

AN ALTERNATIVE APPROACH FOR DEVELOPING INTAKE VELOCITY DESIGN CRITERIA

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Abstract. Recurring fish losses at power plant cooling-water intakes demonstrate the need for improving intake design and operation to reduce the impact on aquatic resources. An approach is proposed for deriving intake velocity criteria which focuses on the interaction of bioenergetics and fish behavior. A model based on an energetic optimum and selected swimming speed is used to predict the response of fish to hydraulic flow fields. Data on oxygen consumption rates for juvenile chinook salmon (*Oncorhynchus tshawytscha*) indicate maximum energetic efficiency occurs at a swimming speed of 25 cm/sec. Juvenile chinook salmon exposed to a velocity gradient behaviorally select a velocity of approximately 21 cm/sec. These results support the basic hypothesis that the behavioral response of fish to a hydraulic flow field is not random but is predictable in terms of an energetically optimal swimming speed for a given species and size class. Physical and biological factors which influence predictions of the model are described. Applications of the model in understanding fish response to water intakes are suggested. Limitations of this approach in establishing power plant intake design criteria are also discussed.

INTRODUCTION

The demand for electrical power in the United States is increasing at a rate of about 7% annually due to the combined effects of population increase, increases in per capita energy consumption, and dependence of our society upon electrical power (Brady and Geyer 1972). Because of this demand, increases in power plant construction can be anticipated. Since each plant requires a large volume of water for heat dissipation, pressures on the aquatic environment will also increase.

Concern about the impact of power plant operation on fisheries resources was initially focused on the discharge of thermal effluents, the effects of which have been extensively studied and widely publicized. Only recently,

however, has the adverse impact resulting from the entrainment,¹ entrapment,² and impingement³ of aquatic organisms by cooling-water intake systems been recognized.

The magnitude of entrapment-impingement losses at several power plant intakes seems significant (Table 1), but the biological importance of such losses is unknown. During recent years the trend has been to simply document the occurrence of fish loss. This, however, provides little insight into the mechanisms or factors which influence entrapment-impingement, nor is it very helpful when attempts are made to improve intake designs.

Historically, intake design criteria have been developed on a trial and error basis. It is apparent from Table 1 that this technique has resulted in limited success. Some intake designs have functioned well; however extrapolations from one site to another frequently yield unacceptable results. It is obvious that no one has understood why a particular design worked at one site and not at another. Existing criteria lack generality and precision because studies leading to an understanding of basic mechanisms were not made.

Initial attempts to improve general guidelines for developing intake design criteria were based on evaluating fish performance capabilities. Fish performance is determined by using forced swimming trials and time to fatigue for fish exposed to velocities in respirometers or stamina tunnels. In general, these fish are confined within an experimental apparatus in which velocity preferences cannot be tested. As a result of performance studies it is generally recommended that large intake areas should be provided to reduce intake velocities. That swimming capability cannot be considered independent of behavioral response is illustrated by extensive fish losses at plants with low intake velocities.

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Based on microhabitat theory an energetic-based model is proposed encompassing the basic hypothesis that the behavioral response of fish to a hydraulic flow field is not random but rather is predictable in terms of an energetically optimal swimming speed for a specific fish species and size class. The model is based on the conviction that: 1) entrainment, entrapment, and impingement of fish involve a number of interacting variables; and 2) only through systematic, controlled experiments can a data base be assembled that suggests design criteria for intake structures that reduce the hydraulic capture of fish to a minimum level. The probability that a fish will become entrained or entrapped by industrial or agricultural water intakes is influenced primarily by characteristics of the hydraulic flow field and various aspects of fish behavior. The research design outlined here specifically

¹An organism which is drawn into a water intake as part of the volume of water which it occupies is said to be entrained.

²Entrapment refers to the physical blocking of larger entrained organisms by a barrier, generally some type of screen located within the intake structure.

