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THERMAL POLLUTION: A POTENTIAL THREAT TO OUR AQUATIC ENVIRONMENT

By James E. A. John

INTRODUCTION

Thermal pollution has come to mean the detrimental effects of unnatural temperature changes in a natural body of water, caused by the discharge of industrial cooling water. The electric power industry accounts for over 80% of the cooling water used, so this discussion will focus mainly on that industry. So great are the electric power requirements of this nation and the resultant need for cooling water, it is estimated that at certain times of year, the electric power utilities require 50% of the total fresh water runoff for cooling.

At the present time, roughly 85% of the electric power in this country is produced by steam power plants, the remainder by hydroelectric plants. The basic components of the steam power plant cycle, shown in Figure 1, are the boiler, turbine, condenser, and pump. The energy input to the boiler, used for converting liquid water into hot steam, may come either from a nuclear reactor or from a fossil fuel, such as coal, natural gas or oil. At the present time, nuclear power plants account for only about 5% of the power production in the United States; however, this percentage is steadily increasing.

The hot steam from the boiler is used to drive the turbine and produce the electric power output. Steam from the turbine must be converted back into liquid water in the condenser, so as to complete the cycle. In order to carry away the latent heat from the steam in the condenser, it is necessary to provide a method for cooling the condenser tubes. For this reason, the power plant is often located near a natural waterway, such as a river, lake, or...
bay, with the natural water taken from the waterway, passed over the condenser tubes so as to provide the necessary cooling and absorb the heat from the steam, and then allowed to flow back into the river, lake, or bay at a somewhat elevated temperature. The amount of temperature rise in the cooling water depends somewhat on condenser design, but usually is between $10^\circ F$ and $20^\circ F$. The maximum efficiency of a fossil fuel burning steam power plant is currently about $40\%$, which means that, of the total rate of energy input to the boiler, only $40\%$ is converted into useful electric power, and the remaining $60\%$ is rejected as waste heat from the condenser. In other words, at best, for each megawatt of electric power output, one and one half megawatts must be lost, usually resulting in the heating of a natural body of water. The nuclear power plant, not able to operate at as high a cycle temperature as the fossil fuel plant, has an efficiency of closer to $30\%$, so the nuclear plant rejects a proportionately greater amount of waste heat. It is significant to note that a 1000 megawatt plant, typical of the size being constructed today, might require as much as one billion gallons of water per day for condenser cooling purposes. Further, since the electric power requirements of the nation double every ten years, the situation will be considerably aggravated in the future. The important question to ask now is what is the effect of heated water discharge on the ecology of a natural body of water? With electric power production in the United States now between 1.5 and 2 billion kilowatt hours annually, the potential effects of thermal pollution must be assessed and controlled so as to maintain the quality of our natural resources.
The increase in temperature of a natural body of water attributable to thermal effluents can have a very profound effect on the aquatic life in the body of water. High enough temperatures can cause direct mortalities of fish species; even if not high enough for direct mortalities, the high temperatures may adversely affect metabolic rates, reproduction, and growth of aquatic life. Reduction in supply of a living organism that is part of the food chain of a fish species may lead eventually to the depletion of that species.

Fish are classed as poikilothermic animals; i.e., their body temperature closely follows changes in environmental temperature. Usually, the body temperatures of fish are within a degree or two of the surrounding water temperature. It follows that the environmental temperature must be well suited to the internal processes and functions of the fish.

Maximum temperatures have been determined for many species of freshwater fish. For example, the largemouth bass and catfish can survive for short periods at above 90°F, the brook trout at about 75°F. These maximum temperatures may, in many cases, not be meaningful, in that at these temperatures the fish may be too lethargic to be able to capture the required food and may not be able to survive for a long period. A better index is the preferred environmental temperature which fish seek for their survival. For a largemouth bass, this is between 86°F and 89.6°F, bluegill 90.1°F, brook trout 57.2°F to 60.8°F, rainbow trout 56.5°F, carp 89.6°F. Notice that these preferred temperatures are, in many cases, close to the lethal temperature, so that a comparatively small temperature rise in a body of water may lead to a fish kill.

Besides the direct lethal effects of high temperature on adult fish, there are effects on reproduction. The temperature requirements for spawning are usually much more limited than for adult survival. For example, the Federal Water Pollution Control Administration recommends a maximum temperature of 48°F for the spawning of lake trout. Thermal discharges near a shore in shallow water may disrupt spawning areas. A thermal discharge into a river may impose a thermal block that would prevent fish migration to spawning areas. Salmon, for example, do not feed during migration, so the increase in metabolic rates forced by their swimming through warmer water might result in fuel de-
pletion before spawning. Higher temperatures may result in more rapid growth, but in many cases fish attain a larger final size due to slow, continual growth.

