

Feed Moisture = 10%   Fish = 75%

Dry Fed: 90 Units   Gain (Dry) = 25 Units

Dry to Dry Conversion: 90 to 25 = 3.6 to 1.0

$$FE = \frac{1}{3.6} \times 100 = 28\%$$

Generally, "True" FE's Range From:

14% (FC = 2.0)   To 20% (FC = 1.4)

Thus: Up to 80% to Waste, as Energy and Heat.

Effluent

Feed → Via Fish → Waste

"Fish Don't Pollute – Feed Does."

"Cars Don't Pollute – Fuel Does."

Feed: Higher efficiency ~ Low P diets
Fuel: Improved efficiency ~ Pb - free

Assume: FC = 1.0

Diet:	
H_2O	10%
Protein	40%
Carbohydrates	25%
Lipids	15%
Ash	8.5%
Phosphorus	1.5%

Effluent

A. **Solid Waste** (25-60%) Depends on FC.
   Assume: 30% (literature supported)
   Solids: $0.30 \times 100 = 30$ units

B. **Nitrogenous Waste** (40% Protein)
   16% N $\longrightarrow$ .16 × 40 units = 6.4 units
   65% is lost $\longrightarrow$ 0.65 × 6.4 = 4.16 units
   Of this 90% is soluble (mostly NH_3)

C. **Phosphorus** (1.5%)

1.5 units

Fish retain 0.45 units (0.45% wet Wt.)

Excess: 1.5-0.45 units = 1.05 units

20 to 40% is Soluble

80 to 60 % "Particulate"

In the solids ~ until ...

Effluent

Feed→ Via Fish→ Waste (cont.)

Total Waste: (In 100 Units)

Solids..............30 units

N ....4.16 units

P .... 1.05 units

H_2O .... **10.0 units**

Total 45.21 units

Energy + Heat **35 units**

Total 80.21units

Feed Efficiency (dry to dry):

100 units – 80.21 units = 19.79 units = <20%

Assume feed waste equals anything above FC = 1.0

Effluent

Feed → Via Fish → Waste (cont.)

Quality of feed allows for a feed conversion of 1.0, but
instead it is 1.5

Now feed waste is 50 units (dry = 45 units)

1. Solids: 30 + 45 units = 75 units
    Fed: 150 units – Solids = 50% of total
    Increase: 150%!

$$\boxed{\frac{75}{1.5}} \times 10 \quad \text{units}$$

1.5 kg

Solids per kg = 1000g
a) 300 g/kg
b) 500 g/kg

Effluent

Reduce P to 1.0 and 0.75%

@ 1.0% .... 1.00 unit of P

Fish 0.45 units, excess: **0.55 units**

Reduction: 48%

@ 0.75% .... 0.75 units

-0.45 units

Out: 0.30 units

Reduction: 71%

Effluent

Feed $\rightarrow$ Via Fish $\rightarrow$ Waste (cont.)

For FC = 1.5 but should be 1.0

2. **Nitrogen**: 4.16 units

$$4.16 + \frac{0.16 \times 40}{2} \text{ units} = 7.36 \text{ units}$$

Increase: 77%

3. **Phosphorus**: 1.05 units

$$1.05 + \frac{1.5}{2} \text{ units} = 1.80 \text{ units}$$

A look at low P diet strategies.

Effluent

Waste Reduction Strategies

1. ## Diet Composition

   a) High digestibility –reduced solids

   b) Balanced protein/energy ratio, reduced N and solids

   c) Low P diets - $\leq$ 0.75%

2. ## Feeding Strategies

   a) Don't overfeed – reduce FW!

   b) Know the diet – expected performance diet labeling?

   c) Know the fish biomass (size &temperature)

   d) Feed the fish (not the pond)

Waste Reduction Strategies (cont.)

3. Facility Design

   a) Efficient solids interception and quick removal.

