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COMPARISON OF RACEWAYS OF CIRCULAR AND RECTANGULAR CROSS-SECTION FOR THE CULTURE OF RAINBOW TROUT (*salmo gairdneri*)

by

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ABSTRACT

Fish raceways of different cross-sectional shapes were compared in biological and hydraulic tests.

Raceways of rectangular and circular cross-section were used. Two types of circular raceways were studied, one with a smooth wall, made of PVC, and one with a corrugated wall, made of galvanized steel that had been painted.

The biological tests consisted of comparing the weight gain of rainbow trout (Salmo gairdneri) fingerlings (initial weight 6.0 g) held in the different raceways for 69 days. The fish in the painted corrugated steel raceway (final weight 25.6 g) grew more than those in the rectangular (final weight 22.9 g) and PVC (final weight 20.2 g) raceways (significant at $\alpha = 0.05$). Very high stocking densities (130-139 kg/m^3) achieved at the end of the experiment. Critical concentrations of dissolved oxygen or ammonia had not been reached at this point.

Two types of hydraulic tests were done. One consisted of flow visualization studies in which a dye, malachite green, was introduced into the raceway and its movement observed and recorded photographically. In the second hydraulic test, the concentration of malachite green in the effluent was measured at various times after the introduction of the dye. These data were then used to obtain residence time distributions for the

various raceways. No major differences were found between the hydraulic characteristics of the raceways tested.

A biological test using unpainted galvanized corrugated steel raceways was also carried out. Rainbow trout fingerlings (3.6 g) were placed in galvanized raceways that had been flushed for 64 days. The fish were left in the raceways for 29 hours. During this time, 48% of the fish died. The survivors were transferred to fiberglass tanks where an additional 27% of the fish died over the next 50 hours (2 days).

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1. INTRODUCTION

The search for a type of rearing unit in which to culture rainbow trout (Salmo gairdneri) efficiently has prompted aquaculturists to use a number of basic designs. Some of the more common rearing units shapes are raceways, circular ponds or tanks, rectangular circulating ponds and vertical units.

This contribution to that search consisted of studying raceways of circular cross-section to determine whether their hydraulic characteristics would be an improvement over those of conventional raceways of rectangular cross-section. These hydraulic characteristics could, in turn, increase the efficiency of the operation by improving the space and water utilization, reducing the maintenance costs (cleaning), reducing the installation costs, improving the feed utilization and reducing the incidence of disease.

Two types of raceways of circular cross-section were tested, smooth and corrugated. The corrugated circular cross-section raceways were made from galvanized steel which releases zinc that has been found to be toxic to trout under certain conditions (Affleck, 1952; Lloyd, 1960; Lloyd, 1961; Skidmore, 1964; Herbert and Shurben, 1964; Brown, 1968; Sprague, 1971; Sinley et al., 1974). The question of the zinc toxicity was one of topics in this investigation.

The raceways of circular cross-section were compared to a conventional raceway of rectangular cross-section using 1:10 hydraulic models. The experiments were divided into two categories. One category consisted of comparing the growth rate of fish held in the different raceways. The other experiments consisted of comparing the hydraulic characteristics of the different raceways by means of hydraulic tests using tracer dyes.

2. LITERATURE REVIEW

2.1 Rearing Units Used for the Culture of Rainbow Trout

Rearing units may be classified into five distinct categories based on their shape. Each shape exhibits some advantages and some disadvantages when compared to the others. The relative importance assigned to the various characteristics of the culture unit depends on the conditions present at the site for which the trout rearing facility is being considered.

2.1.1 Natural ponds

This category includes those earthen ponds of irregular shape. In many cases, the conditions in these ponds approximate closely those encountered in nature (Wheaton, 1977). Natural ponds are not used extensively for high yield trout production systems due to the lack of control over the environment of the fish, the low water use efficiency, the low stocking densities allowed and the difficulty of harvesting the fish crop.

2.1.2 Raceways.

They consist of long, narrow channels (Figure 1). The inlet and outlet are located at opposite ends of the long

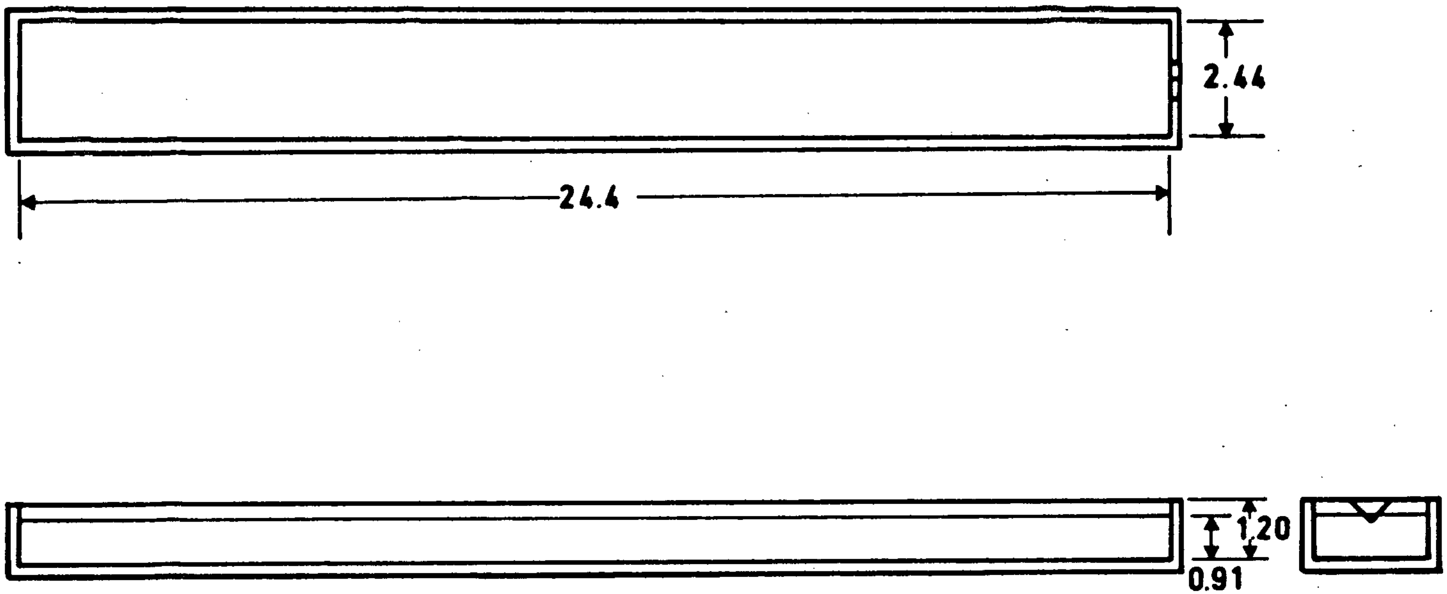


Figure 1. Typical raceway of rectangular cross-section. Dimensions in meters.

channel. The size of raceways varies widely, from 5 m troughs to over 30 m growout raceways. A typical 30 m raceway would be 1.5 to 3 m wide and have a depth of 0.3 to 0.9 m, the cross-section being rectangular. The bottom of the raceway slopes toward the outlet at less than 1%, usually about 0.7% (Burrows and Chenoweth, 1955; Buss and Miller, 1971; Westers and Pratt, 1977). The most common construction material used for raceways is concrete.

Some water flow data reported for raceways are: average water velocity around 0.03 m/s, 1 to 4 exchanges per hour, a carrying capacity of 0.4 to 5 kg/l/min and a stocking density of 16-32 kg/m^3 (Burrows and Chenoweth, 1955; Buss and Miller, 1971; Bardach _et al_., 1972) (Table 1).

The settling of solids in the raceways due to the low velocity of flow is one of the drawbacks of this type of impoundment. It has been reported (Burrows and Chenoweth, 1955) that the minimum water velocity required to carry excrement and all but the heaviest debris is 0.24 to 0.3 m/s. As the velocity decreases, the heavier particles settle until at about 0.03 m/s all but the most semibuoyant particles are deposited.

2.1.3 Circular impoundments (Figure 2)

Diameters up to 13 m have been used. The depth usually ranges between 0.6 and 1.2 m and the bottom may be

Table 1. Summary of water flow data for the various shapes of trout rearing units.

Shape	Carrying Capacity kg/l/min	Stocking Density kg/m^3	Rate of Exchange hr^{-1}
Raceway (1,2,5)	0.4 - 5	16 - 32	1 - 4
Circular (2,6,7,8,9)	1.2 - 2.5	16 - 120	0.5 - 1
Rectangular circulating (3)	0.6 - 1.2	16 - 32	1.6
Vertical (4)	1.6 - 1.8	120 - 136	4.5

1. Bardach et al., 1972
2. Burrows and Chenoweth, 1955
3. Burrows and Chenoweth, 1970
4. Buss et al., 1970
5. Buss and Miller, 1971
6. Kincaid et al., 1972
7. Larmoyeux et al., 1973
8. Robinson and Varnasoni, 1969
9. Surber, 1936

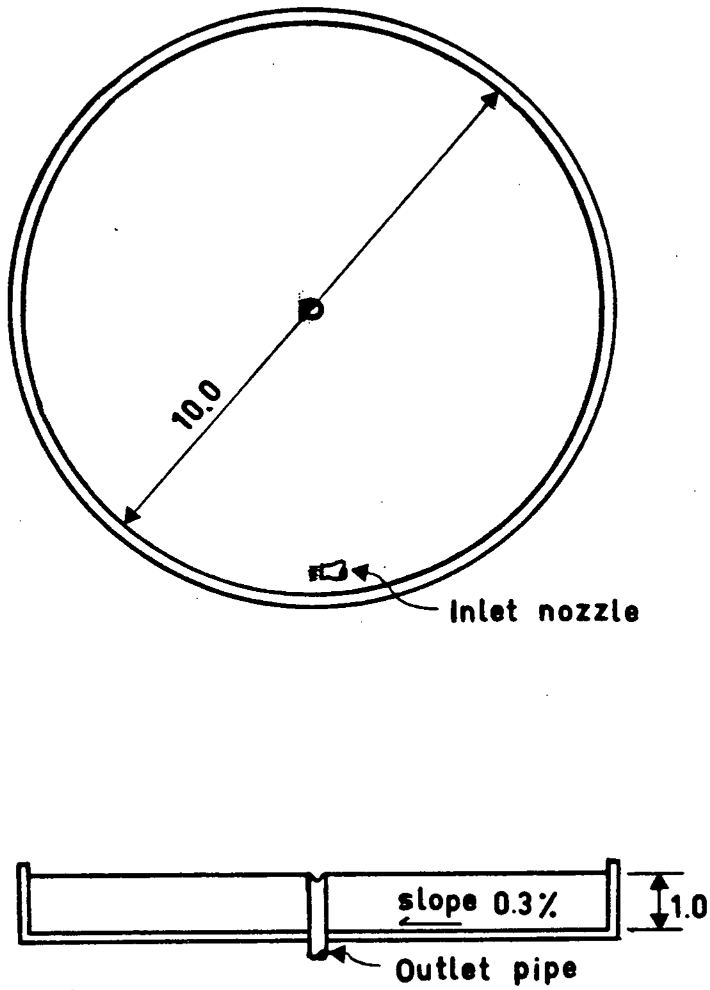


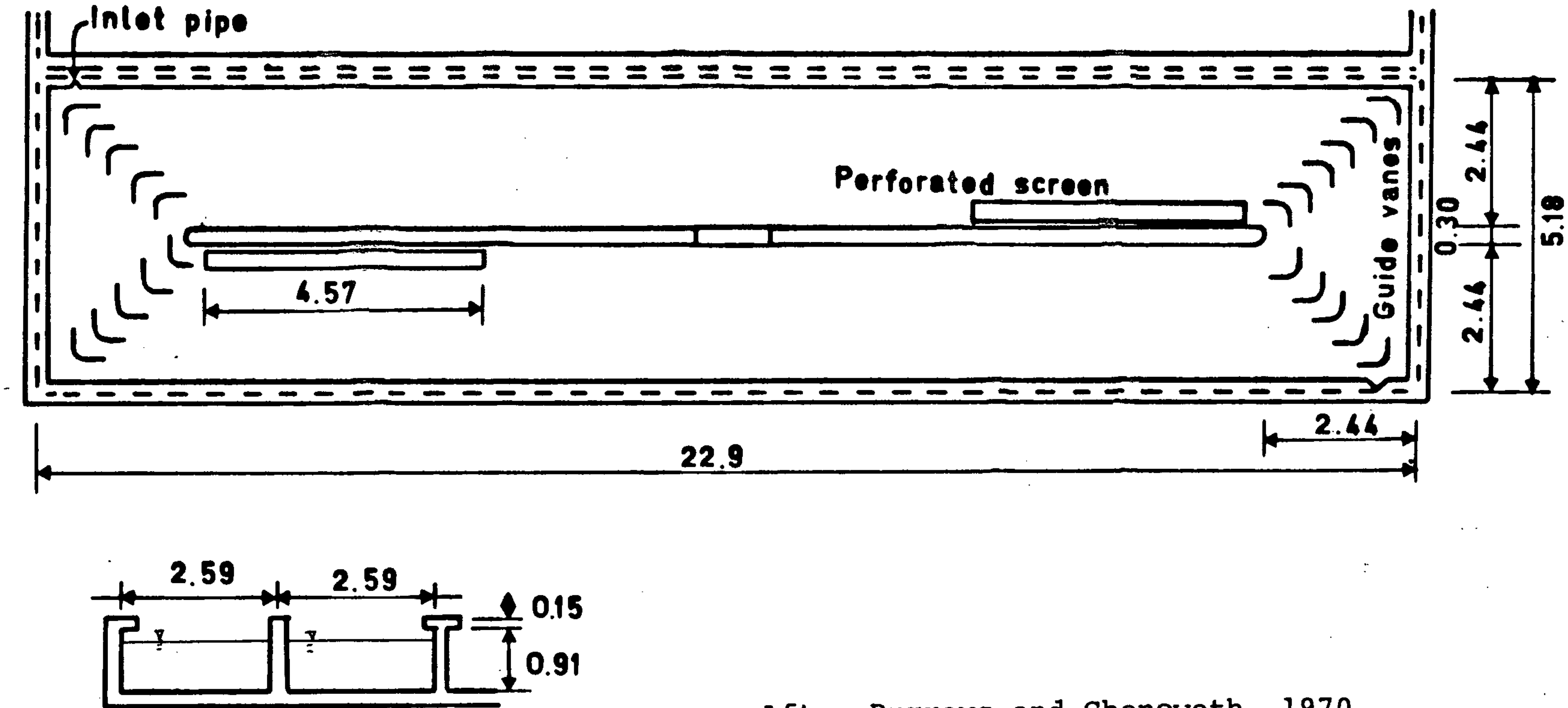
Figure 2. Typical circular pond.
Dimensions in meters.

flat or sloping towards the centre. The inlet is usually a nozzle near the side which directs the water tangentially. The outlet is some form of standpipe located in the centre of the impoundment, or located outside and connected to the centre. The two most common materials used for circular ponds are fiberglass and concrete. Water flow data for circular ponds: 0.5 to 1 exchanges per hour, a carrying capacity of 1.2 - 2.5 kg/l/min and a stocking density of 16 - 120 kg/m^3 (Surber, 1936; Burrows and Chenoweth, 1955; Robinson and Varnasoni, 1969; Larmoyeux *et al.*, 1973; Kincaid *et al.*, 1976)(Table 1).

Due to the circular pattern of the flow, water velocities in circular ponds are higher than those in raceways (Burrows and Chenoweth, 1955). This provides a better sediment carrying capacity to the water stream which carries more solids out of the pond.

2.1.4 Rectangular-circulating pond (Figure 3), also called 'Burrows' pond (Burrows and Chenoweth, 1970)

Unlike the types of impoundments previously considered, the rectangular circulating pond was conceived as a containment that would satisfy specific design criteria. These included hydraulic characteristics, biological characteristics of salmonids and factors affecting efficient pond operation.



After Burrows and Chenoweth, 1970

Figure 3. Rectangular circulating pond.
Dimensions in meters.

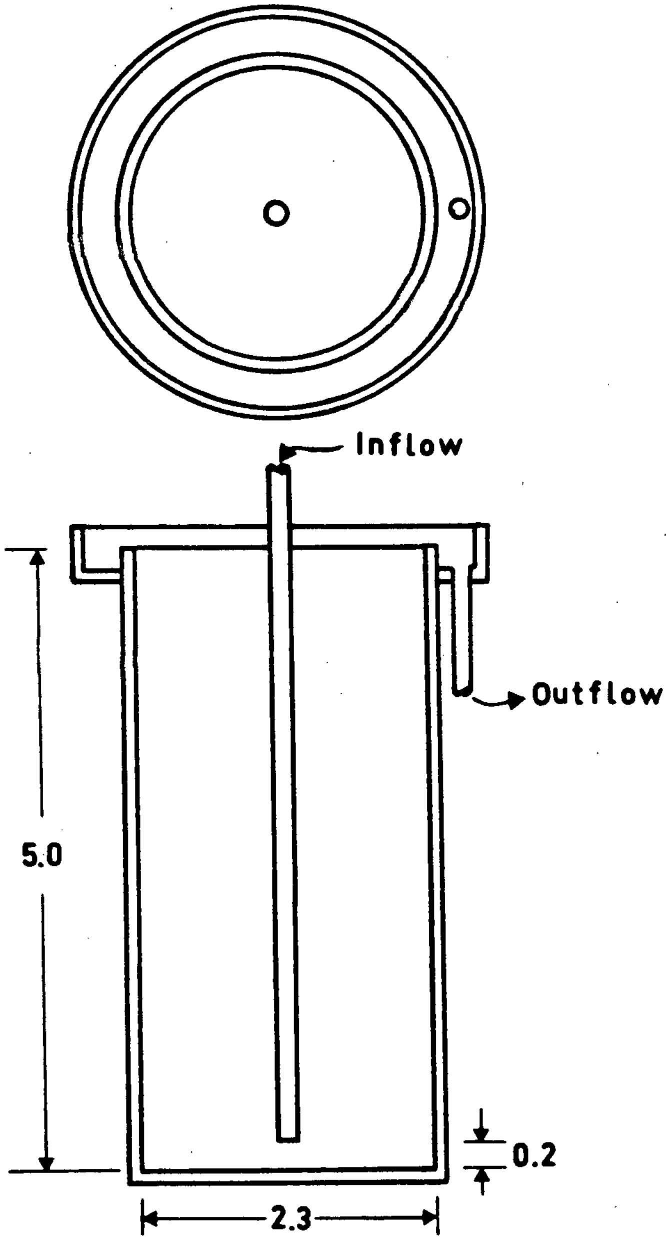
The pond consists of a rectangular concrete pool 15.3 or 22.9 m long. There is a centre wall partly dividing the pond into two 2.4 m wide sections. The flow pattern is controlled by the use of aluminum vertical turning vanes at each pond corner. Water is introduced under pressure through two headers located at opposite ends of the pool. Water leaves through two bottom screens located near the centre wall.

Water flow data for rectangular circulating ponds: 1.6 exchanges per hour, carrying capacity 0.6 - 1.2 kg/l/min, stocking density 16 - 32 kg/m^3 (Burrows and Chenoweth, 1970) (Table 1). The cleaning efficiency for Burrows' pond is comparable to that of the circular pond.

2.1.5 Vertical units (Figure 4)

The idea of culturing trout in vertical units originated from an experiment to select fish that would be exceptionally tolerant to crowding (Buss et al., 1970). The result was an unanticipated high rate of survival among test fish. The overall observation was that water quality was a much more significant factor in rearing rainbow trout than crowding.

Two sizes of vertical units have been used, one made from 55-gallon (208 l) steel drums and the other made from a



After Buss *et al.*, 1970

Figure 4. Vertical rearing tank. Dimensions in meters.

fiberglass tank with a capacity of 20.6 m^3. Water is introduced through a pipe discharging against the bottom of the tank at its centre. Water exits to a collecting gutter through a screen located, like a ring, around the top of the tank.

Water flow data for vertical units: 4 to 5 exchanges per hour, carrying capacity 1.6 - 1.8 kg/l/min stocking density 120 - 136 kg/m^3 (Table 1).

There is no reported data that would allow a comparison of cleaning efficiency between vertical units and the other types of impoundments. On the other hand, Buss and co-workers (1970) reported the accumulation of some sediment along the bottom edge of the tank and recommended a monthly cleaning.

2.1.6 Comparison between flow through and circulating ponds

Of the five types of impoundments mentioned above, three account for the great majority of commercial facilities in Canada and the U.S. They are, the raceways, the circular ponds and the rectangular circulating ponds. These can be grouped into two distinct types according to the way in which the water flows in them, the flow-through and the circulating types. Raceways belong to the flow-through type. Circular and rectangular circulating ponds are considered of the circulating type (Westers and Pratt, 1977).

The basic hydraulic characteristics of the two types of ponds are completely different. In the circulating pond, the incoming water is mixed with the water in the pond and approximately homogenous water conditions result. In contrast, the flow-through pond exhibits a very distinct gradient in water quality between the inlet and the outlet. In theory, a flow-through pond is an example of plug flow while the flow in a circulating pond is mixed (Levenspiel, 1972). While some researchers (Burrows and Chenoweth, 1955, 1970; Larmoyeux _et al_., 1973) see advantages in the circulating type, others (Westers and Pratt, 1977) see the advantages in the flow-through type. The advantages claimed for the circulating ponds include: a homogeneous environment for the fish, a more even distribution of fish throughout the pond, better feed distribution in the pond with corresponding savings in labour due to the reduced time required for feeding, a better cleaning efficiency due to higher water velocities.

