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SOME PRINCIPLES OF SALMONID HATCHERY DESIGN

Harry Westers, Fisheries Biologist

SUMMARY

Successes, in particular with anadromous salmonids released as smolts, have resulted in the construction of many new salmonid hatcheries during the last decade. Many are multi-million dollar facilities designed for the production of millions of fish annually. Several consulting engineering firms have become interested and involved in hatchery design. This required fish culturists and biologists to communicate ideas to engineers generally unfamiliar with biological concepts.

The biologists on the other hand, unfamiliar with engineering rationale, experienced difficulty in following the engineers' reasoning. These situations had much potential for misunderstanding which would lead to frustration and confusion.

One fact the engineers quickly discovered was the wide range of opinions among fish culturists on almost any facet of hatchery design. Few could support their position with precise facts or scientific data; something the engineers were interested in. To date, considerable progress has been made in narrowing these gaps as some parameters have been established to serve design engineers. However, much information is yet lacking. The state of the art, to a large degree, is still one that depends upon personal opinions, theories, ideas, preferences, traditions, etc.

The need for applied research in fish culture, aimed at establishing design parameters, becomes very important when multi-million dollar facilities are involved.

SOME PRINCIPLES OF SALMONID HATCHERY DESIGN

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INTRODUCTION

It was in the mid 1860's that salmonid fish culture made its start in North America with such pioneers as Drs. Theodatus Garlich and H. A. Achley of Cleveland, Ohio; Dr. D. W. Shapman and Seth Green of New York. In Michigan, N. W. Clark started a trout hatchery in Oakland County (near Detroit) in 1867. In 1873, the Michigan Fish Commission was established by Act 124; their first hatchery was built in 1873 for $1,200. It was located in southwest Michigan near Niles, and consisted of a hatching house and a series of ponds. It had a spring water supply of 300 gpm. Other hatcheries followed. Changing programs were responsible for the ups and downs of fish culture's role in fisheries management.

Major fish management programs for Michigan were the following:

Fry Era - 1873-1929

Fingerling Era - 1930-1949

Legal Size Trout Era - 1950-1964

Modern Management Era - 1965-Present

Hatchery facilities were required to adjust their production to the changing programs, from fry to fingerling, to legal fish. This was generally accomplished with the addition of rearing ponds (raceways) to the existing hatcheries and the building of trout rearing stations on selected streams. In the years from 1927 through 1929, a three-year period, Michigan built 18 trout rearing stations. All have since been abandoned. The last one to go was the Sturgeon River Rearing Station, which became infected with Whirling Disease in 1975.

Michigan built 36 hatcheries and 22 rearing stations from 1873 through 1936. Only six hatcheries are now in operation, including the new 6.5 million dollar Platte River Hatchery completed in 1974. This brings the account up-to-date.

During the last few decades, many new large salmonid hatcheries have been built in the northwest pacific states as required mitigation against dam construction. Management successes with salmon and steelhead released as smolts further encouraged the construction of new, large production hatcheries. The recent success with Pacific salmon introductions into the Great Lakes has created there too, the need for new modern salmonid hatcheries. These facilities are no longer the relatively simple hatcheries of earlier years, with frame construction buildings and earthen rearing ponds. Instead they are multi-million dollar fish factories built with concrete and steel, and equipped with complex and expensive mechanical systems for water delivery, pre-treatment, monitoring, alarms, back-up provisions, automation, and effluent treatment. Projects of such magnitude could often not be handled by agency engineering departments because of a lack of manpower and specialized disciplines.

Consulting engineering firms became interested and involved in hatchery design and during the last decade, quite a lot of experience has been obtained. It has been an interesting challenge to both engineers and fish cultural specialists who were required to communicate their know-how and ideas to the engineers, to be translated into a workable, safe and efficient hatchery facility. The engineers rather quickly discovered that biological principles differed from engineering principles, and that a wide range of personal opinions existed among fish culturists on almost any facet of hatchery design. The engineers, accustomed to working and thinking in terms of predictability, based on unalterable physical laws, had to communicate with biologists who worked with concepts of variability. This created interesting, and at times, frustrating communication problems. Few biologists (fish culturists) could support their positions on various hatchery design criteria with scientific data--something the engineers were looking for. This problem was recognized and in 1972 the Great Lakes Fishery Commission sponsored a Great Lakes Fishery Biology Engineering Workshop in Traverse City, Michigan. This "Bio-Engineering Fish Rearing Facility Design Workshop," was a first of its kind. The chairman of this workshop, Mr. Ray R. Vaughn, considered the greatest challenge and opportunity of this workshop to be that of developing a "common language" and rapport between biologists and engineers.

RECOGNITION OF CERTAIN IMPORTANT PRINCIPLES

Although much progress has been made during the last five years in identifying and refining design parameters, much of the credit is due some fish culturists who recognized important principles more than 20 years ago. The true pioneer, I believe, is David C. Haskell of New York State, who provided the foundation for estimating the carrying capacity of troughs and ponds based on the following assumptions:

1) Carrying capacity is limited by

    a. oxygen consumption and
    b. accumulation of metabolic products

2) Amount of oxygen consumed and the quantity of metabolic products are proportional to the amount of food fed. (Haskell, 1955).

Through experience, Haskell arrived at specific permissible feeding levels per cubic feet of rearing space, which varied for trough and rearing pond. He stated that this method of computing carrying capacity should be considered a temporary approach until further knowledge of water quality and trout metabolism provide the fundamental knowledge for a more realistic solution. Harvey Willoughby (1968), assuming Haskell's basic premises to be valid, developed a method of determining carry capacity based on known oxygen consumption per pound of food fed. If oxygen is the first limiting factor, this method, he states, can be used to predetermine carrying capacities without trial-and-error experiments, giving the engineers dealing with hatchery design a tool for predicting the capacity of a hatchery on the basis of volume and oxygen content of the water supply.

Brockway (1950) suspected that ammonia might be a significant adverse factor in fish cultural operations. He demonstrated that increased water turn-over rates in rearing ponds could reduce the ammonia levels in the pond significantly.

A simple application of this principle would be the lowering of the water levels during periods of high ammonia output (warm temperatures; high feeding levels). He suspected that where water was re-aerated from pond to pond, ammonia build-up rather than oxygen depletion, was the limiting factor.

In an attempt to determine the toxicity of ammonia on fish, Burrows (1964) conducted experiments with chinook salmon. He found that concentrations of un-ionized ammonia as low as 0.006 ppm under conditions of continuous exposure for six weeks, produced extensive hyperplasia in the gill epithelium of chinook salmon fingerlings. He further observed that these same fish could tolerate un-ionized ammonia levels as high as 0.7 ppm for one hour per day without apparent harm. Toxicity levels of ammonia, other than lethal levels, are difficult to ascertain according to Burrows, because the effects are insidious and indirect.

The above account briefly covers some important groundwork accomplished from 1950 to 1964 which, no doubt, has contributed greatly to where we are today.

