

Technical Evaluation of the Utility of Intake Approach Velocity as an Indicator of Potential Adverse Environmental Impact under Clean Water Act Section 316(b)

Technical Report

Technical Evaluation of the Utility of Intake Approach Velocity as an Indicator of Potential Adverse Environmental Impact under Clean Water Act Section 316(b)

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Final Report, December 2000

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REPORT SUMMARY

This report addresses issues related to causes of fish impingement at cooling water intake structures (CWIS), specifically the relationship of water velocity, site geometry, fish swimming ability, and environmental conditions. CWIS approach velocity is central to the ongoing U.S. EPA effort to regulate CWIS under Section 316(b) of the Clean Water Act. Energy producers, federal and state resource agencies and regulators, and the public will find this report a valuable reference on impingement issues and appropriate approaches to minimize potential impingement impacts.

Background

Under an October 1995 Consent Decree, the U.S. EPA is proposing rules for new and existing CWIS that address the requirements of Section 316(b) of the Clean Water Act. The regulations will, in part, address the meaning of “adverse environmental impact” (AEI), approaches for assessing the potential for AEI, and measures for minimizing AEI. These measures may include requirements affecting design, construction, location, and CWIS capacity that are determined to reflect the “best technology available” (BTA). Potentially impacted are all power plants and industrial facilities withdrawing cooling water. To minimize potential impingement impacts, EPA is considering use of an approach velocity standard both as a screening tool for existing facilities and as a design standard for new facilities. More specifically, EPA is proposing a criterion of 0.5 f/s. This approach velocity criterion has been an informal guideline since the 1970s; however, no known detailed technical reviews or analyses have been performed to support it. This provided the reason for a synthesis, review, and analysis of existing data on approach velocity and an assessment of its utility as a regulatory parameter for precluding impingement impacts at CWIS.

Objective

To perform a technical literature review and requisite data analysis to determine and discuss the appropriateness of 0.5 f/s (15.25 cm/s), or an alternative criterion, as a *de minimis* value that would essentially preclude impingement impacts.

Approach

The project team analyzed the effects of CWIS intake velocity on impingement rates of juvenile and adult fish using available scientific literature, government agency reports, and reports by energy companies and their consultants. Analyses included (1) a review of the historical evolution and technical support for the criterion of 0.5 f/s, including approach velocities recommended by other federal and state agencies, (2) a review of methods for appropriately measuring and reporting relevant CWIS velocities, (3) a comprehensive literature review of the swimming capabilities of freshwater, estuarine, and marine fish, and (4) integration of the data

gathering and analyses to specifically address the project's objectives. The project team formed their research around these core questions:

- Is approach velocity an appropriate parameter for determining the potential for impingement impact?
- Assuming approach velocity is technically supportable, what are the approaches and methods that can be universally applied to CWIS for its proper measurement?
- Is a single value appropriate and, if so, is 0.5 f/s a technically supportable criterion, or is an alternative criterion more appropriate?

Results

Evaluation of the geometry of water (and fish) approaching intake screens indicates that there are several relevant velocity components: approach velocity at a distance from the screen, approach velocity near the screen, through-screen velocities, sweeping velocities and other vectors at an angled screen, and heterogeneity of all velocities in a complex hydraulic environment of an intake structure. Component interaction, swimming abilities of specific fish, and environmental factors all contribute to determining susceptibility to impingement. The research concluded that (1) approach velocity is an appropriate regulatory parameter, (2) it should be measured with detailed attention to the intake's geometry (preferably as a vector parallel to the main water flow at a distance from the screen), (3) a single regulatory value probably should not be applied considering the variety of organisms and sizes at a site (a site-specific analysis using site geometry and data on swimming speeds of local fish is recommended), and (4) a screening criteria value of 0.5 f/s would be useful to delineate CWIS where significant impingement is unlikely except under unusual environmental circumstances (for example, unusual cold snaps).

EPRI Perspective

This report will be a valuable resource for steam and hydroelectric energy producers, other CWIS owners, and resource agency and regulatory personnel as approaches are designed to address CWIS impingement issues. It will be particularly valuable to the U.S. EPA as it attempts to draft regulations that address the requirements of Section 316(b) of the Clean Water Act.

Keywords

Section 316(b)

Impingement

Approach velocity

Cooling water intake structures (CWIS)

ABSTRACT

This study addressed issues related to using water velocity as a criterion for regulating cooling water intakes at steam electric power stations. In principle, a low intake velocity would minimize the entrapment, impingement, and likely mortality of organisms on intake screens because the fish could simply swim away from the screens. However, maintaining a low intake velocity can be technically difficult as well as costly, so it is important to justify the biological benefits. A through-screen velocity of 0.5 foot per second (f/s; = 15.25 cm/s) has been proposed by the U.S. Environmental Protection Agency (EPA) as one element of “best technology available” (BTA) performance standards for cooling water intake structures (CWIS). EPA has proposed a tiered analysis for judging adverse environmental impact in which velocity would be used as a screening criterion for the first tier of evaluation (plants with velocities as low as this would not be required to conduct detailed analyses). Velocity would also be used as a potential evaluation criterion for more detailed analyses. We evaluated the geometry of intakes, criteria used by other agencies, and swimming speed data from the scientific literature to answer whether velocity is an appropriate regulatory parameter, how it should be measured (if it is appropriate), whether a single value is useful, and whether a value of 0.5 f/s is the best one. Our evaluation of the geometry of water (and fish) approaching intake screens indicates that there are several potentially relevant velocity components: approach velocity at a distance from the screen, approach velocity near the screen, through-screen velocities, sweeping velocities and other vectors at an angled screen, and heterogeneity of all velocities in a complex hydraulic environment of an intake structure.

Velocity criteria developed by the National Marine Fisheries Service and the state of Washington primarily for screens at irrigation diversions included values near 0.5 f/s that apply to the most sensitive organisms (salmon fry) under certain circumstances. However, these values are applied within a framework that considers the geometry of the intake (including criteria for sweeping velocities) and allows for application of less stringent values when less sensitive organisms (e.g., adult salmonids) are the only ones present. Because of how the EPA criterion for CWIS would be imposed, it is more restrictive than the NMFS criteria.

The scientific literature has a large amount of information on the swimming capabilities of fish. There are several types of swimming: cruising (normal activity), prolonged (or critical, the velocity that can be maintained under forced swimming), burst (short-duration darts) and “fast-start” (the initial thrust of a burst). We tabulated information on prolonged swimming speeds by healthy fish according to species, and we analyzed it in several ways. Swimming speed varies primarily by fish size and water temperature, with small fish and those at cold temperatures performing most poorly. Fish in different taxonomic families and with different body shapes have different swimming capabilities (e.g., eels and eel-like fish are poor swimmers, fish of the herring family are especially vulnerable, salmonids are good swimmers). All fish assemblages (estuarine, riverine, etc.) have a range of good to poor swimmers. The lowest average values are

near 0.5 f/s. However, there is a large amount of individual variability, and impingement likely reflects the poorest individual performers among a school of the same species. Prolonged swimming speeds are markedly affected by environmental variables and reduced by stressors, and we summarize these in the text.

We conclude that (1) approach velocity is an appropriate regulatory parameter, (2) it should be measured with detailed attention to the geometry of the intake (preferably as a vector parallel to the main water flow at a distance from the screen), (3) a single regulatory value probably should not be applied considering the variety of organisms and sizes at a site (a site-specific analysis using the site geometry and data on swimming speeds of local fish is better), and (4) a screening criterion value of 0.5 f/s (about 15 cm/s) in front of an intake, based on critical swimming speed data, would be useful to delineate power station intakes where significant impingement is unlikely except under unusual environmental circumstances (e.g., unusual cold snaps) or where particularly weakly swimming species (e.g., delta smelt, splittail) occur. Approximately this value would likely have been concluded regardless of its prior proposal by EPA. However, laboratory critical swimming speed data are but one line of evidence for predicting impingement. Weakly swimming early life stages would likely be entrained.

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1

INTRODUCTION

1.1 Background

Under an October 1995 Consent Decree, the U.S. Environmental Protection Agency (EPA) currently is engaged in a rulemaking process for implementing Clean Water Act Section 316(b), which applies to cooling water intake structures (CWIS). As part of that effort, EPA is developing a set of proposed regulations. The proposed regulations will, in part, address the meaning of “adverse environmental impact” (AEI), approaches for assessing the potential for AEI, and measures for minimizing AEI. These measures may include requirements affecting the design, construction, location, and capacity of CWIS that are determined to reflect the “best technology available” (BTA). Potentially impacted are all power plants and industrial facilities withdrawing cooling water. EPA has issued a draft set of rules for new power station CWIS (65 FR 49060; August 10, 2000) and currently is collecting data that it will use to formalize the new-plant rule and to develop its proposed rule for existing power stations.

A draft framework for the proposed EPA rule was presented and discussed at EPRI’s April 1999 Conference on Power Generation Impacts on Aquatic Resources (Nagle and Morgan 2000). Although now outdated, that framework stimulated this review of the relevant scientific literature. At that time, the draft framework contemplated a three-tiered analysis designed to evaluate the extent of adverse environmental impact (AEI) from operation of a facility’s cooling water intake structure and to determine the best available technology (BTA) to minimize the adverse impacts when they were indicated. The intent of Tier 1 was to establish operational standards for the performance of the cooling water intake technologies that would be most effective in minimizing impingement and entrainment. If a facility could not demonstrate compliance with those standards, a site-specific evaluation in subsequent tiers would be necessary.

The proposed EPA Tier 1 screening process was designed to provide the first estimate of the potential for an intake to cause adverse impact from impingement and entrainment. Within this tier, selected performance characteristics, along with limited site environmental characteristics, would be evaluated. Characteristics to be evaluated would include: (1) CWIS approach velocity; (2) total intake flow; (3) intake flow as a percentage of source water body flow or volume; (4) site environmental characteristics (e.g., presence of threatened and endangered species); and (5) other operational or site characteristics as determined by state permitting authorities. The EPA’s proposed criterion for the CWIS velocity was 0.5 feet-per-second (f/s; 15.25 cm/s; 65 FR 49060; August 10, 2000). Criteria have also been proposed for total intake flow as a percentage of source water body flow or volume. [Note: Except when referring to the proposed EPA criterion of 0.5 f/s or other regulatory criteria, we will use metric measures in this report. To convert

between feet per second and centimeters per second, multiply f/s by 30.48 to get cm/s; multiply cm/s by 0.03281 to get f/s.]

The suggested criterion of about 0.5 f/s (15.25 cm/s) as a velocity that would preclude impingement impacts at CWIS has been an informal guideline since the 1970s. It has been used in National Environmental Policy Act Environmental Impact Statements and numerous licensing proceedings. However, no detailed technical reviews, analyses, or discussions are known to have been performed to support the criterion for power station cooling-water intakes. Similar criteria have, however, been used for other types of intakes, such as for hydropower and irrigation. The purpose of this project was to perform the technical literature review and requisite data analysis to determine and discuss the appropriateness of 0.5 f/s or an alternative criterion, as a value low enough that it would essentially preclude impingement impacts and allow for rapid CWIS review. Specific questions this report addresses include the following, as presented by EPRI staff and its Water Technical Committee:

- Is approach velocity an appropriate parameter for determining the potential for impingement?
- Assuming approach velocity is technically supportable, what are the approaches and methods that can be universally applied to CWIS for its proper measurement?
- Is a single value appropriate and, if so, is 0.5 f/s a technically supportable criterion or is another criterion technically supportable?

1.2 Approach

The effects of CWIS intake velocity on impingement rates of juvenile and adult fish were analyzed using available scientific literature, government agency reports, and reports by utilities and their consultants. We performed the following analyses:

- a. Reviewed the historical evolution and technical support for the criterion of 0.5 f/s. We reviewed the technical basis for this criterion at power station CWIS. We reviewed other velocity criteria (e.g., National Marine Fisheries Service and State of Washington criteria for hydropower and irrigation diversion intakes) and provided technical documentation for these alternative criteria should the criterion of 0.5 f/s not be supportable.
- b. Reviewed methods for appropriately measuring and reporting relevant CWIS velocities (e.g., average and/or maximum through-screen velocities, approach velocities at an appropriate distance in front of screen, sweeping velocities, etc.). We evaluated the “landscape” of intakes and their approaches (canals, etc.) and the suggestion that CWIS may have a “point of no return,” beyond which an individual fish is incapable of avoiding impingement either by random or directed swimming. We reviewed how the physical layout of intakes might be employed in the design and operation of CWIS to reduce fish impingement. We initiated the process of relating critical swimming speeds of fish to hydraulic flow field characteristics of different intake designs, with an eye toward site-specific evaluations and remedial measures.
- c. Conducted a comprehensive literature review of the swimming capabilities of freshwater, estuarine, and marine fish. Data on the swimming capabilities of healthy fish were tabulated and the factors that tend to reduce swimming capabilities (and thus make fish more susceptible to

impingement) were discussed in a narrative text illustrated with examples. Swim speed data were subdivided in ways that focus fish assemblages characteristic of specific ecological types, such as streams, rivers, lakes, estuaries, coastal waters. We recognized a level of uncertainty in the correspondence between these laboratory studies and performance of fish in the field. Keeping wild fish in the laboratory can be stressful, for example. Conversely, a fish in the laboratory is somewhat pampered and may perform better than it would in the wild. Nonetheless, we believe the laboratory results to be indicative and useful for predictive assessments when used in conjunction with retrospective assessments of actual impingement rates. This juxtaposition of predictive and retrospective elements is a key feature of current EPA risk assessment guidelines (EPA 1998).

d. Finally, we addressed the questions posed specifically by EPRI, based on the results of our literature searches and analyses.

e. In addition, we recognized that EPRI has commissioned Alden Research Laboratory, Inc. to document the relationship between CWIS approach velocity and rate of impingement at operating power stations (the retrospective part of the evaluation). Relevant factors to be evaluated in that review were to include:

- water body type (lakes and reservoirs, rivers, estuaries and oceans)
- fish species, size, and age
- swimming speeds of fish
- the influence of fish behavior on the likelihood of impingement
- internal factors that may influence the rate of impingement (e.g., disease, condition)
- CWIS design and orientation (intake type, hydraulics)
- Other environmental factors relevant to impingement; i.e., pressure, turbulence, other flow field characteristics, temperature, and dissolved gas concentrations

2

COOLING-WATER INTAKES

2.1 Types of CWIS

Operation of power plant condenser cooling systems requires large amounts of water that are withdrawn directly from surface waters. These surface waters contain aquatic organisms that may be injured or killed through their interactions with the power plant. Fish and other aquatic organisms that are drawn into the intake structure and are too large to pass through the intake debris screens may be impinged against the screens. Mortality of impinged fish is high at many plants because impinged organisms are eventually suffocated by being held against the screen mesh or are abraded, which can result in fatal infection.

Steam electric power plants use a wide variety of intake structure designs, ranging from intake tunnels a mile or more offshore, to shoreline intakes, to intakes that are recessed from the shoreline by canals. Similarly, there are numerous designs for debris and fish protection screens that are contained in the intake structure. Cannon et al. (1979) reviewed intake structures and concluded that the design features that contributed to high rates of impingement are (1) undesirable location in biologically productive areas; (2) relatively large intake system flow; (3) high screenwell velocities; (4) intake conveyance channels; (5) intrusion of the intake structure into the main streamflow; (6) non-uniform velocities across the screen face that may reduce the effective screen area; and (7) screenwell entrapment areas. They recognized that it is often difficult and impractical to ascertain quantitatively the effectiveness of intake structure modifications when one or all of the above design features are eliminated.

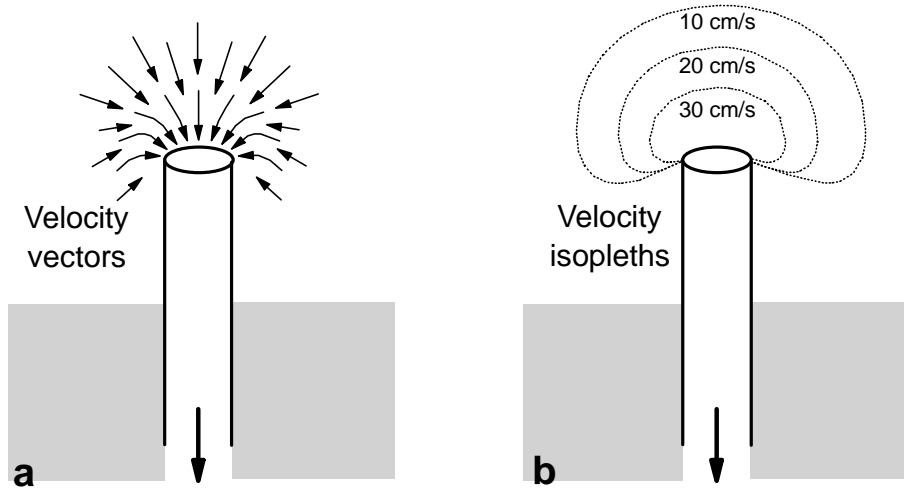
Irrespective of the intake location, system flow rate, and particular design configurations, the primary approach toward minimizing intake-related impacts has been to design the intake so that its velocities avoid disturbance of the fish schooling and swimming patterns and permit ease of egress for those fish that swim into the sphere of influence of the intake flow. However, given the variability in design type, one should recognize that the velocity at the screen face (if a screen exists) is not always the most critical when it comes to impingement effects. For example, the design and location of an unscreened offshore intake may be such that entrainment of organisms is virtually non-existent, thereby making the velocities at a screen face that could be located onshore meaningless with regards to impingement probabilities. The converse could also be true. If the initial intake opening of a canal or pipe is constricted creating high velocities that readily entrained fish, it wouldn't matter how much velocities were moderated at the face of the screen further down the system if entrapped fish had no way to leave the canal or holding area. Therefore, for many facilities, the area of critical interest is the initial opening to the cooling system intake, particularly if no fish collection or bypass system further down the line is present.

2.2 Flow Fields

Nearly all intakes at water diversion facilities (whether for cooling water, hydroelectric generation, municipal supply, or irrigation) have a local effect on the velocity and flow direction of water near the intake. The extent of this effect depends largely on the quantity of water diverted relative to the size of the waterbody and the design features of the facility (e.g., the positioning of the intake structure relative to the natural flow of the water body). These two components, water velocity and direction of flow, define the flow field around the intake structure and are two of the most important factors in fish impingement and entrainment. Fish that happen into the flow field created by the intake system are at potential risk of impingement unless (1) they have the swimming capability to maintain position in the flow field and sufficient cues are available that they will avoid the screens (perhaps leaving the area entirely) or (2) they are successfully transported out of the flow field and away from the intake.

The flow field in front of an intake (or intake screen) is typically comprised of a range of velocities depending on proximity to the intake or screen and other structures that alter flow. The flow field can be described graphically as a collection of vectors that indicate velocity and direction of flow (Figure 2-1a). A graph of velocity isopleths is a useful tool for understanding the potential effects of the flow field on fish (Figure 2-1b,c, and d). Although nearly every design is unique, the typical velocity field is characterized by increasing velocities as one approaches the intake, though not necessarily at a level that fish cannot avoid impingement. For intakes located where little natural flow exists, the velocity field typically decreases with distance from the intake (Figures 2-1b and c). Where a long uniform canal leads to the intake, we would expect velocities to be fairly uniform as well, right up to the screen, at which point the water accelerates as it passes through the screen (Figure 2-1d). In reality, intake configurations and velocity fields are rarely as uniform as those shown in these illustrations. Irregularities in design and flow can result in heterogeneous environments that often provide holding areas and escape routes for fish that happen into the intake's flow field. In rivers, tidal zones, and other areas where natural currents exist, the flow field is a function of the combined effects of the natural water movement and the intake rate and design.

Offshore Intakes (overhead view)



Canal Intakes (overhead view)

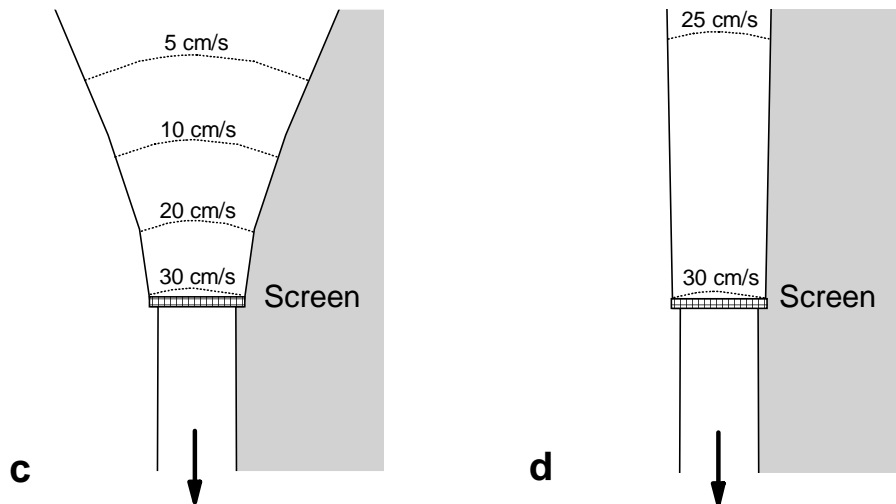


Figure 2-1
Hypothetical velocity fields at a variety of intake designs: (a) velocity vectors at offshore intake, (b) velocity isopleths at offshore intake, (c) velocity isopleths at irregularly shaped intake canal, (d) velocity isopleths at uniform width intake canal.

2.3 Fish Effects

A fish's ability to avoid impingement depends on its swimming ability relative to the velocities in the flow field and the distance it needs to swim to reach a safe area. For each individual fish there is a theoretical point (i.e., distance from the intake) beyond (or outside of) which a fish is able to swim away from the intake flows of the facility and move away from a potential adverse encounter with the intake. Inside of this fish-specific, theoretical point-of-no-return (i.e., nearer to the facility), the velocities and distance that must be overcome to escape the intake would be beyond the swimming ability and stamina of that particular fish. Other fish of a different size, condition, or swimming ability might have a different point of no return and would not necessarily be affected the same way. This is an important concept to understand in order to evaluate the importance of approach velocity in the rate of impingement at water intakes.

Even if a fish is able to initially avoid impingement upon first encountering a screen, it may not be able to sustain swimming at a speed that would carry it beyond the influence of the facility and it could eventually become fatigued and return to the face of the screen. This point-of-no-return varies among facilities and species and also is dependent on other factors such as fish size, physiological condition, water temperature, and dissolved oxygen. For fish at a screen with relatively slow approach velocities, there may be no "point-of-no-return"; in this case, a healthy fish should be able to swim away from the screen when the screen is approached.

Once at the screen, the ultimate fate of a fish that is beyond this theoretical point-of-no-return can take several paths. At a screen with no bypass or fish collection capabilities, the fish may become impinged against the screen where it will die and eventually be removed from the screen with other debris. Alternatively, some screens are designed to collect fish off the screen and return them to the water body beyond the influence of the intake facility. Although these fish collection systems may return fish to the water alive, the stresses associated with impingement, collection, and transport will sometimes still result in premature mortality. The design of the fish return system and the location and environmental quality of the return location are also important factors in fish survival.

Some facility designs, particularly those located on streams and rivers, provide bypass systems that transport the fish around fish screens in a manner that usually requires less physical contact than other fish collection devices. These systems typically depend on fish coming in contact (or near contact) with the screen. Designs that minimize contact with the screen and minimize the abrasive nature of the screen material can reduce the amount of descaling and skin abrasions experienced by fish that come in contact with the screen thereby increasing the survival of fish that are directed in one way or another away from the screen.

The success of any of these systems in preventing impingement and transporting a healthy fish to a safe area is largely dependent on the design of the facility, the approach velocities near the screen, and characteristics of the fish (e.g., species, size, and behavioral response to different intake designs). Although prevailing thought may be that slower approach velocities are always more protective, some fish collection and bypass systems are more effective at higher velocities. For example, some fish collection systems depend on fish getting impinged before removal (but see Fletcher (1990 and 1994) for a discussion of the difficulties in achieving this goal). The quicker they become impinged the less fatigued they are and the greater the likelihood of a

healthy recovery. Some bypass systems are designed to direct the fish along the screen to the bypass, and therefore, higher flows mean less time that the fish is in contact with the screen and the quicker it is bypassed. For example, in a laboratory study conducted at different velocities with angled screens, Wert et al. (1987) found that fish were impinged at a higher rate at 3–4 f/s than at 6–10 f/s.

2.4 Intake Velocities and Hydraulics

In order to clearly discuss the intake velocity regulations and effects, basic terminology must first be established.

Stream velocity—The velocity of flow in the water body. In rivers it is the velocity of the river flow passing the intake location. In estuaries and bays, it is the velocity of tidal currents, which are likely to change both magnitude and direction daily. In large lakes, prevailing winds can establish currents that can modify the effect of intake velocities.

Standard approach velocity—The term “approach velocity” has taken on a variety of meanings, which can lead to some confusion (R2 Resource Consultants 1997c). For the purpose of this review, we are defining the standard approach velocity, V_0 , as the average water velocity measured a few inches in front of the screen taken in the same direction as the general flow. The directionality of this flow is not necessarily perpendicular to the screen, but may be. This definition of approach velocity describes the velocity experienced by the fish as it swims freely near the front of the intake screen (Figure 2-2a). Approach velocity can be calculated as:

$$[1] \quad V_0 = (\text{intake flow})/(\text{intake cross-sectional area})$$

Perpendicular velocity vector - Many people have taken to defining approach velocity as the velocity component perpendicular to the screen face regardless of the angle of the screen relative to the normal direction of flow (Figure 2-2b; NMFS 1995). In this review we refer to this flow component as the “perpendicular velocity vector” to differentiate it from the previously defined approach velocity. The perpendicular vector, V_1 , is calculated as

$$[2] \quad V_1 = V_0 * \text{sine}(\theta),$$

where V is the normal approach velocity a few inches in front of the screen and θ is the angle of the screen relative to the normal flow direction (e.g., θ for a screen parallel to the flow is 0 degrees, and θ for a screen perpendicular to the flow is 90 degrees). This velocity component can also be estimated by dividing the flow (cfs) at the screen by the total area of the screen. Although this definition of approach velocity is widely used, it is nothing more than a mathematical component, and does not represent an actual direction of flow through the screen (Fletcher 1985, R2 Resource Consultants 1997c). The perpendicular velocity vector by definition will always be less than the standard approach velocity as long as the screen is angled relative to the flow.

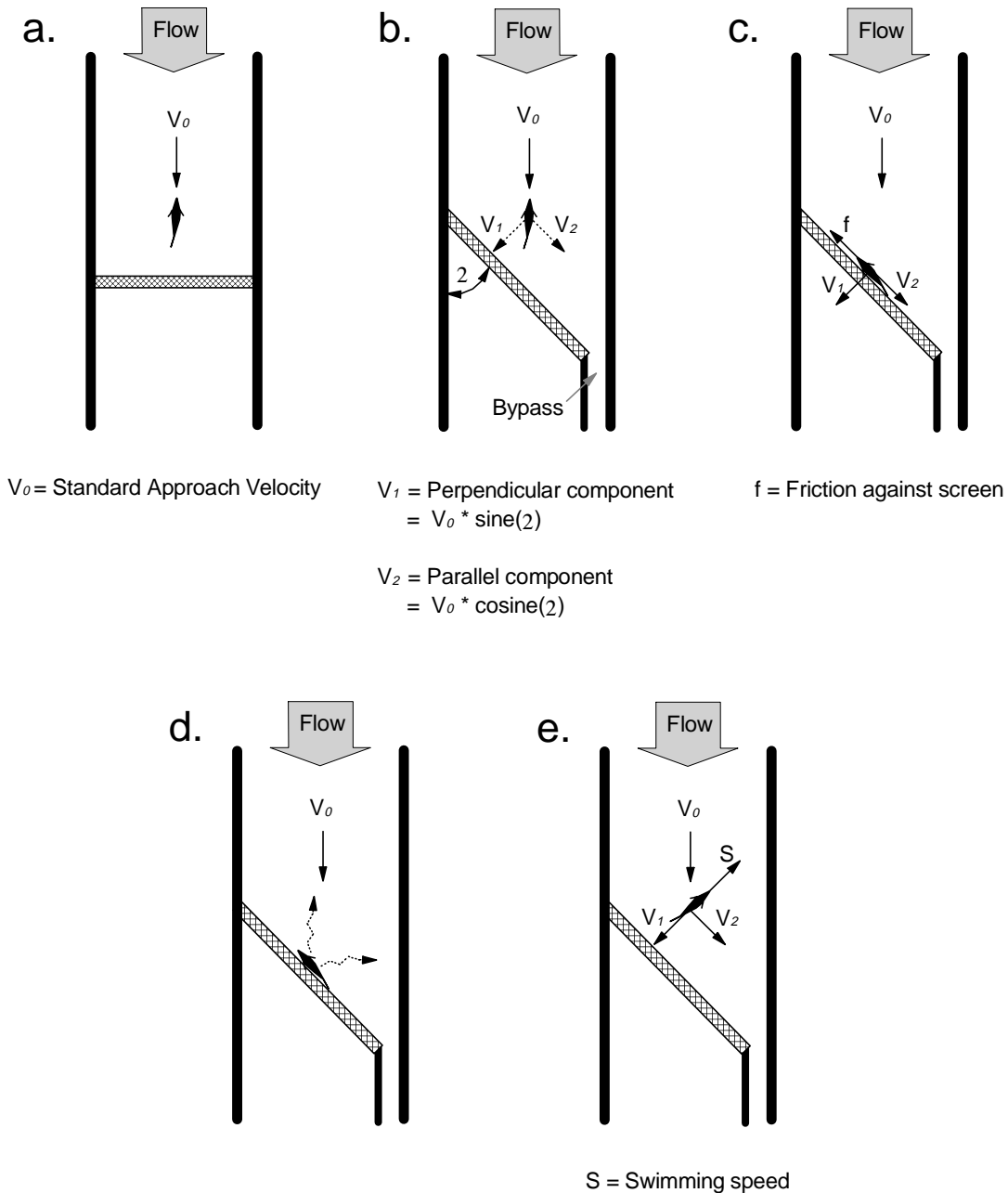


Figure 2-2
Effects of water velocity on fish when near or impinged on water intake screens: (a) standard straight-on approach velocity, (b) angular velocity components, (c) forces experienced when impinged, (d) alternate directions of escape from impingement, (e) forces experienced when positioned perpendicular to screen face.

Parallel velocity vector—As a companion vector to the perpendicular velocity vector, many people also refer to the velocity component parallel to the screen face, also known as the sweeping velocity (Figure 2-2b). The parallel vector, V_2 , can be estimated as

$$[3] \quad V_2 = V_0 * \cos(\theta).$$

Like the perpendicular velocity vector, this entity is just a mathematical construct and does not describe the direction of an actual parcel of water that would affect a fish swimming straight into the current in front of the screen.

Screen porosity—The amount of open area of a screen determines the through-screen velocity and may affect the ability of a fish to escape once it has made contact with the screen. Porosity is usually expressed as the percent of the entire screen area that is open to water passage. For example, a typical wedgewire screen constructed of 2-mm width wires spaced 2 mm apart would have 50% porosity when clean and free of debris. Low porosity can affect the rate of water delivery to the facility, and actually lower the water surface elevation on the downstream side of the screen. As debris accumulates on a screen, the effective porosity decreases and the average velocity at the screen face increases. Debris accumulation usually results in a greater variation in velocities across the face of the screen, making the screen less effective and more hazardous to approaching fish.

Through-screen velocity—The velocity of the water as it passes between the structural components of the screen is referred to as through-screen velocity and by definition will always be greater than approach velocity measured in front of the screen. The through screen velocity would be experienced only when an organism is right at the face of the screen or passing through the screen. It is not likely to be as important a factor in whether a fish becomes impinged as is the rest of the velocity field. However, the through screen velocity may relate to how difficult it is for a fish to remove itself from a screen once impinged.

Through-screen velocity, V_{ts} , is often estimated as:

$$[4] \quad V_{ts} = (\text{intake flow}) / (\text{screen open area})$$

where the screen open area is the total area of the submerged portion of the screen (i.e., components plus space) minus the actual area of the screen material. The open area also can be calculated as the product of the screen porosity and the total submerged screen area. A screen with 50% porosity and 1 f/s approach velocity would have a through-screen velocity of 2 f/s (assuming that the additional influence of support frames and other structural components is negligible). Debris accumulation on the screen can decrease porosity thereby increasing through-screen velocity.

Estimating through-screen velocity as in equation [4] (as opposed to actually measuring it with a velocity meter) should be accurate when the screen is at a right angle to the direction of the flow. However, if the screen is angled, the total open area of the screen increases (assuming the same cross-section of flow is intercepted) and equation [4] would then predict a decrease in mean through-screen velocity. We believe that for angled screens this is not the appropriate way to estimate through-screen velocity assuming the direction of the flow is not changed. Instead the denominator of the equation should be the cross-section of the area intercepted measured perpendicular to the flow.

3

HISTORICAL EVOLUTION OF VELOCITY CRITERIA

3.1 Criterion of 0.5 f/s for CWIS

The origin of a 0.5 f/s criterion for intake velocities at steam electric power stations is lost in a murky history. Review of the Atomic Energy Commission's Environmental Impact Statements for nuclear power plant construction and operation from the early 1970s revealed an oft-used illustration derived from impingement studies at the Indian Point Plant on the Hudson River (Figure 3-1). This figure illustrates the number of fish counted in screen washings when the intake water was flowing at several velocities. There is a strong rise in impingement when the intake velocity exceeded about 1 f/s. Although 1 f/s is generally discussed, the curve may have led to selection of 0.5 f/s as a conservative figure.

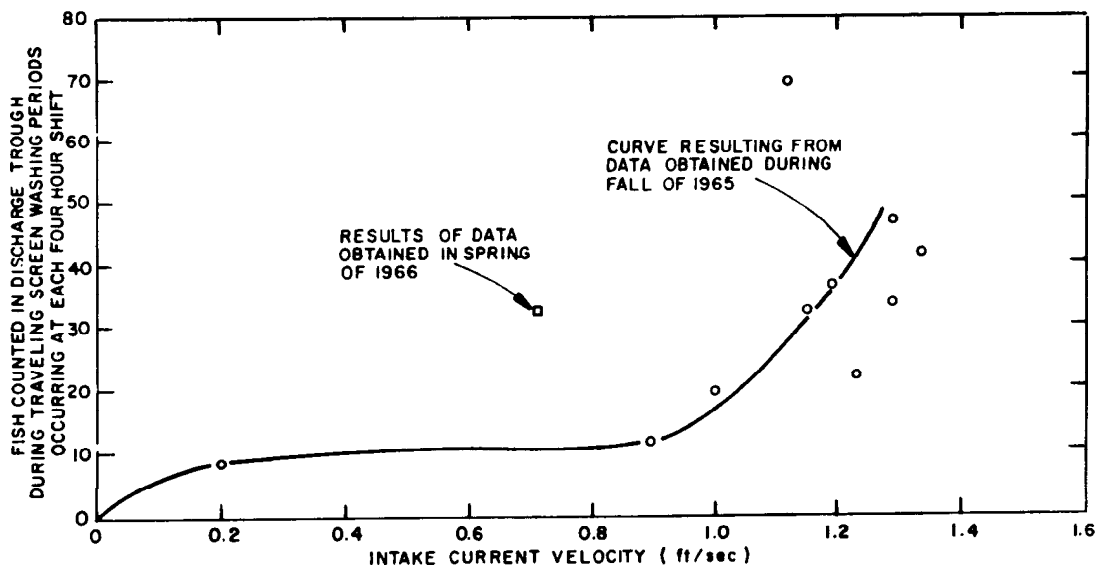


Figure 3-1
Environmental Impact Statements by the Atomic Energy Commission in the early 1970s used this figure of fish counts on intake screens at the Indian Point Plant on the Hudson River to illustrate increased impingement above about 1 f/s (30.48 cm/s). From USAEC (1975).

Studies of water diversion intakes in California in the 1950s produced swim speed data in relation to impingement rates, and yielded a recommended limit of 1.5 f/s for the assemblage of species including striped bass and chinook salmon (Kerr 1953). However, Dorn et al. (1979), after comparing the swimming speeds of southern California coastal marine species to species

actually trapped in the Redondo Beach Generating Station concluded that “intake velocity should not be a major consideration in evaluating the causative factors of fish entrainment. Swimming performance tests would not appear to be useful for such future analytical efforts.” Only two of the nine common species tested by Dorn et al. were actually entrapped in large numbers in the water intakes.