In contrast, proponents of the flow-through pond (Westers and Pratt, 1977) claim that the existence of a distinct gradient in water quality is a more desirable characteristic for the rearing environment of salmonids. The reason being that it gives them the opportunity to select the higher water quality while in the circulating pond, the fish are continually exposed to an average environment which could be mediocre in quality. Another disadvantage claimed for the circulating ponds is that fast exchange rates of water are not possible without upsetting a well-balanced hydraulic pattern. This is particularly important in view of recent findings (Buss et al., 1970) which show that water quality is a much more significant factor than crowding in the rearing of rainbow trout. Flow-through ponds permit high exchange rates without creating too high velocities and increased concentrations of fish may be grown requiring less rearing space.

2.2 Model Theory

In order to obtain some experimental information on what the hydraulic characteristics would be in a production raceway, a model experiment was set up. The function of a model experiment is to provide design data for a large scale installation (Johnstone and Thring, 1957), or to facilitate the study of the behaviour of a full size operation, the prototype. Certain laws of similarity must be observed in order to insure that the model-test data can be applied to the prototype or large scale. These laws, in turn, provide means for interpreting the test data. The model should be geometrically similar to the prototype, but this geometric similarity is not enough to insure that the fluid motion in the prototype will be accurately reproduced in the model. If the direction of flow and the relative velocities are the same in model and prototype, the flow is said to be kinematically similar. If both densities and velocities are proportional, the model is said to be dynamically similar to the prototype. Complete similitude requires that all of the properties of the fluid in the model be related correctly to the corresponding properties of the fluid in the prototype. The proper density and viscosity of the fluid in the model depend on the geometric scale ratio between model and prototype, and on the characteristics of the fluid in the prototype. Complete similarity is then a practical impossibility, fortunately, it is not necessary. In any particular hydraulic problem, one law is usually the dominating one and other effects may be ignored if they are small, or the results of following the major law can be adjusted to take care of the secondary influences.

In the case of flow in raceways (open channel flow), the predominant forces are gravity and inertia forces, giving rise to the Froude number, $Fr = v/\sqrt{gL}$ where v is velocity, g is acceleration due to gravity and L is some characteristic dimension (Burrows and Chenoweth, 1955; Henderson, 1966; Binder, 1973). Hydraulic models of open channels should be designed such that Fr for model and prototype are the same. To achieve this, the velocity in the model should be to the velocity in the prototype as the square root of the linear dimension of the model is to the square root of the linear dimension of the prototype. i.e., in a 1:10 model, the velocity should be $1/\sqrt{10}$ or 0.316 times the velocity in the prototype. The flow, being the product of velocity and area, would be proportional to the 2.5 power of the linear dimension ratio. The flow through a 1:10 model should then be 0.00316 times that through the prototype.

In open-channel flow, the second most important influence is due to viscosity. The ratio of inertia forces to viscous forces is represented by Reynolds number, $Re = \rho vL/\mu$ where ρ is the density of the fluid, v is the velocity, L a characteristic dimension and μ the viscosity of the fluid.

The only perfect way of dealing with the effect of viscosity is to keep both Fr and Re the same in model and in prototype. This is a practical impossibility requiring different fluids for model and prototype. If viscosity affects the flow pattern in the prototype, any model smaller than the prototype will have a distorted flow pattern. If the flow in the prototype is fully turbulent (i.e., all velocities high enough that viscosity is not a factor), there is a critical model size above which no appreciable distortion occurs and below which a gradually increasing distortion of the flow pattern results as the model size is decreased. Velocities in raceways are low enough that viscosity affects the flow pattern. Because of these viscous effects, the flow is not fully defined by geometry throughout the prototype, and there is no critical model size. The smaller the model, the greater is the effect of viscous drag.

2.3 Zinc Toxicity to Rainbow Trout

A review of the literature revealed a small number of references in which original research on the toxicity of zinc to rainbow trout was reported. Affleck (1952) exposed rainbow and brown trout of different ages to water that had passed through galvanized iron pipes.

Later on, other workers looked at some of the factors that influence the toxicity of zinc to rainbow trout (Lloyd, 1960; Lloyd, 1961; Skidmore, 1964; Herbert and Shurben, 1964; Brown, 1968; Sprague, 1971; Sinley et al., 1974), including the effect of combining zinc with other toxic substances.

The toxic concentrations and some of the conditions under which they were obtained by the different researchers are summarized in Table 2.

The recommended safe value for continuous exposure is 1% of the 96 hour LC_{50} determined through bio-assay (U.S.E.P.A., 1976). Using this criterion on the data on Table 2 would yield safe concentrations between 0.001 and 0.008 mg/l.

Table 2. Acute toxicity (48-, 96-hr LC_{50} values) of zinc to rainbow trout.

Size	Exposure Time (hr)	Exposure Type	Temperature (C)	Zinc Concentration (mg/l)	pH	Hardness mg/l as $CaCO_3$	Reference
3.9 g	96	FT*	14.8-15.5	0.285	7.3-7.7	45	(5)
4.9 g	96	FT	14.8-15.5	0.506	7.3-7.7	45	(5)
28.4 g	96	FT	14.8-15.5	0.820	7.3-7.7	45	(5)
Juveniles	96	FT	12.7	0.43	6.8	26	(6)
7.0 g	96	FT	11.6-12.4	0.10	6.8-7.0	20-25	(2)
Fingerlings	48	FT	17.7	0.91	6.9	44	(4)
1.5 g	96	S**	10.0	0.09	7.0	20	(3)
Juvenile	96	FT	16.2	7.21	7.8	333	(6)
3.9 g	96	FT	14.8-15.5	2.40	7.3-7.7	100±10	(5)
4.9 g	96	FT	14.8-15.5	2.66	7.3-7.7	100±10	(5)
28.4 g	96	FT	14.8-15.5	1.95	7.3-7.7	100±10	(5)
------	48	S	15.0	3.20	7.6	300	(1)

* FT - Flow-through bioassay

** S - Static bioassay

References:
(1) Brown, 1968
(2) Chapman, 1976
(3) Garton, 1972
(4) Herbert and Shurben, 1964
(5) Holcombe and Benoit, 1976
(6) Sinley *et al.*, 1974

Chronic toxicity studies done by Sinley and co-workers (1974), showed that zinc concentrations below 0.036 mg/l produced no detectable effects on rainbow trout exposed for 21 months from the fry stage to the adult stage. In general, the literature is in agreement over the factors that influence the toxicity of zinc. The duration of exposure is the most important factor determining whether a given concentration of toxicant is sufficient to kill a fish. Toxicity is modified by several environmental factors particularly temperature, water hardness and dissolved oxygen (Skidmore, 1964; U.S.E.P.A., 1976). Toxicity also depends on the life stage at which the fish are first exposed to the toxicant and on acclimatization of the fish due to previous exposure to non-lethal concentrations of the toxic substances.

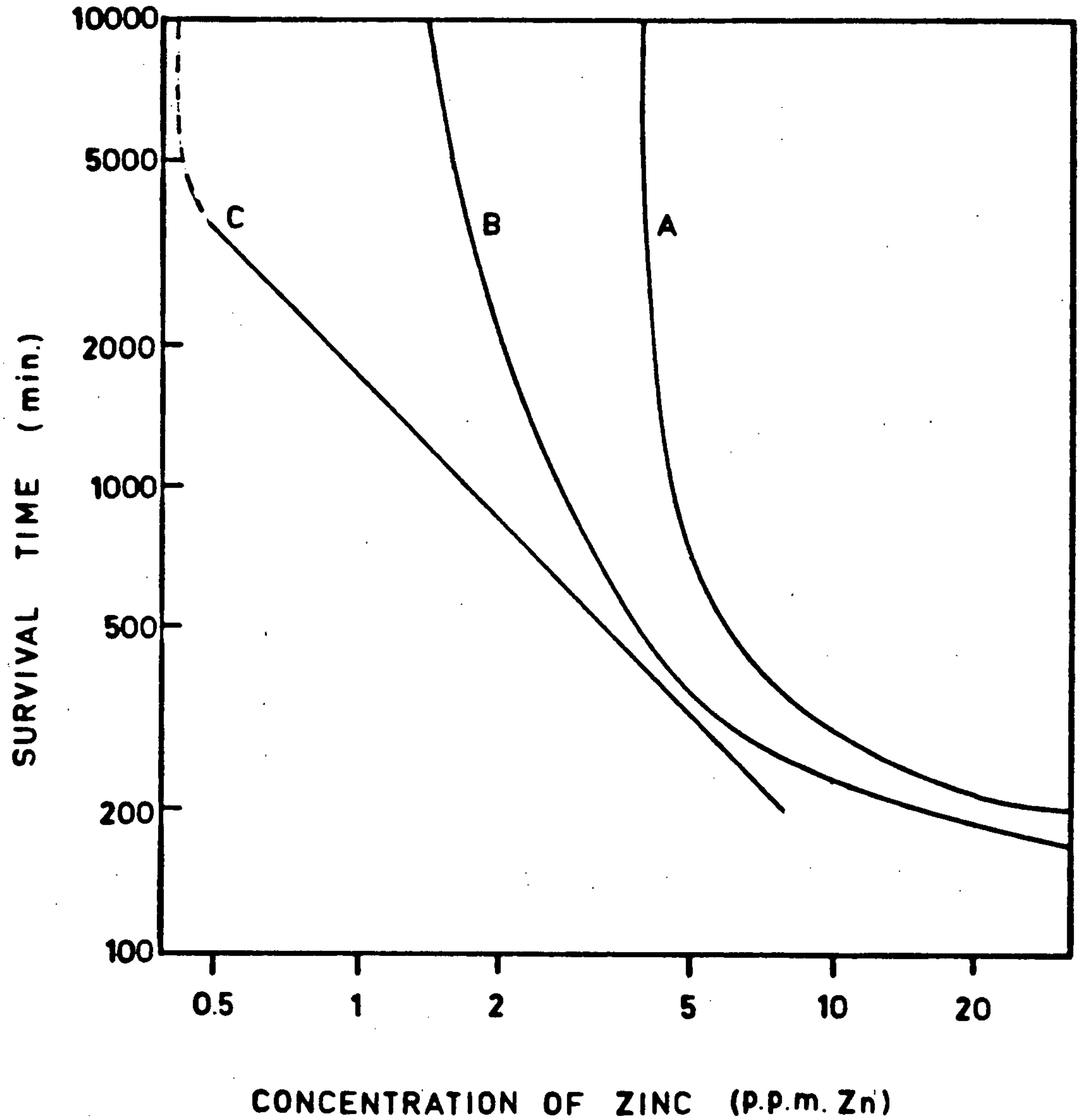
2.3.1 Effect of temperature

There has been only one study reported that looked at the effect of temperature on the toxicity of zinc to rainbow trout. The study (Lloyd, 1960) compared the survival times of rainbow trout in four concentrations of zinc, in hard water, tested at four temperatures. Fish were tested at 13.5, 15.5, 18.5 and 21.5^{o}C. Survival times were generally lower in the warmer water, but the threshold concentration appears to be unchanged.

2.3.2 Effect of water hardness

Hardness is considered to be the most important factor modifying the toxicity of zinc (Lloyd, 1960; Skidmore, 1964; Sinley et al., 1974). Lloyd measured the survival time of rainbow trout in a series of concentrations of zinc, at three hardness levels (Figure 5). He observed that the effect of hardness increased with increase in period of survival, until there was a ten-fold difference between the toxicities of zinc in the hardest (320 mg/l as $CaCO_3$) and the softest (12 mg/l as $CaCO_3$) water over 2.5 days exposure.

Sinley and co-workers (1974) looked at the effect of water hardness on the toxicity of zinc to juvenile rainbow trout in an acute toxicity test (96 hours) and in a chronic toxicity test (21 months). The 96 hour LC_{50} obtained for juvenile rainbow trout in hard (330 mg/l as $CaCO_3$) and soft (25 mg/l as $CaCO_3$) water at 15 C were 7.210 and 0.430 mg/l respectively. The results of the chronic toxicity tests also show that the toxicity of zinc decreases as water hardness increases. The maximum acceptable toxicant concentration (MATC) in hard water was found to be between 0.640 mg/l where there was some zinc caused mortality and 0.320 mg/l where there was no zinc caused mortality. In soft water the MATC was found to be, between 0.260 mg/l and 0.140 mg/l, for fish exposed to the zinc from the egg stage, and between 0.071 and 0.036 mg/l for fish first exposed to the zinc at the fry stage i.e., 1.5 g.



A = total hardness 320 mg l^{-1} as $CaCO_3$

B = total hardness 50 mg l^{-1} as $CaCO_3$

C = total hardness 12 mg l^{-1} as $CaCO_3$

(After Lloyd, 1960)

Figure 5. Toxicity of zinc sulfate to rainbow trout in waters of different hardness.

It is believed that the reason for the decreased toxicity of zinc in hard waters is the antagonistic action between the z-nc ions and the ions of the alkaline-earth metals (Skidmore, 1964). As reported by Skidmore (1964), Jones (1939) established a difference in the antagonistic action between copper and the various alkaline-earth metals. Strontium was found to cause the greatest antagonistic action, followed by calcium, magnesium and barium in that order.

2.3.3 Effect of dissolved oxygen

The effect of dissolved oxygen on the toxicity of zinc to rainbow trout has been studied by Lloyd (1961). He exposed rainbow trout to five lethal concentrations of zinc sulfate at three non-lethal concentrations of dissolved oxygen, in hard water (320 mg/l as $CaCO_3$). He calculated that, over an exposure period of 1000 minutes, the concentration of zinc necessary to kill half of the fish was 1.4 times higher at an oxygen concentration of 8.9 mg/l than it was at 3.8 mg/l.

2.4 Zinc Release From Galvanized Metals

Galvanized steel sub-merged in water corrodes releasing zinc. Many factors such as water hardness, pH and time of exposure affect the rate of corrosion of the zinc surface. Zinc corrodes fairly rapidly during the early stages of exposure but corrosion slows down quickly with the formation of protective films on the zinc surface. The films are composed of corrosion products like zinc oxide and zinc carbonate that are strongly adherent and have a low solubility. The rate of corrosion is lower when the conditions are favourable for the formation of the films. Such conditions are: pH in the range 6.5 to 12, low dissolved oxygen and CO_2 in the water, high water hardness (Zinc Development Association, 1965; Slunder and Boyd, 1971; Proskurkin and Gorbunov, 1972; Noyce et al., 1975).

There are many reports available on the corrosion of zinc in natural waters but few give quantative data which can be used. The figure given for zinc release in soft water is 25 $mg/dm^2/day$ and 2.5 $mg/dm^2/day$ in hard water (Slunder and Boyd, 1971).

It is interesting to note that water hardness has a double effect on the use of galvanized raceways for culturing trout. On one hand, water hardness affects the rate of zinc release and hence the zinc concentration in the raceway. The other effect of water hardness is on the toxicity of the zinc to the fish. In both cases, soft water aggravates the problem by causing more zinc to be released and at the same time making it more toxic to the fish.

3. THEORY FORMULATION

The basic theory supporting this project has been developed from: 1) A set of propositions which are already known to be true. 2) A set of assumptions which are tentatively assumed to be true for the sake of building the theory. 3) A set of inferences.

3.1 Propositions

- Hydraulic models can be used to study open channel flow.
- The characteristics of the flow in a raceway depend on the shape of the raceway and on the water flow rate.
- The settling of solids in a channel is dependent on the characteristics of the particles and on the velocity and turbulence of the water flowing in the channel.
- Galvanized materials corrode and release zinc.
- The rate at which zinc is released is dependent on the chemical and physical characteristics of the water flow.
- The toxicity of zinc to rainbow trout depends on the age at which the fish are first exposed to the zinc and on the physical and chemical characteristics of the water.

3.2 Assumptions

- The rate at which zinc is released from the walls of the galvanized pipe can be predicted.
- Safe concentrations of zinc can be established for trout under continuous exposure.
- The growth rate of fish is affected by the hydraulic characteristics of the raceway in which they are reared.

3.3 Inferences

- There is less settling of solids in a raceway of circular cross-section than in a raceway of rectangular cross-section if both raceways have the same cross-sectional area and the same average velocity.
- Fish grow faster in a raceway of circular cross-section.
- It is safe to use galvanized pipe raceways for rearing trout under certain conditions.

4. MATERIALS AND METHODS

From observations of fish rearing facilities and from work done by other researchers (Burrows and Chenoweth, 1955) it has become readily apparent that a very strong correlation exists between the performance of fish and the hydraulic characteristics of the environment in which the fish live. Because this correlation is not fully understood and because factors other than hydraulic influence the performance of the fish, it was decided to separate the experimental work into two distinct areas of concern. One area had to do with the study of the hydraulic characteristics of the raceways under consideration, the other with the performance of fish reared in different types of raceways.

A detailed review of the two areas of research follows.

4.1 Fish Performance Studies

In order to make the description of the experiments clearer to the reader, it will be presented in four phases that follow a chronological order: Phase 1, before August 15, 1979 (Construction and installation of equipment). Phase 2, August 15-16, 1979 (Stocking of the raceways). Phase 3, August 17 to September 14, 1979 (Intermediate stage, experiment redesigned). Phase 4, September 14 to November 22, 1979 (Comparison of three raceways).

4.1.1 Phase 1. -- Before August 15, 1979 (Construction and installation of equipment)

The work done in this phase consisted of the preparation of the site, the construction and installation of the raceways and the performance of preliminary water analyses.

4.1.1.1 Equipment

The sizes of test raceways were determined by the application of model theory. The prototype or large scale rectangular raceway is a hypothetical raceway of the following dimensions: length 24.4 m, width 2.4 m, depth 0.91 m, bottom slope 0.5%. A scale ratio of 1:10 was selected for the model rectangular raceway as the most practical for these studies. The sizes of the raceways of circular cross-section were chosen so they would have the same length and cross-sectional area as the model rectangular raceway. The dimensions of the 1:10 model of the rectangular raceway are: length 2.44 m, width 0.24 m, depth 0.09 m and slope 0.5%. The raceways of circular cross-section are of the same length as the rectangular model, namely 2.4 m.

The diameters of the pipes used and the depth to which they were filled were chosen such that the cross-sectional area are approximately equal to that of the rectangular raceway. The cross-sectional area of the rectangular model is 0.022 m^2. A pipe of 0.20 m diameter would have to be filled to 0.78 times the diameter (i.e. 0.16 m) and a pipe of 0.25 m diameter would be filled to 0.41 times the diameter (i.e. 0.10 m).

For the initial fish trials, two Corrugated Steel Pipe (CSP) raceways of 0.20 m diameter (Appendix I-A) and two PVC raceways of 0.20 m diameter (Appendix I-B) were used (Figure 6). The concentration of zinc in the CSP raceways can be predicted based on the figures given for the rate of zinc release in soft water (Section 2.4). In soft water, zinc is released at the rate of 25 $mg/dm^2/day$ (Slunder and Boyd, 1971). With a flow of 5 l/min through the CSP raceway, the expected average zinc concentration in the effluent would be 0.380 mg/l. If a supply of hard water were available, the zinc concentration would be reduced to 0.038 mg/l. It is unfortunate that a supply of hard water could not be found and all the experiments had to be carried out in very soft water, 5 mg/l as $CaCO_3$ as determined by the EDTA titrimetric method (American Public Health Association, 1976).

The four raceways used in the first section of the experiments, two PVC and two CSP, received the water from two constant head towers (Appendix I-H), through orifices

(Appendix II)(Figure 6). A constant flow rate was maintained to the raceways. The water exited the raceways through a perforated pipe inserted through the end cap of the raceway (Appendix I-G). The perforated pipe was connected to a standpipe (Appendix I-G) for the control of the water level in the raceway. The raceways were placed on stands (Appendix I-F).

4.1.1.2 Equipment preparation and testing

4.1.1.2.1 Orifice calibration. Calculations to determine the diameter of the orifice required to obtain the desired discharge were made from the equation

$$Q = c \frac{\pi d^2}{4} (2gH)^{1/2} \qquad \text{(Binder, 1973)}$$

where d is the orifice diameter, c is a constant for the orifice, g is the gravitational acceleration, H is the head and Q is the discharge. Initial calculations for orifice size were made with an assumed constant c. The orifices were then drilled and calibrated. The necessary adjustments in orifice diameter were made in order to satisfy the flow requirements. All orifices were calibrated and the data is presented in Appendix II.