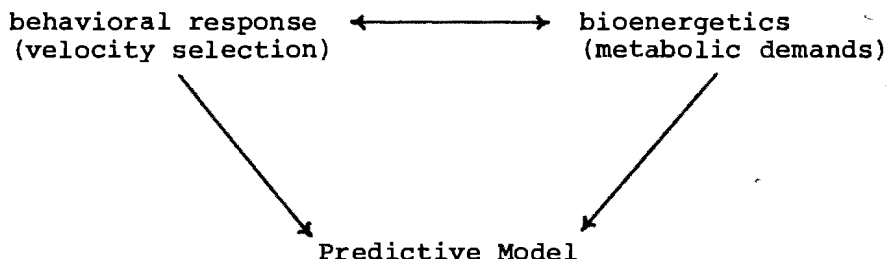
³Impingement occurs when the entrapped organism is held in contact with the barrier.

x Table 1. Estimated entrainment-impingement losses at several power plant cooling-water intakes.

Plant	Location	Study Duration	# of Fish	Reference
Allen Steam Station	Lake Wylie	Oct. 1973 - Sept. 1974	898,913	Edwards <i>et al.</i> (1976)
Oconee Nuclear Station	Lake Keowee	July 1974 - May 1975	1,064,262	Edwards <i>et al.</i> (1976)
Marshall Steam Station	Lake Norman	Apr. 1974 - Mar. 1975	3,769,300	Edwards <i>et al.</i> (1976)
Buck Steam Station	Yadkin R.	July 1974 - June 1975	4,069	Edwards <i>et al.</i> (1976)
Palisades Nuclear Power Plant	Lake Michigan	July 1972 - June 1973	584,687	Edsall (1975)
Waukegan Generating Station	Lake Michigan	June 1972 - June 1973	1,200,000	Edsall (1975)
Nine Mile Point	Lake Ontario	January - December 1973	5,000,000	Edsall (1975)
Zion Plant	Lake Michigan	Sept.-Dec. 1973 Mar.-June 1974	929,000	Edsall (1975)
Quad Cities Plant	Mississippi R.	January - December 1974	10-14,000,000	Truchan (1975)
Muddy Run Pumped Storage Generating Plant	Susquehanna R.	June-July 1970	56,600,000*	Snyder (1975)

* Entrainment and subsequent passage of juvenile fishes.

recognizes the interaction of these variables. In light of the myriad of interacting variables, however, we have focused attention on the general conceptual framework illustrated below.



The model we propose predicts that for each fish species and size class an optimal swimming speed exists at which each fish is most energetically efficient. The model also predicts that fish will behaviorally select their energetically optimal swimming speed when exposed to a velocity gradient.

To critically evaluate our model predictions a series of experiments were performed using juvenile chinook salmon, *Oncorhynchus tshawytscha*, (mean fork length = 84.8 mm, S.D. = 8.7; mean weight = 6.1 g, S.D. = 1.9). Following is a discussion of the development of predictions based on the concept of energetic optimality and verification of these predictions.

Energetic Optimality

The concept of energetic optimality was used to test the hypothesis:

- H₁: there exists an optimal velocity/swimming speed for traversing a distance expressed as a minimum energetic expenditure for swimming.

The energetic expenditure for swimming was measured using oxygen consumption rates for fish swimming at velocities ranging from 7 to 29 cm/sec in a recirculating respirometer. Fish were fed to satiation in the laboratory holding tank, transferred to the respirometer and allowed 24 hours to recover from handling effects before testing. Water temperature was maintained at 15.0 ± 0.5 C in both the holding tank and respirometer.

Following a 2-hour period of orientation to a velocity of 7 cm/sec the test velocity was selected and a 2-hour trial begun. Dissolved oxygen measurements were made at 15-min intervals using a dissolved oxygen meter (YSI Model 54). The oxygen consumption rate was calculated using the slope of a least squares linear regression determined for each 2-hour trial and expressed as mg oxygen consumed/kg body weight/hour.

Results presented in Figure 1 illustrate the relation between oxygen consumption per unit body weight per hour (log scale) and swimming speed (cm/sec). This relationship is expressed by the least squares linear regression: $\log \text{ oxygen consumption} = 2.47 + 0.018 (\text{swimming speed})$. Standard metabolic rate for this group of fish is estimated to be 295 mgO₂/kg/hr.

