

# Entrapment and Impingement of Fishes by Power Plant Cooling-Water Intakes: An Overview

CHARLES H. HANSON, JAMES R. WHITE, and HIRAM W. LI

*ABSTRACT—An overview of the recent information available on fish entrapment and impingement by power plant cooling-water intakes is presented. The types of biological problems caused by intake structures, the strengths and weaknesses of various water intake/fish protection systems, and the biological/ecological processes relevant to this problem are discussed. Factors contributing to direct and delayed mortality in screen-impinged fish are examined with emphasis on the relationship between water velocity, impingement time, and physiological stress. In considering the present state of developing impact assessments we have pointed out areas which need refinement, omissions, and limitations of our present knowledge. The biological impact of water withdrawal for power plant cooling can be minimized by consideration of intake siting and design criteria including site evaluations, cooling system design (i.e., closed-cycle cooling or once-through cooling system), and the use of guidance, diversion, and fish salvage systems. We conclude that future research should focus on examining basic behavioral and physiological mechanisms associated with fish entrapment and impingement in combination with ecological processes of those populations and communities influenced by proposed and existing projects.*

## INTRODUCTION

Despite pleas for energy conservation, the demand for new electrical generating plants has continued to increase. This rapid growth in generating capacity will continue to place new demands on the nation's water resources to provide cooling water needed for steam condensation. Entrainment,<sup>1,2</sup> entrapment,<sup>3</sup> and impingement<sup>4</sup> of fish and other aquatic organisms by water intake structures and the discharge of thermal and chemical effluents create potentially serious environmental problems.

Aroused public concern for the conservation of natural resources is reflected in the enactment of the Federal Water Pollution Control Act of 1972 (Public Law 92-500). This act emphasizes the need to minimize thermal effects associated with discharges from power plant cooling systems (Section 316a) and the need to minimize entrainment, entrapment, and impingement of aquatic biota by cooling-water intake structures (Section 316b). Section 316b of Public Law 92-500 requires that each intake system reflect the best available design and technology for minimizing deleterious effects on aquatic life and assuring continued balance of aquatic ecosystems. However, no clear guidance or criteria are available to date for determining whether an adverse environmental im-

pact has occurred. The environmental consequences of such losses, whether from entrainment or impingement, can be evaluated only in the context of the effect on the ecological balance of the aquatic community.

The purpose of this review is to describe the types of problems caused by intake structures, to assess the strengths and weaknesses of various water intake/fish protection systems, to summarize the extent of our understanding of biological processes relevant to this problem, and to propose the direction for future research which will lead to the design of better intake structures.

## OVERVIEW OF THE PROBLEM

Population growth and the shift of our culture towards energy-intensive activities will combine to increase the demand for energy in the decades ahead. A concomitant increase in the demand for cooling water is inevitable. To characterize the magnitude of this demand, consider that conventional 1,000 MWe (megawatts electrical) fossil fuel and nuclear power plants require cooling water at a rate of approximately 50 and 75 m<sup>3</sup>/s, respectively. This demand is currently being met by diverting natural surface waters which also serve as habitat for a diverse aquatic flora and fauna.

The use of natural surface waters for thermal dissipation from steam electric generating stations imposes two major potential sources of damage on aquatic organisms: thermal discharges and mortality at cooling-water intakes. Effects of the thermal component of power plant effluent have been extensively studied and widely publicized. However, the potentially adverse impact on aquatic organisms resulting from entrainment, entrapment, and impingement by cooling-water intake systems went largely unnoticed until the early 1970's. Expanded awareness of the magnitude of intake related problems has precipitated an intensive effort by regulatory agencies, power utilities, and environmental consultants to document the problem, arrive at rational decisions regarding the consequences of these losses, and formulate

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

<sup>2</sup> For information on entrainment, see reviews by Beck and Miller (1974) and Marcy (1975).

<sup>3</sup> Entrapment refers to the physical blocking of larger entrained organisms by a barrier, generally some type of screen located within the intake structure.

<sup>4</sup> Impingement occurs when the entrapped organism is held in contact with the barrier.

*The authors are with the Division of Wildlife and Fisheries Biology, University of California, Davis, Davis, CA 95616.*

acceptable solutions for minimizing adverse environmental effects.

Power plants having cooling system intakes which impinge excessive numbers of fish may be required to implement closed-cycle (recirculating) cooling systems, thus reducing the required cooling-water volume and decreasing the intake approach velocity which should result in lower impingement mortality. Closed-cycle cooling has been proposed as the best available technology for minimizing the adverse impact of cooling-water intake structures on fisheries resources and aquatic ecosystems (Anonymous<sup>5</sup>). Closed-cycle cooling, however, is expensive to install in existing plants and may not, in all cases, represent the most efficient design for a particular site. In cases where entrainment or impingement mortality is considered excessive, all potential alternative methods should be considered.

A major conflict exists, however, in evaluating the significance of fish losses resulting from impingement and arriving at rational criteria for establishing the level of intake damage which is legally "acceptable." For example, one power station located on a river in the midwest United States impinges an estimated 100,000 fish per year. A Gulf coast station, on the other hand, impinges an estimated 20 million fish per year. In each case, impinged fish ranged from 40 to 100 mm in length and represented juvenile life stages. What is the potential impact on the aquatic ecosystem resulting from the loss of these fish? Clearly each must be viewed as a separate case, unique in terms of the species involved, the characteristics of the receiving water ecosystems, and the potential impact.

## IMPINGEMENT DAMAGE

Conventional intake systems rely on screens to prevent the entry of debris and large fish, but these systems do not completely prevent the passage of small fish. In addition, it is difficult to predict

<sup>5</sup> Anonymous. 1975. Guidelines to determine best available technology for the location, design, construction, and capacity of cooling water intake structures for minimizing adverse environmental impact. Section 316(b) P.L. 92-500. U.S. Environ. Prot. Agency. Unpubl. Manuscr., 69 p.

the magnitude of entrainment and entrapment by various intake designs, especially in power plants sited in estuaries which serve as nursery areas for anadromous and marine species. Entrapment and impingement of juvenile and adult fish may result in immediate death due to mechanical abrasion and suffocation. Exposure to stress conditions which does not result in immediate death may lead to eventual mortality of the organism due to a lowered resistance to predation and disease or an inability to actively compete for food. Severity of the loss of juvenile fish may not be noticeable for some time since mean generation time for many species is measured in years. By this time changes in the population dynamics and structure may be substantial and irreversible.

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

Historically, intake design criteria have been developed on a trial-and-error basis. It is apparent from Table 1 that this technique has resulted in limited success. Some intake designs have functioned well; however, extrapolations from one site to another frequently yield unacceptable results. It is obvious that no one has understood why a par-

ticular design worked at one site and not at another. Existing criteria lack generality and precision because studies leading to an understanding of basic mechanisms were not made.

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

The damage incurred by fish at water intakes depends on the species, the stage of life history, and size. Survival of fish encountering an intake is in part a function of preimpingement excitement and stress. Chittenden (1973) observed the variability of the effects of handling on American shad, *Alosa sapidissima*, concluding that the intensity of excitement determined whether the fish lives, dies immediately, or dies later. Several investigators reported delayed mortality of fish following periods of hyperactivity and the associated lactic acid accumulation in the blood (Black, 1958; Beamish, 1966; Chittenden, 1973). Lactic acid, the end product of the biochemical pathway

Table 1.—Estimated entrapment-impingement losses at several power plant cooling-water intakes.