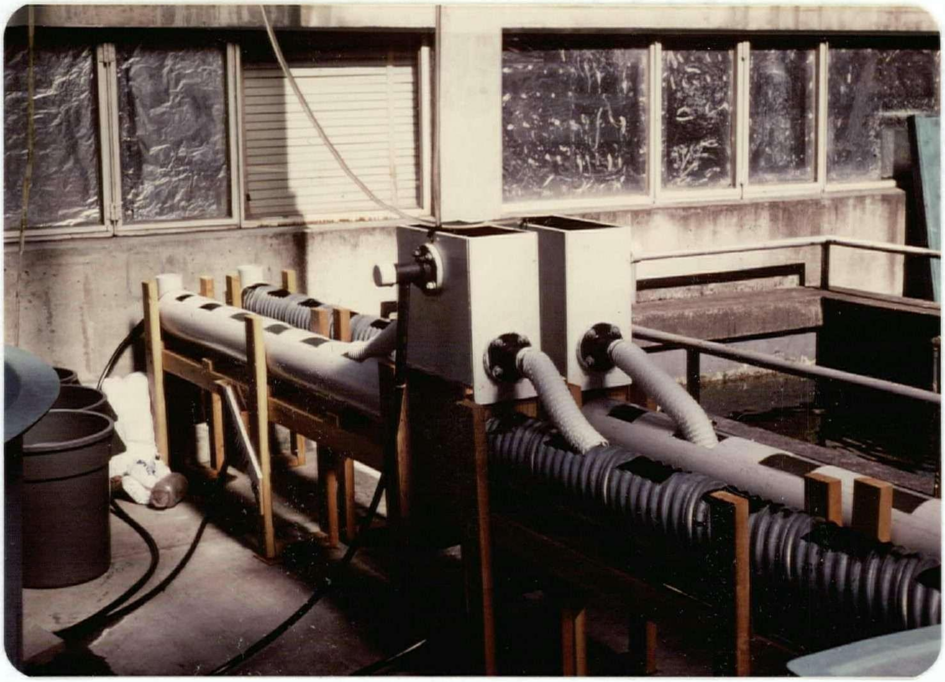


Figure 6. Pilot Plant Apparatus in the Biology Building, U.B.C.

4.1.1.2.2 Conditioning of the corrugated steel raceways. After construction and testing for leaks, the raceways were flushed with tap water for a period of 26 days at a flow rate of approximately 13 l/min per raceway. The water temperature was $10^{o}C$. During this time, 400 ml water samples were taken on days 3 and 16 from the effluent, acidified with 1.5 ml/l nitric acid (70% HNO_3) and analyzed for zinc using a Jarrel Ash (Division of Fisher Scientific), Model 800 atomic absorption spectrophotometer. Due to the very low concentrations of zinc present, it was necessary in some cases to concentrate the acidified sample by evaporation without boiling (American Public Health Association, 1976).

After flushing, the raceways were transferred to the courtyard of the Biology Building on campus, where a supply of dechlorinated city water is available (Appendix VII). The raceways were installed as shown in Figure 6. They were then flushed for a period of 30 days with a flow of 5 l/min per raceway. Samples were again collected and analyzed for zinc on days 40 and 64 from the initiation of the flushing. At the end of the 30 day flushing period, the fish were stocked.

4.1.2 Phase 2 -- August 15-16, 1979
(Stocking of the raceways)

The purpose of this section of the experiments was to determine whether the amount of zinc released from the walls of the galvanized CSP raceways was enough to cause heavy mortalities to the trout.

On August 15, 1979, rainbow trout fingerlings (average weight 3.65 g) were secured from Sun Valley Trout Farms in Mission, B.C. The fish were transported in buckets with oxygen being bubbled throughout the trip. Upon arrival, the fish were weighed and distributed equally in the four raceways. The weighing was done with a Toledo model 4030 balance with a capacity of 5 kg. A four litre bucket was filled with approximately two litres of water and its weight was recorded. Some fish were then netted and placed in the bucket containing the weighed water. The new weight of the bucket was recorded and the weight of the fish was determined by subtracting the initial bucket weight. Consecutive batches of fish weighed in this fashion were placed in different raceways.

The average weight of the fish was determined by weighing a sample of 100 fish. The number of fish was calculated from the total weight and the average weight.

Unexpectedly high mortalities of the fish in the galvanized CSP raceways prompted the termination of this phase of the experiment during the second day (Aug. 16, 1979). The surviving fish from the galvanized raceways were transferred to two fiberglass tanks.

4.1.3 Phase 3 -- August 17 to September 14, 1979 (Intermediate stage, experiment redesigned)

The third phase of the experiment constituted an intermediate stage in which preparations were made for conducting a redesigned experiment in the fourth phase. During this time, the fish were held in two PVC raceways and two fiberglass tanks. The fish were fed an amount equivalent to 3% of their body weight per day distributed in three feedings, according to the recommendations of the feed manufacturers. The feed used was Ewos number 2 Salmon Starter, manufactured by Ritchie-Smith Ltd. of Abbotsford, B.C.

In preparation for the fourth phase, a rectangular cross-section raceway was built. Construction details are presented in Appendix I-C. The rectangular and the galvanized CSP raceways were both painted with green inter-racing anti-fouling paint manufactured by International Paints (Appendix III). The surface of the galvanized CSP raceway was prepared by applying a coat of zinc chromate primer. The antifouling paint contains copper and some apprehension existed as to the possible toxicity to the trout. Lovegrove (1979) reported the use of a similar paint in rainbow trout tanks. He found that the copper concentration in the tank water dropped very quickly from 9 μg/l two hours after flooding the tanks to 2 μg/l eighteen days after flooding. The E.P.A. minimum risk level is 10 µg/l (U.S.E.P.A., 1976). In our case, the painted raceways were flushed for six days at 5 l/min before three fish were introduced in each. The fish were observed for 10 days. No deleterious effects were observed and the raceways were stocked.

4.1.4 Phase 4 -- September 14 - November 22, 1979 (Comparison of three raceways)

During the fourth phase of the experiments, the performance of the fish held in three types of raceways was compared. The raceways were: a PVC pipe raceway, a painted galvanized CSP raceway and a wooden, rectangular cross-section raceway.

On September 14, the fish from the two PVC raceways were weighed and divided into three groups of equal weight. The fish from the fiberglass tank were also weighed and divided in three groups. One group from each of the two sets was placed into each of the three raceways used in the fourth phase.

The fish were fed three times a day. The amount of feed was adjusted based on the increasing fish weight and the changing water temperature, following the manufacturers recommendations.

Water samples from each of the raceways and from the supply were collected prior to feeding. The dissolved oxygen and temperature were measured at the site, immediately after collection. Ammonia and pH were measured in the laboratory within one hour of collecting the samples. The procedures used were:

a. Dissolved oxygen. It is recommended that the effluent have a dissolved oxygen not lower than 5 mg/l (Willoughby, 1968; Buss and Miller, 1971; Westers and Pratt, 1977). A membrane electrode was used to measure the dissolved oxygen with a model 54, Yellow Springs Instruments dissolved oxygen meter. The instrument was calibrated following the procedure indicated in the manual for the apparatus.

b. Temperature. The temperature was measured using a thermocouple incorporated in the dissolved oxygen electrode and checked against a mercury thermometer at least once every two weeks.

c. pH. Measured with a Fisher Accumet Model 420 Digital pH/ion meter.

d. Ammonia. Measured by the Nessler method using a Hach DR-EL/2 Direct Reading Engineer's Laboratory Kit (Hach Chemical Co., Ames, Iowa). The Hach method was calib rated against industrial method No. 154-71W for ammonia in water and seawater utilizing a Technicon Auto Analyzer II (Technicon Industrial Systems, Tarrytown, N.Y.)(Appendices IV, V and VI). A calibration equation was obtained (Appendix IV). The values for ammonia presented throughout this thesis were obtained by use of the calibration equation.

4.2 Hydraulic Studies

The reason for doing hydraulic tests of the raceways was to obtain a characterization of the flow without fish. Superimposed on this undisturbed flow are the turbulences generated by the fish in a loaded raceway.

Two tests were done on each raceway, one provided qualitative information in the form of observation of the movement of a tracer within the raceway. The second test produced some quantitative information as residence time distributions.

4.2.1 Flow patterns

The study of flow patterns provides qualitative information on the way in which the water moves through the raceway. It makes possible the identification of areas of slow moving water as well as areas of high velocity.

The flow patterns were made visible by the introduction of a dye into the incoming stream of water.

4.2.1.1 Materials

The study of flow patterns requires that the raceways have transparent walls. Because of this, only two raceways were studied. One raceway was of rectangular cross-section with sides made of clear acrylic glass 2.4 m long, 0.24 m wide and was filled to a depth of 0.09 m (Appendix I-E). The other raceway tested was made from a 0.20 m diameter acrylic glass pipe filled to 0.8 times the diameter or 0.16 m. The length of this raceway was 2.4 m (Appendix I-D). The flow to the raceways was regulated using a calibrated orifice under a constant head.

4.2.1.2 Procedure

Two flow rates were used in the tests, 5.0 and 10.0 l/min. They were determined using Froude's number, based on what are considered typical flows for the prototype raceway. The recommended flow for the prototype raceway is between 900 and 3600 l/min corresponding to one and four exchanges per hour (Burrows and Chenoweth, 1955; Buss and Miller, 1971). Using a constant Froude number as the criterion for the scaling of the flow rate, the required flow for the model can be found to be between 2.9 and 11.6 l/min. The flow rates used in the tests, 5.0 and 10.0 l/min are within the range required. These flow rates correspond to 1.75 and 3.50 exchanges per hour in the prototype.

The flow patterns were made visible by the introduction of a dye, malachyte green, into the incoming stream of water.

The malachyte green crystals were diluted in distilled water to make a 10 g/l stock solution. The amount of dye used differed for the two flow rates. At 5.0 l/min, 10 ml of stock solution were used. At 10 l/min, 20 ml were used. The dye was injected with a pipette into the incoming stream of water as the stream hit the water surface in the raceway. The duration of the dye injection was approximately 10 seconds in all cases. The movement of the dye along the raceway was recorded on black and white film (Kodak tri-x pan). A red filter (Vivitar 25A) was placed in front of the camera to improve the clarity of the impression on the black and white film. The photographs were taken at various times after the introduction of the dye.

4.2.2 Residence time distribution

The study of residence time distributions provides information on the behaviour of a fluid in a container by looking only at its inputs and outputs. Residence time distribution data may point out the presence of short circuiting streams or dead areas in a raceway, but it does not provide an indication as to where in the raceway these are.

4.2.2.1 Materials

In addition to the raceways used in the flow pattern studies, two more were tested for their residence time distribution. One was made from 0.25 m (10 in, nominal size) diameter CSP and it was filled to 0.4 times the diameter. The other was made from 0.20 m (8 in, nominal size) diameter CSP and it was filled to 0.8 times the depth. Both raceways were 2.4 m long (Appendix I).

4.2.2.2 Procedure

The procedure consisted in introducing the dye for a period of 10 seconds into the inflow and then collecting samples from the effluent to determine the concentration of dye leaving the raceway with time (Burrows and Chenoweth, 1955; Levenspiel, 1972).

The tracer and the procedure for introducing it into the raceways were similar to those used in the flow pattern studies. Samples from the effluent were collected at predetermined time intervals. The samples were then analyzed using a Hitachi Perkin-Elmer 139 UV-VIS spectrophotometer to determine the concentration of malachyte green present. Absorbance was measured at 616.9 nm, the wave length of peak absorbance for malachyte green (Stecher, 1968). The concentration was then determined by reference to a calibration run in the spectrophotometer (Figure 7).

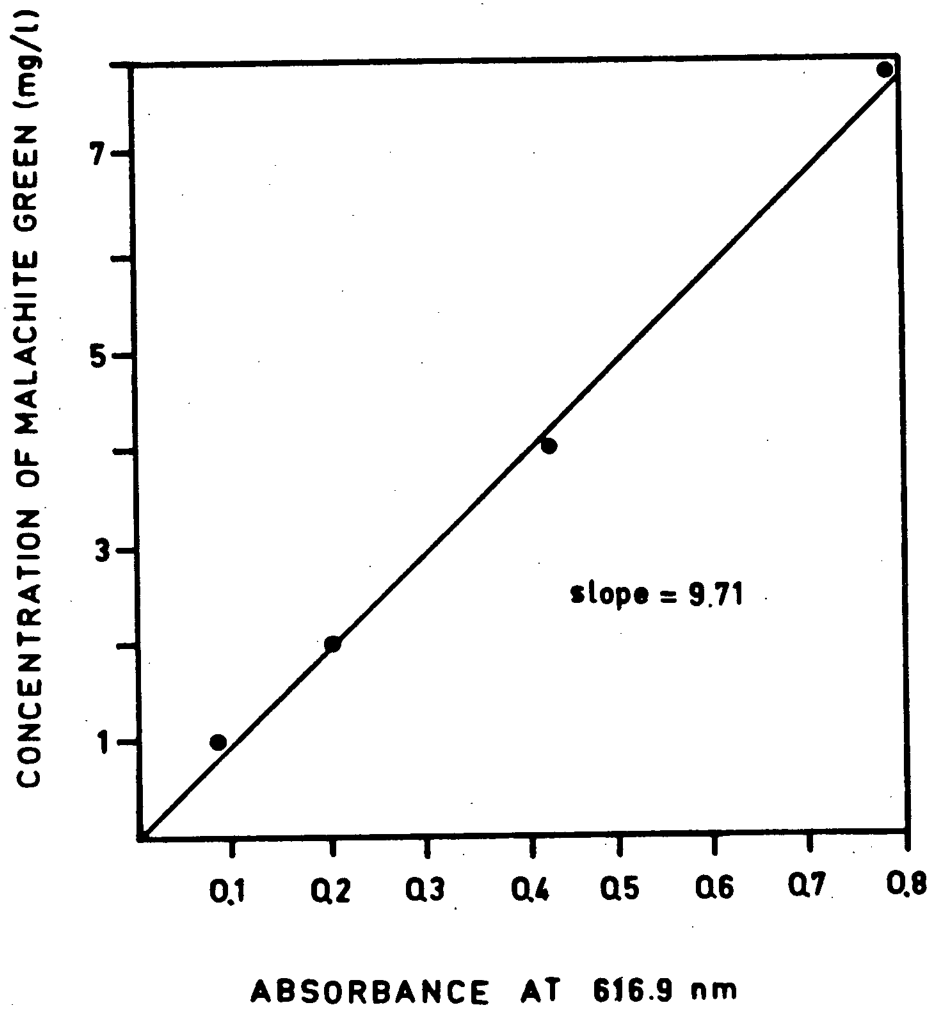


Figure 7. Absorbance of Malachyte green standards at 616.9 nm.

The concentrations thus obtained were normalized by dividing them by the area under the concentration versus time curve. When the normalized values are plotted against time, the E-curves are obtained (Levenspiel, 1972). The area under the E-curves is unity.

The four raceways were each tested at two flow rates, 5.0 and 10.0 l/min.

5. RESULTS AND DISCUSSION

5.1 Phase 1 -- Before August 15, 1979 (Construction and installation of equipment)

During the preparation period, the data collected consisted of water quality parameters such as: temperature, dissolved oxygen, pH, hardness and zinc.

Temperature: At the start of the flushing period, the water temperature was 10°C. By the end of the flushing, the temperature had risen to 13°C (Table 3). Both temperatures are suitable for the culture of rainbow trout.

Dissolved oxygen: The values fluctuated from a low of 7.7 mg/l (68% saturation at 10°C) to a high of 10.0 mg/l (88% saturation at 10°C)(Table 3).

pH: The water presented a slightly acidic pH, fluctuating between 6.2 and 6.5 (Table 3).

Water hardness: A very low value for the water hardness was found. Three measurements were made prior to the introduction of the fish. The analyses were done at one week intervals. The values obtained were 5.0, 4.5 and 5.5 mg/l as $CaCO_3$.

Zinc: The values obtained for the zinc concentration are presented in Table 4. It is interesting to note that the expected decay in rate of release (Slunder

Table 3. Water quality during Phase 1.

Day Number	Date	Temperature (°C)	D.O. (mg/l)	pH
33	July 19/79	10	8.0	
40	July 20/79	10	7.7	6.2
44	July 24/79	10	10.0	
45	July 25/79	9.5	10.0	6.5
50	July 30/79	11	9.4	
64	Aug. 13/79	13	9.2	6.3

Water hardness 5 mg/l as $CaCO_3$.

Table 4. Zinc concentration in the galvanized CSP raceways during Phase 1.

Day Number	Date	Zinc Concentration (mg/l)	
		Raceway 1	Raceway 2
3	June 13/79	0.43	0.12
16	June 26/79	0.02	0.16
40	July 20/79	0.16	0.05
64	Aug. 13/79	0.23	0.24

and Boyd, 1971) did not occur. The reason for this is thought to have been the removal of some of the protective film that had formed on the galvanized pipe The removal may have come about when the sediment and some scales that had formed on the zinc surface (Figure 8) were removed by gentle scraping with the bare hand in preparation for the introduction of the fish. The zinc concentration in the raceways was measured one day before stocking the fish and found to be 0.23 and 0.24 mg/l for each of the two CSP raceways.

5.2 Phase 2 -- August 15-16, 1979 (Stocking of the raceways)

The unsuitability of the environment in the galvanized raceways was demonstrated by the heavy mortalities sustained. The first deaths occurred between four and eighteen hours after the fish were introduced in the raceways (Table 5). The fish continued to die even after having been transferred from the galvanized raceways to fiberglass tanks.

The zinc concentrations at the time the fish were brought in were 0.24 and 0.23 mg/l (Table 4) for the two raceways. The reported safe values range from 0.038 to 0.260 mg/l for soft water, with 96 hour LC_{50}'s in the range 0.100 to 0.820 mg/l (Section 2.3). It is thought that the unexpectedly high mortalities were due to the extremely unfavourable water conditions, specifically the very low water hardness, 5 mg/l as $CaCO_3$.

Figure 8. Scales on the surface of the galvanized CSP raceways.

Table 5. Mortalities in the galvanized CSP raceways.

Time After Stocking (hr)	Time Interval (hr)	No. of Dead Fish Raceway 1	No. of Dead Fish Raceway 2	Avg.Death Rate/hour Raceway 1	Avg.Death Rate/hour Raceway 2	No.of Fish Remaining Raceway 1	No.of Fish Remaining Raceway 2
3.5*	3.5	0	0	0	0	438	438
18.5	15.0	59	51	3.9	3.4	379	387
24.5	6.0	46	48	7.7	8.0	333	339
29.0**	4.5	42	71	9.3	15.8	291	268
42.5	13.5	121	141	9.0	10.4	170	127
48.0	5.5	19	10	3.5	1.8	151	117
53.0	5.0	21	10	4.2	2.0	130	107
66.5	13.5	10	7	0.7	0.5	120	100
72.0	5.5	2	1	0.4	0.2	118	99
80.5	8.5	0	2	0	0.2	118	97

* Time 0 is at 13:25, August 15/80.

** The survivors were transferred to fiberglass tanks at 29.0 hrs.

5.3 Phase 3 -- August 17 - September 14, 1979 (Intermediate stage, experiment redesigned)

During this period, August 17 to September 14, 1979, fish were held in two PVC raceways and the survivors from the galvanized pipe raceways were held in two fiberglass tanks (Figure 9) until August 29 when they were counted and put in one fiberglass tank only. Table 6 shows the total weight, average weight and number of fish in each raceway for this period. Note that some of the values are measured and others calculated. The total weights were measured by the procedure outlined in Section 4.1.2. The average weights were determined by counting two 50 fish batches and weighing them. The number of fish was found by dividing the total weight by the average weight, except for mortalities and survivors in the fiberglass tank that were counted.

At the end of this period, it was found that fish in the raceway PVC 2 had grown more than those in the raceway PVC 1 which in turn had grown more than those in the fiberglass tank. The average weights were found to be 6.4, 5.8 and 5.5 g respectively. When a 10% error estimate is taken into account, these weights become 6.4 ± 0.6, 5.8 ± 0.6, and 5.5 ± 0.6. The error originates in the weighing techniques. Every time a fish is netted and placed in the weighing bucket, an undetermined amount of water is introduced. The amount of water would be directly related to the number

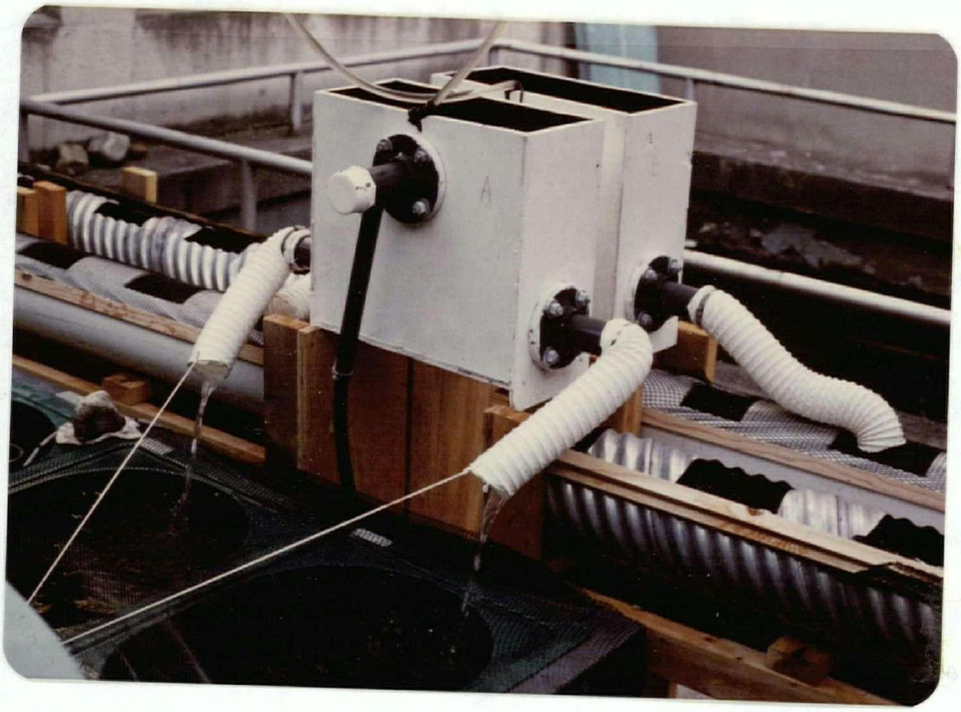


Figure 9. Fiberglass tanks used to hold the survivors from CSP raceways.