Another effect of increased water temperature is a reduction of the dissolved oxygen content of the water. The increased water temperature also causes increased metabolic rates for the fish and a greater use of oxygen. This combined effect can be detrimental. However, the increase in temperature also increases photosynthesis, and oxygen is a product of photosynthesis. The balance in this case is dependent on the nutrient supply in the water.

An increase in water temperature may lead to the elimination of certain species of algae and the establishment of undesirable species. With an adequate supply of nutrients and an increase in water temperature, the dominance of green and blue-green algae becomes more probable, leading eventually to possible accelerated eutrophication, as in Lake Erie. The demand of the algae depletes the oxygen supply of the lake.

Finally, the rate of temperature rise or drop as well as the entire temperature time history has a role in fish survival. Interestingly enough, it has been found that fish are far more susceptible to a sudden temperature drop, rather than a sudden rise in temperature. Thus a sudden shutdown of a power plant is far more dangerous to fish than a plant startup.

In all of this discussion, it must be remembered that the fish is mobile and is able to swim away from a region of hot water in which he may not be able to survive. Unless the fish is trapped, he is able to avoid unfavorable temperatures. For this reason, there have not been a large number of reported cases of extensive fish kills near power plants. It is really the more subtle, ecological effects of thermal discharges that must be studied, effects which may occur to the life processes in a body of water over several years. At the present time, a biological indicator is not available for rating overall effects of thermal effluents; rather, a limited number of species is investigated in the field and in the laboratory. Keep in mind that it may be possible, by holding the temperature of a body of water at an optimum level, to maximize the fish yield of the water.

Before completing this discussion of biological effects, it is interesting to look at a few actual power plant sites where biological effects have been studied.
Investigations have been conducted on the Columbia River in the state of Washington before and after the installation of the Hanford power plants, in order to determine the effect of the plants on the chinook salmon and the rainbow trout. It should be mentioned that the Columbia River is a fast flowing body of water, with daily peaks of 160,000 cubic feet per second. This high flow tends to promote mixing of the hot discharge water with the river water; under these conditions, only a relatively small area near the point of exhaust is exposed to high temperature. Results of fish tagging equipment indicated no inhibition in the spawning migration characteristics of either species. Both species, incidentally, were found to migrate along the shoreline opposite the plant. Spawning was observed within 100 meters of effluent outfall. Results of the investigation concluded that the warm water discharges have not adversely affected the environment for the species of concern.

A study is being made of the Connecticut River near Haddam Neck, where the Connecticut Yankee Atomic Power Plant has been constructed. The plant returns 372,000 gallons per minute of cooling water to the river at a temperature of 20° F above that at which it was withdrawn. The average flow of the Connecticut River at this point is 16,000 cubic feet per second. Investigations were made of aquatic life at this point in the river starting 30 months before the plant opened and continuing to the present. At the point of discharge, the hot water plume reaches the opposite banks of the river, but does not act as a thermal block, since the warm effluent does not extend to the bottom of the river, 20 to 30 feet below the river surface. Of particular interest is the shad population, since this fish is the river’s most important natural resource. Since the power plant startup in 1967, the number of shad that have entered the river to spawn has not changed significantly. It was found that the areas adjacent to the discharge harbored a greater variety of benthic organisms than before, these bottom dwelling organisms an important link in the river’s food chain. The only detrimental effect noted was the washing away of the sand and silt of the river bottom near the intake, making this area unsuitable for the clams and worms that formerly inhabited it. Also, in the immediate vicinity of the discharge canal, blue-green algae were observed. Catfish entering the hot water of the discharge canal itself were observed to fare badly. Results of the preliminary report indicated that the heat-
ing of the water in the vicinity of the plant has had no significant deleterious effects on the biology of the river, although subtle ecological effects may take years of research to evaluate.

A contrasting report on the ecological effects of waste heat on Lake Michigan was issued by the Fish and Wild Life Service in September 1970. Several power plants are already located on Lake Michigan, and as many as 100 may be discharging waste heat into the lake by the year 2000. This report indicated the possibility of considerable thermal effects on the inshore waters, the beach, and lake shore zones. A fish kill was described at the Campbell plant near Port Sheldon in 1968, where fish were attracted to the warm water of the discharge and exposed to considerable stress. Some Lake Michigan temperatures may be close to maximum limits for optimum growth, reproduction and survival of yellow perch, whitefish, lake trout, herring, alewife and coho salmon. Artificial heating would have a detrimental effect on these species. Further, the report indicated that bacterial growth would be favored by warm water, increasing the probability of fish and bird kills from disease. Finally, nutrients in the inshore waters were reported as approaching limits found in Lake Erie; the increase in temperature of these waters could be expected to lead to the extensive growth of green and blue-green algae and accelerated eutrophication of the lake.