Emphasizing the role of temperature in swim speed capabilities of estuarine species such as white perch, King (1971) recommended different maximum intake velocities for cold and warm months. He recommended 24.4 cm/s (0.8 f/s) in winter when water temperatures are often near 2 C in the mid-Atlantic states, and 30.5 cm/s (1 f/s) when temperatures are above 7 C.

As the power station impact assessment strategies developed in the 1970s with advent of CWA section 316(b), evaluation of CWIS began to focus on population modeling and estimates of population effects of entrainment and impingement losses, largely because of the intense attention to power plants on the Hudson River (Barthouse et al. 1998). Velocity criteria and other criteria for minimizing numbers of fish impinged were considered on a more site-specific basis rather than as national criteria.

Because impingement on power station intake screens seemed to occur at approach velocities less than the average critical swimming speed of fish species (the most commonly used measure of swimming capability; see definitions in section 4.1), Hanson and Li (1978) proposed different predictors and design criteria. They proposed use of the “energetically optimal swim speed” and the “behaviorally selected swim speed”, which they found to be similar for a species at common temperatures and fish sizes. The energetically optimal swim speed is the speed that can be sustained in an oxygen-uptake respirometer using the lowest oxygen uptake rate (Figure 3-2). The behaviorally selected swim speed is that speed at which a fish species of a certain size, and at a specific water temperature, cruises in absence of water velocity or that it selects in a gradient of velocities.

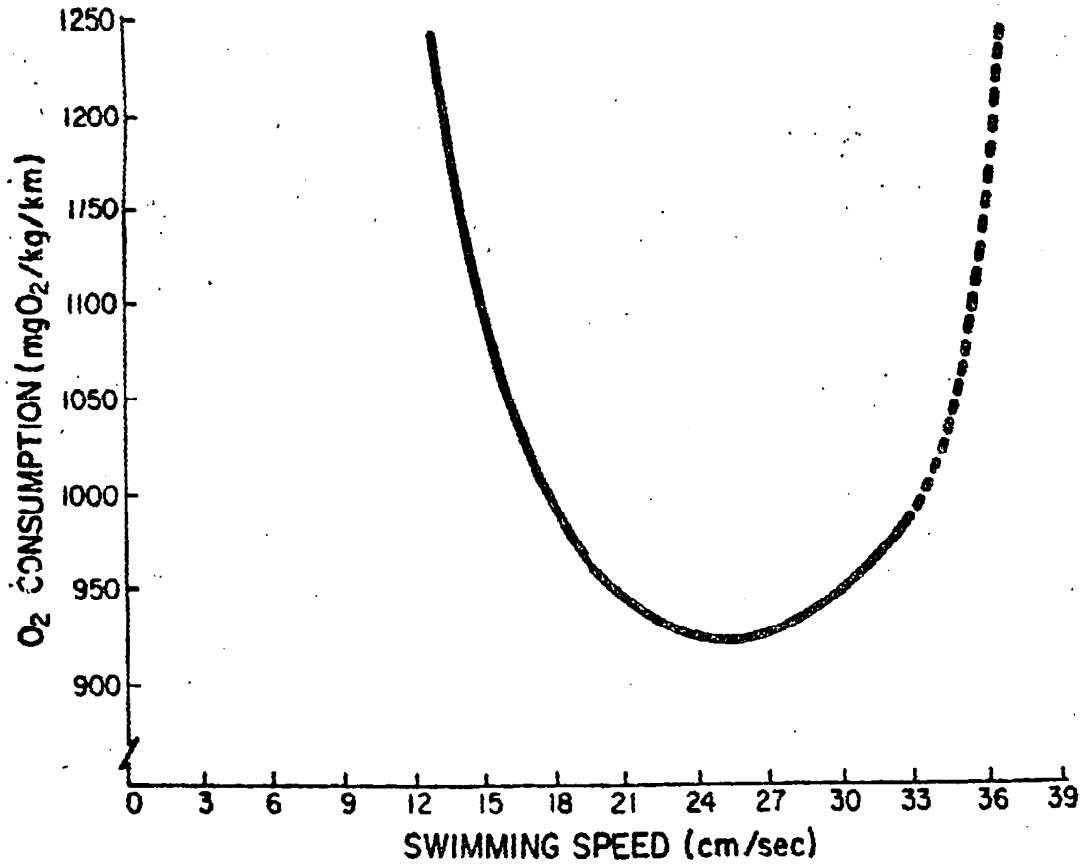


Figure 3-2

There is minimal oxygen consumption per kilogram of fish per distance swum within a certain range of velocities. This optimal range has been suggested by Hanson and Li (1978) as one measure suitable for setting intake velocity criteria to protect fish from impingement. It is less than the critical swimming speed, and closer to the natural cruising speed.

Hanson and Li (1978) proposed criteria for maximum intake velocities that would not exceed these speeds. After conducting experiments with juvenile chinook salmon, bluegill, and Mississippi silversides, these authors found a correlation of 0.92 between the energetically optimum swim speed and the behaviorally selected swim speed, a reasonably close relationship. Thus, they suggested an interchangeability, with the energetically optimal speed as the preferred index, because it could be determined in a simple respirometer device. The estimated optimal swimming speeds ranged from 0.23 f/s (7.1 cm/s) for 30-mm bluegill to 1.28 f/s (39 cm/s) for 89-mm wild, juvenile chinook salmon, with most results less than 0.5 f/s (15.25 cm/s; Table 3-1). The variation was anticipated, and the authors noted that key species and life stages would have to be selected for protection at a site. In Europe, by contrast, Stahlberg and Peckmann (1987) concluded from studies of swimming speeds of four small stream fish that a velocity of 40 cm/s should not be exceeded in stream improvements. Thus, with the origin of a general criterion of 0.5 f/s unclear, and several alternatives available in the literature, we looked elsewhere for justification of this or similar intake-velocity criteria.

Table 3-1
Estimated optimal swimming speeds for groups of 3 species and sizes of fish (Hanson and Li 1978)(BL=body lengths).

Species	Mean Length (mm) [SD]	Speed (cm/s)	Speed (f/s)	Speed (BL/s)
Chinook salmon (wild)	37.1 [2.4]	9.3	0.31	2.51
Chinook salmon (wild)	37.2 [1.3]	9.0	0.30	2.42
Chinook salmon (hatchery)	40.5 [1.4]	13.7	0.45	3.38
Chinook salmon (hatchery)	40.0 [2.0]	22.0	0.72	5.50
Chinook salmon (wild)	88.6 [4.2]	39.0	1.28	4.40
Bluegill	29.9 [3.0]	7.1	0.23	2.37
Silversides (wild)	46.1 [4.6]	11.3	0.37	2.60

3.2 State and Federal Approach Velocity Criteria

Several state and federal agencies have developed intake screen criteria to protect fish from being impinged at water intake screens (Table 3-2). The National Marine Fisheries Service (NMFS) has established criteria for protection of anadromous species, and the US Fish and Wildlife Service (USFWS) develops criteria when federally listed freshwater species are present. Many state environmental protection agencies and fish and game agencies also develop criteria to protect local populations of fish.

Many of the states in the northwest US have adopted criteria that are very similar to those developed by NMFS (1995) to protect juvenile salmonids, many of which are federally-listed endangered species. NMFS based its criteria on those established by the State of Washington in 1988 (Bates 1988) and were developed primarily for angled fish diversion screens. The Washington criteria were based largely on studies on salmonid swimming stamina by Smith and Carpenter (1987) discussed elsewhere in this report. The NMFS criteria apply for intakes in lakes, reservoirs, and tidal areas as well as rivers and streams. We discuss the NMFS criteria below as a representative example of agency criteria and then compare them to those criteria recently proposed by EPA.

Table 3-2
Partial listing of various State and Federal agency velocity criteria for water intake screens
(Pearce and Lee 1991; NMFS 1995; NMFS 1997).

Agency	Perpendicular approach velocity ¹ (f/s)		Sweeping velocity ² (Parallel velocity vector)
	Fry (< 60 mm)	Juv. (>60 mm)	
NMFS-Northwest Region	0.4	0.8	> approach velocity
NMFS-Southwest Region	0.33-0.4	0.8	> approach velocity
California DFG/USFWS	0.2 ³	Same as fry	At least 2X approach velocity
Oregon DFW	0.5	1.0	≥ approach velocity
Washington DFW	0.4	--	≥ approach velocity
Alaska DFG	0.5	Same as fry	No criterion
Idaho DFG	0.5	Same as fry	Sufficient to avoid physical injury to fish
Montana DFWP	0.5	1.0	No criterion
New York	0.5, 1.0 ⁴	Same as fry	No criterion
Virginia	0.25	Same as fry	No criterion

¹ Velocity component perpendicular to screen face calculated as (sine [screen angle]*approach velocity).

² Velocity component parallel to screen face calculated as (cosine [screen angle]*approach velocity).

³ Specific criteria where Delta smelt are present

⁴ New York has no official written criteria, but the general guidance is 0.5 f/s at fixed screens and 1.0 f/s at traveling screens (personal communication with Ed Radle of New York State Department of Environmental Conservation).

3.2.1 NMFS Northwest Criteria

Approach Velocity—The approach velocity criteria established by the Northwest Region of NMFS refers to the perpendicular velocity component, V_p , described earlier, measured (or estimated) at three inches in front of the screen. The criterion for fry (<60 mm length) is 0.4 f/s and for fingerling (>60 mm length) 0.8 f/s. Some state criteria vary slightly from the NMFS criteria, ranging from 0.25 to 1.0 f/s. The lowest criterion (0.2 f/s) is found in California and only applies when the endangered Delta smelt is present (NMFS 1997).

Sweeping Velocity—NMFS requires that the sweeping velocity (i.e., V_2 , the water velocity vector parallel and adjacent to the screen face) be greater than the perpendicular velocity vector. This is accomplished by angling the screen at an angle less than 45 degrees relative to the normal direction of the flow. Most western states also have adopted this criterion for water bodies where salmon are present. California requires that sweeping velocity be at least twice as much as the perpendicular velocity component, which would require a screen angle of 26 degrees or less.

Screen openings and porosity—NMFS provides screen opening criteria for both fry and fingerling salmonids for different types of screen material (i.e., perforated plate, profile bar screen, and woven wire screen) to prevent fish from passing through the screen. Regardless of the material, the screen must provide a minimum of 27% porosity if fry are present and 40% porosity if fingerling are present. It is not clear why a minimum porosity would be required and not a maximum since an unlimited maximum would allow more fish to pass through the screen and become entrained.

Bypass layout—NMFS requires that the screen and bypass work in tandem to move out-migrating fish to the bypass outfall with a minimum of injury or delay. Screens placed in the diversions shall be constructed with the downstream end of the angled screen terminating at a bypass entrance. Multiple bypass entrances (intermediate bypasses) shall be employed if the sweeping velocity will not move fish to the bypass within 60 seconds, assuming fish would be passively transported at a rate equivalent to the sweeping velocity.

The NMFS criteria were designed under the assumption that fry-sized salmonids and low water temperatures are present at all sites. However, NMFS does state that “Since these guidelines and criteria are general in nature, there may be cases where site constraints or extenuating circumstances dictate that certain criteria be waived or modified.” For example, if field observations show specifically when particular sizes of salmonids are in the vicinity of the intake, criteria could conceivably be adjusted such that the protection is aimed at that size class. [Note: Washington DFW standards also include this flexibility, and we suspect others do as well.]

3.2.2 Comparison to Proposed EPA Criteria

The intake velocity performance standard proposed by EPA for CWIS at new facilities is 0.5 f/s (65 FR 49060; August 10, 2000). This standard is specifically referred to as the “design intake velocity” since it would be used to evaluate proposed facility designs prior to construction. EPA defines the design intake velocity as “the average speed at which intake water passes through the open area of the intake screen or other device against which organisms might be impinged.” This is comparable to the through-screen velocity defined above. The proposed rules do not mention any regulations on screen spacing or angles, but do propose limits on the amount of water that can be diverted as a function of the total volume of the affected water body.

In order to compare the NMFS criteria and the performance standard proposed by EPA, the values need to be converted to common terms. We will make two comparisons, first converting EPA's proposed standard to NMFS conditions (i.e., the perpendicular velocity vector 2-3 inches in front of the screen) and then converting NMFS criteria to EPA requirements (through-screen velocity irrespective of angle).

For the first comparison we assume that the screen angle is at 45 degrees, the minimum allowed by NMFS for juvenile salmonids, and that screen porosity is 50%. Porosity less than 50% is common at many fish screens. Converting the EPA proposed standard of 0.5 f/s through screen velocity to in-front-of-screen velocity is easily done solving equations [1] and [4] for intake flow,

$$[1a] \quad (\text{intake flow}) = V_0 * (\text{intake area})$$

and

$$[4a] \quad (\text{intake flow}) = V_{ts} * (\text{screen open area})$$

setting the right sides of each equal to each other,

$$[5] \quad V_0 * (\text{intake area}) = V_{ts} * (\text{screen open area})$$

and solving for V_0

$$[6] \quad V_0 = [V_{ts} * (\text{screen open area})] / (\text{intake area}).$$

Thus, where the open area of the screen is 0.5 compared to a unit of intake area, the equivalent in-front-of-screen velocity is

$$V_0 = [0.5 * 0.5] / 1 = 0.25 \text{ f/s.}$$

If this velocity was applied to a screen angled at 45° the calculated perpendicular velocity vector, V_x , would be

$$V_x = 0.25 * \text{sine}(45^\circ) = 0.18 \text{ f/s.}$$

For the alternative comparison (i.e., converting NMFS criteria to the EPA conditions of through-screen velocity), we need to first back calculate from the perpendicular velocity vector V_x to the straight on approach velocity V_0 (see equation 2). For this exercise, we will use the most conservative of the NMFS criteria, 0.4 f/s, which is the perpendicular velocity allowed for fry.

$$V_0 = V_x / \text{sine}(\theta) = 0.4 / \text{sine}(45^\circ) = 0.57 \text{ f/s}$$

This result represents the straight-on velocity in front of the screen. To convert to through-screen velocity, V_{ts} , for comparison to EPA criteria, we assumed screen porosity of 50% as above and from equation 5 we see that

$$[7] \quad V_{ts} = [V_0 * (\text{intake area})] / (\text{screen open area})$$

so

$$V_{ts} = [0.57 * 1] / 0.5 = 1.14 \text{ f/s.}$$

The above analysis is summarized in Figure 3-3 and Table 3-3.

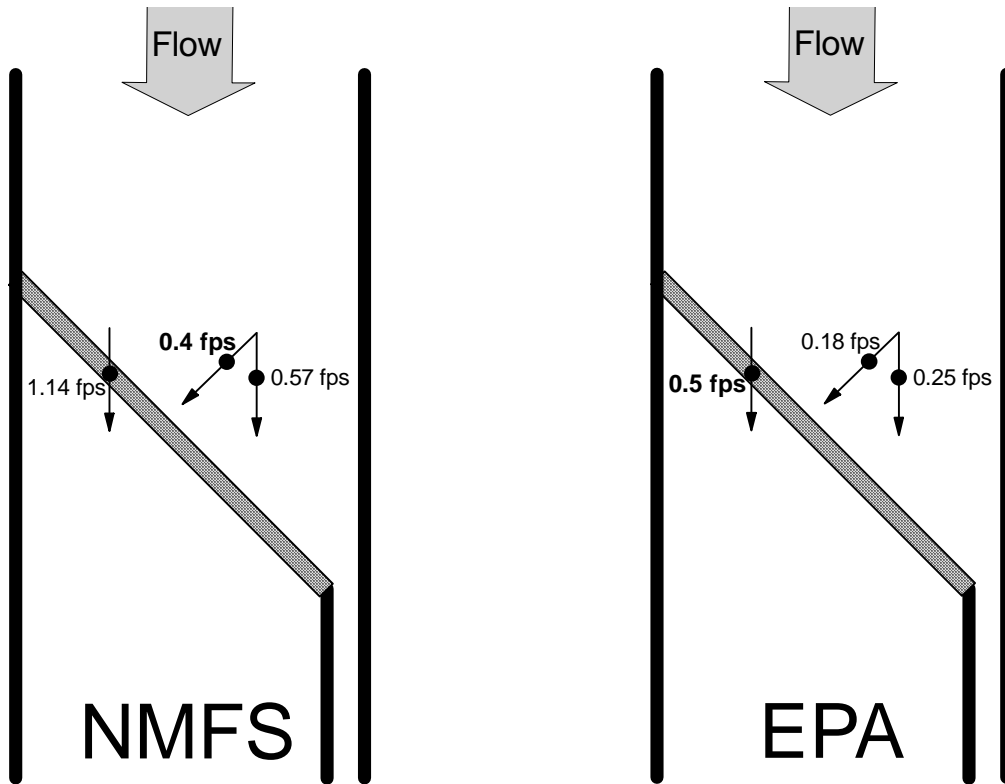


Figure 3-3
 Comparison of NMFS approach velocity criteria and proposed EPA criteria for three different measures of approach velocity, (from left to right) through-screen velocity, perpendicular velocity component, and standard approach velocity.

Table 3-3
 Comparison of approach velocity criteria developed by NMFS and proposed by EPA.

	Perpendicular velocity vector, V_1 , in front of 45° angled screen	Straight-on approach velocity, V_0	Through screen velocity, V_{ts} , with 50% screen porosity
NMFS criteria	0.4 f/s	0.57 f/s	1.14 f/s
EPA proposed criteria	0.18 f/s	0.25 f/s	0.5 f/s

Although EPA states that it “. . . is not proposing the more stringent criteria of 0.33 ft/s and 0.40 ft/s, developed by NMFS and the State of California, respectively, because they would be overprotective . . .” (65 FR 49060; AUGUST 10, 2000), we have shown here that when the criteria are presented in equivalent measures, the proposed criteria are actually more stringent than those of NMFS.

An additional source of difference among the different criteria/standards is whether they apply to a maximum or average value of those measured across the screen. The EPA standard applies to the average estimated velocity based on the design criteria, which would therefore not take into account the effect of partial clogging of the screen by debris. The NMFS standards only state that the criteria can not be exceeded, but don't clarify whether this is at any single point of measurement or on average. The NMFS criteria do require that uniform flow distribution be maintained over the screen surface. Those establishing standards for operational screens need to consider the implications of applying the standard to an average or maximum value in relation to the effect of debris accumulation.

4

EVALUATION OF SWIMMING SPEED INFORMATION AS A PREDICTIVE TOOL

4.1 Types of Swimming

How fish swim is relevant to the risk of their being impinged on intake screens of a power station. Performance of fish in certain swimming modes has been used to estimate acceptable approach velocities for power station intakes, as discussed in section 3 (e.g., Kerr 1953; King 1971; Hanson and Li 1978). This review has re-evaluated the scientific literature on swimming to further assess and develop this predictive capability.

There is extensive literature on the mechanisms of fish swimming (for example, Webb 1994) that has been summarized for the popular literature (Webb 1984) and has recently been applied to the operation of man-made propulsion systems in the aquatic environment (Sfakiotakis et al. 1999). Most of this literature focuses on establishing the principles of propulsion kinetics rather than quantifying swimming performance for applications such as evaluating CWISs.

The most recent tabulation of fish swimming capabilities from the scientific literature was published in 1978 by Beamish. However, Hammer (1995) provided a recent critical review of fatigue and exercise tests with fish, including a summary of the terminology and classification of swimming speeds. The physiological basis for the classification was explained with regard to burst, prolonged, and cruising speeds and the velocities that are critical to fish. The protocols for velocity tests, both fixed (fatigue) and increased (incremental) were reviewed. The experiments carried out by different authors were compared with respect to methodologies, which differed primarily in the different time intervals and velocity increments employed. The dependency of the critical swimming speed (CSS or U_{crit} ; see definitions below) on factors such as species specificity, race and population, size, season, time of day, temperature, sex, pollutants, light, food, training, and ambient gas content was outlined. Most such relationships were judged to be incompletely defined. Hammer concluded that the utility of critical swimming speed studies as a simple and sensitive measure of environmental or physiological factors is compromised by individual variability, which is not often quantified. He did not tabulate the critical swimming speeds.

We approached this review with the assumption that the accumulated knowledge would be useful for critiquing or developing intake velocity and design criteria. The knowledge largely would take two forms, one being a current tabulation of critical swim speed data and the other being a summary of the factors that cause a decline in critical swimming speeds that could affect fish impingement or entrainment at power station intakes (and the experimental evidence for them).

4.1.1 Sustained, Prolonged and Burst Swimming

Most fish generate thrust by bending their bodies into a backward-moving propulsive wave that extends to the caudal fin, a type of swimming classified under body and/or caudal fin (BCF) locomotion (Breder 1926). There are two basic types of such swimming (Weihs and Webb 1983):

1. Continuous, periodic propulsive (or steady, sustained) swimming, characterized by a cyclic repetition of the propulsive movements, used for covering relatively long distances at a more or less constant speed, and
2. Transient, discontinuous (or unsteady) movements that include rapid (fast) starts, burst or sprint swimming, acceleration, and turns lasting a short time and typically used for catching prey, avoiding predators, or responding to disturbances.

Most authors recognize two types of continuous periodic swimming, sustained and prolonged (Beamish 1978). Sustained swimming can be maintained indefinitely and is often called the cruising speed. Prolonged swim speed is maintainable for only a certain length of time before the animal fatigues. Also, discontinuous swimming can occur (without bursts) at low velocity and not for catching prey, avoiding predators, or responding to disturbances, but simply as the preferred mode.

The three types of swimming capability (sustained continuous, prolonged continuous, and transient) can be distinguished in experiments that relate time to fatigue at speeds given relative to body length (Figure 4-1; Beamish 1980). Burst swimming results in rapid fatigue; prolonged swimming can be sustained for longer times before fatigue occurs; sustained swimming can go on essentially endlessly. The three types can be shown by broken-stick graphs such as Figure 4-1. The types of swimming use different aerobic and anaerobic energy supply systems (or different combinations of them), a level of physiological detail that is available in the literature but will not be further explored here.

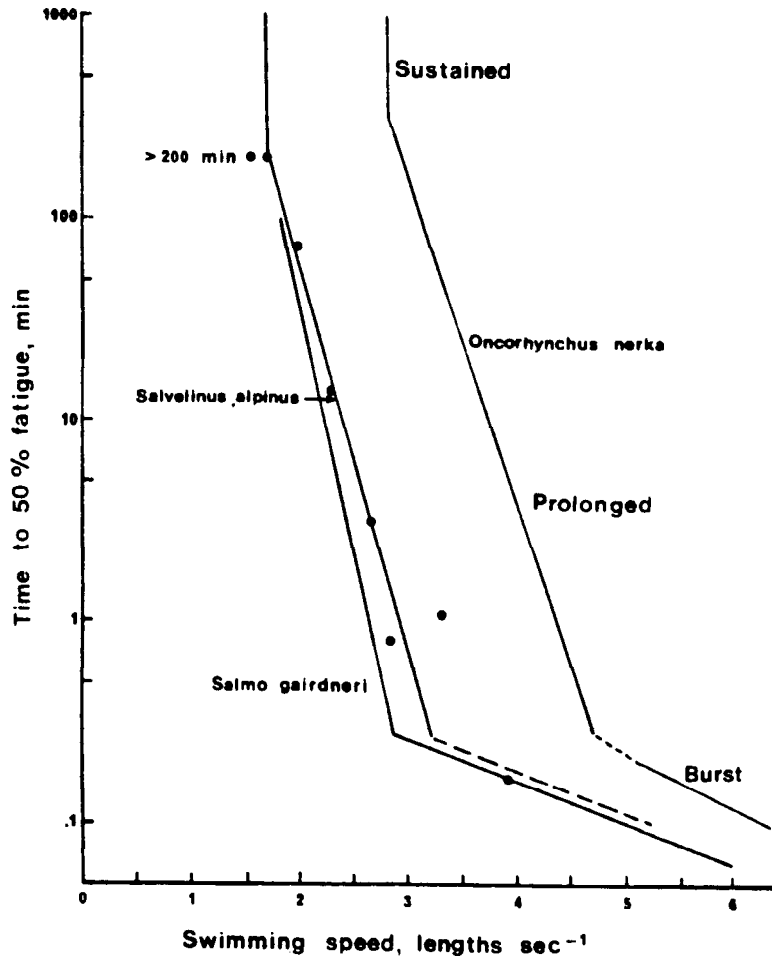


Figure 4-1
 Three principal types of swimming by fish are illustrated in terms of time to fatigue. Sustained swimming (cruising; top part of curve) does not fatigue; prolonged swimming (middle slope) can occur without fatigue for lengths of time that depend on the velocity; burst swimming (lower part of curve) occurs at high velocities but for very short time periods. From Beamish (1980).

Each type of swimming that uses the main tail-fin thruster is relevant to impingement at power station intakes. Sustained, continuous (periodic) swimming (cruising speed) is the mechanism that probably causes most fish to encounter the intake in their normal travels (Figure 4-2). Prolonged, periodic swimming (critical swimming speed) is the mode of swimming that is probably used for holding station in front of an intake screen or for gradually moving upstream in an intake canal to escape the intake. Transient movements probably occur when a fish encounters and recognizes an intake structure or the rapid change in velocity field associated with it. Turning, fast starts, swimming bursts, and the like are probable behavioral responses to discovery of the intake and the means for initial escape. Alternatively, the swimming mode may not change when the fish encounters a screen. These conjectures need support from field studies that are not now available.

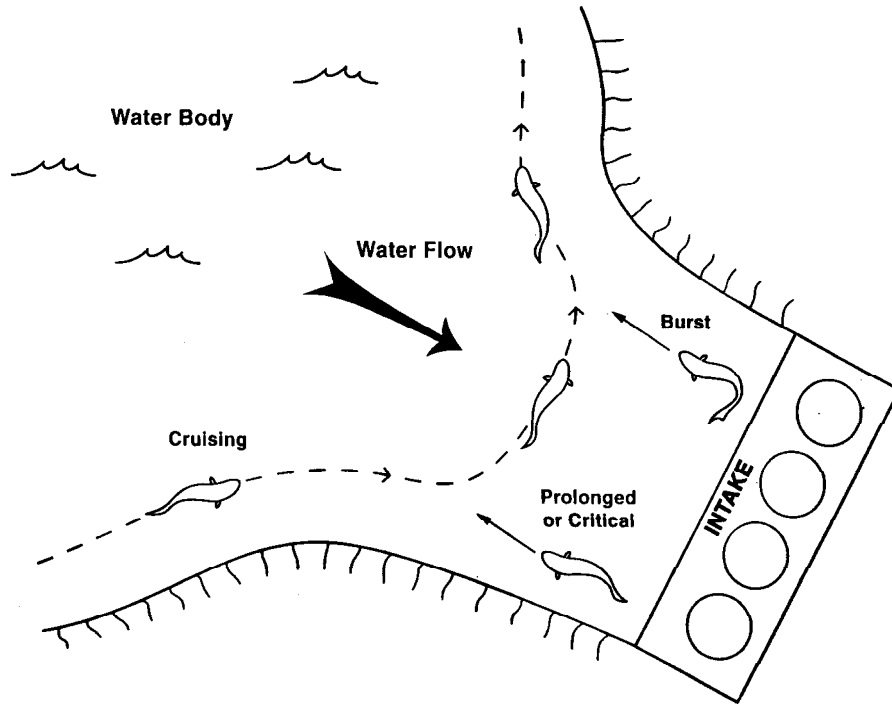


Figure 4-2

Three types of swimming are illustrated in a hypothetical cooling-water intake. Cruising speed is voluntary in the source water body. Prolonged or critical swimming speed is forced swimming for a long duration either in place until fatigue or until escape. Burst swimming is the energetic, rapid, darting action to escape that can be continued for only seconds. Critical swimming speeds have been the most studied.

Other fish have developed alternative swimming mechanisms that involve use of their median and/or paired fins (MPF) for locomotion. Although about 15% of fish species use MPF locomotion nearly exclusively (electric eels and seahorses, for example), a much greater number of species that typically rely on body and caudal fin (BCF) modes for propulsion employ MPF locomotion for maneuvering and stabilization. The sunfishes are familiar examples, that can dart about using BCF locomotion but more often move, brake, and change direction using primarily their pectoral fins. High reliance on MPF propulsion could, in principle, make MPF-dependent fish more vulnerable to impingement because of the lack of high propulsive power. In the generally acute instance of encountering an intake, MPF locomotion alone is likely inadequate for escape.

Swimming performance under BCF propulsion is size dependent. It varies approximately according to the square root of body length (Bainbridge 1960; Brett 1965; Fry and Cox 1970). Thus, measures of swimming performance are often reported as body lengths per time interval (usually second) to incorporate this effect. This relative measure of swimming ability has more applications to physiological studies than it does to the absolute water velocities of water intakes and other physical structures. Nonetheless, both absolute and relative measures often are reported.

Swimming is essentially an interaction of biology and hydraulics, as a fish moves (or is moved) through the incompressible, viscous medium. A fish propelling itself through water disturbs a standing watermass by creating vortices and fluid displacement. Schooling fish apparently make use of vortices in the wakes of caudal fin movements of those preceding them to gain advantages in propulsion (Weihs and Webb 1983). Average energy savings compared to swimming alone can amount to 10–20% (Magnuson 1978). The configuration of schools, often a diamond-shaped building block structure (Figure 4-3), is described by wake width, vortex spacing, and lateral distance among fish of the same column. The dependence of schooling fish on uniform and predictable hydraulics may partially explain why intakes, which radically alter the hydraulics of a waterbody in their vicinity, tend to impinge schooling fishes disproportionately greatly (although impingement of schooling fishes is often also associated with episodic changes in temperature or dissolved oxygen, as discussed in section 4.3).

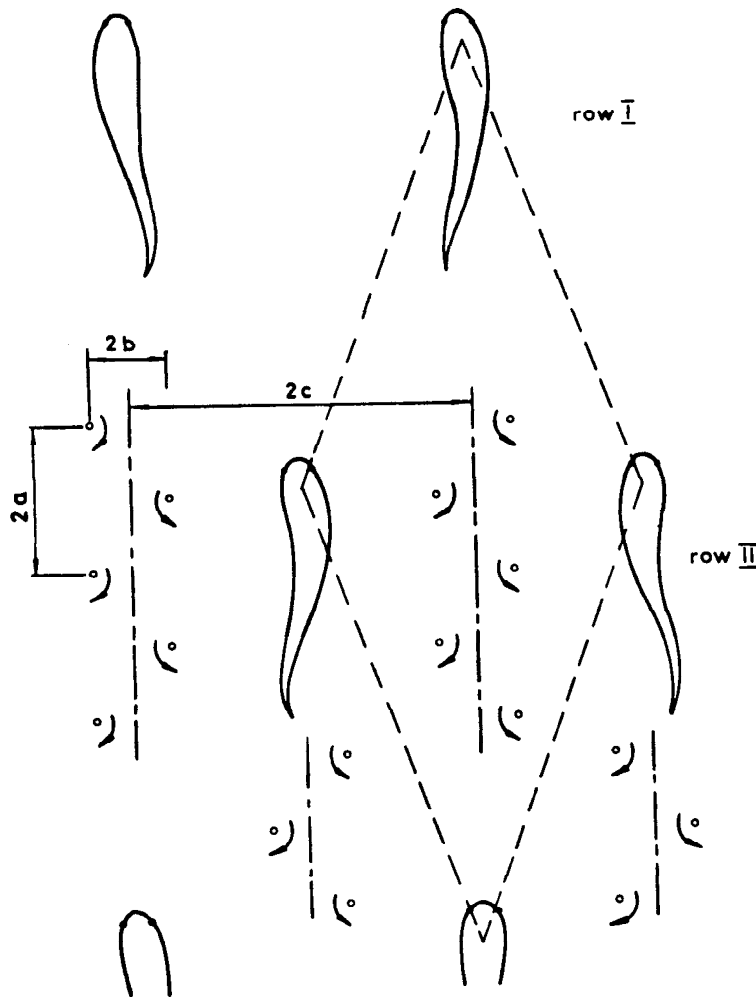


Figure 4-3
Fish swimming in schools make use of vortices from adjacent fish to reduce swimming effort. Figure shows part of a horizontal layer of fish within a school and the discrete vortex wakes shed. Fish tend to swim in antiphase in a characteristic diamond pattern. From Weihs 1975.

Burst swimming and the fast-start swimming that initiates it is associated with natural activities such as feeding and avoiding predators. It also is relevant to the initial stages of moving away from an intake screen once the screen has been touched or otherwise recognized as something to be avoided. All fish show basically similar fast-start body movements (Eaton et al. 1977). There are typically three stages of movements originally described by Weihs (1973).

The overall swimming performance of a fish is a combination of capability and motivation to swim at a maximum rate of speed (MacPhee and Watts 1975). Swimming capability refers to the physical ability of a fish to swim, which our literature review has shown to be dependent largely on size and shape of the fish and its body temperature (and at a physiological level, on its red:white muscle ratio). In contrast, the voluntary response or motivation of a fish to swim at a maximum rate of speed is governed by the psychological and physiological state of the fish, which can be influenced by many factors. Although physical factors such as temperature are important, more internal (innate) factors are also relevant, such as state of reproductive maturation or activity. These, in turn, are affected by hormonal cycles and photoperiodism. For example, Arctic grayling studied by MacPhee and Watts (1975) had to be in their upstream migration mode for spawning to show an inclination to enter and swim through their test culverts. Delta smelt *Hypomesus transpacificus* studied by Swanson et al. (1998) employed three velocity-dependent swimming gaits with a volitional switch between them: a discontinuous “stroke and glide” below about 10 cm/s, continuous swimming above 15 cm/s, and a discontinuous “burst and glide” swimming above the critical swimming speed of about 28 cm/s. There was often a swimming failure between 10 and 20 cm/s during volitional transitions between gaits that caused a fish to fall back against the screen of the text chamber.

Motivation to swim in the field implies some recognition by the fish of a need to swim. Further, the fish needs to know which type of swimming is most appropriate for the stimulus. The particular velocity, change in velocity, or other cues that serve to initiate swimming behavior is poorly known. These motivational cues are probably as important (perhaps more so) as the physiologically maximum swimming capability. Knowledge of normal migratory or other movement behavior becomes important for interpretation of the swimming performance of fish, whether voluntary or forced. This behavioral aspect was reviewed for hydropower intakes by Coutant and Whitney (2000), but deserves further review and synthesis with respect to location, design and operation of cooling-water intakes.

4.1.2 Swimming Behavior of Bottom Fish

Bottom-dwelling fish are a special case. They often are not strong swimmers, but have evolved a swimming behavior that conserves energy even at relatively high water velocities. For example, largescale suckers *Catostomus macrocheilus* studied by Kolok et al. (1993) exhibited a 3-phase response to increasing water velocity in an experimental apparatus designed to determine critical swimming speed. In the first phase, 40-cm-long fish held position against the bottom in water velocities up to 30–40 cm/s (0.75–1 BL/s), depending on temperature. Holding station did not involve any obvious changes in fin position or posture, nor did it involve the use of the mouthparts to suck onto the bottom of the chamber. When fish were no longer able to hold station, they first adopted a burst-and-glide method of swimming (phase 2). During this period (roughly 35–45 cm/s or 0.9–1.1 BL/s, depending on temperature) fish slowly slid to the back of the chamber, touched the downstream restraining screen, then swam to the front of the chamber

to repeat the cycle. This phase continued until the velocity (generally >45 cm/s) required continuous swimming (phase 3). At the lowest temperature tested (5°C) swimming was impaired such that fish did not swim (other than a few abortive bursts) when subjected to water velocity in which they could not hold station.

Mottled sculpin *Cottus bairdi*, another benthic fish, used the first two phases (bottom holding, burst-and-hold) to maintain position rather than any continuous swimming (Facey and Grossman 1990). In studies of this species by Webb et al. (1996), behavioral modifications of the forces acting on the body appeared more important for bottom holding than passive physical properties. Longnose dace *Rhinichthys cataractae* (Facey and Grossman 1990) and Sacramento sucker *Catostomus occidentalis* (Myrick and Cech 2000) used all three phases. Stone loach *Noemacheilus barbatulus* used pectoral fins as depressors to hold to the bottom at high velocities (Stahlberg and Peckmann 1987). Swimming velocity increased steadily until 47 cm/s, after which swimming velocity decreased and holding increased.