Table 6. Weight, average weight and number of fish in each raceway during Phases 2 and 3.

	Weight of Fish (g)		Avg. Weight of Fish (g/fish)		Estimated No.of Fish		Mortalities for Aug.15/79 to Sept.15/79 (No.of Fish)
	Aug.15/79	Sept.15/79	Aug.15/79	Sept.15/79	Aug.15/79	Sept.15/79	
PVC Raceway 1	1612	2524	3.65*	5.8**	442***	434***	8
PVC Raceway 2	1606	2795	3.65*	6.4**	440***	437***	3
Combined CSP Raceways	3196	920	3.65*	5.5**	876***	168***	678
Total:	6414	6239	3.65*	6.0	1758	1039	689

* Calculated from a sample of 100 fish at Sun Valley Trout Farms

** Calculated from two samples of 50 fish each

*** Number of fish = (Weight)/(Average Weight).

of nettings for a batch and also depends on the technique of the weigher i.e., the length of time between catch and release in the bucket, the amount of shaking taking place during the transfer.

Overall, the fish grew from an average weight of 3.6 ± 0.4 to 6.0 ± 0.6 g in the 30-day period.

5.3.1 Water quality

The water quality data for the period is presented in Tables 7 and 8.

Temperature: No difference in temperature was detected between the inflow and the effluent. The temperature ranged from a high of 16°C to a low of 13°C. Temperatures were measured at different times of the day and no daily fluctuations were noted.

Dissolved oxygen: The D.O. of the supply fluctuated quite considerably from a high of 9.4 to a low of 7.4 mg/l (Table 7). It is thought that these variations are related to the management of the filtering system for the water supply (Appendix VII).

The dissolved oxygen in the effluent from the raceways fluctuated widely, following the supply fluctuations in addition to day-to-day variations of its own.

Table 7. Feed, temperature and dissolved oxygen during Phase 3.

Day No.	Date	Feed/ Raceway (g)	Temp. (°C)	Dissolved Oxygen (mg/l) Supply	PVC-1	PVC-2
1	August 15	48				
2	16	48	14	9.4	7.5	7.4
3	17	48	14	8.5	7.3	7.0
4	18	48				
5	19	48	15	8.2	6.7	7.2
6	20	52	15	8.2	6.9	6.7
7	21	60	15	8.2	6.9	7.0
8	22	56	15	8.4	7.3	6.8
9	23	56	15	8.0	6.9	7.1
10	24	52	16	8.1	6.5	7.1
11	25	48	15	8.3	6.5	7.0
12	26	48	14	8.2	7.0	7.2
13	27	48				
14	28	48	14	8.3	7.0	6.9
15	29	48				
16	30	48	13	9.4	6.8	7.2
17	31	48	15	8.2	6.5	7.0
18	Sept. 1	32				
19	2	36	16	8.3	7.0	7.0
20	3	60				
21	4	60				
22	5	60	15	8.0	6.1	5.5
23	6	60	15	7.9	5.7	5.8
24	7	60	15	7.5	5.7	5.7
25	8	60				
26	9	40				
27	10	64				
28	11	64				
29	12	60	14	7.4	5.5	6.0
30	13	60	13	7.9	6.3	6.7
31	14	40	13	8.1	6.4	6.5

Table 8. Ammonia and pH during Phase 3.

Day No.	Ammonia-N (mg/l) Supply	PVC-1	PVC-2	pH Supply	PVC-1	PVC-2
2				6.6	6.4	6.4
7	0.04	0.13±0.05*	0.08±0.05	6.6	6.5	6.5
9	0.04	0.08±0.05	0.08±0.05	6.5	6.6	6.5
14	0.04	0.08±0.05	0.08±0.05	6.4	6.5	6.4
17	0.04	0.26±0.07	0.22±0.06	6.6	6.5	6.5
22	0.04	0.17±0.05	0.17±0.05	6.2	6.1	6.1
27	0.04	0.13±0.05	0.13±0.05	6.2	6.1	6.1

* Error associated with the experimental procedure (See Appendix IV).

The dissolved oxygen depletion in the raceways increased from around 1.3 mg/l in the initial days to a high of 2.1 mg/l around day 23 (September 6, 1979). A slight decline in oxygen use occurred towards the end of the 30-day period. The final oxygen depletion was down to 1.6. This decline could be due to the drop in water temperature from 15 to 13 C.

Dissolved oxygen measurements in the effluent were always done prior to feeding the fish.

pH: Both the supply and the effluent pH's decreased over the duration of the experiment. The initial supply pH was 6.6 on day 2, while the final reading was 6.2 on day 27 (Table 8). The effluent pH was slightly (0.1 to 0.2 units) lower than the inflow except for two cases where the effluent pH was 0.1 units higher than the supply.

In all cases, the pH was low enough to insure that the amount of ammonia in the raceways did not present a threat to the fish (Lloyd, 1961; Warren, 1962; Trussell, 1972, U.S.E.P.A., 1976).

Ammonia: Total ammonia (NH_3 plus NH_4^+) was very low in all cases. The highest concentration recorded was 0.26 ± 0.07 mg/l Ammonia-N (Table 8). Compare this to the total ammonia-N concentration of 21.0

mg/l, the value considered toxic to the fish at a pH of 6.5 at 10°C (Warren, 1962; Trussell, 1972; Westers and Pratt, 1977).

Although the autoanalyzer is admittedly more accurate than the Hach (Boyd, 1977), practical considerations prompted the decision to use the Hach kit for the ammonia analyses in these experiments. The Hach kit had the advantage of being inexpensive to run and even a small number of samples could be analyzed as soon as they were collected. The results could then be used to make management decisions regarding the flow, feeding level and fish density in the raceways (Haskell, 1955; Willoughby, 1968; Boyd, 1977; Westers and Pratt, 1977).

5.3.2 Observations on the management of the raceways

In all the raceways, the inflow was directed from the orifice by a flexible hose. The hose prevented the interference of the wind with the incoming water stream. This hose should be securely tied down to prevent the accidental disruption of the water flow to the raceways. The flexible hose should be placed as close to the head end of the raceway as possible to prevent the occurrence of backflows.

The outlet box collected solids that had to be siphoned out at least once a week. The perforated pipe that extended into the raceway had to be cleaned by introducing a tube through it to siphon out the material accumulated.

The pipe delivering the effluent from the outlet box to the drain had to be cleaned out at least once per month by introducing a wire through it. The raceways were found to be self-cleaning. No solids accumulated in the raceways stocked with fish.

The raceways were covered with nets (Figure 6). On several occasions, fish jumped out of some of the raceways due to small maladjustments in the placing of the netting.

After approximately two weeks of being stocked, algae started growing on the PVC raceways. At the end of Phase 3 the raceway walls were covered by a green slimy layer that had to be cleaned by hand.

5.4 Phase 4 -- September 14 - November 22, 1979 (Comparison of three raceways)

In the period from September 15 to November 22, 1979 (69 days), fish were held in three raceways, one made from PVC, one made from painted CSP and one made from wood (Appendix I). Initially all raceways were loaded with approximately 2080 g each (Table 9), or 346 fish at 6.0 g each. The flow through each of the raceways was 5 l/min. The fish were fed three times per day for a total of 60 g per raceway per day initially. This amount was increased to 90 g per day by October 22 (day 38)(Table 10). The water quality parameters monitored were: temperature, dissolved oxygen, pH and ammonia (Tables 10 and 11).

Fish growth: The fish weight data is presented in Table 9. Initially, each raceway held approximately 2080 g of fish or 346 fish at an average weight of 6.0 g. During the first day in the new raceways, 26 fish jumped out of the corrugated steel raceway due to a poorly positioned net. Other than these, the total mortalities for the period were six. The final average weights were determined by counting and weighing four samples of 20 fish from each of the raceways. The values indicate a higher growth rate for the fish in the CSP raceway (25.6 g/fish), followed by the fish in the rectangular raceway (22.9 g/fish) and by the fish in the PVC raceway (20.2 g/fish). (significantly different at $\alpha = 0.05$, by Duncan's multiple range test (Walpole and Myers, 1972)).

Table 9. Weight, average weight and number of fish in each raceway during Phase 4.

	Weight of Fish (g)		Avg.Weight of Fish (g/fish)		Estimated No.of Fish		Mortalities for September 15/79 to Nov.22/79 (No.of Fish)
	Sept.15/79	Nov.22/79	Sept.15/79	Nov.22/79	Sept.15/79	Nov.22/79	
PVC Raceway	2080	7505	6.0*	20.2**	346	371	2
Rectangular Raceway	2072	7521	6.0*	22.9**	345	328	3
CSP Raceway	2087	7034	6.0*	25.6**	348	275	27
Total:	6239	22060	6.0*	22.7	1039	974	32

* See Table 6.

** Calculated from two samples of 50 fish each.

*** Number of fish = (Weight)/(Average Weight).

Table 10. Feed, temperature and dissolved oxygen during Phase 4.

Day No.	Date	Feed/ Raceway (g)	Temp. (^{o}C)	Dissolved Oxygen (mg/l) Supply	PVC	RECT	CSP
1	Sept. 15	40	13	7.8	6.4	6.3	6.6
2	16	60					
3	17	60	11	7.8	6.7	7.6	6.6
4	18	40	11	7.3	6.1	6.7	6.7
5	19	60					
6	20	60					
7	21	60					
8	22	60					
9	23	45					
10	24	60	14	8.0	6.8	6.7	6.6
11	25	60					
12	26	60	14	7.6	5.9	6.1	6.0
13	27	60					
14	28	60	14	7.9	6.1	6.6	6.1
15	29	60					
16	30	60	15				
17	Oct. 1	60	14	7.4	5.7	6.0	5.8
18	2	60					
19	3	66	14	8.3	6.4	6.0	6.2
20	4	72					
21	5	72					
22	6	48					
23	7	72					
24	8	72	13	8.2	6.6	6.3	6.3
25	9	48					
26	10	72					
27	11	72					
28	12	72	14	8.5	5.9	6.1	6.1
29	13	72					
30	14	48					

. . . . .

Table 10. (Cont'd)

Day No.	Date		Feed/ Raceway (g)	Temp. (^{o}C)	Dissolved Oxygen (mg/l) Supply	PVC	RECT	CSP
31	Oct.	15	72	14	8.0	6.7	6.2	7.0
32		16	72					
33		17	50					
34		18	75	12	8.1	6.1	6.1	5.8
35		19	75					
36		20	75					
37		21	60	12	9.8	6.5	6.1	6.3
38		22	90					
39		23	90					
40		24	90					
41		25	90	12	11.0	6.1	7.0	7.3
42		26	90					
43		27	90					
44		28	60					
45		29	90	11	11.0	7.7	7.7	8.1
46		30	90					
47		31	90	10				
48	Nov.	1	90	10	11.0	7.9	6.5	8.1
49		2	90	10				
50		3	90					
51		4	60	10	11.0	8.6	7.8	8.0
52		5	90					
53		6	90	10	11.1	7.6	7.5	7.6
54		7	90					
55		8	90	10				
56		9	90					
57		10	90					
58		11	60	9				
59		12	85	9				
60		13	90	9	11.1	7.7	7.5	7.3

. . . . .

Table 10. (Cont'd)

Day No.	Date	Feed/ Raceway (g)	Temp. (°C)	Dissolved Oxygen (mg/l) Supply	PVC	RECT	CSP
61	Nov. 14	90	9				
62	15	90					
63	16	90					
64	17	90	9	11.2	7.8	7.9	8.0
65	18	45					
66	19	90	8	11.4	7.7	8.0	7.6
67	20	90					
68	21	90	8	11.5	8.1	8.0	7.3
69	22	90					

Table 11. Ammonia and pH during Phase 4.

Day No.	Date	Ammonia-N (mg/l)				pH			
		Supply	PVC	RECT	CSP	Supply	PVC	RECT	CSP
9	Sept. 23	0.08±0.05*	0.17±0.05	0.22±0.06	0.17±0.05	6.2	6.0	5.9	6.1
31	Oct. 15	< 0.04	0.13±0.05	0.08±0.05	0.13±0.05	6.4	6.2	6.2	6.2
46	Oct. 30	0.08±0.05	0.22±0.06	0.13±0.05	0.13±0.05	5.7	6.0	5.5	5.7
69	Nov. 22	< 0.04	0.17±0.05	0.13±0.05	0.13±0.05	6.8	6.2	6.3	6.4

* Error associated with the experimental procedure (See Appendix IV).

On December 24, 1979, the inflow pipe to the PVC raceway was accidentally knocked off and all the fish in the raceway died. The count of dead fish was 330. This value is in close agreement with the number calculated from the average and total weights (Table 9). The apparent disagreement in the figures for the other raceways and between the calculated number of fish on September 15 and on November 22 can be explained by the errors associated with the weighing process (Section 5.3).

5.4.1 Carrying capacity and stocking density

The carrying capacity and stocking density for the raceways are summarized in Table 12. Note that values far in excess of those recommended for raceways (Table 1) were obtained. Note also that the values obtained were not maximum possible loading rates, and that the peak loadings were not reached since neither dissolved oxygen nor ammonia had reached limiting levels.

It should be pointed out that these results are not unique. Other workers have reported similar carrying capacities and stocking densities: Buss and co-workers (1970) obtained 1.6 - 1.8 kg/l/min and 120-136 kg/m^3. Piper (1970) reported a stocking density of 90 kg/m^3 in aluminum troughs (the size of the troughs and the carrying capacity were not stated). Kincaid and co-workers (1976) obtained

Table 12. Carrying capacity* and stocking density** of the raceways at various stages of the experiments.

Date	Raceway	Flow Rate		Carrying Capacity		Stocking Density
		l/min	m^3/s	$kg/m^3/s$	kg/l/min	kg/m^3
Aug. 15	PVC-1	5	8.3×10^{-5}	1.94×10^{4}	0.322	29.8
	PVC-2	5	8.3×10^{-5}	1.92×10^{4}	0.321	29.7
Sept.15	PVC-1	5	8.3×10^{-5}	3.02×10^{4}	0.505	46.7
	PVC-2	5	8.3×10^{-5}	3.35×10^{4}	0.559	51.8
Sept.15	PVC	5	8.3×10^{-5}	2.49×10^{4}	0.416	38.5
	Rectangular	5	8.3×10^{-5}	2.48×10^{4}	0.414	38.4
	CSP	5	8.3×10^{-5}	2.50×10^{4}	0.417	38.6
Nov. 22	PVC	5	8.3×10^{-5}	8.99×10^{4}	1.501	139.0
	Rectangular	5	8.3×10^{-5}	9.01×10^{4}	1.504	139.3
	CSP	5	8.3×10^{-5}	8.42×10^{4}	1.407	130.3

* Carrying Capacity = (Weight of Fish)/(Flow Rate).

** Stocking Density = (Weight of Fish)/(Volume of Raceway).

stocking densities as high as 170 kg/m^3 in 8.8 liter circular tanks and carrying capacities of 1.58 kg/l/min in 37.5 liter circular tanks.

Calculations of stocking densities and carrying capacities using the procedures proposed by various researchers (Willoughby, 1968; Westers, 1970; Westers and Pratt, 1977) yielded values ranging between 118 and 158 kg/m^3 for the stocking density and between 1.3 and 1.7 kg/l/min for the carrying capacity. These values are in close agreement with those obtained experimentally.

The results obtained in our experiments, and in the trials performed by other workers (as mentioned above), together with the values obtained when calculating stocking density and carrying capacity indicate that most commercial trout farming operations are underutilizing their pond space and water resources. Monitoring of environmental parameters such as dissolved oxygen, temperature and ammonia would convince the farmers that larger fish populations can be maintained in their ponds without stressing the fish. Growing the fish at high densities requires reliable water supplies and adequate back up systems that would correct any supply failure rapidly to prevent a devastating fish kill.

5.4.2 Water quality

The water quality data for the period is presented in Tables 10 and 11.

Temperature: No difference in temperature was detected between the influent and the effluent. The temperature at day one was 13°C. It reached a peak of 15°C on day 16. After that it started a very gradual decline and at the end of the experiment (day 69), it had reached 8°C.

Dissolved oxygen: The dissolved oxygen of the water supply oscillated around 7.8 mg/l initially and increased as the temperature dropped. On day 68, when the temperature was 8°C, the dissolved oxygen had climbed to 11.5 mg/l. The dissolved oxygen depletion in the raceways increased from around 1.2 mg/l to a high of 4.9 mg/l. The higher uses occurred towards the end of the test period due to the increased loading. The lowest dissolved oxygen value for the effluent was 5.7 mg/l. It occurred on day 17 and was caused by a combination of high temperature (15°C) and low dissolved oxygen (7.4 mg/l) in the influent water. At the end of the test period, the dissolved oxygen content of the effluent was around 7.8 mg/l even with the heavy oxygen use noted above.

pH: The pH remained on the acid side throughout the experiment. The supply fluctuated from a high of 6.8 to a low of 5.7. The effluent had a lower pH than the supply in all cases. The lowest pH was 5.5 and it occurred on day 46 when the supply had a pH of 5.7.

Ammonia: The ammonia Nitrogen concentration remained low throughout the experiment. The highest value obtained was 0.22 ± 0.06 mg/l. It was observed in the rectangular raceway on day 9 and in the PVC raceway on day 46. There was no definite trend for the ammonia-N concentration in the three raceways relative to each other. In other words, no one raceway had a consistently lower or higher concentration of ammonia-N than the other raceways.

5.4.3 Observations on the management of the system

The observations noted in Section 5.3.2 for the third phase of the experiments apply equally to this phase. In addition, it was noted that the antifouling paint prevented the growth of algae on the walls of the CSP and rectangular raceways. No algae growth was detected and the walls were not covered by a slimy layer as was the case for the PVC raceway.

5.5 Hydraulics

The results of the hydraulic studies being presented, characterize the flow in the raceways in the absence of fish. Superimposed on the established flow patterns are the disturbances and turbulence generated by fish swimming. The quantification of the effect of the fish on the flow characteristics is beyond the scope of this thesis. A description of two events will, however, illustrate the extent of the influence of the fish activity on the hydraulic characteristics of the raceways. The two events are similar in nature but occurred at different times and in different raceways.

Event 1. On September 3, three fish were put in the CSP raceway that had just been painted and flushed. The fish were to be used for testing the suitability of the environment prior to the transfer of a large batch of fish.

It was noted that soon after the introduction of the three fish, solid wastes started accumulating in the raceway (Figure 10). This accumulation continued until the time when the batch of 348 fish was introduced in the raceway. At this point, the solids became suspended in the turbulent water and were eventually carried out of the raceway. It should

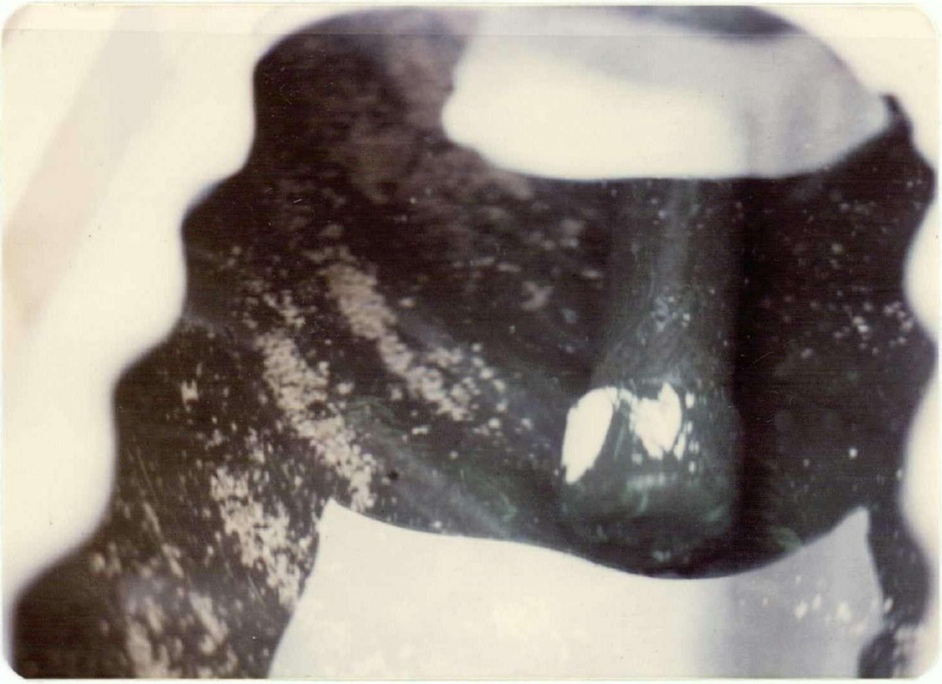


Figure 10. Sediment accumulated in the CSP raceway with the reduced loading.

be pointed out that no noticeable build-up of solids has taken place since.

Event 2. On December 24, an accident occurred which wiped out all but three fish in the PVC raceway. At that time, 333 fish had been kept in this raceway for 3-1/2 months without solids accumulating in the raceway. After the accident, the three survivors were left in the raceway and feeding was reduced to a trace. Solids soon started building up in the raceway (Figure 11) and had to be suctioned out.

