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CHAPTER 4. EFFECTS AND IMPACTS OF PHYSICAL STRESS ON ENTRAINED ORGANISMS

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I. INTRODUCTION

Environmental studies of power plants have recently shifted their emphasis from examination of the effects of heated discharges to studies of the impacts of entire cooling systems. One of the major impacts arises when planktonic organisms are carried into and through a plant with the cooling water. Because of their relatively immobile, free-floating character, planktonic organisms are highly vulnerable to being "entrained" or passively drawn into the cooling water condenser systems of power plants. More than 70% of estuarine animals have planktonic eggs and larvae. The environmental impact of entrainment is related to the composition and abundance of affected organisms, the numbers of organisms in the adjacent waters, survival rates during entrainment as related to natural survival, the ecological roles of entrained organisms, and their reproductive strategies. Abiotic factors affecting entrainment impact include the location of the power plant, the design and operation of the cooling system, the quantity of water withdrawn, and the ambient conditions of water used for cooling.

Plankton, small fishes, and invertebrates which pass through the intake screens intact are subjected to various and simultaneous stresses which often lead to inner-plant mortality (see Chapter 5). Power plants can be represented as large predators that not only reduce the abundance of vulnerable organisms but may also disrupt the community structure through selective mortality and enhancement of the growth of some of the surviving species. Entrainment survival is determined by:

- sizes, life-stages, and relative susceptibility to injury of the species involved,
- ambient temperatures and the quality of the withdrawn and receiving water,
- amplitude of the temperature rise (ΔT) as the water passes through the condenser cooling system,
- duration of exposure to elevated temperatures,
- pressure changes resulting from turbulence (shear forces) and acceleration, as well as physical abrasion during passage through the system,
- exposure to biocides used for fouling control, and
- gas bubble disease (the formation of air embolisms) possibly caused by pressure and temperature changes in the cooling system.

The extent to which physical damage contributes to the total inner-plant mortality has not been adequately assessed at most power plants. Certain entrainment studies are now beginning to separate the effects of physical, thermal, and chemical stresses and to describe their synergistic effects. Thermal and chemical stresses vary in length and magnitude, depending on thermal exposure regimes and chlorination procedures. Physical stresses, on the other hand, are continuously applied whenever cooling water is being pumped.

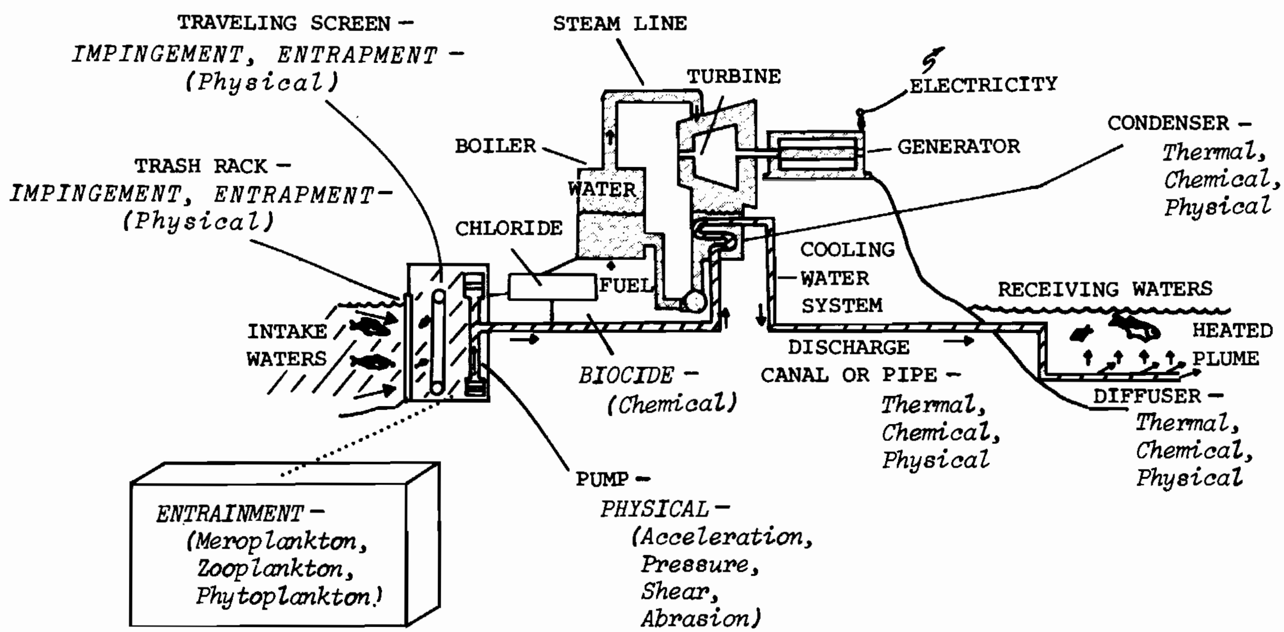
In passing through a power plant cooling water system, entrained biota experience an array of stresses. Fig. 1 illustrates the areas of stresses in a typical steam electric generating station with once-through continuous flow of cooling water.

A plant normally interfaces the receiving water body at the intake and discharge structures. Water and organisms enter the intake through heavy steel trash bars which block floating debris. Typical intake approach velocities are on the order of 15 to 60 cm/sec; EPA (1973) recommends velocities of 15 cm/sec or less. The water then passes through a traveling screen with openings about half the diameter of the steam condenser tubes, or 0.75 to 1.25 cm in most cases. On reaching the pumps, organisms are exposed to pressure fluctuations, velocity shear forces, and physical buffeting and abrasion. The water passes into a large water box where velocities may increase up to eight times, then through two right angle turns, through banks of several thousand 2.3 cm (I.D.) condenser tubes where heat exchange takes place, and down and out a discharge pipe or canal to the receiving water body.

Entrained organisms are stressed by mechanical buffeting, acceleration, velocity shear forces, and changes in hydrostatic pressure. Inner-plant physical stresses arise from:

- contact with fixed or moving equipment, such as screens, pumps, and piping,
- pressure changes, especially the negative pressures or vacuums within the pumps,
- shear forces in areas of extreme turbulence or boundary proximity,
- accelerative forces resulting from changes in velocity and direction,
- buffeting and collision with the particles (i.e., organic load) passing along with the organisms, damage depending on load density and size, and
- cavitation in regimes of partial vacuum.

STEAM ELECTRIC GENERATING STATION



Fish culturists have recognized the impact of physical trauma on developing fishes for many years (Hayes, 1949; Davis, 1953; Leitritz, 1963). Physical disturbance during early development causes many of the deformities observed, e.g., misshapen heads in carp fry (Matlak, 1970), deformed yolk sacs in alevins (Emadi, 1973), and vertebral compression (Mathur and Yazdani, 1969). After eye pigment develops, larvae of white flounder are extremely sensitive (50% mortality) to physical transfer shock for approximately 5 days (MacPhee, pers. comm.). Despite evidence of trauma due to relatively mild physical stresses, until recently little attention has been given to the physical rigors experienced by an organism passing through a cooling system.

II. FIELD STUDIES SHOWING PHYSICAL DAMAGE

Eraslan et al. (1976) point out that entrainable life stages could be exposed to vastly different physical stresses at different power plants. The mortalities of entrained species observed in field studies at 15 operating power plants are summarized in Table 1, Chapter 5. Table 1 provides data on mortality caused by physical damage alone as compared to total mortality from the combined effects of thermal, chemical, and physical stresses. Percentages of total mortality caused by physical stress as reported in the literature are in many cases approximations and are often difficult to compare because of the use of varied methodologies in field collection and mortality determination techniques.

A. Fish/Ichthyoplankton

Marcy (1975) and Adams (1968) indicate that physical stresses may have a much greater impact on fish eggs and larvae than does temperature. The limited data that are available

Table 1 Summary of Percentage Physical Damage Mortality of the Total Mortality Observed in Plankton Entrainment Studies at Power Plants

Power Plant	Reference	Percent Physical Damage	Percent Total Mortality
	Fish/Ichthyoplankton		
Millstone Point	Nawrocki (1977)	22.8	22.8
Chalk Point	Morgan et al. (1973, 1976)	20-50	–[1]
Calvert Cliffs	Morgan et al. (1973, 1976)	50-100	–[1]
Connecticut Yankee	Marcy (1971, 1973)	80	100
Ludington Pump Storage	Serchuk (1976)	37.2-61.5	56.5-67.7
Vienna	Flemer et al. (1971a)	99.7	99.7
Brayton Point	EPA (1972a)	100	100
Northport	Austin et al. (1973)	27-57	27-57
Indian Point	Lauer et al. (1973)	7-39	–[1]
Brunswick	Copeland et al. (1975)	30	0-50
Monticello	Knutson et al. (1976)	8.5-42.4	100
Nanticoke	Teleki (1976)	49.5	96.3-99
	Zooplankton		
Prairie Island	Middlebrook (1975)	20.5	20.5
Big Rock	Grosse Ile Lab. (1972)	29.5	–[1]
Waukegan	Industrial Bio-Test Lab. (1972)	6.0[2]	–[1]
Zion	McNaught (1972)	Some[2]	–[1]
Point Beach	Edsall and Yocum (1972)	8-19[2]	–[1]
Connecticut Yankee	Massengill (1976)	<1	100
Millstone Point	Carpenter et al. (1974)	70	100
Morgantown	Beck and Miller (1974)	40	60
Palisades	Consumers Power (1972a)	5-7	–[1]
Point Beach	University of Wisconsin (1972)	4-14	–[1]
	Phytoplankton		
Allen	Hardy (1971)	11	–[1]
Morgantown	Flemer et al. (1971b)	13	–[1]
Alamitos and Haynes	Briand (1975)	Some	42
Florida plants (4)	Weiss (Unpub. ms)	Some	70-90
Millstone Point	AEC (1974)	74	–[1]
Kewaunee	Wisconsin Public Service Corp. (1974)	11	–[1]
Palisades	Consumers Power Company (1973)	0-68	0-81
Zion	Restaino et al. (1975)	11-12	3-20

1 Unspecified
2 Highest percentage of total mortality

concerning the passage of fish eggs and larvae through power plants show mortalities between 28 and 100% (many near 100%) due to various combined stresses (Table 2). Mortality of entrained ichthyoplankton at the 16 operating power plants discussed below (including those in Table 2) ranged from 0 to 100% and averaged 72%.

Physical damage caused 80% of the 100% mortality of the young of nine fish species (2.6 to 40 mm) entrained at the Connecticut Yankee plant (Marcy, 1971, 1973). Almost all (99.7%) of the striped bass eggs which passed through the Vienna, Maryland generating station were killed and a high percentage of the eggs disintegrated (Flemer et al., 1971a). The 100% mortality of 164.5 million menhaden (5 to 50 mm) during one day at the Brayton Point Plant in Massachusetts was attributed to physical damage (EPA, 1972a). Passage through the Northport, New York plant caused 27 to 54% maceration mortality of four species of juvenile marine fish (Austin et al., 1973). Nawrocki (1977) found that damage to 17 larval marine fishes by physical stresses averaged 22.8% and that several species of clupeid larvae sustained 62.5% physical damage.