BOD = ORGANIC LOADING

Heterotrophic Bacteria

Efficiency of Nitrification

g BOD per m$_2$/d
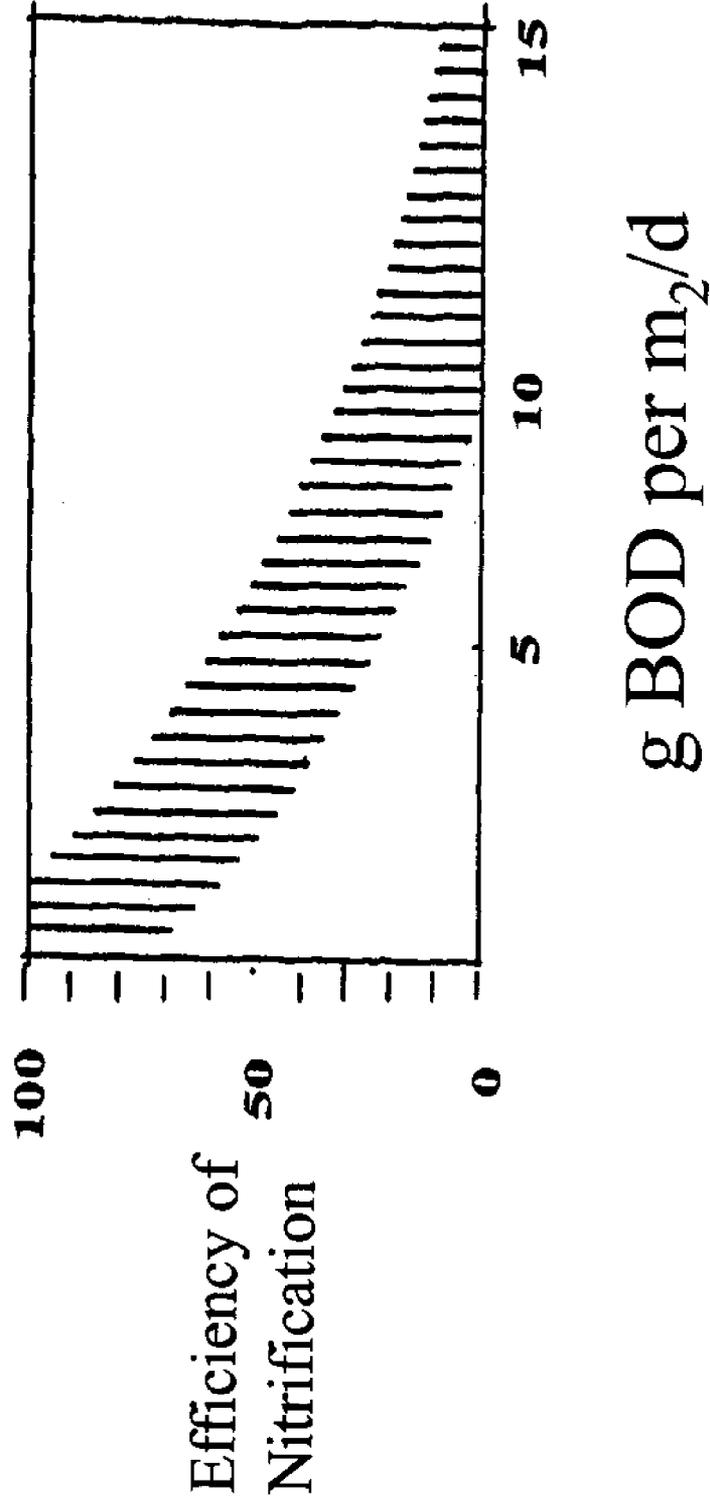
Notation I

Bioengineering

Unit I	Bioengineering
Ld	kg per lpm or lb per gpm
D	kg per m^3 or lb per ft^3
R	Water Turnover Rate in #1 hour
LdF	kg Feed/lpm or lb Feed/gpm
Q	Flow Rate in lpm or gpm
BM	Biomass Fish in kg or lb
MBM	Maximum Biomass
MLd	Maximum Loading
MD	Maximum Density
RV	Rearing Volume in m^3 or ft^3
RU	Rearing Unit

Notation II

Unit I   Bioengineering

DO	Dissolved Oxygen
OF	Gram O_2 per kg Feed/Day
AO	Available O_2 for Fish in mg/l
DO_{in}	Incoming DO
DO_{out}	Minimum DO
TAN	Total Ammonia Nitrogen
TANF	Gram of TAN per kg Feed (lb Feed)
%UA	% Unionized Ammonia (NH_3)
MUA	Maximum Unionized Ammonia (mg/l)
1.44	Gram per mg/l/day (1440 min)
TANC	TAN Concentration in mg/l

Notation III

Unit I   Bioengineering

UAC   Unionized Ammonia Concentration(mg/l)

MAO   Maximum Available Oxygen (mg/l)

Unit II

MR   Respiration/Osmoregulation Metabolic Rate ($mgO_2/kg/hr$)

Unit III   Growth Rates and Feeding

k   Metric Condition Factor

c   English Condition Factor

L   Weight of Fish in g or lb

W   Length of Fish in cm or inch

Notation IV

Unit III   Growth Rates and Feeding

FC   Feed Conversion

FE   Feed Efficiency

TFC   True Feed Conversion

ΔL Daily Length Gain

TUG   Temperature Unit Growth Rate

SGR   Specific Growth Rate

Unit IV   Rearing Unit Design

$L_{m\ or\ ft}$ Rearing Unit Length in m or ft

$W_{m\ or\ ft}$ Rearing Unit Width in m or ft

Notation V

D	Rearing Unit Depth in m or ft
V	Velocity in cm/s or ft/s

Design Process

C	Circular
PF	Plugflow

Recirculation (PRAS & RAS)