Observations throughout the duration of the experiments with the fish revealed that the cleaning or flushing action was sporadic and followed patterns of fish activity usually associated with feeding. The suspension of the sediments and their subsequent exit from the raceways occurred at times of high activity by the fish which usually took place around feeding time.

The observations presented point out the extent of the influence of the fish on the characteristics of the flow in a raceway. This influence detracts from the usefulness of hydraulic studies of raceways with no fish in them. There are, however, several factors that serve as justification for studying the hydraulic characteristics of trout culture units. Factors such as:

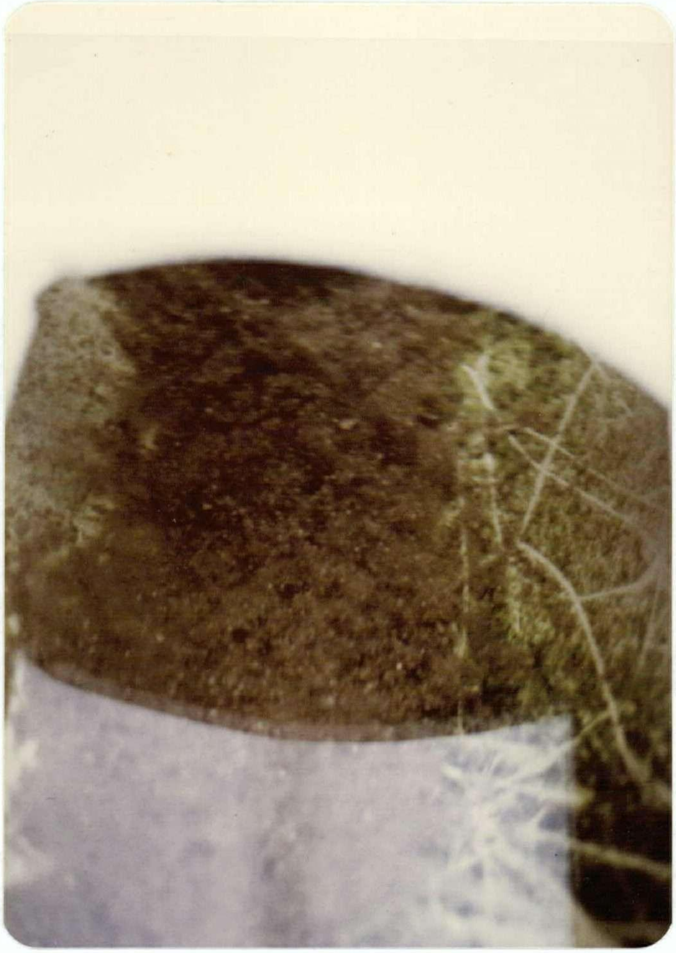


Figure 11. Sediment accumulated in the PVC raceway with the reduced loading.

- The sporadic nature of the high activity periods. This means that the fish may be swimming in conditions not too far removed from the no-fish situation for extended periods of time.
- The very different densities at which raceways are stocked by different operators and also the increasing density in a raceway as a batch of fish grows. All this means that the extent of the disturbance on the no-fish flow pattern will be highly variable.
- Perhaps the strongest confirmation of the importance of the background flow characteristics in a raceway, comes from the fact that very different carrying capacities and loading densities can be obtained from different shapes of impoundments having different flow characteristics (Table 1).

5.5.1 Flow patterns

A total of four complete runs were made. The photographs showing the movement of the dye are presented in Figures 12 to 15. Visual observations, not recorded in photographs were made in the four complete runs and also in runs on the CSP raceways. These observations are described below.

5.5.1.1 Acrylic glass pipe raceway

The dye movement in this raceway is shown in Figures 12 and 13 for the two flow rates, 5.0 and 10.0 l/min. In both cases, complete mixing of the inflow occurred almost instantaneously and no dead spots were detected close to the inlet, indicating the presence of a region of high turbulence.

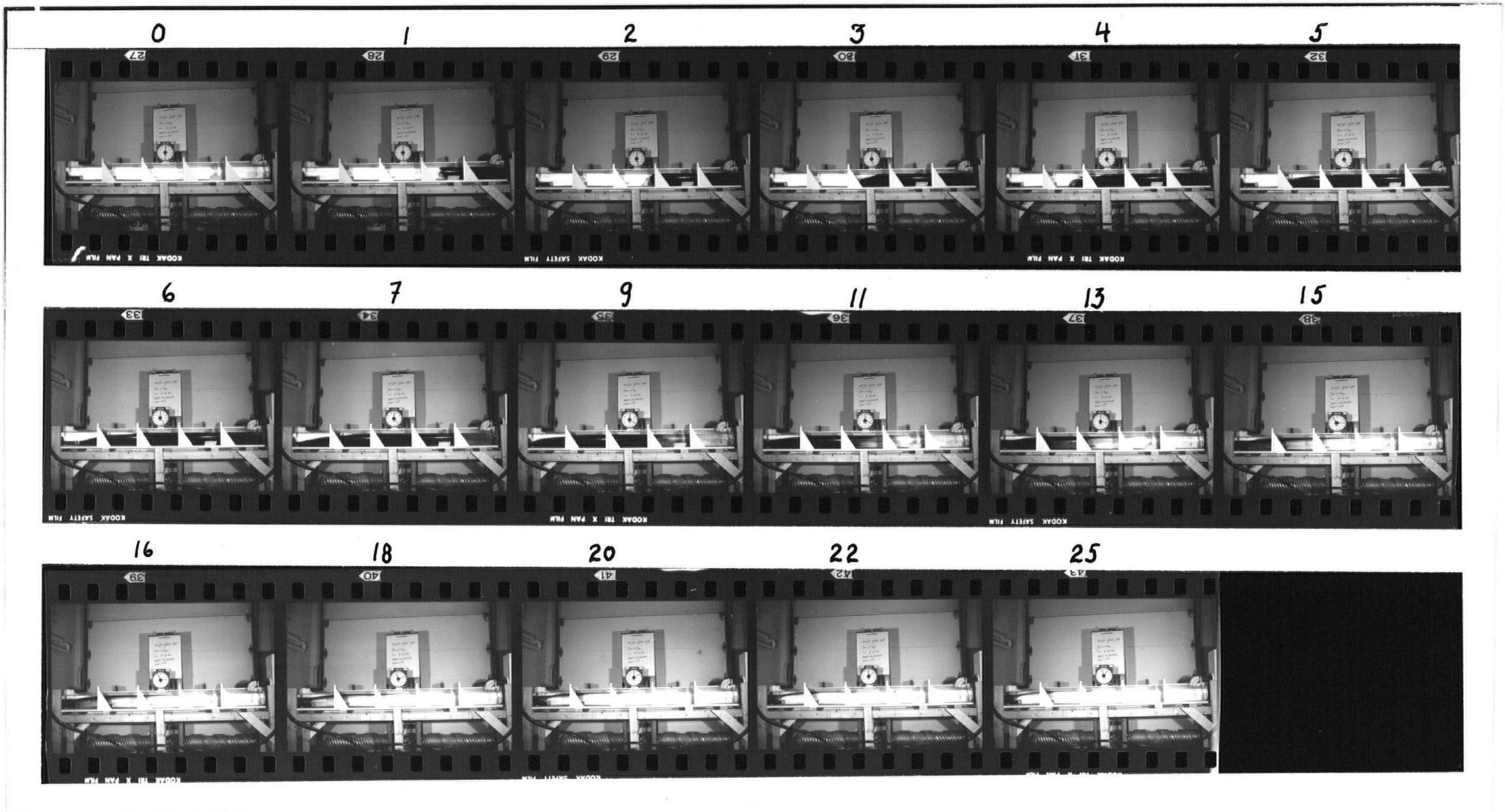
No dead areas were detected in the first half of the raceway. In the second half, a drawdown caused by the location of the outlet became apparent. A zone of rapid water flow appeared on the lower section of the raceway with a corresponding stagnant area close to the surface. The depth of the stagnant area increased as it got closer to the outlet.

Observations from above revealed some minor stagnant areas extending back from the outlet end along the sides of the pipe a distance of about one-fifth of the raceway length.

There were no dead areas close to the bottom of the raceway.

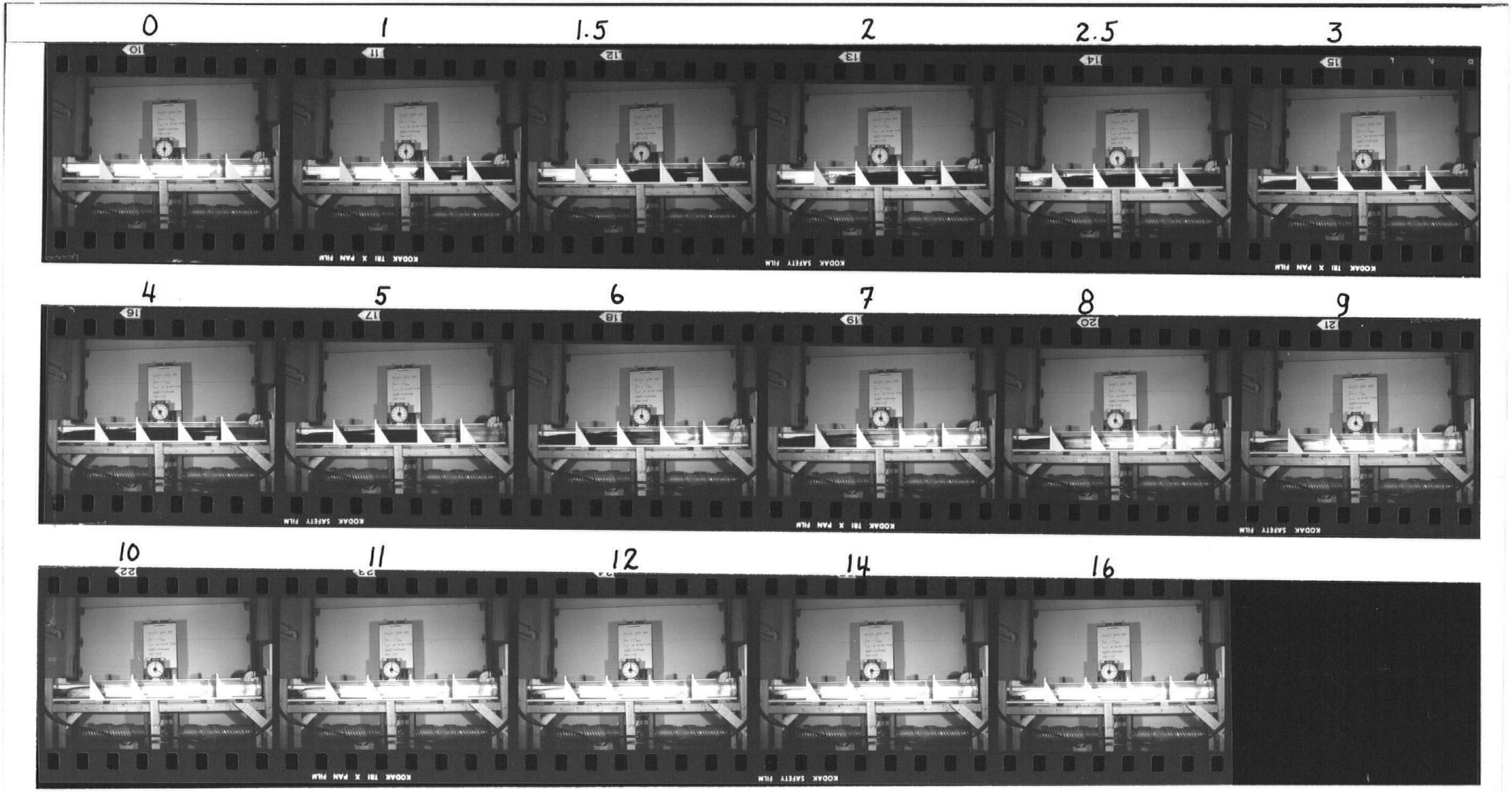
5.5.1.2 Rectangular raceway

The dye movement for this raceway is shown in Figures 14 and 15 for the 5.0 and 10.0 l/min flow rates. As was the case in the pipe raceways, a region of high



Numbers indicate the time (minutes) after the injection of the dye.

Figure 12. Flow patterns in the circular raceway at 5 l/min.



Numbers indicate the time (minutes) after the injection of the dye.

Figure 13. Flow patterns in the circular raceway at 10 l/min.

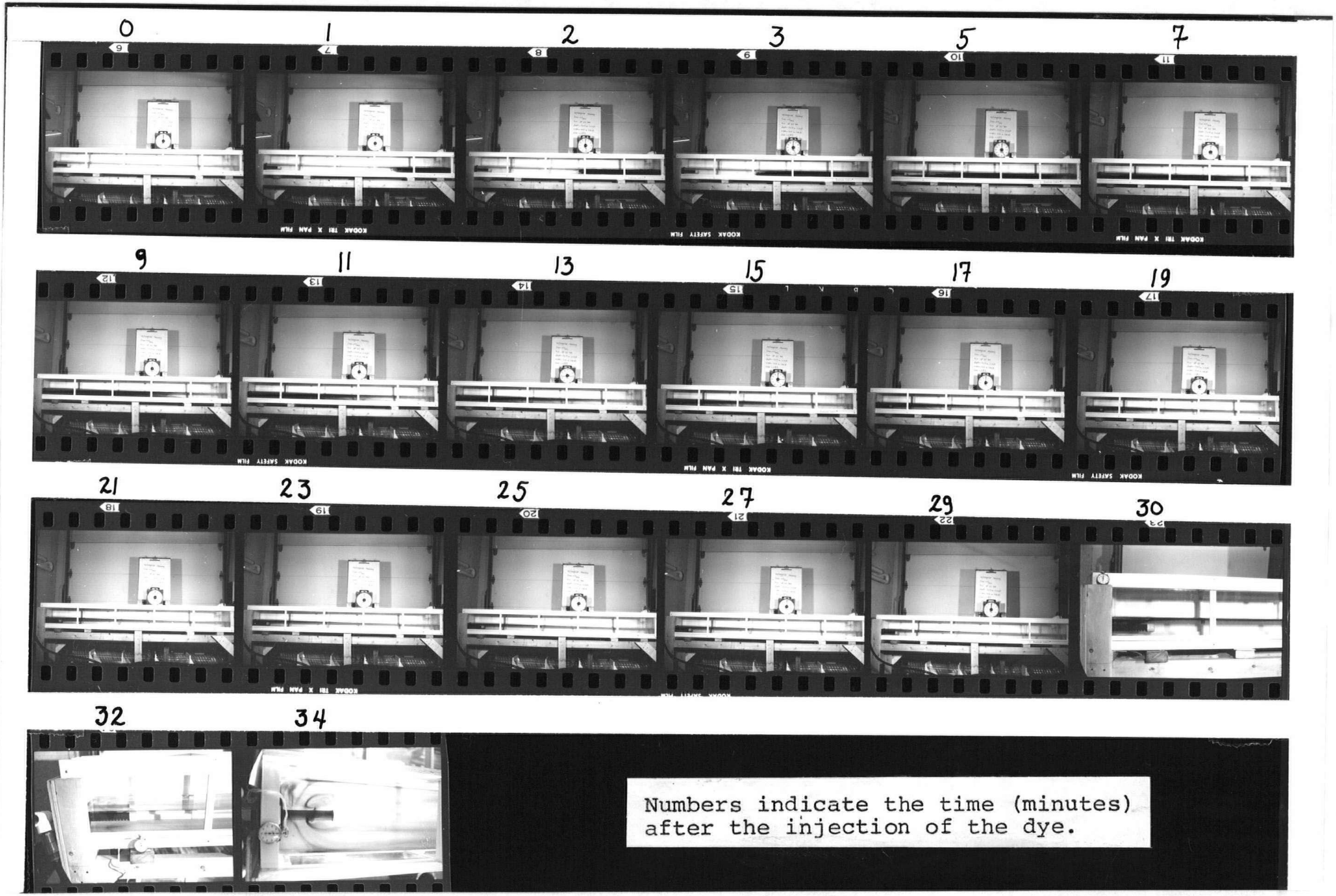


Figure 14. Flow patterns in the rectangular raceway at 5 l/min.

Numbers indicate the time (minutes) after the injection of the dye.

Figure 15. Flow patterns in the rectangular raceway at 10 l/min.

turbulence occurred near the inlet and complete mixing of the inflow resulted. Dead areas were detected in the second half of the raceway. In this case, they were both at and near the surface and the bottom. Dead areas were also present along the sides of the raceway extending back from the outlet.

5.5.1.3 CSP raceways

Observations made on these raceways were done from above only. The outstanding behaviour of the flow observed was the presence of dead areas in the corrugations, especially close to the outlets. Other than that, no dead areas could be detected due to the difficulty in making the observations. The location and extent of the stagnant areas are important for the management of the raceways. If the stagnant area is at or close to the water surface, food particles falling in the water will move slowly downstream and towards the bottom, giving the fish more time to reach the food. When the food particles finally sink, they will enter a region of higher velocity and will be carried to the outlet. Feces from the fish will be affected in a similar way by the water flow. If, on the other hand, the stagnant areas are close to the bottom of the raceway, particles reaching them will settle and sediments will accumulate in the raceways. Of the raceways tested, only the circular smooth raceway did not show stagnant areas close to the bottom.

Table 13. Concentration of malachyte green in the effluent of the raceways at time t after the introduction of the dye in the inflow.
(Concentration of Malachyte Green mg/l)

	Flow = 5.0 l/min				Flow = 10.0 l/min			
Time (min)	Circular Raceway	Rectangular Raceway	CSP (25 cm) Raceway	CSP (20 cm) Raceway	Circular Raceway	Rectangular Raceway	CSP (25 cm) Raceway	CSP (20 cm) Raceway
2.0							0.00	0.00
2.5					0.00	0.05	1.55	0.05
3.0					0.10	0.68	3.01	0.00
3.5			0.00		3.11	4.76	4.27	6.12
4.0			0.00	0.05	5.63	6.12	3.40	0.31
4.5			0.63	0.00	6.22	6.12	3.20	0.63
5.0		0.00	1.70	0.15	5.15	4.57	2.67	1.07
5.5			1.94	0.29	3.79	3.35		
6.0	0.34	1.07	2.52	0.49	2.57	2.09	1.84	1.55
6.5		1.70	2.67	0.73	1.89	1.60	1.21	
7.0	0.97	2.14	2.33	1.41	1.21	0.97	0.58	1.17
7.5	1.12	2.23	1.89	1.46	0.97	0.63	0.58	
8.0	1.26	2.77	1.60	1.57	0.68	0.49	0.44	0.92
8.5	1.55				0.39			
9.0	1.70	2.48	1.41	1.82	0.29	0.24	0.39	0.53
9.5	1.36							
10.0	1.07	2.09	1.07	1.75	0.24	0.15	0.15	0.44
10.5	1.12							
11.0	0.87	1.36	0.63	1.36	0.24	0.05	0.10	
12.0	0.53	1.12	0.25	1.12				
13.0	0.39	0.78	0.24					
14.0	0.39		0.19	0.63				
15.0	0.24	0.39						
16.0			0.10	0.34				
17.0		0.15						
18.0			0.02	0.29				
19.0		0.10						

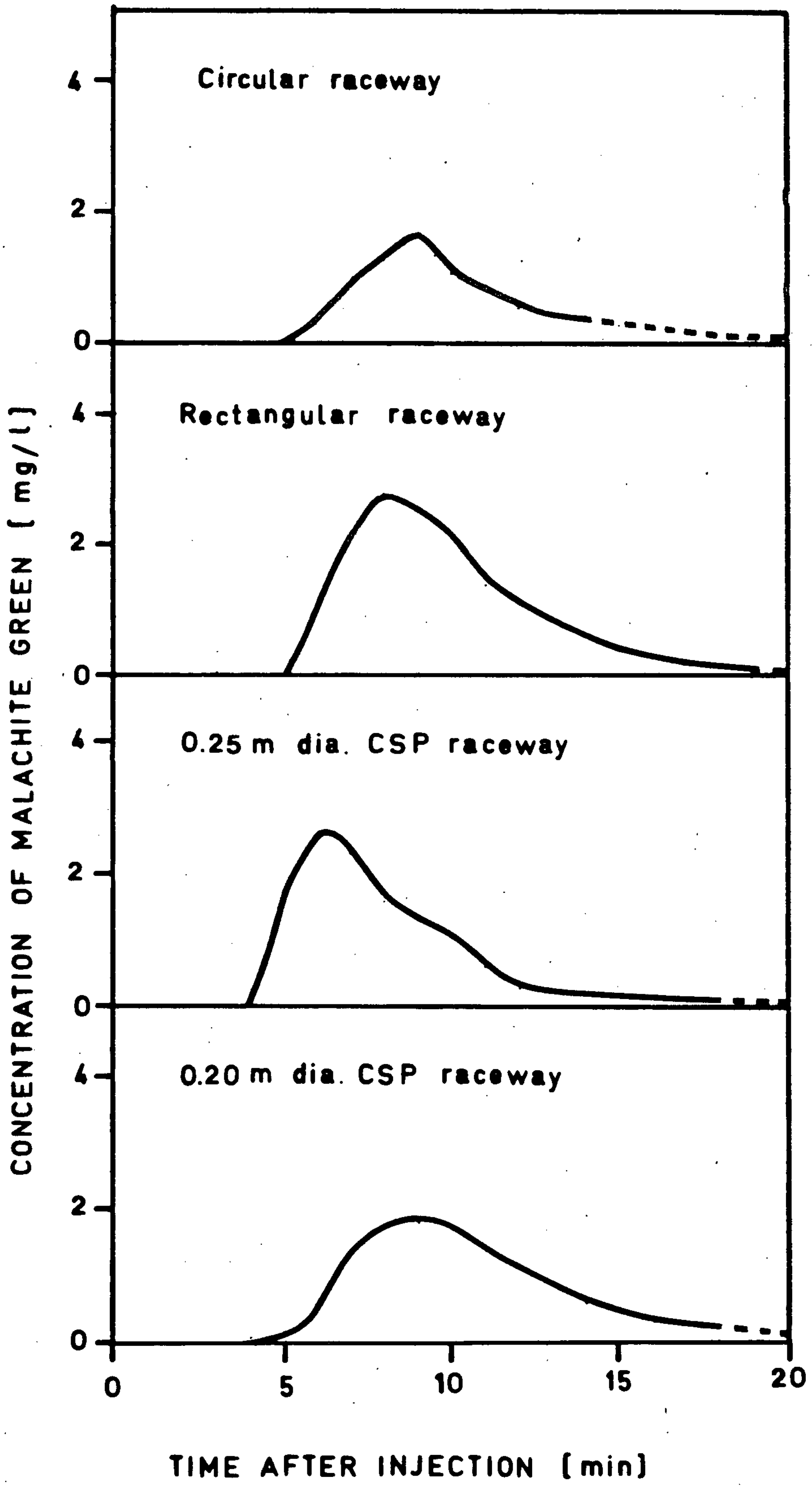


Figure 16. Concentration of malachyte green vs. time at 5 l/min.