Recently some engineers have made helpful contributions to aid in the rational design of salmonid hatcheries (Dydek, 1972; Liao, 1972; Speece, 1973). Recent additional data provided by fish culturists on the relationship of food to metabolic waste products (Willoughby et al, 1972) and the effects of ammonia on trout (Smith and Piper, 1975) can be applied readily as design parameters.

In this presentation, I will attempt to review with you my thoughts on the importance of water quality, pond design, flow rates, and rearing densities relative to hatchery design.

Some of the views given are based on scanty data. I hope this discussion will stimulate fish culturists and engineers alike to do more data gathering to apply to models which can aid in the design of modern salmonid fish hatcheries.

WATER QUALITY

In order to demonstrate the effects of certain water quality characteristics upon its carrying capacity, I will use nine factors considered valid to hatchery rearing of salmonids. They are of great importance to hatchery design and represent, basically, the groundwork laid by the authors previously mentioned.

1) Carrying capacity is limited by

   a. oxygen consumption and
   b. accumulation of metabolic products

2) Amount of oxygen consumed and quantity of metabolic products produced are proportional to the amount of food fed.

These are the assumptions proposed by Haskell in 1955. They have been found valid and thus have practical application.

3) Oxygen consumption is 0.25 pound per pound of food.

4) Ammonia production is 0.03 pound per pound of food.

These two criteria, under normal conditions, have been found to be the most significant limiting factors affecting the carrying capacity of the hatchery. The values are "averages" and may vary slightly depending on type of food, water temperature, fish size and species as well as other environmental characteristics. Since only un-ionized ammonia is toxic, we are not concerned with total ammonia levels unless the un-ionized portion reaches the critical level.

5) The maximum level of un-ionized ammonia is 0.025 ppm. (Smith and Piper, 1975).

6) The incoming water is assumed to have 90 percent saturation of dissolved oxygen.

7) The outgoing water has 5.0 ppm of dissolved oxygen.

8) Food conversion is 1.5.

9) The growth rate is 1 inch per 1000 temperature units. A temperature unit (T.U.) in this case represents one degree F above 32°F for 24 hours. A constant temperature of 42°F provides 10 T.U.'s per day, 300 per month.

With good water quality, either oxygen or un-ionized ammonia will become the limiting factor as poundages of fish and food utilization increase. Both oxygen and un-ionized ammonia levels can be manipulated to a certain degree, through aeration, de-nitrification, or changes in pH. It is important to determine the economic feasibility of such manipulations.

The following figures illustrate the effects of certain water quality criteria on the carrying capacity of the water itself. The relationship is expressed in pounds per gallon per minute. It has been worked out for three different fish sizes: 2.0 inch, 4.0 inch, and 6.0 inch; for three different temperatures, 10, 15 and 20°C, and five pH values (7.8 - 8.2). These pH values represent the range found in Michigan's salmonid hatcheries.

Figure 1 illustrates the effects of temperature and pH on ionization of ammonia. The 0.025 ppm un-ionized ammonia level is the constant. Figure 2 illustrates the same for pH values 7.8 through 8.2; the conditions used in this exercise. Figures 3, 4, and 5 show the pounds per gallon per minute that can be produced for three fish sizes, under the specific conditions of three temperatures and five pH values. Both the oxygen (5.0 ppm) and un-ionized ammonia limitation (0.025) curves are presented in these figures. Since the oxygen depletion is independent of the pH value, its limitation "curve" is a straight, horizontal line. In contrast, the significance of the pH value of the water with respect to the degree of ionization of ammonia is obviously reflected in the ammonia limitation curve.

In all instances, for these specific temperatures and pH values, oxygen depletion is the first limiting factor. In other words, the 5.0 ppm dissolved oxygen level is attained before un-ionized ammonia has reached the level of 0.025 ppm. However, for the 20°C temperature and a pH of 8.2 they nearly coincide.

For a pH value of 7.8 and a temperature of 20°C the water can be used three times (provided it is re-aerated twice to its 90 percent saturation level) before ammonia becomes a limiting factor. For a temperature of 10°C it could be used 3.5 times. The advantages of relatively low temperatures and pH values are very obvious.

Returns per energy input (aeration) are much greater for low temperatures. To correct an ammonia problem it might be more practical to alter (lower) the pH of the water, than to provide de-nitrification systems. Changes in pH of up to one full unit will not affect the fish adversely.

Since an ammonia problem may not occur until the hatchery reaches the peak loading in its production cycle, it is important to identify the critical time,duration as well as magnitude of this limiting factor. This will then permit one to determine the degree of water quality manipulation and the cost per unit production gained. This is especially valid for those salmonid hatcheries used for the production of fish for management programs, since they are often low in poundage during a significant portion of the year.

POND DESIGN

The rearing or production components of a typical salmonid hatchery are incubators, starting tanks, intermediate rearing raceways, and large outdoor rearing ponds.

An interesting evolution has occurred with respect to the rearing pond, the major production component of the hatchery. Originally an earthen structure (and still so in many places), it was designed in many different shapes. Ultimately the long, narrow pond became the most popular. It was called a raceway, and water would travel in a directly linear fashion from the upper to its lower end. When built in series, one above the other, water could be re-aerated by simple gravity, dropping it six inches or more from pond to pond.

Due to erosion, maintenance, and operational problems, many earthen ponds were converted to concrete and most new ponds are now built of concrete. Interest in pond design, however, continues since fish culturists observe differences in productivity and fish health from one type of pond to another. Such observations, although often correct, are not analyzed as to the real reason for better or poorer performance. Opinions and controversies developed. This has challenged several investigators to attempt to determine factors responsible for good (or poor) pond performance (Burrows and Chenoweth, 1955; Haskell, et al 1960; Buss and Miller, 1971).

Two principle types of rearing pond have been developed: the flow-through pond, and the circulating pond. Careful design has resulted in hydraulic characteristics, which avoid short-circuiting, stagnation, eddies, etc., as much as possible.

Of the flow-through types, the relatively narrow, rectangular raceway is the most popular. Relative dimensions vary, but a length:width:depth ratio of 30:3:1 is very acceptable within reasonable measurements, which will be mentioned later. Intake and outlet should cover the full width of the pond.

Of the circulating type, the following three are most commonly used: the circular pond, the Burrows pond, and the Swedish pond.

The circular pond has been in use for many years and is now available in pre-assembled form, constructed out of styrofoam and fiberglass.

The Burrows pond, with specifically established dimensions, is rectangular in shape with rounded inside corners. Multi-level underwater intake occurs at one corner, or at two opposite corners. The pond is equipped with turning vanes to aid in hydraulic stability aimed at a smooth laminar flow throughout the pond, and with relatively high velocities along the outer edge, diminishing towards the so-called baffle wall. (Burrows and Chenoweth, 1970).

The Swedish pond was developed specifically for Atlantic salmon; it is square in shape with rounded corners. Water intake is at the surface.

In principle, all circulating ponds mix the incoming water with used water. The smoother the hydraulic characteristics, the more quickly the entire water-mass, or pond environment, becomes homogeneous. In contrast, the flow-through pond has a very distinct gradient in water quality from intake to outlet.

