

PROBLEMS OF THERMAL EFFLUENTS IN MARINE  
AND ESTUARINE WATERS

Presented at the  
Pacific Marine Fisheries Commission Meetings  
Coeur d'Alene, Idaho  
November 21, 1968

By Anthony J. Novotny  
Fishery Research Biologist

Bureau of Commercial Fisheries  
Biological Laboratory  
2725 Montlake Boulevard East  
Seattle, Washington 98102

## CONTENTS

	<u>Page</u>
The future of thermal electric power generation in marine and estuarine waters . . . . .	1
Defining marine and estuarine waters in the Pacific Northwest. . . . .	2
Physical aspects of thermal effluents in estuarine and marine waters . .	2
Influences of thermal effluents on marine and estuarine biota. . . . .	4
Microflora . . . . .	4
Macroflora . . . . .	5
Microinvertebrate fauna. . . . .	6
Macroinvertebrate fauna. . . . .	6
Vertebrate fauna . . . . .	9
Prospectus for the future . . . . .	12
References . . . . .	15

## The Future of Thermal Electric Power Generation in Marine and Estuarine Waters

The rapid expansion of plants for the thermal generation of electricity in small countries such as Great Britain has placed a serious burden on the limited supply of fresh water to cool condensers. By the end of this decade, Great Britain's electric power stations will be discharging  $2.2 \times 10^{10}$  BTU per hour in the form of waste heat. The United States will be discharging  $12.5 \times 10^{10}$  BTU of waste heat per hour by 1970 (Naylor, 1965). Both of these countries will have stretched their hydroelectric capacities to the planned limit by the early 1970's and are now looking for sites for additional thermal power generating stations. The greatest sources of cooling water for steam turbine condensers in the two countries are the coastal estuarine and marine waters. Undoubtedly, marine and estuarine waters will be utilized by the larger, nuclear-fueled plants which require the greatest quantities of cooling water. This appears to be the practice in Great Britain, and there is no reason to believe it will be much different in the United States.

J. R. Adams<sup>1/</sup> lists 12 marine thermal power plants in Great Britain and 15 in the United States (some of these are in estuarine waters). These plants will require quantities of cooling water ranging from 50,000 to 1,800,000 gallons per minute (gpm); temperatures range from about 3° to 16° C. over ambient. The 1.8-million gpm flow is from the relatively new Turkey Point plant on Florida's Biscayne Bay.

The nuclear-fueled thermal electric station at Biscayne Bay is of interest to us in the Northwest because its size (1,440 MW<sub>e</sub>). It is fairly typical of the first marine and estuarine generating stations to be built here. The Bonneville Power Administration's Thermal Task Force Committee has recently reported that a minimum of 20 nuclear-fueled thermal power generating stations will be built in the Pacific Northwest by 1990. The minimum plant size is about 1,000 MW<sub>e</sub>. A plant this size would use about 700,000 gpm of cooling water, with a water temperature rise of at least 10° C. over ambient. It must be anticipated that at least several of these plants will be on marine or estuarine sites. The recent Battelle report (1967) lists seven possible marine and estuarine sites in Oregon and Washington suitable for minimum sized stations. Direct discharges of waste heat from these power stations will cause some disturbances to the environment. The direct environmental impact of such large volumes of heated water could be more severe if the plant were located on a river with runs of anadromous fish, for example. The disturbances to a marine environment receiving such thermal discharges may not be as direct, but they will be more complex.

It is the complexity of these disturbances that I wish to emphasize in this paper--most specifically, complex situations in the Pacific Northwest and some possible solutions.

---

<sup>1/</sup> "Thermal Effects and Other Considerations at Steam Electric Plants--A Survey of Studies in the Marine Environment", unpublished. March 1968.

## Defining Marine and Estuarine Waters in the Pacific Northwest

Pritchard (1967) defines an estuary as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage." Depending on the numeric value of "measurably diluted," this would include Puget Sound, the coastal bays and harbors of Oregon and Washington, and the Columbia River from the bar to a short distance above Tongue Point, Oregon. There are measurable "tides" as far up the Columbia River as Bonneville Dam; some typical estuarine fish species (such as the starry flounder) are found as far as Portland. Nonetheless, the limit of salt water intrusion is just above Tongue Point.

Marine water sites, then, are the open coast, the Strait of Juan de Fuca, and possibly a portion of the Strait of Georgia.

### Physical Aspects of Thermal Effluents in Estuarine and Marine Waters

Rivers may vary in velocity and volume, but their flow is unidirectional. Consequently, thermal discharges into a river will usually have a feather- or tear-drop-shaped plume below the point of discharge.

The pattern becomes more complex in marine waters. This is mainly due to the mixed semi-diurnal tides and variations in current patterns. Figure 1 is an example of a predicted thermal discharge from a thermal power station on the Pacific coast. Measurable temperature increases are predicted within a radius of 6,000 yards (5,500 meters) as the tide changes from one cycle to another. Several items are not evident in this illustrations: (1) there is no definition of the shape or extent of the plume during the slack water periods, which occur four times each 24 hours; because the warmer, less dense discharge water will presumably rise to the surface, a strong on-shore wind could concentrate the plume between the discharge terminus and the shore during slack tide; (2) the vertical temperature gradient is not indicated; and (3) there is the distinct possibility that current patterns in an area might return heated water to or near the discharge point to be reheated again. An offshore current pattern is shown in Figure 2, as an example. Note that at least some portion of a water mass could return to a point of origin in less than three tidal cycles.

Figure 3 is a theoretical example of what might be classed as an estuarine site. Although the configuration and radial directionality of the thermal plume is similar to that of a typical coastal site; there are some differences between marine and estuarine situations (especially in Puget Sound) which should be borne in mind.

Estuaries are typified by tidal basins (such as Puget Sound) with irregular shore lines and bottom contours. Islands are often numerous. Peninsulas, lagoons, and bays are common. These structural features of a tidal basin create complex tidal current patterns and velocities which might favorably dilute thermal discharges at times. However, there are areas where heat sinks might form, which would be unsuitable. Therefore, current patterns and velocities must be thoroughly analyzed.

The patterns and velocities of surface currents are not sufficient data for determining the site of an estuarine thermal power station. Variations in the discharge of fresh water into a tidal basin seriously complicate the density structure of the water column. Normally, one would expect heated saline water from a thermal generating station to rise to the surface where the heat would be well dissipated by atmospheric cooling and lateral mixing. I have diagrammed an example (Fig. 4) of what could happen if a layer of fresh water were on the surface. Cold, dense saline water is pumped from the depths through the condensers, heated, and then discharged into deep water again. Because heating lowers the density, the warm saline water rises. However, although the fresh water layer is cold, it is still the least dense. The warm saline water spreads just below the fresh water with the aid of lateral current. Dispersion is entirely by mixing. This actually occurs at the Marchwood Station in England. Current patterns and velocities, and salinities, then, must be known throughout the vertical water column.

The turbulence in the pumps should maintain dissolved gases at or near saturation levels, and indeed this has often been true (Markowski, 1959). Nash<sup>2/</sup> found that there are times when even supersaturation of dissolved gases can occur. Perhaps supersaturation occurs more frequently than we had thought.

In confined estuarine waters, great care must be taken in positioning the intake orifice and outfall structure. Under certain circumstances water masses could be heated over and over again. This would not only create problems of undesired thermal loading; it could seriously affect the dissolved gas concentrations. If water with little or no dissolved oxygen were pumped through the condensers, then heated, discharged, and pumped through again a short time later, dissolved oxygen levels might have little chance to build up.

I would not expect a thermal discharge to profoundly affect the physical chemistry of sea water, provided there is adequate mixing and the discharge is not in confined estuarine waters. Sea water has great buffering capacity when large volumes of water are involved.

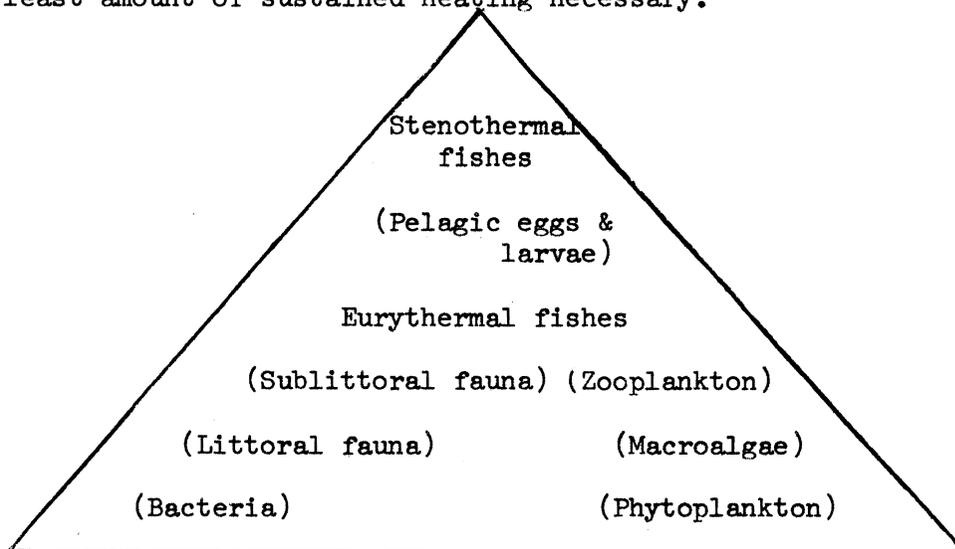
---

<sup>2/</sup> Dr. Colin E. Nash, Whitefish Authority, Hunterston, Scotland. Personal communication.

Influences of Thermal Effluents on Marine  
and Estuarine Biota

In the Pacific Northwest, our main concern over this problem of heating marine waters is with the living organisms in the water. If it weren't for the biota, the recreational value along of warm sea water would probably be quite high. But our waters are teeming with marine organisms. They are valuable, and they are sensitive to changes in the environment.

First, one aspect must be borne in mind: we have already discussed tidal cycles. Therefore, some organisms will be subjected to rapid heating followed by rapid cooling. A sudden drop in temperature can often have a greater effect on an organism than a sudden rise. What we are really interested in then is the reaction of the whole biological community to patterns and ranges of temperature which are beyond the norm. The sensitivity of the biological community can be diagrammed pictorially, where the base of the pyramid represents the greatest amount of sustained heating necessary to effect a change, and the apex the least amount of sustained heating necessary.