Schubel (1973) noted that ΔT's up to 10°C were not detrimental to the egg development or hatching success of five estuarine fish and that physical damage may have a much greater impact on development and hatching success than does temperature.

When juvenile and adult fish passed through the Ludington pump storage facility, 37.2 to 61.5% were physically damaged (of a total mortality between 56.5 and 67.7%) (Serchuk, 1976). Most of the damaged fish were lacerated or decapitated, indicating that physical contact and shearing forces caused the damage. At the Brunswick nuclear plant, with no heat added to the system, entrainment mortality of fish larvae ranged between 9 and 50%, about one third of which was attributed to physical damage (Copeland et al., 1975). Mortalities of the ten species of larvae entrained were highest during the summer. Fragile anchovies suffered the highest physical damage. Knutson et al. (1976) passed marked fathead minnows (30 to 60 mm) through the Monticello nuclear station and found that physical damage caused between 8.5 and 42.4% mortality while thermal damage caused only 8.6% mortality. At the Nanticoke generating station, Long Point Bay, Lake Erie, Canada, Teleki (1976) found 96.3 to 99% mortality of entrained young-of-the-year fish. Smelt *(Osmerus mordax)* constituted 95% the total larvae entrained. Physical injury accounted for 49.5% of the plant-induced mortality.

B. Zooplankton

In a recent review of the literature, the staff of the AEC (1973) found that losses of zooplankton in cooling systems ranged from 15 to 100% but suggest that 30% "may be more representative". Middlebrook (1975) states that studies of power plants (e.g., Icanberry and Adams, in press; Davis and Jensen, 1974) showed negligible to 15% mortality of zooplankton.

Mortality of entrained zooplankton at the 18 plants discussed below ranged from 0 to 100% and averaged 36%. Zooplankton mortalities of 29 to 55% at the Big Rock power plant on Lake Michigan were attributed to both physical and heat damage (Grosse Ile Laboratory, 1972). When EPA (1972b) compared the Big Rock plant and the Escanaba plant, where there was only a 7% mortality, they attributed the difference in mortality to higher physical damage at Big Rock because of its longer discharge pipe. According to McNaught (1972), physical damage caused the greatest mortality of zooplankton passing through the Zion plant. Data on passage of zooplankton through the condensers at the Waukegan plant show an average mortality of 6.0% due to physical effects and 1.8% due to thermal stress (Industrial Bio-Test Laboratories, Inc., 1972). Studies of zooplankton at the Point Beach nuclear plant show that physical damage (8 to 19% mortality) during condenser passage was more critical than thermal impact (Edsall and Yocum, 1972). Entrained zooplankton mortality attributed to only

TABLE 2 Fish Eggs and Young: Inner-plant Mortalities, Entrained, as Noted in

Source	Location	Percent Mortality	Species Entrained
Marcy (1971, 1973, 1976)	Connecticut Yankee Plant, Haddam, Connecticut River	100	Alewife, Blueback herring, White perch, Carp, White catfish, Spottail shiner, American shad, Johnny darter
Profitt (1969)	White River, Indiana	100	Spottail shiners
Clark and Brownell (1973)	Indian Point Plant, Hudson River, New York	97.5	Not specified
Carpenter et al. (1972)	Millstone Point Plant, Niantic, Connecticut	High	Flounder, Menhaden, Blueback herring
EPA (1972a)	Brayton Point Plant, Mount Hope Bay, Mass.	100	Menhaden, River herrings
Lauer et al. (1974)	Indian Point Plant, Hudson River, New York	39	Striped bass, Hogchoker, White perch, River herring
Flemer et al. (1971a)	Vienna Plant, Maryland	99.7	Striped bass
Flemer et al. (1971b)	Chalk Point Plant, Maryland	92.4	Not specified
AEC (1973)	Oyster Creek Plant, New Jersey	100	24 species

Estimated Numbers Lost, and Percentage of Population Entrainment Studies at Power Plants

Life Stage	Estimated Numbers Lost	Percentage of Intake Water Body Population Entrained
Larvae and juveniles 97.5% (2.6-15.0 mm) 2.5% (15.1-40 mm)	179 million/ year	4.0% (1.7-5.7%) with-drawal of 61% of river larval population
Young	--	--
Larvae and early juveniles	--	--
Larvae and juveniles	Up to 20 million/day	--
Larvae (5.0-50 mm)	7-165.5 million/day	--
5 species of eggs 17 species of larvae	--	--
Eggs	--	--
Larvae	--	--
Eggs and larvae	150 million eggs/year 100 million larvae/year	--

TABLE 2

Source	Location	Percent Mortality	Species Entrained
Nawrocki (1977)	Millstone Point Plant, Niantic, Connecticut	27.8	Clupeids, Tautog, Sea robin, 16 species total Clupeids-67.5% mortality Sea robin-32.7% mortality Tautog-44.7% mortality
Voightlander (1974)	Browns Ferry Nuclear Plant, Tennessee River/ Wheeler Reservoir	-	90-95% Gizzard or Threadfin shad
Carlson and McCann (1969)	Cornwall Pump Storage Plant, Hudson River, New York	-	Striped bass
Copeland et al. (1975)	Brunswick Nuclear Plant, Southport, N.C.	9-50	Anchovy, Goby, Croaker, Spot
Knutson et al. (1976)	Monticello Nuclear Plant, Mississippi River, Minn.	-	33 species
AEC (1974)	Millstone Point Plant, Niantic, Connecticut	Most Killed	13 species, (Menhaden, Blueback herring, Grubby, Winter flounder)
Hess et al. (1975)	Millstone Point Plant, Niantic, Connecticut	Most	Winter flounder
Edsall (1976)	Monroe Plant, Lake Erie	High	Not specified

(Continued)

Life Stage	Estimated Numbers Lost	Percentage of Intake Water Body Population Entrained
Larvae	--	--
Larvae	1.17618×10^{10}/ 120 period	2.8% of 4.10208×10^{11} in reservoir (open cycle-0.91-2.81%) (closed cycle 0.5-0.14%)
Eggs	--	4%
Larvae	--	12% (Withdrawal from river cross-section)
Larvae	5×10^{4} larvae/ pump day 3.6×10^{6} larvae/pump day	--
Larvae, Juveniles	9.2 ± 4/hour 22,635/hour	--
Larvae	50 million Aug. 10-21	2.5 million winter flounder entrained (April-late June) of 1-6 million estimated in Niantic Bay
Larvae	--	1% reduction in Niantic Bay recruitment due to entrainment losses
Larvae	300 million April-Aug. 1973	--

physical effects ranged from 2.5 to 14.9% at five Lake Michigan plants; physical effects alone accounted for most mortalities as compared to combined physical and thermal effects (NALCO Environmental Sciences, 1976). A 5 to 30% loss in mobility of zooplankton as the result of passage through just the pumps and condensers was observed at many plants (Statement by Dr. Wright, Westinghouse Environmental Systems Department, in testimony at the Wisconsin hearings, Department of Natural Resources, 1971). Less than 1% of the zooplankton which passed through the Connecticut Yankee plant were physically damaged, although nearly all insect pupae and a cladoceran were selectively killed by physical stress within the plant (Massengill, 1976).

Two recent studies show much higher mortalities of zooplankton from the physical component than were reported in early studies of power plants. Carpenter et al. (1974) report that 70% of the copepods entering the cooling water system of the Millstone Point plant at Niantic, Connecticut were killed by the physical or hydraulic stresses of passage and that total mortality ranged from 69 to 83%. Beck and Miller (1974) cite unpublished data which indicate that physical damage caused mortality of 50% of zooplankton and that the primary cause of the mortality was pumping effects.

In a two year study, more than 70% of the dominant inshore zooplankton species, *Oithona* spp. and *Acartia tonsa,* were killed at the Turkey Point plant on Biscayne Bay in Florida (Prager et al., 1971). Conditions that damaged the entrained plankton populations in the first year also prevailed in the second year, although dilution water which had passed through unheated condensers was added in the second year. "In the dilution water, whatever damage was due to hydrodynamic forces persisted, although no additional temperature stress was imposed by Unit 3. If temperature were the only stress upon the plankton, one would expect to encounter less than half the plankton mortality per unit volume of water than occurred in last year's samples since the dilution factor is about 2X......Although temperature increases in August of 1971 were less than half those the plant caused in 1970 the zooplankton mortalities were only 10 -20% less..." (Prager et al., 1971). Thus, physical damage at the Turkey Point plant may cause mortalities up to 50%.

Mysid and polychaete larvae (1.5 to 5.0 mm) suffered severe physical damage as the result of entrainment at the Morgantown nuclear plant in Maryland (Gentile and Lackie, unpubl. ms). Sandine (1973) showed that physical "abuse" in the cooling system injured larger macrozooplankters (arrow worms, ctenophores, and coelenterates). Mihursky and Dorsey (1973) indicate that large ctenophores suffered greater mortality from physical effects than small ones. Copeland et al. (1975) note little difference between percentage of mortality at the intake and discharge (2 to 43% intake vs. 2 to 49% discharge). Mortality of entrained lobster larvae at the Pilgrim nuclear plant in Massachusetts was due to physical action, heat, and chemicals (AEC, 1972).

Copepods entrained at the Turkey Point nuclear plant in Biscayne Bay, Florida were damaged by a combination of mechanical turbulence and chlorine (larvae survived to 40°C) (Lackey and Lackey, in press). Consumers Power Company (1972a, 1972b) and Benda (1972) note that zooplankton mortalities between 8 and 13% were caused by a combination of thermal and physical damage. At four fossil-fuel sites in Florida, zooplankton abundance was reduced by 70% at one plant and by 20% at three other plants, due in part to physical damage (Weiss, unpubl. ms). Coutant (1970) suggests that physical destruction during passage through a power plant caused the reduced number of zooplankton carcasses in the discharge canals. Physical effects produced little copepod mortality in summer but were a major factor during the cooler months at the Crystal River site in Florida (Maturo et al., 1974). Middlebrook (1975) found a statistically significant **20%** mortality of zooplankton at the Prairie Island nuclear station after cooling tower entrainment; thermal elevation (ΔT) did not appear to be a significant cause of mortality. Conversely, at the Crane Power Plant on a tributary of Chesapeake Bay, Davies, Hanson, and Jensen (1976) found no significant increases in mortality because of physical effects.

C. Phytoplankton

There appears to be a conflict of results on the effects of phytoplankton entrainment. Few data are available concerning only physical effects on phytoplankton. Adverse impact has been demonstrated in several cases, but the contribution of physical stress to total mortality is not known. At two power stations, productivity was stimulated between 18 and 30%, while at six stations mortality ranged from 11 to 100% and averaged about 55%. Some stimulation of photosynthesis from the physical effects of condenser passage occurred at the Allen generating plant on Lake Wylie, North Carolina (Gurtz and Weiss, 1972). Williams (1971) found no significant physical effects and Smith and Brooks (1971) found that some stimuation (17.5 to 30%) in productivity could occur from physical effects. On the other hand, Hardy (1971) observed that factors other than heat reduced productivity by 11%. Flemer et al. (1971b) found a 13% reduction in productivity which they attributed to physical effects. Morgan and Stross (1969) concluded that physical damage, cell disruption due to chlorination, or some other factor inhibited photosynthesis in samples of the Chalk Point effluent.