I believe that a distinct gradient in water quality is the more desirable characteristic for the rearing environment of salmonids. The fish require well oxygenated water and have a relatively low tolerance for un-ionized ammonia, especially when exposure is continuous. Since oxygen and ammonia are probably the most critical factors that determine the carrying capacity of the water as discussed earlier, anything in pond design that can reduce their negative effects, is therefore very desirable.

Unfortunately, sufficient empirical data are lacking to fully support the supposition set forth in the following discussion. Water should enter a rearing pond at 90 percent or more saturation of dissolved oxygen and the outflow should not go below 5.0 ppm. In the flow-through pond, a gradual decline in dissolved oxygen will occur from the head to the foot of the pond;

the reverse is true of ammonia or any other metabolic waste product. With the circulating pond, this gradient is absent, especially where hydraulic characteristics accomplish a homogeneous environment as quickly as possible. As soon as that equilibrium is reached, the pond environment will virtually remain constant throughout the day.

At the Platte River salmon hatchery in Michigan, a circulation pond (Burrows type) was modified into a flow-through pond (Figure 6). Data on oxygen and ammonia were collected one day during the production season. These data are presented in Figures 7 and 8. Indeed, it is observed that the circulating pond essentially lacks a gradient in dissolved oxygen and ammonia, while the flow-through pond shows a distinct gradient. Unfortunately, very little data were obtained.

I believe that a gradient in water quality is better for the fish because it gives them the opportunity to select the higher quality water; even if it means higher density of the population. If density, however, becomes an irritating factor, the fish have the option to move into the less dense area of the pond. The flow-through pond offers intermittent exposure to a variety of environmental conditions. In the circulating pond, there is no opportunity for selection of higher oxygen levels and lower ammonia levels, and the fish are exposed to the "average" environment which could be mediocre in quality. The fish may be distributed more evenly in this type of pond, but whether this is an advantage or not is debatable. Another disadvantage of the circulating pond is the fact that fast exchange rates of water are not possible without upsetting a well balanced hydraulic pattern and water velocities.

The flow-through pond on the other hand, permits a high exchange of water without creating too high velocities. It is my opinion that water exchange rates of four or even more per hour (number of complete displacements per hour of water in the pond) are very practical for most salmonids, without having to sacrifice on the production per gallon per minute. Densities, of course, must increase proportionally. The following equation can be used to demonstrate this fact:

$$\text{LBS/GPM} = \frac{8}{R}\ \text{LBS/Cu. Ft.}$$

Where (R) represents the hourly exchange rate (Westers, 1970)

Hatcheries with rectangular flow-through raceways require less rearing space if relatively high exchange rates are used. Such high exchange rates also prevent long term or continuous exposure to metabolites, since peak activity (metabolic output) is normally followed by periods of relative rest. Long term exposure of even very low levels of ammonia can be harmful to the fish (Burrows, 1964). In addition, since no metabolites will linger on, the environment will not become conducive to establishing a nitrification process which could produce the highly toxic nitrite compound. It requires a certain amount of time to establish a culture of the nitrifying bacteria, which will convert the ammonia to nitrite. (Collins, et al, 1975). The flow-through raceway, where a complete water exchange occurs every fifteen minutes, provides salmonids with an excellent rearing environment.

One additional comment should be made with regard to the rectangular, flow-through raceway. This pertains to a modification where baffles are installed to increase the bottom velocity to accomplish self-cleaning of the raceway and in addition, offer the fish a choice of velocities.

In Michigan, this technique has been tested at several State Fish Hatcheries in troughs, rearing tanks, and raceways. It appears to have enough advantages to include baffles in the design of all our new and renovated units. This is not a novel idea, however, since in the late 1940's it was already in a slightly different way, utilized at Cortland, New York (Rodgers, 1949). This technique, in conjunction with a properly designed clean-out and solid collection arrangement, offers an excellent potential for an effective effluent treatment system (solid removal).

REARING DENSITIES

In salmonid culture, densities are usually expressed in terms of pounds of fish per cubic foot of rearing space. The following equation is helpful in determining the densities under certain specific conditions:

$$\text{LBS/Cu. Ft.} = \frac{R}{8}\ \text{LBS/GPM}$$

Again, "R" represents the exchange rate per hour and it is the only selected value. The others are pre-determined as discussed earlier for pounds per gallon per minute (Figures 3, 4, and 5).

Selection of the exchange rate has a very significant effect upon hatchery design, since it dictates the amount of rearing space required per single water use (one pass). The higher the exchange rate, the less rearing space is needed, thus reducing both capital outlay and operational costs.

Circulating ponds, as we know them today, offer little flexibility in the selection of exchange rates. I am of the opinion that four changes per hour is about ideal, and advocate a lower rate only where temperatures are a constant low (less than 50°C).

Returning to Figures 3, 4, and 5 we can obtain the rearing densities in cubic feet by dividing the pounds per gallon per minute for the one-pass system by two. These values are represented in Figure 9. Note from this figure that maximum allowable densities are much greater under low temperature conditions. If one desired higher densities under the conditions of relatively high temperature, the exchange rate would have to be increased, but this may not be desirable under conditions of such high temperature. Four changes per hour, I believe, is a good selection for the following reasons:

1. Some grace time is allowed in case of water shut-off. Reliable water sources and intake systems to the rearing ponds are imperative. The ponds should also be protected with an alarm device that responds as soon as flows to the pond diminish.

2. Solids will settle, allowing removal through special clean-out systems. Solids will settle effectively (90 percent) when velocities remain at 0.1 foot per second or less (Jensen, 1972). If we accept a rate of four water changes per hour (R=4), a linear rectangular flow-through raceway should not be longer than 100 feet, unless velocities are greater than 0.1 foot per second. The relationship can be expressed by the following equation:

$$V = \frac{R \times L}{3600}$$

Where V equals velocity in feet per second, R is rate of exchange, and L is length of raceway in feet. Lowering the exchange rate would allow longer raceways, while maintaining the pre-determined velocity of 0.1 foot per second (Figure 10).

3. Metabolites are removed relatively quickly. I am of the opinion that a water exchange every fifteen minutes accomplishes efficient cleansing and the quick removal of metabolites. This might be compared with a good ventilation system in a crowded meeting room.

4) It gives a good ratio of available water to rearing space from a management, as well as economic, point of view.

I believe that a hatchery built on the principle of four water changes per hour through its major rearing components will not be "top heavy" with rearing space.