Studies have been conducted by the Natural Resources Institute of the University of Maryland at Pepco's Chalk Point plant on the Patuxent River in Maryland. Of the species investigated, results have shown the opossum shrimp to have a relatively low tolerance to high temperature; this species is important in the diet of the striped bass. Populations of the opossum shrimp were found to sag in the vicinity of the power plant. It should also be mentioned that several years ago 40,000 dead blue crabs were observed in and around Chalk Point's cooling water discharge canal.

The possibility of damage to natural waterways from hot water discharges has encouraged several states and the Federal government to impose regulations restricting the maximum temperature in the vicinity of the discharge. A maximum allowable value is generally specified as 90° F. Results discussed above, however, indicate that the ecology of each body of water must really be considered on an individual basis. Certainly, a trout stream should never be exposed to temperatures near 90° F;
however, in some areas, temperatures as high as 90° F could lead to optimal conditions for certain fish. Without doubt, biological factors must be considered in the selection of a site for a power plant, as long as a natural waterway is to be used as a cooling medium.

**Cooling Methods**

If direct discharge of cooling water into a body of water is to be used, several methods of discharge are available which may reduce the thermal impact on the body of water. The hot water may be spread over the surface of a lake, thus resulting in a hot surface layer but not affecting the greater volume of water below this thin top layer. Thus, potential damage would be very much confined with this method of discharge. The increase in surface temperature would also have the effect of increasing the rate of heat dissipation to the local atmosphere. Eventually virtually all the waste heat must be discharged to the atmosphere, since only a very small percentage is conducted to the ground. The natural stratification of the water, with heated less dense water on top, would tend to retain this separation of hot and cold water. In this connection, one suggestion is to extract the cooling water from the hypolimnion (the cooler bottom layers of a body of water) and, after the water has picked up heat from the power plant, to discharge to the epilimnion (the surface layer). The disadvantage of this scheme is thought to be an increase in the size of the epilimnion and possible accelerated eutrophication.

A completely different method is to discharge below the water surface and encourage mixing with the surrounding water so as to rapidly drop the effluent temperature by dilution with the cooler river water. This scheme would be advisable when discharging into a turbulent, rapidly moving river, such as the Columbia River, discussed above.

In some regions, however, power plants must be constructed where appropriate natural waterways of sufficient magnitude are not available. In other cases, thermal overloading either already has occurred or may occur in the near future as electric power requirements continue to increase. For this reason, thought must be given to artificial cooling methods, such as the cooling tower and cooling pond.

The cooling tower attempts to increase the rate of heat dissipation from the heated water to the ambient air. In a wet
cooling tower, the heated water and air come in direct contact; the water is sprayed or broken into droplets through which air is blown or moved (Figure 2). In a natural draft tower, the air flow is generated naturally, with a chimney effect; in the mechanical draft tower, the air flow is provided by fans. The cooled water from the tower is then pumped back to the condenser. A consideration in the use of a cooling tower is that cooling is due to water evaporation; water must be provided to make up for the roughly three percent of the cooling water lost due to evaporation. Natural draft towers may reach sizes of 300 feet in diameter by 400 feet high; mechanical draft towers may be as large as 600 feet long by 70 feet wide by 60 feet high. Generally, mechanical draft towers cost less than natural draft towers: $7 per kilowatt for a mechanical draft wet tower, $11 per kilowatt for a natural draft wet tower. For a typical power plant, the cost of a cooling tower system is usually estimated at approximately 6 to 7% of the total cost of the plant. For example, the Vermont Yankee nuclear plant cooling tower costs were reported to cost $6,000,000; the Keystone, Pennsylvania plant cooling towers $7,000,000.

While alleviating problems associated with thermal pollution, wet cooling towers have an effect on the environment. Extreme fogging and icing in colder climates may result in the vicinity of the tower, making visibility difficult and imposing dangers on nearby roadways.

In the dry cooling tower, there is no intimate contact between water and cooling air. The warm water is circulated inside pipes, with the air blown over these pipes to carry away the necessary heat. With no water evaporation, no makeup is required; however, this system tends to be much less efficient. Large fans are
required to provide sufficient cooling; the system tends to be much more expensive ($25 per kilowatt) than the others. In order to carry away the necessary heat, it may be necessary to operate at higher condenser temperatures, thus decreasing the thermal efficiency of the entire power plant. The only systems of this type operating in conjunction with electric power plants are in Europe and are for relatively small plants.