Entrainment studies of marine phytoplankton passing through two southern California coastal plants indicate that plant passage disrupted the community severely by reducing diversity, promoting differential survival of some species, and reinforcing the dominance of the two major species (Briand, 1975). Mortalities, a portion of which were physically related, approached 42% during passage. As a result of his findings, Briand (1975) advocates using deep sea water rather than shore zone water for cooling.

Some inhibition of phytoplankton after condenser passage (ΔT 5.9°C) at the Michigan City plant was noted and photosynthesis was significantly decreased between intake and discharge (ΔT 6.9°C) at the Bailly plant (Arnold and the Pennsylvania Cooperative Fishery Research Unit, 1975). Industrial Bio-Test Laboratories, Inc. (1971) found no significant phytoplankton kill at the Waukegan plant.

Carbon fixation (primary production) was reduced by 98% at the Morgantown plant, due primarily to heat effects (Bongers et al., 1973). Gross photosynthesis was reduced 70% by condenser passage at four fossil-fueled plants in Florida and abundance (total cell numbers) was reduced 80 to 90%; reductions were attributed in part to physical abrasion (Weiss, unpubl. ms). Two years of studies at the Chesterfield plant on the James River in Virginia showed nearly 100% mortality of phytoplankton at times in the summer. These mortalities were probably due primarily to heat and may have contributed to critically depressed oxygen levels (Smith and Jensen, 1974). Passage of diatoms through the Millstone Point plant without chlorination or thermal addition resulted in mortalities as high as 72% for five species (AEC, 1974).

III. BIOTA-MORTALITY RELATIONSHIPS

The effects of plant passage on entrained organisms, especially physical impacts, can cause changes in community structure through changes in diversity caused by elimination of less tolerant species and life stages, and size selectivity because of damage or mortality to various life stages of species.

A review of the data and of Table 1, Chapter 5 provides insight into physical and biological factors related to mortality, including:

- organism size, shape, life stage mortality,

- species-life stage susceptibility,
- plant design and operational effects.

A. Size/Life Stage Related Mortality

Increased physical injury with increased size during plant passage has been reported for a few species of fish (Markowski, 1962; Oglesby and Allee, 1969; Marcy, 1971, 1973; Beck and Lackie, 1974). Marcy (1973), for example, found that the greatest physical damage occurred at night when larger fish (20 to 40 mm) were available for entrainment. During the day, the majority of entrained fish were less than 15 mm long.

At the Waukegan plant, zooplankton larger than 0.9 mm suffered 17% mortality while sizes smaller than 0.9 mm suffered only 4% mortality; zooplankton larger than 2.0 mm had 21% immobility while those around 0.4 mm had only 4% (Industrial Bio-Test Laboratories, Inc., 1971, 1972). Based on zooplankton data from the Waukegan, Zion, and Kewaunee stations, physical effects during entrainment were more detrimental to larger organisms (>0.95 mm) than to smaller organisms (<0.5 mm) and percent immotility varied directly with the size of the zooplankton species (NALCO Environmental Sciences, 1976). At the Morgantown nuclear plant in Maryland, mortality of zooplankton at sizes between 0.05 and 0.5 mm was low and mortality of *Acartia tonsa* in the 0.5 to 1.5 mm range was 18%, but both mysid and polychaete larvae (1.5 mm to 5.0 mm) suffered severe physical damage (Gentile and Lackie, unpubl. ms).

Physical "abuse" during entrainment injured larger macro-zooplankters (e.g., arrow worms, ctenophores, and coelenterates) (Sandine, 1973). At the Morgantown station, Mihursky and Dorsey (1973) found that larger ctenophores suffered greater mortalities than smaller ones and they suggest that the internal diameter of the condenser tube was a limiting factor in survival. Maturo et al. (1974) found that the extent of physical damage to zooplankton was related to size of the organism at the Crystal River, Florida plant where *Oithona* suffered little mortality but *Labidocera* was affected throughout the year. In later studies at this same plant, Alden, Maturo, and Ingram (1976) concluded that "The mortality caused by mechanical damage associated with passage through the power plant seems to depend, at least in part, on the size of the entrained organism." They again found that damage was lowest for the smallest zooplankton (*Oithona* sp.), highest for the largest (*Labidocera* sp.) and intermediate for intermediate sizes. McNaught (1972) found that mortality due to abrasion varied from 3.1% when small zooplankton were most abundant to 11% when larger zooplankton were most abundant.

A hypothetical size (and time) related mortality plot was presented by Beck and Lackie (1974). A binomial regression analysis (size vs. mortality), based on larval fish and zooplankton mortality and size data, shows that mortality increased with size; however, the observed mortality was due to the combined effects of thermal and physical stresses (Fig. 2). Generally, the highest mortality of entrained organisms from physical stress was found with the relatively large (>15 mm) fragile fish larvae.

The generalized model provided below, after some alteration of the available data to permit statistical analysis, provides a rough approximation of expected mortality to entrained organisms from physical stress as related to size. The data utilized are not truly comparable because studies were conducted at various sites and used different sampling methodologies. Results are also influenced by species-specific tolerances to physical stress and by plant design and operating characteristics. The equation is:

$$\text{Arc-Sine (mortality/100)} = 0.07571 + 0.04053 \text{ (size)}$$

The equation relates size and mortality as a linear function, based on an arc-sine transformation of the data, where $r = 0.92$ and $R^2 = 0.846$. The term on the left side of the equation is an angle measured in radians and expressed as a decimal. To estimate

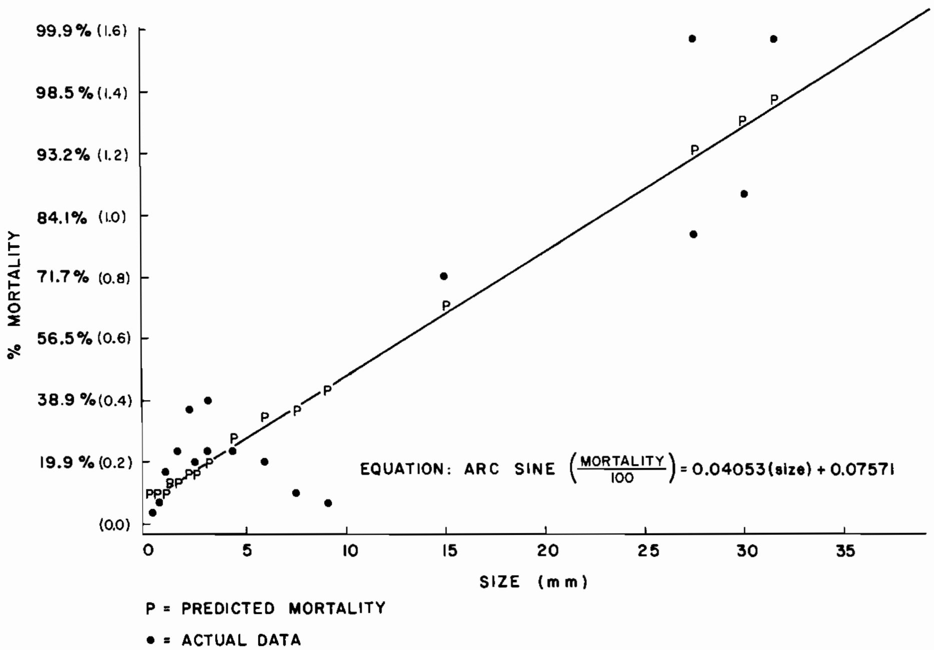


Fig. 2. Predicted size related mortality of ichthyoplankton and zooplankton in cooling water systems (Data from Marcy, 1975; Beck and Lackie, 1974; Nawrocki, 1977; EPA, 1972a and Tarzwell, 1972).

the mortality, the sine of the decimal number is multiplied by 100. For example, a 20 mm fish larvae yields an arc-sine (mortality/100) value of 0.88631 radians. The sine of 0.88631 is 0.7747, which multiplied by 100 results in an estimated mortality of 77.5%.

A few studies have showed mortality to decrease with increasing size. At the Millstone Point plant, mortality decreased from 36.3 to 9.3% as sizes increased from less than 2.25 mm to 10.25 mm (Nawrocki, 1977). At the Nanticoke Station on the Canadian side of Lake Erie, all smelt larvae longer than 14 mm were killed whereas only 77% of the smelt larvae 40 mm long were killed (Teleki, 1976). The results of the latter study support the observation that, once larvae are beyond a critical developmental period, they can withstand a greater degree of physical abuse; however, the results of the study are in contradiction to those of other studies and apply only to certain species, thus limiting the usefulness of the data.

B. Species Susceptibility

Size alone is only a partial measure of potential mortality of entrained organisms. Individual species in the same size range exhibit a wide range of susceptibility during plant passage. A review of Table 1, Chapter 5 reveals this wide variability in species mortality.

Different species and life-history stages show different susceptibilities to physical damage. The high percentage of physical damage (80%) noted in the Connecticut Yankee study was linked to the fact that 97.5% of the entrained fish were in the critical post-yolk sac stage and 97% of the larvae were fragile clupeids (Marcy, 1973). High physical damage of the fragile anchovy, as compared to nine other species entrained, was noted at the Brunswick nuclear plant (Copeland et al., 1975) and yolk and post-yolk sac stages were the most vulnerable to damage at the Millstone Point station (Nawrocki, 1977). Of the physical damage mortality of zooplankton entrained at the Connecticut Yankee plant, those species killed were considered fragile and had larger respiratory apparatus (Massengill, pers. comm.)

The head area, especially in fishes, appears to be the most vulnerable to physical damage (Marcy, 1971, 1973; Nawrocki, 1977; Knutson et al., 1976; Tarzwell, 1972). For example, of the mortality of marked fathead minnows (30 to 60 mm) passed through the Monticello plant's cooling system, 21% of the mortalities were due to decapitation, 63% were associated with damage to opercula-isthmuses-branchiostegal membranes, 2% with eye loss, and 14% with lateral cuts with bloody swellings (Knutson et al., 1976).

At the Millstone Point plant, where physical damage during entrainment to 17 species of larval fish ranged from 2.9 to 62.5%, larvae of the fragile clupeids, Atlantic silverside, sea robin, tautog, and cunner sustained the highest damages while those of the common pipefish experienced the lowest; eel larvae were unharmed (Nawrocki, 1977). In studies of plant passage at Northport, Long Island, maceration of fish larvae ranged from 27.6 to 57.1%, depending on the species (Austin et al., 1973). Menhaden larvae experienced 100% physical destruction (Tarzwell, 1972) at an estuarine plant in Massachusetts whereas no mortality of eel juveniles was found in studies at a Hudson River power generating station (Lauer et al., 1973).