Sturgeons, both adult shovelnose *Scaphirhynchus platyrhynchus* (Adams et al. 1997) and pallid *Scaphirhynchus albus* (Adams et al. 1999) use large pectoral fins to grasp the bottom, using flowing water to exert a downward force pressing the fish to the bottom, called substrate appression. They also exhibited pelagic swimming (free swimming) and substrate skimming (body touching the bottom, but propulsion with body and caudal fin undulation).

The maximum speed at which bottom fish are able to hold station without active swimming has been called the “critical current speed” by Matthews (1985) and the “critical holding velocity” by Rimmer et al. (1985). Matthews tested two darter species from streams and found critical current speeds of 16.2 cm/s (SD 3.19) for juvenile fantail darter *Etheostoma flabellare*, 24.0 cm/s (SD 5.65) for adult fantail darter, and 30.2 cm/s (SD 5.32) for adult Roanoke darter *Percina roanoka*. Rimmer et al. (1985) studied this behavior in juvenile Atlantic salmon *Salmo salar* in a stream environment.

Some bottom fish will not actively swim at all. The riffle sculpin *Cottus gulosus* would not perform in a respirometer-type swim speed apparatus (Baltz et al. 1982). They clung to the bottom with their pelvic fins and showed no swimming response to increased current velocities.

Bottom substrate makes a difference in apparent critical swimming speeds. Gudgeon *Gobio gobio* showed an increase in critical swimming speed from 55 cm/s to 61.7 cm/s when the bottom substrate in the test tunnel was changed from smooth to gravel (Stahlberg and Peckmann 1987). This difference is most likely due to a bottom boundary layer that reduces actual velocities experienced by the fish.

4.1.3 Threshold Swimming Speed

Many fish exhibit a minimum speed for orientation into a current or rheotaxis, called the “threshold swimming speed” (King 1971). At this speed, the somewhat random and exploratory movements, often powered by the pectoral fins (MPF swimming), are replaced by steady, sinusoidal movements of the body and use of the caudal fin with pectoral fins folded against the body. This threshold has not been measured customarily, but King (1971) reports that the

threshold increases with size in white perch (from an average of 15 cm/s for fish 85-117 mm to 42 cm/s for 150-mm fish). King noted that some species (black crappie and pumpkinseed sunfish) did not make the change to rheotactic behavior in his tests, which he attributed to their normal still-water habitats. Such a lack of directed swimming behavior could make these species more susceptible to impingement.

4.2 Prolonged (Critical) Swimming Speed

Critical swimming speed is a special category of prolonged swimming speed that was initially identified by Brett (1964). Intuitively, we believe that fish can sustain a maximum swimming speed for only so long before they tire and must slow down or cease swimming. This is swimming capability, which assumes some motivation for swimming. A standardized measure of this phenomenon was developed by Brett (1967) for physiological performance studies and is called the “critical swimming speed” or “Ucrit”. It is obtained by applying increments of increased velocity at specified time intervals in a standardized apparatus (after a period of acclimation of the test fish to the test chamber) until fatigue occurs and the fish drifts backward into a downstream endpoint (often a screen). The most common apparatus is a closed tube or tunnel often also used as a respirometer (Blazka-type; Blazka et al. 1960; Brett 1964; Figure 4-4), which is functionally analogous to a fish holding station in front of an intake screen. Similar results have been obtained from open flumes and circular or oval troughs (MacLeod 1967). This stepwise testing appears to give good approximations to maximum prolonged swimming speeds derived by fixed velocity testing methods, at least for salmonids (Griffiths and Alderdice 1972). However, Swanson et al. (1998) found that delta smelt, a relatively weak, compared with salmonids, swimming osmerid, showed many ‘prefatigue failures’ in such a swimming tunnel, attributed to swimming mode changes (between discontinuous swimming and continuous) with increased velocities. Rigorous comparisons of laboratory results with prolonged swimming speeds observed in the field or in volitional swimming experiments are not available. There is some suggestion, however, that tunnel respirometry experiments used for determining critical swimming speeds yield somewhat lower swimming speeds than field data (A. Hoar, USGS Conte Laboratory, personal communication). Intake velocities can exceed critical swimming speeds, as shown by Turnpenny and Bamber (1983; Figure 4-5). Numerous studies using many species and sizes have quantified the critical swimming speeds of fish or their close equivalents (Table A-1).

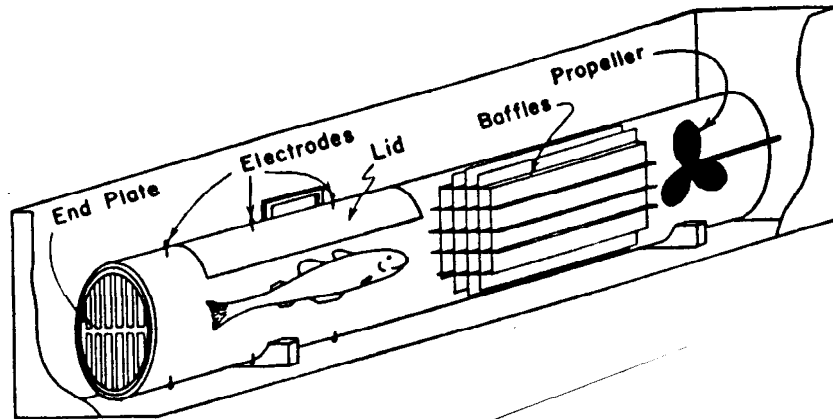


Figure 4-4
Laboratory determinations of critical swim speeds are usually conducted in swim tunnels in which a single fish swims at designated stepped velocities and time increments of exposure in relatively laminar flow until fatigue forces it against the end plate or screen. Electrodes have traditionally given mild shocks to stimulate swimming. Such chambers are usually recirculating loops. A common variant is to use an open channel or flume. From Beamish (1966).

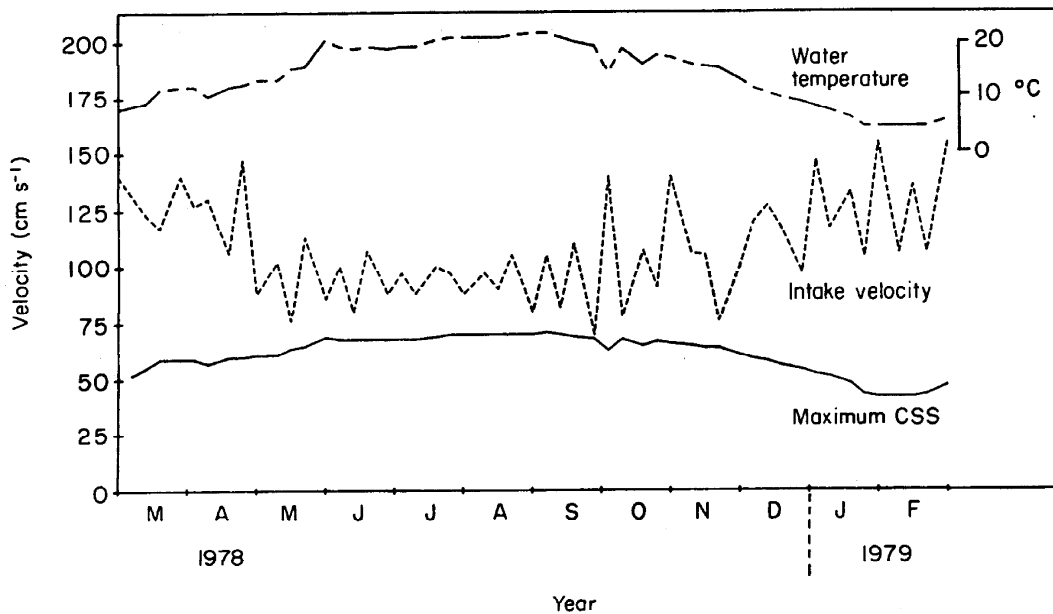


Figure 4-5
Intake velocities can exceed critical swimming speeds (CSS) of fish. This is shown for the Fawley Power Station, England, over an annual cycle. From Turnpenney and Bamber (1983).

The specific test conditions can influence the “critical speed” that is determined. Different velocity increments during the ramping-up process of a test and the duration of exposure at each velocity can affect the current velocity at which a fish fatigues and fails to maintain position (Brett 1964). A series of velocities and times used to test largemouth bass showed a rather complex relationship (Figure 4-6; Farlinger and Beamish 1977). As seems logical, shorter time increments (less time to fatigue) allow swimming to higher speeds as the velocity is gradually increased. Critical swim speed was less sensitive to differences in the velocity increment. For each time increment, there appears to be a modal velocity increment (a specific increment that gives a maximum critical speed). Intuitively, the overall pattern of relationships may persist, but the numerical scale would change for different sizes of fish, because swimming performance varies approximately according to the square root of body length (Bainbridge 1960; Brett 1965; Fry and Cox 1970). Thus, experimenters have selected different increments of velocity and time for their tests, generally scaling them in proportion to fish sizes (Table A-1).

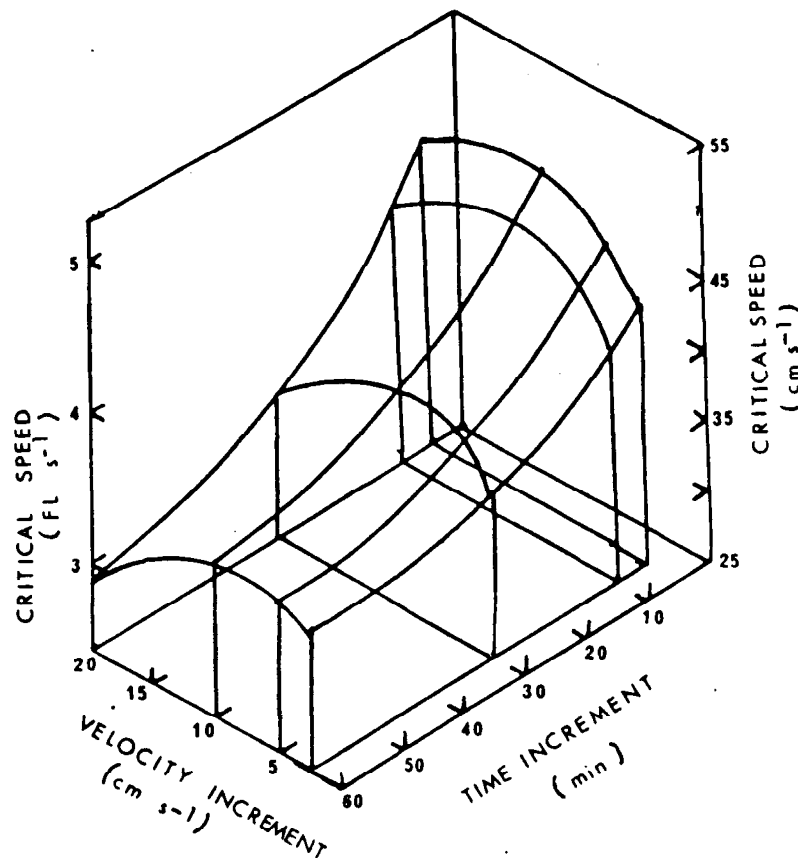


Figure 4-6

Critical swimming velocities determined in stepped-velocity tests are somewhat affected by experimental conditions (velocity increment and time increment). The relationships were established for largemouth bass juveniles by Farlinger and Beamish (1977). For this reason, both time and velocity increments are given for data in Table A-1.

The maximum prolonged (sustained) swimming speed, whether quantified by the critical swimming speed protocol or something similar, is largely a function of the size (length) of the fish and the water temperature. Size determines physical propulsive thrust while temperature determines the physiological efficiency of the metabolic process that powers the propulsion. The science behind this simplistic summary has been explored in an extensive literature see, for example, papers by Webb and Weihs cited in the references section). Beamish (1970) provided an excellent conceptual view of the relationships among maximum swimming speed, fish length (or weight), and temperature based on extensive research on largemouth bass *Micropterus salmoides* (Figure 4-7). Beamish's graph shows a family of lines (one for each temperature) delineating increasing maximum swimming speed with increasing fish size (length or weight), in which swimming speed is greater at higher temperatures. The temperature effect is more pronounced in small fish than it is in large fish.

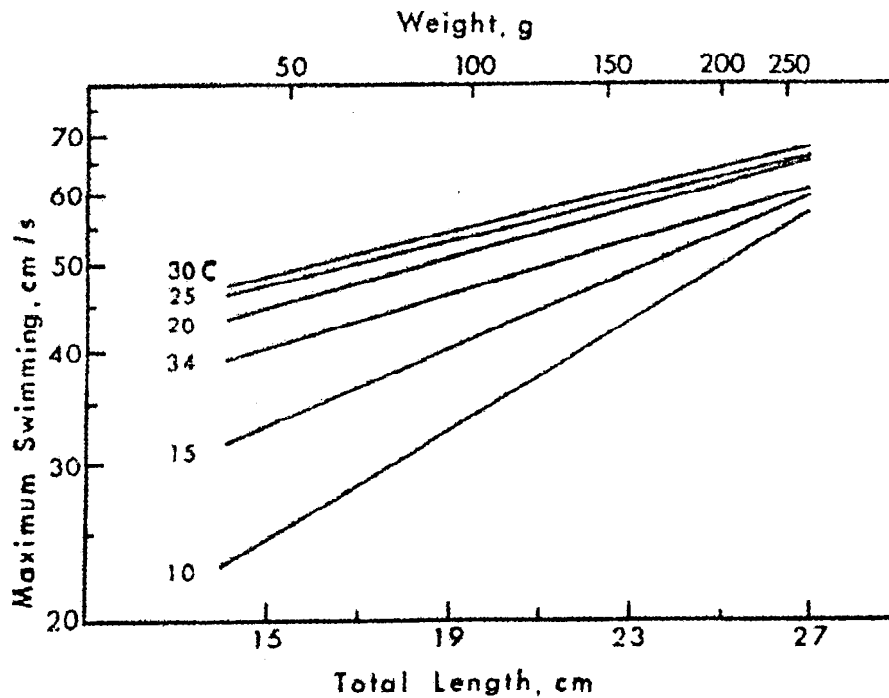


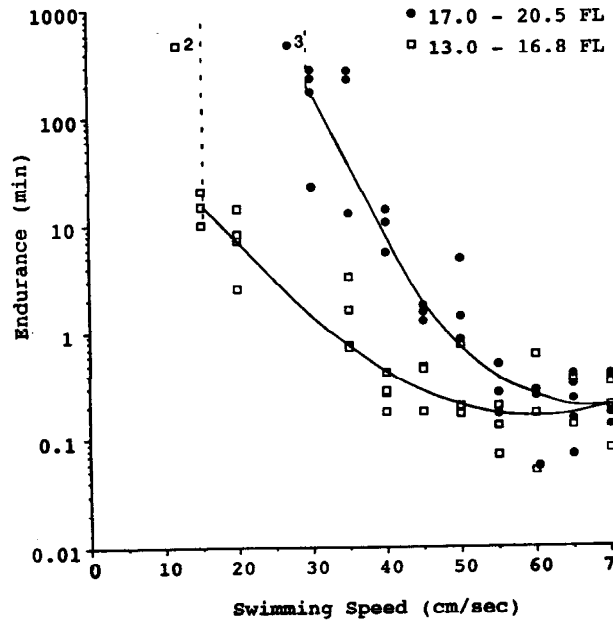
Figure 4-7
Maximum sustained swimming speeds of largemouth bass in relation to total length and weight at different temperatures. From Beamish (1970).

The species-specific critical swimming speed data summarized in Table A-1 can be considered experimental “snapshots” of portions of a complete picture such as Figure 4-7, in which the actual values are species specific but incomplete. Few species summarized in Table A-1 have been studied extensively enough to draw their complete patterns comparable to Figure 4-7 for largemouth bass. When the individual results in Table A-1 are examined, it is useful to visualize them against the template of a graph like Figure 4-7.

4.3 Fatigue Times or Endurance

Fatigue (or endurance) times at constant swimming speeds also have been determined as measures of swimming endurance in fish, often in conjunction with traditional critical swimming speed studies. Curves of endurance times versus current velocity are useful for separating burst, prolonged (critical) and sustained swimming speeds, as noted above (Figure 4-1). As is the case for critical swimming speeds, endurance times are dependent on fish size, water temperature, and other variables (Bernatchez and Dodson 1985; Ojanguren and Braña 2000). Endurance times at given velocities also have been converted to distances capable of being swum at specific velocities (e.g., Beamish 1974), with application to design of culverts (MacPhee and Watts 1975). For an environmental risk analysis of impingement, endurance time would be useful for establishing the relationship between swimming performance of local fish and the length of an intake canal or channel.

Fewer species have been tested for fatigue or endurance times than have been tested for critical swimming speeds. Furthermore, the standard representation for the data is as a graph, as in Figure 4-1, which expresses velocity in terms relative to body size (body lengths per second) rather than as absolute velocities (cm/s). The same graphical patterns emerge when the data are plotted in absolute terms (Figure 4-8). Tabular data supporting the graphs are rarely presented in publications. Therefore, considerable effort would be required to obtain original data from the authors and to re-analyze it to obtain absolute velocities. Relevant graphs, as presented in the original publications, are provided in Appendix B.



- *Acipenser fulvescens* 23 cm TL; 21 C
- *Oncorhynchus nerka* 18 cm TL; 10 C
- *Scaphirhynchus albus* 17 - 20.5 cm FL; 18 C
- *Salvelinus fontinalis* 18 cm FL; 20 C
- *Scomber j. peruanus* 10 cm TL; 19 C

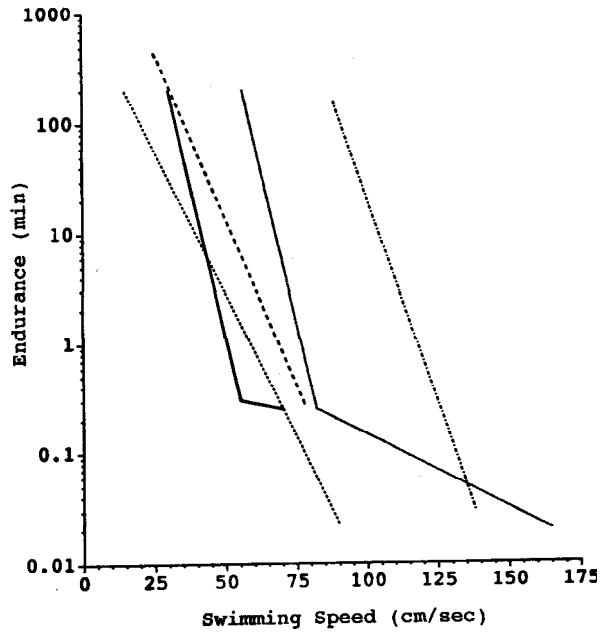


Figure 4-8
 Relationship between endurance time and swimming speed (expressed in cm/s) for the pallid sturgeon (top) compared to other fish species. From Adams et al. (1999).

4.4 Factors That Affect Swimming Capability

4.4.1 Individual Variability

Individual fish vary considerably in their swimming abilities, even when other variables such as fish length are constant. This variability is reflected in a range of critical swimming velocities when numerous individual fish are tested (Figure 4-9). For example, critical velocities for coho salmon studied by Glova and McInerney (1977) varied about 20 cm/s among individual early fry, advanced fry, pre-smolts, and smolts (Figure 4-8). In most studies, the median or average critical swimming speed is reported and the variation is treated as statistical noise (Hammer 1995; Kolok 1999); usually a standard error of the mean or standard deviation is reported. As Kolok (1992) pointed out, this approach overlooks a significant source of performance variation. For impingement at power station intakes, it is probably the weaker individuals that are impinged, and thus the initial individual's failure in critical swimming performance tests is of interest (and tabulated in Table A-1 when available). Fortunately, both the central value and the variation seem to be repeatable in at least seven studies involving five fish species (Kolok 1999; Figure 4-10). Some of this individual variability may be attributed to growth rates, for Kolok and Oris (1995) found the fastest-growing fathead minnows *Pimphales promelas* to be the poorest swimmers. Individual variability seems to be accentuated when fish have been exposed to sublethal toxicants, for only some of the fish will show marked declines in swimming performance while others' performance can remain little changed (Kolok et al. 1998). Hatchery-reared fish tend to have a poorer swimming capability than wild fish of the same species (e.g., Duthie 1987). Plaut and Gordon (1994) showed that swimming performance variation had a strong genetic component in zebrafish *Brachydanio rerio*. Genetically cloned (identical) zebrafish showed essentially no variation in swimming performance. Again, it is those most susceptible that will be reflected in power plant impingement.

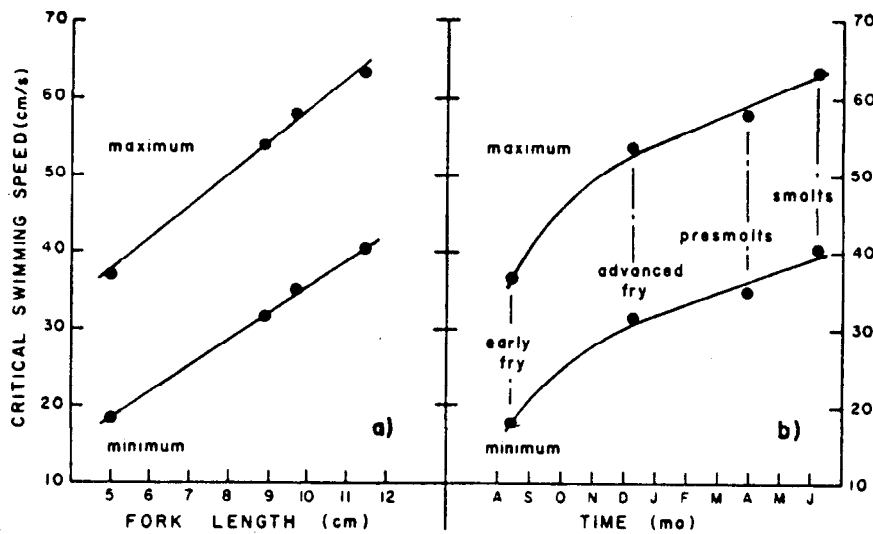
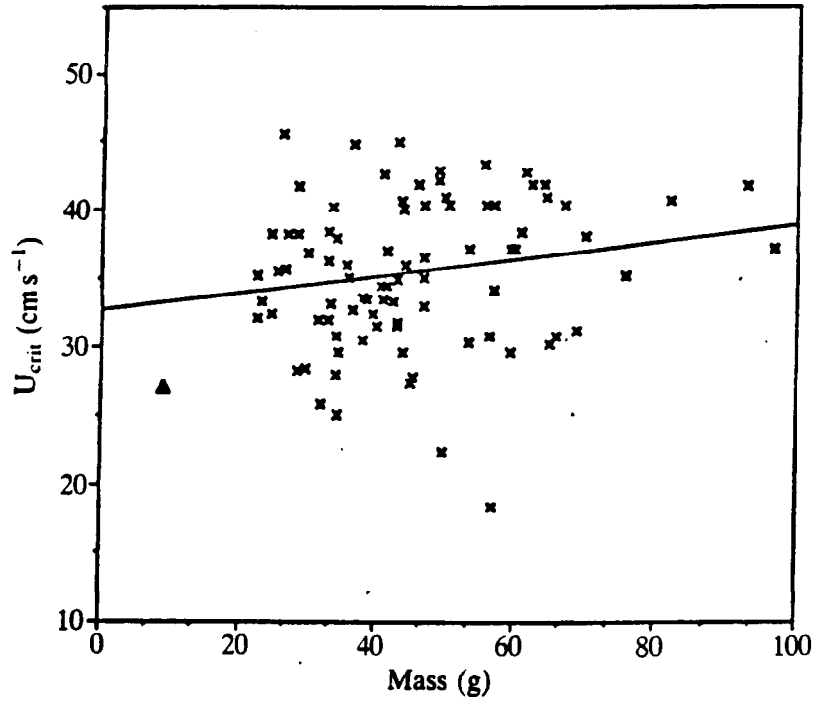


Figure 4-9
 There is high individual variability in critical swimming speeds of fish, as shown in graphs comparing critical swimming speeds to body mass (upper; all individual data points are shown) and fork length (lower; maximum and minimum data points are shown). From Nelson (1989; upper) and Glova and McInerney (1977; lower).

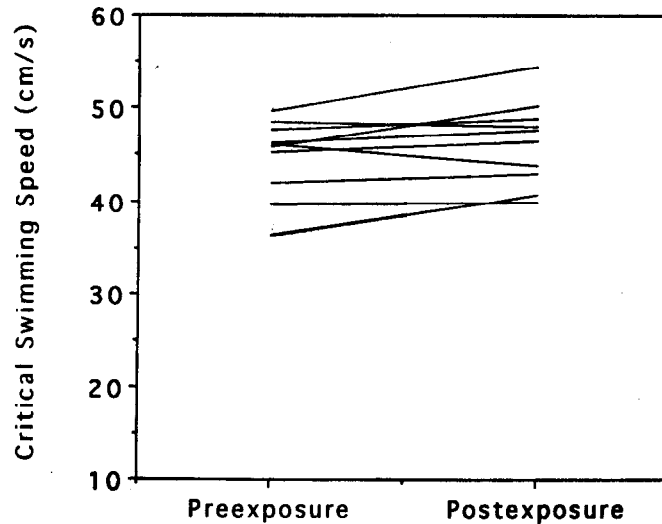


Figure 4-10
Swimming performance of individual fish is fairly repeatable. Experiments by Kolok et al. (1998) determined critical swimming speeds of 10 fathead minnows in two swim tests 10 to 14 days apart (same fish are connected by lines). These fish were controls for sediment toxicity exposures.

4.4.2 Exercise Conditioning

Several studies have shown that exercise conditioning will increase fish stamina and therefore elevate the critical swimming speed (Davison 1989, 1997). For example, young largemouth bass were shown initially by MacLeod (1967) to perform better in swim tests when used again on subsequent days. Largemouth bass swum at 35 cm/s conditioning velocity showed an increase in Ucrit from 41.6 to 44.6 cm/s after 5 days and a further rise to 47.7 cm/s after 30 days (Farlinger and Beamish 1978). Rainbow trout *Oncorhynchus mykiss* swam 12% faster after exercise training for 28–52 days (Farrell et al. 1990). Young and Cech (1993) showed improved swimming performance by young-of-the-year striped bass *Morone saxatilis* after exercise conditioning. The coalfish *Gadus virens* (a cod) increased its swimming capability by 11% with exercise conditioning (Greer Walker and Pull 1973). However, sprint training (forced, rapid swimming) did not improve critical swimming speed of rainbow trout in experiments by Gamperl et al. (1991), although acceleration in burst swimming did improve. However, exercise conditioning with insufficient food can lower the condition factor of fish and negate any potential increase in critical swimming speed (Farrell et al. 1991).

4.4.3 Fish Length

Prolonged swimming speeds are highly dependent on fish length, which is the predominant determining variable. The logarithm of swim speed at a given temperature usually increases with the logarithm of length according to the equation:

$$\log S = a + b \log L$$

where S is the critical swim speed, cm/s and L is total length, cm. Speed relative to body length decreases linearly with the logarithm of length in a manner described by the equation:

$$C = a - b \log L$$

Where C is the relative critical swim speed, body lengths/s and L is total length, cm.

The dependence of swim speed on length appears to be described best for salmonids by a coefficient (b) of 0.4 to 0.5 (Beamish 1980 based on data from Blaxter and Dickson 1959; Bainbridge 1960, 1962; Brett 1965; Fry and Cox 1970, Jones et al. 1974). In contrast, coefficients near unity have been reported for other teleosts (Beamish 1980 based on Blaxter and Dickson 1959; Houde 1969). Some of the studies tabulated in Appendix A included equations relating critical swimming speed to body length. Wherever possible, the equations were included in the table. We derived a regression equation for all of the species tabulated in this report:

$$U_{crit} = 32.8 + 1.32 L$$

4.4.4 Body Shape

Body form has a great deal to do with swimming speeds (Lindsey 1978; Figure 4-11). Anguilliform species (eels, lampreys) are particularly poor swimmers. Adult sea lampreys *Petromyzon marinus* were estimated to be able to sustain swimming speeds of only about 1 cm/s for 30 min at 15°C and less at 5°C (Beamish 1974). Eel *Anguilla anguilla* elvers could swim for 3 minutes at 25 cm/s but only 0.7 min at 36 cm/s (McCleave 1980). They swim so poorly that conventional tests of critical swim speed have not been performed, rather emphasis has been placed on endurance times at a variety of water velocities. These tests have generally fallen in the category of burst swimming speeds. Clearly, the anguilliform species provide unique challenges for screening, both in CWIS and other situations (hydropower and irrigation diversions).

negative relationship between Ucrit and SGR at high SGR levels (2%/d). There was no significant relationship at intermediate feeding levels (Gregory and Wood 1999). Exercise-conditioned striped bass grew, as well as swam (Ucrit), faster than non-conditioned fish (Young and Cech 1994).

4.4.6 Dissolved Oxygen

Low dissolved oxygen causes lower swimming speeds, generally after a threshold concentration is reached. Sustained swimming speeds of juvenile coho and chinook salmon *Oncorhynchus tshawytscha* were reduced significantly at dissolved oxygen concentrations below about 10 mg/L (Davis et al. 1963). However, first failure in swim tests occurred above about 20 cm/s even at a low level of 2 mg/L dissolved oxygen. Similar results were shown for largemouth bass and coho salmon by Dahlberg et al. (1968). Early studies by Katz et al. (1956) had indicated a surprisingly high swimming performance of chinook and coho salmon juveniles and largemouth bass at oxygen concentrations not much above the level that would be lethal in standing water. Young Atlantic salmon showed marked reduction in swimming ability in the range of 4–5 mg/L dissolved oxygen in studies at several constant swimming speeds at 15°C by Kutty and Saunders (1973) (Figure 4-12). Swimming ability of the fathead minnow was reduced by low dissolved oxygen resulting from suspensions of wood fiber from pulpwood (MacLeod and Smith 1966). Reduction in dissolved oxygen reduced the maximum swimming velocity of rainbow trout (6% reduction at oxygen partial pressure of 60 mm of mercury; 24% at 40 mm) (Bushnell et al. 1984). Pre-acclimation to low oxygen levels had little influence on the end results of that study.

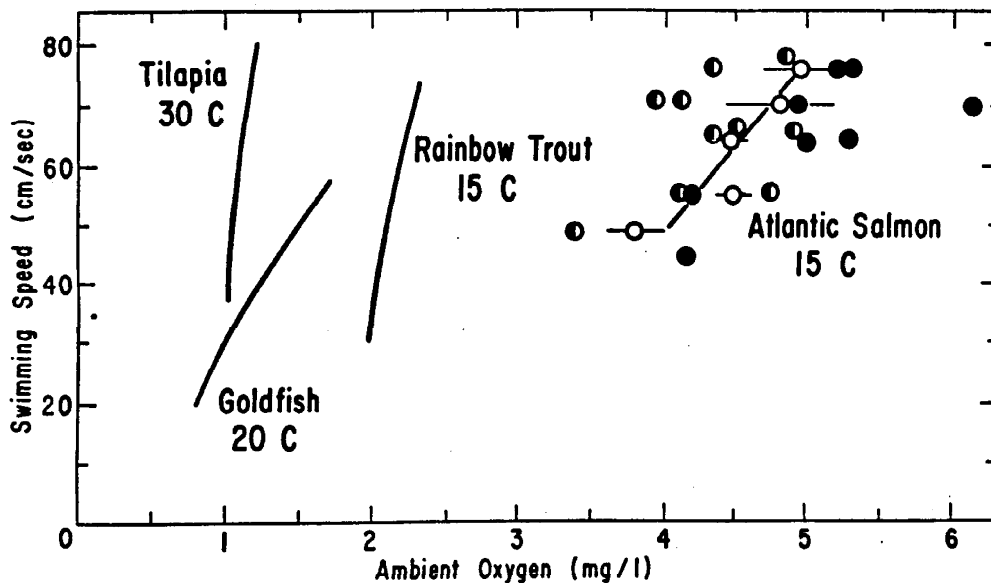


Figure 4-12
 Low dissolved oxygen concentration reduces critical swimming speeds at different concentrations for each species. Summary curves are shown for three species (left) and data points and summary line for Atlantic salmon. From Kutty and Saunders (1973).

4.4.7 Supersaturated Dissolved Gas

Supersaturation of dissolved atmospheric gases can lower swimming speeds. Juvenile chinook salmon exposed to selected levels of dissolved atmospheric gas ranging from 100% (control) to 120% saturation showed decreased performance between 106% and 120% when tested immediately (Schiewe 1974). Recovery of swimming capability occurred within 2 hours when fish were returned to 100% saturation before testing.

4.4.8 Temperature

Water temperature has a strong effect on critical swimming speed of nearly all fish tested. Often, there is a range of temperatures with relatively constant swimming speeds, with marked changes in swimming speed above and below that temperature range (Figures 4-13, 4-14). For largescale suckers, for instance, critical swimming speed was not significantly different between 10°C and 16°C, but from 10°C to 5°C there was a significant and dramatic decline in swimming performance (Kolok et al 1993). The Ucrit declined from near 50–55 cm/s (1.3–1.4 BL/s) at 10°C and 16°C to about 32 cm/s at 5°C (0.8 BL/s; about a 30% decline). Delta smelt Ucrit was unaffected by temperature in the 12–14°C range (Swanson et al. 1998). Effects of cold winter temperatures (5°C) were likely responsible for lower critical swimming speeds of rainbow trout, rosyside dace *Clinostomus funduloides*, mottled sculpin and longnose dace in winter compared to spring (10°C), summer (15°C), and fall (10°C)(Facey and Grossman 1990). Failure of some fish to swim at all in swim-speed tests was related to low temperatures in studies of juvenile Colorado squawfish *Ptychocheilus lucius* (Childs and Clarkson 1996). All fish appeared “less motivated” to swim at lower temperatures. Each species seems to have a characteristic pattern of responses to temperatures within its normal range of activity, even within a taxonomic Family, such as the Salmonidae (Figure 4-13).

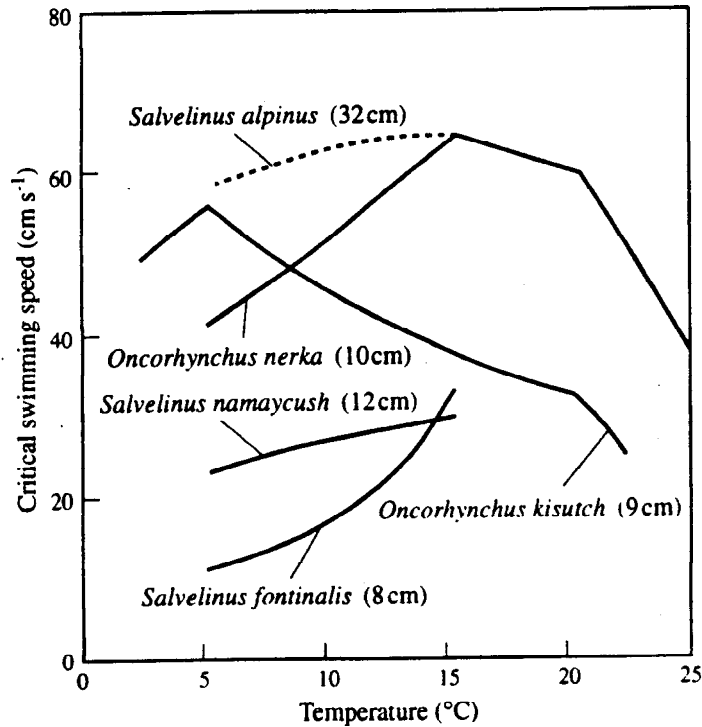


Figure 4-13
Critical swimming speeds of different species vary in relation to temperature, even within a taxonomic Family such as the Salmonidae. From Beamish (1980).

As for all temperature relationships, the swim-speed response is a combined function of test temperature and the prior holding (acclimation) temperature. The general features of acclimation were illustrated for lethal temperatures by Fry (1971). His conceptual view was used by Griffiths and Alderdice (1972) to illustrate critical swim speeds of coho salmon at different combinations of acclimation and test temperatures (Figure 4-14). Response-surface equations were also provided. The entirety of the relationships are too complex to tabulate in Table A-1, where results of only the same acclimation and test temperatures are shown.

