THERMAL POLLUTION

1. Introduction

An important by-product of most energy technologies is heat. Few energy conversion processes are carried out without heat being rejected at some point in the process stream. Historically, it has been more convenient as well as less costly to reject waste heat to the environment rather than to attempt significant recovery. The low temperatures of waste heat in relation to process requirements often make reuse impractical and disposal the only attractive alternative.

Heat rejected to the environment by most industries is of little consequence. Cooling flows of air or water are deployed over equipment or through heat exchangers and the relatively small quantities of heat are dissipated to the surrounding air. Small cooling towers, often of the evaporative type, have become ubiquitous in an industrial facility.

Concern over heat rejection arose when quantities at localized sites rose dramatically as the electric utility industry shifted to water-cooled, thermal-electric generating stations of high unit capacity in the 1950s. The term thermal pollution took on fearsome portents among aquatic scientists, fishery managers, and eventually water pollution control agencies (1). Directly lethal effects of high temperatures on aquatic life were predicted and, where sublethal temperatures were maintained, effects on reproductive cycles, growth rates, migration patterns, and interspecies competition were hypothesized (2).

Much research involving monitoring of thermal effects at power stations was conducted in the 1970s and 1980s. The increased knowledge gained and more stringent regulations led to approaches for using biological requirements of aquatic organisms plus local environmental characteristics of the rivers, lakes, and estuaries used for cooling to design nondamaging cooling systems specific for a site. Because the rate of increase in demand for electricity and development of new generating stations also diminished, new power plants were evaluated more thoroughly and located in less susceptible environments. Approaches for regulating thermal power stations that evolved by the mid-1980s are still in practice as of 2007. They involve meeting water temperature standards for the receiving water established by the states (in the United States) or site-specific demonstrations of balanced ecological communities under Section 316 of the Clean Water Act.

2. Cooling Techniques

Power station cooling is fairly straightforward. Generation of electricity by the steam cycle, the most common method regardless of fuel type, ie, coal, oil, gas, nuclear, solid waste, entails production of waste heat (Fig. 1). Although there are some atmospheric losses in the steam cycle, most of the heat is rejected to flowing water through the heat of condensing steam. For a modern 1200 MW (electrical) lightwater nuclear power plant, this release is $\sim$ 7100 kJ/(kW·h) [1700 kcal/(kW·h)], ie, approximately twice the thermal equivalent of the generated electric energy. The amount of reject heat is proportionately less in fossil-fueled plants, in which up to 40% of the fuel energy can be converted to electricity. The flowing water for the steam condenser was traditionally pumped from a nearby lake or river, then returned to this water body at an elevated temperature in the once-through or open-cycle system. A 1000-MW nuclear power plant having once-through cooling requires $\sim$ 49 m^3/s of water ($\sim$ 13,000 gal/s). The water is usually elevated $\sim$ 10°C. Screens at the water intake prevent entry of objects larger than $\sim$ 1 cm. A biocide, usually chlorine, is used to clean heat-exchange surfaces and water conduits.

3. Risks

A risk is considered herein to be the biological or ecological damage that could be done by a human alteration of the environment with the likelihood or probability that the specific damaging alteration will actually occur. For purposes of clarifying risks to aquatic life, a clear distinction must be made between heat, a quantitative measure of energy that depends on the mass of an object (in this case the volume of cooling water), and temperature, a measure of energy intensity. An amount of heat distributed in two unit volumes of water yields one-half of the elevation of temperature as the same amount of heat distributed in one unit. Although heat is the waste product of electricity generation, temperature is the environmental characteristic to which organisms respond. Thus, the quantity of water used to carry away the load of reject heat is crucial to determining the temperatures created in the environment.

Initially, the source of environmental risk from cooling water was assumed to be the pollutant discharged, ie, heat, in the form of the elevated temperature of the water released from the condensers (thermal pollution). Heat is now recognized as being only one of several potential risks of cooling power stations (Fig. 2). Thermal effects on aquatic life need to be evaluated in the context of other stressors associated with power station cooling so that the overall risks can be minimized. There are often trade-offs and balancing necessary because multiple stressors are acting simultaneously.

Generally unheralded until the early 1970s was the physical entrapment and impingement of fish on cooling-water intake screens. Always occurring at chronic low levels at small fossil-fueled plants, the losses of fish and some large invertebrates rose markedly with the startup of new nuclear stations. In particular, plants on the Hudson River began to impinge large numbers of juvenile striped bass, a species of considerable importance locally.