Zooplankton mortality was selective at the Connecticut Yankee plant: all insect larvae and a predaceous cladoceran *(Leptodora kindtii)* were killed while other species were not (Massengill, 1976). Mortality of different species of copepods ranged from 7 to 100% in studies by Prager et al. (1970, 1971). Investigations at two west coast power plants report differential mortality to copepod species of the same genus: in a year-long study at Morro Bay, California, *Acartia tonsa* males exhibited 38.2% mortality whereas no mortality was observed for *A. longiremis* males. At Moss Landing, California, mortalities were

59.8, 27.8, and 23.2% for *A. tonsa*, *A. longiremis*, and *A. clausi* males, respectively (Icanberry, 1973). Heinle (1976) reported different sensitivities to inner plant passage of the copepods *Scottolana canadensis*, *Eurytemora affinis*, and *A. tonsa*; *S. canadensis* was the most sensitive, *A. tonsa* the least.

These data on zooplankton are general for combined stress effects of entrainment. It is probable that physical stress alone could cause similar species-specific mortality.

At Millstone Point, Connecticut, plant passage without chlorination or thermal addition resulted in differential kill of 17 species of phytoplankton (AEC, 1974). Mortality of five species of diatoms ranged up to 72% mortality while 12 other species were not significantly affected.

Briand (1975) found that entrainment effects on phytoplankton were very disruptive, changing the community structure and continually reducing species diversity. Passage through the condenser tubes affected algal species differently, killing diatoms in greater numbers (45.7%) than dinoflagellates (32.8%) and reinforcing the dominance of two major species. He indicated that only productive cells survived entrainment.

C. Plant Design and Operational Effects

Physical damage to menhaden larvae varied from 27.6 to 100% at two operating plants (Beck and Lackie, 1974). Mortality of *Acartia tonsa* males ranged from 0 to 9.09, 38.2, and 59.8% at four power plants on the west coast (Icanberry, 1973). Eraslan et al. (1976) point out that entrainable life stages could be exposed to vastly different physical stresses at different power plants.

Certain power stations have been reported to produce near total destruction of meroplankton while others cause much less damage (Jensen, 1977). Jensen postulates that these differences may be related to excessive turbulence and pressure from cavitation in inefficiently operated circulating pumps.

Davies, Hanson, and Jensen (1976) concluded that zooplankton mortality did not increase significantly because of physical stress at the Crane Power Plant, Chesapeake Bay. This contrasts with observed results at Millstone Point, Connecticut (Carpenter, Peck, and Anderson, 1974), Haddam Neck, Connecticut River (Marcy, 1974), and Morgantown, Maryland (unpublished data cited in Beck and Lackie, 1974).

Beck and Miller (1974) found that differences in effects of entrainment passage on organism mortality were generally different between west coast and east coast power plants at marine sites. There also appear to be plant-related differences in the effects of condenser passage on phytoplankton (Marcy, 1975).

Differential mortality of entrained organism as related to the design and operational characteristics of various plants is little understood at present. An understanding of the kinds and magnitudes of the entrainment stresses involved, coupled with a knowledge of the precise effects and sites of damage, should provide insight into the design of cooling systems which would minimize mortality of entrained species.

IV. STRESSES CAUSING PHYSICAL DAMAGE

A. Pressure

Little work has been directed toward the effects of the pressure changes encountered in power plants. The rapid pressure changes that occur in power plants may have the greatest potential for damaging entrained organisms, especially fishes (American Nuclear Society, 1974). Pressure changes encountered in plant passage may be sufficient to produce air embolism in fry. These embolisms, even if not lethal in themselves, may buoy fry to the surface, keep them in the warmest part of the plume, subject them to increased thermal shock, and cause them to become more vulnerable to predation (Edsall and Yocum, 1972). The following is an account of pressure differentials in a power plant cooling system:

> "Abrupt changes in pressure occur at various points in the circulating water system. As water approaches the impeller of the intake pump there is a rapid drop in pressure which is immediately followed by a pressure increase on the back side of the impeller. The magnitude of the pressure differential experienced by entrained organisms depends on the depth from which they and the cooling water are withdrawn and the design of the intake pump impeller. The positive pressure behind the intake pumps rapidly drops to low absolute values in the condenser system. The reduction to negative pressure is concurrent with the temperature rise and occurs within about 10 to 20 seconds during condenser passage. The maximum negative pressure is expected to occur at the condenser water box. As the flow enters the discharge system, there is a rapid return to positive pressure, the magnitude of which is dependent on the depth in the discharge system." (American Nuclear Society, 1974)

Negative pressures appear to be more damaging than positive pressures (American Nuclear Society, 1974). Changes in hydrostatic pressure should induce minimal physical strain upon an aquatic organism containing no gas vacuoles. Large positive pressure changes are usually benign unless the organism possesses a natural gas space, in which case the cavity may implode. Negative pressure changes, by contrast, have a high potential for inducing physical damage, especially during decompression. In organisms possessing a gas cavity, it may explode if the organism is unable to equilibrate the pressure across the membrane wall fast enough. Also, the solubility of dissolved gases drops as the ambient pressure drops. The water then becomes supersaturated with dissolved gases and, in the presence of living tissue, which serves as a form of catalyst, the gas may come out of solution and the consequent bubbles may cause physical trauma (gas bubble disease) (see Wolke et al., 1975).

Preliminary laboratory studies show that physical damage from the effects of pressure may be the largest cause of mortality to the larvae of bluegill, carp, and gizzard shad (Coutant, pers. comm.). Rapid pressure changes are characteristic of water passing through the cooling system: pressures fall just ahead of the pump impeller, build up to around 1.7 to 2.0 atm at the condenser tubes, and then fall to around 0.14 to 0.34 atm beyond the condenser tubes (Clark and Brownell, 1973). Pressure changes experienced by pump-entrained organisms as they pass from pumps to the discharge canal at the Indian Point plant ranged from 0.3 to 1.6 atm (Lauer et al., 1973). Roach (*Rutilus rutilus*) fingerlings exhibited 100% mortality at a pressure release rate of 3 atm/sec, 40 to 72% at 0.1 to 0.5 atm/sec, and 10% below 0.1 atm/sec (Tsvetkov et al., 1972). The high mortality of fish larvae passing through the Millstone Point nuclear plant was attributed, in large part, to pressure changes (2 atm at the water box dropping to 0.5 atm as the water falls from the condenser to sea level) (Nawrocki, 1977). Bioassays of the effect of pressure change on striped bass eggs and larvae showed little in the way of significant induced mortalities (Beck et al., 1975). Positive pressure impulses up to almost 100 atm yielded no strong pattern of mortality. Those mortalities judged to be nominally significant were largely associated with pressure drops from atmospheric to sub-atmospheric (0.3 atm) pressures or with organisms acclimated to higher pressures (because of water depth) and released to atmospheric pressures. Large pressure changes can also exist at plants with deep water intakes [New York University Medical Center (1975)]. However, pressure changes in problem areas can be easily manipulated and controlled during the design stages (O'Conner, pers. comm.). Studies which show pressure to have an impact on entrained organisms and which provide an overall review of the effects of changes in hydrostatic pressure on aquatic organisms include Beck et al. (1975), Sleigh and MacDonald (1972), Zimmerman (1970), Kinne (1972), and Knight-Jones and Morgan (1966).

B. Acceleration

Acceleration forces, which result from changes in the velocities of flowing waters as they pass from the intake to the discharge area, may cause high mortality of entrained organisms (Ulanowicz, 1975). The lowest forces include accelerations due to changes in the bulk speed of water flow; they commonly range from very low to near that of gravitational force. These forces probably cause little damage. The next range includes those forces resulting from turbulent eddies. These forces are of such magnitude, usually several times that of gravity, as to possibly cause immediate or latent damage to entrained fish larvae. The highest range of acceleration forces is that of the short duration, high magnitude forces that result from impact with solid surfaces. Forces in this range are many times the force of gravity and, combined with damage from mechanical abrasion on impact, are probably immediately lethal. Only limited data are available on the effects of acceleration forces on aquatic organisms.

Post et al. (1973) examined the effects of acceleration rates 1, 2, 5 and 10 times that of gravity on different developmental stages of the relatively hardy rainbow trout and found that survival at hatching (72 to 84%) was not significantly different from that of the controls. Acceleration/shear stresses should have a stronger impact on more fragile organisms. Acceleration/shear forces of roughly 3 times that of gravity can be lethal to eggs and larvae of striped bass and white perch.

There are very few studies on the effects of acceleration on eggs and larvae, especially in terms of the forces experienced during plant passage. In two experiments for which the data are available, Battle (1944) and Rollefsen (1930) studied the effects of acceleration by dropping eggs of the cod, stickleback, mummichog, four-beard rockling from various heights on to a stretched piece of silk. Unfortunately, the heights of release (20, 40, and 60 cm) cannot be readily converted into impulse profiles. Using Newton's second law, the impulses per unit mass of egg work out to approximately 198, 280, and 343 dyne-sec per gram of egg mass, respectively, but the spring characteristics of the silk bed are not known and thus it is impossible to calculate the maximum inertial force associated with the impact. Speculating that the characteristic impact time is on the order of 50 ms would imply corresponding forces of 4.0, 5.7, and 7.0 times that of gravity. The experimental results indicate that these intermediate accelerating forces are potentially lethal to the fragile ichthyoplankton. Battle's (1944) results showed that vulnerability to physical stress among the four species tested varied widely and that damage decreased with increasing size and age of all four species tested.

C. Shear

Shear forces, expressed as units of force per unit area (dynes/cm^2) develop when spatial differences in velocity exist in a moving fluid, for example, at the edges of eddies in a turbulent flow regime or when water flows across a solid surface (Ulanowicz, 1975). The greatest shear stresses occur in close association with solid surfaces, such as pipe walls, pump impellers, traveling screens, and water boxes. Shear stress has two major components: rotation and deformation. When a fish egg is caught in a changing velocity field, the rotational effect of shear disturbs the internal order of the egg while the deformation effect stresses the outer membrane (Fig. 3), leading to possible break-up of the egg if the shear forces are high enough (Ulanowicz, 1975).

Morgan et al. (1973, 1976) attempted to measure the mortality caused by the shear fields that are created by water movement over the surface of fish eggs and larvae. Based on shear-time

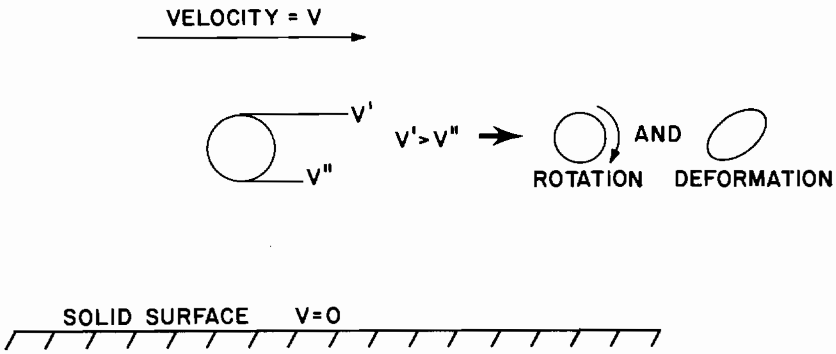


Fig. 3. Possible effects on a fish egg of shear stress resulting from water velocity.

exposure experiment, LD_{50} values were developed for white perch and striped bass. The results show that shear stresses between 120 and 785 dynes/cm^2 were lethal to 50% of the eggs and larvae at exposures of 1 to 20 min. The data obtained were used to predict the shear or physical stress created by water passing through the Chalk Point fossil-fuel plant. Preliminary results indicate conservative estimates of mortality between 20 and 50% for both species (Morgan and Ulanowicz, pers. comm.). Morgan calculated the shear force of water passing through the Calvert Cliffs nuclear plant and estimated that shear stress alone would be enough to cause 100% mortality of entrained eggs and larvae.