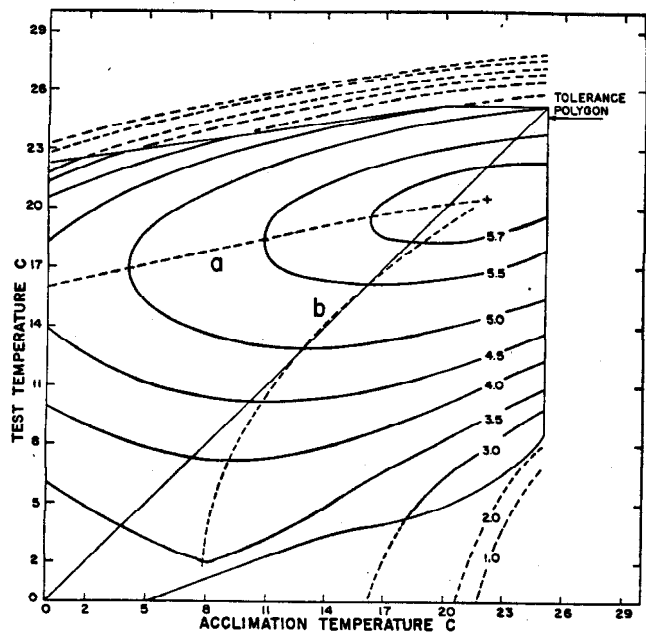
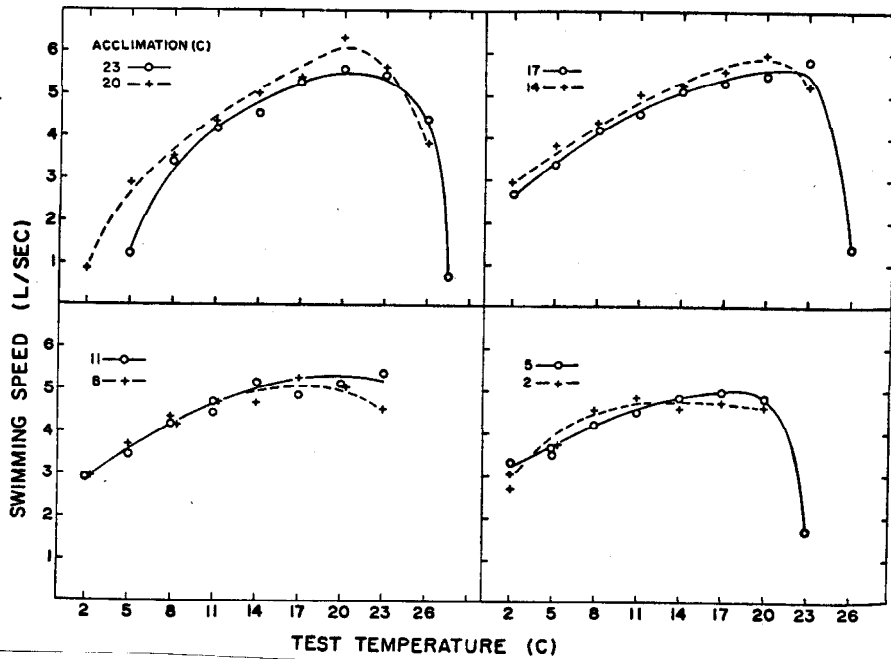


Figure 4-14

Critical swimming speeds are typically lower at low and high temperatures, regardless of temperature of acclimation (prior holding temperature). Combinations of acclimation and test temperatures for coho salmon yield isopleths of equal swimming speeds, which can be compared to the zone of thermal tolerance (temperature polygon) as defined by for this species by Brett (1952). Swimming speeds are shown in body lengths per second. From Griffiths and Alderdice (1972).

Critical swimming speeds at specific temperatures have been found to differ depending on the time of year fish were collected and tested (Brett 1964; King 1971; Webb 1971). Brett (1964) first observed that there was a difference in the critical swimming speed of sockeye salmon dependent on the time of year at which the measurements were made (at the same laboratory acclimation temperature). A similar difference was seen in rainbow trout by Webb (1971). Field-acclimated fish tested in the laboratory by (King 1971) at the temperatures of collection differed between spring and fall. King attributed this effect to an acclimation process in the field, in which fish acclimate more rapidly to warming temperatures (spring) than to cooling ones (autumn). This feature of acclimation rate in the laboratory was earlier identified by Brett (1956). It is also possible that this effect could occur simply because the assumed acclimation temperature (field collection temperature) would be higher (spring) or cooler (autumn) than the true acclimation temperature, which could lag the observed field temperature. This source of uncertainty would not appear in test fish acclimated for several days in the laboratory. Thus, the acclimation state is important for both tested fish and fish for which the information is to be applied in an assessment.

Rapid temperature changes cause a shift in swimming speeds that may exceed those attributable to changes in acclimation state. Rapid declines can cause a temporary “undershoot” in critical swimming speed, that is, an initial new swim speed capability that is temporarily less than the stabilized value exhibited after several days acclimation (Figure 4-15). The swimming ability stabilizes at a value somewhat higher than the temporary undershoot that is characteristic of the new acclimation temperature. This undershoot has been shown for yellow perch *Perca flavescens* (Otto and O’Hara Rice 1974) and juvenile largemouth bass (Kolok 1992b), each of which was tested for a change from 20°C acclimation to 10°C. The undershoot effect may explain why many impingement episodes occur shortly after cold weather fronts have passed in fall, winter and early spring (McLean et al. 1979).

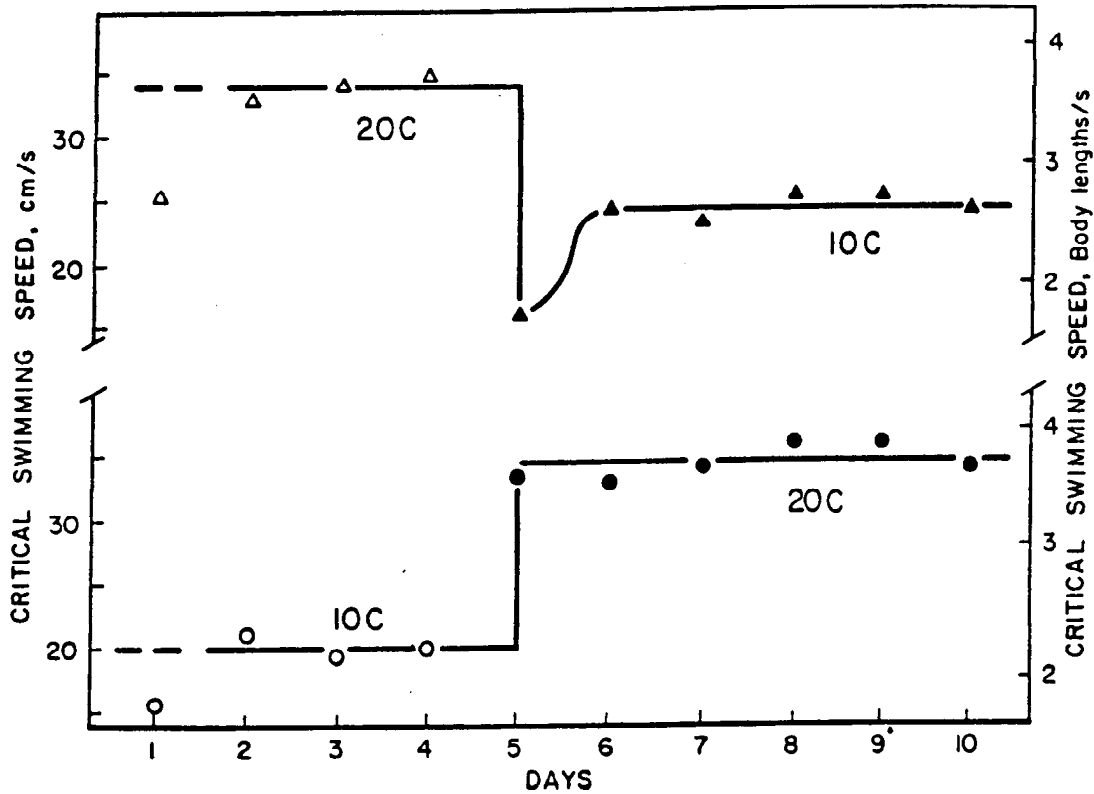


Figure 4-15
 Abrupt temperature change can change critical swimming speed. Especially, a drop in temperature induces a marked temporary reduction (undershoot in top curve). From Otto and O'Hara Rice 1974.

Thermal plume and warm-water recirculation effects of a heated effluent need to be considered in evaluating swim speeds of fish in relation to the plant's intake. Fish moving in the vicinity of a power station may encounter rapid temperature changes as they pass in and out of a thermal plume near the intake. The magnitude of temperature change depends on the size and temperature differential of the plume, the rapidity of plume mixing, and the movement trajectory of the fish. These rapid changes may cause temporary declines in critical swim speed. Also, the general warming of waters in the vicinity (e.g., by tidal mixing) may cause the acclimation temperature to differ from a more distant ambient temperature. Generally, however, the local temperature will be warmer than ambient, causing local fish to have a better swimming performance than those quickly passing through.

4.4.9 Seasonality Not Related to Temperature

Swim speeds can differ among seasons in ways that do not reflect just temperature effects. For example, smallmouth buffalo *Ictiobus bubalus* tested seasonally by Adams (1998) at field acclimatization temperatures exhibited minimum critical swim speeds in autumn at temperatures (16.6°C, SD 1.89) considerably above winter temperatures (10.0°C, SD 0.92). Fall fish also had the lowest single swim speed (6.73 cm/s) and the most non-performers (those fish that failed to

swim at all in the swim-speed apparatus) for the year. Fall swim speeds were significantly lower than in spring, even when tested at comparable temperatures. Reproductive stage seems to have been the cause of poor performance, for all smallmouth buffalo tested had gonads laden with eggs or sperm, except for one female (that swam 60% faster than other females).

Reproductive stage also was believed to be the cause of seasonal changes in swimming performance of pink salmon *Oncorhynchus gorbuscha* (Williams and Brett 1987). Critical swim speed declined with increased stage of maturation from initial upstream migration through the post-spawning period. This was probably a reflection of the quantity of energy reserves for the non-feeding life stage of this anadromous fish.

Endogenous seasonal changes in physiology or behavior may be responsible for seasonal changes in swimming performance in some cases. Sandström (1983) observed a winter decline in the maneuvering component of swimming performance of Eurasian perch *Perca fluviatilis*, which he proposed to be an endogenously related change in behavior leading to economical use of stored energy in winter.

4.4.10 Light

Orientation of fish in currents has long been known to be effected by the functioning of certain sense organs, which provide spatial context for a fish (Schiementz 1927; Dijkgraaf 1933, 1962; Pavlov 1966, 1970). These are the organs of vision, tactile sensation, and changing pressure (turbulence). Vision depends on both light intensity and the presence of relatively stationary reference points in the field of view. Light intensity varies by a million times in the course of 24 hours, and may be the most changeable environmental variable influencing the responses of fish to water flow.

Experiments by Russian scientists have shown a marked difference in swimming speeds of freshwater fish under illumination and in the dark, and they have identified thresholds of illumination below which fish show large declines in the velocities at which they can maintain position (Pavlov et al. 1972). They also identified sizes at which growing young fish developed an ability to maintain position in the dark. The critical velocity for the young of almost all teleost (bony) fish tested was found to be considerably less in darkness than in light (Figure 4-16a). It was only for the young of one of seven species tested (stone-loach *Nemachilus barbatulus*, an open-water, bottom fish) that alteration of illumination had practically no effect on the critical velocity. The threshold of illumination for marked loss of critical swim speed generally occurred near intensities of 0.01 lux but occurred at higher intensities for smaller fish (Figure 4-16b). Fish in early young stages were nearly incapable of resisting even a weak current in darkness (Figure 4-16c). The transition to having some orientation in the dark was associated with developmental changes in the visual apparatus (transition to use of rod cells in the retina) at lengths of 20-45 mm, depending on species (Pavlov 1966, 1970). It was also associated with development of the functions, including the lateral line (pressure). Position could be maintained at higher velocities when there were more fixed reference points in view (Pavlov et al. 1972; Figure 20d). Young sturgeons (sevruga *Acipenser stellatus* and Russian sturgeon *Acipenser guldenstadti*) showed no response to light intensity, and apparently rely entirely on tactile and pressure (turbulence) orientation as befits a bottom-hugging species.

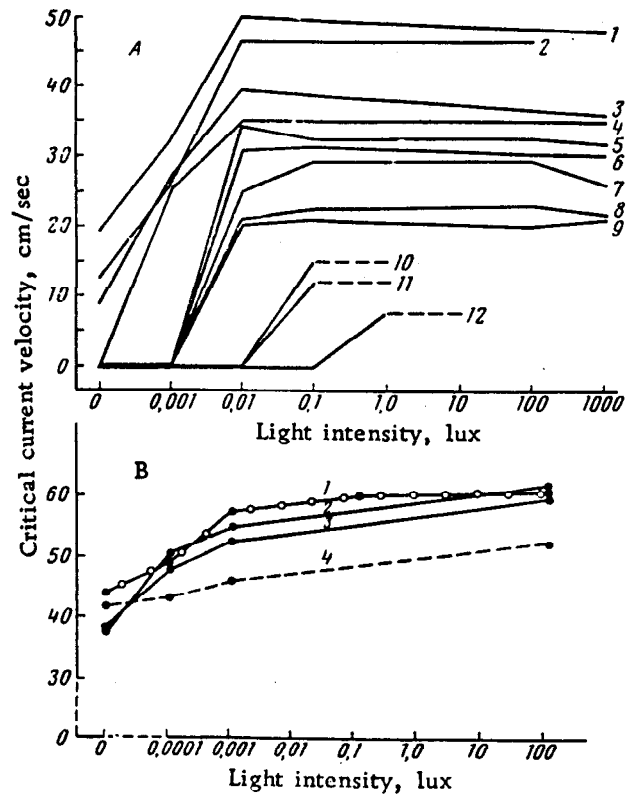


Figure 4-16
Low light intensity can reduce the critical swimming speed of fish. Data are shown for several size classes of Caspian roach (top, as lines without data points) and European perch (open circles, bottom), and rudd (solid circles, bottom). From Pavlov et al. (1972).

Loss of position-holding capability under low light conditions is described by Pavlov and colleagues as loss of critical swim speed, which is not quite the same as most usage of the term. A distinction needs to be made between physiological and behavioral modulation of swimming performance (i.e., fish may be physiologically capable of maintaining daytime critical swim speeds in the dark, but are behaviorally prevented from doing so because of lost visual orientation). The distinction would be between maximal and volitional performance. Perhaps a new set of terms is needed, such as “fundamental critical swimming speed” and “realized critical swimming speed” that is comparable to the “fundamental niche” and “realized niche” of habitat occupancy literature (Hutchinson 1957). Nonetheless, the Russian authors rightly stress the importance of light in modulating swimming behavior.

The Russians have applied knowledge of the relationships of critical swim speeds of fish to illumination to the use of light to protect fish against being entrained at water intakes (Pavlov 1970). The presence of light above threshold levels and provision of visual reference points allowed a 84–91% reduction in fish entrainment, whereas there was no more than 40% improvement with light alone. These results have not been consistently replicated in North America, however (N. Taft, Alden Research Laboratory, personal communication). North American studies of constant light as a repellent at intakes (e.g., see EPRI 1999) may have shown effects because of an increase in effective (realized) critical swimming speed and not because of a behavioral repulsion by the light source.

Consideration of light *per se* as a stimulus factor does not automatically include a related and potentially important factor, daytime versus nighttime behavioral differences. Many species exhibit substantially different behavior (including responsiveness to flow, distribution within their environment, etc.) during the night. Water withdrawal at an intake round the clock would interact with both daytime and nighttime behavior, responsiveness, and perhaps physiological capacity.

4.4.11 Photoperiod

Artificial (seasonally incorrect) photoperiods used in laboratory testing can alter the critical swim speed that is determined. Kolok (1991) found that a constant 12:12 hour photoperiod reduced the critical swim speed of juvenile largemouth bass in cold temperatures (5 and 10°C) but not at warmer temperatures (15 to 19°C) compared to that at the seasonally consistent photoperiod. This photoperiod effect may explain the inability of Beamish (1970) to get fish at a laboratory acclimation of 5°C to swim in his test apparatus (the photoperiod was 16:8 light-dark). Thus, experiments at cold temperatures need to be scrutinized for the photoperiod used in order to determine if the resulting critical swim speed estimates may be lower than for wild fish under seasonally correct photoperiods.

4.4.12 Schooling

Average critical swimming speeds of a group of fish may be higher than that of an individual. That is, schools may be able to tolerate higher velocities, as discussed earlier. This is reasonable on theoretical grounds because of the hydraulic protection one fish in a school can provide for another (Weihs 1975). It has been demonstrated experimentally, also. Schools of five roach *Rutilus rutilus* each had critical swimming speeds of about 4 cm/s higher than individual fish when tested over a range of turbulence intensities (Pavlov et al. 1983). Stahlberg and Peckmann (1987) showed a small increase in critical swimming speed of the verkhovka *Leucaspis delineatus* with schools of 20 fish but not of 4, when compared to tests on individuals. Chan et al. (1997) cite unpublished data by G. L. Boyd on golden shiner *Notemigonus crysoleucas* that shows mean critical swimming speeds to be higher for groups of 6 fish than for individuals. The potential alternative causes of lowered swimming ability from stress of isolation of individuals from the normal group environment and the lack of hydraulic assistance have not been isolated. The higher critical swimming speed of herring schools compared to solitary individuals observed by Domenici and Batty (1997) is interpreted to suggest that isolated individuals will experience longer latencies and slower responses in the face of circumstances requiring escape behavior. This latency is somewhat compensated for by the school by showing more appropriate directionality of the whole escape response. Schooling may be a factor in the responses of fish swimming abilities changing under different light conditions (noted above) because light levels can alter schooling behavior (Blaxter and Parrish 1965; Whitney 1969; Higgs and Fuiman 1996).

4.4.13 Turbulence

Turbulent flow has been shown to reduce critical swimming speeds of fish (Pavlov et al. 1983, 1994). In turbulent flow, the liquid particles move in irregular paths and at changing velocities, caused by eddies, vortices, upwellings, and the like, rather than in definite, smooth paths that

characterize laminar flow (Chaudhry 1993). Although truly laminar flows are rarely found in nature, the degrees of turbulence vary widely. Power station intake forebays have highly non-uniform velocities (Figure 4-17), probably a result of turbulence. When critical swimming speed is plotted against a standard measure of turbulence intensity (K = the standard deviation of the instantaneous flow velocity divided by the mean velocity), a distinct relationship is evident (Figure 4-18). Critical swimming speeds for the gudgeon at two length ranges dropped markedly as turbulence intensity rose from background levels to values of about 0.1. Thereafter, the reduction in critical swimming speed was less marked but still showed a decline with increasing K .

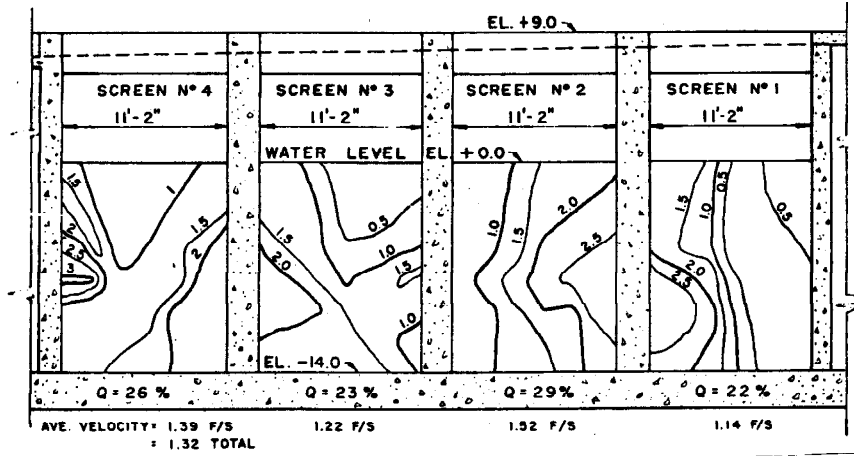


Figure 4-17
Velocities into intakes are not uniform. Figure shows velocity contours taken in front of four operating traveling screens of the Contra Costa Steam Plant, California (Kerr 1953).

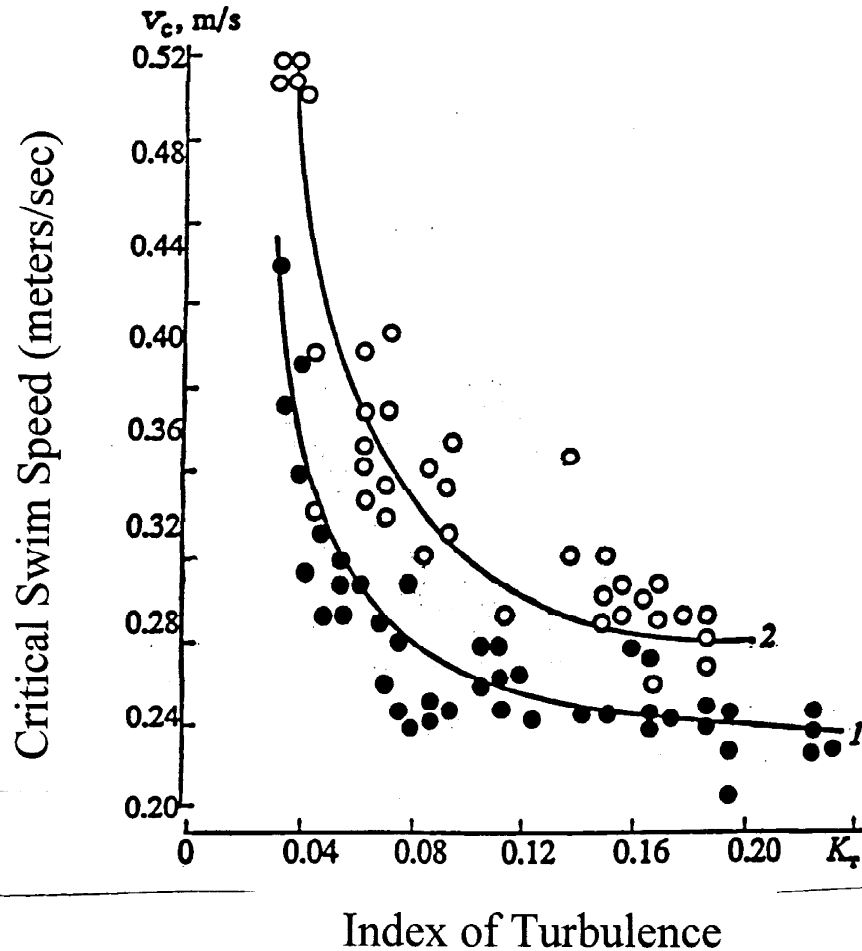


Figure 4-18

Turbulence in water reduces critical swimming speeds, as shown for two length categories of gudgeon. The index of turbulence is turbulence intensity, which is proportional to the standard deviation of instantaneous unidirectional velocities. From Pavlov et al. (1983).

The cause of this reduction probably lies in the added energetic costs of maintaining orientation of the body against a changing current pattern with greater pulses of velocity and pressure (Pavlov et al. 1983). This energetic difference seems closely related to the differences between spontaneous swimming costs for fish compared to forced swimming at constant speeds and directions in flumes (Webb 1991; Boisclair and Tang 1993; Tang et al. 2000). Brook trout *Salvelinus fontinalis* swimming spontaneously in rectangular tanks, which involved numerous turns and changes in swimming speed, showed an 8-fold average increase (range 3 to 22) in energy costs than predicted by forced-swimming models (Tang et al. 2000).

4.4.14 Disease

Although most testing has been done purposely with healthy fish, some diseased fish have been tested and have shown reduced swimming capabilities. Mature sockeye salmon that were

infected with opportunistic *Vibrio* and *Sporocytophagosis* infections as a result of capture and handling swam at critical velocities about 30% below those of healthy fish (Jain et al. 1998). Repeat performance of these fish after a brief rest period was markedly less than that for healthy fish (healthy fish performed essentially the same in the second test whereas diseased fish withstood critical velocities about 40% less than in their first test).

4.4.15 Toxicants

Toxic substances in water can reduce the swimming capabilities of fish. The list of examples is long, partly because the standardized critical swimming speed procedure has been adopted as an indicator of sublethal stresses in fish. Sublethal doses of the herbicides Diquat and Simazine in commercial formulations reduced swimming speeds and induced downstream drift of rainbow trout in test chambers (Dodson and Mayfield 1979). The herbicides also reduced the percentage of fish exhibiting normal rheotactic responses and increased the frequency of those not responding at all to water currents. Methyl parathion, an insecticide, decreased swimming performance of larval striped bass, Japanese medaka *Oryzias latipes*, and fathead minnows, probably associated with impaired muscular coordination (decreased acetylcholinesterase activity) (Heath et al. 1993a,b, 1997). Maximal critical swimming speeds were not achieved by coho salmon fingerlings in concentrations of bleached kraft mill effluent above a threshold concentration between 10-20% of the 96-hour LC50 (50% lethal concentration; Howard 1975). Reduction in performance was related to effluent concentration but not to exposure time after the initial 18 hours. Swimming performance returned to the levels of controls after 6-12 hours recovery. Exposure of mature sockeye salmon to between 0.12 and 0.77 mg/L of dehydroabietic acid (DHA) for 8–14 hours before swim tests reduced the initial Ucrit by about 10% and also reduced the ability of the fish to recover and perform in a second swim trial (Jain et al. 1998). Prior exposure to cyanide in sublethal concentrations markedly reduced the swimming performance of juvenile rainbow trout tested at acclimation temperatures of 6, 12, and 18°C in cyanide-free water (Kovacs and Leduc 1982). The effect was greater at lower temperatures. Pentachlorophenol also reduced swimming capabilities of cichlid *Cichlasoma bimaculatum* and coho salmon (Krueger et al. 1968). The pesticide Permethrin adversely affected the swimming speeds of rainbow trout in a manner that reflected its effects on basal metabolic rate (Kumaraguru and Beamish 1983). Methyl mercuric hydroxide at sublethal concentrations significantly reduced the swimming performance of roach *Leuciscus rutilus* in proportion to the mercury content of muscle tissue (Lindahl and Schwanbom 1971). Swimming endurance was reduced in young-of-the-year bluegill *Lepomis macrochirus* exposed to sub-lethal levels of hydrogen sulfide (Oseid and Smith 1972). Copper reduced the swimming performance of rainbow trout, particularly after 5 days of exposure (Waiwood and Beamish 1978). There was a fairly complex relationship among copper, pH, water hardness and duration of exposure, with greatest effect at low pH, low hardness, and high copper. The wood preservative, TCMTB, reduced swimming speed of coho salmon in a concentration-dependent manner, with a threshold between 8 and 10 micrograms per liter (McKinnon and Farrell 1992). Critical swimming speed was reduced from 11 to 25% over the concentration range of 10 to 20 micrograms per liter.

As a general principle, stress to a fish, whether toxic substances or other factors are the cause, seems to reduce swimming performance (Strange and Cech 1992). Stress is considered in the strict physiological sense, of inducing changes in plasma cortisol, glucose, and lactate concentrations in the bloodstream.

4.4.16 Acidity

Lowered pH (increased environmental acid) lowers critical swim speeds. Acute acid exposure of rainbow trout fingerlings had a marked detrimental effect on critical swim speed in studies by Graham and Wood (1981). Speeds were significantly depressed at all pH's below 4.4 in hard water and 4.6 in soft water (Figure 4-19). Over these ranges, speed varied in an approximately linear fashion with pH, declining about 4% per 0.1 pH unit. At the lowest pHs, swim speed was significantly greater in hard water than in soft water. Equations were developed for the relationships below pH 5:

$$\text{Hard water CSS} = 1.99 (+/- 0.16)\text{pH} - 3.90 (+/- 0.61)$$

$$\text{Soft water CSS} = 2.40 (+/- 0.10)\text{pH} - 5.59 (+/- 0.40)$$

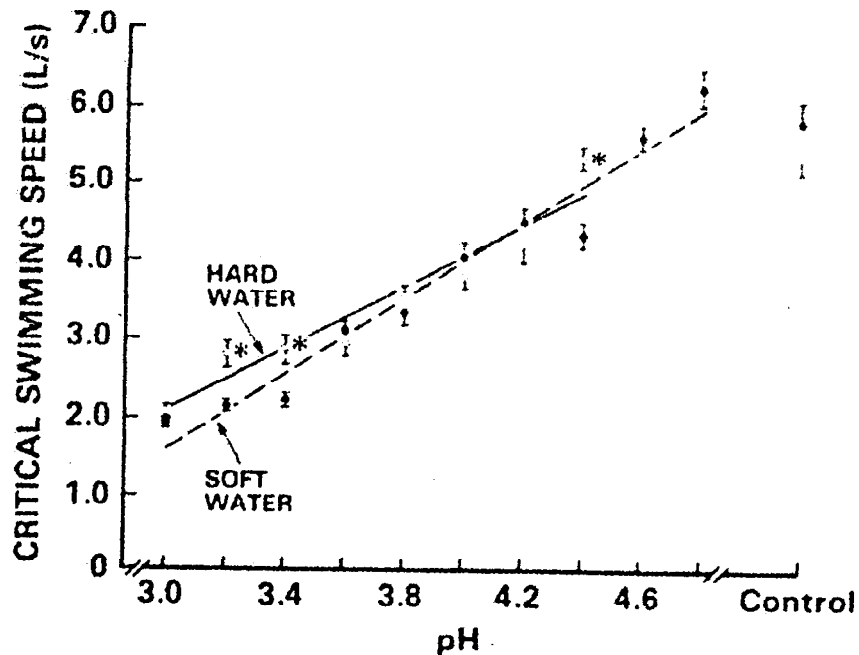


Figure 4-19
Low pH (high acidity) lowers critical swimming speeds, regardless of water hardness, as shown for juvenile rainbow trout. From Graham and Wood 1981.

Water of pH 4, 5, and 10 reduced the critical swimming speed of rainbow trout to 55, 67, and 61%, respectively, of that at neutral pH 7 (Ye and Randall 1991). A pH of 5.2 resulted in persistent impairment of critical swimming speed of rainbow trout by about 13% (Wilson and Wood 1992) and 10% (Wilson et al. 1994). In combination with sublethal aluminum (38 micrograms/L), the impairment was about 16% (Wilson et al. 1994) to 30% (Wilson and Wood 1992). These results seemed to be the result of physiological and structural changes in the gills, which affected oxygen supply (Wilson and Wood 1992). Heath (1987) concluded that critical swimming speed is especially sensitive to impairment of oxygen transfer across the gills.

4.5 Analysis of Tabulated Data on Critical Swimming Speeds

In this section we present our analyses of the data tabulated in Appendix A. Both general trends and some specific observations are relevant to the issue of using velocity as an indicator of adverse environmental impact of cooling water intake systems.

Critical swimming velocities (average or median responses) are highly dependent on length of the fish (as is recognized in the literature and discussed above), a feature that shows strongly when all data are plotted together (Figure 4-20). Most tested fish were under 20 cm long and exhibited critical swimming speeds (or close equivalent measure) in the 25 to 60 cm/s range. Some test results fell below 0.5 f/s (15.25 cm/s) and the NMFS criteria, but most were well above them. Although Brett (1964) recommended standardizing critical swimming speed tests to body lengths per second to eliminate the length-dependence effect in data presentations, body lengths per second are also length dependent (but negatively rather than positively). First failures are less consistently reported and vary widely, but they, too, are length dependent.

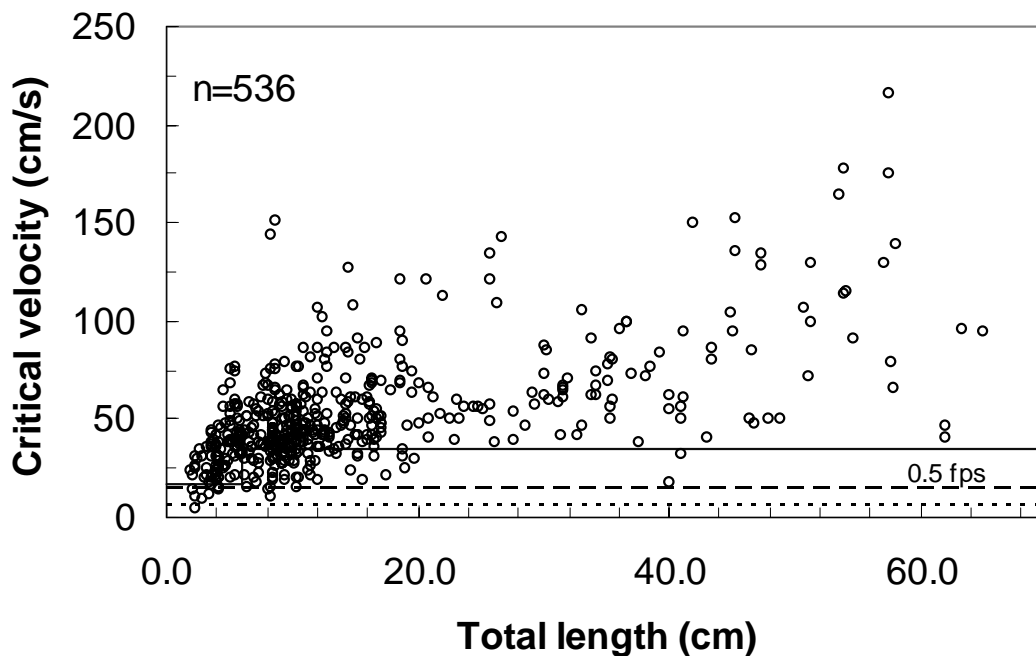


Figure 4-20

Critical swimming velocities are strongly related to fish length, as shown in this illustration of all critical swimming speed data in Table A-1. Dashed line is 15.25 cm/s (0.5 f/s), and other lines represent proposed EPA standard (dotted line) and NMFS criteria (solid line), both converted to straight-on velocities in front of screen as in Table 3-3.

When separated by taxonomic family, the overall pattern remained similar (Figures 4-21a-d). Results for Salmonidae reflect testing on two size groups: juveniles less than 20 cm long and adults larger than about 30 cm. The smallest centrarchids and clupeids tested fell at or somewhat below 0.5 f/s, whereas salmonids and cyprinids were all above 0.5 f/s. The salmonids, which are the target species for the NMFS criteria, showed several critical swimming speed data points that fell below the stepped criteria for sizes near 10 cm.