Microflora

Sieburth (1967), for example, found that there was a seasonal selection of thermal types of heterotrophic bacteria isolates from a Rhode Island estuary and that this selection occurred in all taxonomic groups. Sieburth also felt that a water temperature change of several degrees in the spring and fall can apparently change the rate of bacterial growth by one-third. Bacteria are required for the recycling of nutrients, but it is possible that maximal activities of bacteria in sustained warm water can bind or recycle nutrients in such a manner as to prevent phytoplankton blooms.

Sustenance of warm water during the summer would probably increase phytoplankton blooms until the bacteria-nutrient limiting factors enter in. It is conceivable that blooms might be over-productive at times, which can put shellfish "off their feed" and limit their growth. There is also a real danger of dinoflagellate blooms. Blooms of the dinoflagellate Gonyaulax, which cause the "brown tides," are rare in Puget Sound. The limiting factors are thought to be nutrients and temperature. Sustained warming of the water might produce localized blooms of this undesirable phytoplankton.

Sustained heating of the water in the winter is not a key environmental ingredient at our latitude for maintaining high levels of phytoplankton production. Light is the limiting factor, as shown in Figure 5. Certain enzyme reactions inhibit photosynthetic activity under low light levels. Naturally, the level of light inhibition will determine the magnitude of any net increases in phytoplankton productivity. There is no evidence to indicate that phytoplankton are affected by rapid, short-term warming, such as in a condenser tube. Any discrepancies of phytoplankton counts between the intake and discharge of condenser water is more likely due to the introduction of anti-fouling agents in the intake water.

### Macroflora

Generally speaking, macrophytes can be considered eurythermal. Macrophytes which attach themselves to an immobile substrate can only redistribute themselves by fragmenting parts capable of regeneration or pelagic spore formation. Thus, attached plants in temperature limits exceeding their eurythermal range might be killed outright. Others might be shifted outside their natural optimum range but not killed. Growth may be inhibited and retardation of spore formation may inhibit reproduction entirely. Such was the case with vegetative reproduction of Ruppia in the Patuxent estuary (Anderson, 1968). Anderson also found that some species of plants may be in the lower limit of their temperature range. Raising the water temperature can put plants into their optimum range and species succession may occur.

Sub-littoral species of the macrophytes high in the intertidal zone could be expected to survive the greatest change in temperature range. However, even this can be misleading, as grazing by overactive microfauna in warm water during the winter could injure plants beyond their capacity to recover.

### Microinvertebrate Fauna

Evidence of direct damage to zooplankton passing through the condenser tubes of a thermal power station is limited. Heinle (1968) found that the calanoid copepod Acartia tonsa had an upper lethal level of 30° C. regardless of the acclimation temperature. However, field studies in a section of the Patuxent estuary receiving thermal effluents contradicted laboratory studies. Heavy mortalities of copepods were noted when temperatures rose from 23° C. to 29° C. and from 13° C. to 16° C. in the discharge area; the causative agent may have been chlorine released in the condenser water.

Sustained warm water discharges may have more subtle effects on zooplankton, especially those in the sub-littoral zones. Heinle (1968) noted that temperature can and does alter their filtering rate. Undoubtedly, the resting and active metabolic rates are affected (Cross, Dean, and Osterberg, 1967) found that the zooplankton Anonyx sp. would accumulate radioactive zinc at a faster rate in warm water than cold (Fig. 6). After 100 hours, Zn<sup>65</sup> accumulations were four times greater at 7° C. than at 3° C. The metabolic turnover rates are also higher at the elevated temperatures (Fig. 7) as indicated by the biological half-life.

Sustained warming may influence the reproductive behavior and growth of zooplankton. Barnett (1968) studied the influence of the thermal effluent from the nuclear-fueled station at Millport, Scotland. Oceanographic conditions and sites are similar to our Pacific Northwest. Salinities range from 32 to 34 ‰; the annual temperature range is 5° C. to 15° C. and the  $\Delta T$  is about 10° C. Barnett found no effects on zooplankton beyond the thermal discharge area and no changes in species composition either in the discharge area or on the beach. However, he did find that the reproductive cycle of Eurythure, a sand-burrowing amphipod, was advanced. Gravid females appeared in April instead of late May. The juveniles of this amphipod appeared earlier in the warmed zone than in other nearby areas. The subtle relations of an animal to its total environment became evident in Barnett's studies of the sub-littoral harpacticoid copepod Ascilopsis intermedia. Gravid females of Ascilopsis appeared in the warmed zone 2 months earlier than in nearby unaffected areas. Juveniles appeared earlier in the warmed zone also. However, the young copepodids grew at a much slower rate than those in unaffected nearby zones at the normal time. The most logical conclusion is that there were insufficient quantities of the proper food in the warmed zone to satisfy the metabolic requirements of the juveniles.

### Macroinvertebrate Fauna

The macroinvertebrates inhabit all regions of the marine and estuarine environment. Some of our most valuable and potentially valuable shellfish (clams, oysters, crabs, etc.) are in this group. The macroinvertebrates can be broadly organized into eurythermal and stenothermal types. This classification may vary somewhat during the life cycle, especially during the reproductive and juvenile stages.

The eurythermal species, for example, inhabit the intertidal or upper littoral zones, and had little or no locomotive abilities. Most of the species, such as oysters and mussels, will be permanently fixed to a substrate early in life--or, as in clams, burrow beneath the substrate. They may, however, exhibit stenothermic responses during pelagic juvenile or reproductive stages.

The stenothermal types are more likely to be in the littoral, sub-littoral and benthic regions and exhibit some means of locomotion, ranging from the slow moving gastropods to the fast swimming cephalopods. Their juvenile and reproductive stages are generally temperature sensitive.

Most macroinvertebrates inhabit zonally-restricted habitats. The natural environmental conditions within a zonal habitat will be reflected by the ability of various species to adapt to extremes.

Vernberg (1968) studied the respiration of different species of crabs inhabiting waters of varied depths. He found that crabs inhabiting the deeper waters had lower respiration rates than those in the intertidal zone, with corresponding rates in the intermediate ranges for crabs inhabiting intermediate zones. The crabs from the deeper zones exhibited the greatest rate of change in respiration when subjected to different temperature changes. Crabs inhabiting inshore areas exhibited the least respiration change. This is a clear demonstration of an adaptative response to natural environmental conditions.

In his studies of thermal effluents at Millport, Scotland, Barnett (1968), found that most species of lamellibranches inhabiting areas warmed by thermal discharges grew at faster rates than those in nearby unaffected areas. He also found that some gastropods had lighter shell weights in the warmed areas than in nearby unaffected areas. Although the shell weights were lighter, the ratio of meat to shell weight was higher than for specimens in unaffected areas. This suggests a subtle physiological change and redirection of metabolite utilization.

Pearce (1968) noted some subtle responses to temperature alteration in Mytilus edulis, the common bay mussel. He found that the bay mussels collected from different areas responded differently to elevated water temperatures (Table 1).

These studies strongly suggested that the bay mussel was extremely sensitive to the environment, and capable of developing unique adaptative features which are measurable and long-lasting. Pearce, in seeking additional supportive evidence of this form of adaptation, placed Cape Cod mussels in water at Sandy Hook for a 4-week period. When subjected to the test temperatures, they responded as if they had never left Cape Cod.

Mytilus edulis exhibits strong behavioral responses to increasing water temperatures. As temperature approaches 23 to 24° C., the tenacity of the byssal thread to hold the mussel fast to a substrate drops to almost zero. The byssal threads enable the mussel to move about. At 15° C. (normal temperature), mussels placed at equidistant points from each other on a substrate congregated in one spot after a short time. Mussels subjected to the same treatment, but at temperatures of 25° C., were incapable of congregating (Pearce, 1968). When mussels congregate, the combined strength of the interaction of the byssal threads makes it difficult to remove any one mussel. This is an excellent protective mechanism against predation that is lost at the higher temperatures.

Elevated water temperatures also affect at least one predator of the mussel, Asterias sp. Pearce found that as the water temperature increased above 20° C., the feeding rate of this starfish dropped off rapidly. Thus, although the mussel may lose its congregative defense mechanisms at elevated temperatures, its chief predator is also adversely affected.

The normal habitat of Mytilus edulis is the intertidal zone, where one would normally expect mussels to be exposed to summer air temperatures in excess of 25° C. at low tide. In the laboratory, Pearce found that M. edulis could indeed withstand exposures to water temperatures in excess of 25° C. for 6 hours, provided that this period was followed by a similar exposure period to cold water. The normal mixed semi-diurnal tidal cycles have a periodicity of 6 hours.

Economically important invertebrates such as oysters, clams, crabs, lobsters, and crayfish of the Pacific, Atlantic, and Gulf Coast release enormous numbers of pelagic eggs and larvae. The survival of these organisms through metamorphosis and settling to the bottom is entirely dependent on stringent environmental conditions at precisely the proper time during each stage of development. The failure of any one parameter of these multiple conditions can mean failure of a "set," with very few survivors reaching adulthood. The probability that these natural conditions will be met so precisely each year is remote. Where the probability of survival is low, the fecundity of the female is high.

The greatest danger to the economically important invertebrates, then, is during this early developmental period when they can be drawn through the condenser tubes of the large thermal stations, or swept into warm-water discharge areas and subjected to sustained warming.

## Vertebrate Fauna

Discharges of heated water are much less likely to cause direct fish kills in the marine or estuarine environment than in fresh water. Except where discharges are made into shallow bays or enclosed inlets, the marine and estuarine environments allow more lateral and vertical space for fish to practice avoidance responses. Species of fish in the middle or upper portion of their temperature range will normally avoid warm water discharges. Species in the lower portion of their preferred temperature range will often be attracted to warm water discharges. This is especially true during the winter. Littoral fishes will frequently rearrange their distributions to satisfy preferred or optimum temperature requirements.

The greatest difficulties that might be experienced between fish and thermal discharges in the marine or estuarine environment are:

1. The fish may remain in the affected area with no physiological discomfort, but food organisms may be affected. This has evidently happened to the opossum shrimp Neomysis sp. in the Patuxent estuary. Neomysis is the prime food for young striped bass.
2. Undesirable species of fish may be attracted to the discharge area, altering predator-prey densities. Warm water discharges from certain California stations have attracted thousands of rays in the winter, for example.
3. Anadromous or catadromous fishes having to face thermal discharges will often manifest migratory instincts which are stronger than avoidance instincts.
4. Estuaries are prime nursery areas. Shoals of young fish feed extensively in coastal shallows and estuarine habitats. The eggs and larvae of pelagic spawning species of fish drift in and out of these nutrient rich areas.