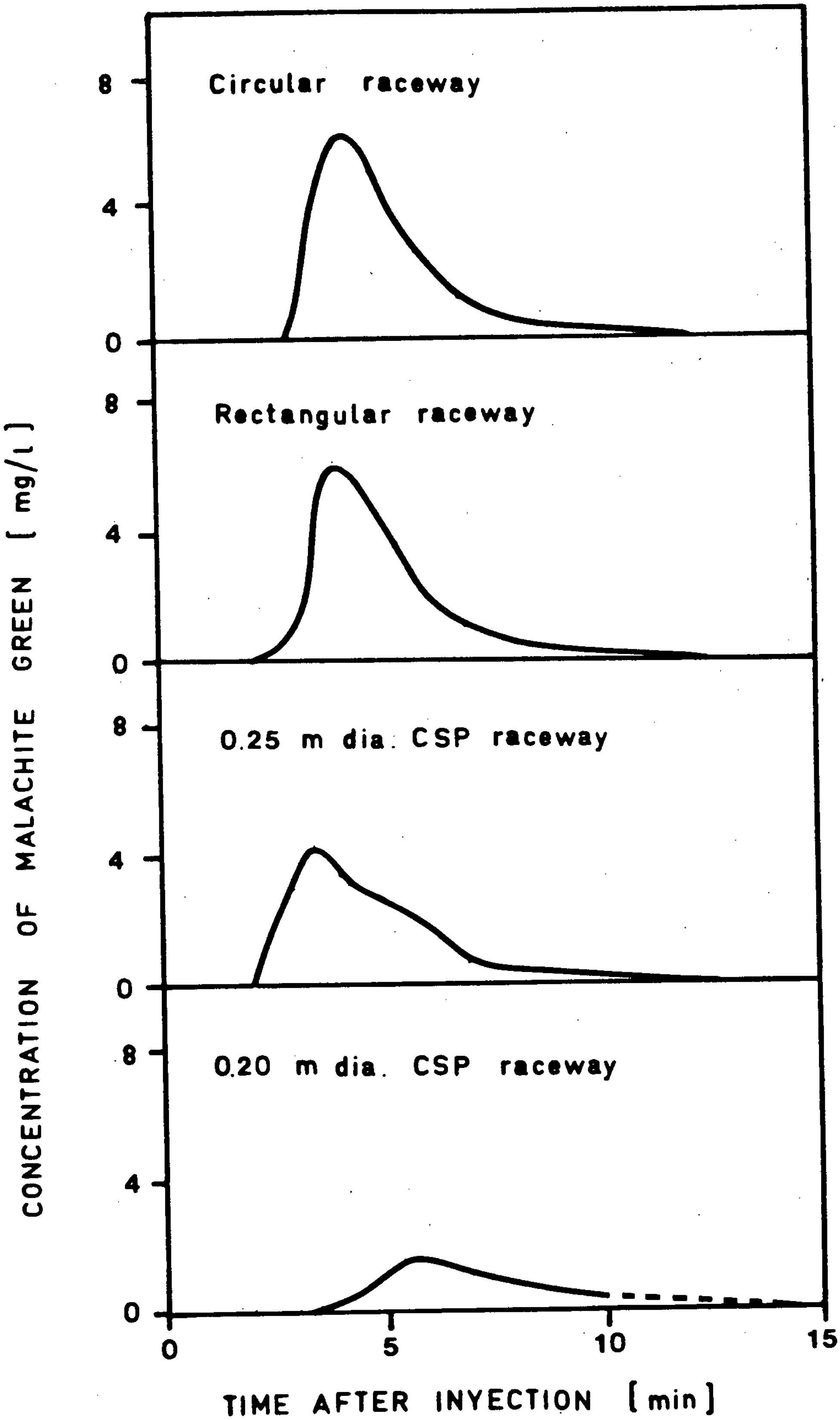


Figure 17. Concentration of malachyte green vs. time at 10 l/min.

Table 14. Normalized concentration values at 5 l/min.

Time (min)	E-values (l/min) Circular Raceway	Rectangular Raceway	0.25 m CSP Raceway	0.20 m CSP Raceway
3.5			0.000	
4.0			0.000	0.004
4.5			0.052	0.000
5.0		0.000	0.140	0.012
5.5			0.160	0.022
6.0	0.038	0.070	0.208	0.038
6.5		0.111	0.221	0.056
7.0	0.108	0.140	0.193	0.108
7.5	0.124	0.146	0.156	0.112
8.0	0.140	0.181	0.132	0.121
8.5	0.172			
9.0	0.189	0.162	0.117	0.140
9.5	0.151			
10.0	0.119	0.137	0.088	0.135
10.5	0.124			
11.0	0.097	0.089	0.052	0.105
12.0	0.059	0.073	0.021	0.086
13.0	0.043	0.051	0.020	
14.0	0.043		0.016	0.048
15.0	0.027	0.025		
16.0			0.008	0.026
17.0		0.010		
18.0			0.002	0.022
19.0		0.007		

Table 15. Normalized concentration values at 10 l/min.

Time (min)	Circular Raceway	Rectangular Raceway	0.25 m CSP Raceway	0.20 m CSP Raceway
	E-values (1/min)			
2.0			0.000	0.000
2.5	0.000	0.003	0.117	0.007
3.0	0.006	0.043	0.226	0.000
3.5	0.187	0.299	0.321	0.017
4.0	0.339	0.385	0.256	0.043
4.5	0.375	0.385	0.241	0.088
5.0	0.310	0.287	0.201	0.149
5.5	0.225	0.211		
6.0	0.155	0.131	0.138	0.215
6.5	0.114	0.101	0.091	
7.0	0.073	0.061	0.044	0.163
7.5	0.058	0.040	0.044	
8.0	0.041	0.031	0.033	0.128
8.5	0.023			
9.0	0.017	0.015	0.029	0.074
9.5				
10.0	0.014	0.009	0.011	0.061
10.5				
11.0	0.014	0.003	0.008	

5.5.2 Residence time distribution

The original concentration versus time data is presented in Table 13 and plotted in Figures 16 and 17. The curves were extrapolated and the area under each curve was measured using a Numonics Graphics Calculator (electronic planimeter). The distribution was then normalized by dividing the concentration by the area under the concentration versus time curve obtaining E, with units of 1/time. The normalized concentration, E, was then plotted against time and the E-curves were obtained (Levenspiel, 1972) and are shown in Figures 18 and 19. At the 5 l/min flow rate, the dye was detected earlier in the 0.25 m diameter CSP raceway than in the others. This indicates the presence of a more marked short circuiting stream. The circular and rectangular raceways have very similar residence time distributions indicating that they exhibit approximately the same extent of short circuiting and of intermixing. The 0.20 m diameter CSP raceway has the least short circuiting of the four raceways studied. The lower peak of dye in the effluent and the slower decay indicate that there is a large degree of intermixing taking place in this raceway.

At the 10 l/min flow rate, the raceways behaved in much the same manner as they had at the lower 5 l/min flow rate. The 0.25 m diameter CSP raceway again exhibited the most marked short circuiting while the 0.20 m diameter CSP raceway exhibited the least. It should be remembered that the 0.25 m diameter raceway was filled to a depth of 0.4 times the diameter while the 0.20 m diameter CSP and the circular raceways were both filled to 0.8 times the diameter, but all three had the same cross-sectional area.

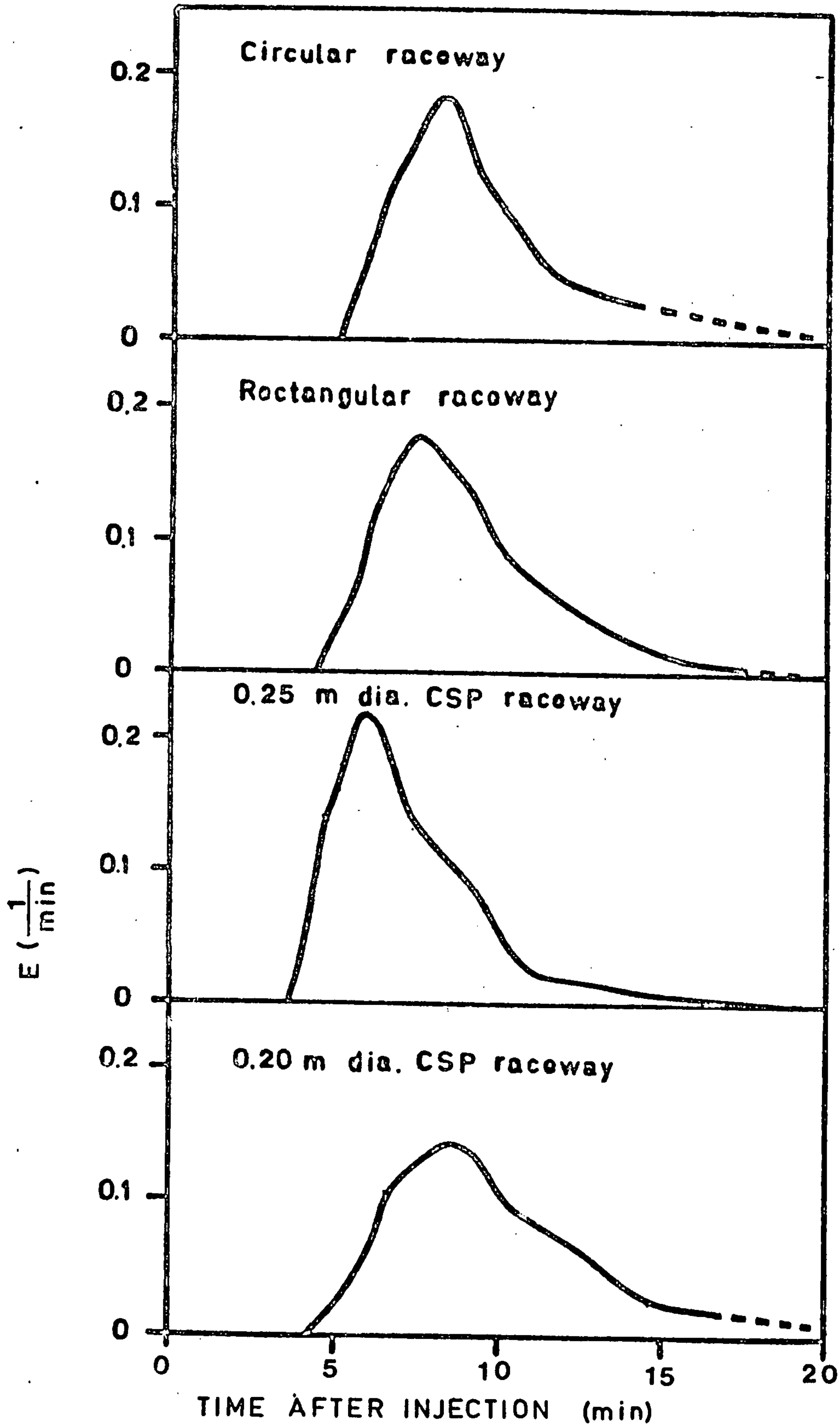


Figure 18. E -curves at 5 l/min.

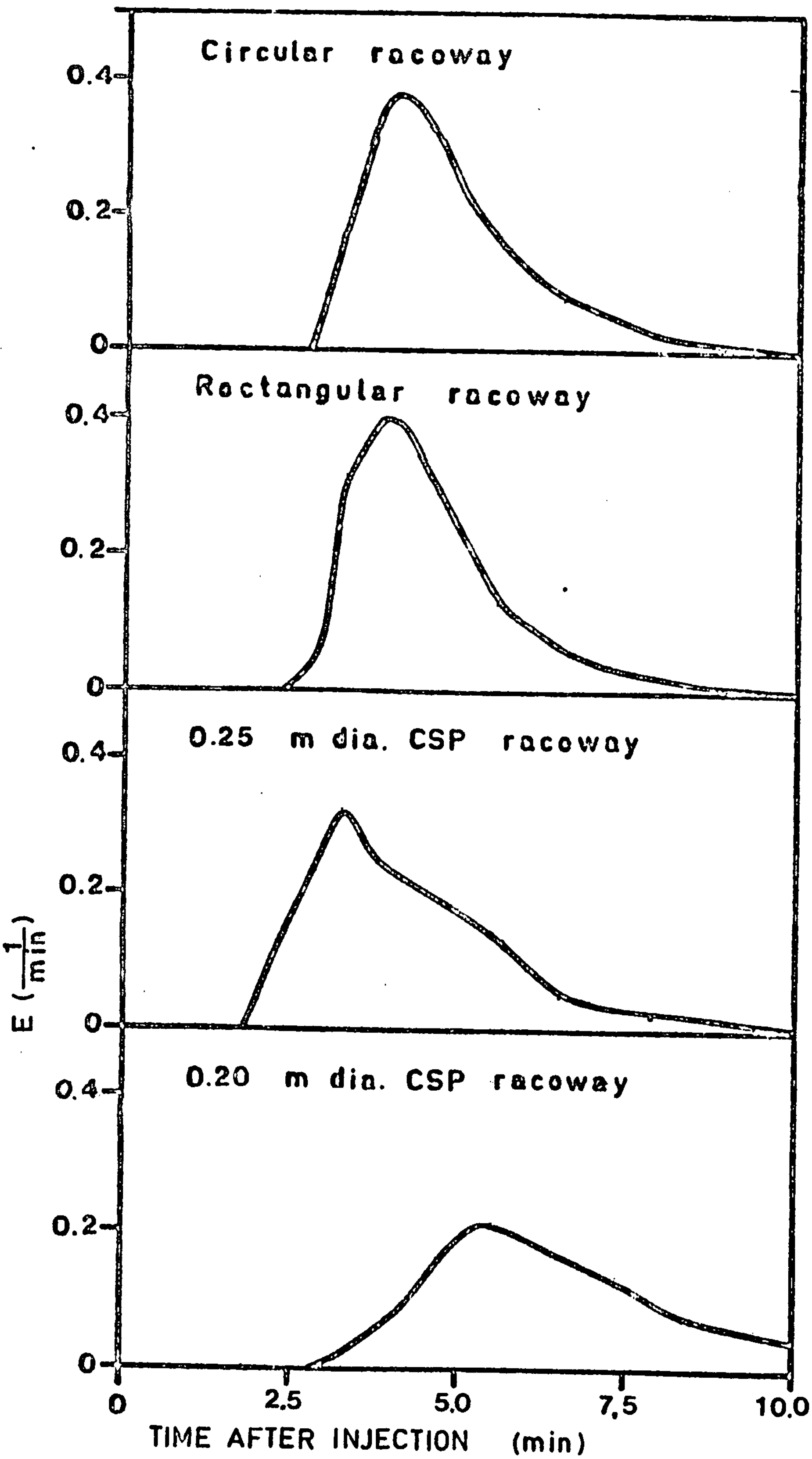


Figure 19. E -curves at 10 l/min.

6. CONCLUSIONS

1. Galvanized steel raceways are unsuitable for holding rainbow trout, *Salmo gairdnieri*, under the conditions of the test, even after flushing for 64 days.

2. The galvanized CSP raceways are suitable for holding rainbow trout when the inside is coated with inter-racing antifouling paint as was done in these experiments.

3. The paint used, inter-racing antifouling produced by International Paints, is not toxic to the fish and it reduces the growth of algae on the walls of the raceways.

4. Fish can be grown in raceways of circular cross-section.

5. Rainbow trout fingerlings (initial weight 6.0 g) grew faster in the CSP raceway than in the rectangular raceway and the PVC raceway.

6. The raceways are self-cleaning under the conditions of water flow rate and fish densities tested.

The term self-cleaning as used here means that there is no accumulation of solids in the raceways.

7. Fish can be grown in the raceways tested at much higher densities (weight of fish/ volume of pond) than those reported for conventional raceways.

8. No major differences between the hydraulic characteristics of the raceways were found.

9. The fish affect the characteristics of the flow in the raceways. Sediments did not accumulate in the raceways stocked with fish, but the sediments did build up when the raceways had only a few fish in them.

7. RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

During the experiments, several problems were encountered in the management of the raceways. What follows are some suggestions for modifications of the raceways.

1. Locate the inlet closer to the head end of the raceway. In the present set up, the inflow is coming in approximately 0.3 m from the head end of the raceway. The present location of the inlet causes backflows.

2. Improve the netting close to the ends of the raceways. There were several cases of fish jumping out close to the ends of the raceways due to improperly adjusted and poorly fitting enclosing nets.

3. Increase the size of the screen on the effluent pipe. This can be achieved by one or a combination of several of the following means:

   a. Maintaining the same slat width and spacing between slats,

      i) increase the diameter of the pipe, or

      ii) increase the length of pipe in the raceway

b. Increase the number of slats on the pipe

c. Increase the size of the slats.

4. Increase the diameter of the pipe carrying the effluent from the outlet box, to prevent the system from backing up and overflowing.

5. Provision for the complete drainage of the raceways should be made by installing a plug on the bottom of the raceways.

6. Install a bottom drain on the outlet box for the removal of solids accumulated in the box.

7.1 Suggestions for Future Work

a. Experiments in scaled up raceways. The results of the scaled up experiments would tell how good the models were for predicting the behaviour of the large scale raceways.

The conclusions presented in Section 6 should apply to the large scale raceways. Fish management considerations limit the depth of the large scale circular raceways to a maximum diameter of 1.0 m. The flow rate and length should be determined by the use of the model laws as outlined in

Section 2.2. For a 1.0 m diameter raceway, filled to 0.8 times the diameter, the length of the raceway would be 12.2 m. The flow rate for such a raceways would be 280 l/min (corresponding to the 5 l/min flow rate in the model). At the same carrying capacity as the model, the large raceway could carry 419 kg. The stocking density in this case would be 61.7 kg/m^3. The stocking density could be increased if the flow rate were increased. The upper limit on the flow rate is determined based on the amount of energy used up by the fish swimming in the raceway.

b. Experiments in the model raceways to determine if the high stocking density affects the growth rate of the fish even before stressful levels of dissolved oxygen or ammonia are reached. This would involve stocking equal raceways at different densities and comparing the growth of the fish.

c. Compare the growth rate of fish reared in raceways, circulating tanks, and vertical units. All the units would be stocked at a predetermined optimum level.

d. Test the galvanized CSP raceways under different water conditions. Water supplies of different hardness should be used.

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APPENDICES

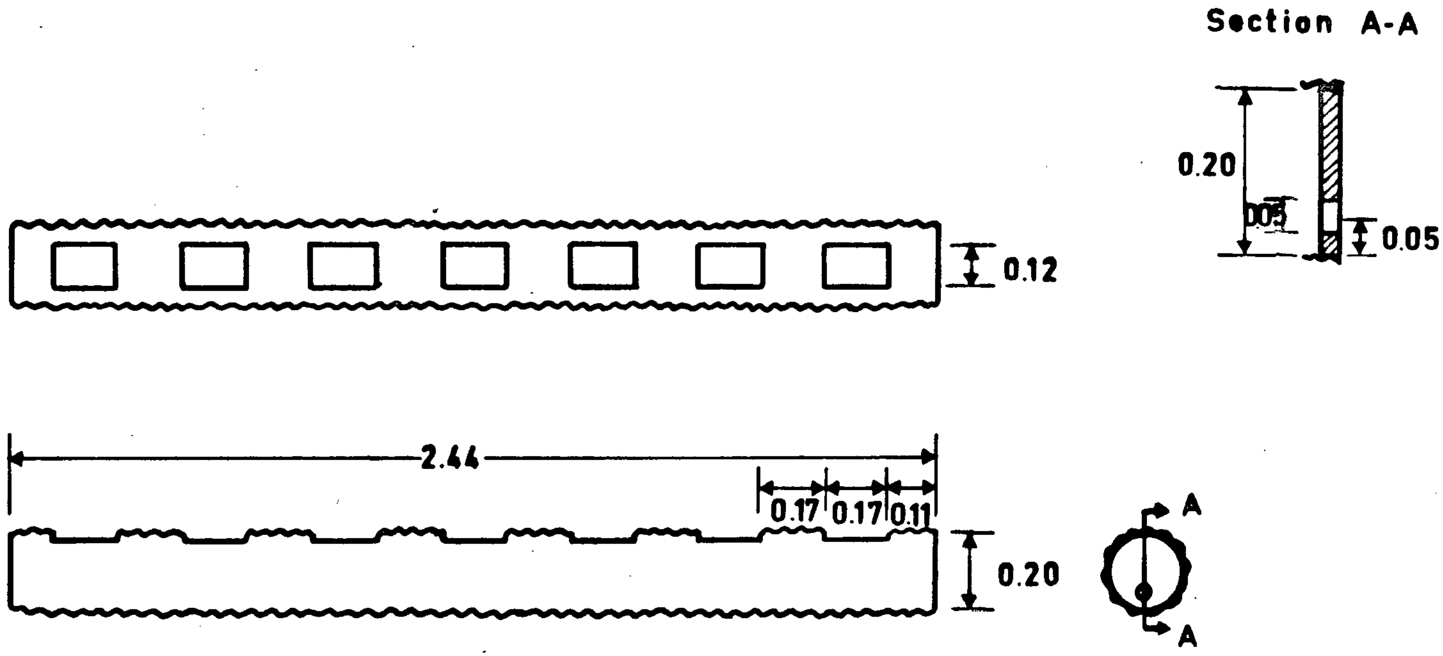
APPENDIX I-A. Corrugated Steel Pipe Raceway.