Data presented in Figure 1 can be transformed to express the oxygen consumption rate for fish swimming a constant distance at each swimming speed using the formula:

$$\text{mgO}_2/\text{kg}/\text{km} = (\text{mgO}_2/\text{kg}/\text{hr at speed } S_1) (\text{hr}/\text{km at } S_1).$$

The distance, in this case one kilometer, was chosen arbitrarily. Using this technique a relation between energetic expenditure for swimming a specific distance at a specific speed can be developed (Figure 2). The parabolic shape of this relationship is indicative that an energetic optimum

does exist for this group of fish. The energetically optimal swimming speed is defined as that point at which the first derivative of the polynomial regression equals zero. From these data we predict that the juvenile chinook salmon tested would be energetically most efficient swimming at a rate of 25 cm/sec.

Verification

To evaluate predictions of the model a series of experiments were conducted to test the hypothesis:

- H₀: juvenile chinook salmon exhibit a characteristic behaviorally selected swimming speed which reflects the energetic optimum for fish exposed to static and dynamic experimental conditions.

Experiments were conducted in an oval flume 15.9 m in circumference, 1.0 m wide and 0.4 m deep. Flow was generated by a motor-driven six-blade paddle wheel. Water velocity in these experiments conducted under flowing (dynamic) conditions was measured in a 25 point matrix replicated at eight transects around the flume circumference. Water velocity in each dynamic experiment averaged 10.7 cm/sec throughout the test flume. Rotation of the paddle wheel during dynamic tests did not obstruct fish passage.

In each experiment 10 fish were transferred from the laboratory holding tank to the test flume and allowed 24 hours to recover from handling effects. All fish were fed to satiation prior to transfer into the test flume; no food was provided during testing to eliminate inducement of activity cycles based on feeding. Water temperature averaged 12.5 ± 0.5 C.

Swimming speed during static experiments was determined by measuring the time required for fish to complete one revolution (1590 cm) of the test flume. Since all fish observed during dynamic experiments swam in the direction of water flow, swimming speed was defined as travel speed minus average water velocity and calculated using the formula:

$$\text{swimming speed} = \frac{1590 \text{ cm}}{\text{revolution time, sec}} - 10.7 \text{ cm/sec.}$$

Results of 141 swimming speed determinations for fish exposed to static conditions in five replicate experiments are presented in Figure 3a. Under static test conditions fish swam steadily around the 15.9 m flume circumference. Selected swimming speed averaged 21.6 cm/sec (S.D. = 3.3) and ranged from 10 to 30 cm/sec. Seventy-eight percent of the selected swimming speeds ranged from 19 to 24 cm/sec.

The frequency distribution of 109 swimming speed determinations made during five replicate experiments under flowing water conditions is presented in Figure 3b. Selected swimming speed under this test regime averaged 20.4 cm/sec (S.D. = 4.5) and ranged from 10 to 30 cm/sec. Sixty-one percent of the selected swimming speeds ranged from 16 to 24 cm/sec.

DISCUSSION

Past attempts to provide design criteria for water intake systems have relied on determining swimming endurance at various velocities (e.g. Boyar 1961; and others). Intake velocities, ranging from 15 to 30 cm/sec at most cooling-water intakes, are generally well below the expected swimming performance capabilities of most fish. Based on results of swimming performance studies we would not predict entrapment-impingement losses of the magnitude observed at many locations (see Table 1). Clearly other factors, such as behavioral attraction, metabolic demands of the fish, etc. are influencing the behavioral response of those fish encountering a water intake.