Plant	Location	Study duration	No. of fish	Reference
Allen Steam Station	Lake Wylie	Oct. 1973-Sept. 1974	898,913	Edwards et al. (1976)
Oconee Nuclear Station	Lake Keowee	July 1974-May 1975	1,064,262	Edwards et al. (1976)
Marshall Steam Station	Lake Norman	Apr. 1974-Mar. 1975	3,769,300	Edwards et al. (1976)
Buck Steam Station	Yadkin R.	July 1974-June 1975	4,069	Edwards et al. (1976)
Palisades Nuclear Power Plant	Lake Michigan	July 1972-June 1973	584,687	Edsall (1975)
Waukegan Generating Station	Lake Michigan	June 1972-June 1973	1,200,000	Edsall (1975)
Nine Mile Point	Lake Ontario	Jan.-Dec. 1973	5,000,000	Edsall (1975)
Zion Plant	Lake Michigan	Sept.-Dec. 1973	929,000	Edsall (1975)
Quad Cities Plant	Mississippi R.	Mar.-June 1974		
Muddy Run Pumped Storage Generating Plant	Susquehanna R.	Jan.-Dec. 1974	10-14,000,000	Truchan (1975) <sup>1</sup>
		June-July 1970	256,600,000	Snyder (1975)

<sup>1</sup> Truchan, J. G. 1975. Guidelines to determine best available technology for the location, design, construction, and capacity of cooling water intake structures for minimizing adverse environmental impact, Sec. 316(b) P.L. 92-500. Unpubl. manuscr., 69 p. U.S. Environ. Prot. Agency.

<sup>2</sup> Entrainment and subsequent passage of juvenile fishes.

(glycolysis) which meets energy demands of muscle tissue during anaerobic metabolism, accumulates in the circulatory system during periods of excitement or intense swimming effort. Energy demands of swimming during entrainment or entrapment result in increased concentration of lactic acid in the tissues causing muscle fatigue and suffocation (Dominy, 1971). Probable causes of delayed mortality following preimpingement excitement include acidosis and inadequate oxygenation of blood due to the Bohr effect.

Fish impinged on power plant intake screens are killed outright or may suffer delayed mortality due to exhaustion, suffocation, or external or internal injury. The extent of physical damage is directly related to the duration of impingement, techniques of handling impinged fish, and the intake water velocities. Pressure due to the latter hinders respiration, especially critical for fish fatigued prior to impingement. Factors contributing to delayed mortality in screen-impinged fish have been examined exclusively in short-term survival studies. Very little information exists on indirect delayed mortality in impinged fish as a result of increased susceptibility to disease or predation for those fish which successfully bypass the diversion and are returned to the receiving waters.

Since the species and life history stages of fish differ from one geographical region to another it is not surprising that impingement mortality varies greatly from one site to another. For example, juvenile menhaden, blueback herring, striped bass, alewives, and shad appear to be particularly vulnerable to impingement. Catfish, carp, and many salmonids, on the other hand, appear to be relatively less sensitive to impingement stresses. Furthermore, it has been shown (Prentice and Ossian-der, 1974; Skinner, 1974) that as fish size increases, mortality resulting from impingement decreases.

The relationship between water velocity and impingement time on physiological stress and survival has been examined by Prentice and Ossian-der (1974). In general, the degree of oxygen stress observed in juvenile salmon increased with both increasing

water velocity and increasing impingement time. For example, oxygen stress and a loss of equilibrium were evident in fish impinged 15 min at a water velocity of 61 cm/s. Reduced activity was evident in fishes 48 h after impingement of 9 min or longer at a velocity of 61 cm/s. As might be expected, survival decreased as the duration of impingement and water velocity increased.

Prentice and Ossian-der (1974) reported internal hemorrhaging in impinged salmonids and found the minimal velocity at which hemorrhaging occurred was approximately 46 cm/s. At 61 cm/s hemorrhaging occurred in approximately 10 percent of the fish tested after a 30-s impingement, increasing to 33 percent after impingement for 60 s. Bell (1974) observed internal hemorrhaging, eye loss, and bent gill opercula in fish as a result of impingement. Impingement may also result in fish being partially descaled. Loss of scales destroys the integrity of the protective body covering causing disruption of essential osmotic differentiation between fish body fluids and their environment and increasing susceptibility to disease and parasitism. Clupeids, which have deciduous scales, are particularly vulnerable to descaling. Mortality among this group as a result of impingement and mechanical damage has been high.

Smith et al.<sup>6</sup> found the injury rate resulting from scale loss was inversely proportional to fish size (i.e., small fish are affected greatly by scale loss). They reported that delayed mortality following partial descaling was a significant problem; studying salmon (*Oncorhynchus* spp.) less than 30 cm in length, death occurred 3-18 h after 30-50 percent scale loss. In addition, fish behavior after scale loss was observed to change markedly. One hour after descaling, juvenile salmon were noticeably less active and less alert to visual stimuli than were controls. Loss of equilibrium occurred approximately 3 h

<sup>6</sup>Smith, L. S., J. B. Saddler, R. D. Cardwell, A. J. Mearns, H. M. Miles, and G. T. Sakagawa. 1969. Some physiological changes in juvenile Pacific salmon after capture and tagging. Fish. Res. Inst., Coll. Fish., Univ. Wash. Rep., Seattle, Wash. Unpubl. manuscr., 29 p.

after descaling, followed by a decrease in respiration and activity. In general, death occurred approximately 4 h after descaling. The time sequence varied with the severity of scale loss. Loss of body weight followed descaling in marine species, presumably as the result of osmotic removal of water and body fluid through the injured skin surface and the gills. Delayed mortality resulting from scale loss may arise from an osmotic imbalance and an increased susceptibility to infection and disease. In addition, physiological stress due to scale loss may substantially decrease the ability of a fish to avoid predators.

Mortality resulting from mechanical abrasion may increase in areas characterized by high silt and debris loading. High debris densities and algal mats have been reported to trap and impinge fish on intake screens.

Accumulation of debris on trash racks and intake screens not only serves to entrap and entangle fish, resulting in increased mechanical damage, but also effectively alters the hydraulic flow field and approach velocities associated with each intake structure. High concentrations of suspended sediment abrade the eyes, gills, and epidermal tissue of impinged fish. Environmental factors such as suspended sediments and debris loading may significantly reduce the effectiveness of an otherwise acceptable cooling-water intake.

From the literature it appears that mechanical damage may be a significant factor in survival of entrapped and impinged organisms. However, data are insufficient to evaluate the conflicting nature of many of the findings. Refinement in sampling methodologies is a prerequisite for accurately determining the importance of mechanical abrasion as a source of biological damage.

## IMPACT ASSESSMENT

Predicting the magnitude of fish loss resulting from entrapment and impingement by cooling system intakes is a major challenge. Estimating the population and community response to intake related mortality of either a proposed or existing power plant is extremely complex. Mathematical

models of population dynamics have been utilized to evaluate the potential impact of a project on the aquatic ecosystem. Model simulations typically include estimates of species diversity and abundance, the ecological role of susceptible species and their reproductive strategies, and the location and design of the power plant and its condenser cooling-water system.