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Figure I Permissible Total Ammonia in PPM

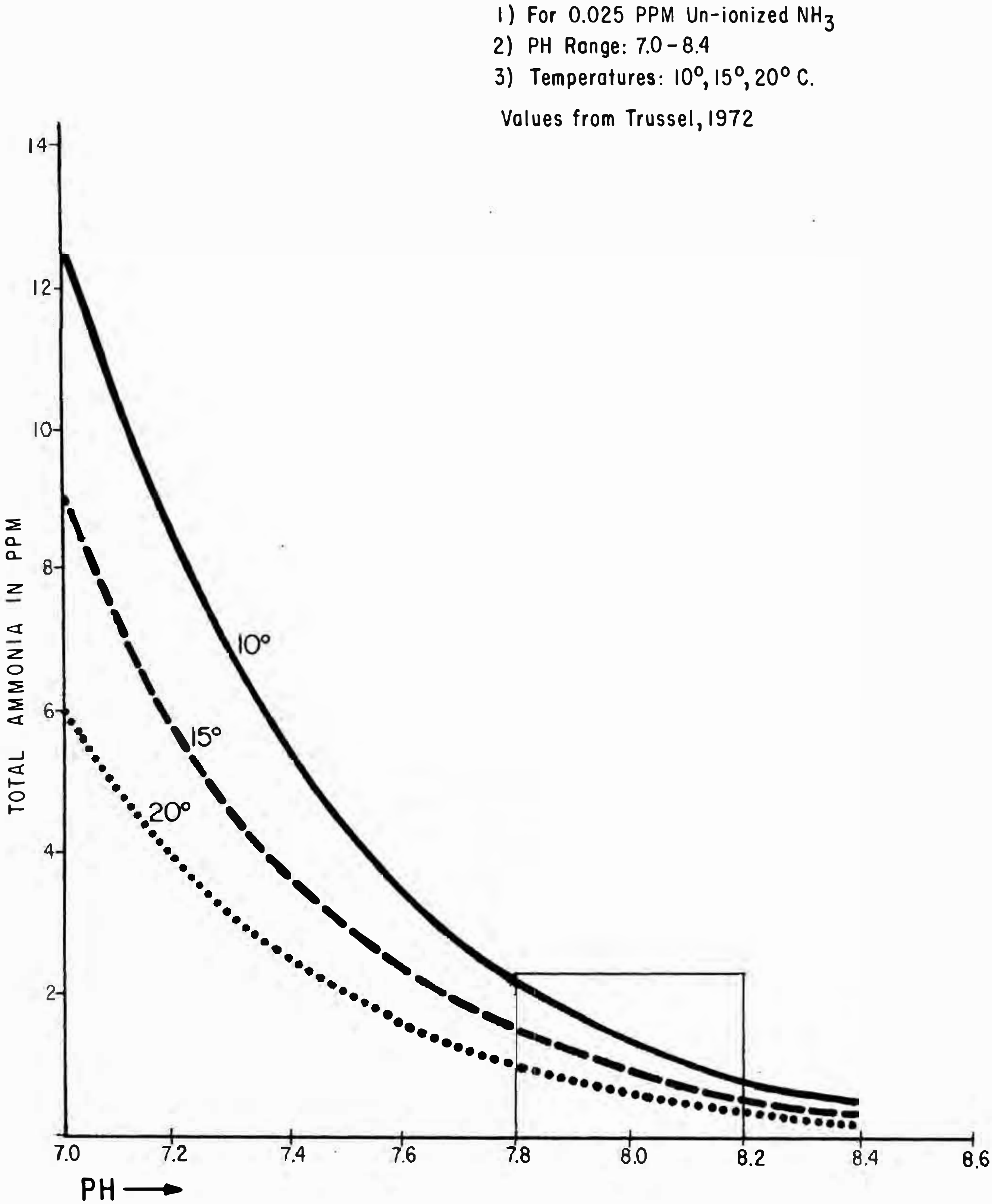

Figure 2 Permissible Total Ammonia in PPM

1) For 0.025 PPM Un-ionized NH_3
2) PH Range: 7.8 - 8.2
3) Temperatures: 10°, 15°, 20° C.

