THE MECHANICAL EFFECTS OF WATER FLOW ON FISH EGGS AND LARVAE

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ABSTRACT

The impact of mechanical stresses upon ichthyoplankton entrained in power plant cooling systems has long been considered negligible. Arguments and evidence exist, however, to show that such a supposition is not universally true, especially in nuclear power plants. The mechanisms of mechanical damage can be detailed in terms of pressure change, acceleration, and shear stress within the fluid flow field. Laboratory efforts to quantify the effects of mechanical stress have been very sparse. A well-planned bioassay is urgently needed.

INTRODUCTION

In his pioneering paper on the effects of the Contra Costa electric generating facility on the local striped bass and salmon fisheries, Kerr (1953) devoted the bulk of his report to the mortality of adult fish due to impingement upon intake water screens. Passing mention was made of smaller juvenile forms passing through the screens to say that mortality due to mechanical stresses further along in the system was negligible. This work set the pattern for much of the research which followed. Most subsequent work on the theme of mechanical damage in cooling water systems repeated the theme that mechanical injury increased with increasing size (e.g., Markowski, 1962; Oglesby and Allee, 1969; Marcy, 1971).

Meanwhile, fish culturists were aware that mechanical trauma could be quite detrimental to the survival of juvenile fishes in hatcheries (Hayes, 1949; David, 1953; Leitritz, 1963). It is worth noting that much of the damage induced in developing young is not acute (i.e., immediate) but manifests itself later as deformities which could result in premature mortality. For example, Matlak (1970) inferred that misshapen heads in carp fry were attributable to mechanical disturbances. Emadi (1973) observed a high incidence of yolk sac deformation in alevins raised in trays with smooth bottoms--presumably a result of the fry's inability to maintain position and the consequent abrasion of the sac against the bottom surface. Mathur and Yazdani (1969) observed a vertebral mechanical compression in an adult Heteropneustes fossilis which he suggested was due to mechanical injury in early development.

If ichthyoplankton can be so sensitive to mechanical damage in the controlled environment of the hatchery, it would seem logical to expect some damage to the organisms when they are subjected to the rigors of the pumps and conduits of a cooling water system. Perhaps suspecting this, Barton Marcy (1973) was inspired to search for mechanical damage to entrained ichthyoplankton in the Connecticut Yankee Nuclear Power Plant. Marcy sampled the fish eggs and larvae in the discharge canal with the pumps operating, but without added heat or biocides. His data revealed that 80 percent of the entrained juveniles failed to survive the pass through the plant. While care must be taken not to transfer these results, quantitatively or qualitatively, to other power stations, they do nonetheless, point out the unequivocal need for more attention to the possibility of mechanical impact on entrained organisms.

Fortunately, an awareness of this problem is beginning to creep into environmental impact work. Lauer (1973) reported that pressure changes of the magnitude found in the Indian Point Power Plant were not damaging to striped bass eggs and larvae. Goodyear and Coutant (1973) added that one must also consider turbulence and shear as possibly inducing mortality. The authors of the impact statement for the Pilgrim Nuclear Power Station were careful to ascribe lobster larvae mortality to heat, mechanical action, and chemicals (A.E.C., 1972).

Mechanisms of Damage

While the whole issue of mechanical damage to entrained ichthyoplankton has not been studied thoroughly, it is possible, nonetheless, to outline the physical forces which could stress the organisms. It is important to emphasize that we are dealing with forces in the Newtonian sense. Thus, we should be careful not to speak of mortality caused by water velocity. The velocity, per se, of an organism or the fluid surrounding it can cause no damage. Rather, the three major forces (often associated with high velocities) to be reckoned with are (1) pressure change, (2) acceleration, and (3) shear.

The problem of pressure change, cause and effect, is the subject of another paper in this symposium, and hence will not be mentioned further in this manuscript.

Acceleration is the time rate of change of velocity and is always accompanied by a force according to Newton's second law of motion. In a cooling water system we can speak in terms of at least three ranges of acceleration.

At the lower end of the scale are the accelerations due to change in the bulk speed of the fluid flow. Typically these accelerations would be encountered near the intake as the water speeds up to its terminal velocity in the conduit, at the outlet as the water slows down, or at the upstream (or downstream) end of a constriction in the flow. These forces usually range from very slight to the order of magnitude of the gravitational force. In all likelihood they are not very damaging.