Model simulations to date, however, have been hindered by inadequate information regarding entrainment and impingement mortality and the population dynamics of those organisms inhabiting the area. This lack of information—particularly on natural mortality levels, age specific fecundity rates, immigration and emigration, recruitment into the population from surrounding areas as well as recruitment from one age class to another within a population—has forced model simulations to rely on unsubstantiated assumptions or estimates. The problems of predictive modeling are compounded by the intake of larval and juvenile fish which pose a particularly serious problem due to their high vulnerability during early life stages and long population regeneration times. The importance of these larval and juvenile fish cannot be underestimated since they form the biological foundation for recruitment into the adult population. Confidence in available models is reduced since impact assessments based on model predictions have not been independently verified in field studies. Despite these drawbacks, predictive models serve an important function in integrating available data and providing an estimate useful in evaluating the impact (assessment) of a particular project.

In the process of developing impact estimates from mathematical models, it has become apparent that there is a need for standardization of information concerning engineering, water quality, and ecological data. Data are needed to evaluate once-through cooling systems and alternative technologies. A great deal of work on entrapment and impingement of fish in power plant cooling systems either has not been published or is contained only in reports which have limited distribution. Data omission and lack of statistical accu-

racy in many existing reports makes interpretation of available information exceedingly difficult.

Information on the mechanisms of population regulation for species subject to intake-related mortality is a prerequisite to evaluating the effect of impingement mortality at the population level. Research defining the temporal and spatial distributions of important species at critical life stages is required to estimate the vulnerability of a species to entrainment, entrapment, and subsequent impingement. An evaluation of the potential biological impact resulting from impingement necessarily involves integration of biological data with physical data on the hydrology, tidal flux, and hydraulics of the particular environmental system in question. Finally, there is a need to assess the impact of entrainment and impingement mortality, natural mortality, and the cumulative effects of multiple mortality sources on the population and recovery potential in the receiving waters. Regulatory decisions are currently based on often inadequate information regarding fish behavior, entrainment and impingement mortality, and the population dynamics of the receiving water ecosystem for determining the environmental impact resulting from power plant cooling systems.

The ultimate consideration—the impact of intake-related mortality on the community dynamics or the trophic structure of the receiving water ecosystem—has not been determined. Evaluation of short- and long-term responses of organisms directly affected by entrainment, entrapment, or impingement are required to determine subtle alterations in trophic interactions and energy flow through the aquatic ecosystem in the receiving waters. Research devoted to determining population recovery potential and mechanisms of biologic compensation—mechanisms which allow the populations to compensate for natural disturbances and the effects of man's activities on the environment—is required for precise estimation of ecosystem effects resulting from damage to entrained organisms. Until information on natural mortality, predation, disease resistance, and long-term survival is available for each life history

stage of species entrained, entrapped, or impinged in cooling water systems, little confidence can be placed in estimates of ecosystem effects due to damage to these organisms. The present level of knowledge on the interrelationships between aquatic species, the carrying capacity of the ecosystem, and the aquatic environment hinders the evaluation of the impact of intake mortality on the total aquatic resource.

## CONSIDERATIONS OF INTAKE SITING AND DESIGN

Intake structures are the first engineering interface between a power plant cooling system and the source of cooling waters. It is at this interface that engineering feasibility and ecological constraints have a considerable influence on design criteria which reduce entrainment, entrapment, and impingement of fish. Design criteria include the following factors: specific site characteristics, cooling system designs, and design of the cooling water intake. In general, three basic strategies exist for minimizing the impact of a cooling-water intake on the aquatic ecosystem and fisheries resources (see footnote 5):

- 1) minimizing the probability of organisms encountering the intake through site evaluation and intake location;
- 2) minimizing the volume of water withdrawn and reducing intake approach velocity; and
- 3) maximizing organism survival through use of fish protection devices incorporated in behavioral or physical barriers.

In the sections which follow we briefly discuss each of these strategies and review several of the major types of fish guidance and diversion systems which are applicable to power plant cooling water intakes.

### Site Evaluation

Through comprehensive site evaluations, intake mortality can be minimized by avoiding areas of high fish population densities. Baseline information on the temporal and spatial distribution of motile organisms, diel and annual migration patterns, and cyclic reproduction is vital to avoid power

plant siting on critical spawning and nursery areas or on migratory pathways. Site evaluations require analysis of the most favorable intake and discharge locations to avoid areas of high density stratifications of aquatic organisms. Furthermore, site evaluations should determine potential maintenance problems resulting from biofouling accumulations and deterioration of cooling system components. Preoperational site evaluations must, in addition, lead to cooling system designs which minimize the probability of organisms being reentrained or recirculated as a result of basic geographic or hydraulic characteristics of the site.

Critical analysis of preoperational and operational follow-up studies must be conducted using appropriate quantitative techniques for statistical comparisons. This has been wanting in many impact studies. The development of information documenting changes in community structure over a sufficient time period is one fundamental approach to improving environmental analyses. Numerical indices of community composition and diversity are often useful in evaluating such changes. Supplemental indicators may be derived from commercial and recreational fisheries data which are particularly valuable for evaluating historical trends for selected species. In conjunction with fisheries records, techniques of mark-recapture, stock and recruitment analyses, and resource exploitation provide indicators applicable in defining population dynamics, seasonal abundance, migration patterns, and resource utilization; each contributing to the environmental assessment as well as providing information useful in resource management.

### Cooling System Design

Two fundamental power plant cooling system designs exist—once-through cooling and closed-cycle cooling. Closed-cycle cooling, proposed as the best available approach for minimizing adverse effects of power plant cooling on aquatic resources (see footnote 5), offers two principal advantages over once-through cooling systems. Closed-cycle cooling requires 3-14 percent of the water volume

needed for once-through cooling, thus resulting in a substantial decrease in the magnitude of phytoplankton, zooplankton, and ichthyoplankton entrainment. In addition, the intake approach velocity can be decreased in those power plants utilizing closed-cycle cooling thus reducing the magnitude and severity of fish entrapment and impingement. However, closed-cycle cooling—utilizing either cooling towers or cooling ponds—is expensive to install and maintain in existing and proposed power plants. Furthermore, cooling towers are not aesthetically pleasing—a factor which must be taken into consideration in cooling system design. In light of these factors and additional considerations regarding closed-cycle cooling (i.e., problems of icing, fog, etc.), we conclude that off-stream cooling may not, in all cases, represent the most efficient design for a particular site and that all potential alternative methods should be considered.

### Guidance and Diversion Systems

Two philosophies exist regarding the design of fish protection devices for maximizing the survival of organisms encountering a cooling-water intake. The first focuses on utilizing the behavioral response of the organisms (i.e., guidance or avoidance responses) to a variety of behavioral barriers which guide or divert organisms into bypass channels. This approach, however, requires a predictable behavioral response in order to be effective. The alternative approach utilizes a positive physical barrier to completely block the passage of entrained or entrapped fish. This technique relies on impinging fish for brief periods while the fish are mechanically transferred to a bypass channel. It is our opinion that the most efficient intake systems for minimizing adverse effects on fish utilize a combination of behavioral and physical barriers.

The primary objective to be considered in evaluating any intake system is its ability to remove fish quickly while maintaining maximum survival. The system should, in addition, be effective in preventing passage of diverse fish species and life stages over a wide

range of temperatures, flow conditions, and light levels. The demands of these criteria make it exceedingly difficult for an engineer or a biologist to design an intake system which minimizes a potentially deleterious impact upon biological systems. The wide variety of aquatic habitats and fish populations has also contributed to this difficult task. Compilation and synthesis of available information on both behavioral and physical barriers represents a summary of state-of-the-art information relative to intake and screening structures. The discussion of principal cooling water intake systems which follows, although not comprehensive, summarizes biological, engineering, and mechanical considerations of major intake designs.