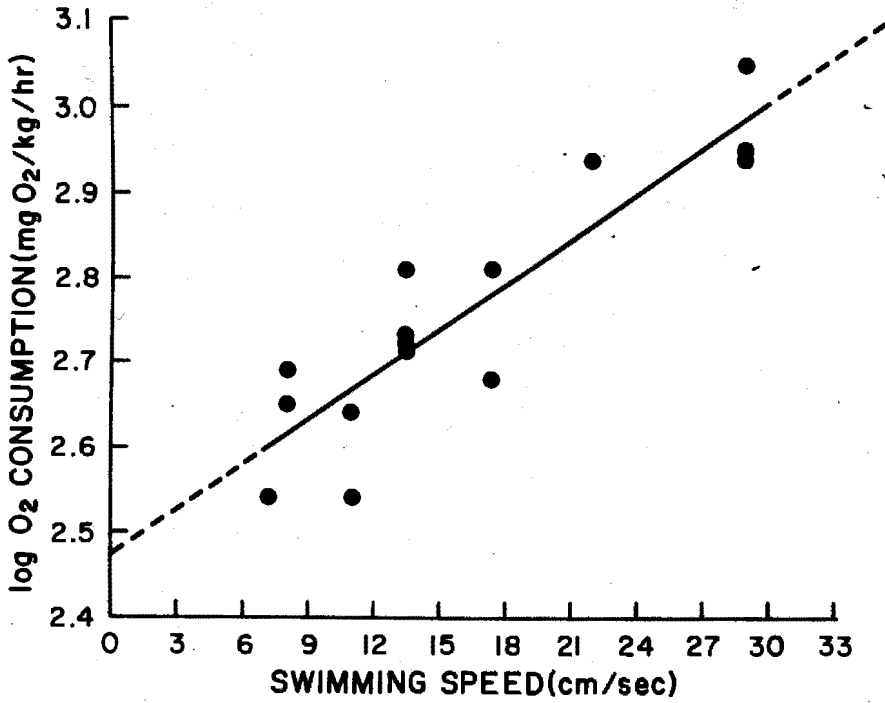


Fig. 1. Least squares linear regression illustrating the relationship between the logarithm oxygen consumption (mgO₂/kg/hr) and swimming speed (cm/sec).

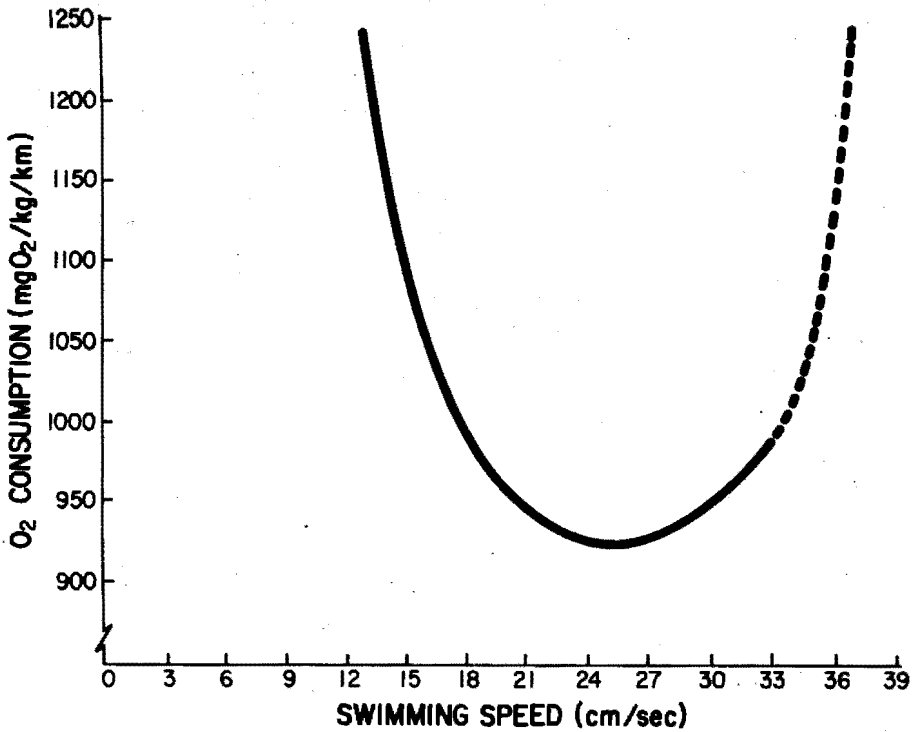


Fig. 2. Relation between oxygen consumption (mgO₂/kg/km) and swimming speed (cm/sec) illustrating the energetic optimum for juvenile chinook salmon.