Two sizes of CSP raceways were built. Some from 0.20 m diameter pipe and some from 0.25 m diameter pipe. Figure I-1 shows the 0.20 m diameter raceway.

The CSP used was helical pipe meaning that the seam of the steel plate runs helically along the length of the pipe. The wall thickness was 0.13 cm (18 gauge). The ends were capped with 2.5 cm thick gumwood discs. The discs were first screwed in place and then the voids were filled with polysulfide caulking compound to achieve a water-tight seal. The polysulfide sealant was coated with antifouling paint on the inside of the raceway.

Rectangular openings were cut on the raceway as shown in Figure I-1. Care should be taken to avoid the seams of the pipe when making the holes. The holes were made by drilling on two opposing corners of the hole to be cut and then cutting the metal using a jigsaw.

When the raceways were painted for the fourth phase of the experiment, a zinc chromate primer was applied prior to the application of the green antifouling paint.

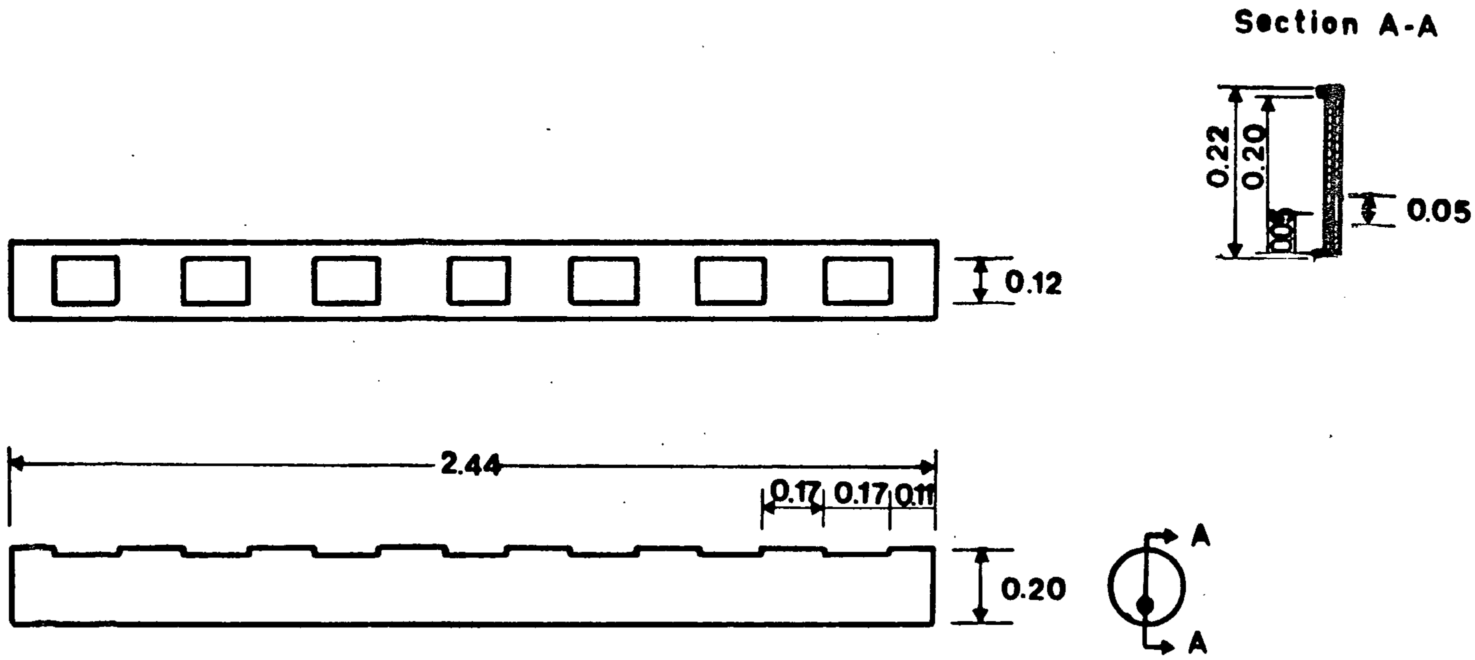


APPENDIX FIGURE I-1. Corrugated Steel Pipe Raceway. Dimensions in meters.

APPENDIX I-B. PVC Raceway.

The PVC raceways were built from 0.20 m diameter PVC pipe of 0.6 cm wall thickness. The end caps were made from 0.6 m thick PVC sheeting. Two discs were cut, one to fit inside the pipe and the other had the same diameter as the pipe. The two discs were glued together and then glued to the ends of the raceways.

Rectangular openings were cut in the top of the raceways as shown in Figure I-2. The procedure used for cutting the openings was similar to that described for the CSP raceways.

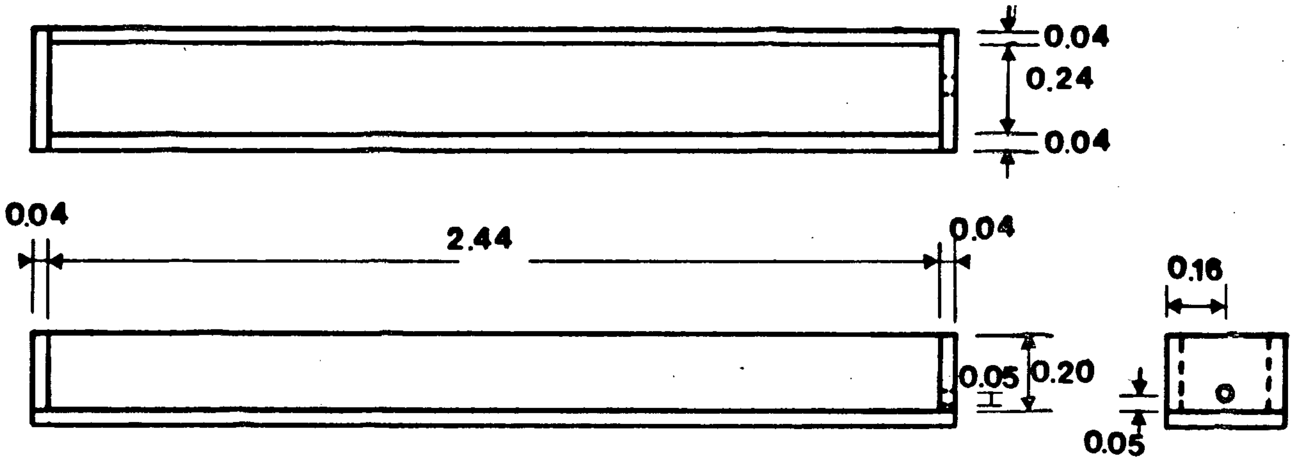


APPENDIX FIGURE I-2. PVC Raceway.
Dimensions in meters.

APPENDIX I-C. Rectangular Raceway for Fish Trials.

The rectangular raceway was built from 3.8 cm thick fir planks. The wood was glued and screwed together. It was then primed and finally two coats of green antifouling paint were applied. The seams were then sealed with silicone sealant.

The raceway is shown in Figure I-3.

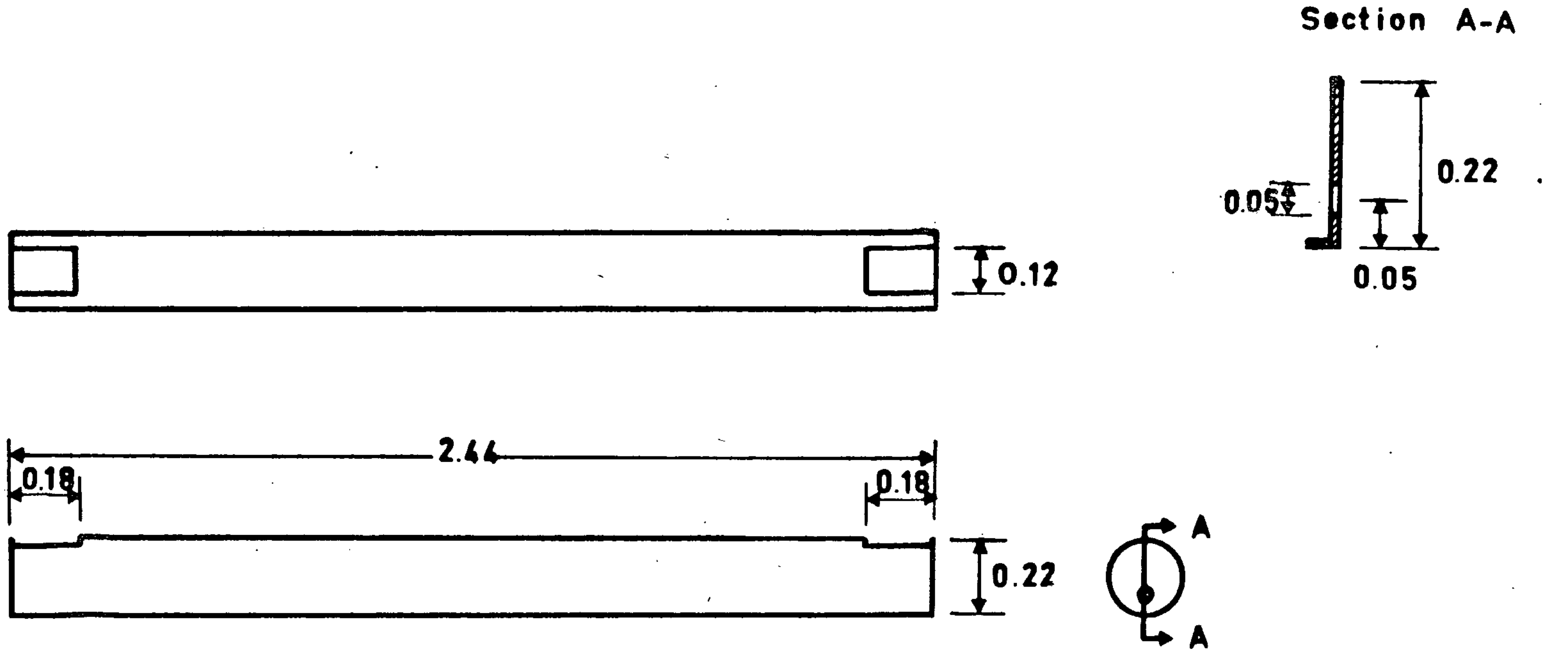


APPENDIX FIGURE I-3.   Rectangular Raceway for Fish Trials.
Dimensions in meters.

APPENDIX I-D. Acrylic Glass Pipe Raceway.

The acrylic glass pipe raceway was built from 0.20 m diameter pipe of 0.6 cm wall thickness. The pipe was available in maximum lengths of 1.8 m so a joint had to be made in order to obtain the desired 2.44 m length.

Rectangular openings were cut in the pipe as shown in Figure I-4. The end caps were discs of 0.6 cm thickness.

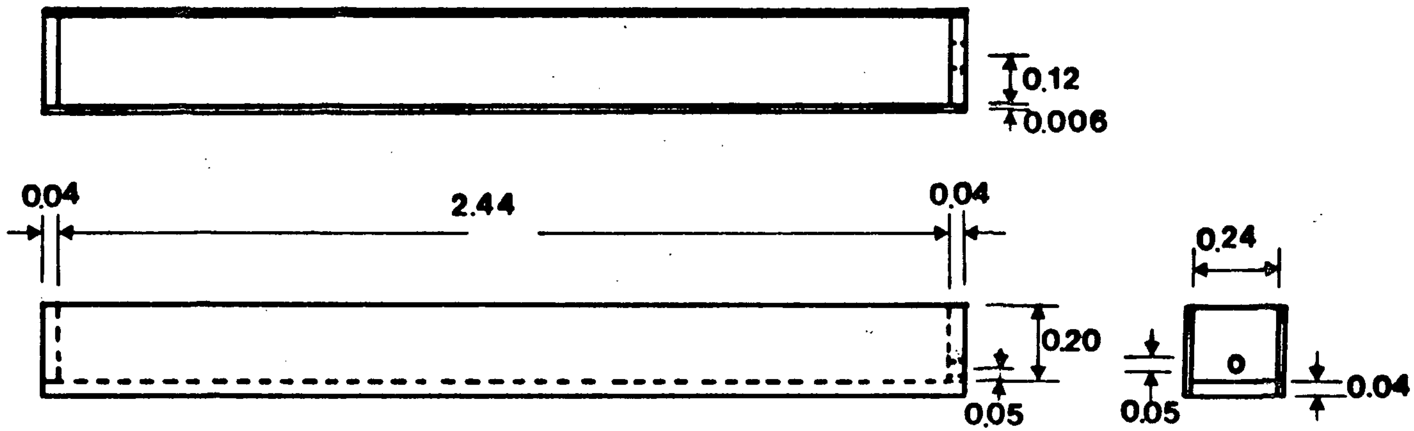


APPENDIX FIGURE I-4. Acrylic Glass Pipe Raceway. Dimensions in meters.

APPENDIX I-E. Rectangular Raceway for Hydraulic Studies.

This raceway was built from wood and acrylic glass (Figure I-5). The bottom and ends were 3.8 cm thick fir. The sides were 0.6 cm acrylic glass. Vertical supports were placed along the sides to prevent the acrylic glass from bending. The vertical members were 2.5 cm wide by 0.6 cm thick steel sections. Further support was provided by horizontal wood pieces along the top and bottom edges of the sides. The top pieces were connected by cross-pieces to prevent the acrylic glass from bending out when the raceway was filled.

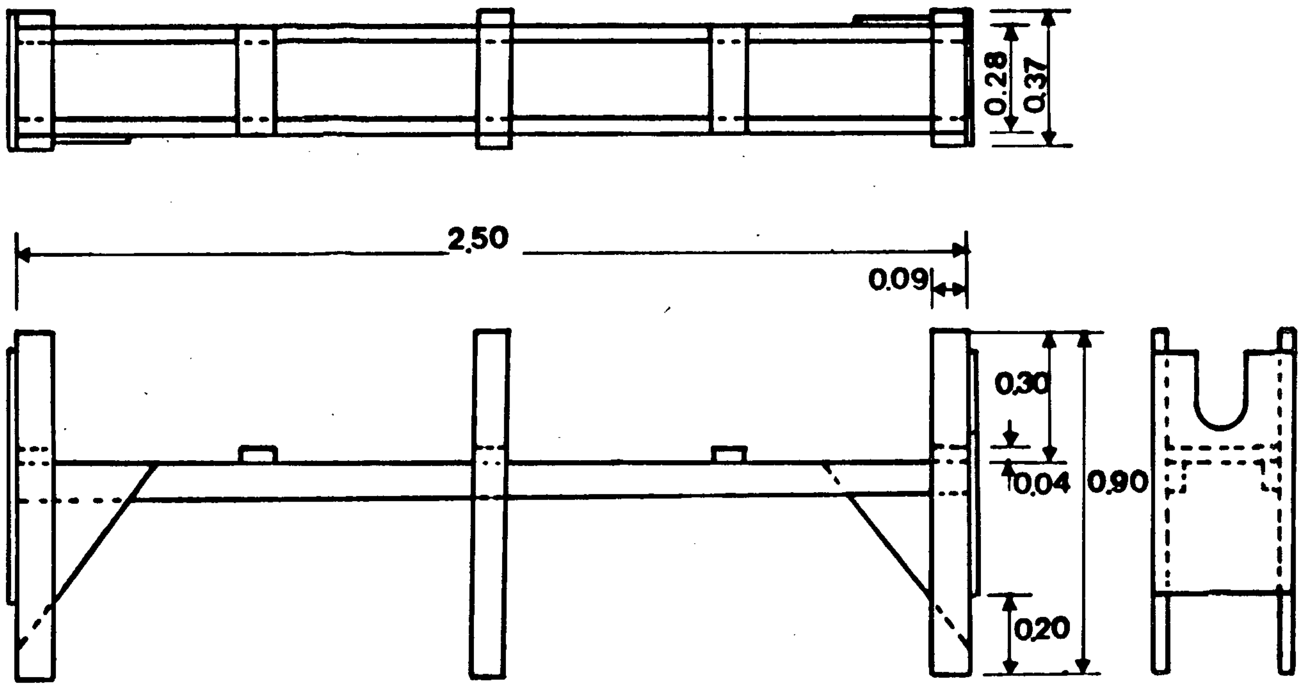
The wood was primed painted with white marine enamel. The seams were sealed with silicone sealant.



APPENDIX FIGURE I-5. Rectangular Raceway for Hydraulic Studies.
Dimensions in meters.

APPENDIX I-F. Stands for the Raceways.

Stands for supporting the raceways were made from 2"x4" (nominal size)(5x10 cm) fir. End sections of 1.8 cm plywood were added to provide support for the constant head tower and to improve the stability of the structure. Triangular braces of plywood were also installed as shown in Figure I-6.



APPENDIX FIGURE I-6. Stands for the Raceways.
Dimensions in meters.

APPENDIX I-G. Outlet Boxes.

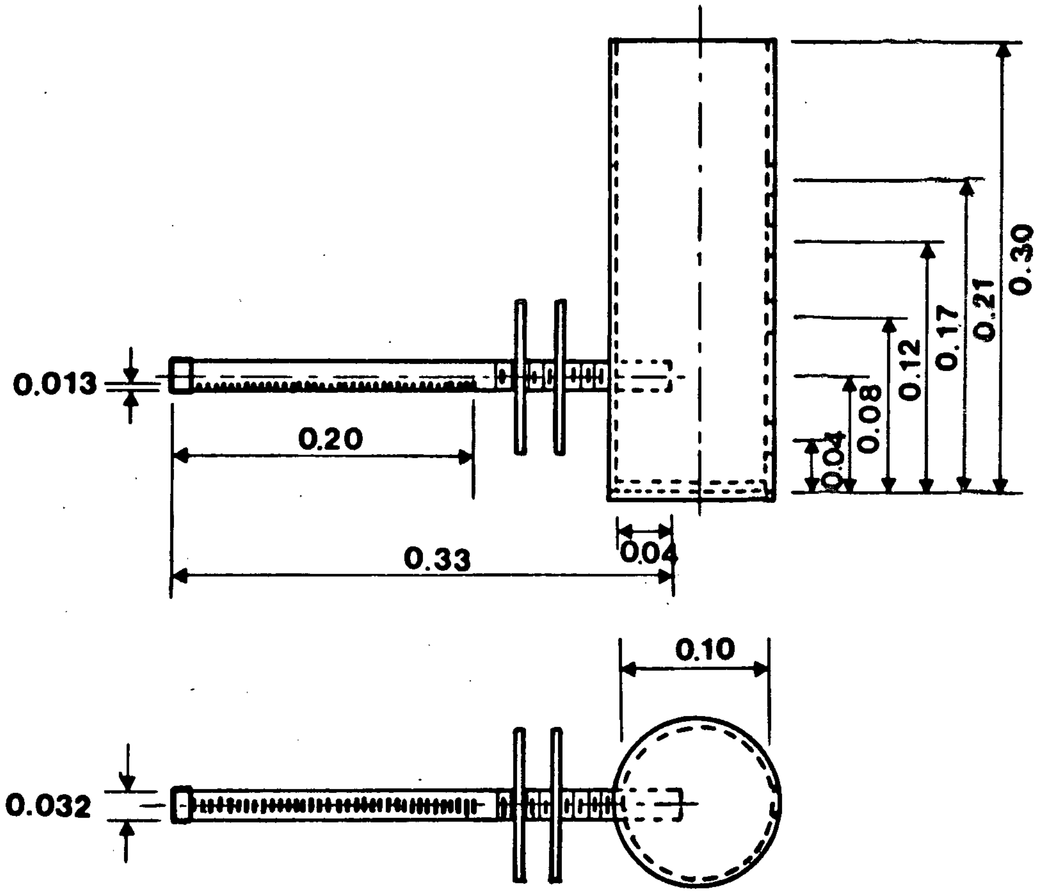
The outlet boxes are constructed from 0.10 m diameter PVC pipe. Holes are drilled and threaded for 1" (2.5 cm) I.D. pipe as shown in Figure I-7.