Doubtless, there are other difficulties that marine and estuarine fishes will encounter in their relations with thermal discharges; of the ones that I have listed, the last two are of the greatest importance in the Pacific Northwest.

The eggs and larvae of pelagic spawning fishes are not capable of avoiding predators, let alone masses of warm water into which the tides and currents might carry them. This is another instance where the survival to metamorphosis is precarious, and perpetuation of the species depends on high fecundity.

Alderdice and Forrester (1968) conducted a series of laboratory studies on Parophrys vetulus, the English sole. They found that the eggs of this fish had optimum survival at water temperatures of 8 to 9° C. and salinities of 25 ‰. They concluded that the eggs of the English sole would survive best in water temperatures ranging from 5 to 12° C. and salinities not less than 20 ‰, or greater than 35 ‰. They were able to correlate salinity and temperature in the Pacific Ocean with the distribution and abundance of the species. Interestingly enough, they concluded that salinity was less important for survival of the egg than water temperature. Their experiments demonstrated that it took a salinity change of 4 ‰ to have the same effect on egg survival as did a water temperature change of 1° C.

This is only one example of the importance of water temperature to the eggs and larvae of pelagic species of fish in North Pacific waters. One can only conclude that organisms adapted to water temperatures from 5 to 12° C. (normal range for most Puget Sound waters) may be in difficulty if they are subjected to temperatures from 15 to 25° C. Therefore, each marine or estuarine site chosen will require studies of the natural distribution and abundance of the pelagic eggs and larvae of vertebrates and invertebrates. Only in this way can we assess the value of the water at each location in relation to organisms with pelagic spawn.

The last point I wish to bring out on the vertebrate fauna is anadromy, with special reference to the genus Oncorhynchus, the Pacific salmon.

The Pacific salmon in the Northwest are subjected to an intensive, competitive fishery, and have a high economic yield. The adults come within dozens of yards of the shore while feeding in the marine environment and while migrating through the estuarine environment. It has been documented (Coutant, 1968) that adult salmon on spawning migrations up the Columbia River will avoid warm water discharges and seek the coldest water. There have been few laboratory studies on the effects of temperature on adult salmon in a marine environment. Experimental and commercial catches of salmon on the high seas have been correlated with surface sea temperatures; from this data it is evident that the salmon would not normally be found in waters above 15° C. (Manzer and Ishida, 1965). It is imperative that we begin studies now of the responses of adult salmon to changes in water temperature in a marine environment.

The juveniles of all species of the Pacific salmon spend some time in the estuary. This is true even of chum (O. keta) and pink salmon (O. gorbuscha) which immediately after the yolk sac has been absorbed can be transferred directly from fresh water to high salinity sea water (30 ‰). Hurley and Woodall (1968) conducted a series of exhaustive experiments on the salinity and temperature preferenda of pink salmon fry migrating through the Fraser River estuary.

Adult pink salmon spawn in the main stem and tributaries of the lower Fraser River (downstream from the Thompson River and Seton Creek). The time of emergence of the young fry in the spring will depend on when the parents spawned and water temperatures during the incubatory period. (Pink salmon fry from other nearby rivers swarm through the same complex estuary on their way to the open sea.) Thus, in the spring we have an early peak, and a late emergence of fry.

Hurley and Woodall found that the early emerging fry would select progressively stronger salinities with time, taking over 30 days to select maximum salinity. The peak emergence of fry took less time, and late fry emergence took the shortest time to select maximum salinities (Fig. 8). Once a salinity level was selected, the fish did not return to lesser salinities.

Hurley and Woodall found that the early emerging fry exhibited the widest temperature preferenda when testing temperature selection versus days after emergence; that peak fry and larger fish selected colder waters at a faster rate; and that late fry had the least variability in temperature selection. The late emerging fry selected progressively colder water at a faster rate than any others (Fig. 9).

What is the adaptative significance of their behavior and how might warm water discharges influence this behavior? I can only speculate. The behavior pattern is definitely related to time. The numbers of fry involved are large; they all utilize the same general area. Early in the spring, food should be most abundant in the warmer, shallower areas. This is when the early fry emerge. As the early fry grow they may require food organisms of a larger size and perhaps start moving out, leaving the area open for the fry of the peak migration. Food organisms in the shallows would be much more abundant then, water temperatures would be slightly warmer, the peak fry would grow at a faster rate, and move out sooner, and so on. I have diagrammed a hypothetical flow pattern in Figure 10.

A sustained discharge of warm water in the path of this migration (which lasts from April through May in the Fraser River delta) might upset the orderly sequence of this pattern, especially with the early fry. Apparently it is this orderly sequence which gives us the maximum utilization of the estuary.

### Prospectus for the Future

I have tried to cite specific examples of temperature as an important environmental factor in the continuous struggle for survival by marine biota. I have done this to emphasize the point that the direct discharge of large quantities of waste heat into the marine environment cannot be done without forethought and serious study. In fact, it may not be possible to allow direct thermal discharges at all in some places. Local fishery resources may be too valuable to justify the risk.

What, then, are the alternatives?

I will leave the relative merits of such things as cooling towers and recreational value to the total concept planners and concentrate on the one avenue of approach which is of prime interest to fishery people... sea farming or aquaculture.

The cultivation of marine organisms for food has been practiced for hundreds of years, and Iverson (1968) has devoted an entire book to a review of sea farming.

However, it was not until this decade that the culture of marine organisms in the warm water discharges of thermal power stations was begun (Naylor, 1965). The rate of progress in this area is developing rapidly, and in another 3 to 5 years an entire book will be needed to review this aspect of sea farming alone.

There are three prime ways of using heated marine effluents for sea farming:

(1) The water can be used for conditioning fish and shellfish for reproduction and as a nursery habitat for rapid early growth. The juveniles are then moved to larger growing areas in a natural environment.

(2) Juveniles are captured in the wild and placed in the heated environment where they are grown to a marketable size.

(3) The heated water is used to raise the organism from the fertilized egg to a marketable sized specimen.

There are no large scale users of marine thermal effluents anywhere in the world today. Private corporations, institutional groups, and governmental authorities are presently conducting limited experimental research in the United States and the British Isles. The U.S. efforts are in New York (Long Island), Florida, and California.

The Interchem Corporation has an oyster hatchery at Oyster Bay, Long Island, New York, managed by George Vanderborgh. Cultchless spat of the American oyster (Crassostrea virginica) are raised in the hatchery to a shell diameter of several millimeters. The spat are then moved to the thermal effluent discharge channel of the Long Island Light and Power Company plant at Northport, Long Island for additional growth. The young oysters are later transferred to leased oyster beds in Long Island Sound. The Northport plant uses fossil fuel to operate the turbines, and requires about 375 cfs of water to cool the condensers of one turbine. This is the only commercial application of sea farming in thermal effluents in this country that I know of. The Interchem Corporation is actively expanding this operation. A new shellfish hatchery was in the initial stages of construction directly over the discharge channel when I visited there on November 11, 1968.

Dr. A. D. Ansell of the Marine Station at Millport, Scotland, is actively engaged in large scale research of the utilization of thermal effluents for rearing shellfish. Dr. Ansell has even gone so far as to use the scrubbed flue gases for increasing algae production in rearing ponds.

However, the only research and actual production usage of thermal effluents from nuclear fueled power plants in the world is by the White Fish Authority of Scotland. The results of the research on plaice by Dr. J. Shelbourne at the thermal station on the Isle of Mann, and by Dr. D. E. Nash at the Hunterston (Ayrshire, Scotland) nuclear plant have been so successful, that each new nuclear-fueled electric power station to be built will have some areas set aside for sea farming.

The White Fish Authority has raised the production of plaice in thermal effluents beyond the experimental stage and can now guarantee a specific annual harvest.

The Hunterston operation is typical of the new pilot plant developments (Nash, 1968). The thermal discharge is approximately 800,000 cfs, and the  $\Delta T$  is about  $10^{\circ} C$ . A bypass line travels from the discharge pipe to the sea farm area, which consists of spawning tanks, hatching sheds, and rearing tanks. Unheated water is also available.

Plaice are allowed to spawn, and the fertilized eggs are held in water starting at  $6^{\circ} C$ . Antibiotics are added, and the temperature is raised  $0.5^{\circ} C$  each week from fertilization through metamorphosis; this process reduced the period of early development, through metamorphosis, from 7 weeks to 3 weeks.

Nash found that rearing plaice at a temperature of 15 to  $16^{\circ} C$ . was ideal for optimum growth. He was also successful in achieving optimum growth of another flatfish, the lemon sole, at temperatures of 18 to  $20^{\circ} C$ . and felt that the lemon sole were easier to culture than plaice. Both plaice and lemon sole were fed the meat of the common bay mussel, Mytilus edulis. Growth was much faster than in the sea. Over 60% of the plaice reached a marketable size of 25 cm in less than 2 years.

The most interesting feature of the Hunterston operation is the level of free chlorine in the water. Whereas many U.S. plants treat the intake water with heavy doses of chlorine for an hour or so each day to prevent fouling, the new British plants do not. The Hunterston nuclear plant maintains a constant level of 0.5 ppm chlorine in the condenser intake. This level has been sufficient to prevent fouling.

Nash monitors the level of chlorine in his tanks and has found that it ranges from 0.02 to 0.12 ppm and that these levels do not harm either the plaice or the lemon sole.

None of these activities utilize the full flow of the available thermal effluents at each plant. However, estimates can be made of meat yields of pond and raceway cultures of fish and the raft and rack cultures of shellfish using the total effluent stream.

Gaucher (1968) reports that refinements in Russian carp culture have raised carp production from 15 Kgm/m<sup>2</sup> to 100 Kgm/m<sup>2</sup> per annum and that the Japanese are up to 400 Kgm/m<sup>2</sup>. This is without the benefits of heated effluents, but under intensified cultural means.