### Behavioral Barriers

The behavioral response of fish to physical stimuli such as light, sound, velocity gradients, or electric shock varies between species of fish, as well as within a species due to differences in age or physiological state (Sonnichsen, 1975). This diversity of behavioral patterns among fish compounds diversion problems encountered at cooling system intakes. Thus behavioral barriers may have their greatest application when used in combination with conventional intake systems (e.g., vertical traveling screens, etc.) particularly during periods when vulnerable species are abundant.

#### Light

Intense illumination was characterized by Bibko et al. (1974) as a passive deterrent for striped bass, *Morone saxatilis*, only temporarily deterring fish passage under experimental conditions. Fields (1966), reported the avoidance response of salmonids to artificial light varied, depending on the light adaptation of the species, water clarity, and flow conditions. Constant light was more effective than interrupted or flashing light for guiding young salmon. Adaptation of fish to light intensity substantially decreases the guidance efficiency of light barriers.

It has been speculated (Grimes, 1975; Brehmar, pers. commun.), that

light may attract fish into intake systems of many power plants during hours of darkness. Attraction and subsequent entrapment of fish at lighted intake systems at night has not, however, been adequately documented.

### Sound

Sonic techniques for repelling fish from industrial water intake structures have been reported by Burner and Moore (1953, 1962), Moore and Newman (1956), VanDerwalker (1964), and Trefethen (1968). Moulton and Backus (1955) reviewed the literature regarding the guidance efficiency of sonic barriers.

In general, maximum avoidance response has been observed with low frequency, high intensity sound; however, variation in hearing ability among species and high-level background noise lead to poor repeatability of the behavioral response of fish to sonic barriers. Burner and Moore (1962) reported the behavioral response to frequency or intensity of sound was insufficient to be effective in guiding young salmonids to safe passage around dams and diversions. The Virginia Electric and Power Company attempted to use relatively high intensity, multifrequency sound to repel fish from power plant intakes (J. C. White, pers. commun.). It was concluded that, although sound was partially effective, sound alone was inadequate for repelling fish from the cooling-water intake due to the diversity of species and sizes of fish encountered and the diversity of behavioral response patterns.

### Velocity Gradients

Kerr (1953), Clay (1961), Bates (1964), Bates and VanDerwalker (1964), Niggol (1964), and Prentice<sup>7</sup> discussed flow acceleration or deceleration barriers for guiding or deflecting fish. Flow acceleration barriers produce an increase in approach velocity over a relatively short distance by use of wedges in approach channels. Bates and VanDerwalker (1964), reported a 70

percent diversion efficiency of an experimental waterjet deflector at an approach velocity of 76 cm/s. High diversion efficiencies (81 percent) have been reported by Prentice and Ossiander (1974) for vertical flow accelerators oriented at a 20° deflection angle for channel velocities ranging from 37 to 73 cm/s. Horizontal flow accelerators had an average deflection efficiency of 56 percent for channel velocities from 46 to 79 cm/s. No difference in diversion efficiency was observed between tests conducted during the day and night. Blinded fish, tested by Gerold and Niggol (1964), were guided by flow acceleration barriers and diversion efficiencies comparable to normal fish were observed. Demands of high waterjet volumes, extensive maintenance, and fluctuating hydrologic conditions, however, make waterjet and flow barriers impractical as diversion systems.

The avoidance response of fish to areas of rapidly changing velocity has been proposed to explain the effectiveness of louver systems in diverting fish (Maxwell, 1973). Weight (1958) observed that although fish perceive and respond to horizontal changes in water velocity, they are relatively insensitive to vertical velocity changes. As a result of these observations a "velocity cap" was developed and installed in offshore intakes at several southern California and Great Lakes power plants. The velocity cap acts to convert vertical water movement into a horizontal flow. Reduced fish entrainment and entrapment has been reported under experimental (Weight, 1958) and actual operating conditions (Maxwell, 1973) using the velocity cap.

### Bubble Screens

Air-bubble screens have generally been reported as unsuccessful at consistently diverting fish (Brett and MacKinnon, 1953; Fields, 1966; Mayo, 1974). However, several cases have been reported where partial success was observed. Bibko et al. (1974) reported that striped bass, *Morone saxatilis*, would not actively pass through an air-bubble screen at 4.5° or 11.1°C, but were found to drift passively through air-bubble screens when the water temperature was 0.8°C. Striped bass

were found to pass through an air-bubble screen at all test temperatures if openings 5.1 cm or greater were allowed in the screen. Shad, *Dorosoma cepedianum*, would not pass through an air-bubble screen at a water temperature of 11.1°C, but were not deterred at 0.8°C (Bibko et al., 1974). Bates and VanDerwalker (1969), studying juvenile migrant salmon (*Oncorhynchus* spp.), reported air-bubble screens produced diversion efficiencies up to 95 percent during daylight but declined in efficiency to 28 percent at night. Poor diversion efficiency at night was not improved by artificial lighting. Alevras (1974) observed that an air-bubble screen at the Indian Point Nuclear Power Plant on the Hudson River did not repel fish during the daytime; and that, based on preliminary data, the air-bubble screen may attract fish during periods of darkness.

### Electric Barriers

Electric barriers have been used to divert fish from several small power plants, dams, irrigation canals, and municipal water supply systems with variable success. Holmes (1948) discussed the history, development problems, and practical applications of electrical techniques for fish diversion. Applegate et al. (1954) reviewed the literature on electric barriers.

Pugh (1962), Pugh et al. (1964), and Elliott (1970) reported pulsed current was most effective in terms of guidance, diversion, and power requirements. The behavioral reactions of fish to an electric field are: 1) scare mode or avoidance response, 2) electrotaxis, and 3) electronarcosis leading to paralysis and eventual fish death (Applegate et al., 1954; Elliott, 1970; Maxwell, 1973). In general, the required current density and resulting behavioral response varies between species and sizes of fish (Pugh, 1962; Pugh et al., 1964).

Trefethen (1955) reported moderate guidance efficiency of electrical barriers (68 percent) in large-scale laboratory experiments using fingerling salmon (*Oncorhynchus* spp.) Guidance efficiency for salmonids decreased as water velocity exceeded 15 cm/s

<sup>7</sup>Prentice, E. F. 1966. Response of juvenile salmonids to four flow accelerator wedge geometries. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest Fish. Cent., Seattle, Wash. Unpubl. manuscr.

(Pugh, 1962; Pugh et al., 1964). Maxwell (1973) reported variable success of electric barriers used at small intakes on fresh water, usually with resident rather than migrating fish species. Due to the low electrical resistance, no application of electric fish barriers has been made in salt or brackish waters.

### Physical Barriers

Water intake system design criteria are similar for industrial or hydroelectric usage, irrigation or pump storage facilities: 1) elimination of entrained fish from industrial waters while preventing fish loss due to entrapment, impingement, and mechanical injury, either singly or in schools; 2) removal of entrained debris; and 3) mechanical dependability of the intake system. The application of technology and experience gained at hydroelectric dams and water diversion projects has proven to be of considerable value in design and evaluation of steam electric generating station cooling-water intakes.

#### Stationary Screens

Stationary screens have long been used in irrigation canals and industrial water intake systems. Debris accumulations at the screen surface reduce water volume and efficiency of these screen installations which, in addition, offer no bypass facility, thus completely blocking the passage of fish.