Another method of dissipating heat from power plants is the use of a man made cooling pond. The warm effluent is allowed to flow into the pond, where cooling takes place from the pond surface. The warm water is led around the lake by means of barriers or baffles and then pumped back to the condenser. Cooling here is due to evaporation, convection, and radiation from the pond surface; the amount of cooling depends directly on the pond surface area. For example, depending on the local atmospheric conditions of relative humidity, wind speed and dry bulb temperature, one to two acres of pond surface area are required for each megawatt output of a power plant. For a 1000 megawatt plant, this would mean 1000 to 2000 acres; clearly the use of such a pond is dependent on land costs. The cooling pond has the advantage of providing a year round recreational facility for boating and fishing. With the pond water warmed from the power plant, fishing would not be restricted to summer months, but would be available twelve months of the year. Incidentally, it has been shown that certain species of bass reproduce and reach maturity faster in warmer water (the cooling pond surface may reach temperatures of 100°F in the summer in some localities). The pond need have no contact with natural waterways, and could be stocked with fish able to prosper in warmer waters.

The cooling pond, depending on evaporative heat transfer, presents the danger of fogging discussed with respect to the cooling tower. Also, makeup water must be provided, the losses of water being comparable to that of a cooling tower. If makeup water for the pond is to be supplied from runoff, the drainage area for the pond is dependent on rainfall, evaporation, etc., but may be ten times the pond surface area. Another possibility is to pump the makeup water from a nearby stream or river.

Potential Uses of Waste Heat

The enormous quantity of energy rejected to the condenser cooling water from electric power plants has, at the present time, found no widespread use. A great deal of research and
thought are currently being directed towards the potential utilization of this waste heat. It must be remembered this thermal energy might be termed "low grade" heat; that is, the heat is available at a comparatively low temperature, less than $100^\circ\ F$. As such, this heat is difficult to transport without great expense, so it must be used in the immediate vicinity of the power plant.

One possibility for coastal sites is to locate a desalination plant near the electric generating station and use the waste heat for distilling salt or brackish water. Irrigation or drinking water for a city could be supplied from such a plant.

It has been suggested that the condenser heat load be used for greenhouse heating, for which temperatures below $100^\circ\ F$ would be sufficient. By extending the growing season and providing a hot, moist environment, it is estimated that very large quantities of vegetables could be raised. Experiments carried out in Mexico indicate that many vegetables mature more rapidly and provide greater yield when grown in a greenhouse. A combined electrical power, food and desalting facility appears very attractive.

In Oregon and Washington, warm water irrigation projects are being conducted to determine the effect of warm water on crop growth. One intent here is to study the possible extending of the spring and fall growing seasons. Another possibility is to pass the warm water in pipes underground, keep the surface warm all year round, and increase the number of crops harvested each year.

Perhaps the most productive use of the heated water is in the control and maintenance of pond temperatures for aquacultural purposes, e.g., fish farming. In England, three times normal shrimp production has been obtained in the warmed water near the Hinkley Point Power Station on the Bristol Channel. Shrimp reach maturity here in 18 months, instead of the normal three to five years.

By using warm water throughout the year, it is estimated that yields of catfish of 5,000 to 10,000 pounds per acre can be expected. Experiments on Long Island and in Maine have indicated increased growth rates and yields of oysters and lobsters with controlled, warmed water. A study at Par Pond, South Carolina, by DuPont indicated that the hot water pumped to the pond by a power plant appears to make turtles and fish grow faster and in greater abundance. It is also reported that the alligators that thrive on these turtles and fish are rapidly increasing. It is clear that by maintaining a body of water at an optimum temperature,
the maximum yield of fish can be gained from that body of water. Such facilities may someday be a prime source of food.

**Conclusions**

In the next decade and beyond, with the very large amount of thermal energy to be discharged into our rivers, lakes and streams, there is a very real danger of degrading our aquatic environment. Up to the present time, there have been some reported cases of fish kills due to heated water effluents, yet not a large number. Rather, what has been reported are subtle effects that have been observed by scientists. It is clear that, if the number of power plants on lakes and rivers is allowed to increase without control, these subtle effects can only multiply and increase in magnitude, producing irreversible effects on our environment.

One of the key factors in the control of thermal pollution is the selection of a suitable site for a power plant. In the past, site selection has been based mainly on economic considerations. In the future site selection must also take into account the effect of the power plant on the ecology of the surrounding area. The engineer will have to work hand in hand with the biologist on both site selection and operation of the plant. In many locations, it may be necessary to incur the added cost of cooling towers or ponds to protect rivers, lakes and streams.

It is quite clear that, in the long run, our ultimate goal, and one that seems within the reach of today's technology, should be to utilize the waste heat from a power plant for the benefit, rather than to the detriment, of man and his environment.

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**Footnote**

*Professor, Department of Mechanical Engineering, University of Maryland.*

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5 Kolflat, T., Testimony before the Subcommittee on Air and Water Pollution of the Committee on Public Works of the United States Senate, 1968.