We know that the commercial raceway culture of trout in the United States produces between 30 and 70 pounds of fish per annum for each gallon of water per minute flow. Figure 11 is an estimate of the possible annual yield in raceway culture utilizing the full effluent stream from a nuclear power plant. A minimum yield of 30 pounds of fish/gpm per annum would produce over 10 million pounds of fish a year utilizing the full flow from a 1,000 cfs discharge. The aspects of feeding such large quantities of fish would become highly involved, but not impossible. The Japanese, for example, are presently rearing salmon in pens beneath the sea. They feed the fish once each day through "chimneys", and allow the fish to feed on natural foods between feeding periods. They are harvesting 1.3 pounds of fish for every pound of food used. Commercial catfish growers are harvesting between 1 pound of fish for every 1.2 to 3 pounds of food utilized.

Mussel culturists in Spain are harvesting over 800,000 pounds of mussels per year per surface acre, using deep water raft culture techniques. Large scale raceway cultures of high economic yield fish, such as trout and salmon, will require large amounts of feed. Trawl fleet collections of trash fish and firm contracts with mussel growers might be required to supply the needs.

Portions of the water can also be used for rearing shellfish spat and even commercial quantities of the mature shellfish. It is now possible to harvest annually between 3 and 3.5 Kgm/m<sup>2</sup> of oysters by raft culture in water 3 to 4 m deep. Seed for these stocks and all other oyster growers on the Pacific Coast could come from one hatchery operation alone.

Today, wastes of almost all types can be considered to be a resource. We use oyster shells in the poultry industry, garbage from restaurants in swine production, and solids processed from human waste for the commercial fertilizer, Milorganite. There is no reason why aqueous wastes in large quantities cannot be used for farming of the sea under controlled conditions, especially along the Pacific Coast, where there is still time for planning and constructing the facilities.

Figure 12 is a design concept for the utilization of effluent from a primary treatment plant, and the thermal effluent from a nuclear power plant. The utilization of the sources of rich nutrient energy and thermal energy under optimum conditions for the growth of valuable marine organisms is vital to the future of sea farming. It takes man out of the concept of "hunter", which is where he was hundreds of years ago in his relationships to terrestrial animals, and places him in the concept of "farmer". Eventually, the sea farmer will share the burden of feeding the growing populations of the world with the land farmer.

#### REFERENCES

- Alderdice, D. and C. R. Forrester.  
1968. Some effects of salinity and temperature on the early development and survival of the English sole (Parophrys vetulus). Journ. Fish. Res. Bd. Canada, 25(3). pp. 495-521.
- Anderson, R.  
1968. Temperature and rooted aquatics. Paper presented Nov. 4, 1968 at the Second Thermal Workshop (I.B.P.), Solomons, Md.
- Barnett, P.  
1968. "Temperature and Benthos." Ibid.
- Battelle-Northwest.  
1967. "Nuclear power plant siting in the Pacific Northwest." Report to the Bonneville Power Administration. Battelle-Northwest, Pacific Northwest Laboratories. July 1967.
- Coutant, C. C.  
1968. Temperature-Reproduction and Behavior. Paper presented Nov. 4, 1968 at the Second Thermal Workshop (I.B.P.), Solomons, Md.
- Cross, F. A., J. M. Dean, and C. L. Osterberg.  
1967. The effect of temperature, sediment, and feeding upon the behavior of four radionuclides in a marine benthic amphipod. From: Ecological studies of Radioactivity in the Columbia River and adjacent Pacific Ocean. Progress Report, Oregon State University, Department of Oceanography, J. E. McCauley (Ed.), July 1967, pp. 157-176.

- Gaucher, T. A.  
1968. "Potential for Aquiculture." From: General Dynamics Electric Boat Division Report No. M 413-68-016. Chapter 4, pages 1-22. January 1968.
- Heinle, D. R.  
1968. Temperature and Zooplankton. Paper presented Nov. 4, 1968 at the Second Thermal Workshop (I.B.P.), Solomons, Md.
- Hurley, D. A. and W. L. Woodall.  
1968. Responses of young pink salmon to vertical temperature and salinity gradients. Progress Report No. 19. Internat. Pac. Salmon Fish. Comm., 1968.
- Iverson, E. S.  
1968. Farming the Edge of the Sea. Fishing News (Books) Ltd., 110 Fleet Street, London, England. 293 pp.
- Manzer, J. I. and T. Ishida.  
1968. Salmon of the North Pacific Ocean. Part V. Offshore distribution of salmon. Internat. North Pac. Fish. Comm. Bulletin No. 15, 452 pp.
- Markowski, S.  
1959. The cooling water of power stations, a new factor in the environment of marine and fresh water invertebrates. Journ. Animal Ecol., 28(2), pp. 243-258.
- Nash, D. E.  
1968. "Constructive Uses of Thermal Additions--Vertebrates." Paper presented Nov. 4, 1968 at the Second Thermal Workshop (I.B.P.), Solomons, Md.
- Naylor, E.  
1965. Effects of heated effluents upon marine and estuarine organisms. In: Advances in Marine Biology. Vol. 3, 1965. F. S. Russell (Ed.) Academic Press, N.Y. pp. 93-103.
- Pearce, J.  
1968. Temperature and Benthos. Paper presented Nov. 4 1968 at the Second Thermal Workshop (I.B.P.), Solomons, Md.
- Pritchard, D. W.  
1967. What is an estuary: Physical viewpoint. In: Estuaries, G. H. Lauff (Ed.), Publication No. 83, American Association for the Advancement of Science.
- Sieburth, J. M.  
1967. Seasonal selection of estuarine bacteria by water temperature. Journ. Exper. Mar. Biol. and Ecol., 1(1): 98-121.
- Vernberg, F. J.  
1968. Temperature and Invertebrate Respiration. Paper presented Nov. 4, 1968 at the Second Thermal Workshop (I.B.P.), Solomons, Md.

Table 1.--Mortalities of the bay mussel, Mytilus edulis from different locations along the eastern seaboard at temperatures of 27° and 28° C. (adapted from Pearce, 1968)

Location	Number of hours at which 50% had died (TLM <sub>50</sub> )	
	27° C.	28° C.
Cape Cod, Mass.	645 hours	41 hours
Sandy Hook, N.J. (Littoral zone)	1,056 hours	100 hours
Sandy Hook, N.J. (20 meters)	477 hours	20 hours
Sandy Hook, N.J. (Oil polluted waters)	---	39 hours

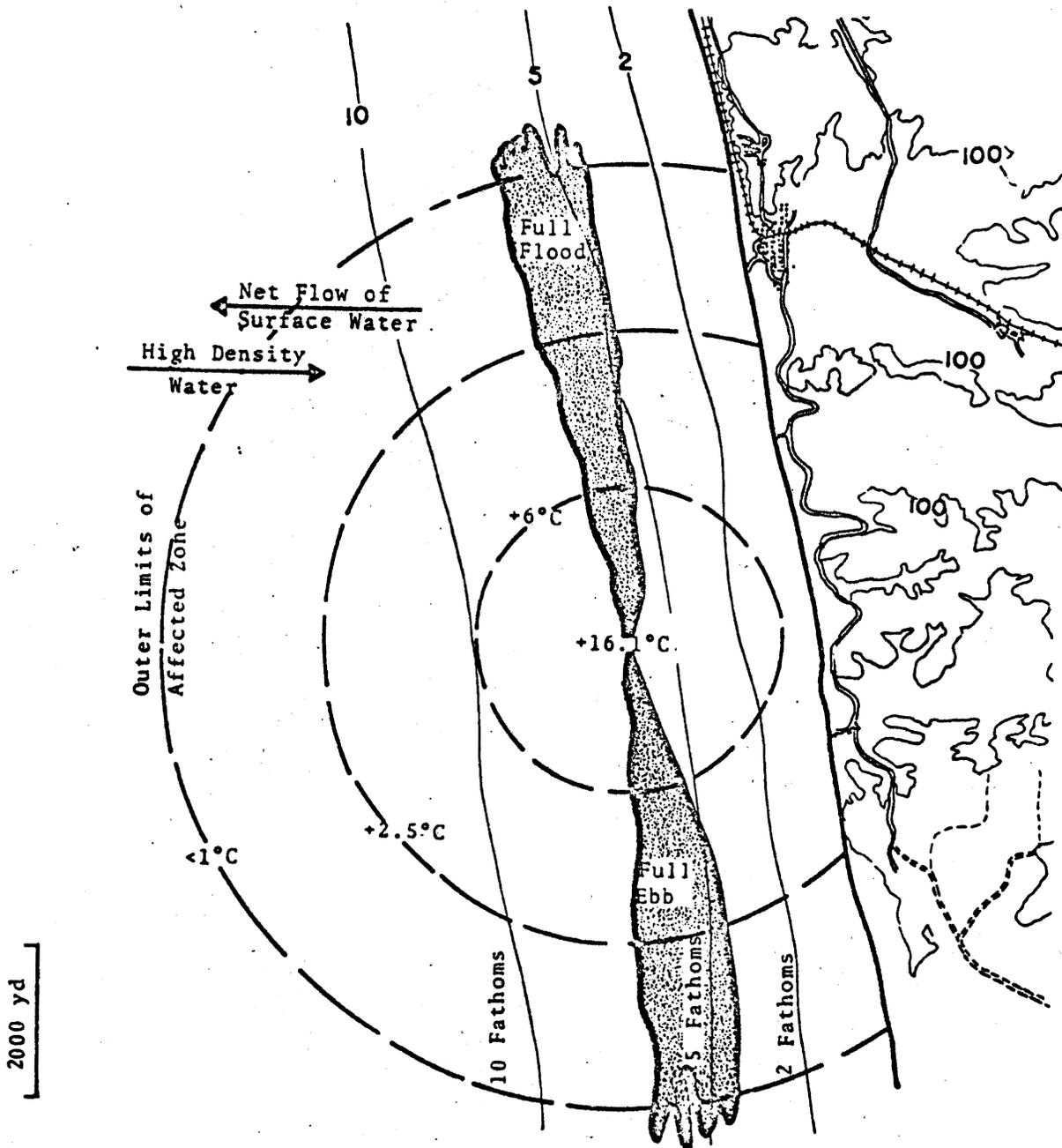


Fig. 1.--Hypothetical thermal effluent release 7500 feet off a Pacific beach (1000 MWe plant; 1113 CFS discharge;  $\Delta T=16.1^{\circ}\text{C}$ ).