#### Vertical Traveling Screens

Vertical traveling screens have been used in hydroelectric dams and steam generating power stations for many years. These screens have proven to be a reliable method of eliminating debris from power plant cooling waters. Through proper design and installation, vertical traveling screens provide a positive barrier for juvenile and adult fish; successful diversion of fish eggs and larvae has not, however, been achieved. Screen rotation carries impinged fish into bypass facilities and provides self-cleaning of debris. Vertical traveling screens are commonly inclined 20° to 30° in hydroelectric dams in an attempt to guide fish to bypass facilities (Marquette and Long, 1971; Bell, 1973; Eicher, 1974; Farr, 1974;

and Mayo, 1974). At steam electric power stations, however, screens are oriented vertically to the water flow, thus increasing problems associated with fish impingement. In addition, vertical traveling screens at many power plant intakes have been recessed within cul-de-sac approach channels which serve to entrap fish. In general, vertical traveling screens have proven to be a relatively good engineering and biological design, not greatly affected by fluctuations in water level.

Research to improve the diversion efficiency and survival of screen-impinged fish is currently underway. Prentice (1974) presented a design concept (Fig. 1) for a vertical traveling fish basket collector and rubber scraper to aid in screen cleaning. A similar fish basket collector installed on traveling screens at the Chesterfield Power Sta-

tion on the James River appears to have reduced impingement mortality. (J. C. White, pers. commun.) Fish impingement mortality has also been reduced by implementation of high volume, low pressure spray jet wash systems on vertical traveling screens. Research is currently underway on the design of fish bypass systems, the rate of screen rotation, and the use of inclined screens with pump augmented bypasses as proposed by Eicher (1961).

#### Horizontal Traveling Screens

The horizontal traveling screen (Fig. 2) developed by Bates (1969) has been proposed for fish diversion in canals, hydroelectric dams, and irrigation intakes. The National Marine Fisheries Service is developing and testing prototype screen designs applicable for power plant intakes.

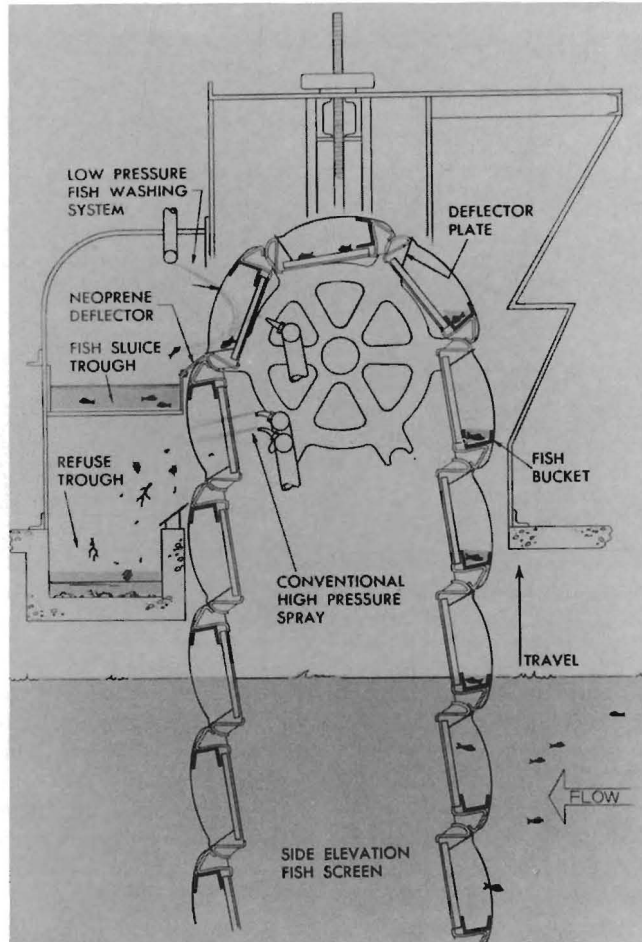


Figure 1.—Diagram of a vertical traveling screen and fish salvage system. (Photo courtesy of Envirex, Division of Rexnord Company, Waukesha, Wis.)

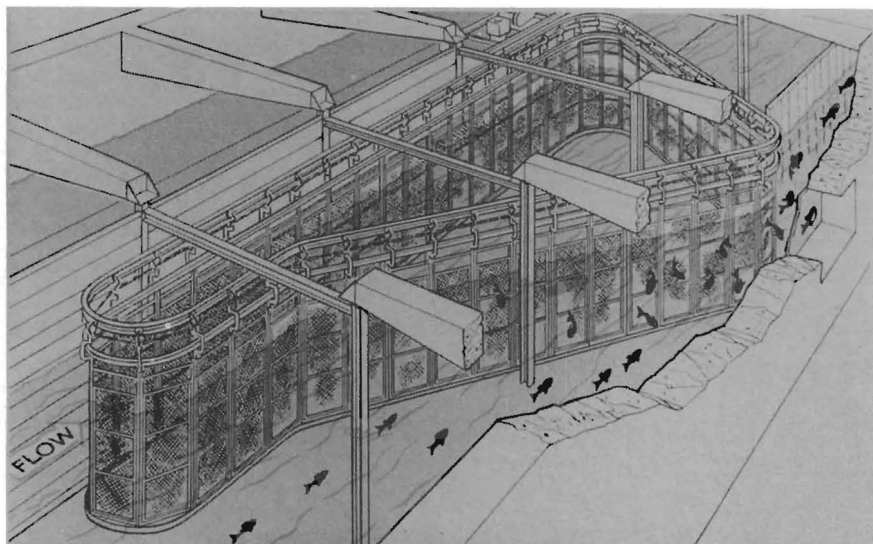


Figure 2.—Diagram of a horizontal traveling fish screen. (Photo courtesy of Envirex, Division of Rexnord Company, Waukesha, Wis.)

Major attributes of the horizontal traveling screen concept include: 1) formation of a complete physical barrier, 2) high diversion efficiency of juvenile migrant fish, and 3) release of impinged fish into a bypass without passing the air-water interface. Operation of horizontal traveling screens is not greatly affected by fluctuations in water depth. The screen is self-cleaning, thus minimizing head loss, and is capable of operating under higher approach velocities than normally possible with other types of screening installations. Research and development of the horizontal traveling screen has been reported by Bates (1969), Bates et al. (1970), Farr and Prentice (1974), and Prentice and Cssiander (1974).

Prentice and Ossiander (1974), studying 70-mm fingerling salmonids (*Oncorhynchus tshawytscha*), observed 97.9 percent diversion efficiency of a traveling screen 30° to a flow of 46 cm/s under lighted conditions and a 91.5 percent diversion efficiency under dark conditions. Diversion efficiency of 170-mm salmonids tested under similar conditions were 99.6 and 99.8 percent during the day and night tests, respectively. No screen impingement was observed during these tests; 48-h posttest survival exceeded 97 percent for all experiments.

Mechanical performance is not, at

present, acceptable for continuous operation of a horizontal traveling screen at a power plant intake. Prototype tests designed to examine mechanical operation and to assess performance limitations are discussed by Farr and Prentice (1974). Solutions to mechanical problems resulting from suspended sediment and sediment bedload have yet to be perfected.

#### *Vertical Drum Screens*

Vertical drum screens have been used for fish diversion in irrigation canals and in British steam electric stations for protection of salmonids with variable success (Eicher, 1974). Vertical drum screens having diameters of approximately 3 m are commonly aligned in rows leading to a bypass channel. Screen rotation carries impinged fish toward the bypass and provides debris self-cleaning. Vertical drum screens provide a positive barrier for adult and subadult fish but do not appear to be acceptable for the protection of eggs and larval fish. Fluctuations in water depth do not affect the performance of vertical drum screens.