Impingement risks for affected species seem more direct and identifiable than the indirect aspects of temperature change because these are more visible. The effects of impingement include long periods of futile swimming in screen wells, being held by water currents against the screen mesh (often resulting in suffocation through inability to ventilate the gills), and physical injury from the rotating screen or high pressure water spray used to wash the screen. Beyond risks to individual fish are risks for populations of important species that could be seriously depleted by introducing a new form of chronic mortality into the life cycle. Impingement acts selectively, affecting some species more than others, ie, generally schooling, pelagic fish.

Serious analysis of the risks associated with power plant impingement began when environmental impact statements for nuclear power plants were initiated following the U.S. National Environmental Policy Act of 1969 (NEPA) and the ensuing Calvert Cliffs court decision that assigned responsibility for all cooling-water impacts of nuclear stations to the Atomic Energy Commission (now the Nuclear Regulatory Commission). The analogous problem of impingement of downstream migrating salmon on screens of irrigation diversion dams had been addressed for many years on the U.S. West Coast, but it was not until 1973 that the commonality of both of these problems and of possible engineering solutions was widely recognized (4). Emphasis on solutions was stimulated by the U.S. Federal Water Pollution Control Act Amendment of 1972, which allowed once-through cooling only where intakes minimized losses.

Biocides, principally chlorine, used periodically (0.5 h/day per condenser) for condenser cleaning were also identified as toxic risks for any organisms in the cooling circuit at the time and for those in the vicinity of the discharge where the biocide dissipates. Concern over residual toxic effects of power-plant chlorination was also largely an outgrowth of NEPA reviews of nuclear stations in the early 1970s, when it coincided with renewed concern over ecological effects of chlorination of treated sewage effluents and evidence of chlorinated organic materials formed in chlorinated water (5,6).

A fourth risk is from combined damages, ie, thermal, physical, and chemical, sustained by small organisms that are pumped through the cooling system, ie, entrainment. These damages were among the earliest to be recognized, but the early emphasis on thermal stresses alone retarded examination of the physical components of the damage, which are appreciated as the principal risks at many installations (7). During entrainment, any organisms, including phytoplankton, zooplankton, larval fish, invertebrates, and many small fish that cannot swim against the induced current at the cooling-water intake, are drawn into the cooling circuit unless they are large enough to be screened out initially. In the cooling circuit, they receive in rapid sequence (usually <1 min) a series of stresses. These include a pressure drop in front of the pump impeller, risk of physical impact with the impeller or shear stress of a near miss, rapid pressurization downstream of the pump, shear stress as the cooling water is divided among hundreds of condenser tubes ~ 2.5 cm in diameter, rapid temperature elevation as heat is transferred to the water through condenser tubes, maintenance of high temperature (usually 8–10°C above ambient) through the discharge system, decreasing pressure in discharge piping (sometimes below atmospheric), followed by turbulent mixing and cooling as the condenser water rejoins the source water body (8). Many entrained organisms do not survive. During periods of biocide treatment to remove heat-transfer-retarding biological slimes from condenser tubes, entrained organisms are also exposed to lethal concentrations of a toxicant, usually chlorine.

Many organisms are exposed to some of the thermal, chemical, and physical stresses of entrainment by being mixed at the discharge with the heated water; this is plume entrainment. The exact number exposed depends on the percentage of temperature decline at the discharge that is attributed to turbulent mixing rather than to radiative or evaporative cooling to the atmosphere.

Entrainment was in the forefront of concerns over condenser cooling in the early 1970s as two trends in the planning of power plants developed: gradual decrease in the temperature rise (ΔT) across condensers to reduce thermal effects, which was necessarily accompanied by an increase in volume of water pumped, and increased exploitation by large nuclear stations of estuarine waters, which generally contain far more planktonic eggs and larvae of important fishes and invertebrates than inland rivers or lakes. The long-term risk with entrainment lies in chronic losses of vulnerable stages to physical stresses that can contribute to localized instability or decline in populations of valued species. Complex scientific debates over the magnitudes and probabilities of population effects of entrainment mortalities have punctuated power plant licensing proceedings since 1971, particularly those for the Indian Point Nuclear Power Plant on the Hudson River (9). Computer models have been developed to estimate numbers of organisms, eg, fish larvae, that can be killed in a population by both natural- and human-caused mechanisms, without affecting the continued success of the population as a whole. The Electric Power Research Institute (Palo Alto, California) and Oak Ridge National Laboratory (Tennessee) have been leaders in developing such models.