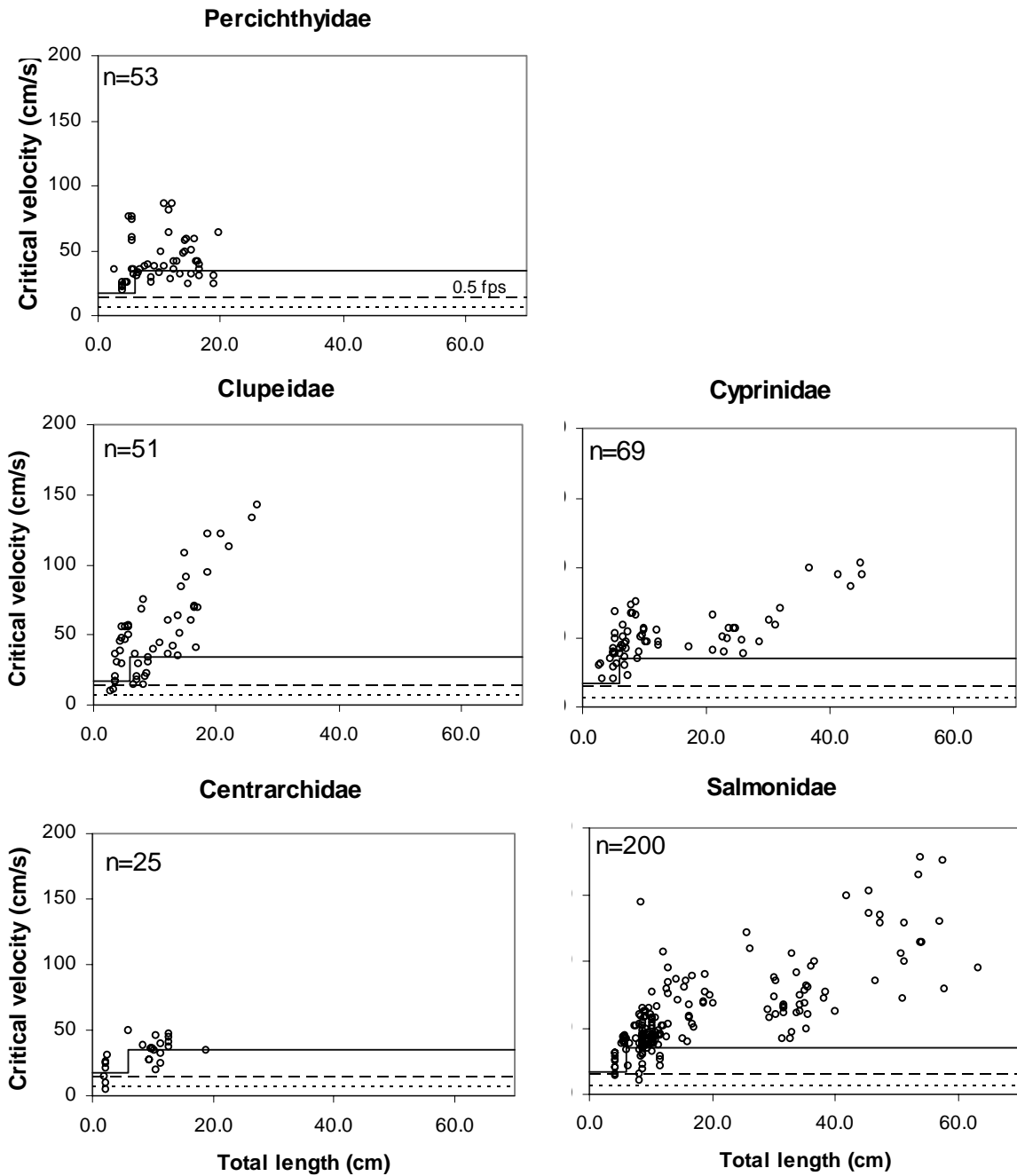


Figure 4-21
 The pattern of lower critical swimming speeds in smaller fish is similar regardless of taxonomic Family (Cyprinidae, Percichthyidae, Clupeidae, Salmonidae, Centrarchidae). Dashed line is 15.25 cm/s (0.5 f/s), and other lines represent proposed EPA standard (dotted line) and NMFS criteria (solid line), both converted to straight-on velocities in front of screen as in Table 3-3. Data from Table A-1.

When separated by assemblage, the pattern also remained similar to that for the data as a whole (Figure 4-22a–d). The Pacific assemblage reflected the data on salmonids that fell below the NMFS criteria. Lake and Atlantic assemblages showed the influence of very small fish on the overall picture.

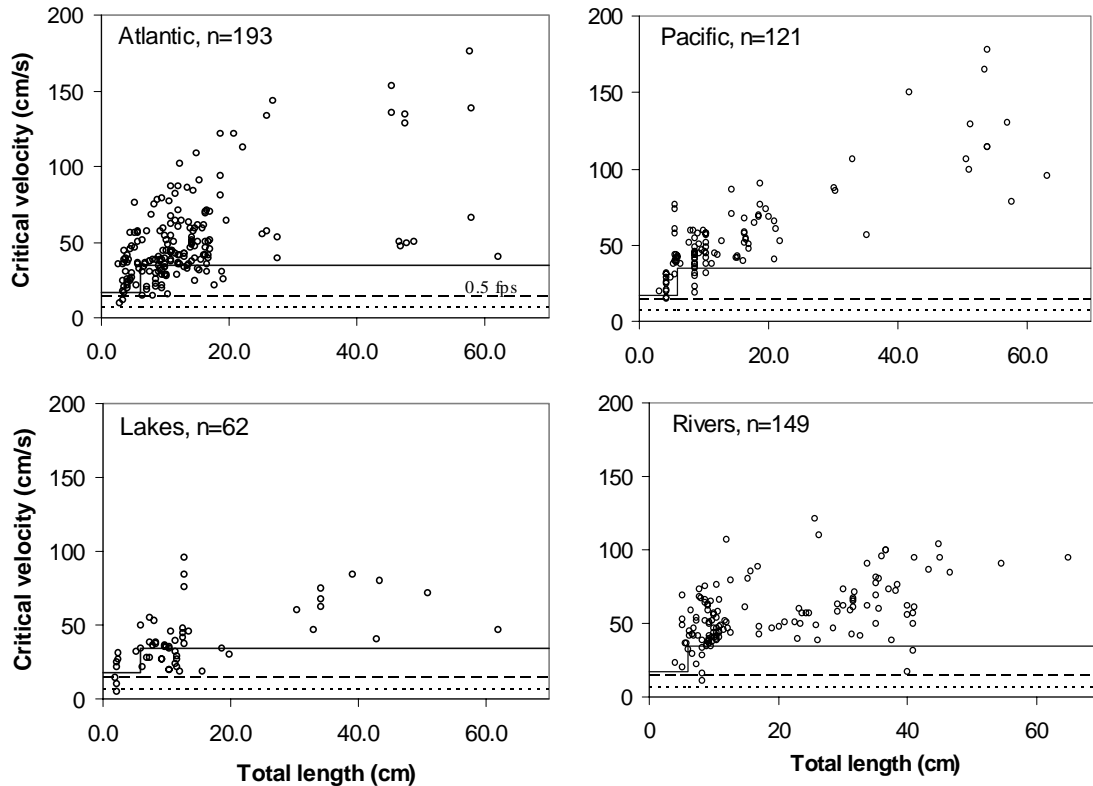


Figure 4-22
The pattern of lower critical swimming speeds in smaller fish is similar regardless of fish assemblage (a- Atlantic coast; b-Pacific coast; c- lakes; d- rivers). Dashed line is 15.25 cm/s (0.5 f/s), and other lines represent proposed EPA standard (dotted line) and NMFS criteria (solid line), both converted to straight-on velocities in front of screen as in Table 3-3. Data from Table A-1.

It is instructive to see which species and sizes have been shown to have average (or median) swim speeds less than or near EPA’s proposed criterion of 0.5 f/s. They are Atlantic estuarine species known to be impinged in large numbers at estuarine power stations (Ringger 2000): small bay anchovy *Anchoa mitchilli* near 3 cm long in summer, small Atlantic menhaden *Brevoortia tyrannus* near 3 cm long in summer, and Atlantic silverside *Menidia menidia* in winter. The group also includes smallmouth bass *Micropterus dolomieu* fry, juvenile coho

salmon, juvenile brook trout at cold temperatures (less than 15°C, 2–3°C, and 5–10°C, respectively), and Pacific lamprey *Lampetra tridentata*. A 0.5 f/s criterion based on average or median swim speed responses would not protect all members of this group, because it presumes that about half of the individuals would have lower critical swimming speeds than the reported average or median. The smallest fish tabulated (such as smallmouth bass fry) would probably not be impinged, but would pass through the screens and be entrained in the cooling-water flow.

If a 1 f/s (30.48 cm/s) criterion were to be selected, the available laboratory data would indicate that many other species would potentially be at risk. From the Atlantic assemblage, these include somewhat larger Atlantic menhaden (4.5 cm) and spot *Leiostomus xanthurus* about 4 cm in summer, striped mullet *Mugil cephalus* about 3 cm, and small white perch *Morone americana* in winter (2–7°C), striped bass, red hake *Urophycis chuss* and spotted hake *Urophycis regius* at cold temperatures, bluefish *Potamou saltatrix*, northern searobin *Prionotus carolinus*, striped cusk-eel *Rissola marginata*, rough *Membras martinica* and Atlantic silversides *Menidia menidia* in winter, and blueback herring *Alosa aestivalis* in winter. In the Pacific estuarine group, both splittail and delta smelt. Of the salmonids, juvenile coho salmon up to 13°C and lake trout *Salvelinus namaycush* about 11 cm long would be included. Stream species include longnose sucker, rosieside dace in winter (5°C), and mottled sculpin in winter and spring. Lake species would include small (6 cm) broad whitefish *Coregonus nasus*, small northern pike *Esox lucius*, juvenile largemouth bass in winter (5–11°C), yellow perch in winter (2–10°C), lake sturgeon *Acipenser fulvescens*, smallmouth buffalo *Ictiobus bubalus* in the fall, and fathead minnows. Clearly, a criterion of 1 f/s (30.48 cm/s) would be insufficiently protective just about everywhere if it were used as a screening criterion with these laboratory swimming speed data.

The correspondence between species commonly impinged and those for which critical swimming speed data are available is not particularly good (Table 4-1). Of the 40 fish species reported by utilities to the EPRI Intake Structure Database (EPRI 1995) as being impinged at 5 or more power plants, 19 (48%) have not had laboratory determinations of critical swimming speeds (or close equivalents). Three of the top 5 have not been studied, including the top two (gizzard shad *Dorosoma cepedianum* and freshwater drum *Aplodinotus grunniens*). Eight of the 15 species (53%) reported impinged at ten or more plants have not been studied. Inclusion of species in the EPRI database reflects the large number of power plants located on freshwater rivers, lakes, and reservoirs. In contrast, 9 of 12 species (75%) that were one of the five most abundantly impinged species at the Calvert Cliffs Nuclear Power Plant on Chesapeake Bay at some time in the years 1975–1995 (Ringger 2000) have critical swimming speed data in the literature. The availability of swimming speed data reflects academic interest in fish swimming physiology and behavior (for which common species such as rainbow trout, sockeye salmon, and largemouth bass were ready subjects), or concerns over swimming performance of migratory species such as salmon. Concerns over certain commercially or recreationally important freshwater species overshadowed interest in forage fish species such as gizzard shad, threadfin shad *Dorosoma petenense*, and freshwater drum, which are among those most often impinged. There is considerable swimming speed data on estuarine species at all trophic levels, however, such as striped bass, white perch, menhaden, bay anchovy, and striped mullet, which are of major concern at a few large estuarine power plants (e.g., Ringger 2000).

Table 4-1
Species occurrences at power plants for which impingement numbers were reported in EPRI's 1995 Intake Structure Database (ISDB) (five or more occurrences only) compared to the number of swimming speed studies in the literature.

Common Name	Number of Plants	Number of Studies
Gizzard Shad	71	0
Freshwater Drum	38	0
Alewife	32	1
Rainbow Smelt	29	0
Yellow Perch	27	2
Channel Catfish	21	1
Emerald Shiner	20	1
Bluegill	19	0
White Bass	16	0
Atlantic Menhaden	16	2
Black Crappie	14	0
Bay Anchovy	14	1
Trout Perch	13	0
Spottail Shiner	13	0
Winter Flounder	10	1
White Perch	9	1
Threadfin Shad	9	0
Carp	9	0
White Seaperch	8	1
White Croaker	8	1
White Crappie	8	1
Walleye Surfperch	8	1
Spot	8	2
Shiner Surfperch	8	0
Queenfish	8	0
Hogchoker	8	0
Blueback Herring	7	1
Black Bullhead	7	0
Atlantic Silverside	7	2
Atlantic Croaker	7	1
Smallmouth Bass	6	1
Pumpkinseed	6	1
Logperch	6	0
Brown Bullhead	6	1
White Sucker or Common Sucker	5	1
White Catfish	5	0
Striped Searobin	5	0
Slimy Sculpin	5	0
Rockbass	5	0
Northern Pike	5	1

EPRI is currently funding an update of the 1995 impingement database by Alden Research Laboratory, Inc. Collaboration with the Alden Laboratory in a continuation of this project will further reconcile the predictive information presented here with the retrospective information from actual power station operations.

Despite the spotty match between impinged species and available critical swimming speed data, the existing laboratory tests data have fairly well characterized many of the species at risk. This is especially true for the Atlantic estuarine assemblage. For example, bay anchovy, Atlantic menhaden, spot, and Atlantic silversides show up in laboratory tests as poor swimmers under certain environmental conditions and at certain sizes and also on lists of high impingement. The Pacific estuarine species, delta smelt and spottail, are likewise at risk. Thus, the age-old question of relevance of laboratory data to field situations may be put to rest. How well the exact numerical values for swimming speeds in the laboratory would match swimming performance in field situations, however, could use further study. We may expect too much if we want predictability within a few centimeters per second.

This tabulation of fish critical swimming speeds should have application to site-specific analyses as well as for consideration of a velocity value for screening purposes to identify sites likely to have a low potential for adverse impact. Each power station that needs to do a site-specific 316(b) analysis and demonstration for a NPDES permit under the Clean Water Act will have this table available as a resource to research the swimming capabilities of the fish species that occur at its site.

Limitations in the applicability of critical swimming speeds from laboratory testing need to be kept in mind, however. Critical swimming speed is one very useful tool for swimming performance assessment. However, it measures the aerobic swimming capacity of the fish under (almost always) relatively uniform, laminar flow conditions in a confined space. Critical swimming speed is not an adequate tool alone for assessment of fish behavior in artificial flow conditions near a water intake. It is not necessarily the best estimator of the velocity threshold for intakes from which a fish could escape. Hanson and Li (1978) noted instances in which fish were impinged at velocities substantially below their U_{crit} . Fish do not always respond to a current as we would expect by swimming into it and, in many habitats (e.g., turbid water or in nighttime conditions) they might not be able to respond visually to the intake screen until it was too late. Predictions of vulnerability to impingement based exclusively on how fast fish are physiologically capable of swimming ignore the possibility that fish may not be stimulated to swim. Such caveats as these reinforce our recognition of the need for more study of the behavior of fish in the field (Coutant 1999; Coutant and Whitney 2000) and an understanding of what is normal for both hydraulics and fish behavior in the vicinity of an intake (Coutant 2000).

4.6 Burst Swimming Speeds and Fast Starts

When a fish is drawn backward toward an intake screen while swimming steadily into the current at velocities greater than its critical swimming speed, it eventually touches the screen with its tail or otherwise senses the obstacle. Video monitoring of actual screens as well as observations in experimental flumes and tunnels (often as part of critical swim speed tests) indicates that most fish initiate a burst of swimming activity to quickly distance themselves from the screen. The burst of activity has been characterized by physiological researchers as occurring

in two general stages, an initial c-shaped flexing of the body and caudal fin with a rapid propulsive force as the body is straightened (1–2 sec.), and a sequence of rapid and forceful tail beats that propels the fish a considerable distance. A third phase is the variable transition to other swimming modes, and can be a continued acceleration (at a reduced rate), continued swimming at uniform speeds, or glides (Webb 1978). Through their burst swimming, fish can change direction quickly in a small area (Webb 1983). The escape trajectory is related to the angle of the stimulus, with most escapes being close to opposite the stimulus (Eaton and Emberley 1991; Figure 4-23). This trajectory can be important for guiding fish toward a fish bypass, as discussed below. This fast-start process has been discussed by Weihs and Webb (1983), Taylor and McPhail (1985), and Webb (1995). The burst of activity consumes large amounts of metabolic energy in the white muscles and cannot be continued very long (more than a few seconds). The fish must then revert to a more energy-conserving swimming rate. While some fish use bursts only occasionally, others regularly use an alternation of bursts and glides rather than steady swimming (Webb 1995). As might be expected, differences in body shape (lateral profile) and robustness influence burst swimming capabilities (Weihs 1973; Webb 1977; Taylor and McPhail 1985). Contact with the bottom affects fast-start performance in flatfishes (Webb 1981). The physiological limits to exhaustive exercise have recently been reviewed (Kieffer 2000).

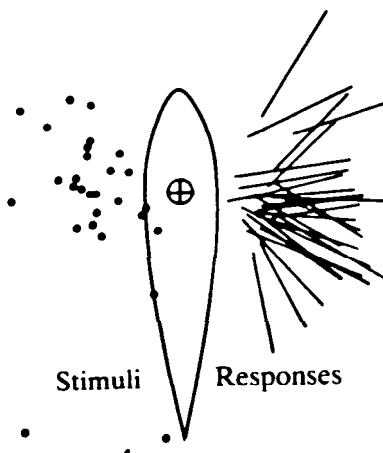


Figure 4-23
Escape trajectory in a fast-start response varies according to the angle of the stimulus (dots represent the location of the stimulus; lines represent the direction of escape). From Eaton and Emberley (1991).

Several quantitative aspects of the fast-start and burst swimming capabilities of fish would be relevant to velocity criteria at intakes and to intake design to prevent entrapment and impingement. For example, behavioral cues for burst swimming, if given at a distance from the cooling-water intake screens (such as at the entrance to an intake canal), could prevent fish from even coming near the site of potential impingement. Once at the intake screen, the propulsive force of the fast-start reaction would determine if a fish could dislodge itself from an actual or nearly impinged state caused by the water velocities immediately at the screen (either through-screen velocity or average velocity at the screen face considering the area blocked by screening material). The burst swimming speed and duration after the initial freeing from the screen would determine the distance a fish could travel to potential refuge from the velocities in the close

vicinity of the screen (Figure 2-1). For angled screens, the distance and direction of a fast-start, with or without a subsequent burst, would determine the distance a fish is swept along the screen toward a bypass (Figure 2-1e). Both the propulsive force and the distances swum in bursts would certainly vary with fish size, species, and temperature in much the same manner as does the critical swimming speed.

The available literature on fast-starts and burst swimming speeds is rich with concepts but poor on quantitative data. Research emphasis has concentrated on deciphering mechanisms of swimming (how the body moves in relation to water) and the energy physiology and biochemistry of various muscle types and other internal systems. There are too few data relevant to power station intake applications to warrant tabulation at this time. We did, however, accumulate numerous articles for future reference.

5

ADDITIONAL CONSIDERATIONS

5.1 Measures to Minimize Impingement and Related Injury and Mortality

By our earlier definition, once a fish passes the point-of-no-return, it will either become impinged on the screen or bypassed away from the facility (or both). A fish's ability to avoid impingement partially depends on whether it can swim against the current produced by the intake structure long enough to reach a point of safety. For an offshore intake placed in an open area of a lake, bay, or estuary, the point of safety would be described as that distance from the intake where velocities created by the intake do not exceed a swimming speed that can be sustained by the fish indefinitely. Burst swimming alone could be enough to prevent a fish from becoming impinged, but since burst swimming is of short duration, escape could only be attained when the point of no return is near the screen or when an escape route (e.g., a bypass) is a relatively short distance from the screen. It is better to rely on a fish's sustained swimming speed to carry it to safety. The intake velocity which matches the sustained swim speed occurs farther away from an offshore intake than does the velocity that matches the burst swim speed, so the margin of safety for a potentially entrapped fish is greater. In more enclosed systems (e.g., in many rivers and intake canals), bypass routes are incorporated into the intake screen design to provide fish safe passage around the screen and back to the river or other body of water.

Many design features that have been developed to minimize the rate and effects of impingement are discussed below. These measures were designed to reduce mortality and injury by (1) reducing impingement time, (2) reducing impingement "force" (i.e., through-screen velocity), and (3) minimizing screen abrasiveness.

Screen angle and position relative to flow direction—River and tidal flow both affect the susceptibility of fish to impingement on intake screens, and various designs have been developed to address this flow effect. The primary design consideration is the position of the screen relative to the direction of the flow. For example, an intake screen positioned in line with the river bank and parallel to the natural flow usually presents conditions that are more conducive to avoiding impingement.

The intent of angled barriers is that fish could more easily be directed or swept toward the bypass at the downstream end of the screen. It is a misconception that the parallel velocity component of flow describes a directional flow that could push a forward-facing fish toward the downstream end of the screen where bypasses are typically located (Fletcher 1985, Alden Research Laboratory 1981). The angled screen does, however, aid in the successful bypass of fish in other ways.

Fletcher (1985) concluded that the diversion efficiency of angled barrier screens seems to increase with steepness of pitch. However, he argued that angled screens only improve the conditions when fish are actually pressed against the screen, and provide no benefits otherwise. We believe that the forces experienced by fish once impinged are as presented in Figure 2-2c. The force V_1 presses the fish against the screen, and V_2 moves the fish along the face of the screen, but only if V_2 is greater than f , the friction between the fish and the screen. As the angle of the screen becomes more steep (i.e., θ gets smaller), V_2 becomes greater making it more easy to overcome f which remains the same, thereby sliding the fish more easily along the face of the screen.

Bates and Visonhaler (1956) describe the behavior of fish at a facility fitted with an angled array of louvers designed to direct fish toward a downstream bypass. As the fish were drawn near the louvers, they positioned themselves one to three feet in front of them in an orientation perpendicular to the line of louvers. This caused the fish to be at an angle to the flow, from which orientation they were apparently affected by the parallel-to-the-screen velocity component and swept along the louvers to the bypass. In this instance, the sweeping component is experienced only if the fish provides the force to keep it away from the screen at an angled orientation. The fish is influenced by the force associated with V_2 (see Figure 2-2c), not by water that is actually flowing parallel to the screen. If a fish darts away from the screen and then quits swimming it will drift straight back to the screen in line with the general direction of the flow.

Distance to bypass—Fletcher (1985) states that any effectiveness in bypassing fish derived by angling the screen likely decreases as the screen gets larger, because this often results in a longer distance that the fish must travel to the bypass. Where bypasses are included to provide passage for fish around the intake, it is important that the distance that a fish must travel along a screen to reach the bypass not be so long that a fish becomes fatigued and then impinged on the screen without enough energy to escape. Likewise, if a fish becomes impinged and is slid across the screen to the bypass, the longer the fish is in contact with the screen, the greater the likelihood of being injured or killed. Multiple bypasses may be necessary to quickly and safely move fish away from the intake screen depending on the length and angle of the screen, the approach velocity, and the swimming ability of the species present.

5.2 High Velocity Technologies

Even though criteria for intake velocities (if they exist at all) often restrict velocities to less than 1 f/s, there are continuing efforts to design intake systems that are equally protective of fish at higher velocities. Studies on the success of high flow intake screens and bypass systems (e.g., Eicher screens and modular inclined screens) with approach velocities up to 10 f/s have been conducted on both small-scale and large-scale intake designs in the laboratory and at hydroelectric dams (EPRI 1994, 1996). R2 Resource Consultants (1997a, 1997c, 1997d) provide a thorough review of these studies. These systems have been developed not so much to minimize impingement, but to maximize the successful passage of healthy, viable fish around the intake regardless of whether they contact the screen or not. These studies show that the development of screens that can successfully pass healthy fish with relatively high approach velocities is a potentially achievable goal. They also indicate that drawing fish toward a screen via high approach velocities does not necessarily have to be a bad thing. Our summary of these studies is separated into small-scale laboratory studies and large-scale field trials.

5.2.1 Laboratory Studies

Before new screen designs are tested in the field, small-scale laboratory studies are often conducted to perfect the design. Wert et al. (1987) evaluated passage of juvenile salmon at an angled screen bypass system at velocities of 6 f/s. Chinook salmon, coho salmon, and steelhead trout were passed around the screen with no scale loss or delayed mortality. The smaller fish (chinook) of those tested were swept through the bypass more quickly. This study also included an evaluation of impingement rates of rainbow trout at several velocities from 3–10 f/s. The authors found that the highest impingement occurred at <4 f/s; faster velocities swept the fish from the screen into the bypass.

A study of an experimental modular inclined screen system was performed to evaluate the effects of velocities from 2 to 10 f/s on the passage of 10 species (EPRI 1994). The screen was angled vertically at 15 degrees and operated at flows from 16 to 80 cfs. Passage efficiency declined with increasing velocity, but exceeded 95% for most tests up to 10 f/s. The lowest passage efficiency (about 90%) occurred with alosid species. Most injuries were observed at the highest velocities, 8 to 10 f/s. The largest fish tested, Atlantic salmon (170 mm), had an injury rate of 4% and a survival rate after passage of 100%.

5.2.2 Field Studies

A number of field trials have been performed in recent years on a variety of screen systems designed to operate under velocities higher than 1 f/s. Several of those studies are summarized below.

Bomford and Lirette (1991) evaluated the passage efficiency of an operating screen in a hydroelectric canal. The screen was angled downward at a 6.5 degree angle and was evaluated at approach velocities of 0.66–1.31 f/s and flows of 1500 cfs. Juvenile salmon were passed at 80% efficiency.

Matthews and Taylor (1994) and Smith (1997) report on the effectiveness of an Eicher penstock screen and bypass system designed to pass juvenile salmon at the Puntledge River hydroelectric plant. Tests were performed at velocities of 6 f/s with a screen angled at 16.5 degrees and 58% porosity. Depending on the species being monitored, passage efficiency ranged from 96 to 100%. The new screen system resulted in a drop in mortality from near 60% prior to the new system to less than 5%.

Winchell et al. (1993) evaluated salmon passage and survival at an intake system with Eicher screens and approach velocities of 4 to 7.8 f/s. Passage efficiency for steelhead, coho salmon, and chinook salmon fry and smolts ranged from 96 to 99%. Four-day survival rates ranged from 91 to 98%. Descaling increased with velocity, and mortality was common for chinook and steelhead with even minor descaling. Mortality rates ranged from 1 to 5% for fish with an average length of 44 to 52 mm, but were less than 1% for those greater than 73 mm.

Cramer (1997) reports on the evaluation of a combination of a louver guidance system and an Eicher screen bypass system at a hydroelectric facility. Flow through the unit with the experimental screen was about 400 cfs with an approach velocity of 6 f/s. The screen angled at

19 degrees provided 82–92% bypass efficiency for juvenile chinook salmon and steelhead. The average occurrence of injury and descaling of those individuals passed was 0.44% and 1.8%, respectively.

Field testing of the modular inclined screen (MIS) system (vertically angled at 15 degrees) was summarized in EPRI (1996) and Taft et al. (1997). Passage efficiency and fish survival were tested at velocities of 2 to 7.5 f/s. A greater than 99% passage efficiency and survival was observed for rainbow trout and golden shiners at all velocities. The survival rates of alosid species varied depending on velocity and ranged from 95% at 2 f/s to 27% at 6 f/s. Individuals of this species were reportedly in poor condition when tested; therefore, these results may understate the potential effectiveness of the MIS with alosid species.

Although these studies of high velocity screens show a great deal of promise, there are still several concerns that need to be addressed, including minimizing descaling of salmon smolts and decreasing the added negative effects of debris accumulation on injury and descaling. Studies to date have been performed on a relatively narrow size range and limited test conditions. EPRI is currently testing angled bar racks and louvers for hydroelectric applications that may have application for CWIS. Final results are expected in 2001.

6

ALTERNATIVE MEASURES FOR PREDICTING IMPINGEMENT RATES

Reliance on a single criterion, i.e., approach velocity measured near or at the face of a fish screen, may be of limited value for predicting whether a fish is likely to get impinged. Although approach velocity has a major, perhaps primary, influence on impingement, there are many other contributing factors related both to characteristics of the fish community and the intake design.

One of the design-related factors is the extent and magnitude of the velocity field around the intake. Whether a fish can escape from being impinged once it reaches a screen depends not only on what magnitude of approach velocities it must counteract but also for what length of time/distance it must swim before eventually reaching a place outside of the influence of the intake. The amount of swimming (velocity and duration) necessary to move a fish from the front of the screen to a point outside of the intake's influence can be estimated. A comparison of this measure to the sustained swimming ability of various sizes and species of potentially impinged fish could conceivably be used to more accurately predict the risk of impingement for a given CWIS. Such an analysis would also have to include consideration of the motivation of the affected fish. Fish that are attempting to migrate through the area of the intake may not be inclined to turn around and swim away from the intake once attraction flows are detected since their motivation is in the direction of the intake. These fish would likely be more susceptible to impingement than resident non-migratory fish of similar swimming ability.

Similarly, if the intake is fitted with a bypass, the amount of swimming required to reach the bypass could also be used to estimate the likelihood of impingement. Such a consideration is already included in the NMFS criteria as it pertains to the distance to the bypass and the number of bypass entrances required.

For a CWIS without a fish bypass or a fish-handling system (e.g., a Ristroph screen), the numbers of impinged fish can generally be equated to the number of fish killed by impingement. For intakes with fish bypass systems, however, it is also important to evaluate the injury and mortality associated with bypass. A fish that is briefly impinged by greater-than-optimal approach velocities may nonetheless be swept to a bypass and safely returned to the water body. On the other hand, there may be mortality associated with bypassing the fish, and this mortality may be latent, resulting from disease or increased susceptibility to predators. The important point to bear in mind is that for CWIS with effective fish bypass systems at the screens, approach velocities in excess of 0.5 f/s may not result in high impingement mortalities.

Along with a minimum approach velocity, EPA is also proposing another criterion—the ratio of the intake capacity (i.e., flow or volume) relative to that of the affected water body (65 FR 49060; August 10, 2000). The proposed criterion varies based on the type of water body, and is

included apparently to address potential population-level effects. Although it was not the purpose of this report to evaluate the appropriateness of using an index of intake capacity as a criterion to minimize impingement, our initial impression is that a simple criterion like this has limited utility. Similar to approach velocity, the volume of water diverted from a water body is only one factor in the potential impact of water withdrawal on a fish population or community.

Ultimately, the impact of impingement should be evaluated from a population or community perspective. Although an index of intake capacity may work for some facilities, we expect that a more detailed site-specific analysis (perhaps including a population model) is necessary to better assess the potential for population- and community-level effects. Just as difficult as determining what analyses should be performed to determine population- or community-level effects, is determining what would be considered a population- or community-level effect. For risk assessment purposes, Suter (1993) has established a 20% reduction in population as one that is measurable and potentially important. From a community perspective, a significant effect might be a change in fish abundance that upsets the community structure and function, which itself is not easily defined.

7

CONCLUSIONS AND RECOMMENDATIONS

In this section, we address (and make recommendations about) the questions posed by EPRI staff at the initiation of the project:

- Is approach velocity an appropriate parameter for determining the potential for impingement impact?
- Assuming approach velocity is technically supportable, what are the approaches and methods that can be universally applied to CWIS for its proper measurement?
- Is a single value appropriate and, if so, is 0.5 f/s a technically supportable criterion or is another criterion technically supportable?

7.1 Is approach velocity an appropriate parameter for determining the potential for impingement impact?

Water velocity is important to fish impingement at intakes. There is a substantial literature of laboratory and field data that points to increased impingement with increased intake velocities. Velocities in some intake areas can exceed the swimming capabilities of fish, as these capabilities have been determined in standardized laboratory devices and protocols. The relevance of laboratory data has been questioned, but appears to be upheld, at least in broad terms. For example, there appears to be a positive correlation between fish that have low swimming abilities in laboratory tests (e.g., small bay anchovy, small Atlantic menhaden, Atlantic silverside, delta smelt), or fish performing at cold temperatures (e.g., juvenile salmon and trout, white perch, Atlantic menhaden, striped mullet), with the incidence of impingement at power station intakes. The corollary is also generally true that species and life stages with high swimming performance capabilities in laboratory tests are less often impinged, although this depends on various features of organism and environmental health to be discussed below. Joint analysis of power station data (retrospective) and laboratory data (predictive) is planned in conjunction with Alden Research Laboratory, which is analyzing the power station impingement data. These results are expected to be available in 2001.

If emphasis is placed on *approach* velocity, then a more thorough consideration of the various measurements of velocity at an intake is needed. One must specify which of several alternative measures is used, as discussed below.

For the majority of fish for which data are available, impingement probably depends on conditions of organism and environmental health as much as on water velocity alone. Thus, data showing high swimming performance of healthy fish in tabulations such as Table A-1 are no guarantee of low impingement rates under naturally variable and anthropogenically impacted

conditions where these species occur. For example, winter cold torpor (a numbed state of poor responsiveness and poor swimming capability) likely causes many impingement episodes. This phenomenon has been well documented for threadfin shad in southeastern reservoirs used for power station cooling (McLean et al. 1979). Similarly, especially high temperatures or rapid temperature changes can cause some fish to become debilitated and exhibit lower swimming speeds. Low dissolved oxygen, toxicants, low pH, and other water quality problems can debilitate fish and lower their ability to swim and avoid intakes, as was discussed above. The availability of light for visual orientation and direction of swimming behavior is especially important. A fish may be physiologically capable of attaining a swimming performance sufficient to avoid impingement but may be behaviorally unable to do so because of inability to see landmarks to aid its orientation. Therefore, regulation of velocity is only one, albeit important, factor in reducing potential impingement. Careful attention to fish and ecosystem health will make the use of velocity as a regulatory tool more predictable and reliable. How sufficient a velocity guideline can be for limiting impingement will depend on the site-specific characteristics of the waterbody and its fish populations. *We therefore recommend that intake velocity be an important, but not sole, consideration in regulating CWIS. Careful consideration must be given to the exact measure of velocity, because “approach” can be ambiguous.*

7.2 Assuming approach velocity is technically supportable, what are the approaches and methods that can be universally applied to CWIS for its proper measurement?

The precise definition of “approach velocity” can make a difference to the answer to the first question. Velocity can be measured at different locations in the vicinity of an intake screen. These locations include within the holes in the screen, immediately in front of the screen where passage through the holes and blockage by the mesh are averaged, further from the screen where blockage by larger structural members of the screen are also averaged with the through-screen velocity, or even further away, where the geometry of the intake forebay creates vortices and other forms of turbulence that yield a different averaged velocity. All locations might be considered under the broad term “approach velocity.” We have explained the differences in section 3 above. When angled screens are considered, the theoretical directional vectors further confuse the term “approach velocity.” The location and directional vectors that are selected for the regulatory criteria should be specified carefully, because ambiguity can render a measured velocity parameter either appropriate or inappropriate for meeting the criterion. Also, the value measured needs to be relevant to intake hydraulics and behavior of the fish in intakes as they are approaching impingement, potentially being impinged, and seeking to escape.

Ideally, the full range of velocities in the flow field from source water to intake screen pores would be known and these changing velocities could be related to the behavior of fish of different sizes and swimming capabilities expected at a site. It is unlikely that a universally applied measurement location will fit all circumstances of intake design, resulting velocity fields, and fish susceptibility. Nonetheless, the zone close to the screen is generally the most important for a fish seeking to avoid contact with the screen with either prolonged swimming or bursts of activity.

Directionality is also important. For angled screens, there are measurement options related to the screen angle and potential or realized velocity vectors, as discussed above. It seems to us,

however, that the important vector is the one parallel with the main water flow. Features like sweeping velocity seem more theoretical than real when nearly all of the water is passing through the screens.

Consideration of the design and operation of the intake facility and screens is crucial for arriving at an appropriate site-specific approach velocity. Recent developments in screen design suggest that being able to minimize impingement and efficiently bypass healthy fish around a screen at relatively high velocities (perhaps up to 10 f/s) may be an achievable goal.

We recommend that the most appropriate single velocity would be measured parallel to the main water movement in the intake forebay and in the zone between about 3 inches (7.5 cm) and 1 foot (30 cm) from the screen face, to consist of the velocity prior to divergence of flows past structural members of the screen. Site-specific analyses (Tiers 2 and 3) should measure or provide adequate reference citations to the entire velocity field from source water body to the holes in the screen mesh.

7.3 Is a single value appropriate and, if so, is 0.5 f/s a technically supportable criterion or is another criterion technically supportable?

A single velocity value is not an adequate representation of all of the factors that influence impingement of fish, as discussed above. For well-founded regulation of an intake, a site-specific analysis is essential. It is possible, however, to use a single velocity value (taken in the most appropriate location and manner) as an indicator of the likely low occurrence of impingement problems (the apparent intent of EPA's proposed Tier 1). Based on laboratory data, one would predict that a single value near 0.5 f/s (15.25 cm/s) would preclude most impingement of healthy fish large enough to be unable to pass through the screens, with certain (and important) exceptions noted above and thus make further detailed analyses unnecessary. This criterion for separating intakes of low potential impact may have little practical value for existing power stations, however, for few existing intakes currently have velocities this low. If the low-impact, screening criterion were to be raised to 1.0 f/s (30.48 cm/s) then the numbers of fish species and sizes potentially exceeding laboratory-derived critical swim speeds increases greatly. However, these susceptible species/sizes do not occur everywhere, and a higher criterion may be acceptable in certain regions, such as where only larger salmonids occur.