#### *Horizontal Drum Screens*

Horizontal drum screens have been used for fish diversion in irrigation facilities, power plants, and hydroelectric projects as discussed by Maxwell

(1973), Eicher (1974), and Mayo (1974). These well developed and proven screens provide a positive barrier for adult and subadult fish. Horizontal drum screens are not, however, acceptable for protection of fish eggs or larvae. Self-cleaning of debris from the screen surface is achieved through screen rotation which has proven to be detrimental to impinged fish if no bypass facility is provided. Diversion efficiency of horizontal drum screens is sensitive to fluctuating water levels.

#### *Perforated Plates*

Perforated plates provide a positive barrier for adult and subadult fish and hold the potential for protection of eggs, larvae, and juvenile fish (Wales et al., 1950; Maxwell, 1973). Perforated plate diversions incorporate a simple design concept and operation into a system which is not affected by changes in water surface level. Perforated plates are, however, not self-cleaning and thus require back washing and mechanical removal of debris and biofouling accumulations. Additional research is required to establish biological design criteria and to evaluate the diversion efficiency for perforated plates under various approach velocities and flow conditions.

#### *Rapid Sand Filter*

The high capacity rapid sand filter (Fig. 3) has the potential to prevent entrainment, entrapment, and impingement of all species and life stages of fish in power plant cooling systems. Free flow across the filter surface and low approach velocity combine to eliminate potential fish kills and the need for handling and disposal of trash.

A prototype high capacity rapid sand filter was tested as a method for the exclusion of larval fish from thermal power plant cooling system intakes by Stober et al. (1974). Hydraulic and biological characteristics of seawater filtration through an anthracite-gravel filter were examined. Filter flow velocities of 0.30 to 0.61 cm/s did not result in sink flow rates affecting the vertical or lateral mobility of juvenile fish and larger vertebrates above the filter surface. Test data were utilized to



determine the engineering feasibility and probable requirements for construction, operation, and maintenance of a rapid sand filter design concept capable of providing cooling water at a rate of  $42 \text{ m}^3/\text{s}$  for a 1,000 MWe nuclear power plant (Strandberg, 1974). Continuous operation of a prototype high capacity rapid sand filter over one annual cycle would be desirable to provide additional data to determine biological and engineering feasibility and provide operating and maintenance experience prior to final design evaluations.

### FUTURE CONSIDERATIONS

The need for future research into the complex problems of fish entrainment, entrapment, and impingement is put into perspective by the magnitude of the problem. Estimates of 179 million fish larvae and juveniles entrained per year at the Connecticut Yankee Power Plant, 150 million eggs and 100 million larvae entrained into the Oyster Creek Power Plant per year, to name but two cases, speak for themselves. Furthermore, entrapment-impingement mortalities approaching or exceeding 1 million fish per year have been documented at several power plants. The problems associated with documenting fish losses and, more importantly, predicting the impact of such losses on aquatic resources are complex and it would be naive to imply the existence of a quick or simple solution. The demand for extensive research into this problematic area is evident.

A prerequisite to meeting future research demands is to overcome the problems of interdisciplinary communications and open channels of cooperation between biologists, engineers, and political decision makers. The flow of data and ideas between these groups will greatly improve the results of future research efforts. This interdisciplinary approach—directed toward solutions to particular problems—demands the commitment of strong political and economic support.

It is apparent from preceding sections that, at present, our understanding of environmental perturbation permits little more than an acknowledgement of

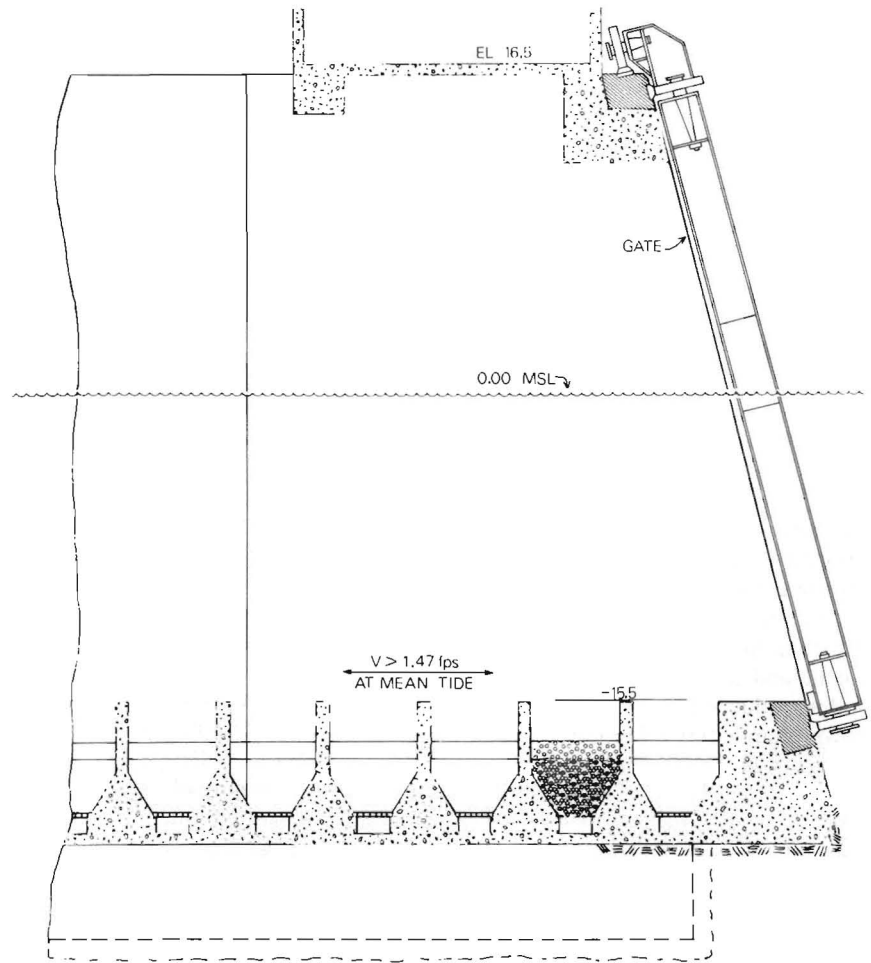


Figure 3.—Longitudinal cross section of a rapid sand filter. (Photo courtesy of Q. J. Stober.)

the problem. In addition, difficulties in extrapolating generalizations from one site to another has plagued researchers and decision makers alike. The fundamental problem which must be faced in future research is that of prediction. In the process of developing predictive estimates it has become apparent that there exists a considerable need for standardization of information including relevant engineering, water quality, and ecological data. Data omission and lack of statistical accuracy in many existing reports make interpretation of available information, upon which predictive estimates and licensing regulation decisions are based, exceedingly difficult.

The principal conclusion of this review is that estimates of the short- and long-term impacts of a proposed power

plant will depend upon developing better simulation models. In considering the present state of model simulations, we have pointed out areas which need refinement, omissions, and limitations of our present knowledge. Future research should focus on examining basic behavioral and physiological mechanisms associated with entrapment and impingement in combination with ecological processes of those populations and communities influenced by proposed and existing projects. Such an approach requires integration of laboratory studies concerning the interrelationship between hydraulics, orientation behavior of fish, sensory physiology, and fish energetics, all of which would provide a broader basis for developing intake structure design criteria. Complementing laboratory

studies is field research into mechanisms and processes involved in recruitment, biological compensation, population dynamics, and community response to environmental perturbations. Coordination of field site evaluations and predictive laboratory investigations will provide data essential for developing predictive models for optimizing intake design and locations.