Values from Trussel, 1972

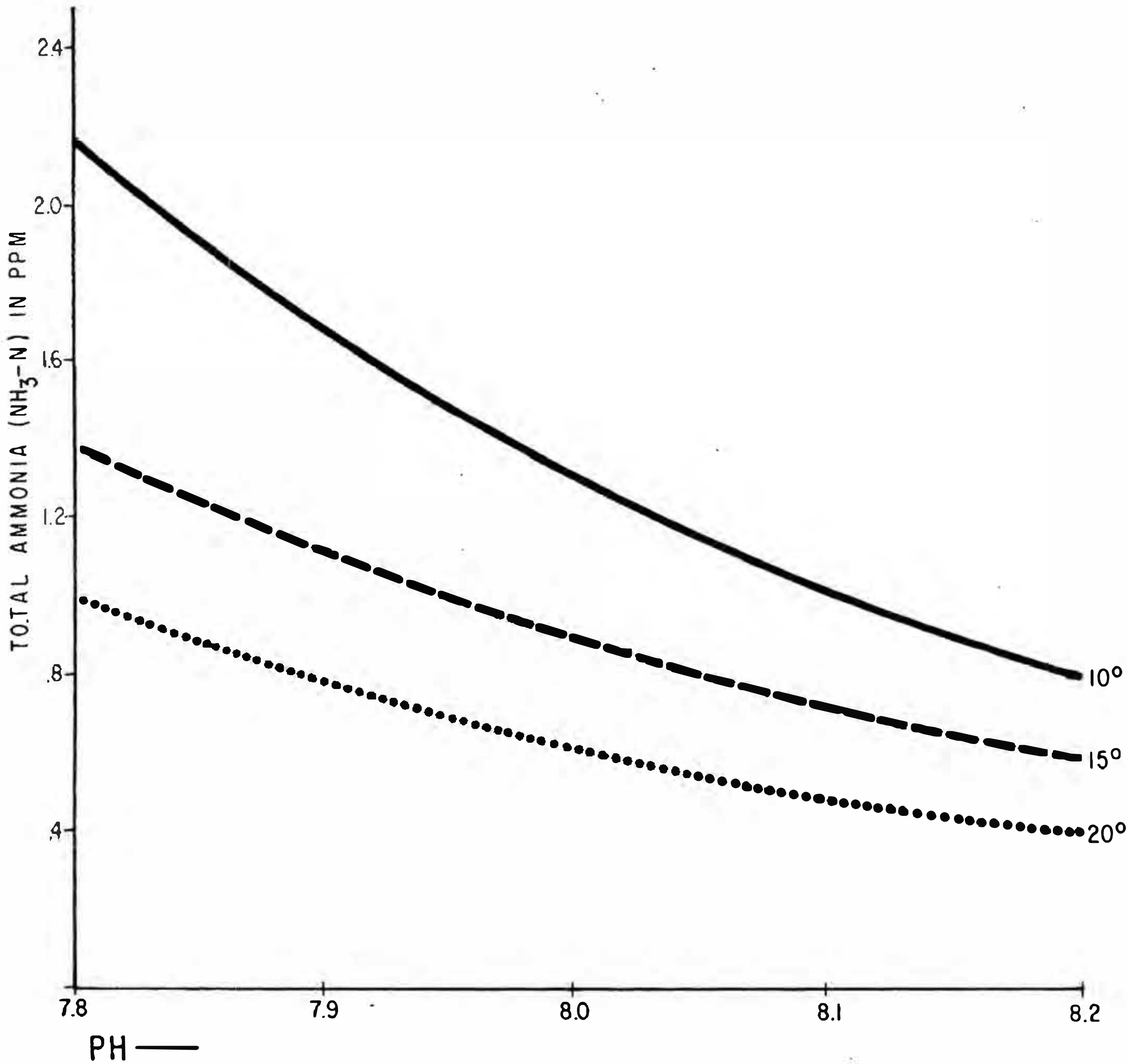

Figure 3 Production in Pounds Per Gallon Per Minute Flow

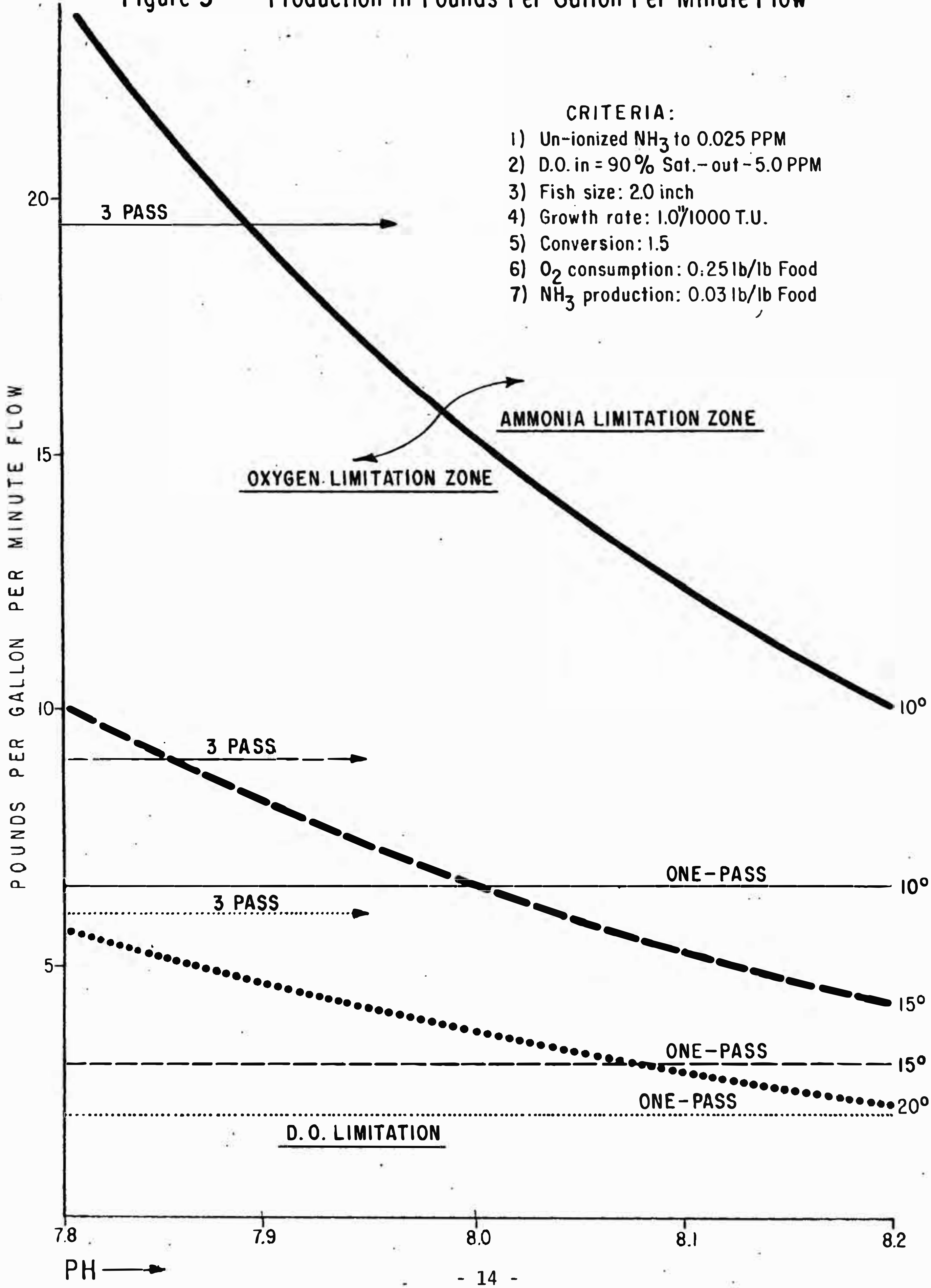

Figure 4 Production in Pounds Per Gallon Per Minute Flow