Coastal Tidal Current Vectors

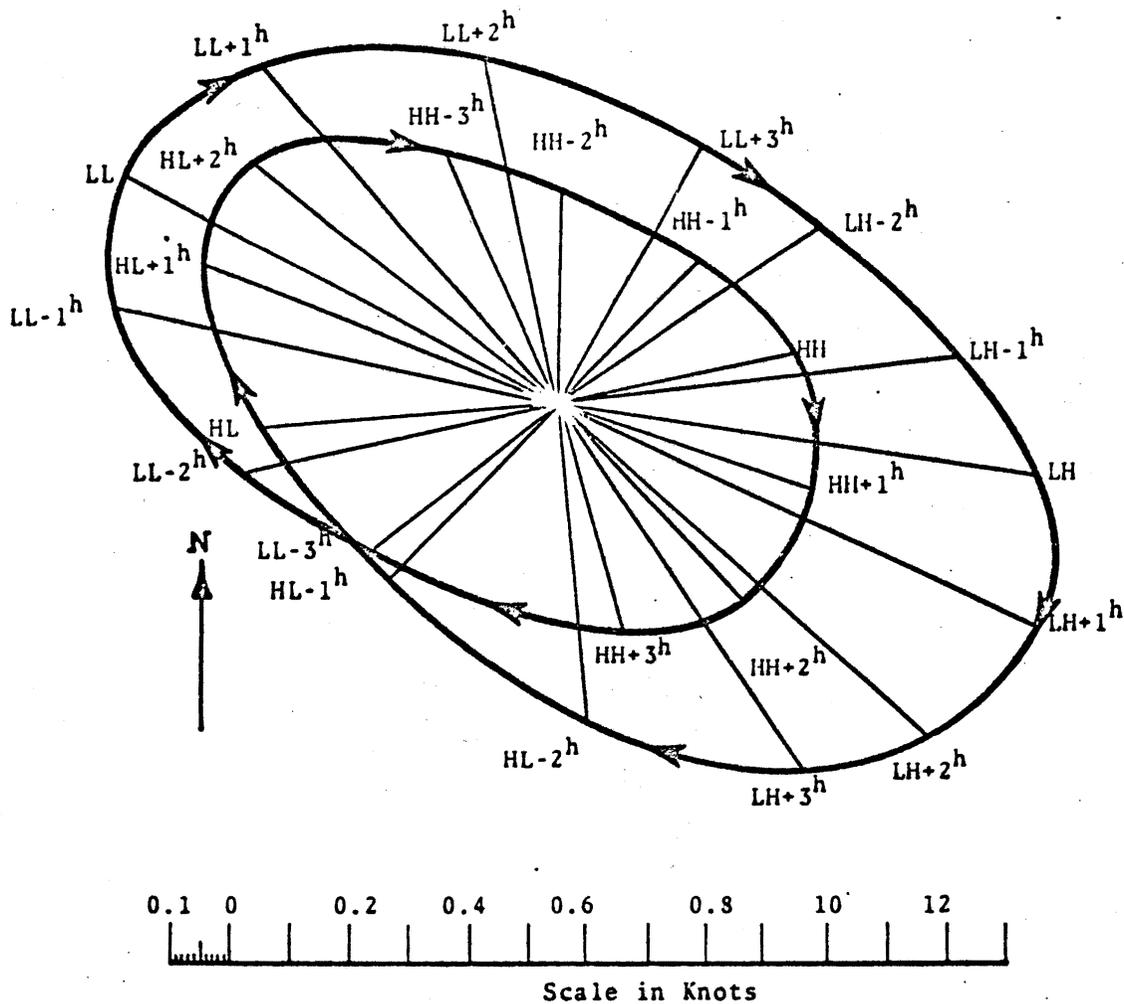


Fig. 2.--Tidal Current Curve, Swiftsure Bank. Referred to predicted time of tide at Astoria, Oregon (from USCGS Tidal Current Tables, 1967). Source: Battelle Northwest, 1967.

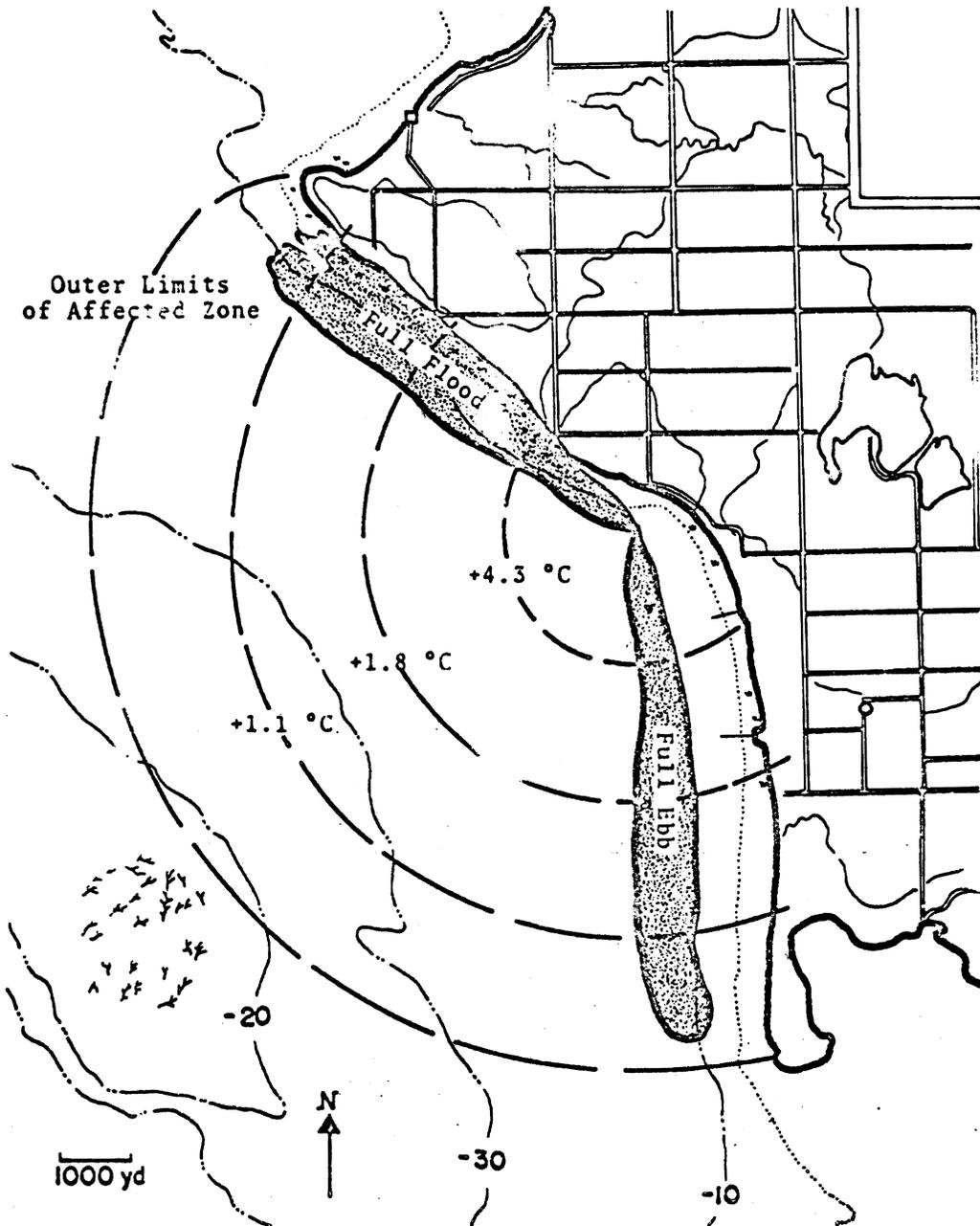


Fig. 3.--Representative effluent plumes for a 1000 MWe thermal power station in the Strait of Georgia. Plumes shown for maximum tide conditions, other areas are affected on a transitory basis only. (From Battelle-Northwest, 1967)

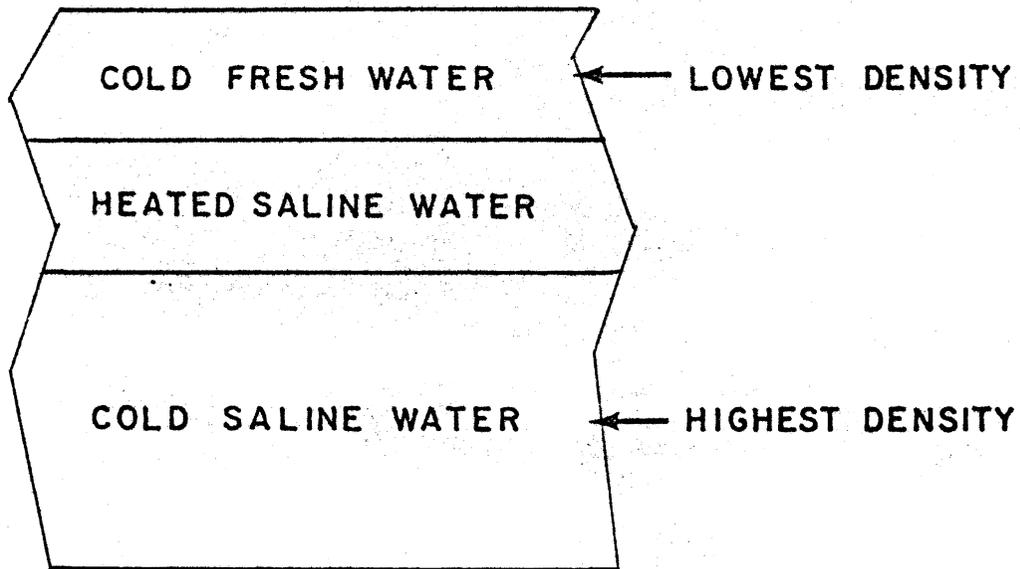


Fig. 4.--An example of heat dispersion in an estuary. Dispersion is entirely by mixing (no atmospheric cooling). The situation is caused by pumping from highly saline water. (Marchwood power station, South Hampton, U.K.)