The slots on the outlet pipe are 0.3 cm wide, 1.3 cm deep and 1.3 cm apart. They were cut in a milling machine.

The outlet pipe is held in place by two threaded discs, one on each side of the end wall. Silicone sealant is used to prevent leaks.

The pipe carrying the effluent from the outlet box is 1.9 cm I.D. flexible plastic pipe.

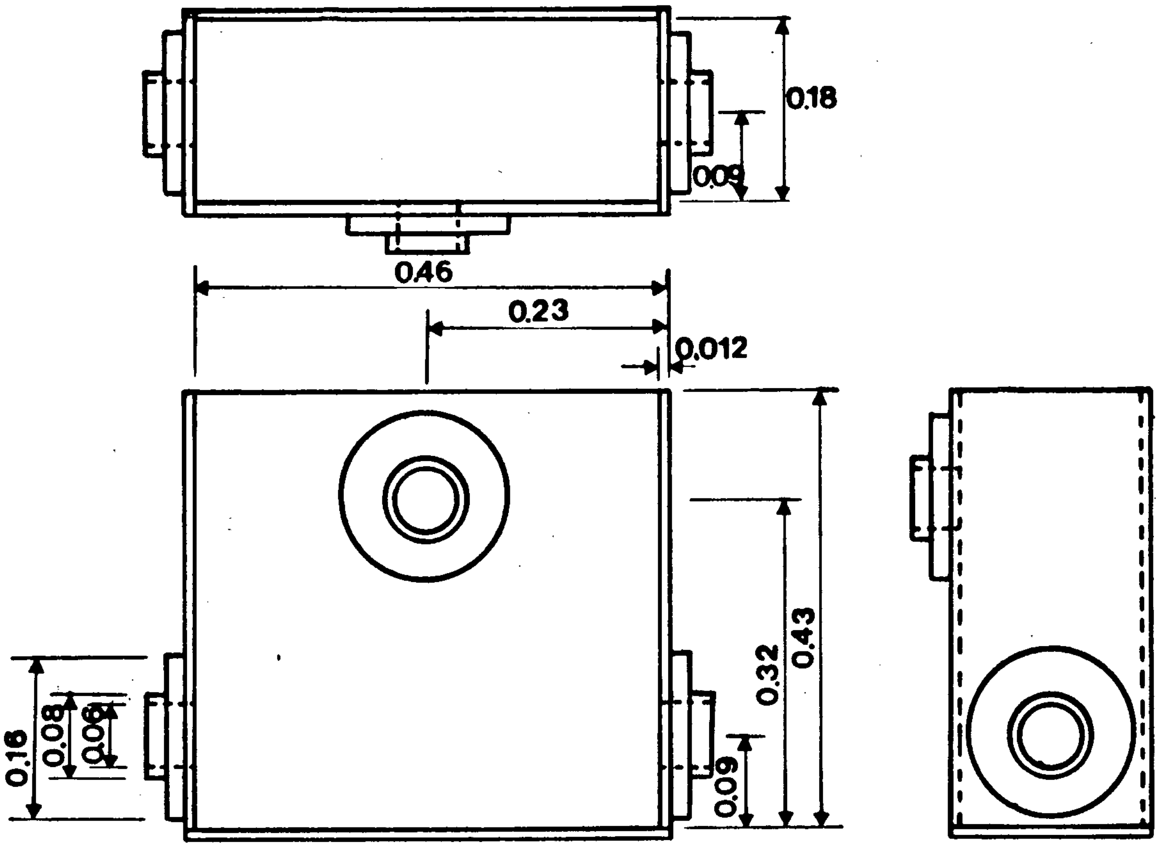
The outflow and water level control units are entirely manufactured from PVC parts except for the pipe carrying the effluent from the outlet box.



APPENDIX FIGURE I-7. Outlet Box.
Dimensions in meters.

APPENDIX I-H. Constant Head Tower.

The constant head boxes were built from 1.1 cm plywood. The fittings are all PVC (Figure I-8). After assembly, the wood was primed and two coats of green antifouling paint were applied. The seams were sealed with silicone sealant.



APPENDIX FIGURE I-8. Constant Head Towers. Dimensions in meters.

APPENDIX II. Drawings and Discharge Data for Orifices.

The orifices were drilled on PVC caps for 5 cm (2") I.D. pipe. They were countersunk from the outside at 45^{o}. The orifice sizes were determined from the equation

$$Q = c \frac{\pi d^2}{4} \sqrt{2gH}$$

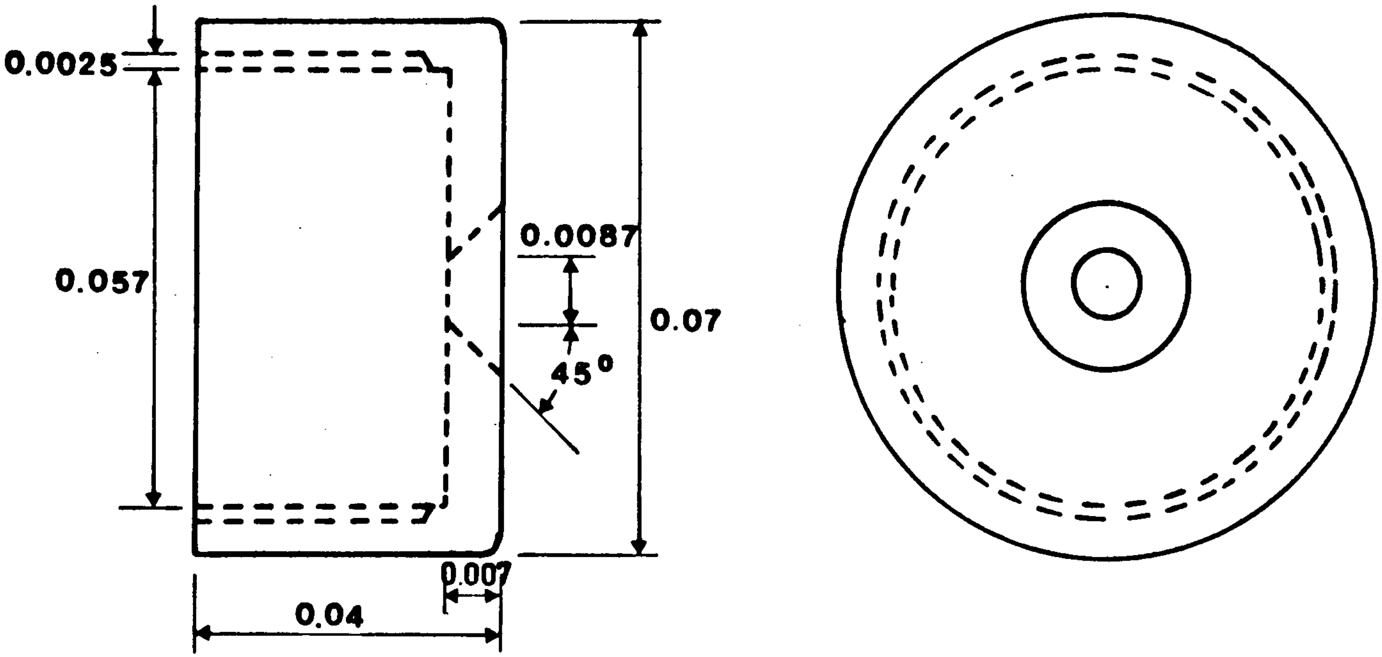
(Binder, 1973), where Q is the discharge, c is a constant for the orifice, d is the orifice diameter, g is the acceleration due to gravity and H is the head above the orifice.

Once calculations for an orifice size were made using an assumed constant c, an orifice was made (Figure II-1) and the discharge through it was measured. From this data, a new estimate for c was obtained. This estimate was used in a second set of calculations and the required orifice diameter was found. Four orifices were made and tested (Table II-1).

The desired flow was 5 l/min or 8.3×10^{-5} m^3/s. The head was 0.22 m. With a constant c = 0.65, the required diameter was found to be 0.87 cm (11/32"). The orifices were drilled and tested (Table II-1).

APPENDIX TABLE II-1. Discharge Data for Orifices, diameter = 0.87 cm, head = 0.22 m.

Date	Orifice Number	Discharge (l/min)
July 24/79	1	4.8
	2	4.8
	3	5.0
	4	4.8
Sept. 24/79	1	4.9
	2	5.0
	3	5.0



APPENDIX FIGURE II-1. Orifice.
Dimensions in meters.

APPENDIX III. Data Sheet for Inter-racing Antifouling Green Paint.

Manufacturer:	International Paints (Canada) Ltd.
Vehicle Type:	Rosin and other film formers
Pigment:	Cuprous oxide, Phthalo green, Hansa yellow
Solvent:	Aromatic hydrocarbons
Flash Point:	$26^{o}C$
% Solids by Volume:	53
Recommended Dry Film Thickness:	5.08×10^{-5} m
Theoretical Coverage:	12.5 m^2 per litre at 5.08×10^{-5} m D.F.T.
Dry Time:	Touch: 2-3 hours Hard: 6 hours
Overcoating:	Overnight
Colour:	Green
Finish:	Semi-gloss
Method of Application:	Brush
Shipping Weight:	7.2 kg.
Thinner:	073102

APPENDIX IV. Comparison of the Hach and Auto-analyzer Methods of Measuring Ammonia.

Ammonia was measured using a Hach DR-EL/2 Direct Reading Engineer's Laboratory Kit (Hach Chemical Co., Ames, Iowa), and a Technicon Auto Analyzer II (Technicon Industrial Systems, Tarrytown, N.Y.). The procedures for the tests are presented in Appendices V and VI.

Samples were collected daily from the effluent of each of the raceways and from the water supply. The samples were stored in a refrigerator at $4^{o}C$. The pH was approximately 6.1. On the fifth day of collection, all the samples (15 in total) were analyzed using both the Hach Kit and the auto-analyzer. The results are presented in Table IV-1 and plotted in Figure IV-1. The auto-analyzer value is assumed to be the correct value (Boyd, 1977). A regression equation is obtained as follows

$$y = 0.45\ x - 0.10$$

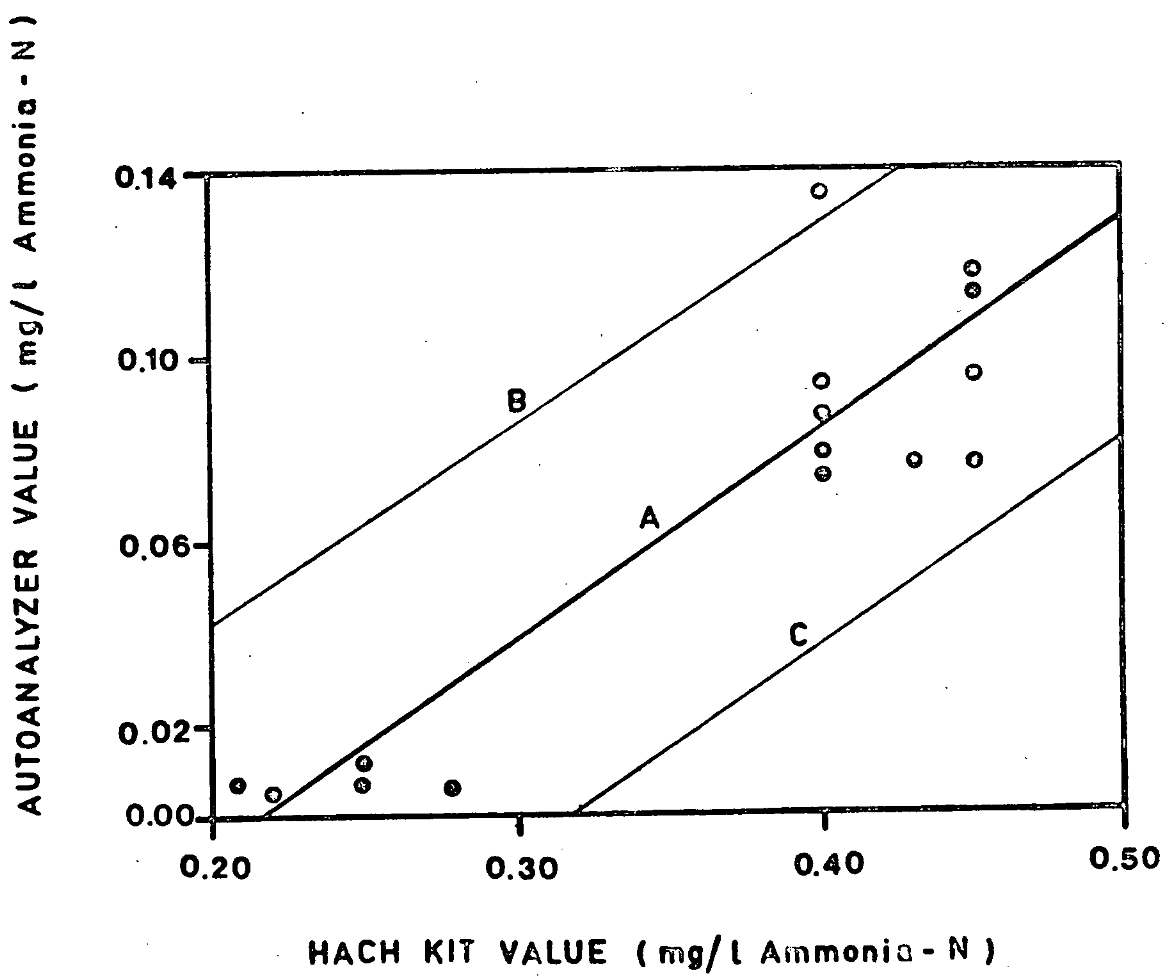
where y is the ammonia concentration in mg/l of ammonia-N, x is the Hach kit reading also in mg/l of ammonia-N. The correlation coefficient for the relationship is r = 0.905.

APPENDIX TABLE IV-1. Ammonia-N Measured With the Hach Kit and the Technicon Auto-Analyzer.

Day of Sample Collection	Ammonia-N (mg/l)					
	Supply		Effluent From Rectangular Raceway		Effluent From CSP Raceway	
	Hach	Auto-Analyzer	Hach	Auto-Analyzer	Hach	Auto-Analyzer
Monday	0.28	0.006	0.45	0.118	0.45	0.075
Tuesday	0.25	0.011	0.40	0.135	0.45	0.113
Wednesday	0.25	0.007	0.43	0.076	0.40	0.086
Thursday	0.22	0.006	0.40	0.073	0.40	0.093
Friday	0.21	0.007	0.40	0.078	0.45	0.095

Note: all samples were analyzed on Friday.

APPENDIX FIGURE IV-1. Auto-analyzer vs. Hach Kit Readings of the Ammonia-N Content of Samples.



Furthermore, a 95% confidence interval for single measurements of the ammonia concentration can be constructed using a t-statistic as follows (Walpole and Myers, 1972):

$$y = 0.45\ x - 0.10 \pm t_{0.05/2}\ s\ \sqrt{1 + \frac{1}{n} + \frac{(x_i - \bar{x})^2}{S_{xx}}}$$

where $t_{0.05/2}$ = 2.16 for n - 2 = 13 degrees of freedom

$n = 15$

$$s = \left(\frac{SSE}{n-2}\right)^{1/2} = \left(\frac{S_{yy} - 0.45\ S_{xy}}{13}\right)^{1/2}$$

$$S_{yy} = \sum_{i=1}^{15} y_i^2 - \frac{\left(\sum_{i=1}^{15} y_i\right)^2}{15}$$

$$S_{xy} = \sum_{i=1}^{15} x_i y_i - \frac{\left(\sum_{i=1}^{15} x_i\right)\left(\sum_{i=1}^{15} y_i\right)}{15}$$

$$S_{xx} = \sum_{i=1}^{15} x_i^2 - \frac{\left(\sum_{i=1}^{15} x_i\right)^2}{15}$$

The confidence interval is plotted in Figure IV-1. Analysis of prepared standard ammonia solutions in the Hach kit, yielded values ranging from 63% to 127% of the known concentrations.

The autoanalyzer analysis were off by a maximum of 5% of the known concentration. In contrast, on the analysis of the samples from the water supply, the Hach kit yielded values which were up to 50 times those obtained by the autoanalyzer. This results would indicate the presence of interfering agents in the water supply. The interfering agents are not identified and the Hach Kit should be calibrated for each water supply in a manner similar to that presented here.

APPENDIX V. Procedure for Measuring Ammonia Using the Hach Kit.

Nessler Method.

Range: 0-2 mg/l

Procedure:

1. Take a water sample by filling a clean 25-ml graduated cylinder to the 25-ml mark. Pour into a clean sample cell.
2. Measure 25 ml of demineralized water by filling another clean 25-ml graduated cylinder to the 25-ml mark.Pour the demineralized water into another clean sample cell.
3. Using the 1-ml calibrated dropper, add 1 ml of Nessler Reagent to each sample cell and swirl to mix. A yellow color will develop if ammonia nitrogen is present. Allow at least 10 minutes, but not more than 25 minutes for the color to fully develop before performing Steps 4 and 5.
4. Place the sample cell containing the prepared demineralized water solution in the cell holder. Insert the Nitrogen, Ammonia (Nessler Method) Meter Scale in the meter and adjust the Wavelength Dial to 425 nm. Adjust the LIGHT CONTROL for a meter reading of zero mg/l.
5. Place the prepared sample in the cell holder and read the mg/l ammonia nitrogen (N).

APPENDIX VI. Procedure for Measuring Ammonia with the Auto-Analyzer.

Industrial Method No. 154-71W

Range: 0-140 µg/l

General Description

The automated procedure for the determination of ammonia utilizes the Berthelot Reaction, in which the formation of a blue colored compound believed to be closely related to indophenol occurs when the solution of an ammonium salt is added to sodium phenoxide, followed by the addition of sodium hypochlorite. A solution of potassium sodium tartrate and sodium citrate is added to the sample stream to eliminate the precipitation of the hydroxides of calcium and magnesium.

Performance at 60 Samples Per Hour Using Aqueous Standards

Sensitivity at 10 µgat N/l (140 µg N/l)	0.15 absorbance units
Coefficient of Variation at 8.0 µgat N/l (112 µg N/l)	0.31%
Detection Limit	0.2 µgat N/l (2.8 µg N/l)

Reagents

Complexing Reagent

Potassium Sodium Tartrate		
($KNaC_4H_4O_6 \cdot 4H_2O$)	33	g
Sodium Citrate		
$HOC(COONa)(CH_2COONa)_2 \cdot 2H_2O$	24	g
Distilled Water, q.s.	1000	ml
Brij-35* (Technician		
No.T21-0110)	0.5	ml

Preparation:

Dissolve 33 g of potassium sodium tartrate and 24 g of sodium citrate in 950 ml of distilled water. Adjust the pH of this solution to 5.0 with concentrated sulfuric acid. Dilute to one liter with distilled water. Add 0.5 ml of Brij-35.

Alkaline Phenol

Phenol (C_6H_5OH)	83	g
Sodium Hydroxide, 20% w/v(NaOH)	180	ml
Distilled Water, q.s.	1000	ml

Preparation:

Using a one liter Erlenmeyer flask, dissolve 83 g of phenol in 50 ml of distilled water. Cautiously add, while cooling under tap water, in small increments with agitation, 180 ml of 20% NaOH. Dilute to one liter with distilled water.

Sodium Hypochlorite (Stock)

(Technicon No. T01-0114)

Any good commercially available household bleach having 5.25% available chlorine may be used.

Sodium Hypochlorite (Working)

Dilute 200 ml of stock sodium hypochlorite to one liter with water.

Sodium Nitroprusside

Sodium Nitroprusside ($Na_2Fe(CN)_5NO.2H_2O$)	0.5	g
Distilled Water, q.s.	1000	ml

Preparation:

Dissolve 0.5 g of sodium nitroprosside in 900 ml of distilled water and dilute to one liter.

Standards

Stock Standard A, 5000 µgat N/l (70,000 µg N/l)

Ammonium Sulfate $(NH_4)_2SO_4$	0.3310	g
Distilled Water, q.s.	1000	ml
Chloroform	1	ml

Preparation:

In a one liter volumetric flask, dissolve 0.3310 g of ammonium sulfate in 900 ml of distilled water. Dilute to volume with distilled water. Add 1 ml of chloroform as a preservative.

Stock Standard B, 100 µg at N/l (1400 µg N/l)

Stock Standard	2 ml
Distilled Water, q.s.	100 ml

Preparation:

Dilute 2 ml of stock standard A in a volumetric flask to 100 ml with distilled water. Prepare fresh daily.

Working Standards

ml Stock B	µg at N/l	µg N/l
0.2	0.2	2.8
2.0	2.0	28.0
4.0	4.0	56.0
6.0	6.0	84.0
8.0	8.0	112.0
10.0	10.0	140.0

Preparation:

Pipette stock B into a 100 ml volumetric flask. Dilute to 100 ml with distilled water. Prepare fresh daily.

APPENDIX VII. Filter and Dechlorinator Unit in the Biology Building, U.B.C.

Information on the filter and dechlorinator unit was obtained from Mr. Collin Parkinson (1979), of the Zoology Department at U.B.C.

A sketch of the filter is shown in Figure VII-1. All dimensions given are approximate.

The flow through the filter is unknown. A minimum estimate would be 200 l/min.

The filter is backflushed twice a week for about 15 minutes each time.

The fill is changed every two to three years.

APPENDIX FIGURE VII-1. Filter and Dechlorinator Unit.