The utility of field data depends largely on the integrity of the sampling scheme. In general, sampling should be sufficient to establish statistical accuracy (i.e., confidence limits, sampling error, and variance). The sampling scheme should focus on identifying critical development stages of organisms and their vulnerability to entrainment, entrapment, and impingement damage. In this regard, information on the temporal and spatial distribution of organisms, diel, seasonal, and annual migration patterns, and reproductive cycles is vital to avoid power plant siting on critical spawning and nursery areas or migratory pathways.

A problem common to both field studies and predictive modeling is that of natural variability. Natural populations fluctuate seasonally and annually in response to environmental conditions. Such natural fluctuations and variability (both temporally and spatially) necessitate field studies be conducted for at least 3 yr to estimate the magnitude of natural variability. In addition, it is exceedingly difficult, without extensive baseline data, to determine whether fluctuations in populations or community structure reflect the impact of power plant-related damage or are the result of natural variability. The "masking" effect of natural variability becomes particularly serious when considering the long lag time—measured in years or decades—before chronic, low-level mortality resulting from entrainment, entrapment, or impingement may be recognized. By the time such damage is realized the population dynamics or trophic structure of the receiving water ecosystem may be significantly altered. The "masking" effect of natural fluctuations requires a great deal of future consideration and

must be analyzed if predictive estimates are to be refined.

Predictions and environmental analyses are further complicated since natural surface waters often support a multiplicity of uses. For example, a river or estuarine system may be used as a source of cooling waters for one or more electrical generation stations, as receiving waters for the discharge of municipal sewage, for intense commercial fisheries, for recreation, or other purposes. Examination of the potential impact of a proposed power plant out of context with other demands on the system lead to misunderstanding and possible mismanagement of the aquatic ecosystem.

Throughout the preceding discussion we have concentrated on the biological aspects of power plant siting with little mention of the input of model predictions and ecological concerns into the decision making process. As biologists we are often asked to express environmental loss or ecological damage in terms of a dollar value. The concept and philosophy of monetary value as the least-common-denominator in a cost-benefit analysis warrants a great deal of future consideration. Equating the value of a fisheries resource or aquatic community against the cost of building cooling towers or loss in revenue, jobs, and electrical supply is one major component of environmental analysis which must be approached with extreme caution.

## CONCLUSION

It is apparent from the available literature that there exists a need for systematic studies which provide biological and hydraulic criteria for design and evaluation of major water intake systems. Historically, an empirical trial-and-error approach has been used in the design of agricultural and industrial water diversions and associated fish protective facilities. This approach has resulted in a serious lack of basic information and rigorous experimental research concerning the interrelationship between hydraulics, orientation behavior of fish, sensory physiology, and fish energetics, all of which would provide a broader basis for developing

intake structure design criteria. The need is clear, as well as urgent, to develop more sensitive, informed, and responsible approaches to the design, evaluation, and management of existing and future cooling water intakes.

In summary, ecological research on the entrapment and impingement of fish by power plant cooling-water intakes is in an embryonic state of development. A nucleus exists, founded on an interdisciplinary approach to finding ways to minimize environmental impact, upon which future research can be based. Two issues of major importance which must be addressed in future research include: 1) what effect, if any, does the entrapment or impingement of fish have on the productivity of the aquatic ecosystem or the fisheries resources; and 2) what criteria determine the best available intake-design technologies for minimizing effects on aquatic life and assuring continued balance of diverse aquatic ecosystems.

Decisions regarding these and other pertinent environmental-engineering issues should be founded on objective, concise, and clearly defined research data. Recommendations should be considered in perspective with the economic and social demands of our times as well as our responsibility to the future.

## ACKNOWLEDGMENTS

The work upon which this publication is based was supported in part by funds provided by the U.S. Department of the Interior (Grant 14-34-0001-7354) as authorized under the Water Resources Research Act of 1964, as amended; the Electric Power Research Project RP-49; and the Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary.

We thank the following individuals for comments on earlier drafts of this manuscript: L. Jensen, R. Davies, L. Brush, D. Powers, S. Olesko/Szuts, and M. Wolman. Specific sections have been improved by discussions and comments from: J. Sonnichsen, E. Prentice, Q. Stober, C. Coutant, J. Skinner, D. Odenweller, and J. Norton. We are grateful to S. Hanson for typing many earlier drafts of this manuscript.