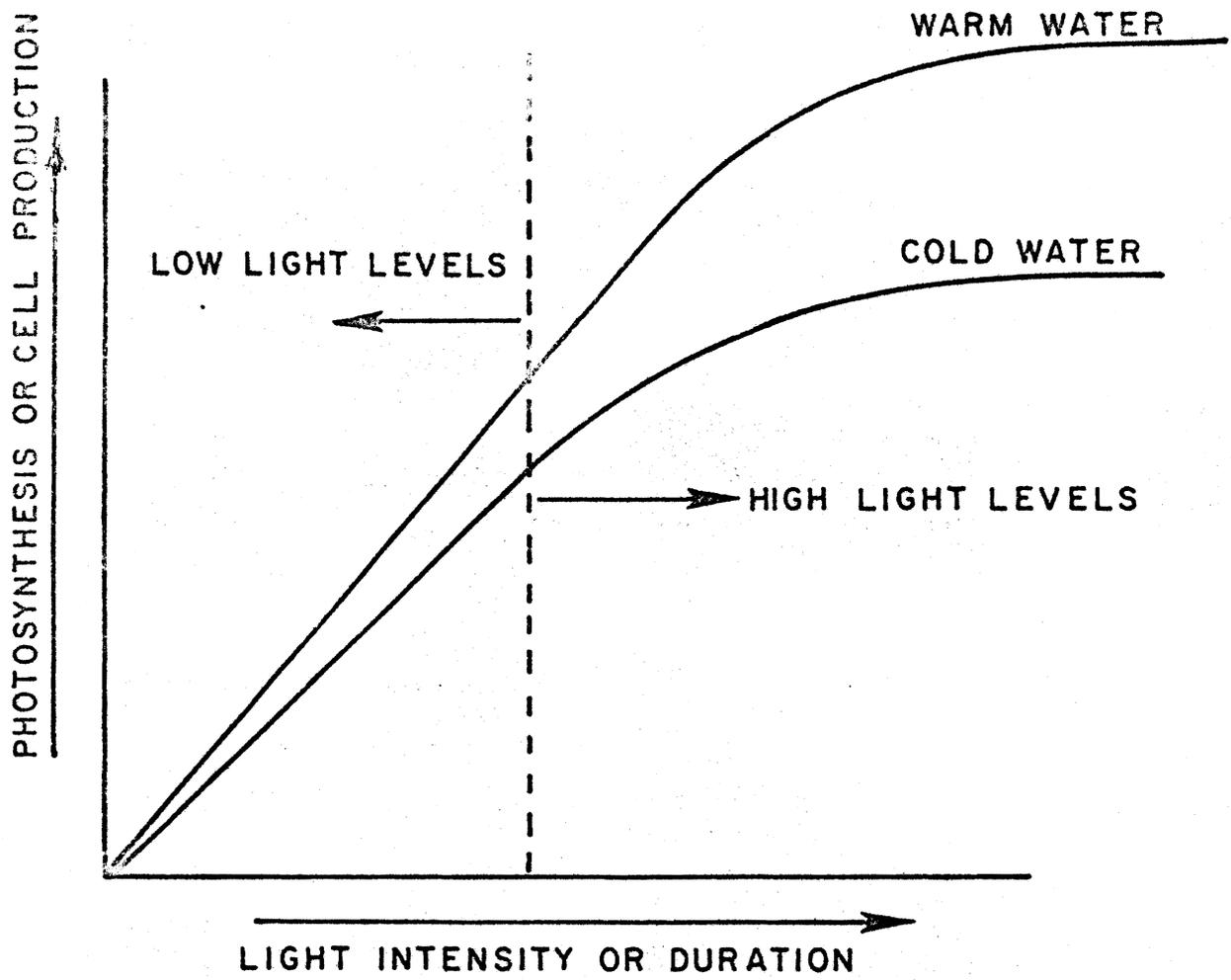


Fig. 5.-- Relationship of cold and warm water temperatures to phytoplankton production at different light intensities.

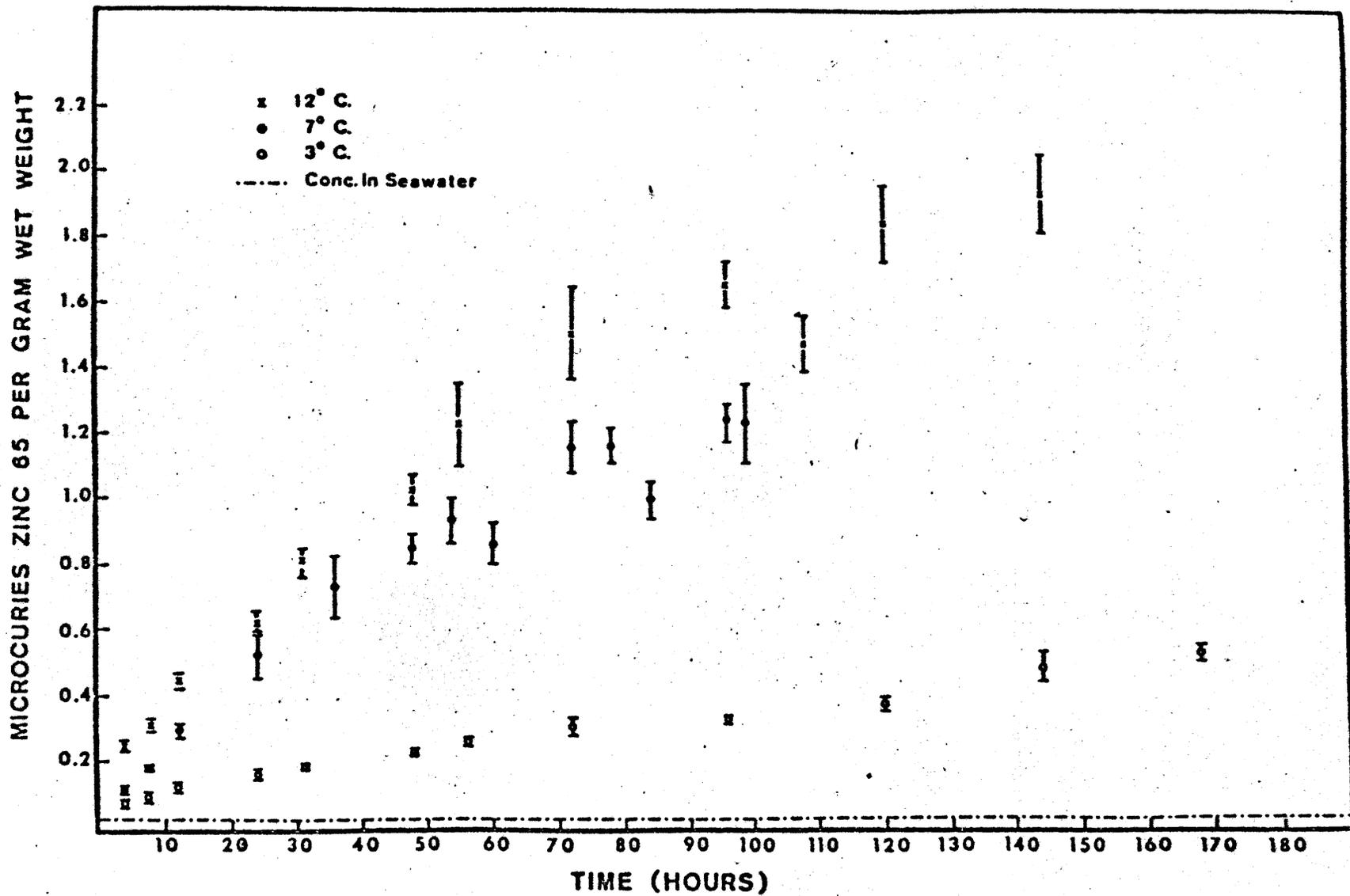


Fig. 6.--Accumulation of  $^{65}\text{Zn}$  by *Anonyx* sp. as a function of temperature. Each point represents the mean and standard error of six amphipods. (Osterberg-1965)

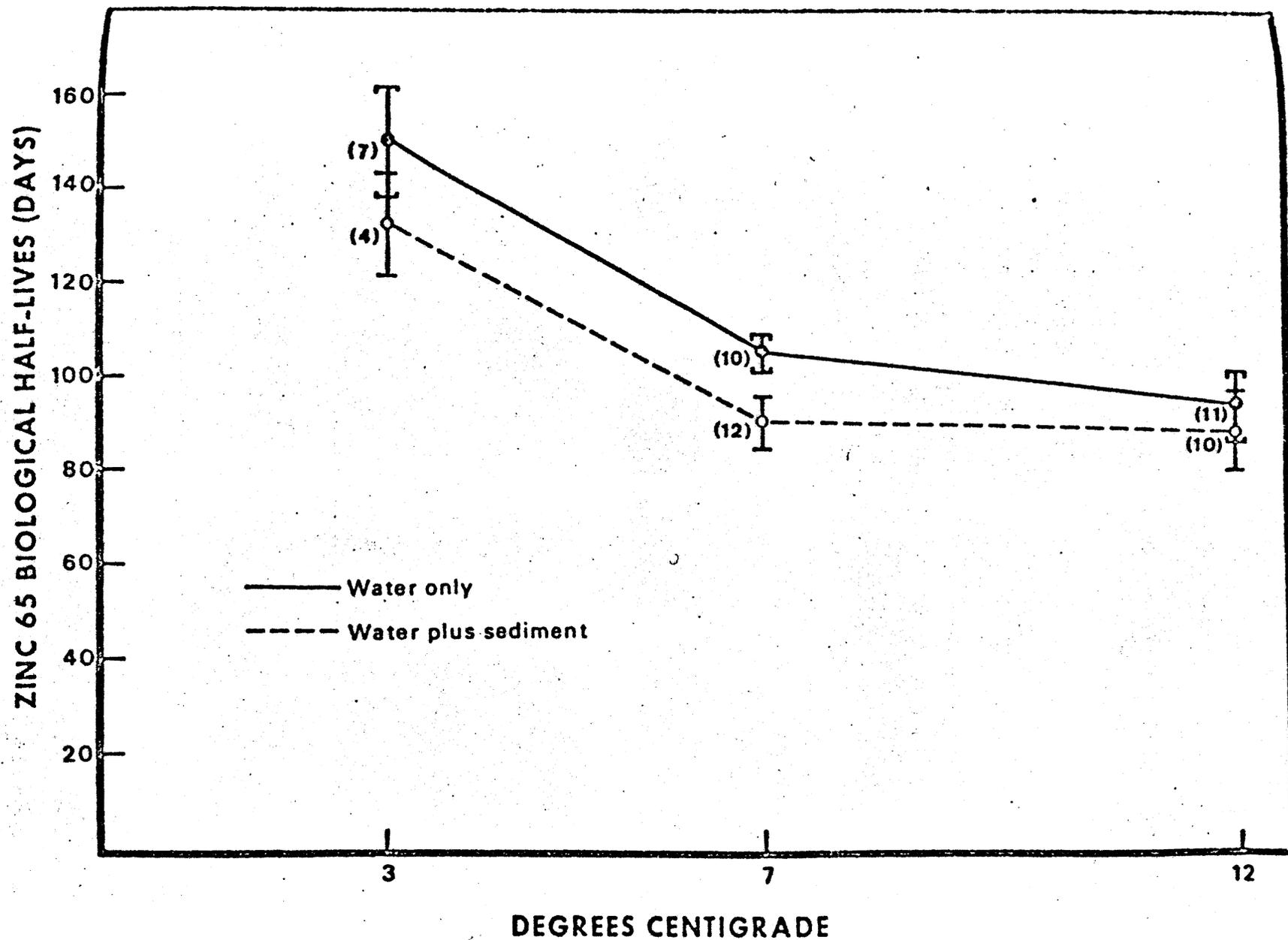


Fig. 7.--The effect of temperature and sediment on the  $^{65}\text{Zn}$  biological half-life. Each point represents the mean and standard error of the number of individuals indicated in the parentheses. (Osterberg-1965)