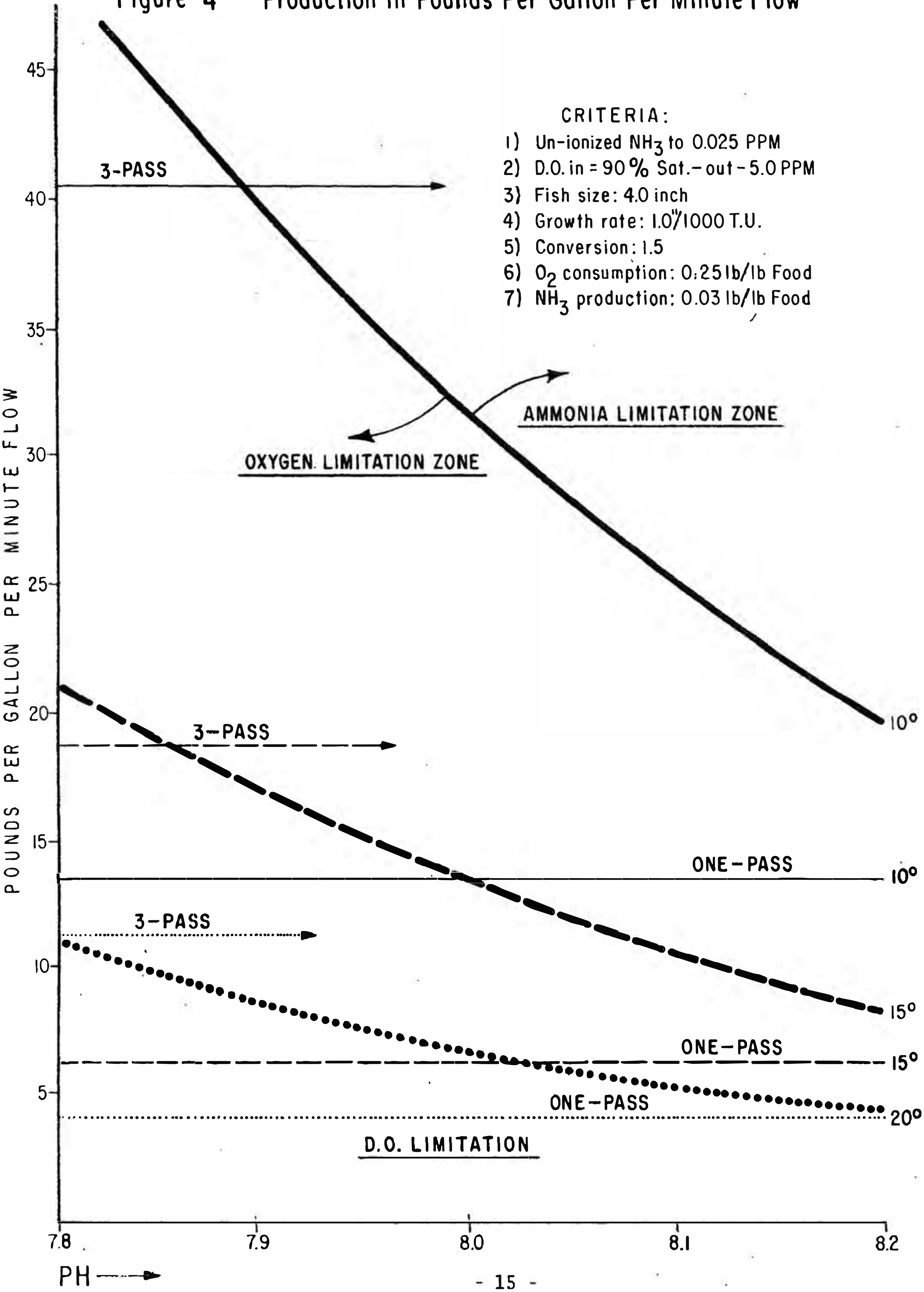

Figure 5 Production in Pounds Per Gallon Per Minute Flow

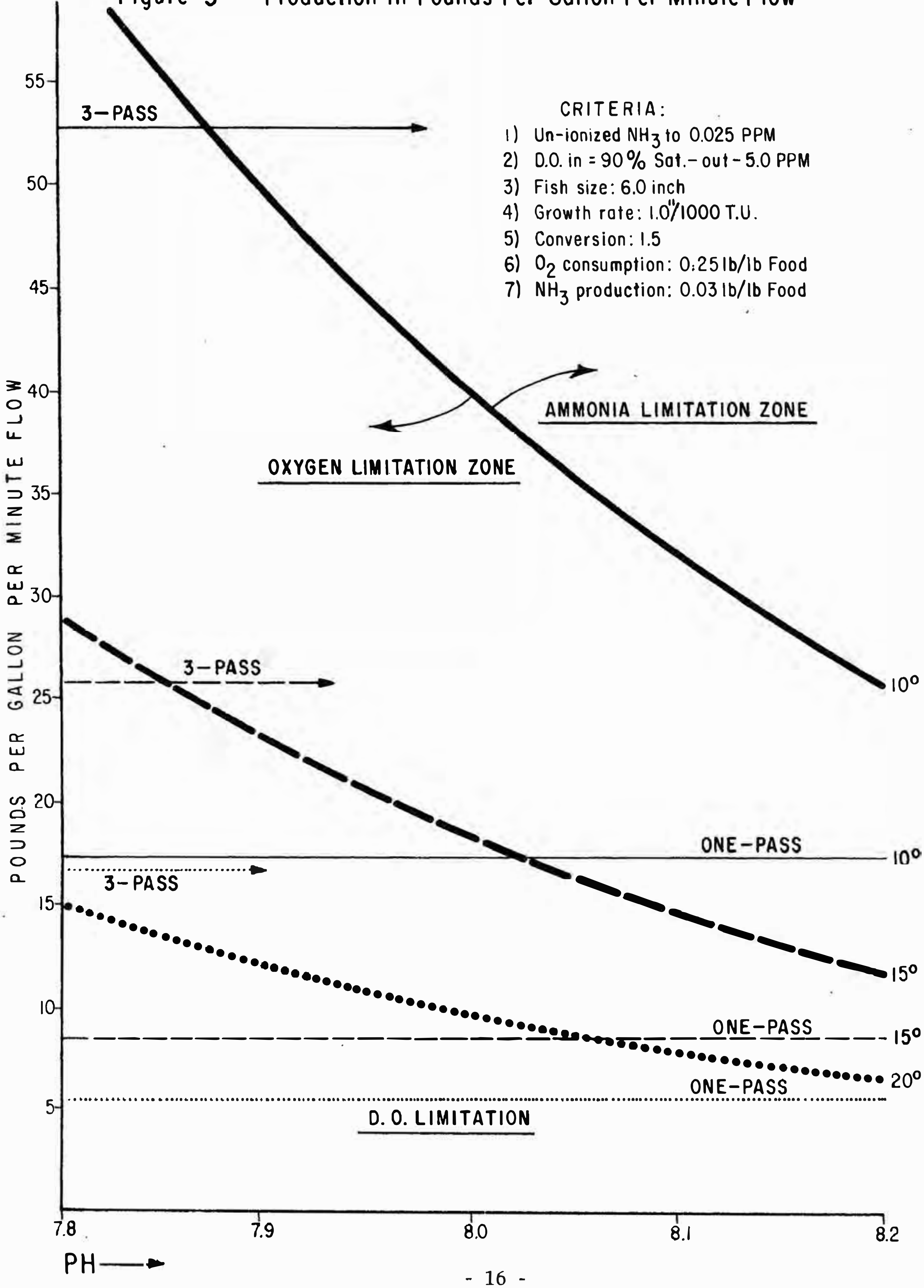

Figure 6 Platte River—Hatchery Rearing Pond