Questions also arose over the risks to aquatic life from changes in gas content of the water as a by-product of temperature change. Warmer water holds less gas in solution. Dissolved oxygen was hypothesized to decrease below levels necessary for fish by a combination of physical solubility relationships and increased biological demand for oxygen at elevated temperatures. Supersaturation of dissolved gases in water was also viewed, particularly in the northwest United States, as a significant risk arising from heating already saturated river water. Fishery scientists on the Columbia River were especially sensitive to this potential problem, because high gas saturation levels from dam spillways were demonstrably harmful to experimental salmon and trout (10).

Physical changes in habitats near the cooling water intake and discharge structures of power stations were also identified in NEPA analyses as posing some risk or at least potential for change to segments of aquatic communities. Concrete structures, rock jetties, and altered current patterns contribute to habitat modifications that influence suitability of the area for desirable species and can be linked to the overall problem of dissipating rejected heat.

Risks from cooling towers were identified by comparative ecological analyses of cooling-system alternatives and the risks became part of the assessment process. Evaporative cooling towers, whether natural or mechanical draft (see Fig. 1), were seen as the panacea: a closed cooling cycle to replace the transgression of the once-through system on natural waters.

The evaporative closed cycle is, however, not really closed. Among the first environmental risks recognized from cooling towers were increases in fogging and icing in northern climates. Wherever cooling towers are used for coastal waters, sea salts are dispersed from the towers to adjacent lands with gradual salt accumulation and detrimental effects on agriculture and corrosion of structural materials. Continuous evaporation gradually accumulates unwanted salts if there is not some flow through in addition to replacement of cooling water for evaporative losses. This flow through or blowdown carries with it numerous chemicals added to the cooling circuit to prevent corrosion, eg, chromates, zinc, and organophosphorus complexes, to slow mineral scaling of heat-exchange surfaces by, eg, acids or to eliminate biological fouling, eg, by chlorine. Blowdown was traditionally discharged untreated into water bodies that supplied the tower intake, and organisms susceptible to the chemicals were placed at risk. The chemicals also escape the towers in drift in the form of small water droplets and aerosols that are dispersed with air flows to terrestrial surroundings. Cooling-tower sludge, the solid material that accumulates in tower basins, must also be discarded. This sludge includes precipitated chemical elements from the water supply, corrosion inhibitors, and airborne dust, pollen, and tree leaves washed from the tower air flow. At the intake, entrainment and impingement are not eliminated by the addition of cooling towers, although water flows can be reduced to 5–10% of that needed for once-through cooling. The presumed advantage of reduction in water volume for minimizing entrainment risks may be illusory, as organisms entrained into cooling-tower circuits are exposed to lethal conditions, whereas many often survive a rapid once-through passage at well-designed open-cycle plants. Cooling towers can also be noisy (if mechanical draft towers with fans) or visually obtrusive (if tall natural draft towers). From a strictly engineering standpoint, retrofitting cooling towers to power plants that currently use once-through cooling introduces thermodynamic issues, such as loss of thermal efficiency and reduction in the amount of electricity that can be generated (necessitating more power plants to supply the needed electric power). Such concerns may open lines of investigation for those interested in thermal power engineering.

An alternative closed-cycle system that is used particularly in the Midwest, Southeast, and Texas is the artificial cooling lake. Such lakes exist in a gradient of designs from large multipurpose public reservoirs, which provide essentially once-through cooling, to privately controlled, diked ponds or canals that rely on evaporative cooling and are often augmented by spray modules. The risks to public resources also vary greatly. Despite the obvious multipurpose benefits of cooling reservoirs where water resources are scarce, these cooling systems were judged in violation of the 1972 Water Pollution Control Act and for several years were not allowed for new power stations. Thus, the number of cooling lakes constructed diminished greatly (11). There has been much debate over cooling lakes. Numerous water and fish management opportunities from their use has brought them back in favor. Many of the most productive fisheries are fresh water species in lakes also used for power plants.