In the intermediate range are the accelerative forces associated with the turbulent eddies characteristic of most cooling water flows. If one follows the tortuous path of a particle in such a flow, he will become aware of abrupt changes in speed and direction. Such accelerations give rise to forces several times that of gravity and could possibly be damaging to ichthyoplankton, either immediately or in later development.

Potentially the most destructive accelerative forces would be short duration, high magnitude impulses from the impact of the organism with a solid surface. Such forces could be many times the acceleration of gravity and would probably be fatal.

Shear stress (or viscous force) is present in a real liquid when the velocity of the fluid varies from point to point in space. This is most commonly noticed when fluid moves with respect to a solid surface and exerts a viscous drag on the surface. The force is present throughout the fluid, however, and its potential effect on an egg in the flow field is illustrated in Figure 1. In this instance a fluid is flowing past a stationary surface. The fluid clinging to the surface wall has a velocity equal to 0. As one moves away from the wall the velocity increases up to some value characteristic of the bulk motion of the fluid. An egg within the changing velocity field would be subject to a fluid velocity on its outboard side (V') greater than that on its inboard side (V"). The resultant forces on the egg can be resolved (both conceptually and mathematically) into a rotational and a deformational component. The rotational effect would be to disturb the internal order of the egg, while the deformation would stress both the membrane and the interior.

The special case of damage incurred when the surface of the organism contacts the solid boundary is termed abrasion and deserves special study, since the resulting damage is a function of the two contacting surfaces.

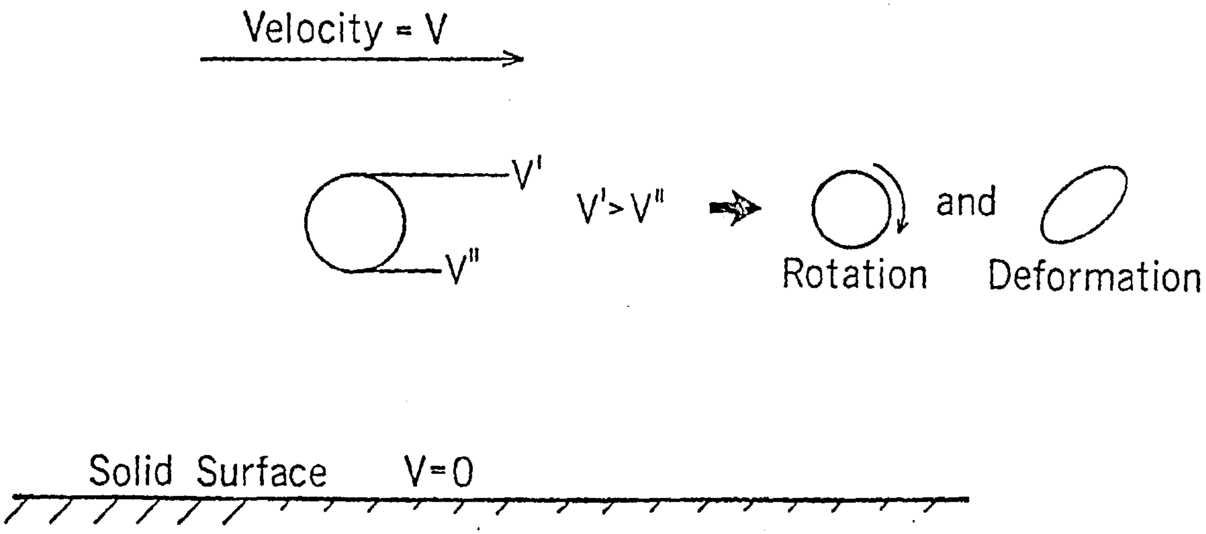

Figure 1. Possible effects of shear stress resulting from water velocity on a fish egg.

Shear stress is commonly reported by fluid dynamicists as a force per unit area (dynes/cm^2), however, the associated rate of shear (sec^{-1}) is often used in biological applications. For a Newtonian fluid, such as water, the two are directly proportional, the constant or proportionality being the coefficient of viscosity.

The destructiveness of shear is documented in the biophysical literature. It is a major cause of hemolysis in heart-lung machines (Williams, 1973; Bernstein, 1973), and is believed to be the principal agent in the degradation of fibrinogen within the circulatory system (Charm and Wong, 1970).

Within a flow field, the greatest shear stresses will be encountered in the near neighborhood of solid surfaces, e.g., conduit walls, pump impellers, screens, vanes, etc. In flows of high turbulent intensity one could also expect high shears to exist at the interfaces between eddies.