An interesting combination of field and laboratory data shows promise for estimating potential physical damage at a power plant, at least in terms of shear-caused damage. Three years of field studies at the Connecticut Yankee Atomic plant show that 80% of the 100% mortality of the young of nine fish species (2.6 to 40 mm) entrained was caused by physical damage (Marcy, 1973).

Clupeids made up 97.6% and white perch 1.3% of the total entrained species. The shear force of the waters passing through the Connecticut Yankee plant's intake, specifically at the walls of the water box, was calculated between 72 and 230 dynes/cm^2 (Ulanowicz, 1975; Morgan et al., 1976). Passage time from intake to the discharge canal at this plant is 93 sec. The LD_{50} shear stress values for laboratory tests on white perch and striped bass were 385 to 540 dynes/cm^2 (Morgan et al., 1976). According to these data, calculated shear forces in the water box are probably not lethal to white perch and striped bass. However, these shear forces may produce high mortalities of the fragile clupeids, which made up 97.6% of the entrained species, but no quantitative data are available on the ability of clupeids to withstand shear stresses.

It may be useful to attempt to relate the absence of physical impact observed by Coutant and Kedl (1975) with the shear bioassay experiments of Morgan et al. (1976). Multiplying the lethal shear (in dynes/cm^2) by the exposure time (in minutes) and averaging Morgan's short exposure trials for each organism, a lethal shear impulse of 570 and 833 dyne-min/cm^2 for striped bass eggs and larvae, respectively, and values of 635 and 900 dyne-min/cm^2 for the eggs and larvae of white perch are obtained. Assuming that the cross-sectional areas of eggs and larvae are characterized by diameters of 0.3 and 0.5 cm, respectively, and further assuming a density close to that of water, then the characteristic force on the organisms over a typical 1-min exposure period is estimated at 2.9 and 2.7 times that of gravity for striped bass eggs and larvae and 3.2 and 2.7 times that of gravity for white perch eggs and larvae.

If these assumptions are accepted, the experiments of Morgan et al. (1976) indicate that juvenile *Morone* spp. begin to exhibit mortality when the shear stress to which they are subjected approaches 3 times the force of gravity.

The condenser replica used by Coutant and Kedl (1975) was 1.89 cm (I.D.) wide and 1,220 cm long. When water and entrained larvae were passed through the tube under a 3 atm pressure drop, the mass-average velocity was 579 cm/sec. Using these figures, the characteristic shear stress at the wall was approximately 776 dynes/cm^2 and the exposure times were slightly over 2 sec. This converts into an impulse of 27.2 dyne-min/cm^2, which is well below those in the experiment of Morgan et al. (1976). Also, using the same assumptions given above on larval size and density, the characteristic force experienced by the test organisms is estimated at 2.4 times the force of gravity. Hence, the results of both Coutant and Kedl (1975) and Morgan et al. (1976) are consistent in indicating that the condenser tubes are an unlikely site for shear damage.

D. Abrasion/Collision

Abrasion can occur when two surfaces move in contact past one another or when a smaller suspended particle with a different velocity impinges upon an organism's surface. Abrasion is a difficult stress to quantify, since it is highly dependent upon the various natures of the contracting surfaces or colliding particles. It acts to decrease the lethal shear threshold of an organism. Under some circumstances it can become the limiting form of physical damage, as was the case in red blood cell destruction in early heart-lung machines. Although no quantitative data exist on abrasion as a factor in entrainment mortality, Emadi (1973) and Marcy (1976) mention abrasion as a possible factor in ichthyoplankton entrainment mortality.

A high silt and detritus load passing through the cooling system with the organisms may cause abrasion/collision mortality (Marcy, 1973, 1975, 1976; Coutant and Kedl, 1975). The average seston concentration in the Connecticut River near the Connecticut Yankee plant was 0.2306 g/m^3 and a concentration of 0.2338 g/m^3 passed through the plant during entrainment studies; such concentrations may be important in the physical damage mortality of certain organisms being pumped through the plant (Massengill, 1976). However, no data are available on hardness, size, shape, and angularity of the particles entrained.

A high organic load during plant passage may have caused the physical damage mortality of phytoplankton and zooplankton at four Florida fossil-fuel plants (Weiss, unpubl. ms). Entrained fish (2.6 mm to 18 mm) made up 2.5% of the total organic load passing through the Monticello nuclear power station. The high organic load possibly contributed to the high mortality observed (Knutson et al., 1976); unfortunately, no data on the characteristics of the particles are given.

V. AREAS PRODUCING PHYSICAL DAMAGE IN COOLING SYSTEMS

Areas where physical damage is likely to occur in a cooling system include fixed or moving equipment (e.g., piping and screens), circulating pumps, the water box, and condenser tubes.

A detailed description of a hypothetical organism's innerplant passage is provided in Appendix A. The areas of physical stress in the system are discussed here as they relate to mortality of a diverse array of organisms as observed in field studies of operating electric power generating stations.

A. Pumps

Once the entrained organisms reach the pumps (Fig. 4), they are exposed to sudden pressure fluctuations, velocity shear forces, and physical buffeting and abrasion (Beck and Lackie, 1974). Once in the pump, rapid positive and negative changes in hydrostatic pressure, ranging from 0.29 to 1.6 atm, occur. In a few seconds, velocity shear forces fluctuate widely, along with severe buffeting and possible contact with pump walls or impeller blades. Physical damage is perhaps most severe in the pumps

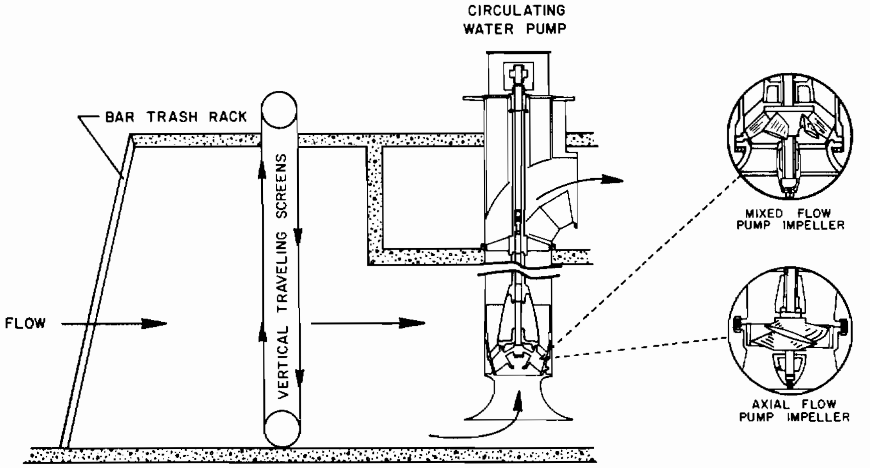


Fig. 4. Representative power plant cooling water intake forebay illustrating the internal characteristics of a typical circulating water pump and showing both axial-flow and mixed-flow impellers.

(Lauer et al., 1973). Gentile and Lackie (pers. comm.) demonstrated that the major cause of mortality to entrained phytoplankton and zooplankton was physical damage, due mainly to pumping effects. Their experiments showed that before the pumps the average mortality was 10%; after the pumps, 50%; and after condenser passage, 60%. In experiments concerned with passage of marked adult and juvenile fish (n = 2,742) through the Ludington pump storage plant's pumping system, mortality averaged 56.5 to 67.7% over a 2 yr period. Physical damage varied from 37.2 to 61.5% and most fish displayed lacerations or decapitation, implying that physical damage and shearing forces in the pump caused the damage (Serchuk, 1976).

The acceleration forces associated with the impact of an organism with an impeller blade are not easily estimated. Kedl (pers. comm.) reports a typical maximum velocity at the pump impeller tip to be about 1,860 cm/sec. Collision with such an object is equivalent to dropping the organism from a height of 17.7 m. In the light of Battle's (1944) results, mortality from such inertial forces is expected. Kedl (pers. comm.) has estimated that the probability of such a collision for a typical mixed-mode pump found in most power plants is about 2 to 5%.

Shear within the pump is an even more difficult quantity to assess with confidence. Using dimensional arguments, however, an order-of-magnitude estimate can be made as to the shear stress on the surface of the impeller blade. A typical power plant 350 hp pump operating at 73% efficiency dissipates approximately 7.31×10^{11} ergs/sec. This energy is passed across the impeller surface (ca. 1.15×10^4 cm^2), moving at a characteristic velocity of 1,860 cm/sec, across a high shear boundary layer into the turbulent flow field. Dividing the dissipated energy by the product of the impeller speed and surface area, a characteristic shear stress of 6,835 dynes/cm^2 at the impeller surface is obtained. This stress is roughly ten times the shear stress at the walls of the condenser tubes and is the highest shear stress and the most probable source of physical damage that an organism would experience during its passage through the cooling system.

Thus, both empirical and theoretical arguments point to the pump as the most likely site of physical damage and the section of the cooling system upon which those studying the impact of physical stress should concentrate their initial efforts.

B. Water Box

The water box can inflict physical damage because this area exhibits the maximum negative pressures found in the entire cooling system, negative pressures being the most damaging (American Nuclear Society, 1974). This area also has the highest flow rates (8 times higher than intake flows) (Marcy, 1973).

C. Condenser Tube

According to Coutant and Kedl (1975), the condenser tube is unlikely as the area where physical damage to fish larvae occurs. A single pass experiment of 2 wk old larval striped bass through a laboratory mock-up of a power plant condenser tube (not including a pump) resulted in mortalities no greater than that of the controls when only physical stresses were exerted. The experiments were conducted using different combinations of turbulent shear, pressure change, and temperature rise.

D. Cooling Towers

Most investigators and regulatory agencies have been assuming 100% mortality of plankton in closed cooling systems with cooling towers, mainly because of the "extreme temperature, mechanical and chemical stresses of the condenser cooling system" (NRC, 1976). Although much less water, and therefore less entrained organisms, is withdrawn from the receiving water body when cooling towers rather than once-through systems are used, few studies have been conducted to determine actual mortalities of plankton.

VI. SUMMARY AND CONCLUSIONS

Observations at operating power plants indicate that many species of organisms cannot tolerate passage through the cooling water system. A wide range of tolerances to plant passage (entrainment) is exhibited by various species. Generally, physical damage, principally occurring in passage through the pumps, is the major cause of mortality during the normal operational cycle of the plant. Thermal and chemical stresses can undergo temporal variations in magnitude of effects, depending on thermal exposure regimes and chlorination procedures. Physical stresses, however, are experienced continuously whenever cooling water is being pumped. Over 70% of estuarine animals have planktonic eggs or larvae (Beck and Lackie, 1974) and, based on present knowledge of biota-plant interactions, it appears that mortality of meroplankton and juvenile fishes due to passage through the plant is the paramount problem to be addressed in attempting to minimize potential environmental damage.