4. Risk Minimization

Selection of the best cooling system in terms of minimal environmental damages involves matching engineering options to the local aquatic system potentially at risk. General principles of aquatic ecology and the life histories and environmental requirements of species represented locally can be adapted to local water resource goals using detailed understanding of the local aquatic setting to achieve site-specific risk prevention. This "scientific" approach can be supplanted by regulatory mandates, however. For example, in 2004 the EPA issued new rules for minimization of impingement and entrainment. These rules are to be applied regardless of any demonstrable environmental impacts. Where society, through such mandates, judges the environmental risks of open-cycle cooling to be unacceptable, closed-cycle cooling is employed. Since the late 1990s, new power stations have been increasingly obliged to consider fully closed, air-exchange cooling, which has essentially no direct environmental impacts to water resources, but with structures that are large and can be visually obtrusive.

4.1. Thermal Effects. Temperature is the most all-pervasive environmental factor that influences aquatic organisms. There is always an environmental temperature, whereas other factors may or may not be present. Nearly all aquatic organisms, with the exception of freshwater and marine mammals, are for all practical purposes thermal conformers. As such, they are not able to exert significant influence on maintaining a certain body temperature by physiological means. Their body temperatures fluctuate in close accord with the temperature of the immediate surrounding water. Only especially large, active-moving fish, such as tunas, maintain deep-muscle temperatures slightly higher than the surrounding water. Intimate contact between body fluids and water at the gills and the high specific heat of water assure a near-identity of internal and external temperatures. Behavioral thermoregulation or the control of body temperature by selection of water temperature in natural gradients is, however, a common feature of many fish. Behavioral thermoregulation serves an important ecological role in partitioning aquatic habitats among species. Understanding behavioral thermoregulation is a powerful feature for estimating and ameliorating the impacts of thermal discharges.

Thermal effects on aquatic organisms have been given critical scientific review. Annual reviews of the thermal effects literature have been published beginning in 1968 (12). Water temperature criteria for protection of aquatic life were prepared by the National Academy of Sciences (NAS) in 1972, and these criteria have formed the basis of the Environmental Protection Agency (EPA) recommendations for establishing water temperature standards for specific water bodies (13,14). These documents are still the most relevant guidance $>$ 30 years later.

The importance of temperature for organisms lies partly in its fundamental physical–chemical influences. The biochemistry of life is, in general, subject to the basic dictum that a rise of temperature by 10°C results in about a doubling of the rate of chemical reactions (ie, metabolism). Life also has an upper thermal limit, set partly by the chemical stability of organic molecules, eg, proteins or enzyme systems, and by the balance of food energy inputs and expenditures, which is characteristic of each species and, in some cases, different life stages. Although aquatic organisms must conform to water temperature, many have evolved internal mechanisms other than body-temperature regulation to allow continued functioning as temperature changes occur geographically, seasonally, and daily. Through gradual biochemical adjustments termed acclimation, physiological processes are maintained relatively constant over a prescribed thermal range that is species- or life-stage specific. Within this range, each species has a zone of optimal physiological performance which, because it tends to coincide with temperatures preferred in gradients, has recently been termed its thermal niche in the environment.

Organisms evolving under annual temperature cycles and in environments with varying temperatures spatially have incorporated thermal cues in reproductive behavior, habitat selection, and certain other features which act at the population level. Thus, the balance of births and mortalities, which determines whether a species survives, is akin to the metabolic balance at the physiological level in being dependent on the match, within certain limits, to prescribed temperatures at different times of year. At the ecosystem level, relationships among species, eg, predators, competitors, prey animals, and plant foods, are related to environmental temperatures in complex ways. Many of these interactions are poorly understood, but scientific research is continuing.

Despite the immensity and complexity of known and suspected roles of temperature in aquatic ecosystems, certain thermal criteria have been especially useful in minimizing risks from thermal discharges. More data have been organized at the physiological level than at higher levels of organization.

4.2. Preventing Mortality. Upper and lower temperature tolerances of aquatic organisms have been well conceptualized and relatively standardized methods are available for determining a species' tolerance ranges under different conditions of thermal history [Fig. 3(**a**)]. On a short timescale, mortality is highly dependent on duration of exposure [(Fig. 3(**b**)], so that brief exposures to potentially lethal temperatures are not actually lethal. Temperature elevations and duration of exposure can be tailored in a plant's piping or in the effluent mixing zone to maximize organism survival (13,15). This is usually accomplished using detailed mathematical models of cooling-water-effluent dispersion and heat dissipation in the near field where temperatures are highest (16,17). One option used extensively for this purpose in the 1970s was increasing the cooling-water flow and thus decreasing the temperature elevation to below lethal levels. This tactic had the undesirable result of increasing the numbers of organisms damaged by the physical effects of entrainment and impingement. As of the 1990s, a quantitative balance between minimizing direct thermal mortalities and increasing those risks related more to the volume of cooling-water flow is employed.