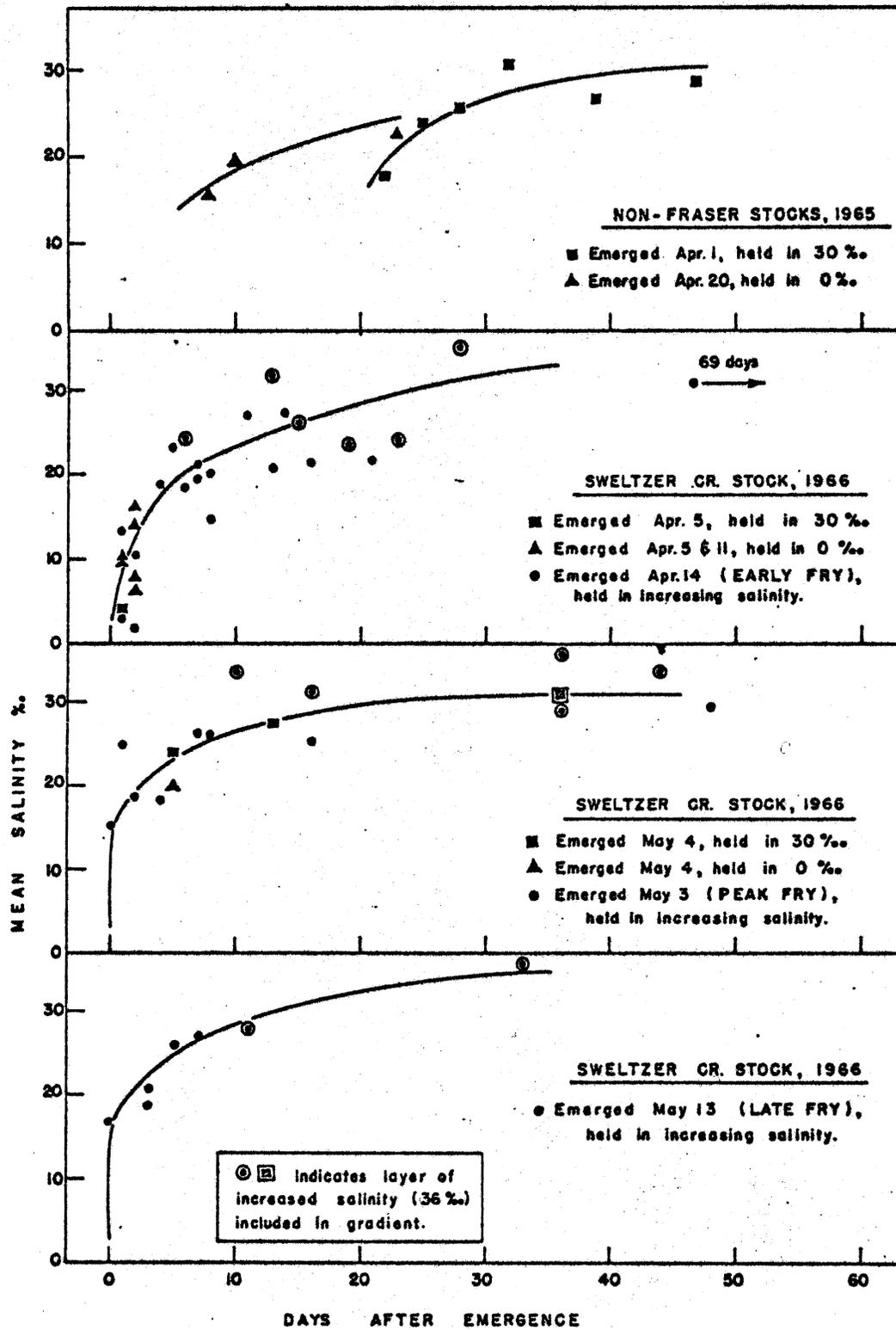


Fig. 8.--Average salinity levels selected by pink salmon fry in relation to number of days after emergence, 1965 and 1966. (Hurley and Woodall-1968)

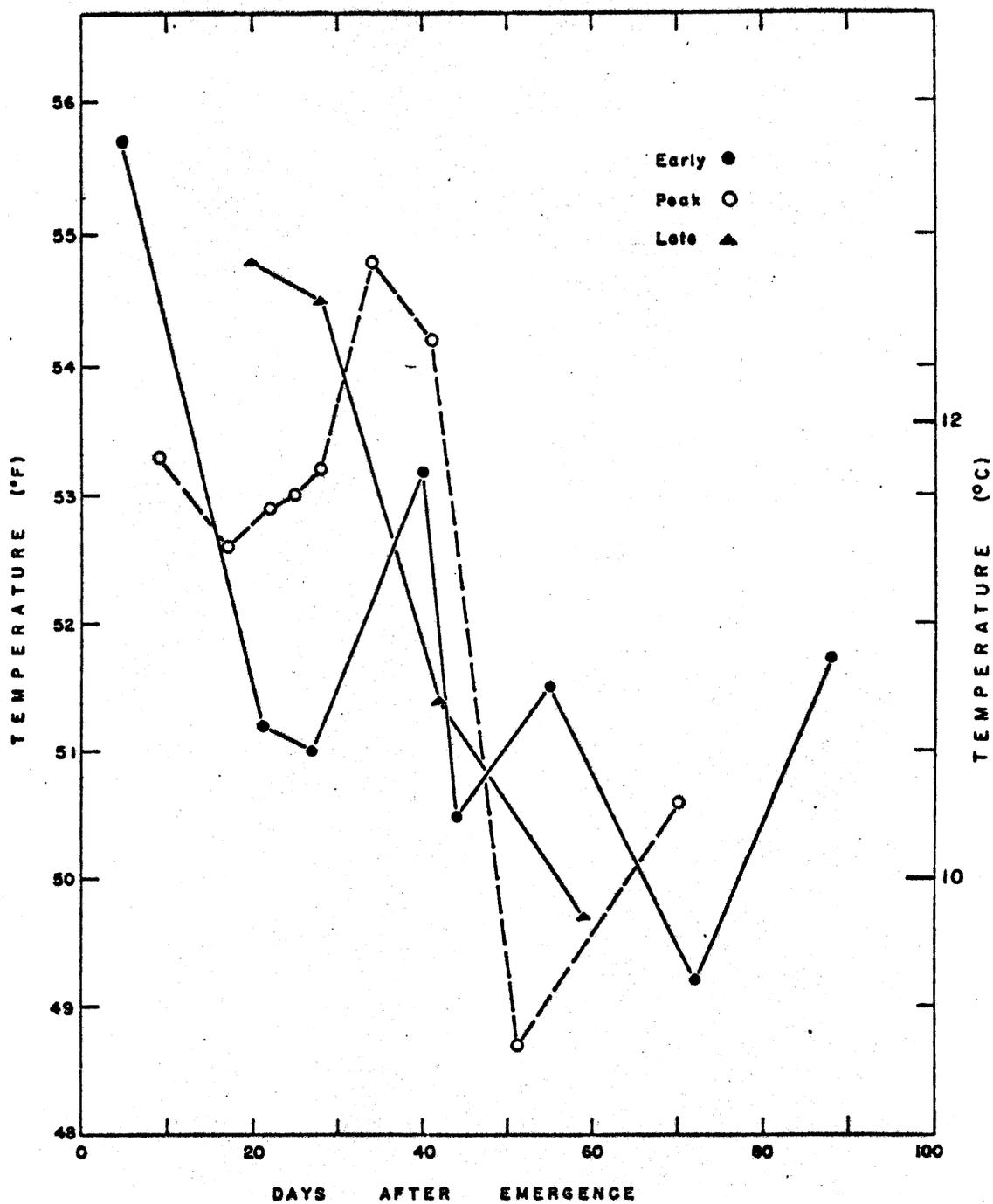


Fig. 9.--Average temperatures selected by early, peak, and late fry in a temperature gradient in relation to number of days after emergence. (Hurley and Woodall-1968)