Available data indicate that mortality of entrained species is at least partially related to several factors: size and life stage, tolerance of the individual species and life stage, and differences in power plant cooling system designs and operational characteristics. At any one site, these factors are interrelated and the use of data to predict mortality, as related to specific characteristics of the biota and the plants' cooling system, is somewhat hampered by the complexity of the interrelationships involved. Also, the many field studies of operating plants are not truly comparable. Lauer et al. (1973) note, for example, that the literature is replete with inconsistent results. They suggest that problems in sampling design and methodology and the lack of understanding of the interaction of cooling systems and biota possibly lead to substantial interpretive error.

The impact of power plants can be minimized by siting in nonproductive areas and, in many cases, by utilizing closed cooling systems, or higher ΔT's, resulting in lower intake volumes, since the significance of the mortality of entrained organisms is directly related to the volume entering the intake. This low volume concept is presently the only immediately effective approach to minimizing adverse entrainment effects if high mortality is assumed or observed during plant passage. Also, it may be possible to increase condenser ΔT's while lowering intake volumes, especially when the physical damage component of the mortality dominates, as appears to the case with entrained meroplankton and juvenile fishes. Teleki (1976), for example, states that, at the Point Beach Lake Erie plant, fish loss due to entrainment would be reduced by decreasing the volume of cooling water. Most organisms were killed by physical or heat shock and reducing volume would expose fewer organisms to plant passage. He calculated that a 59% reduction of loss would be achieved by eliminating the tempering (augmentation) cooling.

At this time, there is a sufficient level of insight and understanding of biota-mortality relationships to support a gross level of predictive capability on entrainment mortality due to physical stress. It is hoped that further knowledge of biota-plant interactions will provide design criteria to maximize survival of organisms during passage through a plant where exclusion from the cooling system is not practical.

VII. RECOMMENDATIONS

A. Research

1. *Meroplankton studies should have highest priority.* Losses of meroplankton, including ichthyoplankton (fish eggs and larvae) and invertebrate larvae, to the aquatic system represent a larger impact on the ultimate population of adults over a broader geographical area than do losses of phytoplankton and zooplankton. This is because regeneration times or reproductives cycle of fish may require 2 to 4 yr as opposed to a few days for zooplankton and a few hours for phytoplankton. As a result, it is recommended that much more emphasis be placed on the effects on meroplankton, especially since many species are recreationally or commercially important.
2. *Cooling water pump warrants close scrutiny.* Available experimental evidence points to the pump as the major site of most of the physical damage inflicted on entrained organisms. Measured pressure values reveal that the greatest and most rapid pressure changes occur within the pump. Estimates based on dimensional considerations indicate that

the highest shear and acceleration forces are present near the impeller. Therefore, future field studies on physical damage should give special attention to possible mortalities within the pump. Further analysis of power plant pump design is needed to determine the magnitude and location within the apparatus of the greatest physical forces. The magnitude of these forces should be compared with the results of the physical stress bioassays. Stresses within alternate pump designs should be evaluated. Laboratory replicas of power plant pumps, properly scaled, could provide useful information on pump damage to various organisms.

3. *Bioassay data on physical stresses are urgently needed.* While some bioassay data exist for lethal doses of heat and biocides, very little information has been gathered on the intensities of shear and acceleration that entrainable organisms can endure. Such basic knowledge is imperative if the scattered work on physical damage is to be brought together within a strong conceptual framework. Research into the response of organisms to various levels of acceleration and shear for different exposure times, under precisely controlled laboratory conditions, is essential to our understanding of the problem of physical damage and is a prerequisite to the optimal design of cooling systems.

4. *Pressure bioassays require extension.* The bioassays on pressure are more complete and precise than most experiments on physical damage. Results to date indicate that pressure effects are not substantial in the operating range of most plants. There is no strong pattern apparent in the effects observed thus far, perhaps indicating that the threshold pressures that cause damage are just being approached in these experiments. It seems advisable to increase the range of applied pressure stress in these experiments to more fully delimit the lethal regions. The sections of the

cooling system most likely to cause pressure effects are the upstream side of the pump and the effluent plume.

5. *Abrasion deserves consideration.* Abrasion damage to entrained organisms may also be caused by collisions with particles of suspended materials passing through the plant with the organisms. The damage would be dependent upon such factors as the size and density of particles and their concentration in the cooling water. Few studies have estimated particle concentrations in the receiving and intake waters or have related such concentrations to degrees of physical damage. Such evaluations are recommended to assess abrasion damage during passage.

6. *Size and life stage susceptibilities need further definition.* Mortality appears to be directly related to size among organisms of similar susceptibility to physical damage. The larger the organism the greater the opportunity for contact with hard surfaces within pumps and piping systems and the greater the potential for damage by shear stress produced by discontinuities of water motion in turbulent flows.

   A tentative hypothesis relating the size of the organism to the rate of mortality was provided by Beck and Lackie (1974). A plot and equation derived from this hypothesis, when combined with additional field data, provide an estimate of mortality, based on the size of entrained organisms. There still are insufficient data and the relationship must be tested further with additional data to enhance its predictive value.

   Certain categories of organisms exhibit relatively high entrainment mortality. Large (total length 5 to 50 mm) clupeid and atherinid fish larvae are the most susceptible organisms. Relatively higher percentages of smaller organisms, including certain species of phytoplankton and zooplankton, survive plant passage.

Unfortunately, most of the data available are from different sites with different species and a wide range of study methodologies and personnel. Coutant (pers. comm.) and O'Connor (pers. comm.) have indicated that studies are being undertaken by the NRC at Oak Ridge, Tennessee and by the New York University Medical Center to simulate in the laboratory the physical stresses generally experienced by entrained organisms in passage through pumps and condensers. It is hoped that these types of investigations will provide the data needed to support or deny the tentative size/mortality hypothesis. Studies are needed on the various life stages and range of sizes of ecologically and/or commercially important representative species that are potentially entrainable. From such studies, the species most sensitive to physical stress would be identified, leading to a better understanding and predictability of entrainment effects on selected important species at individual power plant sites.

7. *Species vulnerability differences should be defined.* There may be a general relationship between size and mortality; however, species susceptibility among organisms of similar size is highly variable and appears to be a more important overall consideration than size alone. At one site, phytoplankton survival has been shown to vary from 11.4 to 87.6%, depending on species, with diatoms generally killed in larger numbers than dinoflagellates (Briand, 1975). Individual mortality by zooplankton in studies by Prager et al. (1971) ranged from 7 to 100%, depending on species. Nawrocki (1977) found that damage to fish larvae in the size range of 10 to 40 mm varied from 0 to 67.5%. Species-specific variability to physical stress strongly demonstrates the need for establishing tolerance data for a diverse array of entrainable species at all trophic levels.

B. Sampling

1. *Inter-plant differences in physical mortality should be analyzed.* Differences in mortality of entrained species are also related to power plant design and operational characteristics. Little is known about specific differences among plants which cause such variation in effects on the biota. Field investigations using standardized methods are needed to accurately compare organism survivals and to relate these to variations in physical stresses imposed during entrainment.

2. *Entrainment sampling methodology should be standardized.* Quantitative samples are necessary both at the intake and discharge in order to estimate survival rates among entrained organisms. If new gear is introduced, data should be included on its efficiency relative to a standard gear. The total number of organisms per cubic meter of water at the intake should be statistically comparable to that at the discharge side of condensers. Sampling net or pump-caused mortalities must be kept to a minimum and must be comparable in both the intake and discharge samples. Mortalities induced by collection devices should be factored into the mortality assessments, following procedures such as those provided by O'Connor and Schaffer (in press).

3. *An entrainment sampling program should have a defensible statistical design which establishes confidence limits, sampling error, variance, power curves, etc.* The adequacy of sampling only a given fraction of the total intake flow per unit time should be statistically demonstrated. Complete physical measurements should be taken during sampling. The developmental stages and the sizes of organisms should be recorded during all determinations of the components of inner-plant mortality in order to estimate relative vulnerability.

Day and, especially, night studies should be conducted to determine if the rates of entrainment of organisms and size-related mortality vary during a 24 hr period. Sampling should be carried out over the entire spawning season of the potentially vulnerable species, at a suitable interval to detect significant temporal and spatial changes in species composition and relative abundance.

Modeling should be used to predict the entrainment impact of proposed new power plants or modifications of existing plants. The potential population of adults lost based on losses of entrained meroplankton should be estimated. New study designs are needed to assess the impact of effluent plume entrainment, especially that due to recent high-speed jet diffuser designs.

C. Operation

1. *Coordinating plant activities with organism densities is one approach which can help to alleviate the entrainment problem.* For example, planning plant shutdowns for refueling or maintenance to coincide with high peaks of egg and larval density; varying pumping rates, day vs. night or flood vs. ebb tides, to correspond with known densities; and, possibly, using multiple intakes in different areas or depths so as to draw water from areas of low organism densities may reduce the adverse effects of entrainment.
2. *The impact of power plants can be minimized by siting in nonproductive areas and, in many cases, utilizing closed cooling systems, i.e., lower intake volumes, since the significance of the mortality of entrained biota is directly related to the volume entering the intake.* This low volume concept is presently the only immediately effective approach to minimizing the adverse effects on entrained organisms if high mortality is assumed or observed during plant passage.

Also, it may be possible to increase condenser ΔT's in conjunction with the lowering of intake volumes, especially when the physical damage component of the mortality dominates as appears to be the case with entrained meroplankton and juvenile fishes.

3. *It may be possible to maintain high flow rates (and thereby low ΔT's) by redesigning pumps to decrease internal physical stress.* However, this is a long-range alternative requiring additional knowledge of the physical tolerances of entrained organisms as well as improved ability to assess physical stress levels within various pump designs.

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REFERENCES

Adams, J. R. 1968. Thermal effects and other considerations at steam electric plants. A survey of studies in the marine environment. Pacific Gas and Electric Co., Dept. of Eng. Res. Rept. No. 6934. Cited in Schubel (1975).

AEC. 1972. Proposed issuance of an operating license to the Boston Edison Company for the Pilgrim Nuclear Power Station. Docket No. 50-293. Draft environmental impact statement. Cited in Ulanowicz (1975).

AEC. 1973. Draft environmental statement related to the Oyster Creek nuclear generating station. Docket No. 50-219.

AEC. 1974. Final environmental statement. Millstone Nuclear Power Station - Unit 3. Docket No. 50-423.

Alden, R. W., III, F. J. S. Maturo, Jr. and W. Ingram III. 1976. Interactive effects of temperature, salinity and other factors on coastal copepods. *In* Thermal Ecology II. Proc. of Symp., Savannah River Ecology Lab., Inst. of Ecology, Univ. Georgia. April 2-5, 1975. ERDA Sym. Ser. 40:336-348.