4.3. Preventing Stressful High Temperatures Over Long Periods. For the long term ($>$1–2 day), simply preventing mortality is insufficient for protecting aquatic species. All of the physiological functions normally performed must be carried out to maintain healthy individuals that are capable of competing in the natural ecosystem. An aggregate measure, growth rate, has proved useful as an integrator of all physiological functions and some behavioral ones, eg, feeding rate. Growth occurs only if all other metabolic demands are being met and when sufficient food energy is left over for adding biomass. Typically, many physiological functions of well-fed, cold-blooded organisms proceed optimally over a temperature range in which growth rate is maximal (Fig. 4). Above the temperatures of maximum growth rate, the rate typically declines steeply to a temperature of zero growth, which often occurs 1–2°C below the temperature at which direct mortalities begin. Intuitively, the healthy fish becomes unhealthy as the long-term temperatures it experiences rise from those that yield maximum growth to that which stops growth. Alternative methods for calculating the upper danger level have been proposed, but each suggests that a long-term decline of growth rate below $\sim$ 75% of maximum at high temperatures is unduly risky (13,15).

Standards for upper limits on water temperatures for particular water bodies over periods of ~1 week or more can be based on species-specific growth rates. Using an inventory of important species and life stages in the area during the warm season, the upper temperature limit that does not stress those in the desired aquatic assemblage can be ascertained. Hydrothermal models of heat dissipation in the far field beyond the zone of effluent mixing are important for estimating the zones that may present a long-term risk from elevated temperatures.

The preferred and avoided temperatures in a gradient have been used as surrogates for optimum growth and upper danger levels for fish. One practical drawback to using growth rate as an index of optimal temperatures is the experimental cost of determining it. As more and more data link temperatures of optimal growth rate with preferred temperatures for a species, there is an increasing tendency to conduct only thermal preference tests (18). Long-term abundance of species at power plant sites appears to be generally correlated with preferred and avoided temperatures.

4.4. Preserving Reproduction Cycles. Organisms in the temperate zone have evolved in concert with seasonal temperature variations. Reproduction success depends in part on the preservation of an annual temperature pattern, although the precise timing is usually not critical. Thermal discharges can be designed, usually with the help of far-field mathematical models, to assure the necessary thermal periodicity. Unless the cooling system is a heavily heat-loaded stream or cooling pond, the thermal output of a power station complex is rarely sufficient to offset the large natural cooling rates of winter. Thus, annual thermal cycles are generally maintained despite anthropogenic heat rejection.

4.5. Maintaining Ecosystem Structure and Function. Thermal heterogeneity of water bodies is an important structural feature of the environment and plays a large role in determining the composition and functioning of most aquatic systems. Vertical thermal stratification of lakes, reservoirs, and many estuaries in summer (Fig. 5) segregates an available habitat into discrete zones with differing thermal and water quality characteristics. In the evolution of aquatic species, these discrete zones have been the basis for partitioning the environment, such that different species or life stages within some species occupy discrete portions based, in part, on temperature selection behavior. The disruption of thermal structure can be more damaging to ecosystem composition and function than the direct killing of many individual organisms.

Particularly significant are thermal refugia during periods of extreme high or low temperatures. Aberrant weather or artificial thermal changes can cause large portions of a water body to exceed the physiological limits of some aquatic species for brief periods. The species usually affected are those at the northern or southern limits of their geographic ranges. These species often survive in isolated zones or refuges that retain suitable temperatures, eg, springs where trout can remain cool in the warmest summer months or water bodies where cold-sensitive species, eg, threadfin shad, find relatively warm waters in midwinter. The demise or survival of such geographically marginal species, which is determined by the availability and sizes of such thermal refugia, can be paramount in establishing the ecological interactions of a water body (19). Power station discharges can prematurely force desirable cool-water species into refuges in summer and can provide essential warm refuges for desirable warm-water species in winter.