There is good reason to want some value for intake velocity that would indicate a low potential for detrimental impacts from impingement. Site-specific analysis entails considerable investment in both site evaluation and basic swimming/impingement studies for many species, often ones not yet studied. The spectrum of species to be considered keeps growing, and established swimming performance criteria based on juvenile salmonids and clupeids may no longer be adequate for any single site. With a fully site-specific approach, there is a possibility that maximum approach velocities for certain times of the year may be determined to be less than 0.5 f/s (e.g., when very small, weakly swimming fishes or unusual environmental conditions dictate). Advocates for this approach should be willing to accept this outcome. It is clear that adopting only a site-specific approach could require considerable research effort, commitment by industry, and patience by management agencies.

We recommend that the value of 0.5 f/s be accepted as a national *screening* value for the regulatory purposes of suggesting low potential adverse environmental impact, that is, a value below which an intake would not be subjected to as much detailed scrutiny for a CWA permit, unless the presence of especially vulnerable species or life stages or subsequent operational monitoring indicates particular problems. These potential problems must be looked for early in the assessment process (e.g., presence of weakly swimming threatened or endangered species should be known) and would then be handled on a site-specific basis. A higher single regulatory value may suffice for certain regions, water body types, or seasons where and when susceptible species/sizes do not occur.

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A

TABLE OF CRITICAL SWIMMING SPEEDS FOR FISH

Table A-1
Summary of experiments on the critical swimming speeds of a various fishes

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
1	<i>Acipenser transmontanus</i>	white sturgeon	Acipenseridae	P	tunnel; Ucrit	14	35.2	5	56.8	1.7 SD	1.65	12	Counihan and Frost 1999
2	<i>Alosa pseudoharengus</i>	alewife	Clupeidae	A	tunnel; Ucrit	2	13.7	7.6	35.7	5.2 SD	2.7	29	King 1971b
3	<i>Ameiurus nebulosus</i>	brown bullhead	Ictaluridae	L	flume; Ucrit	few	5.2	3.1	32		6.2	17	Fricke et al. 1987
4	<i>Anchoa mitchelli</i>	bay anchovy	Clupeidae	A	open flume; maximum speed	6	3.3	gradual increase	11.9	0.21 SD	3.7	23 to 25	King 1971b
5	<i>Anchoa mitchelli</i>	bay anchovy	Clupeidae	A	open flume; maximum speed	45	2.8	gradual increase	10	6.7 SD	3.8	26 to 27	King 1971b
6	<i>Anchoa mitchelli</i>	bay anchovy	Clupeidae	A	open flume; maximum speed	39	3.4	gradual increase	17.7	3.7 SD	5.4	26 to 27	King 1971b
7	<i>Anguilla anguilla</i>	European eel	Anguillidae	A	flume; Ucrit	few	57.9	3.1	139		2.4	17	Fricke et al. 1987
8	<i>Barbus schwanenfeldi</i>	?	Cyprinidae	O	flume; Ucrit	few	14.4	3.1	127		8.8	22	Fricke et al. 1987
9	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	open flume; maximum speed	58	4.6	gradual increase	29.9	6.4 SD	6.6	25 to 28	King 1971b
10	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	circular flume; median failure	195	3.6	gradual increase	17	12 to 26	4.9	12 to 14	Hettler 1977
11	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	circular flume; median	70	3.6	gradual increase	21	14 to 28	6	16.5 to 18	

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
12	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	failure; circular flume; median failure	215	5.2	gradual increase	47	32.5 to 61.5	9.4	24 to 26.5	
13	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	circular flume; median failure	155	5.2	gradual increase	56	48.5 to 66.5	11.2	30 to 35	Hettler 1977
14	<i>Caranx hippos</i>	crevalle jack	Carangidae	A	open flume; maximum speed	5	3.9	gradual increase	41.8	2.7 SD	11	27	King 1971b
15	<i>Carnegiella strigata</i>	Marbled hatchetfish	Gasteropelecidae	O	flume; Ucrit	few	3.2	3.1	22		6.9	22	Fricke et al. 1987
16	<i>Catostomus catostomus</i>	longnose sucker	Catostomidae	RE	tunnel; Ucrit	169		10				7 to 19	Jones et al. 1974
17	<i>Catostomus catostomus</i>	longnose sucker	Catostomidae	RE	tunnel; Ucrit	1	4.0	10	23		5.8	7 to 19	Jones et al. 1974
18	<i>Catostomus catostomus</i>	longnose sucker	Catostomidae	RE	tunnel; Ucrit	1	54.6	10	91		1.7	7 to 19	Jones et al. 1974
19	<i>Catostomus commersoni</i>	white sucker	Catostomidae	RE	tunnel; Ucrit	20		10				12 to 19	Jones et al. 1974
20	<i>Catostomus commersoni</i>	white sucker	Catostomidae	RE	tunnel; Ucrit		17.0	10	48		2.8	12 to 19	Jones et al. 1974
21	<i>Catostomus commersoni</i>	white sucker	Catostomidae	RE	tunnel; Ucrit		37.0	10	73		2	12 to 19	Jones et al. 1974
22	<i>Catostomus macrocheilus</i>	largescale sucker	Catostomidae	RE	tunnel; Ucrit	6	40.9	5	32	3 SE	0.81	5	Kolok et al. 1993
23	<i>Catostomus macrocheilus</i>	largescale sucker	Catostomidae	RE	tunnel; Ucrit	6	40.9	5	50.5	3.5 SE	1.27	10	Kolok et al. 1993

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments (cm/s)	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
24	<i>Catostomus macrocheilus</i>	largescale sucker	Catostomidae	RE	tunnel; Ucrit	6	40.9	5	57	1.6 SE	1.44	16	Kolok et al. 1993
25	<i>Catostomus occidentalis</i>	Sacramento sucker	Catostomidae	RW	tunnel; Ucrit	7	19.1	10	47	0.05 SE	2.46	10	Myrick and Cech 2000
26	<i>Catostomus occidentalis</i>	Sacramento sucker	Catostomidae	RW	tunnel; Ucrit	8	20.0	10	48	0.06 SE	2.4	15	Myrick and Cech 2000
27	<i>Catostomus occidentalis</i>	Sacramento sucker	Catostomidae	RW	tunnel; Ucrit	8	20.9	10	51	0.05 SE	2.44	20	Myrick and Cech 2000
28	<i>Clinostomus funduloides</i>	rosyside dace	Cyprinidae	RE	tunnel; Ucrit	10	6.9	10	47.3	12.6 SD	7.5	10	Facey and Grossman 1990
29	<i>Clinostomus funduloides</i>	rosyside dace	Cyprinidae	RE	tunnel; Ucrit	10	7.4	10	54.3	16.1 SD	8.1	15	Facey and Grossman 1990
30	<i>Clinostomus funduloides</i>	rosyside dace	Cyprinidae	RE	tunnel; Ucrit	10	6.9	10	42.2	12.6 SD	6.7	10	Facey and Grossman 1990
31	<i>Clinostomus funduloides</i>	rosyside dace	Cyprinidae	RE	tunnel; Ucrit	10	7.4	10	22.8	11.4 SD	3.4	5	Facey and Grossman 1990
32	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	31	15.2	3-5 cm/s/min	91.4		6	12.2	Brawn 1960
33	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	50	18.5	3-5 cm/s/min	121.9		6.6	12.1	Brawn 1960
34	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	43	18.5	3-5 cm/s/min	94.5		5.1	12.4	Brawn 1960
35	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	35	20.7	3-5 cm/s/min	121.9		5.9	11.7	Brawn 1960
36	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	30	22.0	3-5 cm/s/min	112.8		5.1	11.6	Brawn 1960

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments (cm/s)	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
					failure								
37	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	46	25.8	3-5 cm/s/min	134.1		5.2	11.7	Brawn 1960
38	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	towed cage; median failure	22	26.7	3-5 cm/s/min	143.3		5.4	11.7	Brawn 1960
39	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	circ. tank, 50% failure		12.0		36.6		3.1		Boyar 1961
40	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	circ. tank, 50% failure		13.0		42.7		3.3		Boyar 1961
41	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	circ. tank, 50% failure		14.0		51.8		3.7		Boyar 1961
42	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	circ. tank, 50% failure		16.0		61		3.8		Boyar 1961
43	<i>Clupea harengus harengus</i>	Atlantic herring	Clupeidae	A	circ. tank, 50% failure		17.0		70.1		4.1		Boyar 1961
44	<i>Coregonus artedii</i>	cisco	Salmonidae	L	tunnel; Ucrit	8	13.5	5	45.8	8.1 SD	3.4	12	Bernatchez and Dodson 1985
45	<i>Coregonus autumnalis</i>	Arctic cisco	Salmonidae	L	tunnel; Ucrit	4	43.4	10	80		1.9	12	Jones et al. 1974
46	<i>Coregonus clupeaformis</i>	lake whitefish	Salmonidae	L	tunnel; Ucrit	159		10				7 to 19	Jones et al. 1974
47	<i>Coregonus clupeaformis</i>	lake whitefish	Salmonidae	L	tunnel; Ucrit	1	6.0	10	34.1		5.7	7 to 19	Jones et al. 1974
48	<i>Coregonus clupeaformis</i>	lake whitefish	Salmonidae	L	tunnel; Ucrit	1	51.0	10	72.1		1.4	7 to 19	Jones et al. 1974
49	<i>Coregonus clupeaformis</i>	lake whitefish	Salmonidae	L	tunnel; Ucrit	8	34.2	5	63	6.0 SD	1.8	5	Bernatchez and Dodson 1985

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50	<i>Coregonus clupeaformis</i>	lake whitefish	Salmonidae	L	tunnel; Ucrit	10	34.2	5	75	9.5 SD	2.2	12	Bernatchez and Dodson 1985
51	<i>Coregonus clupeaformis</i>	lake whitefish	Salmonidae	L	tunnel; Ucrit	9	34.2	5	67.4	4.4 SD	2	17	Bernatchez and Dodson 1985
52	<i>Coregonus nasus</i>	broad whitefish	Salmonidae	L	tunnel; Ucrit	33		10				7 to 19	Jones et al. 1974
53	<i>Coregonus nasus</i>	broad whitefish	Salmonidae	L	tunnel; Ucrit	1	6.2	10	21.7		3.6	7 to 19	Jones et al. 1974
54	<i>Coregonus nasus</i>	broad whitefish	Salmonidae	L	tunnel; Ucrit	1	33.0		46.8		1.4	7 to 19	Jones et al. 1974
55	<i>Coregonus sardinella</i>	least cisco	Salmonidae	L	tunnel; Ucrit	2	30.4	10	60		2	12	Jones et al. 1974
56	<i>Cottus bairdi</i>	mottled sculpin	Cottidae	L	tunnel; Ucrit	10	7.3	10	27.7	9.2 SD	4.2	10	Facey and Grossman 1990
57	<i>Cottus bairdi</i>	mottled sculpin	Cottidae	L	tunnel; Ucrit	10	7.3	10	38.3	7.9 SD	5.8	15	Facey and Grossman 1990
58	<i>Cottus bairdi</i>	mottled sculpin	Cottidae	L	tunnel; Ucrit	10	7.8	10	36.2	9.2 SD	5.1	10	Facey and Grossman 1990
59	<i>Cottus bairdi</i>	mottled sculpin	Cottidae	L	tunnel; Ucrit	10	6.9	10	28.4	7.6 SD	4.5	5	Facey and Grossman 1990
60	<i>Cyprinodon pecoensis</i>	Pecos pupfish	Cyprinodontidae	O	tunnel; Ucrit	23	3.6	2.9	36.28	1.16 SE	11.1		Kodric-Brown and Nicoletto 1993
61	<i>Cyprinodon pecoensis</i>	Pecos pupfish	Cyprinodontidae	O	tunnel; Ucrit	23	3.6	2.9	31.38	1.19 SE	9.6		Kodric-Brown and Nicoletto 1993
62	<i>Cyprinodon variegatus</i>	sheepshead minnow	Cyprinodontidae	O	tunnel; Ucrit	10	4.1	13	46.6	8.7 SD	12.6	30	Cripe et al. 1984
63	<i>Cyprinodon variegatus</i>	sheepshead minnow	Cyprinodontidae	O	tunnel; Ucrit	10	4.0	13	37.4	8.9 SD	10.4	30	Cripe et al. 1984

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64	<i>Epalzeorhynchus kallopterus</i>	Flying fox	Cyprinidae	O	flume; Ucrit	few	6.7	3.1	46		6.9	22	Fricke et al. 1987
65	<i>Esox lucius</i>	northern pike	Esocidae	L	tunnel; Ucrit	192		10				12	Jones et al. 1974
66	<i>Esox lucius</i>	northern pike	Esocidae	L	tunnel; Ucrit	1	12.0	10	19		1.6	12	Jones et al. 1974
67	<i>Esox lucius</i>	northern pike	Esocidae	L	tunnel; Ucrit	1	62.0	10	47		0.8	12	Jones et al. 1974
68	<i>Fundulus grandis</i>	Gulf killifish	Cyprinodontidae	A	tunnel; Ucrit	10	9.3	5	32.9	1.1 SE	3.66	23	Kolok and Sharkey 1997
69	<i>Fundulus grandis</i>	Gulf killifish	Cyprinodontidae	A	tunnel; Ucrit	9	9.1	5	37.6	1.6 SE	4.27	23	Kolok and Sharkey 1997
70	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	3	27.5	5 to 10	53.6		1.95	10	Soofiani and Priede 1985
71	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	2	27.5	5 to 10	39.6		1.44	15	Soofiani and Priede 1985
72	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	6	25.8	13	57.6	5.3 SE	2.24	4	Bushnell et al. 1994
73	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	6	48.8	10	50.7	1.0 SE	1	2	Nelson et al. 1994
74	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	5	46.4	10	50.8	1.2 SE	1.1	2	Nelson et al. 1994
75	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	5	46.7	10	47.5	2.2 SE	1	2	Nelson et al. 1996
76	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	tunnel; Ucrit	6	47.8	10	50	2.5 SE	1.1	2	Nelson et al. 1996
77	<i>Gadus ogac</i>	Greenland cod	Gadidae	A	tunnel; Ucrit	6	25.1	13	55.7	3.1 SE	2.22	4	Bushnell et al. 1994
78	<i>Gadus virens</i>	coalfish	Gadidae	A	flume; Ucrit	25	15.0	5	61.8	5.7 SD	4.13	10.4	Greer Walker and Pull 1973
79	<i>Gadus virens</i>	coalfish	Gadidae	A	flume; Ucrit	16	16.3	5	68.9	5.4 SD	4.23	10.4	Greer Walker and

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													Pull 1973
80	<i>Gasterosteus aculeatus</i>	threespine stickleback	Gasterosteidae	RE	flume; Ucrit	few	5.8	3.1	37		6.4	17	Fricke et al. 1987
81	<i>Gila cypha</i>	humpback chub	Cyprinidae	RW	tunnel; absolute speed	90	9.2		40	95% conf. = 38 - 43	4.4	14	Berry and Pimentel 1985
82	<i>Gila cypha</i>	humpback chub	Cyprinidae	RW	tunnel; absolute speed	71	9.3		51	95% conf. = 47 - 57	5.5	20	Berry and Pimentel 1985
83	<i>Gila cypha</i>	humpback chub	Cyprinidae	RW	tunnel; absolute speed	85	9.9		56	95% conf. = 50 - 62	5.7	26	Berry and Pimentel 1985
84	<i>Gila elegans</i>	bonytail chub	Cyprinidae	RW	tunnel; absolute speed	44	10.0		47	95% conf. = 43 - 50	4.7	14	Berry and Pimentel 1985
85	<i>Gila elegans</i>	bonytail chub	Cyprinidae	RW	tunnel; absolute speed	59	9.7		52	95% conf. = 47 - 59	5.4	20	Berry and Pimentel 1985
86	<i>Gila elegans</i>	bonytail chub	Cyprinidae	RW	tunnel; absolute speed	65	9.9		57	95% conf. = 52 - 63	5.8	26	Berry and Pimentel 1985
87	<i>Hiodon alosoides</i>	goldeye	Hiodontidae	RE	tunnel; Ucrit	2	23.2	10	60		2.7	12	Jones et al. 1974
88	<i>Ictalurus punctatus</i>	channel catfish	Ictaluridae	RE	tunnel; Ucrit	5	14.7	6	61.3		4.2	30	Hocutt 1973
89	<i>Kuhlia sandvicensis</i>	aholehole	Kuhliidae	P	tunnel; Ucrit	40	13.4	gradual increase				23	Muir and Niimi 1972
90	<i>Kuhlia sandvicensis</i>	aholehole	Kuhliidae	P	tunnel; Ucrit	34	13.4	gradual increase				23	Muir and Niimi 1972
91	<i>Kuhlia sandvicensis</i>	aholehole	Kuhliidae	P	tunnel; Ucrit	1	17.9	gradual increase	65		3.9	23	Muir and Niimi 1972

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92	<i>Kuhlia sandvicensis</i>	aholehole	Kuhliidae	P	tunnel; Ucrit	1	9.3	gradual increase	45.1		5.6	23	Muir and Nijimi 1972
93	<i>Lagodon rhomboides</i>	pinfish	Sparidae	A	circular flume; median failure	70	3.8	gradual increase	40		10.8	27	Hettler 1977
94	<i>Lavinia exilicauda</i>	hitch	Cyprinidae	RW	tunnel; Ucrit	5	26.0	10	39	0.07 SE	1.5	10	Myrick and Cech 2000
95	<i>Lavinia exilicauda</i>	hitch	Cyprinidae	RW	tunnel; Ucrit	8	23.7	10	57	0.03 SE	2.4	20	Myrick and Cech 2000
96	<i>Leiostomus xanthurus</i>	spot	Scianidae	A	circular flume; median failure	115	4.4	gradual increase	24.9		5.8	25	Hettler 1977
97	<i>Lepomis gibbosus</i>	pumpkinseed	Centrarchidae	L	tunnel; Ucrit	6	12.7	6	37.2	3.43 SD; 1.40 SE	3	20	Brett and Southerland 1965
98	<i>Leucaspis delineaatus</i>	Belica	Cyprinidae	O	flume; Ucrit	few	5.9	3.1	39		6.6	17	Fricke et al. 1987
99	<i>Lota lota</i>	burbot	Gadidae	A	tunnel; Ucrit	56		10				7 to 12	Jones et al. 1974
100	<i>Lota lota</i>	burbot	Gadidae	A	tunnel; Ucrit	1	12.0	10	36		3	7 to 12	Jones et al. 1974
101	<i>Lota lota</i>	burbot	Gadidae	A	tunnel; Ucrit	1	62.0	10	41		0.7	7 to 12	Jones et al. 1974
102	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	12	10.4	gradual	15.5		1.49	6	Meldrim et al. 1974
103	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	3	9.4	gradual	31.7		3.37	10	Meldrim et al. 1974
104	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	6	8.9	gradual	40.9		4.59	16	Meldrim et al. 1974
105	<i>Menidia menidia</i>	Atlantic	Atherinidae	A	tunnel; Ucrit	15	8.5	gradual	38.6		4.54	20 to 22	Meldrim et al. 1974

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		silverside											
106	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	3	9.4	gradual	38.7		4.12	24	Meldrim et al. 1974
107	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	6	7.0	gradual	57.3		8.19	26	Meldrim et al. 1974
108	<i>Micropogon undulatus</i>	Atlantic croaker	Scianidae	A	circular flume; median failure	15	7.5	gradual increase	37.2		5.1	30	Hettler 1977
109	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	10	2.2	1 bl/s	4.79	0.57 SD	2.2	5	Larimore and Duever 1968
110	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	11	2.2	1 bl/s	10.34	1.0 SD	4.7	10	Larimore and Duever 1968
111	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	10	2.0	1 bl/s	14.98	1.54 SD	6.8	15	Larimore and Duever 1968
112	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	10	2.1	1 bl/s	21.5	2.07 SD	10.2	20	Larimore and Duever 1968
113	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	9	2.3	1 bl/s	26.62	1.69 SD	11.8	25	Larimore and Duever 1968
114	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	10	2.3	1 bl/s	31.17	1.95 SD	13.6	30	Larimore and Duever 1968
115	<i>Micropterus dolomieu</i>	smallmouth bass	Centrarchidae	L	annular tank; displacement speed	10	2.2	1 bl/s	24.8	2.31	11.5	35	Larimore and Duever 1968
116	<i>Micropterus</i>	largemouth	Centrarchidae	L	tunnel; Ucrit	55	8.2	2.3	38.8		4.8	25	Dahlberg et al. 1968

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	<i>salmoides</i>	bass											
117	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	3	5.8	6	49.7		8.08	30	Hocutt 1973
118	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	10	10.5	10	45.7		4.5	25	Farlinger and Beamish 1977
119	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	10	10.3	10	35.1		3.5	25	Farlinger and Beamish 1977
120	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	10	12.6	5	41.6		3.4	25	Farlinger and Beamish 1978
121	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	10	12.6	5	44.6		3.7	25	Farlinger and Beamish 1978
122	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	10	12.6	5	47.7		3.9	25	Farlinger and Beamish 1978
123	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	8	11.3	0.5 bl/s	24.4	2.2 SD	2.22	5	Kolok 1991
124	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	8	11.3	0.5 bl/s	31.9	2.2 SD	2.9	10	Kolok 1991
125	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	8	11.3	0.5 bl/s	39.6	4.4 SD	3.6	17	Kolok 1991
126	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	42	10.4	5	20	0.3 SE; 15.9 to 22.7	2	5	Kolok 1992a
127	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	41	10.0	5	35.7	0.4 SE; 29.7 to 39.7	3.7	20	Kolok 1992a
128	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	7	9.3	5	27.2	23 to 31	3.02	11	Kolok 1992b
129	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	7	9.3	5	27.1	23.4 to 30.6	3.01	11	Kolok 1992b

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130	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	21	9.7	5	35.8	29.8 to 37.9	3.81	22	Kolok 1992b
131	<i>Micropterus salmoides</i>	largemouth bass	Centrarchidae	L	tunnel; Ucrit	21	9.7	5	36.1	33.8 to 39.5	3.84	22	Kolok 1992b
132	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	2	11.8	7.6	28.7	24.9 to 31.6	2.5	2	King 1971a
133	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	19.0	7.6	25.3	3.35 SD	1.4	2	King 1971a
134	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	14.6	7.6	24.4	2.44SD	1.7	2	King 1971a
135	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	8.5	7.6	25.9	4.27 SD	3.1	5	King 1971a
136	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	6	16.5	7.6	36	3.96 SD	2.2	5 to 6	King 1971a
137	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	18.8	7.6	31.1	4.57 SD	1.7	5 to 6	King 1971a
138	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	8.5	7.6	29.5	3.66 SD	3.5	6 to 7	King 1971a
139	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	8	15.1	7.6	32.6	6.71 SD	2.2	6 to 7	King 1971a
140	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	8	16.5	7.6	30.8	5.18 SD	1.9	7	King 1971a
141	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	8	10.8	7.6	38.1	3.35 SD	3.6	7	King 1971a
142	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	7	16.3	7.6	41.8	3.35 SD	2.6	7	King 1971a
143	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	8	9.9	7.6	33.5	6.1 SD	3.5	7	King 1971a

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144	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	6	16.6	7.6	39.9	4.57 SD	2.5	7	King 1971a
145	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	8	9.2	7.6	38.2	5.18 SD	4.3	12	King 1971a
146	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	8	15.1	7.6	50.3	6.71 SD	2.7	12	King 1971a
147	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	7	16.0	7.6	41.8	9.45 SD	2.7	12	King 1971a
148	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	12.9	7.6	42.1	6.1 SD	3.4	12 to 14	King 1971a
149	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	20	14.0	7.6	48.2	2.74 SD	3.5	13 to 16	King 1971a
150	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	10	15.7	7.6	59.7	7.01 SD	3.9	14	King 1971a
151	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	25	14.1	7.6	49.4	8.84 SD	3.6	16	King 1971a
152	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	11	14.5	7.6	59.1	9.45 SD	4.2	19 to 20	King 1971a
153	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	19	14.2	7.6	57.9	8.84 SD	4.4	21	King 1971a
154	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	flume; % fail at constant velocities	1000	10.8	gradual	86.9		8.01	February	Kerr 1953
155	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	flume; % fail at constant velocities	340	11.5	gradual	82		7.13	March	Kerr 1953
156	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	flume; % fail at constant velocities	340	11.5	gradual	64		5.57	March	Kerr 1953

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
157	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	flume; % fail at constant velocities	90	2.5	gradual	35.4	27.4 to 42.1	13.9	August	Kerr 1953
158	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	flume; % fail at constant velocities	55	5.1	gradual	76	28 to 90	14.9	October	Kerr 1953
159	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	tunnel; Ucrit	12	10.3	gradual increase	48.8	27.4 to 61	4.8	17.2	Bibko et al. 1974
160	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	tunnel; Ucrit	12	19.6	gradual increase	64	51.8 to 76.2	3.3	17.2	Bibko et al. 1974
161	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	tunnel; Ucrit	5	13.5	gradual	32.3	30.5 to 38.1	2.39	14 to 15	Meldrim et al. 1974
162	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	tunnel; Ucrit	6		6	86	2.5 SE	3.28	15	Freadman 1979
163	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	tunnel; Ucrit	6		6	76	2.9 SE	2.9	15	Freadman 1979
164	<i>Mugil cephalus</i>	striped mullet	Mugilidae	A	circular flume; median failure	135	3.2	gradual increase	25	15.5 to 30	8	15 to 17.5	
165	<i>Mugil cephalus</i>	striped mullet	Mugilidae	A	circular flume; median failure	60	3.2	gradual increase	36	27.9 to 38.4	11.5	21.5 to 24.8	
166	<i>Mylopharodon conocephalus</i>	hardhead	Cyprinidae	RW	tunnel; Ucrit	10	28.5	10	47	3 SE	1.65	10	Myrick and Cech 2000
167	<i>Mylopharodon conocephalus</i>	hardhead	Cyprinidae	RW	tunnel; Ucrit	7	24.4	10	57	2 SE	2.33	15	Myrick and Cech 2000
168	<i>Mylopharodon conocephalus</i>	hardhead	Cyprinidae	RW	tunnel; Ucrit	12	22.5	10	51	4 SE	2.27	20	Myrick and Cech 2000
169	<i>Noemacheilus barbatulus</i>	Stone loach	Balitoridae	O	flume; Ucrit	few	7.5	3.1	61		8.1	17	Fricke et al. 1987

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170	<i>Notropis atherinoides</i>	emerald shiner	Cyprinidae	RE	tunnel; Ucrit	4	6.5	10	59		9.1	12	Jones et al. 1974
171	<i>Notropis spilopterus</i>	spottin shiner	Cyprinidae	RE	tunnel; Ucrit	3	8.0	6	67.1		8.6	30	Hocutt 1973
172	<i>Oncorhynchus clarki</i>	cuthroat trout	Salmonidae	RW	tunnel; Ucrit	13	9.1	1 BL/s	59.1	2 SD	6.69	19	Hawkins and Quinn 1996
173	<i>Oncorhynchus clarki</i>	cuthroat trout	Salmonidae	RW	tunnel; Ucrit	23	9.2	1 BL/s	50	1.3 SD	5.58	19	Hawkins and Quinn 1996
174	<i>Oncorhynchus clarki x mykiss</i>	cuthroat/steelhead hyb.	Salmonidae	RW	tunnel; Ucrit	31	9.0	1 BL/s	62.5	1.3 SD	7.14	19	Hawkins and Quinn 1996
175	<i>Oncorhynchus clarki x mykiss</i>	cuthroat/steelhead hyb.	Salmonidae	RW	tunnel; Ucrit	35	9.0	1 BL/s	63	1 SD	7.22	19	Hawkins and Quinn 1996
176	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; first failure	45	8.7	2.3				10	Davis et al. 1963
177	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; first failure	45	7.9	2.3				15	Davis et al. 1963
178	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; first failure	30	8.2	2.3				20	Davis et al. 1963
179	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; first failure	60	13.1	4.6				12	Davis et al. 1963
180	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; first failure	15	13.7	4.6				15	Davis et al. 1963
181	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	65	8.4	2.3	59.4		7.1	17	Dahlberg et al. 1968
182	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	23		2.7	2	Griffiths and Alderdice 1972
183	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	18.7		2.2	2	Griffiths and Alderdice 1972

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Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
184	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	31.5		3.7	5	Griffiths and Alderdice 1972
185	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	29.8		3.5	5	Griffiths and Alderdice 1972
186	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	34.9		4.1	8	Griffiths and Alderdice 1972
187	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	38.3		4.5	8	Griffiths and Alderdice 1972
188	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	40.8		4.8	11	Griffiths and Alderdice 1972
189	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	38.3		4.5	11	Griffiths and Alderdice 1972
190	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	44.2		5.2	14	Griffiths and Alderdice 1972
191	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	45.1		5.3	14	Griffiths and Alderdice 1972
192	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	44.2		5.2	17	Griffiths and Alderdice 1972
193	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	43.4		5.1	17	Griffiths and Alderdice 1972
194	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	54.4		6.4	20	Griffiths and Alderdice 1972
195	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	48.5		5.7	20	Griffiths and Alderdice 1972
196	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	46		5.4	23	Griffiths and Alderdice 1972
197	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	8.5	1/8 Ucrit	45		5.3	23	Griffiths and Alderdice 1972

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
198	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	60	6.5	1.6L(exp 0.6)	38	3.2 SD	5.91	13	Howard 1975
199	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	60	8.7	1.6L(exp 0.6)	41.7	3.8 SD	4.95	13	Howard 1975
200	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	60	8.6	1.6L(exp 0.6)	37.4	2.4 SD	4.5	13	Howard 1975
201	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	30	8.7	1.6L(exp 0.6)	35.6	3 SD	4.23	13	Howard 1975
202	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	14.8		3.7	3	Glova and McInerney 1977
203	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	15.6		3.9	3	Glova and McInerney 1977
204	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	20.8		5.2	8	Glova and McInerney 1977
205	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	20		5	8	Glova and McInerney 1977
206	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	26		6.5	13	Glova and McInerney 1977
207	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	24.8		6.2	13	Glova and McInerney 1977
208	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	30.8		7.7	18	Glova and McInerney 1977
209	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	28.4		7.1	18	Glova and McInerney 1977
210	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	31.6		7.9	23	Glova and McInerney 1977
211	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	4.1	1/8 Ucrit	31.2		7.8	23	Glova and McInerney 1977

Table of Critical Swimming Speeds for Fish

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212	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	38		3.8	3	Glova and McInerney 1977
213	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	32		3.2	3	Glova and McInerney 1977
214	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	42		4.2	8	Glova and McInerney 1977
215	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	45		4.5	8	Glova and McInerney 1977
216	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	52		5.2	13	Glova and McInerney 1977
217	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	49		4.9	13	Glova and McInerney 1977
218	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	58		5.8	18	Glova and McInerney 1977
219	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	58		5.8	18	Glova and McInerney 1977
220	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	57		5.7	23	Glova and McInerney 1977
221	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	10.3	1/8 Ucrit	58		5.8	23	Glova and McInerney 1977
222	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	6	9.6	5	47		4.9	11 to 13	Farrell et al. 1997
223	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	6	20.1	5	69		3.4	11 to 13	Farrell et al. 1997
224	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	6	11.3	0.5	37.4	28.6 to 48.4	3.4	15	Besner and Smith 1983
225	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	3	14.3	0.5	70.9	66.7 to 72.3	5.1	15	Besner and Smith 1983

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226	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	11	15.1	0.5	42.6	32.4 to 51	2.9	15	Besner and Smith 1983
227	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	11	17.0	0.5	51.2	46.2 to 50.8	3.1	15	Besner and Smith 1983
228	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	rotating chamber; failure vel.	140		4 to 10	60	35 to 80		10	Fry and Cox 1970
229	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	15	10.9	9	65.9	2.18 SE; 47.1 to 77.6	6.1	11.9	Jones 1971
230	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	14	12.5	9	80	2.75 SE; 62.1 to 101.3	6.3	22.6	Jones 1971
231	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	18	12.5	9	43.4	1.6 SE	3.5	14.1	Jones 1971
232	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	15	11.8	9	52.3	1.5 SE	4.4	22.4	Jones 1971
233	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	73	29.2	6	58.1		2	15	Webb 1971b
234	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	6	31.5	10	66.6	6.3 SE; 47.1 to 83.2	2.2	7 to 12	Jones et al. 1974
235	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	6	33.8	10	91	2.5 SE; 83.3 to 97.9	2.8	7 to 12	Jones et al. 1974
236	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit		46.5		85	80 to 90	2	9 to 10.5	Kiceniuk and Jones 1977
237	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	9.3	5	39.5		4.2	15	Beamish 1978
238	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	10.4	10	42.2		4.1	15	Beamish 1978

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	<i>mykiss</i>												
239	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	10.3	10	39.9		3.9	15	Beamish 1978
240	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	8.9	5	36.1		4.1	15	Beamish 1978
241	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	9.2	5	39.2		4.3	15	Beamish 1978
242	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	9.5	10	35.2		3.7	15	Beamish 1978
243	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	9.3	10	41.9		4.4	15	Beamish 1978
244	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	7.6	6	41.8	0.4 SE	5.5	15	Graham and Wood 1981
245	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	26	30.1	15	73.8	1.6 SE	2.53	7	Daxboek 1982
246	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit		9.6	10	65		7.47		Kumaraguru and Beamish 1983
247	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	10.7	10	58.2	19.4 SD	6	10	Facey and Grossman 1990
248	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	8.6	10	52.3	19.5 SD	6.7	15	Facey and Grossman 1990
249	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	8.6	10	64.7	10.9 SD	8.3	10	Facey and Grossman 1990
250	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	10.3	10	38.5	13.2 SD	4.1	5	Facey and Grossman 1990
251	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	8		0.25 BL/s	68.6	4.58 SE		10 to 15	Farrell et al. 1990
252	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	5		0.25	73.4	4.17 SE		10 to 15	Farrell et al. 1990

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	<i>mykiss</i>							BL/s					
253	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	7	10.8	10	47.5	1.9 SE	4.52	15	Alsop and Wood 1997
254	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	7	10.8	10	40.4	1.7 SE	3.85	15	Alsop and Wood 1997
255	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	7	10.8	10	44.6	2.2 SE	4.25	15	Alsop and Wood 1997
256	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	flume; Ucrit	10	16.7	10	89		5.52	10	Gamperl et al. 1991
257	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	flume; Ucrit	10	15.8	10	86		5.54	10	Gamperl et al. 1991
258	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	10	29.1	15	63.7	3.2 SE	2.19	8.2	Pearson and Stevens 1991
259	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	11	38.5	10	77		2	18 to 19	Gallaugher et al. 1992
260	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	9	35.1	8	69.2	2.7 SE	2.04	8	Keen and Farrell 1994
261	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	9	35.9	8	96.2	2.4 SE	2.76	18	Keen and Farrell 1994
262	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	15	35.5	9	81	64 to 92	2.3	12 to 14	Gallaugher et al. 1995
263	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	16	35.5	9	60	50 to 64	1.7	4 to 6	Gallaugher et al. 1995
264	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	31	10.3	1 bl/s	76.9	1.17 SD	7.69	19	Hawkins and Quinn 1996
265	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	5	40.1	0.2 bl/s	62.6	56.4 to 73.9	1.61	5.5 to 8	Jain et al. 1997
266	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	30	9.7	7	40.69	0.52 SE	4.37	15	Gregory and Wood

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Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
	<i>mykiss</i>												1998
267	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	25	10.1	7	41.26	0.71 SE	4.25	15	Gregory and Wood 1998
268	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	12	12.0	9	106.8	4.3 SE	2.93	9.5	Davidson et al. 1999
269	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	24	10.8	7	44.21	1.26 SE	4.23	16	Gregory and Wood 1999
270	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	22	9.8	7	37.35	1.32 SE	3.82	16	Gregory and Wood 1999
271	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	18	9.1	7	37.72	1.86 SE	4.16	16	Gregory and Wood 1999
272	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	20	8.3	7	28.37	1.08 SE	3.42	16	Gregory and Wood 1999
273	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	9	16.6		53.6	6 SD; 2 SE	3.26	5	Brett 1964
274	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	11	16.2		57.9	4.9 SD; 1.5 SE	3.65	10	Brett 1964
275	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	18.8		76.8	9.2 SD; 3.6 SE	4.12	15	Brett 1964
276	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	9	19.5		74.1	7.8 SD; 2.7 SE	3.9	20	Brett 1964
277	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	5	18.5		68.6	13.9 SD; 6.3 SE	3.75	25	Brett 1964
278	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit								Brett 1965
279	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	5	16.2	10	67.3	6.8 SD	4.16	15	Brett 1967
280	<i>Oncorhynchus</i>	sockeye	Salmonidae	P	tunnel; Ucrit	5	16.0	10	40	34.4 to	2.5	2	Brett and Glass 1973