American Nuclear Society. 1974. Entrainment: guide to steam electric power plant cooling system siting, design, and operation for controlling damage to aquatic organisms. ANS - 18.3 Committee. Draft No. 8.

Arnold, D. E., and Pennsylvania Cooperative Fishery Research Unit. 1975. Biological perspectives on steam-electric generating station discharges to the Great Lakes. Contract No. AT(11-1)-2141, EPA, Great Lakes Res. Div., Univ. of Michigan, Ann Arbor, Mich.

Austin, H. M., J. Dickinson, and C. Hickey. 1973. An ecological study of ichthyoplankton at the Northport power station, Long Island, New York. New York Ocean Sci. Lab., Montauk, N.Y. Rept. to Long Island Lighting Co. Cited in Beck and Lackie (1974).

Battle, H. I. 1944. Effects of dropping on the subsequent hatching of teleostean ova. J. Fish. Res. Board Can. 6:252-256.

Beck, A. D., and N. F. Lackie. 1974. Effects of passage of marine animals through power plant cooling water system. Presented at Am. Fish. Soc. Annual Meeting, Hawaii.

Beck, A. D., and D. C. Miller. 1974. Analysis of inner plant passage of estuarine biota. Presented at the Am. Soc. Civil Eng. Power Div. Spec. Conf., Boulder, Colo., Aug. 12-14.

Beck, A. P., G. V. Poje, and W. T. Waller. 1975. A laboratory study on the effects of exposure of some entrainable Hudson River biota to hydrostatic pressure regimens calculated for the proposed Cornwall pump-storage plant, p. 167-204. *In*

S. B. Saila (ed.), Fisheries and energy production, a symposium. Lexington Books, Lexington, Mass.

Benda, R. S. 1972. Thermal effects studies at the Palisades Nuclear Plant. Preliminary findings from the first few months of operation. Presented at Am. Fish. Soc. Nat. Meetings, Hot Springs, Ark. Cited in Davies and Jensen (1974).

Bongers, L. H., A. J. Lippson, and T. T. Polgar. 1973. An interpretive summary of the 1973 Morgantown entrainment studies. Rept. to Potomac Electric Power Co. by Martin Marietta Labs., Baltimore, Md.

Briand, F. J-P. 1975. Effects of power plant cooling systems on marine phytoplankton. Mar. Biol. 33:135-146.

Carlson, F. T., and J. A. McCann. 1969. Hudson River fisheries investigations (1965-1968). Rept. to Consolidated Edison Co. by the Hudson River Policy Comm.

Carpenter, E. J., S. J. Anderson, and B. B. Peck. 1972. Entrainment of marine plankton through Millstone Unit 1. 3rd and 4th semi-annual rept., Woods Hole Oceano. Instit., Woods Hole, Mass.

Carpenter, E. J., B. B. Peck, and S. J. Anderson. 1974. Survival of copepods passing through a nuclear power station on northeastern Long Island Sound, U.S.A. Mar. Biol. 24:49-55.

Clark, J., and W. Brownell. 1973. Electric power plants in the coastal zone: environmental issues. Spec. Publ. No. 7, Am. Litt. Soc., Highlands, N.J.

Consumers Power Company. 1972a. Palisades Plant. Docket No. 50-255. Special report No. 4, Environmental impact of plant operation up to July 1972. Consumers Power Co., Jackson, Mich. Cited in Davies and Jensen (1974).

Consumers Power Company. 1972b. Palisades Plant. Docket No. 50-255. Semi-annual operations report No. 4, 1 July-Dec. 1972. Consumers Power Co., Jackson, Mich. Cited in Davies and Jensen (1974).

Consumers Power Company. 1973. Palisades Plant. Semi-annual operations report No. 5. January 1-June 30, 1973.

Copeland, B. J., R. G. Hodson, and W. S. Birkhead. 1975. Entrainment and entrainment mortality at the Brunswick Nuclear Power Plant. Part I of: Report on entrainment and entrainment mortality of zooplankton and larvae, and impingement and movement of fish. Rept. to Carolina Power and Light, Raleigh, N.C.

Coutant, C. C. 1970. Biological aspects of thermal pollution. I. Entrainment and discharge canal effects. C.R.C. Crit. Rev. Envir. Control 1:341-381.

Coutant, C. C., and R. J. Kedl. 1975. Survival of larval striped bass exposed to fluid-induced and thermal stresses in a stimulated condenser tube. Publ. No. 637, Oak Ridge Natl. Lab., Oak Ridge, Tenn. (Not a final report).

Davies, R. M., and L. D. Jensen. 1974. Effects of entrainment of zooplankton at three Mid-Atlantic power plants. Rept. No. 10 prepared for Elec. Power Res. Inst. cooling water discharge research project RP-49. EPRI Publ. No. 74-049-00-1NUS.

Davies, R. M., C. H. Hanson and L. D. Jensen. 1976. Entrainment of estuarine zooplankton into a mid-Atlantic power plant: delayed effects. *In*: Thermal Ecology II. Proc. Symp., Savannah River Ecology Lab., Instit. of Ecology, Univ. Georgia. April 2-5, 1975. ERDA Symp. Ser. 40: 349-352.

Davis, H. S. 1953. Culture and diseases of game fishes. Univ. of Calif. Press. Berkeley, Calif.

Edsall, T. A., and T. G. Yocum. 1972. Review of recent technical information concerning the adverse effects of once-through cooling on Lake Michigan. Prepared for the Lake Michigan Enforc. Conf., Sept. 19-21, 1972, Chicago. U.S. Fish Wildl. Serv., Great Lakes Fish Lab., Ann Arbor, Mich.

Edsall, T. A. 1976. Electric power generation and its influence on Great Lakes fish, p. 453-462. *In* Proc. of the Second Conf. on the Great Lakes. Great Lakes Comm.

Emadi, H. 1973. Yolk-sac malformation in Pacific salmon in relation to substrate, temperature, and water velocity. J. Fish. Res. Board Can. 30:1249-1250.

EPA. 1972a. Proceedings in the matter of pollution of Mount Hope Bay and its tributaries.

EPA. 1972b. Lake Michigan entrainment studies, Big Rock Nuclear Power Plant, Escanaba Power Plant, November-December 1971. Grosse Ile Laboratory Working Rept. No. 1. Mimeo. Cited in Arnold and Pa. Coop. Fish. Res. Unit (1975).

EPA. 1973. Reviewing environmental impact statements - power plant cooling systems, engineering aspects. EPA 660/2-73-016. Natl. Envir. Res. Ctr., Corvallis, Ore.

Eraslen, A. H., W. Van Winkle, R. D. Sharp, S. W. Cristensen, C. P. Goodyear, R. M. Rush, and W. Fulkerson. 1976. ORNL/NUREG-8 SPEC. Env. Sci. Div. Publ. No. 766, Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Flemer, D. A., C. W. Keefe, L. Hicks, D. R. Heinle, M. C. Grote, R. P. Morgan, W. Gordon, L. Dorsey, and J. A. Mihursky. 1971a. The effects of steam electric station operation on entrained organisms, p. 1-15. *In* J. A. Mihursky and A. J. McErlean (co-principal investigators), Postoperative assessment of the effects of estuarine power plants. Nat. Res. Instit., Ref. No. 71-24b.

Flemer, D. A., D. R. Heinle, R. P. Morgan, C. W. Keefe, M. C. Grote, and J. A. Mihursky. 1971b. Preliminary report on the effects of steam electric station operations on entrained organisms. A progress report to the Maryland Dept. Nat. Res. under the post-operative assessment of effects of estuarine power plants grant. Univ. of Maryland, College Park, Md.

Grosse Ile Laboratory. 1972. Lake Michigan entrainment studies, Big Rock nuclear power plant, Escabana power plant, Nov.-Dec. 1971. Rept. No. 1, EPA Ofc. Res. and Monitor., Grosse Ile, Mich.

Gurtz, M. E., and C. M. Weiss. 1972. Field investigations of the response of phytoplankton to thermal stress. Envir. Study Program, Duke Power Co., ESE Publ. No. 321, Univ. of N. Carolina, Chapel Hill, N.C.

Hardy, C. D. 1971. Dissolved oxygen survey at Northport, p. 116-119. *In* G. C. Williams, Studies on the effects of a steam-electric generating plant on the marine environment Northport, New York. Tech. Rept. No. 9, Marine Sci. Res. Ctr., State Univ. New York, Stony Brook, N.Y.

Hayes, F. R. 1949. The growth, general chemistry and temperature relations of salmonid eggs. Q. Rev. Biol. 24:281.

Heinle, D. R. 1976. Effects of passage through power plant cooling systems. Envir. Pollut. Vol. II, pp. 39-57.

Hess, K. E., M. P. Sissenwine, and S. B. Saila. 1975. Simulating the impact of the entrainment of winter flounder larvae, p. 1-29. *In* S. B. Saila (ed.), Fisheries and energy production, a symposium. Lexington Books, Lexington, Mass.

Icanberry, J., and J. Adams. In press. Zooplankton survival in cooling water systems of four thermal power plants for the California coast - interim report - March 1971-January 1972. *In* Davies and Jensen (1974).

Icanberry, J. W. 1973. Zooplankton survival in cooling water systems of four California coastal power plants, August 1971-July 1972. Presented at 36th annual meeting ASLO, June 10-14, Univ. Utah, Salt Lake City.

Industrial Bio-Test Laboratories, Inc. 1971. Phytoplankton study, preliminary report, March-July, 1970. IBT No. W8956, Project III. Cited in Argonne National Laboratory (1972).

Industrial Bio-Test Laboratories, Inc. 1972. Intake-discharge experiments at Waukegan generating station. Rep. to Commonwealth Edison Co., Proj. XI, IBT No. W9861, Biol. Sec.

Jensen, L. D. 1977. Effects of thermal discharges upon aquatic organisms in estuarine waters with discussion of limiting factors. *In* Estuarine Pollution Control and Assessment Vol.

1. USEPA Office of Water Planning and Standards, Washington, D.C. pp. 359-372.

Kinne, O. (ed.). 1972. Marine ecology. Vol. 1, Part 3. John Wiley and Sons, Ltd., N.Y. Cited in Beck et al. (1975).

Knight-Jones, E. W., and E. Morgan. 1966. Responses of marine animals to changes in hydrostatic pressure. Oceanog. Marine Biol. Ann. Rev. 4:267-299. Cited in Beck et al. (1975).

Knutson, K. M., S. R. Berguson, D. L. Rastetter, M. W. Mischuk, F. B. May, and G. M. Kuhl. 1976. (manuscript). Seasonal pumped entrainment of fish at the Monticello, Mn. Nuclear Power Installation. Dept. of Biol. Sci., St. Cloud State Univ., St. Cloud, Minn.

Lackey, J., and E. Lackey. In press. Thermal effects at Turkey Point-a study. *In* L. D. Jensen (ed.). Proceedings of the entrainment and intake screening workshop, Feb. 1973. Johns Hopkins Univ. Cooling Water Res. Proj., Johns Hopkins Univ., Baltimore. Cited in Davies and Jensen (1974).