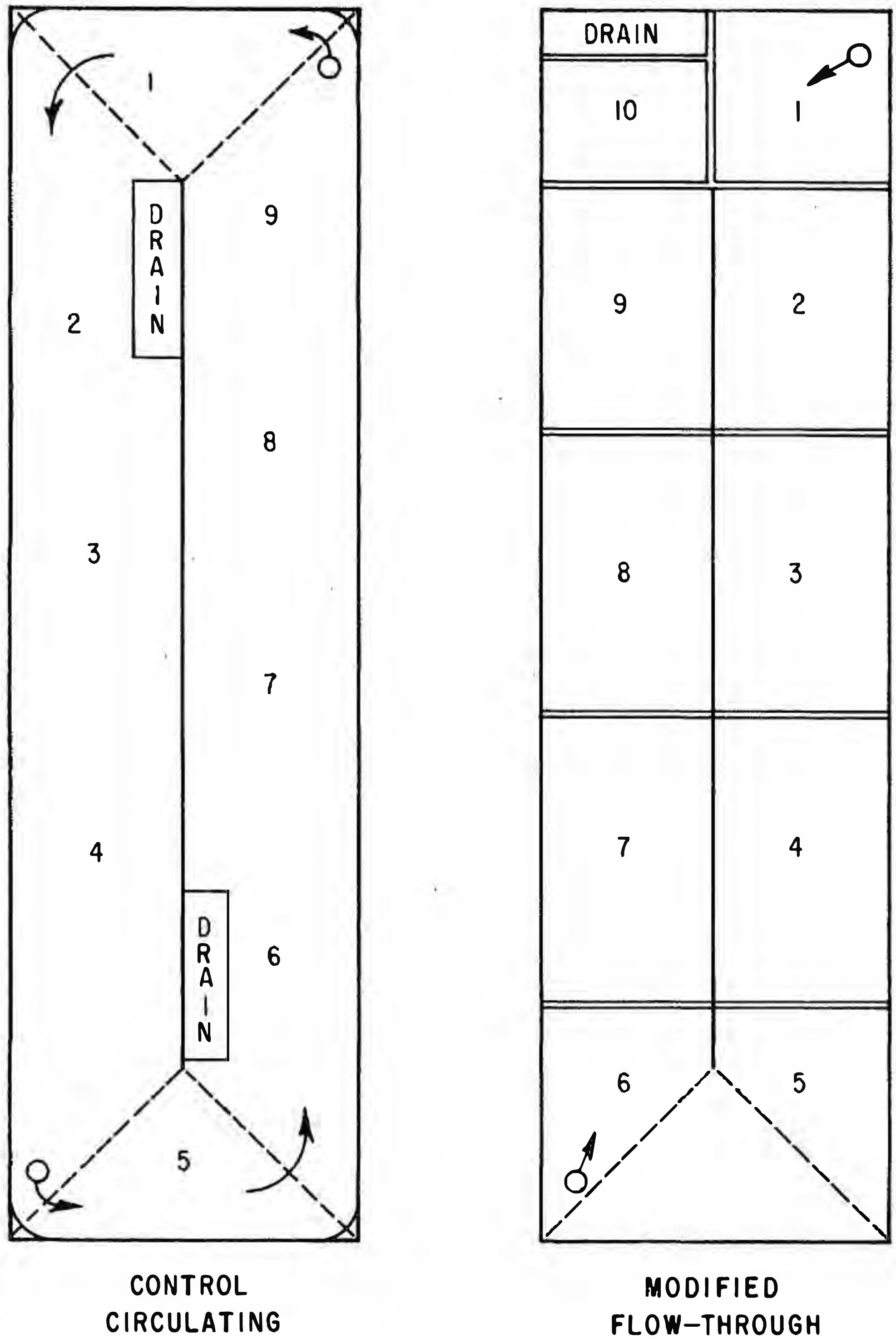

Figure 7 Dissolved Oxygen Levels Through Rearing Pond

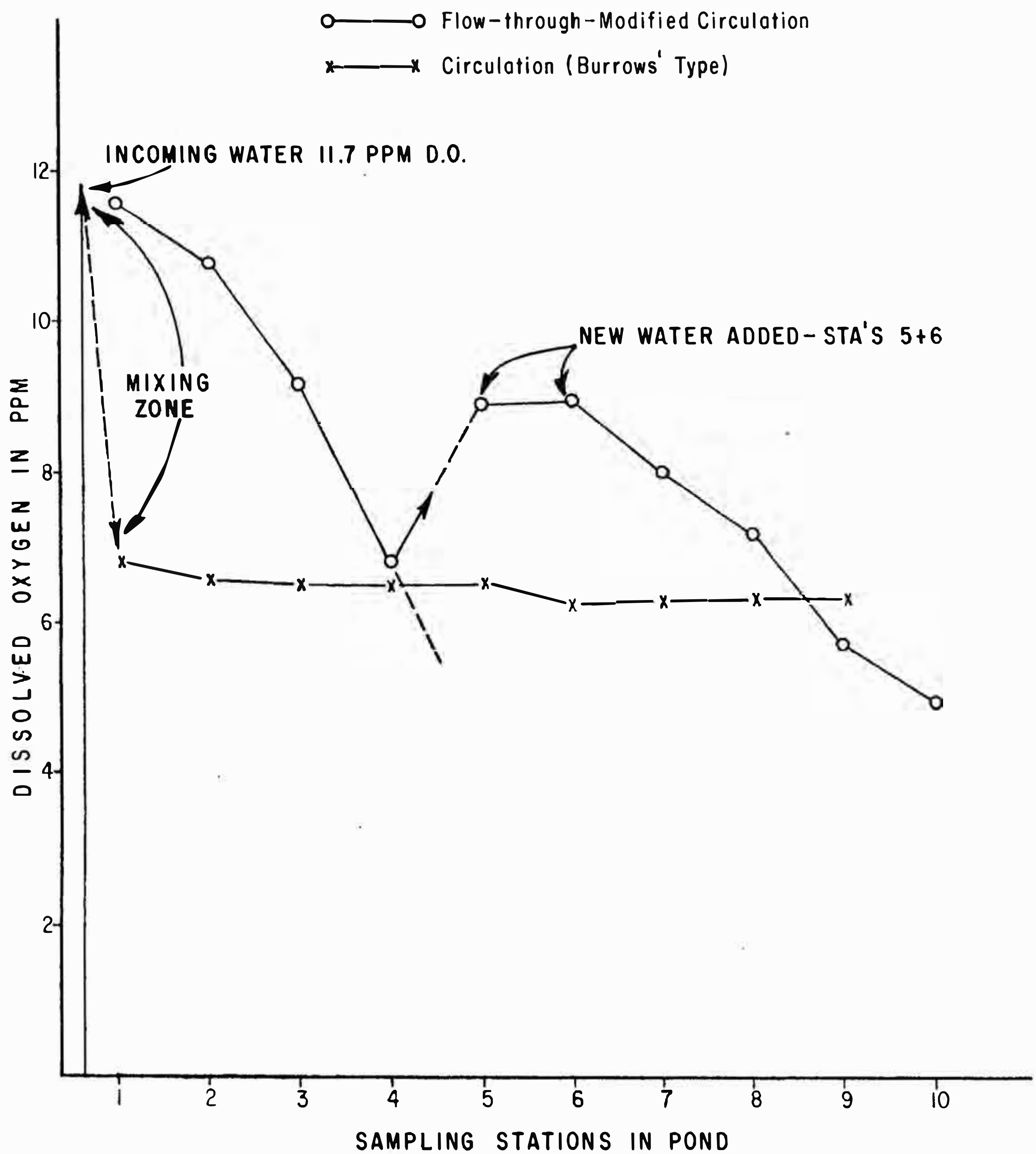

Figure 8 Total NH_3 Levels Through Rearing Pond