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
	<i>nerka</i>	salmon								45.9			
281	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	4	11.6	10	44.3	40.5 to 54.2	3.9	5	Brett and Glass 1973
282	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	16.2	10	59		3.7	10	Brett and Glass 1973
283	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	7.7	10	51.5		6.7	15	Brett and Glass 1973
284	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	10.0	10	59.8		5.9	15	Brett and Glass 1973
285	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	12.8	10	53.2		4.2	15	Brett and Glass 1973
286	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	18.8	10	90.7		4.8	15	Brett and Glass 1973
287	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	41.8	10	150		3.6	15	Brett and Glass 1973
288	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	53.9	10	178		3.3	15	Brett and Glass 1973
289	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	5	5.8	10	42.2	37.1 to 46.0	7.3	20	Brett and Glass 1973
290	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	8	9.0	10	58	52.9 to 64.4	6.5	20	Brett and Glass 1973
291	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	7	57.0	10	130	126 to 136	2.3	20	Brett and Glass 1973
292	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	1	18.5	10	69.4		3.8	24	Brett and Glass 1973
293	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.3	5	38		7.2	15	Webb and Brett 1973
294	<i>Oncorhynchus</i>	sockeye	Salmonidae	P	tunnel; Ucrit	10	5.4	5	40		7.3	15	Webb and Brett 1973

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	<i>nerka</i>	salmon											
295	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.6	5	43.5		7.8	15	Webb and Brett 1973
296	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.7	5	40		7	15	Webb and Brett 1973
297	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.7	5	38.4		6.7	15	Webb and Brett 1973
298	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.8	5	39.1		6.8	15	Webb and Brett 1973
299	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.8	5	44.2		7.6	15	Webb and Brett 1973
300	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	5.9	5	42.9		7.3	15	Webb and Brett 1973
301	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	10	6.0	5	41.9		7	15	Webb and Brett 1973
302	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	3	63.3	0.15 bl/s	95.7	3.0 SE	1.56	19 to 21	Jain et al. 1998
303	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	5	57.7	12.5	79	2.2 SE	1.41	19 to 20	Farrell et al. 1998
304	<i>Oncorhynchus tshawytscha</i>	chinook salmon	Salmonidae	P	tunnel; first failure	10	9.9	irreg. stepped				11.5	Davis et al. 1963
305	<i>Oncorhynchus tshawytscha</i>	chinook salmon	Salmonidae	P	tunnel; first failure	10	7.0	irreg. stepped				19.5	Davis et al. 1963
306	<i>Oncorhynchus tshawytscha</i>	chinook salmon	Salmonidae	P	tunnel; Ucrit	10	30.3	0.25 - 0.5 BL/s	85.5		2.8	10	Thorarensen et al. 1993
307	<i>Oncorhynchus tshawytscha</i>	chinook salmon	Salmonidae	P	tunnel; Ucrit	10	30.1	0.25 - 0.5 BL/s	87.5		2.9	10	Thorarensen et al. 1993
308	<i>Oncorhynchus</i>	chinook	Salmonidae	P	tunnel; Ucrit	6	33.0	20	106	4.8 SE	3.3	14.3	Brauner et al. 1993

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	<i>tshawytscha</i>	salmon											
309	<i>Perca flavescens</i>	yellow perch	Percidae	L	tunnel; Ucrit	6	15.6	7.6	18.9	17.1 to 24.6	1.3	2 to 4	King 1971a
310	<i>Perca flavescens</i>	yellow perch	Percidae	L	tunnel; Ucrit	5	10.5	5	20		2.1	10	Otto and O'Hara Rice 1974
311	<i>Perca flavescens</i>	yellow perch	Percidae	L	tunnel; Ucrit	5	10.5	5	34		3.6	20	Otto and O'Hara Rice 1974
312	<i>Percopsis omiscomaycus</i>	trout-perch	Percopsidae	L	tunnel; Ucrit	3	7.2	10	55		7.6	12	Jones et al. 1974
313	<i>Pimephales promelas</i>	fathead minnow	Cyprinidae	RE	MacLeod oval channel; Smax	440	5.0		20.2	16.5 to 25.8	4.04	15	MacLeod 1967
314	<i>Pimephales promelas</i>	fathead minnow	Cyprinidae	RE	MacLeod oval channel; Smax	135	6.7		30	19.3 to 41	4.48	20	MacLeod 1967
315	<i>Pimephales promelas</i>	fathead minnow	Cyprinidae	RE	tunnel; Ucrit	24		5	35.9	28.8 to 34.4		25	Kolok and Oris 1995
316	<i>Pimephales promelas</i>	fathead minnow	Cyprinidae	RE	tunnel; Ucrit	10	6.3	5	44.7	1.3 SE; 36 to 50	7.33	24	Kolok et al. 1998
317	<i>Pimephales promelas</i>	fathead minnow	Cyprinidae	RE	tunnel; Ucrit	10	6.1	5	42.3	1.8 SE; 33 to 50	7.17	24	Kolok et al. 1998
318	<i>Pimephales promelas</i>	fathead minnow	Cyprinidae	RE	tunnel; Ucrit	9	6.6	5	42.8	1.1 SE; 40 to 49	6.69	24	Kolok et al. 1998
319	<i>Platygobio gracilis</i>	fathead chub	Cyprinidae	RE	tunnel; Ucrit	28		10				12 to 19	Jones et al. 1974
320	<i>Platygobio gracilis</i>	fathead chub	Cyprinidae	RE	tunnel; Ucrit	1	17.0	10	42.9		2.5	12 to 19	Jones et al. 1974

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321	<i>Platygobio gracilis</i>	flathead chub	Cyprinidae	RE	tunnel; Ucrit	1	30.0	10	62.7		2.1	12 to 19	Jones et al. 1974
322	<i>Plecostomus sp.</i>	Armored catfish	Loricariidae	O	flume; Ucrit	few	8.6	3.1	151		17.6	22	Fricke et al. 1987
323	<i>Pomatomus saltatrix</i>	bluefish	Pomatomidae	A	tunnel; Ucrit	6		6	101.9	2.1 SE	4.61	15	Freadman 1979
324	<i>Pomatomus saltatrix</i>	bluefish	Pomatomidae	A	tunnel; Ucrit	6		6	84	5.3 SE	4.01	15	Freadman 1979
325	<i>Pomoxis annularis</i>	white crappie	Centrarchidae	L	tunnel; Ucrit	12	18.7	5	34.7	25.5 to 45; 6.6 SD	2.04	25	Parsons and Sylvester 1992
326	<i>Prosopium williamsoni</i>	mountain whitefish	Salmonidae	RW	tunnel; Ucrit	9	31.3	10	42.5	6.5 SE	1.4	7 to 12	Jones et al. 1974
327	<i>Ptychocheilus grandis</i>	Sacramento pikeminnow	Cyprinidae	RW	tunnel; Ucrit	9	22.9	10	40	6 SE	1.75	10	Myrick and Cech 2000
328	<i>Ptychocheilus grandis</i>	Sacramento pikeminnow	Cyprinidae	RW	tunnel; Ucrit	10	24.7	10	57	4 SE	2.31	15	Myrick and Cech 2000
329	<i>Ptychocheilus grandis</i>	Sacramento pikeminnow	Cyprinidae	RW	tunnel; Ucrit	8	23.3	10	50	6 SE	2.15	20	Myrick and Cech 2000
330	<i>Ptychocheilus lucius</i>	Colorado pikeminnow	Cyprinidae	RW	tunnel; absolute speed	76	8.8		35	95% conf. = 32 - 39	4	14	Berry and Pimentel 1985
331	<i>Ptychocheilus lucius</i>	Colorado pikeminnow	Cyprinidae	RW	tunnel; absolute speed	60	12.1		47	95% conf. = 45 - 48	3.9	20	Berry and Pimentel 1985
332	<i>Ptychocheilus lucius</i>	Colorado pikeminnow	Cyprinidae	RW	tunnel; absolute speed	67	10.4		47	95% conf. = 45 - 49	4.5	26	Berry and Pimentel 1985
333	<i>Ptychocheilus lucius</i>	Colorado pikeminnow	Cyprinidae	RW	tunnel; absolute speed	19	41.1		95	95% conf. = 90 - 103	2.3	14	Berry and Pimentel 1985

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334	<i>Ptychocheilus lucius</i>	Colorado pikeminnow	Cyprinidae	RW	tunnel; absolute speed	15	45.1		95		2.1	20	Berry and Pimentel 1985
335	<i>Ptychocheilus lucius</i>	Colorado pikeminnow	Cyprinidae	RW	tunnel; absolute speed	14	43.3		87	95% conf. = 65 - 117	2	26	Berry and Pimentel 1985
336	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; Ucrit	11	25.8	10	48.7	2.2 SE; 31 to 55	1.96	5	Kolok and Farrell 1994a
337	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; Ucrit	15	31.8	10	71.5	2.8 SE; 41.8 to 81.5	2.35	16	Kolok and Farrell 1994a
338	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; Ucrit	14	31.2	10	59.2	2.8 SE	1.92	16	Kolok and Farrell 1994b
339	<i>Rhinichthys cataractae</i>	longnose dace	Cyprinidae	RE	tunnel; Ucrit	10	7.8	10	73.1	6.4 SD	10.3	10	Facey and Grossman 1990
340	<i>Rhinichthys cataractae</i>	longnose dace	Cyprinidae	RE	tunnel; Ucrit	10	7.7	10	67.9	16.1 SD	9.7	15	Facey and Grossman 1990
341	<i>Rhinichthys cataractae</i>	longnose dace	Cyprinidae	RE	tunnel; Ucrit	10	8.6	10	75.7	11.7 SD	9.7	10	Facey and Grossman 1990
342	<i>Rhinichthys cataractae</i>	longnose dace	Cyprinidae	RE	tunnel; Ucrit	10	8.6	10	66.3	12.5 SD	8.5	5	Facey and Grossman 1990
343	<i>Rhinichthys osculus</i>	speckled dace	Cyprinidae	RE	tunnel; Ucrit		5.1	10	52.7	3.6 SE	11.28	15	Baltz et al. 1982
344	<i>Rhinichthys osculus</i>	speckled dace	Cyprinidae	RE	tunnel; Ucrit		5.1	10	49.2	2.8 SE	10.53	20	Baltz et al. 1982
345	<i>Rhinichthys osculus</i>	speckled dace	Cyprinidae	RE	tunnel; Ucrit		5.1	10	68.9	2.7 SE	14.75	25	Baltz et al. 1982
346	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	8	47.4	17	135	23 SD	2.9	8	Beddow and McKinley 1998

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347	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	8	47.4	17	129	16 SD	2.8	8	Beddow and McKinley 1998
348	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	8	45.3	17	153	25 SD	3.5	18	Beddow and McKinley 1998
349	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	8	45.3	17	136	18 SD	3.1	18	Beddow and McKinley 1998
350	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	4	57.5	10	176	0.06 SE	3	12	Booth et al. 1997
351	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	4	57.5	10	216	0.18 SE	3.8	18	Booth et al. 1997
352	<i>Salmo trutta</i>	brown trout	Salmonidae	R	tunnel; Ucrit	10	35.0	10	78	4 SE	2.18	15	Butler et al. 1992
353	<i>Salmo trutta</i>	brown trout	Salmonidae	R	tunnel; Ucrit	14	35.2	10	50	2 SE	1.42	15	Butler et al. 1992
354	<i>Salmo trutta</i>	brown trout	Salmonidae	R	tunnel; Ucrit	18	33.7	10	62	2 SE	1.85	5	Butler et al. 1992
355	<i>Salmo trutta</i>	brown trout	Salmonidae	R	tunnel; Ucrit	14	32.7	10	42	3 SE	1.27	5	Butler et al. 1992
356	<i>Salvelinus alpinus</i>	Arctic char	Salmonidae	RW	tunnel; Ucrit	11	36.6	10	100.2	3.0 SE	2.8	12	Jones et al. 1974
357	<i>Salvelinus alpinus</i>	Arctic char	Salmonidae	RW	tunnel; Ucrit	8	31.6	5	61		1.93	5	Beamish 1980
358	<i>Salvelinus alpinus</i>	Arctic char	Salmonidae	RW	tunnel; Ucrit	9	31.6	5	67		2.12	10	Beamish 1980
359	<i>Salvelinus alpinus</i>	Arctic char	Salmonidae	RW	tunnel; Ucrit	11	31.6	5	65		2.06	15	Beamish 1980
360	<i>Salvelinus fontinalis</i>	brook char (trout)	Salmonidae	RE	tunnel; Ucrit	6	8.2	5	11		1.34	5	Beamish 1980
361	<i>Salvelinus fontinalis</i>	brook char (trout)	Salmonidae	RE	tunnel; Ucrit	6	8.2	5	16		1.95	10	Beamish 1980
362	<i>Salvelinus fontinalis</i>	brook char (trout)	Salmonidae	RE	tunnel; Ucrit	16	8.2	5	34		4.15	15	Beamish 1980
363	<i>Salvelinus</i>	lake trout	Salmonidae	L	tunnel; Ucrit	6	12.7	5	76.5	2.3 95% CL	6	10	Beamish et al. 1989

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	<i>namaycush</i>												
364	<i>Salvelinus namaycush</i>	lake trout	Salmonidae	L	tunnel; Ucrit	6	12.7	5	84.1	3.1 95% CL	6.6	10	Beamish et al. 1989
365	<i>Salvelinus namaycush</i>	lake trout	Salmonidae	L	tunnel; Ucrit	6	12.7	5	95.4	3.4 95% CL	7.5	10	Beamish et al. 1989
366	<i>Salvelinus namaycush</i>	lake trout	Salmonidae	L	tunnel; Ucrit	8	11.5	5	22		1.91	5	Beamish 1980
367	<i>Salvelinus namaycush</i>	lake trout	Salmonidae	L	tunnel; Ucrit	6	11.5	5	27		2.35	10	Beamish 1980
368	<i>Salvelinus namaycush</i>	lake trout	Salmonidae	L	tunnel; Ucrit	15	11.5	5	29		2.52	15	Beamish 1980
369	<i>Scaphirhynchus platyrhynchus</i>	shovelnose sturgeon	Acipenseridae	RE	tunnel; Ucrit	5	65.0	10	95.3	64.7 to 116	1.53	16	Adams et al. 1997
370	<i>Stenodus leucichthys</i>	inconnu	Salmonidae	O	tunnel; Ucrit	22		10				12 to 19	Jones et al. 1974
371	<i>Stenodus leucichthys</i>	inconnu	Salmonidae	O	tunnel; Ucrit	1	8.2	10	144		18	12 to 19	Jones et al. 1974
372	<i>Stenodus leucichthys</i>	inconnu	Salmonidae	O	tunnel; Ucrit	1	42.2	10	490		12	12 to 19	Jones et al. 1974
373	<i>Stizostedion vitreum v.</i>	walleye	Percidae	L	tunnel; Ucrit	54		10				19	Jones et al. 1974
374	<i>Stizostedion vitreum v.</i>	walleye	Percidae	L	tunnel; Ucrit	1	8.2	10	38		4.7	19	Jones et al. 1974
375	<i>Stizostedion vitreum v.</i>	walleye	Percidae	L	tunnel; Ucrit	1	39.1	10	84		2.2	19	Jones et al. 1974
376	<i>Thymallus arcticus</i>	Arctic grayling	Salmonidae	RW	tunnel; Ucrit	94		10				12 to 19	Jones et al. 1974
377	<i>Thymallus arcticus</i>	Arctic	Salmonidae	RW	tunnel; Ucrit	1	7.2	10	52		7.5	12 to 19	Jones et al. 1974

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		grayling											
378	<i>Thymallus arcticus</i>	Arctic grayling	Salmonidae	RW	tunnel; Ucrit	1	38.1	10	72		1.9	12 to 19	Jones et al. 1974
379	<i>Thymallus arcticus</i>	Arctic grayling	Salmonidae	RW	circular flume; max. swim speed	250	15.3		81		5.44	13 to 17	MacPhee and Watts 1975
380	<i>Trichogaster trichopterus</i>	Three spot gourami	Belontiidae	O	flume; Ucrit	few	8.0	3.1	52		6.5	22	Fricke et al. 1987
381	<i>Acipenser fulvescens</i>	lake sturgeon	Acipenseridae	L	tunnel; Ucrit	9	19.7	5	29.9	23 to 39	1.5	14	Peake et al. 1995
382	<i>Acipenser fulvescens</i>	lake sturgeon	Acipenseridae	L	tunnel; Ucrit	8	42.9	5	40.4	32 to 46	0.94	14	Peake et al. 1995
383	<i>Acipenser fulvescens</i>	lake sturgeon	Acipenseridae	L	tunnel; Ucrit	3	114.3	5	107.3	97 to 121	0.94	14	Peake et al. 1995
384	<i>Alosa aestivalis</i>	blueback herring	Clupeidae	A	tunnel; Ucrit	3	8.5	3	22.7	18.3 to 26.2	2.7	10	Terpin et al. 1977
385	<i>Alosa aestivalis</i>	blueback herring	Clupeidae	A	tunnel; Ucrit	4	8.9	3	34.7	30.5 to 39.6	3.9	15	Terpin et al. 1977
386	<i>Alosa pseudoharengus</i>	alewife	Clupeidae	A	tunnel; Ucrit	4	13.6	3	63.6	50.9 to 84.4	4.71	20	Wyllie et al. 1976
387	<i>Alosa pseudoharengus</i>	alewife	Clupeidae	A	tunnel; Ucrit	4	9.8	3	39.5	26.5 to 54.2	4.12	24 to 25	Wyllie et al. 1976
388	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	McLeod apparatus	15	6.4	gradual increase	15.2	9.1 to 21.3	2.5	22.8	Tatham 1970
389	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	6	8.4	3	20.3	18.3 to 23.8	2.41	10	Wyllie et al. 1976
390	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	5	8.9	3	31	25.9 to 37.8	3.5	15	Wyllie et al. 1976

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Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
391	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	5	8.1	3	14.9	12.2 to 19.8	1.9	5	Terpin et al. 1977
392	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	2	7.0	3	20.4	16.5 to 24.4	2.9	10	Terpin et al. 1977
393	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	2	7.1	3	18.6	18.3 to 18.9	2.6	12	Terpin et al. 1977
394	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	4	7.4	3	30.2	24.4 to 35.4	4.1	15	Terpin et al. 1977
395	<i>Anchoa mitchilli</i>	bay anchovy	Clupeidae	A	tunnel; Ucrit	4	6.8	3	36.3	33.5 to 42.1	5.4	21	Terpin et al. 1977
396	<i>Atherina presbyter</i>	sand smelt	Atherinidae	A	flume; Ucrit	circa 200				50 to 70			Tumpenny and Bamber 1983
397	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	2	8.2	3	75.4	75.1 to 76.8	9.24	20	Tatham 1970
398	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	4	7.8	3	68.2	64.6 to 71.9	8.79	23	Tatham 1970
399	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	2	12.0	3	60.3	50 to 70.7	5.1	15	Tatham 1970
400	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	4	14.8	3	108.6	101.8 to 117.7	7.4	25	Tatham 1970
401	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	4	16.7	3	41.1	33.5 to 47.9	2.49	5	Wyllie et al. 1976
402	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	4	16.4	3	70.9	66.5 to 74.4	4.36	10	Wyllie et al. 1976
403	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	4	16.3	3	70	49.7 to 89.3	4.26	15	Wyllie et al. 1976
404	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	4	14.4	3	84.2	56.1 to 111.6	5.83	20 to 21	Wyllie et al. 1976

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Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
405	<i>Brevoortia tyrannus</i>	Atlantic menhaden	Clupeidae	A	tunnel; Ucrit	5	10.8	3	44.6	36 to 58.2	4.11	24 to 25	Wyllie et al. 1976
406	<i>Chromis punctipinnis</i>	blacksmith	Pomacentridae	P	flume; 60-min. velocity	5	9.4		51		5.9	15 to 20	Dorn et al. 1979
407	<i>Clupea harengus</i>	herring	Clupeidae	A	flume; Ucrit	28	5.7	10	50.1	6.8 SD	9.72	16.2	Turnpenny 1983
408	<i>Clupea harengus</i>	herring	Clupeidae	A	flume; Ucrit	36	5.6	10	56.1	5.1 SD	11.1	16.3	Turnpenny 1983
409	<i>Clupea harengus</i>	herring	Clupeidae	A	flume; Ucrit	23	5.7	10	57.7	4.2 SD	11.2	16.2	Turnpenny 1983
410	<i>Cymatogaster aggregata</i>	shiner perch	Embiotocidae	P	flume; 60-min. velocity	7	10.2		46		4.8	15 to 20	Dorn et al. 1979
411	<i>Cynoscion regalis</i>	weakfish	Sciaenidae	A	tunnel; Ucrit	3	13.9	3	59.9	55.5 to 64.3	4.31	22 to 25	Wyllie et al. 1976
412	<i>Cynoscion regalis</i>	weakfish	Sciaenidae	A	tunnel; Ucrit	3	10.9	3	54.6	51.8 to 56.1	5	21 to 22	Terpin et al. 1977
413	<i>Cynoscion regalis</i>	weakfish	Sciaenidae	A	tunnel; Ucrit	2	11.6	3	42.8	36.9 to 48.8	3.7	15	Terpin et al. 1977
414	<i>Cynoscion regalis</i>	weakfish	Sciaenidae	A	tunnel; Ucrit	3	16.2	3	50.5	35.4 to 61	3.1	10	Terpin et al. 1977
415	<i>Embiotoca jacksoni</i>	black perch	Embiotocidae	P	flume; 60-min. velocity	5	16.4		52		3.2	15 to 20	Dorn et al. 1979
416	<i>Gadus morhua</i>	Atlantic cod	Gadidae	A	endurance	154	57.8		66		1.1	0 to 9.8	Winger et al. 2000
417	<i>Gasterosteus aculeatus</i>	threespine stickleback	Gasterosteidae	RE	tunnel; Ucrit	3	6.0	3	32.8	25.3 to 36.6	5.5	15	Terpin et al. 1977
418	<i>Gasterosteus aculeatus</i>	threespine stickleback	Gasterosteidae	RE	tunnel; Ucrit	43	5.5	6.7	36.3		6.6	18	Stahlberg and Peckmann 1987
419	<i>Genyonemus lineatus</i>	white croaker	Sciaenidae	P	flume; 60-min. velocity	5	21.2		61		3.7	15 to 20	Dorn et al. 1979
420	<i>Gobio gobio</i>	gudgeon	Cyprinidae	O	tunnel; Ucrit	46	11.8	6.7	55		4.7	18	Stahlberg and

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													Peckmann 1987
421	<i>Gobio gobio</i>	gudgeon	Cyprinidae	O	tunnel; Ucrit			6.7	45.6			4	Stahlberg and Peckmann 1987
422	<i>Gobio gobio</i>	gudgeon	Cyprinidae	O	tunnel; Ucrit	5	6.4	gradual increase	51.2	50 to 52	8	16 to 17	Pavlov et al. 1994
423	<i>Hyperproson argenteum</i>	walleye surperch	Embiotocidae	P	flume; 60-min. velocity	4	15.1		42		3.3	15 to 20	Dorn et al. 1979
424	<i>Hypomesus transpacificus</i>	delta smelt	Osmeridae	P	flume; Ucrit	63		3.5	27.6	17 to 37		12 to 21	Swanson et al. 1998
425	<i>Hypsurus caryi</i>	rainbow seaperch	Embiotocidae	P	flume; 60-min. velocity	5	15.2		42		3.1	15 to 20	Dorn et al. 1979
426	<i>Ictiobus bubalus</i>	smallmouth buffalo	Catostomidae	RE	tunnel; Ucrit	9	41.0	10	61.5	12.4 SD	1.65	20	Adams and Parsons 1998
427	<i>Ictiobus bubalus</i>	smallmouth buffalo	Catostomidae	RE	tunnel; Ucrit	11	39.9	10	55.8	16.2 SD	1.54	27.3	Adams and Parsons 1998
428	<i>Ictiobus bubalus</i>	smallmouth buffalo	Catostomidae	RE	tunnel; Ucrit	9	40.0	10	17.6	12.3 SD	0.48	16.6	Adams and Parsons 1998
429	<i>Ictiobus bubalus</i>	smallmouth buffalo	Catostomidae	RE	tunnel; Ucrit	13	37.6	10	39	11.5 SD	1.14	10	Adams and Parsons 1998
430	<i>Lagodon rhomboides</i>	pinfish	Sparidae	A	tunnel; Ucrit	82	3.6	9	38.8	14 to 60	9.4	15 to 25	Rulifson 1977
431	<i>Lampetra tridentata</i>	Pacific lamprey	Petromyzontidae	RW	tunnel; Ucrit	10			15	0 to 30			Dauble and Moursund unpub.
432	<i>Lampetra tridentata</i>	Pacific lamprey	Petromyzontidae	RW	tunnel; Ucrit	30			23	0 to 46			Dauble and Moursund unpub.
433	<i>Leiostomus xanthurus</i>	spot	Scianidae	A	tunnel; Ucrit	4	10.9	3	67.8	54.3 to 75.9	6.3	24	Wyllie et al. 1976
434	<i>Leiostomus</i>	spot	Scianidae	A	tunnel; Ucrit	77	3.9	9	36.6	16 to 67	9.39	15 to 25	Rulifson 1977

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	<i>xanthurus</i>												
435	<i>Leucaspis delineatus</i>	verkhovka	Cyprinidae	O	tunnel; Ucrit	6	2.5	gradual increase	30.3	26 to 35	12.1	19 to 21	Pavlov et al. 1972
436	<i>Leucaspis delineatus</i>	verkhovka	Cyprinidae	O	tunnel; Ucrit	38	5.1	6.7	38.6		7.7	18	Stahlberg and Peckmann 1987
437	<i>Leucaspis delineatus</i>	verkhovka	Cyprinidae	O	tunnel; Ucrit			6.7	22.7			4	Stahlberg and Peckmann 1987
438	<i>Leucaspis delineatus</i>	verkhovka	Cyprinidae	O	tunnel; Ucrit	76	4.9	6.7	38		7.8	18	Stahlberg and Peckmann 1987
439	<i>Leucaspis delineatus</i>	verkhovka	Cyprinidae	O	tunnel; Ucrit	137	5.0	6.7	40.1		8.1	18	Stahlberg and Peckmann 1987
440	<i>Membres martinica</i>	rough silverside	Atherinidae	A	McLeod apparatus	8	9.4	gradual increase	21.3	18.3 to 24.4	2.3	24.4	Tatham 1970
441	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	7	10.1	3	28.2	24.7 to 32.6	2.79	4	Wyllie et al. 1976
442	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	4	10.7	3	43.3	38.4 to 48.4	3.48	6.2 to 7	Wyllie et al. 1976
443	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	13	10.7	3	38.3	26.8 to 49.7	3.61	8 to 9	Wyllie et al. 1976
444	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	4	10.9	3	43.4	30.5 to 55.8	4.07	10	Wyllie et al. 1976
445	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	2	12.0	3	71	67.1 to 75	5.92	20 to 21	Wyllie et al. 1976
446	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	2	9.8	3	35.5	34.4 to 36.6	3.73	5	Terpin et al. 1977
447	<i>Menidia menidia</i>	Atlantic silverside	Atherinidae	A	tunnel; Ucrit	4	10.0	3	44.6	39.9 to 55.8	4.51	10	Terpin et al. 1977
448	<i>Menidia</i>	tidewater	Atherinidae	A	McLeod	12	6.4	gradual	51.8	39.6 to	8.4	22.8	Tatham 1970

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	<i>peninsulæ</i>	silverside			apparatus			increase		57.9			
449	<i>Menicirrhus saxatilis</i>	northern kingfish	Scianidae	A	tunnel; Ucrit	3	9.6	3	59.7	52.1 to 65.2	6.32	22 to 25	Wyllie et al. 1976
450	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	42	4.0	gradual increase	19.6	9.1 to 30.5	5.1	23.9	Tatham 1970
451	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	33	3.9	gradual increase	21.9	15.2 to 27.4	5.8	26.7	Tatham 1970
452	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	57	6.3	gradual increase	30.3	21.3 to 39.6	5	26.7	Tatham 1970
453	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	27	4.5	gradual increase	26	18.3 to 39.6	5.9	29.4	Tatham 1970
454	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	15	5.8	gradual increase	32.3	30.5 to 36.6	5.8	29.4	Tatham 1970
455	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	30	6.8	gradual increase	35.7	27.4 to 42.7	5.4	29.4	Tatham 1970
456	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	48	7.6	gradual increase	37.8	27.4 to 45.7	5.1	29.4	Tatham 1970
457	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	21	4.7	gradual increase	26.5	21.3 to 30.5	5.8	32.2	Tatham 1970
458	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	29	5.6	gradual increase	35.7	27.4 to 39.6	6.6	32.2	Tatham 1970
459	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	21	6.6	gradual increase	33.5	27.4 to 39.6	5.2	32.2	Tatham 1970
460	<i>Morone americana</i>	white perch	Percichthyidae	A	McLeod apparatus	18	8.0	gradual increase	39	36.6 to 42.7	5	32.2	Tatham 1970
461	<i>Morone americana</i>	white perch	Percichthyidae	A	tunnel; Ucrit	4	12.2	3	35.7	24.4 to 42.7	3	5	Terpin et al. 1977
462	<i>Morone</i>	white perch	Percichthyidae	A	tunnel; Ucrit	4	12.3	3	42	32.9 to	3.8	10	Terpin et al. 1977

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	<i>americana</i>									48.7			
463	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	McLeod apparatus	39	4.0	gradual increase	26	18.3 to 33.5	6.8	23.9	Tatham 1970
464	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	McLeod apparatus	51	3.9	gradual increase	23.7	18.3 to 27.4	6.2	26.7	Tatham 1970
465	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	McLeod apparatus	24	5.7	gradual increase	36.2	27.4 to 39.6	6.5	26.7	Tatham 1970
466	<i>Morone saxatilis</i>	striped bass	Percichthyidae	A	tunnel; Ucrit	2	12.0	3	87	78.6 to 95.4	7.4	10	Terpin et al. 1977
467	<i>Morone saxatilis</i>	striped bass	Percichthyidae	P	tunnel; Ucrit	18	5.5	10	58.2	3 SE		18.3 to 24.9	Young and Cech 1993
468	<i>Morone saxatilis</i>	striped bass	Percichthyidae	P	tunnel; Ucrit	18	5.5	10	76.5	3.3 SE		18.3 to 24.9	Young and Cech 1993
469	<i>Morone saxatilis</i>	striped bass	Percichthyidae	P	tunnel; Ucrit	18	5.5	10	60.4	3.2 SE		18.3 to 24.9	Young and Cech 1993
470	<i>Morone saxatilis</i>	striped bass	Percichthyidae	P	tunnel; Ucrit	18	5.5	10	74	3.3 SE		18.3 to 24.9	Young and Cech 1993
471	<i>Mugil cephalus</i>	mullet	Mugilidae	A	tunnel; Ucrit	3	13.4	3	86.1	74.4 to 99.1	6.45	15	Wyllie et al. 1976
472	<i>Mugil cephalus</i>	mullet	Mugilidae	A	tunnel; Ucrit	4	12.3	3	101.8	98.8 to 105.5	8.48	20 to 25	Wyllie et al. 1976
473	<i>Mugil cephalus</i>	mullet	Mugilidae	A	tunnel; Ucrit	79	3.5	9	44.5	20 to 66	12.71	15 to 25	Rulifson 1977
474	<i>Noemacheilus barbatulus</i>	stone loach	Balitoridae	O	tunnel; Ucrit	32	11.0	6.7	60.8		5.5	18	Stahlberg and Peckmann 1987
475	<i>Oncorhynchus gorbuscha</i>	pink salmon	Salmonidae	P	tunnel; Ucrit	103	54.0	10 to 15	114.9	41.2 SD	2.34	15	Williams and Brett 1987
476	<i>Oncorhynchus gorbuscha</i>	pink salmon	Salmonidae	P	tunnel; Ucrit	116	51.2	10 to 15	100	45.6 SD	2.15	15	Williams and Brett 1987

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477	<i>Oncorhynchus gorbuscha</i>	pink salmon	Salmonidae	P	tunnel; Ucrit	17	53.6	10 to 15	165.1	46.8 SD	3.39	15	Williams and Brett 1987
478	<i>Oncorhynchus gorbuscha</i>	pink salmon	Salmonidae	P	tunnel; Ucrit	31	51.3	10 to 15	129.5	37.7 SD	2.78	15	Williams and Brett 1987
479	<i>Oncorhynchus gorbuscha</i>	pink salmon	Salmonidae	P	tunnel; Ucrit	65	53.9	10 to 15	114.7	52.4 SD	2.34	15	Williams and Brett 1987
480	<i>Oncorhynchus gorbuscha</i>	pink salmon	Salmonidae	P	tunnel; Ucrit	97	50.7	10 to 15	106.5	43.3 SD	2.31	15	Williams and Brett 1987
481	<i>Oncorhynchus kisutch</i>	coho salmon	Salmonidae	P	tunnel; Ucrit	10	14.2	5	86.9		6.3	10.5 to 13	Mackinnon and Farrell 1992
482	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	22	8.1	6	38.8	1.28 SE	4.88	15.5	Wilson and Wood 1992
483	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	14	25.7	10	121.2	95.7 to 143.2	4.74	14	Mulchaey 1994
484	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	14	26.2	10	109.7	83.7 to 145.0	4.2	14	Mulchaey 1994
485	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	8	9.3	5	37.2	1.9 SE	4.13	15	Wilson et al. 1994
486	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	8	10.0	5	43.5	1.2 SE	4.48	15	Wilson et al. 1994
487	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit		35.2	0.25 bl/s	82		2.35	10	Thorarensen et al. 1996
488	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	56	10.3	2.5	43.4		4.34	6	Peake et al. 1997
489	<i>Oncorhynchus mykiss</i>	rainbow trout	Salmonidae	RW	tunnel; Ucrit	32	10.3	2.5	54.4		5.44	18	Peake et al. 1997
490	<i>Oncorhynchus nerka</i>	sockeye salmon	Salmonidae	P	tunnel; Ucrit	50	8.0	1 bl/s	60.1	0.5 SE	7.8	10	Taylor and Foote 1991

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491	<i>Oncorhynchus nerka</i>	kokanee	Salmonidae	L	tunnel; Ucrit	50	8.0	1 bl/s	53.3	0.53 SE	6.8	10	Taylor and Foote 1991
492	<i>Peprilus triacanthus</i>	butterfish	Stromateidae	A	tunnel; Ucrit	3	9.9	3	54.7	33.3 to 69.2	5.57	20	Wyllie et al. 1976
493	<i>Peprilus triacanthus</i>	butterfish	Stromateidae	A	tunnel; Ucrit	2	9.3	3	78.8	71.3 to 86.3	8.5	23	Terpin et al. 1977
494	<i>Perca fluviatilis</i>	European perch	Percidae	O	tunnel; Ucrit	5	5.4	gradual increase	58.2	55 to 62	10.8	19 to 21	Pavlov et al. 1972
495	<i>Perca fluviatilis</i>	European perch	Percidae	O	tunnel; Ucrit	4	3.5	gradual increase	43	37 to 49	12.3	19 to 21	Pavlov et al. 1972
496	<i>Perca fluviatilis</i>	European perch	Percidae	O	tunnel; Ucrit	3	4.5	gradual increase	65	60 to 70	14.4	19 to 21	Pavlov et al. 1972
497	<i>Phanerodon furcatus</i>	white seaperch	Embiotocidae	P	flume; 60-min. velocity	4	17.1		48		3.1	15 to 20	Dorn et al. 1979
498	<i>Poecilia reticulata</i>	guppy	Poeciliidae	O	tunnel; Ucrit	27	1.9	2.9	23.7	0.96 SE	13.7	27 to 29	Nicoletto 1991
499	<i>Poecilia reticulata</i>	guppy	Poeciliidae	O	tunnel; Ucrit	108		2.9	24.3	3.39 interquartile range		27 to 29	Nicoletto 1993
500	<i>Pogonichthys macrolepidotus</i>	splittail	Cyprinidae	P	flume; Ucrit	8	20.9	10	41		2	12	Young and Cech 1996
501	<i>Pogonichthys macrolepidotus</i>	splittail	Cyprinidae	P	flume; Ucrit	8	3.1	10	20		6.6	17	Young and Cech 1996
502	<i>Pogonichthys macrolepidotus</i>	splittail	Cyprinidae	P	flume; Ucrit	8	5.5	10	31		6.3	17	Young and Cech 1996
503	<i>Pogonichthys macrolepidotus</i>	splittail	Cyprinidae	P	flume; Ucrit	8	12.1	10	44		3.8	17	Young and Cech 1996
504	<i>Pogonichthys macrolepidotus</i>	splittail	Cyprinidae	P	flume; Ucrit	8	20.9	10	66		3.4	17	Young and Cech 1996