MTANC	Maximum TAN Concentration
MUAC	Maximum Unionized Concentration
%RE	% Recirculation
%RV	% Rearing Volume Replacement

Notation VI

Unit VII   Gas Management

Od   Oxygen per day (g or Liter)

G/L   Gas to Liquid Ratio

Unit VIII   Maximizing Production

MFd   Maximum Feed in kg or lb

RC   Rearing Cycle in Days

L_I Starting Length cm or inch

L_H Harvest Length cm or inch

W_I Starting Weight g or lb

W_H Harvest Weigh g or lb

Notation VII

Unit VIII Maximizing Production

N   Number of Fish/Cohort

MAP   Maximum Annual Production

Fd/Fs   Feed per Fish in Gram

BM/ch   Biomass per Cohort kg or lb

C   Number of Cohorts

Equations I

Unit I

$Ld = (D \times 0.06)/R$

$D = (Ld \times R)/R$

$R = (D \times 0.06)/Ld$

$MBM = D \times RV$

$Q = MBM/Ld$
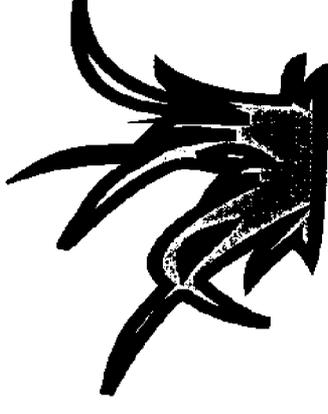
$Q = (RV \times R)/0.06 \text{ or } 8$

$LdF = (AO)/(OF)$

$AO = Do_{in} - Do_{out}$

$TANg = LdF \times TANF$

$TANC = (AO \times TANF)/(1.44 \times OF)$

Bioenergetics

$Ld = (D \times 8)/R$

$D = (Ld \times R)/8$

$R = (D \times 8)/Ld$

Equations II

Unit I Bioenergetics

$$UAC = (TANC \times \%UA)/100$$

$$MAO = (MUA)/(UAC)$$

$$MAO = (MUA \times OF \times 1.44 \times 100)/(TANF \times \%UA)$$

Unit II Respiration/Osmoregulation

Unit III Growth Rates and Feeding

$$k = W/L^3; \ W = kL^3; \ L = (W/k)^{1/3}$$

$$TFC = (\%DF) \times (FC / \%DF)$$

$$\%Gain = [(W_2 - W_1)/(W_1)] \times 100$$

$$\%BW = \% \ Gain \times FC$$

Equations III

$\%Gain = 3 \times \triangle L \times 100$

$\%BW = (3 \times \triangle L \times 100 \times FC)/L$ or $W/k^{1/3}$

$\triangle L = TUG \times {}^{\circ}C$

$W_t = k[W/k)^{1/3} + (TUG \times {}^{\circ}C \times t)]^3$

$W_t^{1/3} = W_1^{1/3} + ({}^{\circ}C/1000) \times t$

$SGR = 100 [(LnW_t - LnW_1)/t]$

Unit IV Rearing Units

$V = (L_m \times R)/36 \qquad (L_f \times R)/3600$

Equations IV

Unit V Design Process

$$AO = (Ld \times OF \times \%BW)/100$$

$$DIA = 2\sqrt{(RV)/(\text{||} \times d)}$$

$$L_m = (V \times 36)/R \qquad L_f = (V \times 3600)/R$$

$$R = (V \times 36)/L_m \qquad R = (v \times 3600)/L_f$$

$$d = (RV)/(L \times W)$$

$$Ld = MBM/Q$$

Unit VI Recirculation

$$\% RE = 100 - [(Ld \times \%BW \times TANF)/(1.44 \times MTANC)$$

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Equations V

$$MTANC = (MUA \times 100)/(\%UA)$$

$$\%RV = (MLd \times \%BW \times TANF \times 4.2 \times R \times 1000)/(60 \times MNO_3)$$

Unit VII Gas Management

$$Odg = Q \times AO \times 1.44$$

$$Odl = Q \times AO(1.01O_2 = 1.43 \text{ g})$$

Equations VI

Unit VIII Maximizing Production

$MBM = (MFd \times 100)/(\%BW)$

$N = (MBM \times 1000)/W_H$

$N = (MFd \times 1000)/Fd/Fs$

$MAP = (N \times W_H \times C \times 365)/(1000 \times RC)$