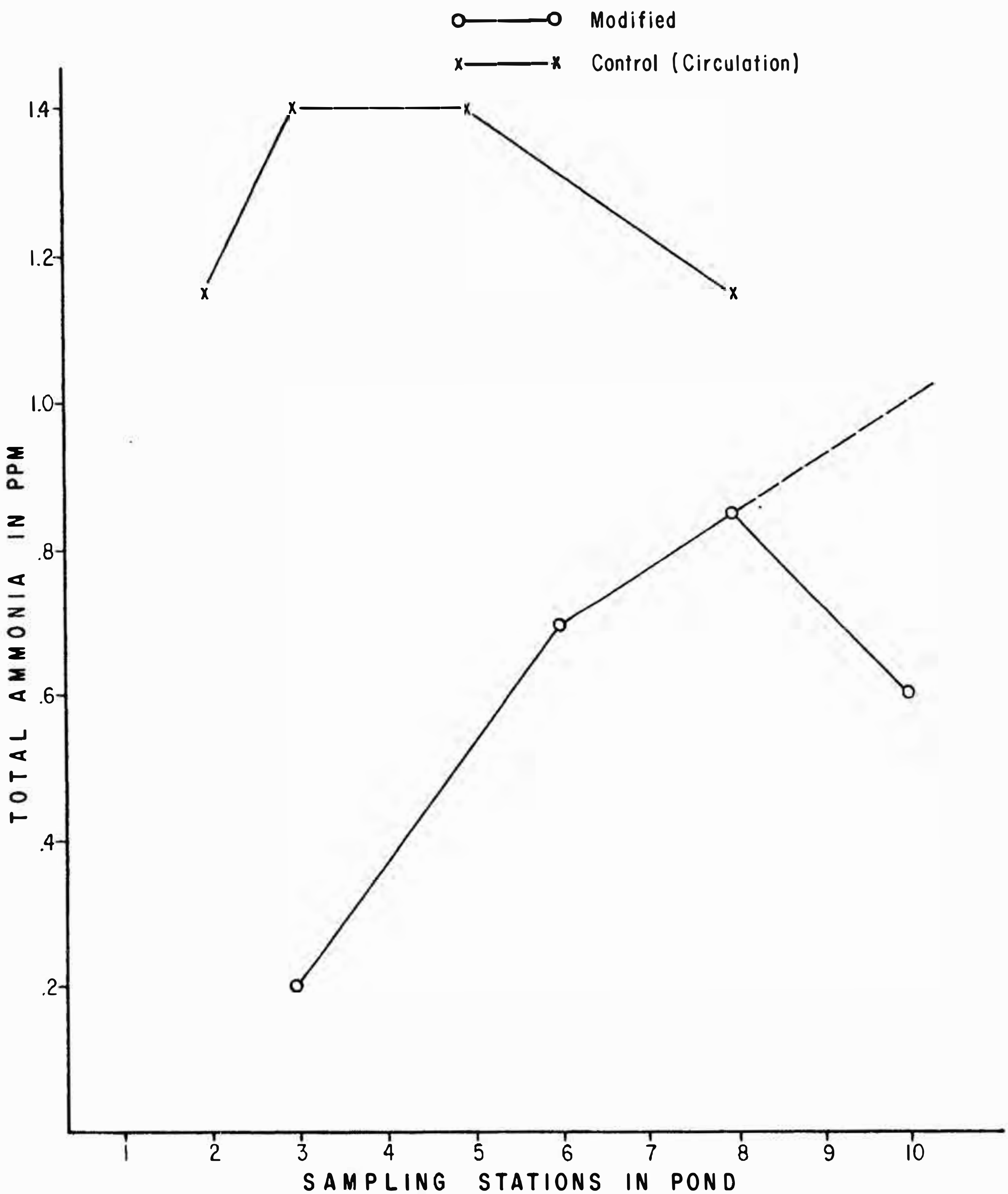

Figure 9 Salmonid Rearing Densities in Lbs/Cu.Ft.

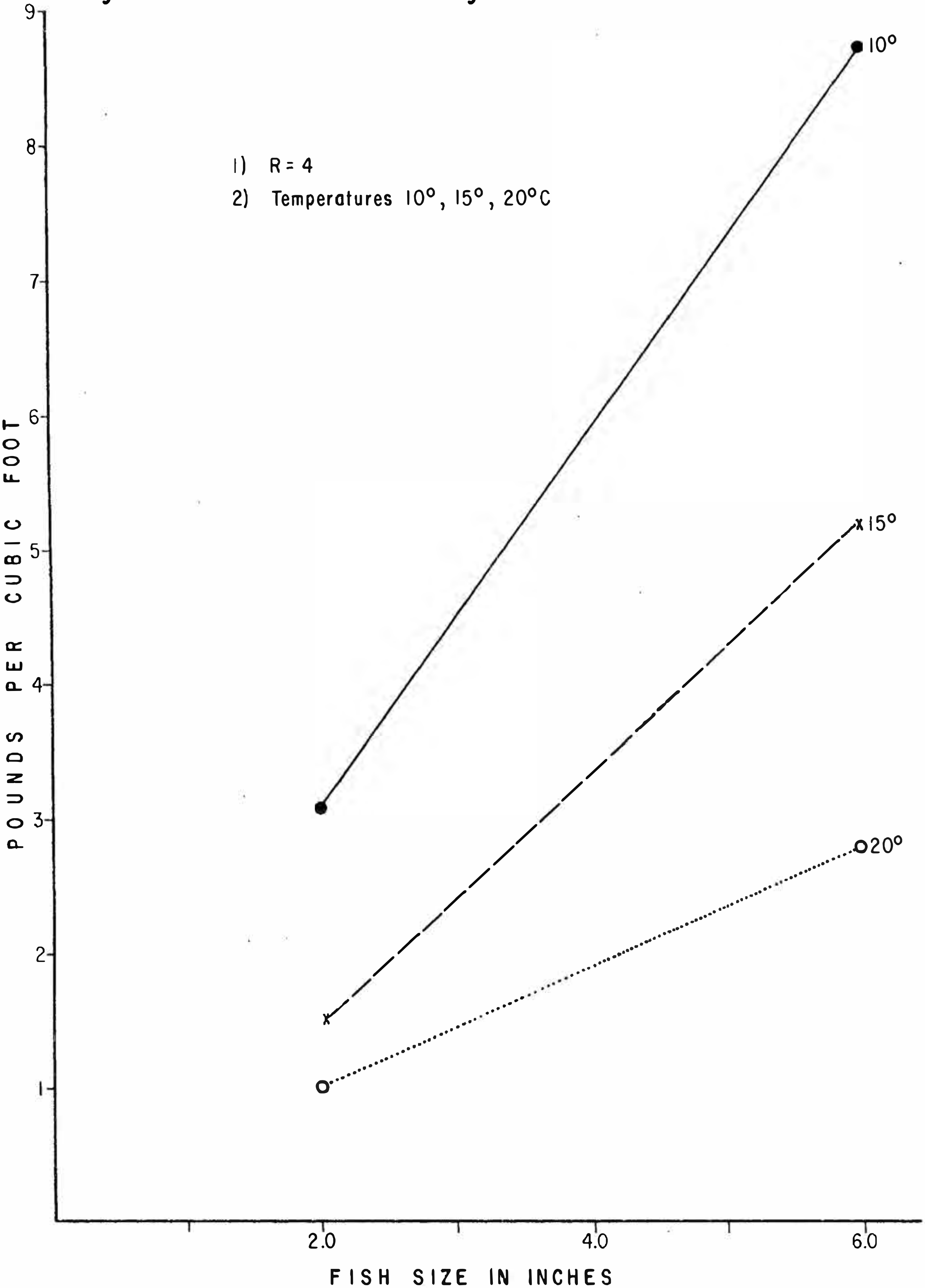

Figure 10 Velocity Versus Raceway Length

For Exchange Rates (R) of 2, 3 and 4 Per Hour