Thermal heterogeneity of the environment, thermal optima for organism growth rates, and behavioral temperature selection are being evaluated in ways that are useful for predicting ecosystem effects of thermal alterations (18). Thermal-niche concepts can be used to identify critical habitats for important species in ways that focus the potential influences of power-station discharges (19,20). For example, striped bass (*Morone saxatilis*), an East Coast species introduced on the West Coast and in freshwater reservoirs, partitions a water body in summer along thermal gradients among its age or size classes. Young striped bass prefer and grow optimally at high temperatures near 24–26°C, subadults prefer ~22°C, and mature adults select temperatures of 20°C or less. Thermal discharges may benefit growth rates and survival of juveniles, but the adults face a different prospect. Forced to cool water in summer by their genetically based temperature preferences, they may find this habitat severely restricted by thermal additions or compromised by simultaneous depletion of dissolved oxygen as a result, in part, of decomposition of thermally stimulated plankton production. Overcrowding in limited thermal refugia that have sufficient dissolved oxygen has led to starvation, high disease incidence, and abnormally high fishing susceptibility, all of which cause high numbers of deaths.

Altered predator–prey interactions, previously viewed as intractable long-term influences of changing water temperatures, can be estimated at least qualitatively through use of thermal-niche concepts. Adult striped bass that are restricted from access to surface waters by high temperatures seek food among the cold-water species, eg, trout in deep water, rather than among the surface-dwelling shad species that are their normal prey. Trout populations can be decimated, as they were in Lake Mead after introduced striped bass grew to the size and thermal preference of adults.

Careful planning of thermal additions, including creation of new cooling reservoirs, can yield thermal structures that enhance rather than damage desirable aquatic species. Knowledge of the thermal niches of these species and their potential competitors or predators can permit special provisions for thermal refugia, eg, cool summer zones in a heavily loaded cooling pond. Cooling-water circulation can be designed so that the thermal stratification patterns that are essential for some desired species are maintained. From a different perspective, aquatic species introduced to waters used for power-station cooling can be selected so that their thermal niche matches the thermal structure that the facility creates. Multiple species introductions can be evaluated beforehand to estimate whether available thermal patterns will abnormally aggregate or separate potential predators and prey.

Certain ecological attributes of a "balanced indigenous community" have been defined in EPA guidelines for evaluating thermal discharges under Section 316(a) of the Clean Water Act. A balanced indigenous community is characterized as one that has diversity, has the capacity to sustain itself through cyclical seasonal changes, contains the necessary food chain species, and is not dominated by pollution-tolerant species. The major adverse impacts that a Section 316(a) analysis is to determine are avoided include

- Decrease in abundance of threatened or endangered species.
- Increase in the abundance of nuisance species.
- Decrease in abundance of indigenous species.
- Damage to critical aquatic organisim, eg, important elements of the food chain, or damage to basic ecosystem process, eg, migration.
- Increased vulnerability to predation or disease.
- Change in population composition, eg, through thermal stress and competition.
- Decrease in commercial or sport fisheries.
- Simplification of trophic structure.

Current directions in biothermal research include physiological responses to temperature changes at the molecular level and the effects of fluctuating temperatures. At the molecular level, heat shock proteins (HSPs), also called stress proteins, are a group of proteins that are present in all cells in all life forms. They are induced when a cell undergoes various types of environmental stressors like heat, cold, and oxygen deprivation. They also respond to forms of toxicity, eg, metal pollution, and are thus general and not specific to temperature shock. As the scientific literature on heat shock proteins has grown over the last decade or so (eg, 21), some environmental analysts have proposed using the abundance of heat shock proteins as a measure of environmental damage, particularly for elevated temperature. Whether HSPs are suitable for indicating stressed states in fish is controversial, although the present view is that this use is premature (22). The reason is that HSPs are also present in cells under perfectly normal conditions, where they serve functions as molecular “chaperones” making sure that proteins are in the proper shape and location for their function, they transport old proteins to intracellular sites for breakdown and recycle, and apparently aid the cell’s immune system to recognize diseased cells. Although levels of HSPs do rise in various tissues following exposure to stressors, the response is complex and not well understood. The HSP responses seem to vary considerably according to tissue, family of HSP (there are several molecular types), organism, developmental stage and stressor. Field research on HSPs in intertidal fishes suggests that an elevated HSP level has functional importance for thermal tolerance and helping an organism successfully cope with thermal fluctuations (23).