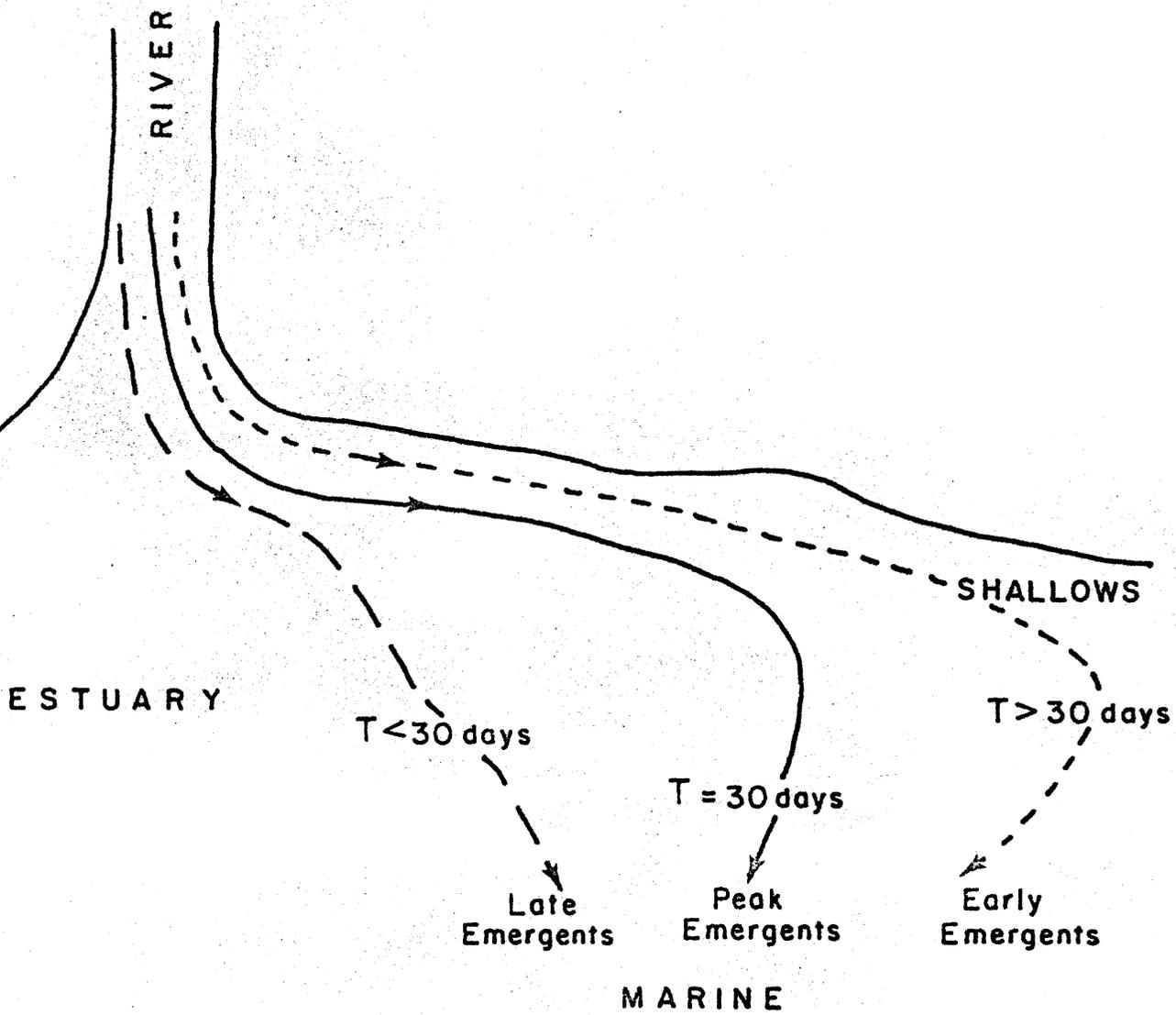


Fig. 10.--Hypothetical diagram showing the relationship of the time of emergence of pink salmon fry to the time ( $T$ ) they spend in the estuarine environment.

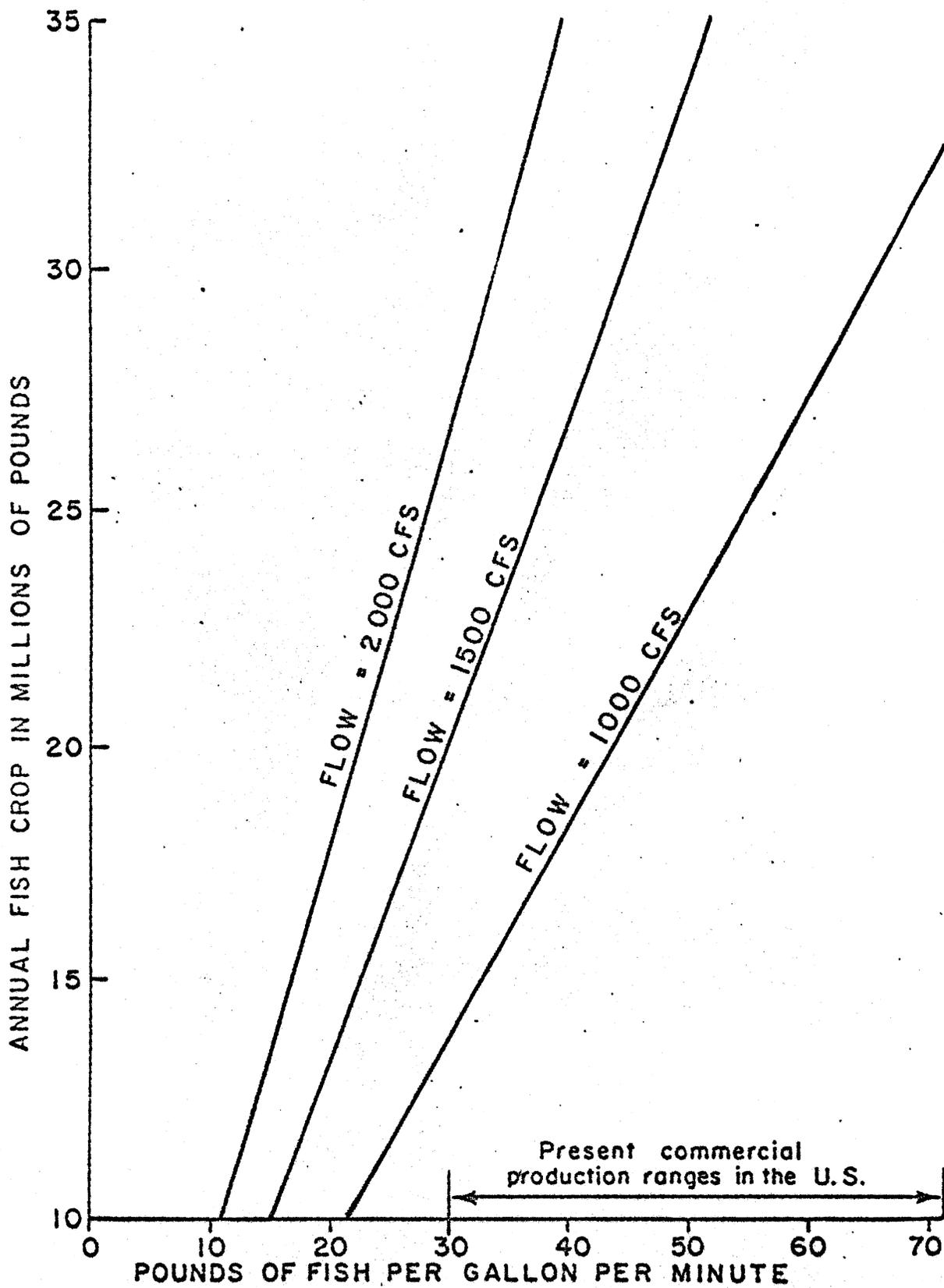


Fig. 11--Possible annual yields of salmonid type fishes in raceway cultures utilizing heated effluents.

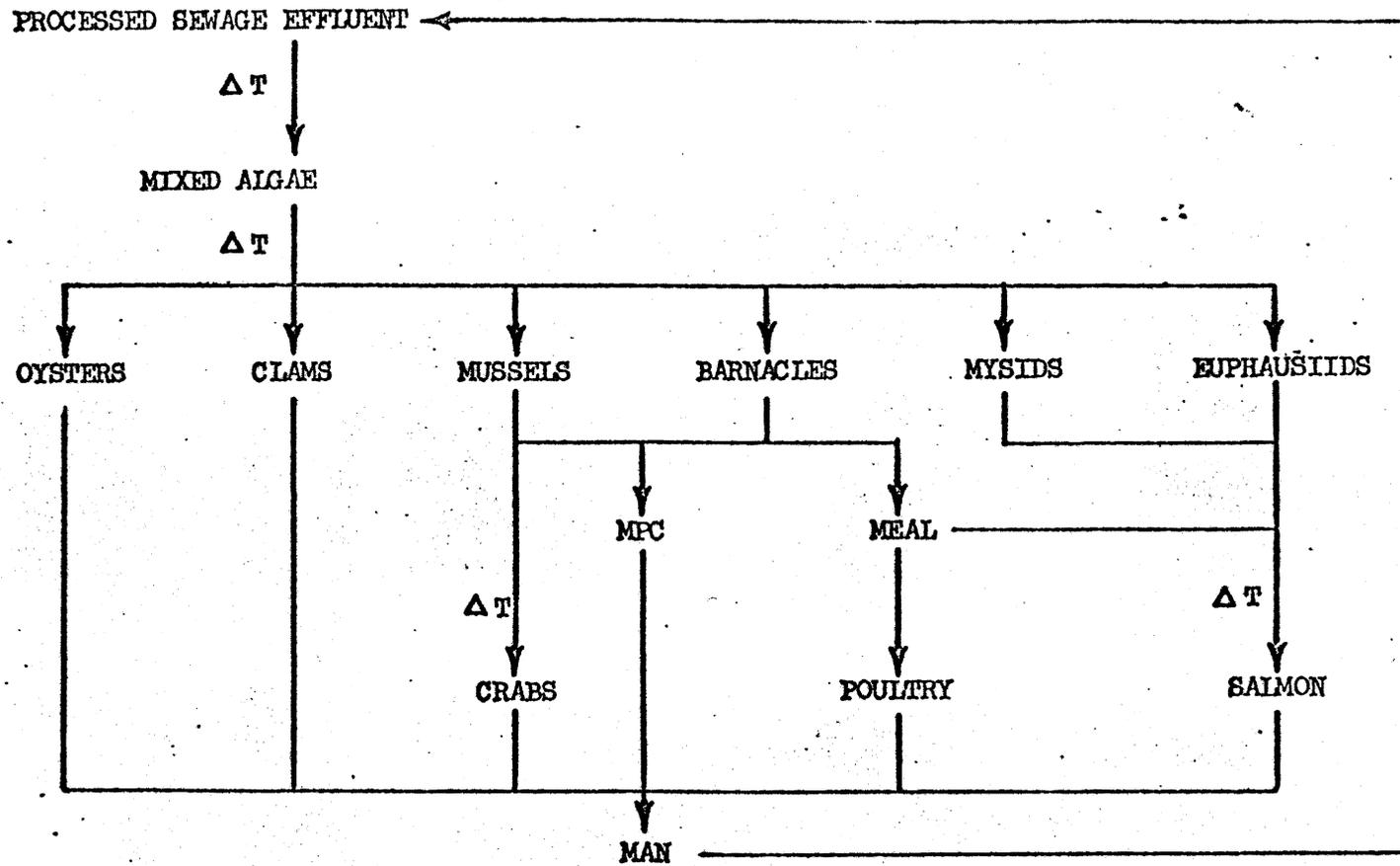


Fig. 12.--Closed ecosystem design for aquaculture using processed wastes and thermal effluents.