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
505	<i>Pogonichthys macrolepidotus</i>	spittail	Cyprinidae	P	flume; Ucrit	8	5.0	10	29		7	20	Young and Cech 1996
506	<i>Potamou salikator</i>	bluefish	Pomatomidae	A	McLeod apparatus	18	5.5	gradual increase	21.3	18.3 to 27.4	4	21.1	Tatham 1970
507	<i>Potamou salikator</i>	bluefish	Pomatomidae	A	tunnel; Ucrit	4	18.6	3	81	73.2 to 98.2	4.36	20	Wyllie et al. 1976
508	<i>Potamou salikator</i>	bluefish	Pomatomidae	A	tunnel; Ucrit	6	9.2	3	57	47.2 to 73.5	6.13	22 to 23	Wyllie et al. 1976
509	<i>Potamou salikator</i>	bluefish	Pomatomidae	A	tunnel; Ucrit	8	12.4	3	64	54.5 to 72.2	5.19	24 to 26	Wyllie et al. 1976
510	<i>Potamou salikator</i>	bluefish	Pomatomidae	A	tunnel; Ucrit	3	10.5	3	77.5	66.5 to 83.8	7.4	23	Terpin et al. 1977
511	<i>Prionotus carolinus</i>	northern searobin	Triglidae	A	tunnel; Ucrit	2	9.4	3	19.7	16.8 to 22.6	2.09	7 to 8	Wyllie et al. 1976
512	<i>Pseudopleuronectes americanus</i>	winter flounder	Pleuronectidae	A	tunnel; Ucrit	11	14.6	3	47.3	33.5 to 63.7	3.39	3.3 to 6.5	Wyllie et al. 1976
513	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; median fatigue velocity	173	36.6		100		2.91	12	Mesa and Olson 1993
514	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; median fatigue velocity				107		3.12	18	Mesa and Olson 1993
515	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; median fatigue velocity	172	44.8		104		2.45	12	Mesa and Olson 1993
516	<i>Ptychocheilus oregonensis</i>	northern pikeminnow	Cyprinidae	RW	tunnel; median fatigue velocity				112		2.65	18	Mesa and Olson 1993
517	<i>Ophidion marginatum</i>	striped cusk-eel	Ophidiidae	A	tunnel; Ucrit	2	17.5	3	22.1	21 to 23.2	1.28	6	Wyllie et al. 1976

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
518	<i>Rutilus rutilus</i>	roach	Cyprinidae	O	tunnel; Ucrit	9	4.9	gradual increase	41.9	34 to 52	8.55	19 to 21	Pavlov et al. 1972
519	<i>Rutilus rutilus caspicus</i>	Caspian roach	Cyprinidae	O	tunnel; Ucrit	12	2.8	gradual increase	31.4	21.5 to 38	11.4	19 to 21	Pavlov et al. 1972
520	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	16	9.6	10	44.8	1.4 SE	4.83	12.5	Stevens et al. 1998
521	<i>Salmo salar</i>	Atlantic salmon	Salmonidae	A	tunnel; Ucrit	15	11.1	10	44.2	2.65 SE	4.11	12.5	Stevens et al. 1998
522	<i>Salvelinus fontinalis</i>	brook trout	Salmonidae	RE	tunnel; Ucrit	6	12.0	3	51.3		5.13	15	Peterson 1974
523	<i>Salvelinus fontinalis</i>	brook trout	Salmonidae	RE		34	11.1	3	48.6		4.85	15	Peterson 1974
524	<i>Salvelinus fontinalis</i>	brook trout	Salmonidae	RE		6	11.4	3	46.3		4.63	15	Peterson 1974
525	<i>Scardinius erythrophthalmus</i>	rudd	Cyprinidae	O	tunnel; Ucrit	4	4.3	gradual increase	34.8	30 to 40	8.1	17	Pavlov et al. 1972
526	<i>Scardinius erythrophthalmus</i>	rudd	Cyprinidae	O	tunnel; Ucrit	4	6.7	gradual increase	36	all 36	5.4	21	Pavlov et al. 1972
527	<i>Sebastes mystinus</i>	blue rockfish	Scorpaenidae	P	flume; 60-min. velocity	5	16.6		55		4	15 to 20	Dorn et al. 1979
528	<i>Sebastes serranoides</i>	olive rockfish	Scorpaenidae	P	flume; 60-min. velocity	6	21.8		53		2.7	15 to 20	Dorn et al. 1979
529	<i>Sphyaena borealis</i>	northern sennet	Sphyraenidae	A	tunnel; Ucrit	4	14.5	3	39.3	32.6 to 50	2.72	25	Wyllie et al. 1976
530	<i>Sprattus sprattus</i>	sprat	Clupeidae	A	flume; Ucrit	13	4.4	10	45.3	8.5 SD	11.47	16.2	Turnpenny 1983
531	<i>Sprattus sprattus</i>	sprat	Clupeidae	A	flume; Ucrit	40	3.9	10	30.7	3.3 SD	8.77	16.2	Turnpenny 1983
532	<i>Sprattus sprattus</i>	sprat	Clupeidae	A	flume; Ucrit	28	4.5	10	56.3	4.7 SD	13.9	16.3	Turnpenny 1983

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
533	<i>Sprattus sprattus</i>	sprat	Clupeidae	A	flume; Ucrit	30	4.2	10	38.4	4.5 SD	10.1	19	Turnpenny 1983
534	<i>Sprattus sprattus</i>	sprat	Clupeidae	A	flume; Ucrit	19	4.6	10	47.7	5.2 SD	11.5	16.2	Turnpenny 1983
535	<i>Sprattus sprattus</i>	sprat	Clupeidae	A	flume; Ucrit	38	3.6	10	36.7	3.9 SD	11.3	16.9	Turnpenny 1983
536	<i>Stenotomus chrysops</i>	scup	Sparidae	A	tunnel; Ucrit	3	10.8	3	62.8	53.6 to 70.1	5.78	17	Wyllie et al. 1976
537	<i>Stenotomus chrysops</i>	scup	Sparidae	A	tunnel; Ucrit	2	8.6	3	77.9	69.5 to 86.3	9	23	Terpin et al. 1977
538	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	3	15.2	3	31.3	27.7 to 34.4	2.07	2	Wyllie et al. 1976
539	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	12	9.8	3	28.4	21.4 to 34.5	3.03	3 to 3.5	Wyllie et al. 1976
540	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	6	16.7	3	50.4	38.2 to 69.5	3.06	4 to 4.4	Wyllie et al. 1976
541	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	6	14.2	3	37.2	31 to 42.6	2.64	5	Wyllie et al. 1976
542	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	6	12.9	3	34.1	30.8 to 38.7	2.72	6	Wyllie et al. 1976
543	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	3	13.4	3	34.8	27.1 to 43.9	2.7	7	Wyllie et al. 1976
544	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	4	16.3	3	46.4	41.8 to 52.12	2.85	10	Wyllie et al. 1976
545	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	7	16.9	3	51.4	47.2 to 61.3	3.13	12 to 13	Wyllie et al. 1976
546	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	4	14.2	3	50.3	45.1 to 56.1	3.55	15	Wyllie et al. 1976
547	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	3	17.0	3	46	40.5 to 53.3	2.71	19	Wyllie et al. 1976

Table of Critical Swimming Speeds for Fish

Obs.	Species	Common name	Family	Assemblage	Experiment type	Number of fish	Adjusted average length (cm)	Velocity increments	Average critical velocity (cm/s)	Variation in average critical velocity	Average critical velocity (BL/s)	Experimental temperature (C)	Reference
548	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	4	15.6	3	38.4	36 to 43.3	2.5	5	Terpin et al. 1977
549	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	6	11.9	3	41.9	35.1 to 56.1	3.6	10	Terpin et al. 1977
550	<i>Urophycis chuss</i>	red hake	Phycidae	A	tunnel; Ucrit	4	13.9	3	46.5	35.7 to 59.4	3.4	15	Terpin et al. 1977
551	<i>Urophycis regius</i>	spotted hake	Phycidae	A	tunnel; Ucrit	6	9.4	3	28.8	24.1 to 36.8	3.1	4	Wyllie et al. 1976
552	<i>Urophycis regius</i>	spotted hake	Phycidae	A	tunnel; Ucrit	5	10.2	3	28.9	25.9 to 31.7	2.83	5	Wyllie et al. 1976
553	<i>Urophycis regius</i>	spotted hake	Phycidae	A	tunnel; Ucrit	4	9.9	3	33.9	28.7 to 37.8	3.46	6 to 7	Wyllie et al. 1976
554	<i>Urophycis regius</i>	spotted hake	Phycidae	A	tunnel; Ucrit	6	11.3	3	50.4	39.9 to 62.5	4.49	11 to 12	Wyllie et al. 1976
555	<i>Urophycis regius</i>	spotted hake	Phycidae	A	tunnel; Ucrit	8	14.2	3	53	48.8 to 60	3.78	23 to 25	Wyllie et al. 1976
556	<i>Urophycis regius</i>	spotted hake	Phycidae	A	tunnel; Ucrit	4	10.2	3	51.2	31.7 to 69.2	5	15	Terpin et al. 1977
557	<i>Urophycis tenuis</i>	white hake	Phycidae	A	tunnel; Ucrit	3	13.0	3	40.9	37.2 to 45.1	3.26	20 to 21	Wyllie et al. 1976

Assemblage types: A=Atlantic coast; P=Pacific coast; L=Lakes; RE=Rivers in eastern U.S.; RW=Rivers in western U.S.; O=others.

B

FISH ENDURANCE (FATIGUE TIMES AT CONSTANT VELOCITIES)

As discussed in the text (Section 4.2), several methods have been used to express or display the time a fish can continue to swim at a constant velocity. There have been few studies of fish endurance compared to the number of studies of critical swimming speed (or slight variations of it) given in Appendix A. The few endurance studies have used different display methods. The most common is a graph comparing time to fatigue on the vertical axis to swimming speed on the horizontal axis, with swimming speed being given in values of body lengths per second. Data tables for the graphs have almost never been published. Without original data in hand, it is difficult to relate these graphs to absolute velocities that are of interest for application to impingement issues (e.g., in cm/s). With some difficulty, the data might be obtained from authors and converted to absolute velocities. We did not do this.

This appendix presents the graphs published by the original investigators, labeled with species and reference. We have also included the original legends, for purposes of explanation. These graphs and their references may serve as starting points for further analyses by persons interested in the performance of a particular species. Such analyses of endurance may be important for evaluating acceptable lengths of intake canals, for instance.

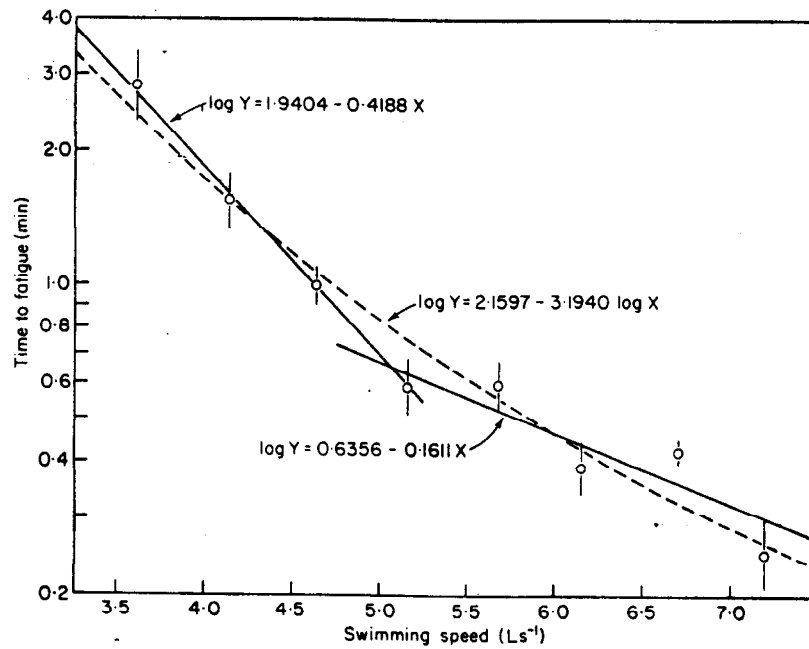


FIG. 1. Relation between swimming endurance time and swimming speed of elvers of the European eel. O, geometric mean; bar, ± 1 standard error; solid lines, semi-logarithmic least squares regression lines; dashed line, logarithmic least squares regression line.

Figure B-1

Relationship between swimming endurance time and swimming speed of *Anguilla anguilla* (European eel), with original figure legend. From McCleave (1980).

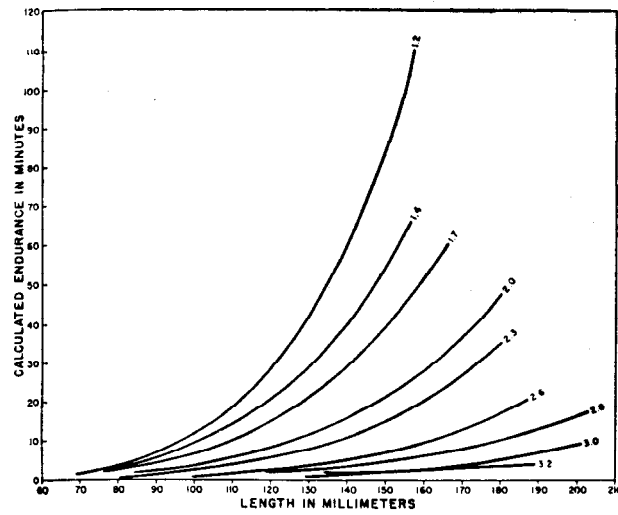


FIGURE 3.—Calculated length endurance relationship of herring exposed to various currents. (Figures at extreme end of curves represent water velocity in feet per second.)

Figure B-2
Relationship between swimming endurance time and length of *Clupea harengus* (Atlantic herring), for a range of velocities, with original figure legend. From Boyar (1961).

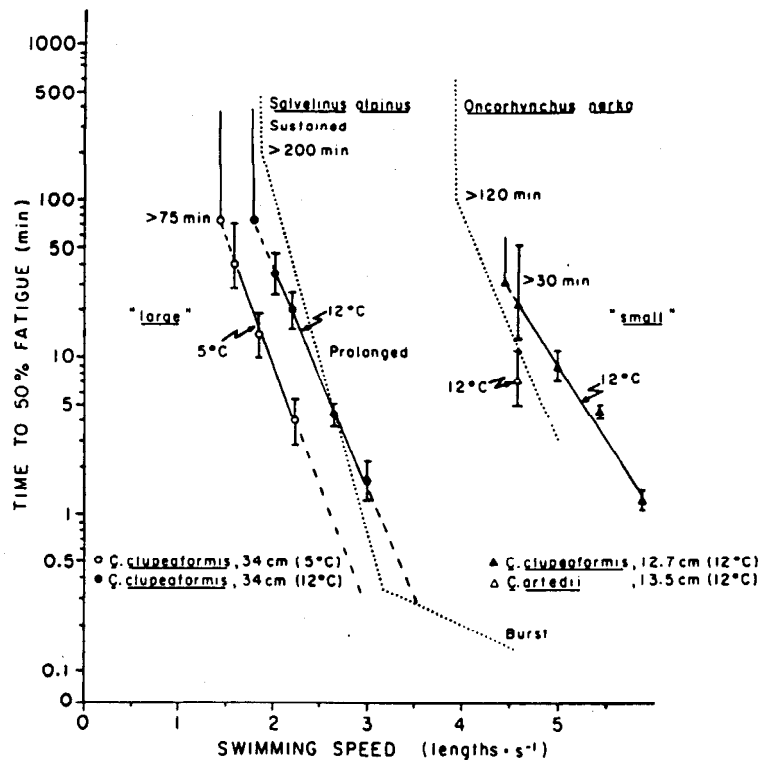


FIG. 3. Relationship between time to 50% fatigue and swimming speed ($\text{lengths} \cdot \text{s}^{-1}$) for lake whitefish and cisco. Horizontal lines indicate 95% confidence intervals. Only one swimming speed could be tested for cisco. Sustained swimming speeds are represented by velocities that could be maintained without fatigue for more than 75 min for 34-cm lake whitefish and more than 30 min for the 12.7-cm lake whitefish. Broken lines represent extrapolations of the fatigue time – swimming speed relationship. The relationship between time to 50% fatigue and swimming speed for *S. alpinus* (34 cm) and *O. nerka* (13.5 cm) were determined by Beamish (1980) and Brett (1967), respectively. Note that smaller fish can swim relatively faster than large fish.

Figure B-3

Relationships between swimming endurance times and swimming speed (body lengths per second) for *Coregonus artedii* (cisco) and *Coregonus clupeaformis* (lake whitefish), compared to two other species studied by others, with original figure legend. From Bernatchez and Dodson (1985).

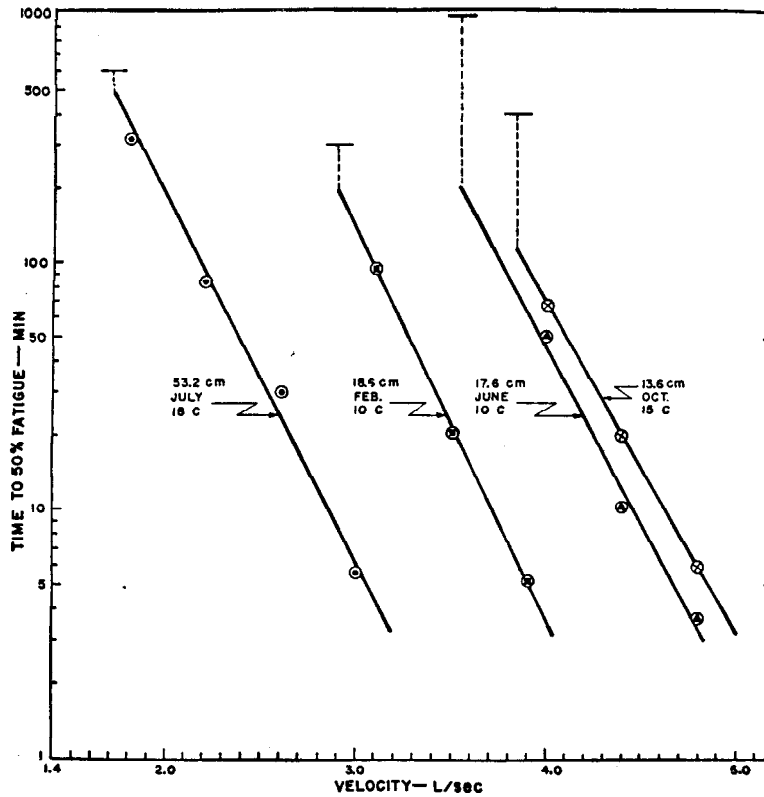


FIG. 3. The relation between time to 50% fatigue (FT_{50}) and velocity (length/sec) for a variety of sizes of sockeye salmon. The temperatures and times of year when the fatigue curves were obtained are indicated. Sustained performance of more than 50% of the fish occurred at the points of inflection (broken lines). Horizontal lines depict the termination time for each test. Experiments on adult salmon (53.2 cm) from Brett and Shoop (unpublished data); those for 18.6 cm and 17.6 cm yearling sockeye from Brett (1964).

Figure B-4
Relationships between swimming endurance times and swimming speeds (body lengths per second) for *Oncorhynchus nerka* (sockeye salmon), with original figure legend. From Brett (1967).

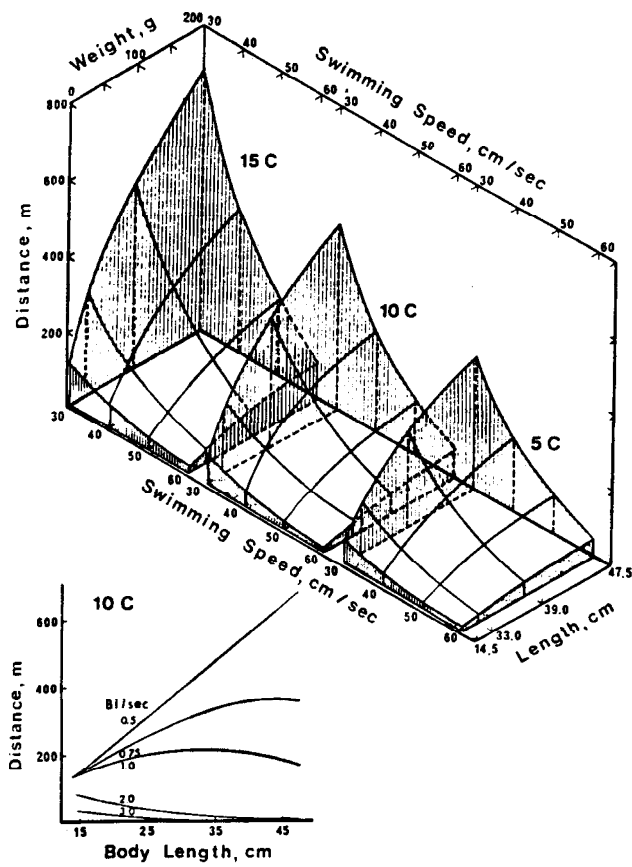


FIGURE 1.—Distance sea lampreys swam in relation to speed, body weight, and temperature. In the lower panel distance at different swimming speeds, expressed as body length (BL)/sec, is presented in relation to body length.

Figure B-5
Distance swam in relation to speed, body weight, and temperature for *Petromyzon marinus* (sea lamprey), with original figure legend. From Beamish (1974).

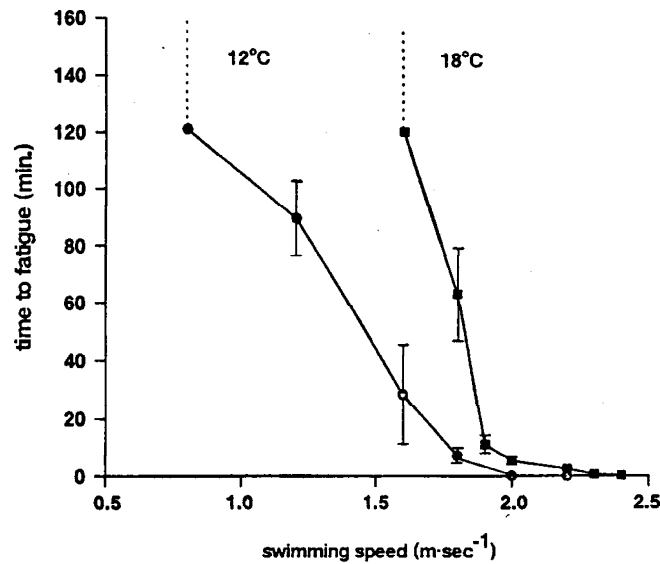


Figure 2. - Calibration of muscle activity with swimming performance in wild Atlantic salmon (N = 5), at 18°C and 12°C. Muscle activity was measured using radio transmitted electromyogram signals from the musculature of adult salmon under forced swimming conditions using a Blazka-type swim chamber.

Figure B-6
Relationship between swimming endurance times and swimming speed for *Salmo salar* (Atlantic salmon), with original figure legend. From Booth et al. (1997).

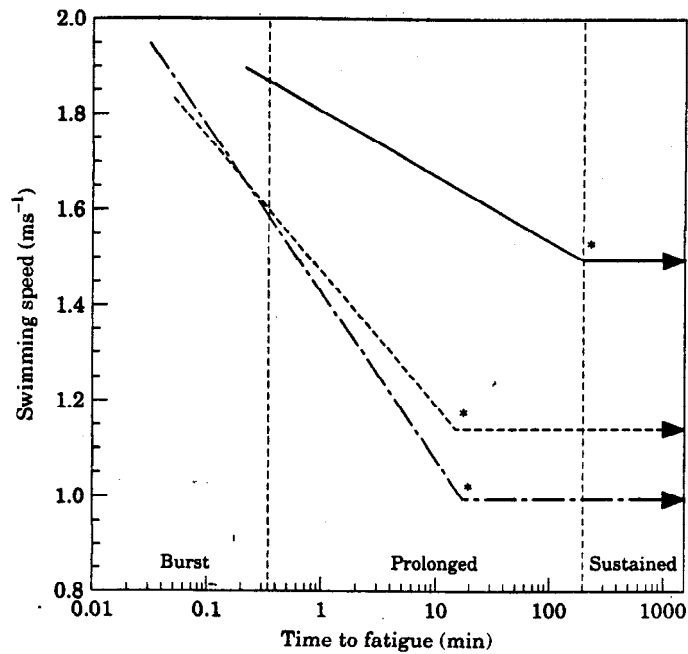


FIG. 2. A comparison of sustained, prolonged, and burst swimming capabilities of anadromous Atlantic salmon smolts (-----) and landlocked Atlantic salmon (-----). Horizontal lines with arrows indicate mean sustainable speeds, taken from Table I, for anadromous (mean length: 15.2 cm) and landlocked salmon (mean length: 15.4 cm) respectively. Line positions were calculated for 15.2- and 15.4-cm anadromous and landlocked fish, using prolonged/burst models given in Table I. Lines extend from the lowest swimming time recorded to the highest. Dotted lines indicate where one swimming mode should transition to another according to Beamish (1978). *Indicates where the transition from sustained to prolonged swimming modes actually occurred. A typical endurance curve (—) is shown also.

Figure B-7

Relationship between swimming endurance times and swimming speed for anadromous and land-locked *Salmo salar* (Atlantic salmon), with original figure legend. From Peake et al. (1997).

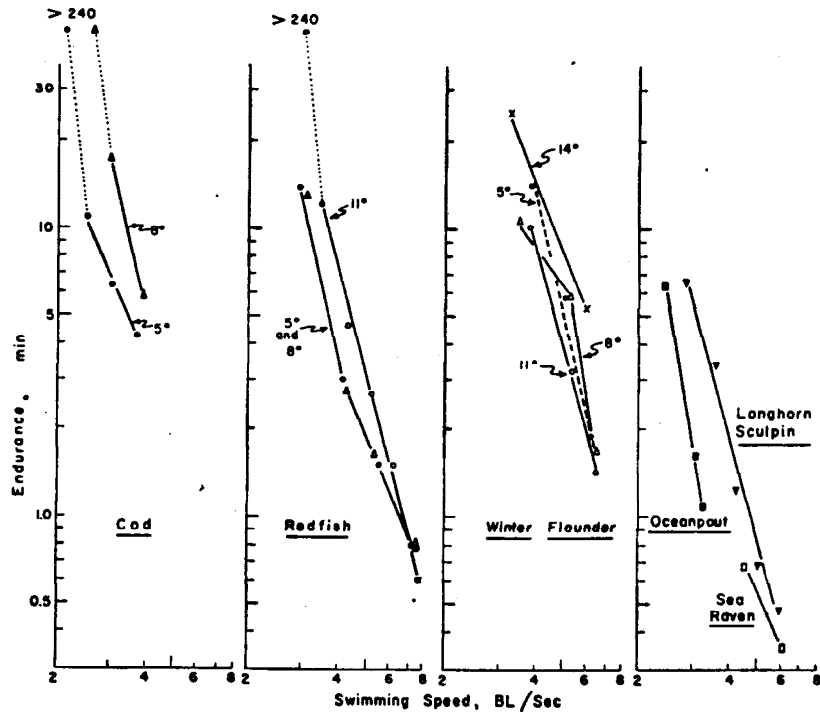


FIG. 2. Swimming endurance of six species calculated on basis of swimming speed in body lengths per second. Where endurance was more than 240 min it was taken as continuous. Broken lines connect continuous swimming with endurance of under 240 min.

Figure B-8
Relationships between swimming endurance and swimming speeds for several species of North Atlantic coastal marine fish, with original figure legend. From Beamish (1966).

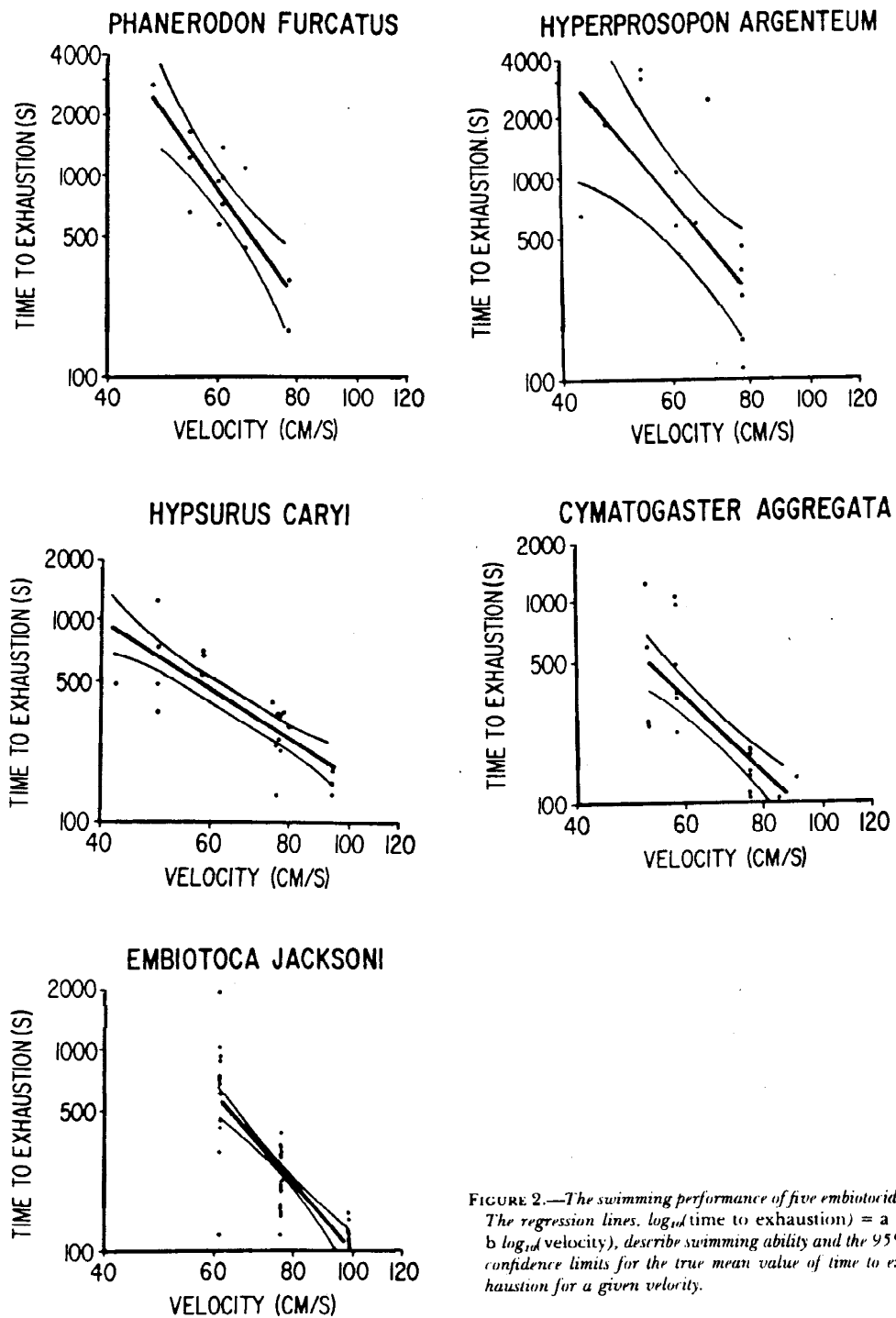


FIGURE 2.—The swimming performance of five embiotocids. The regression lines, $\log_{10}(\text{time to exhaustion}) = a + b \log_{10}(\text{velocity})$, describe swimming ability and the 95% confidence limits for the true mean value of time to exhaustion for a given velocity.

Figure B-9 Relationships between swimming endurance and swimming speed for five species of southern California coastal marine fish, with original figure legend. From Dorn et al. (1979).

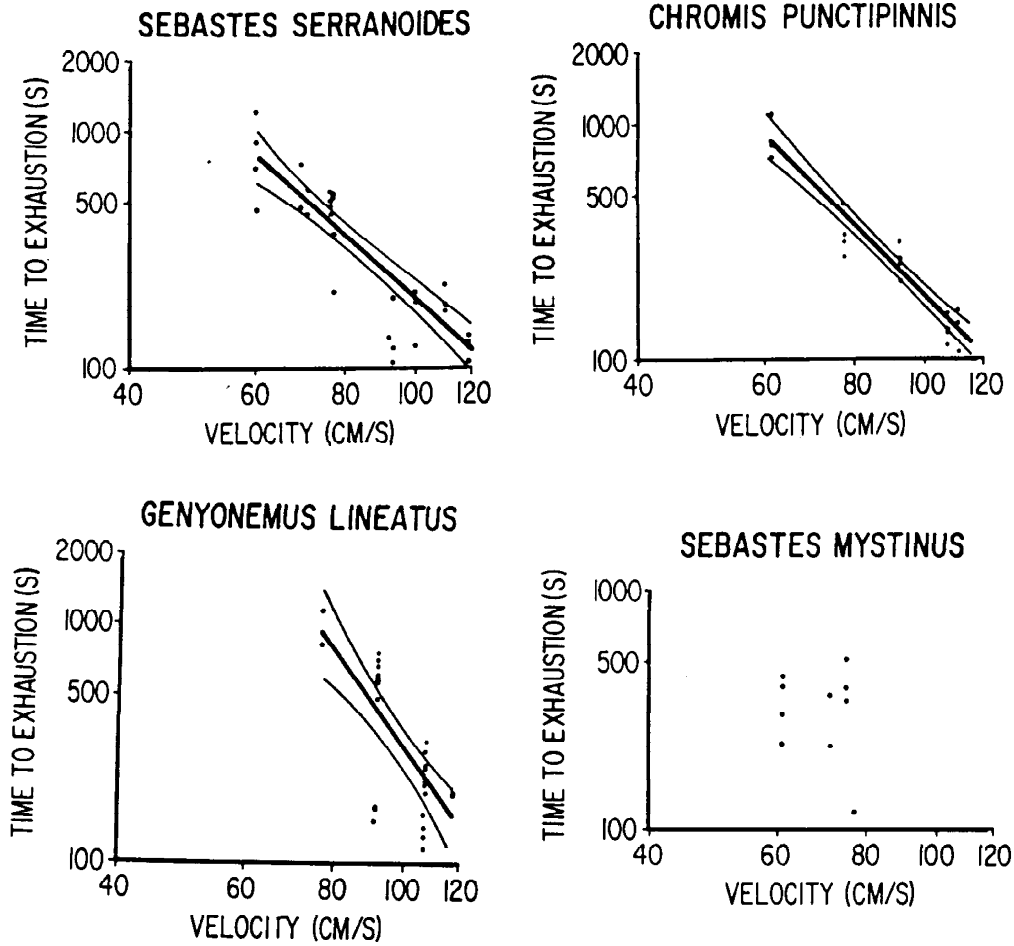


FIGURE 3.—The swimming performance of *Sebastes mystinus*, *S. serranoides*, *Chromis punctipinnis*, and *Genyonemus lineatus*. The regression lines, $\log_{10}(\text{time to exhaustion}) = a + b \log_{10}(\text{velocity})$, describe swimming ability and the 95% confidence limits for the true mean value of time to exhaustion for a given velocity. *Sebastes mystinus* data did not fit a line within the 95% confidence limits.

Figure B-10
Relationships between swimming endurance and swimming speed for four species of southern California coastal marine fish, with original figure legend. From Dorn et al. (1979).

Target:


Section 316 (a) and (b) Fish Protection Issues

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