Although tolerance of aquatic species to constant temperatures is the basis of most regulatory temperature standards, the real world consists of fluctuating temperatures over several time scales (rapid, daily, seasonal). Exposures to elevated temperatures at power plant thermal discharges are nearly always discontinuous due to plume mixing dynamics and animal behavior. There is renewed interest in the biological effects of these fluctuations and whether fluctuations cause increased stress or increased tolerance (eg, 24). Fish exposed to fluctuating temperatures often have survival responses similar to those acclimated to a constant temperature near the midpoint of the fluctuations, or to temperatures slightly higher than the midpoint. When exposure temperatures are briefly in the upper lethal range, a period of lower temperatures (eg, at night after high daytime temperatures) appears to allow recovery and some acclimation to the warmer temperatures, both of which ameliorate the accumulated stress (25). The traditional additive model for lethal exposures includes acclimation, but assumes no recovery processes following brief exposures to potentially lethal high temperatures (15). In environmental impact assessments of thermal discharges, the results of the traditional additive model for thermal exposures often demonstrate that lethal exposures (time and temperature) to high temperature would not occur. Had any recovery processes been included, the estimated effects would have been even less severe. Therefore, the conservative survival assessment remains valid despite recent interest in more information about effects of fluctuating temperatures. Growth also responds to fluctuating temperatures, with temperature fluctuations below optimum growth temperatures tending to enhance fish growth whereas fluctuations much above optimum temperatures usually depress growth (26,27). A reemerging issue is whether different *rates* of temperature change affect biological measures, such as survival and growth, but little research has separated rates of change from the more traditional measures of exposure temperatures and durations.

4.6. Impingement. Most of the techniques to avoid or minimize impingement have been reviewed (4,28). Repellents, eg, sound, electricity, and light, have been used to keep susceptible fish away from intakes with moderate success (29). Orientations of the inlet structure with screens flush with the shoreline allowed lateral escape [Fig. 6(**a**)]. Where this screen orientation was impossible, guidance systems were developed for intake bays to direct fish from the incoming water flows to alternative escape routes [Fig. 6(**b**)]. Guidance devices were also installed at the entrances to unscreened, offshore inlets, where a horizontal velocity cap placed a few feet over a vertical opening proved especially effective in preventing fish entrance [Fig. 6(**c**)]. Small-scale modifications to existing rotating trash screens allow many fish to survive as they are raised from the water and deposited in sluiceways for return to the water. Expansion of hydroelectric power development has led to renewed interest in these guidance techniques.

Experience has also shown that deaths of fish on intake screens, although visually spectacular, often have minor consequences for local populations of many species (31). Most commonly impinged are open-water, schooling species that have high reproductive potential and a propensity for large natural variations in population numbers. The most common season for impingement mortalities, ie, winter, is a time of natural population reduction because of cold stress for several species. Cold-stressed fish may be impinged in large enough numbers to shut down the facility, but evidence suggests that most are moribund and destined not to survive regardless of cooling-water intervention (32).

Minimization of impingement risks focuses on site-specific analyses of potentially vulnerable species and selection of engineering designs that, within acceptable cost limits, keep impingement deaths low. New rules by the EPA in 2004 mandating reductions of impingement have stimulated much new technology development. When impingement is reduced by reducing cooling-water flows at the same levels of electricity generation, there is usually a higher temperature rise, thereby trading reduced impingement and entrainment risk for some increases in thermal stress in the receiving water body.

4.7. Biocides. Chlorine and other biocides are used occasionally in cooling water to kill and dispose of organic growths on heat-exchange surfaces and on piping where water flow could be hampered by such growth. Of necessity, organisms passing through the cooling circuit or residing in the effluent area during periodic chlorine injections experience the potentially lethal exposures. The objective is to maximize the intended kill and minimize extraneous damages, particularly in the receiving water (33).

Chlorine is a toxicant with a typical dose-response pattern for biota (Fig. 7). There is a time-dependent mortality at high concentrations and a low concentration above which long-term chronic effects are shown. Early methods for using the time-dependent effects of high temperature for predicting safe temperatures and exposure times during cooling-water exposures led to a similar approach for chlorine (3). Chlorine toxicity data were scant and different aggregates had to be developed for freshwater and marine assemblages because of the markedly different chlorine chemistry in fresh and salt water.