Previous Work

Now that the qualitative nature of possible mechanical damage to ichthyoplankton has been described, two questions arise: (1) What are the quantitative ranges of accelerative and shear forces which cause immediate and delayed damage to entrained fish eggs and larvae? (2) How does one design a cooling system to minimize such mechanical damage?

The engineering physics of flow systems is reasonably well understood. That is, a good chemical or mechanical engineer, given the design specifications of the system, should be able to invoke Boundary Layer Theory and the Theory of Turbulence along with empirically determined functions to specify where accelerations and shears of given intensities could be expected. His answers could never be determinant, since turbulent flows are stochastic by nature and certain complicated geometries can only be approximated, but his estimated should prove adequate to the task. Minimization of damage could be achieved by iteration of his calculations upon different design specifications.

The immediate bottleneck in evaluating the impact of entrained organisms is the paucity of bio-engineering data to answer the first question. In a reasonably intensive literature search, this writer has discovered only two attempts to gauge the effects of acceleration or shear upon fish eggs and larvae, neither of which was stimulated by power plant considerations.

Acceleration generated by shock waves from underground nuclear explosions was considered as possibly detrimental to trout redds in the vicinity of nuclear test sites (Post *et al.*, 1973). Maximum peak accelerations in the order of 0.9 g were expected along one major trout stream. Post and associates, therefore, constructed a series of simulated rainbow trout redds in one-liter glass aquaria. An accelerometer was attached to replicate pairs of aquaria and the apparatus was dropped onto a resilient mat. Mean accelerations could be controlled to within 10 percent.

Pairs of aquaria were subjected to peak acceleration of 1, 2, 5, and 10 g's at biological development stages of 37.5, 75, 125, and 250 TU (one TU per hour is the product of the water temperature in degrees Fahrenheit above freezing divided by 24). Experiments were repeated at 8.3°C and 11.1°C. The survival rates of hatching (72-84 percent) did not differ significantly in any way from the experimental controls.

Extrapolation of these negative results should be done with caution. As the authors suggest, they probably apply to other salmonid species. But then, there are unconfirmed reports of researchers playing marbles with water-hardened salmon eggs! More fragile eggs, such as those of the striped bass, could prove to be more sensitive. Also, the larval stages of the stressed eggs should be examined for possible malformation or premature mortality. Finally, it would be useful to know what accelerations are necessary to induce mortality.

In an environmental impact study of the widening and deepening of the Chesapeake and Delaware Canal, Morgan *et al.* (1974) performed a series of simple experiments to assess the damage to striped bass, *Morone saxatilis*, and white perch, *M. americana*, eggs from shear fields.

Shear was generated by a plexiglass cylinder rotating axially in the middle of an annular tank of water. The experimental apparatus was designed for simplicity in fabrication, but without foreknowledge of the complicated flow which would be induced in the outer annular space. As a result, it became impossible to determine the exact value of shear which induced a given degree of mortality. It was possible, however, to calculate the maximum shear stress within the flow field and thereby provide reasonable values of shear to associate with observed impacts.

Eggs and larvae of both species were studied under long-term and short-term exposures. In the low-level, long-term experiments organisms were exposed to flows with characteristic shear rates ranging from 0.64 to 86.0 dynes/cm^2 for a period of two days.

Experiments with higher shear levels of from 76 to 404 dynes/cm^2 effective over exposure times of from 1 to 20 minutes completed the program.

Replication of the results of the experiments was very good. The lethal doses of shear required to kill half the specimens (LD_{50}) was calculated by polynomial regression from the experimental results and appears in Table 1.

The immediate question is how do the shear values in Table 1 compare with those within a typical nuclear power plant. Marcy (1973) reports for the Connecticut Yankee that at peak loads approximately 25 m^3/sec flows through twin, single-pass, divided water boxes in which the velocity may approach 2.4 m/sec. These figures imply a Reynolds' number for the flow in the order of 6 x 10^6. Fanning friction factors (see, Bird et al., 1960, p. 186) for such flow range from 0.0025 to 0.008 depending upon the smoothness of the surfaces of the conduit. Translated back into shear at the surface, stresses of from 72 to 230 dynes/cm^2 would be present at the walls of the water box.