## LITERATURE CITED

- Alevras, R. A. 1974. Status of air bubble fish protection system at Indian Point Station on the Hudson River. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 289-291. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Applegate, V. C., P. T. Macy, and V. E. Harris. 1954. Selected bibliography on the applications of electricity in fishery science. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 127, 55 p.
- Bates, D. W. 1964. Exploratory research on guiding juvenile salmon. U.S. Bur. Commer. Fish., Fish-Passage Res. Prog., Seattle, Wash., Review of Progress 1964, Vol. III, 14 p.
- \_\_\_\_\_. 1969. The horizontal traveling screen. *In* F. L. Parker and P. A. Krenkel (editors), Engineering aspects of thermal pollution, p. 225-242. Vanderbilt Univ. Press, Nashville, Tenn.
- \_\_\_\_\_, E. W. Murphey, and E. F. Prentice. 1970. Design and operation of a cantilevered traveling fish screen (Model V). *In* Preliminary designs of traveling screens to collect juvenile fish, p. 6-15. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 608.
- \_\_\_\_\_, and J. G. VanDerwalker. 1964. Exploratory experiments on the deflection of juvenile salmon by means of water and air jets. U.S. Bur. Commer. Fish., Fish-Passage Res. Prog., Seattle, Wash., Review of Progress 1964, Vol. III, 6 p.
- \_\_\_\_\_, and \_\_\_\_\_. 1969. Exploratory experiments on the deflection of juvenile salmon by means of water and air jets. Freshwater and estuarine research program. U.S. Bur. Commer. Fish., Seattle, Wash., 11 p.
- Beamish, F. W. H. 1966. Muscular fatigue and mortality in haddock, *Melanogrammus aeglefinus*, caught by otter trawl. *J. Fish. Res. Board Can.* 23:1507-1521.
- Beck, A. D., and D. C. Miller. 1974. Analysis of inner plant passage of estuarine biota. *In* Electric power and the civil engineer, Conference Papers, Power Division Specialty Conference, Boulder, Colo., Aug. 12-14, 1974, p. 199-226. Am. Soc. Civil Eng., United Eng. Cent., N.Y.
- Bell, M.C. 1973. Fisheries handbook of engineering requirements and biological criteria. Fisheries-Engineering Research Program, U.S. Army Corps of Engineers, North Pacific Division, Portland, Oreg., 506 p.
- \_\_\_\_\_. 1974. Fish passage through turbines, conduits, and spillway gates. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 251-261. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Bibko, P. N., L. Wirtenan, and P. E. Kueser. 1974. Preliminary studies on the effects of air bubbles and intense illumination on the swimming behavior of the striped bass (*Morone saxatilis*) and the gizzard shad (*Dorosoma cepedianum*). *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 293-304. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Black, E. C. 1958. Hyperactivity as a lethal factor in fish. *J. Fish. Res. Board Can.* 15:573-586.
- Breit, J. R., and D. MacKinnon. 1953. Preliminary experiments using lights and bubbles to deflect migrating young spring salmon. *J. Fish. Res. Board Can.* 10:548-559.
- Burner, C. J., and H. L. Moore. 1953. Attempts to guide small fish with underwater sound. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 111, 38 p.
- \_\_\_\_\_, and \_\_\_\_\_. 1962. Attempts to guide small fish with underwater sound. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 403, 30 p.
- Chittenden, M. E. 1973. Effects of handling on oxygen requirements of American shad (*Alosa sapidissima*). *J. Fish. Res. Board Can.* 30:105-110.
- Clay, C. H. 1961. Design of fishways and other fish facilities. Dep. Fish. Can., Queen's Printer, Ottawa, 301 p.
- Dominy, C. L. 1971. Changes in blood lactic acid concentrations in alewives (*Alosa pseudoharengus*) during passage through a pool and weir fishway. *J. Fish. Res. Board Can.* 28:1215-1217.
- Edsall, T. A. 1975. Electric power generation and its influence on Great Lakes fish. Presented at Second ICMSE Conference on the Great Lakes. Argonne National Laboratory, Argonne, Ill. (cited in footnote 1).
- Edwards, T. J., W. H. Hunt, L. E. Miller, and J. J. Sevic. 1976. An evaluation of the impingement of fishes at four Duke Power Company steam-generating facilities. *In* G. W. Esch and R. W. McFarlane (editors), Thermal ecology II. Proceedings of a symposium held at Augusta, Georgia, April 2-5, 1975, p. 373-380. ERDA symposium series CONF-750425.
- Eicher, G. J. 1961. Fish protection at the Iron Canyon Project, Sacramento River, California. Rep. Calif. Dep. Fish Game, 114 p.
- \_\_\_\_\_. 1974. Adaptation of hydro fish facilities to steam-electric stations. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 273-276. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Elliott, F. E. 1970. On the status of electric fishing. *J. Mar. Technol. Soc.* 4:58-60.
- Farr, W. E. 1974. Traveling screens for turbine intakes of hydroelectric dams. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 199-203. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- \_\_\_\_\_, and E. F. Prentice. 1974. Mechanical operation of horizontal traveling screen model VII. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 215-222. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Fields, P. E. 1966. Final report on migrant salmon light guiding studies (contract No. D. A.-45-108 CIVENG-63-29) at Columbia River Dams. Fisheries Engineering Research Program, U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon, 267 p.
- Gerold, M., and K. Niggol. 1964. Comparative response of blinded and non-blinded fingerling salmon to a louver barrier and to a sharp increase in water velocity. U.S. Bur. Commer. Fish., Fish-Passage Res. Prog., Seattle, Wash., Review of Progress 1964, Vol. III, 5 p.
- Grimes, C. B. 1975. Entrapment of fishes on intake water screens at a steam electric generating station. *Chesapeake Sci.* 16:172-177.
- Holmes, H. B. 1948. History, development, and problems of electric fish screen. U.S. Fish Wildl. Serv., Spec. Sci. Rep. 53, 62 p.
- Kerr, J. E. 1953. Studies on fish preservation at the Contra Costa Steam Plant of the Pacific Gas and Electric Company. Calif. Dep. Fish Game, Fish Bull. 92:1-66.
- Marcy, B. C., Jr. 1975. Entrainment of organisms at power plants, with emphasis on fishes - an overview. *In* S. B. Saita (editor), Fisheries and energy production: A symposium, p. 89-106. Lexington Books, Lexington, Mass.
- Marquette, W. M., and C. W. Long. 1971. Laboratory studies of screens for diverting juvenile salmon and trout from turbine intakes. *Trans. Am. Fish. Soc.* 100:439-447.
- Maxwell, W. A. 1973. Fish diversion for electrical generating station cooling systems a state-of-the-art report. Southern Nuclear Engineering, Inc. Report SNE-123, NUS Corporation, Dunedin, Fla., 78 p.
- Mayo, R. D. 1974. Conventional fish screening systems and some promising alternatives. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 277-279. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Moore, H. L., and H. W. Newman. 1956. Effects of sound waves on young salmon. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 172, 19 p.
- Moulton, J. M., and R. H. Backus. 1955. Annotated references concerning the effects of man-made sounds on the movements of fishes. [Maine] Dep. Sea Shore Fish., Fish. Circ. No. 17, 7 p.
- Niggol, K. 1964. Response of juvenile migrants to flow accelerations. U.S. Bur. Commer. Fish., Fish-Passage Res. Prog., Seattle, Wash., Review of Progress 1964, Vol. III, 3 p.
- Prentice, E. F. 1974. Vertical traveling fish basket collector. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 223-224. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- \_\_\_\_\_, and F. J. Osslander. 1974. Fish diversion systems and biological investigation of horizontal traveling screen model VII. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 205-214. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Pugh, J. R. 1962. Effect of certain electrical parameters and water resistivities on mortality of fingerling silver salmon. U.S. Fish Wildl. Serv., Fish. Bull. 62:223-234.
- \_\_\_\_\_, G. E. Monan, and J. R. Smith. 1964. Effect of water velocity on the fish guiding effectiveness of an electric field. U.S. Bur. Commer. Fish., Fish-Passage Res. Prog., Seattle, Wash., Review of Progress 1964, Vol. III, 6 p.
- Skinner, J. E. 1974. A functional evaluation of a large louver screen installation and fish facilities research on California water diversion projects. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 225-249. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Snyder, D. E. 1975. Passage of fish eggs and young through a pumped storage generating station. *J. Fish. Res. Board Can.* 32:1259-1266.
- Sonnichsen, J. C. 1975. Fish protective devices: a compilation of recent designs, concepts, and operating experience of water intakes used in the United States. Hanford Engineering Development Laboratory Report HEDL-TME 75-38 UC-79, Richland, Wash., 82 p.
- Stober, Q. J., C. H. Hanson, and P. B. Swierkowski. 1974. A high capacity sand filter for thermal power plant cooling water intakes. Part I: model studies and fouling control techniques. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 317-334. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Strandberg, H. V. 1974. A high capacity sand filter for thermal power plant cooling water intakes. Part II: design concept. *In* L. D. Jensen (editor), Proceedings of the second workshop on entrainment and intake screening, p. 335-343. Electric Power Res. Inst., Res. Proj. RP-49 Rep. 15, Palo Alto, Calif.
- Trefethen, P. S. 1955. Exploratory experiments in guiding salmon fingerlings by a narrow D.C. electric field. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 158, 42 p.
- \_\_\_\_\_. 1968. Fish-passage research. Review of progress, 1961-66. U.S. Fish Wildl. Serv., Circ. 254, 23 p.
- VanDerwalker, J. 1964. Studies of the response of fish to low frequency vibrations. U.S. Bur. Commer. Fish., Fish-Passage Res. Prog., Seattle, Wash., Review of Progress 1964, Vol. III, 8 p.
- Wales, J. H., E. W. Murphey, and J. Handley. 1950. Perforated plate fish screens. *Calif. Fish Game* 36:392-403.
- Weight, R. H. 1958. Ocean cooling water system for 800 MW power station. *J. Power Div., Proc. Am. Soc. Civil Engr.* 84(6):1888-1 to 1888-222.

MFR Paper 1266. From Marine Fisheries Review, Vol. 39, No. 10, October 1977. Copies of this paper, in limited numbers, are available from D822, User Services Branch, Environmental Science Information Center, NOAA, Rockville, MD 20852. Copies of Marine Fisheries Review are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402 for \$1.10 each.