Lauer, G. J., W. T. Waller, D. W. Bath, W. Meeks, R. Heffner, T. Ginn, L. Zubarik, P. Bibko, and P. C. Storm. 1973. Entrainment studies on Hudson River organisms. New York Univ. Med. Center, Lab. for Environ. Studies Rept. Nov. 1973: 208. Cited in Beck and Lackie (1974).

Lauer, G. J., W. T. Waller, D. W. Bath, W. Meeks, R. Heffner, T. Ginn, L. Zubarik, P. Bibko, and P. C. Storm. 1974. Entrainment studies on Hudson River organisms, p. 37-82. *In* L. D. Jensen, 1974. Proceedings of the second entrainment and intake screening workshop. Rept. No. 15, The Johns Hopkins Univ., Baltimore, Md.

Leitritz, E. 1963. Trout and salmon culture. Calif. Dept. Fish Game Fish. Bull. 107.

Marcy, B. C., Jr. 1971. Survival of young fish in the discharge canal of a nuclear power plant. J. Fish. Res. Board Can. 28:1057-1060.

Marcy, B. C., Jr. 1973. Vulnerability and survival of young Connecticut River fish entrained at a nuclear power plant. J. Fish. Res. Board Can. 30(8):1195-1203.

Marcy, B. C., Jr. 1975. Entrainment of organisms at power plants with emphasis on fishes-an overview, p. 89-106. *In* S. B. Saila (ed.), Fisheries and energy production, a symposium. Lexington Books, Lexington, Mass.

Marcy, B. C., Jr. 1976. Planktonic fish eggs and larvae of the lower Connecticut River and the effects of the Connecticut Yankee plant including entrainment, p. 115-139. *In* D. Merriman and L. Thorpe (eds.), The Connecticut river ecological study: the impact of a nuclear power plant. Am. Fish. Soc. Monogr. No. 1.

Markowski, S. 1962. Faunistic and ecological investigations in Cavendish Dock, Barrow-In-Furness. J. Anim. Ecol. 31:46-51. Cited in Beck and Lackie (1974).

Massengill, R. R. 1976. Entrainment of zooplankton at the Connecticut Yankee Plant, p. 55-59. *In* D. Merriman and L. Thorpe (eds.), The Connecticut River ecological study. The Am. Fish. Soc. Monogr. No. 1.

Mathur, D. S., and G. M. Yazdani. 1969. Observations on a deformed specimen of *Heteropneustes fossilis* Siluriformes Heteropneustidae. Sci. Cult. 35(9):490-491.

Matlak, O. 1970. Vorlaufinger Bericht uber Missbildung des Kopfes beim Karpfenstrich. Acta Hydrobiol. 12(4):391-398.

Maturo, F. J., R. Alden, and W. Ingram. 1974. Effects of power plant entrainment on major species of copepods, p. 69-101. *In* Crystal River power plant environmental considerations. Final report to the Interagency Research Advisory Committee, Vol. IV. Florida Power Co., St. Petersburg, Fla. Cited in Weiss (unpublished ms).

McNaught, D. C. 1972. The potential effects of condenser passage on the entrained zooplankton at Zion Station. Prepared statement at the Lake Michigan Enforcement Conf., Sept. 21, 1972, Chicago, Ill.

Middlebrook, K. 1975. Zooplankton entrainment, p. 2.3.2-1 through 2.3.2-16. *In* Environmental monitoring and ecological studies program for the Prairie Island Nuclear Generating Plant. NSP 1974 annual report. Northern States Power Co., Minneapolis, Minn.

Mihursky, J. A., and L. C. Dorsey. 1973. Macroplankton, p. 152-170. *In* The effects of Morgantown Steam Electric Station operations on organisms pumped through the cooling water system. Final rept. to Maryland Dept. of Nat. Res., Feb. 1973. Cited in Beck and Lackie (1974).

Morgan, R. P., and R. G. Stross. 1969. Destruction of phytoplankton in the cooling water supply of a steam electric station. Ches. Sci. 10(3-4):165-171.

Morgan, R. P., R. E. Ulanowicz, V. J. Rassin, L. A. Noe, and G. B. Gray 1973. Effects of water movement on eggs and larvae of striped bass and white perch. Nat. Res. Instit., Chesapeake Biol. Lab., Univ. of Maryland, NRI Ref. No. 73-111.

Morgan, R. P., R. E. Ulanowicz, V. J. Rasin, L. A. Noe, and G. B. Gray. 1976. Effects of shear on eggs and larvae of the striped bass, *Morone saxatilis*, and the white perch, *M. americana*. Trans. Am. Fish. Soc. 105:149-154.

NALCO Environmental Sciences. 1976. Report to Northern Indiana Public Service Company - Dean H. Mitchell Station. Section 316(a) Demonstration. Hammond, Ind.

Nawrocki, S. S. 1977. A study of fish abundance in Niantic Bay with particular reference to the Millstone Point Nuclear Power Plant. M.S. Thesis. Univ. of Conn., Storrs, Conn.

New York University Medical Center. 1975. The effects of changes in hydrostatic pressure on some Hudson River biota. Instit. of Envir. Medicine. Prog. Rep. for 1975. Prepared for Consolidated Edison Company of New York, Inc., New York, N.Y.

NRC. 1976. Final environmental statement related to the selection of the preferred closed cycle cooling system at Indian Point Unit No. 2. Docket No. 50-247. NUREG-0042.

O'Connor, J. M. and S.A. Schaffer. 1977. The effects of sampling gear on the survival of striped bass ichthyoplankton. Ches. Sci. (In press).

Oglesby, R. T., and D. J. Allee. 1969. Ecology of Cayuga Lake and the proposed Bell station (nuclear powered). Water Res. Mar. Sci. Cent., Cornell Univ., Ithaca, N.Y., No. 27:315-328.

Post, G., D. V. Power, and T. M. Kloppel. 1973. Effects of physical shock on developing salmonid eggs. Trans. Am. Nucl. Soc. 17:27-28.

Prager, J. C., E. W. Davey, J. H. Gentile, W. Gonzlalez, R. L. Steele, M. D. Lair, C. I. Weber, and S. L. Bargo. 1970. A study of Biscayne Bay plankton affected by the Turkey Point thermal electric generating plant during July and August, 1970. EPA Natl. Mar. Water Qual. Lab. Spec. Rept., November. W. Kingston, R.I.

Prager, J. C., R. L. Steele, W. Gonzlalez, R. Johnson, and R. L. Highland. 1971. Survey of benthic microbiota and zooplankton conditions near Florida Power and Light Company's Turkey Point Plant, August 23-27, 1971. Natl. Mar. Water Qual. Lab., W. Kingston, R.I.

Profitt, M. A. 1969. Effects of heated discharge upon aquatic resources of the White River at Petersburg, Indiana. Indiana Univ. Water Res. Ctr., Rep. of Invest. No. 3.

Restaino, A. L., D. G. Redmond and R. G. Otto. 1975. Entrainment study at Zion Station. *In* Compilation of special reports on the effects of Zion Station operation on the biota in southwestern Lake Michigan. 1975. Report to Commonwealth Edison Company, Chicago, Illinois by Industrial Bio-Test Lab., Inc.

Rollefsen, G. 1930. Observation on cod eggs. Rapp. Cons. Explor. Mer. 65:31-34.

Sandine, P. H. 1973. Zooplankton of Barnegat Bay: the effects of the Oyster Creek Nuclear Power Plant. M.S. Thesis. Rutgers Univ., New Brunswick, N.J. Cited in Beck and Lackie (1974).

Schubel, J. R. 1973. Effects of exposure to time-excess temperature histories typically experienced at power plants on the hatching success of fish eggs. Spec. Rep. No. 32-PPRP-4, Ref. No. 73.11. Chesapeake Bay Instit., The Johns Hopkins Univ., Baltimore, Md.

Serchuk, F. M. 1976. The effects of the Ludington Pumped Storage Power Project on fish passage through pump-turbines and on fish behavior patterns. Ph.D. Disser. Mich. State Univ., Ann Arbor, Mich.

Sleigh, M. A., and A. G. McDonald (eds.). 1972. The effects of pressure on organisms. Symposium of the Society of Experimental Biology. Academic Press, N.Y. Cited in Beck et al. (1975).

Smith, R. A., and A. S. Brooks. 1971. Primary production, p. 33-37. *In* R. W. Koss (ed.), An interim report on environmental responses to thermal discharges from Marshall steam station, Lake Norman, North Carolina. Cooling Water Discharge Proj. RP-49, Edison Elec. Instit., The Johns Hopkins Univ., Baltimore, Md.

Smith, R. A., and L. D. Jensen. 1974. Effects of condenser destruction of algae on dissolved oxygen levels in the James River, p. 123-129. *In* L. D. Jensen. Proceedings of the second entrainment and intake screening workshop. Rept. No. 15, The Johns Hopkins Univ., Baltimore, Md.

Tarzwell, C. M. 1972. An argument for open ocean siting of coastal thermal electric plants. J. Environ. Qual. 1(1):89-91.

Teleki, G. C. 1976. The incidence and effect of once-through cooling of young-of-the-year fishes at Long Point Bay, Lake Erie: a preliminary assessment. *In* Thermal Ecology II Proc.

of Symposium, Savannah River Ecology Lab. Instit. Ecology. Univ. of Georgia. April 2-5, 1975. ERDA Sym. Sec. 40:387-393.

Tsvetkov, V. I., D. S. Pavlov, and V. K. Nezdoliy. 1972. Changes of hydrostatic pressure lethal to young of some freshwater fish. J. Ichthyol. 12:307-308. Cited in Beck et al. (1975).

Ulanowicz, R. 1975. The mechanical effects of water flow on fish eggs and larvae, p. 77-87. *In* S. B. Saila (ed.). Fisheries and energy production, a symposium. Lexington Books, Lexington, Mass.

University of Wisconsin-Milwaukee. 1972. Environmental studies at the Point Beach NUclear Power plant. April 1972. Department of Botany. Rep. No. PBR3.

Voigtlander, C. W. 1974. Toward the assessment of impacts of entrainment: estimation of populations and entrainment on a pre-volume basis. Fish. and Waterfowl Res. Branch Tenn. Valley Auth. (manuscript).

Williams, G. C. 1971. Studies on the effects of a steam-electric generating plant on the marine environment at Northport, New York. Tech. Rep. No. 9, Mar. Sci. Res. Ctr. State Univ. New York, Stony Brook, N.Y.

Wisconsin Public Service Corp. 1974. Preoperational thermal monitoring program of Lake Michigan near the Kewaunee Nuclear Power plant. Jan.-Dec. 1973. Third Annual Rep., Green Bay, Wisc. March 1974.

Wolke, R. E., G. R. Boucks, and R. K. Stroud. 1975. Gas-bubble disease: a review in relation to modern energy production, p. 239-265. *In* S. B. Saila, Fisheries and energy production, a syposium. Lexington Books. Lexington, Mass.

Zimmerman, A. M. (ed.). 1970. High pressure effects on cellular processes. Academic Press, N.Y. Cited in Beck et al. (1975).