While these values fall below the range of LD_{50}'s for one minute exposures (385-540 dynes/cm^2), they are within the damaging range. Higher shears could be expected in the pump, and it is probable that mortality in the experiment is being effected by shears lower than the wall stress. Therefore, the possibility that ichthyoplankton are being killed by shear stress in the nuclear cooling system is very real indeed.

SUMMARY AND RECOMMENDATIONS

Historically, the effects of mechanical stresses upon entrained ichthyoplankton have been assumed to be negligible. Mechanical damage to hatchery organisms is well documents, however. Nuclear power plants seem likely to inflict more mechanical damage to fish eggs and larvae passing through them because of their greater water use. The existence of a significant mechanical impact has already been demonstrated for the Connecticut Yankee Power Plant.

Existing laboratory research to quantify the damage to ichthyoplankton by acceleration and shear stress is sparse, fragmentary, and inconclusive. A well-coordinated and exhaustive effort is urgently needed.

Research is required to define the ranges of pressure change, acceleration, impaction, shear, and abrasion which cause mortality of ichthyoplankton of various entrained fishes and important inverte-

Table 1. Estimated LD_{50} values for time-shear exposure experiments on white perch and striped bass eggs and larvae. After Morgan *et al.* (1974).

Organism	Exposure Time	LD_{50} (dynes/cm^2)	
Striped bass eggs	1 min.	450	570
	2 "	290	
	4 "	170	
	2 days	70	
Striped bass larvae	1 min.	540	
	2 "	435	513
	4 "	310	
White perch eggs	1 "	385	
	2 "	385	335
	5 "	150	
	10 "	150	
	20 "	150	
	2 days	57	
White perch larvae	1 min.	435	
	2 "	402	900
	4 "	365	
	2 days	88	

brates. The determinations of damaging exposures should be made over all stages of development from fresh spawn to screenable juveniles. Temperature and salinity, of course, are important parameters to be varied in the experiments. Attention should be paid to the post-exposure development of survivors to assess possible delayed effects.

The huge quantities of heat added by power plants circumscribe the alternatives which would diminish thermal shock, but mechanical stress can be minimized by a large number of design alternatives. Such corrective action, however, awaits the development of reliable bio-engineering data.

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LITERATURE CITED

ATOMIC ENERGY COMMISSION. 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.

BERNSTEIN, E. F. 1973. Mechanisms of hemolysis. Annual summary report. Univ. of California at San Diego, La Jolla School of Medicine 406915.

BIRD, R. B., W. E. STEWART, and E. N. LIGHTFOOT. 1960. Transport phenomena. John Wiley and Sons Inc., New York.

CHARM, S. E., and B. L. WONG. 1970. Shear degradation of fibrinogen in the circulation. Science <u>170</u>: 466-468.

DAVIS, H. S. 1953. Culture and diseases of game fishes. Univ. of California Press, Berkeley.

EMADI, H. 1973. Yolk-sac malformation in Pacific salmon in relation to substrate, temperature, and water velocity. J. Fish. Res. Bd. Can. <u>30</u>: 1249-1250.

GOODYEAR, C. P., and C. C. COUTANT. 1973. Direct biological effects on entrained fish eggs and larvae at Indian Point.

Testimony to the Committee on Merchant Marine and Fisheries, U. S. House of Representatives, February 22, 1973.

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

KERR, J. E. 1953. Studies on fish preservation at Contra Costa steam plant of the Pacific Gas and Electric Company. Calif. Dept. Fish & Game Fish. Bull. 92.

LAUER, G. P. 1973. On the absence of mortality due to pressure changes on striped bass eggs and larvae. Testimony to the Committee on Merchant Marine and Fisheries, U. S. House of Representatives, February 5, 1973.

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

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

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

MARKOWSKI, S. 1962. Faunistic and ecological investigations in Cavendish Dock, Barrow-in-Furness. J. Anim. Ecol. 31: 43-51.

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. Vorläufinger Bericht über Missbildung des Kopfes beim Karpfenstrich. Acta Hydrobiol. 12(4): 391-398.

MORGAN, R. P., R. E. ULANOWICZ, V. J. RASIN, L. A. NOE, and G. B. GRAY. 1974. Effects of shear on eggs and larvae of the striped bass, Morone saxatilis, and the white perch, M. americana. Submitted to Trans. Am. Fish. Soc.

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. Effect of physical shock on developing salmonid eggs. Trans. Am. Nucl. Soc. 17: 27-28.

WILLIAMS, M. C. 1973. Shear-induced hemolysis: Materials and blood composition. Univ. California, Berkeley 071850.