The research we have described, although in a very early stage of development, suggests an approach to developing biological design criteria for water intake systems based on fundamental biological and hydraulic principles. We have applied the reasoning of Weihs (1973), Brett (1965) and Webb (1975) in developing a model which integrates the concepts of energetic optimality and the behaviorally selected swimming speeds for fish. The example using juvenile chinook salmon illustrates this approach. Results of our respirometry experiments (Figure 2) indicate that the predicted energetically optimal swimming speed for juvenile chinook salmon would be 25 cm/sec. Results of the selected swimming speed experiments indicate that juvenile salmon have a behaviorally select swimming speed averaging approximately 21 cm/sec. The general agreement between the predicted optimal swimming speed and behaviorally selected speed supports the fact that an approach based on an understanding of controlling mechanisms may significantly improve our ability to predict the behavioral response of fish to hydraulic flow fields.

It should be noted, however, that under actual field conditions a number of factors may act, either singularly or in combination, to influence both the energetically optimal swimming speed and behavioral response of fish to velocity fields. Physical factors which might affect these response patterns include light intensity, water temperature, and turbulence. In addition, biological factors including biological rhythms (seasonal and diurnal patterns), intraspecific interactions such as schooling and social behavior, and interspecific interactions such as predator avoidance may alter behavioral responses. Energetic optima and selected velocities are also influenced by species-specific and size-class differences in swimming performance and metabolic demands. It is apparent that a number of environmental variables will influence the predictive capabilities of this model. As our understanding of the mechanisms and factors controlling fish behavior in hydraulic gradients advances, confidence in model predictions will increase.

CONCLUSIONS

The energetic-behavioral model proposed in this paper has the potential for improving our understanding of fish behavior in hydraulic gradients. Prior to a complete evaluation of this concept, however, verification is needed for a variety of species and size classes of fish representative of lacustrine, lotic and estuarine environments. In addition, the approach must be demonstrated under actual field conditions. Utilizing this approach at an intake structure of an installation that has experienced fish problems would provide the best possible test of this concept.

The approach we are proposing is applicable to developing intake velocity design criteria for the diversion of water for industrial, municipal, or agricultural usage. It should be kept in mind, however, that this approach must be applied with caution. Intake velocity represents only one facet of the problem. The geographical location, intake geometry, water volume required, tidal action, occurrence of critical biota, and cost must also be considered in the design of an efficient water intake system.

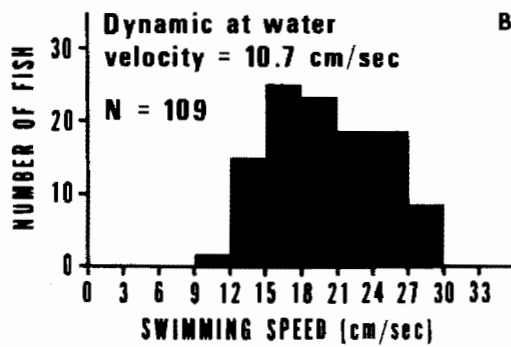
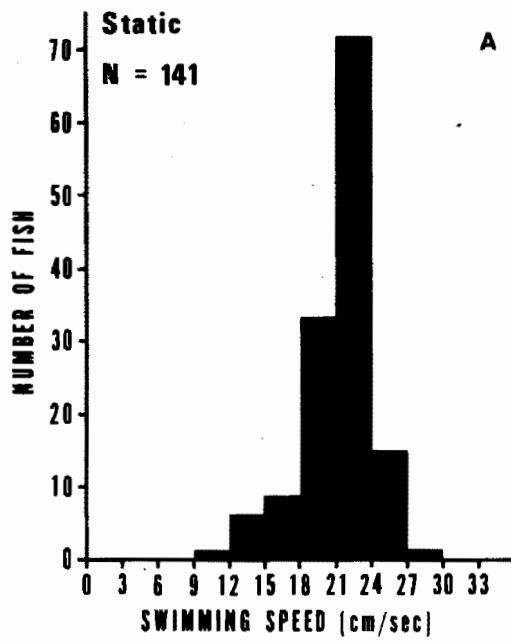


Figure 3. Distribution of selected swimming speeds measured under static (A) and dynamic (B) test conditions.

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