4.8. Entrainment. Stresses to small nonscreenable organisms, eg, fish larvae, during passage through the cooling circuit come from a combination of thermal shock, physical abuses, and periodic injections of biocide. The physical abuses are less well understood (8). Pressure changes, shear forces, and physical contact with pump impellers or tubing walls are sources of potential damage that vary from system to system. Minor differences in configuration of piping can mean the presence or absence of such devastating features as microcavitation cells. The physical configuration does not lend itself easily to laboratory experimentation, although three such physical simulators have been tried (34–36). New EPA rules mandate reduction in numbers of organisms entrained.

A principal frustration in attempts to minimize entrainment damages has been the contradictory demands of thermal and physical stresses. Thermal stresses can be quantitatively predicted based on dose-response data and minimized by increasing water-flow volumes, which dilute the fairly constant supply of rejected heat. The added volume of cooling water, however, includes proportionately more planktonic organisms, which are subjected to physical stresses. Attempts to minimize thermal damage in new power stations had the demonstrable effect of increasing physical damage from entrainment. One proposed solution, which is based on the assumption of a high percentage of mortality resulting from physical stresses, is to return to high condenser temperatures at which all of the relatively few organisms entrained would be killed, but those not pumped from the waterbody would be assured survival (8).

The assumption of high percentage mortality resulting from physical stresses has been criticized, however. Better methods of sampling entrained biota, which involve extensive precautions against damaging stresses during the sampling process itself, indicate a much higher survival of even delicate fish larvae than had been realized with earlier and more crude sampling methods (37). It appears that ameliorations of thermal stress with flow increases generally are not canceled by additional physical mortalities except in cases of exceedingly high flows. An optimization procedure, such as that suggested by the Committee on Entrainment, appears fruitful for identifying on a site-specific and seasonally varying basis the most appropriate cooling-water flow regime (8).

There is also a compromise between entrainment and impingement. One of the engineering methods suggested for minimizing entrainment was replacement of 1-cm-mesh intake screens with screens of much smaller aperture. Although fewer organisms are entrained, most of those saved are, in fact, impinged on the smaller mesh of the screen, and the probable new impingement mortality may exceed the entrainment risks.

4.9. Gas Balance. Oxygen in solution does not generally change in a cooling circuit unless there is strong aeration of originally saturated water heated maximally, in which case some dissolved gas is lost. In no case does the loss reduce levels to below that required by aquatic life. When intake water is undersaturated, the agitation of the cooling circuit generally yields an increase. Abundant data support these generalities. Polluted receiving water does, however, have an accelerated microbial oxygen demand because of raised temperature, and resulting microbial deoxygenation can yield exaggerated dissolved oxygen sag zones downstream. The interaction of thermal effluent and waste stabilization in the river must be considered whenever polluted water is used for cooling, and engineering models for predicting oxygen sag zones are generally capable of incorporating temperature changes.

Damaging supersaturation of dissolved gases has occurred in some cooling-water discharges. Damage has been isolated to circumstances, usually in winter, when temperature elevations above the cool ambient are highest based on the assumption that even a large increase in winter results in temperatures below lethal level or prevalent water quality standards. The practice of winter increases in temperature rise across condensers by cutting back on pumping capacity has either ceased in general practice or the immediate discharge areas have been engineered to prevent long-term residence by susceptible biota. These remedial measures can be completely effective.

4.10. Cooling-Tower Chemicals. The risk posed by changing power-station systems from traditional once-through or open-cycle cooling to cooling towers is from chemicals added to the recirculating water. Blowdown to aquatic systems and drift to the terrestrial landscape carry these chemicals to locations where natural biota can be damaged through direct poisoning or where toxicants can accumulate to potentially detrimental levels by food-chain transfer. Such risks can be minimized using fairly straightforward engineering approaches. Airborne drift has been reduced significantly by installation of physical baffles at the air outlets that intercept droplets, coalesce them, and return the water to the cooling-water flow. Blowdown can be treated for removal of chemical constituents, eg, chromates, with the additional benefit of chemical recycling and, thus, cost recovery. Chemical-laden sludges become a more long-term disposal problem. Practices include ponding and landfills. Chemical-recovery processes are also available for sludge treatment. Of significance for all of these processes is the cost which, when added to the initial capital cost of the cooling towers and the operating costs of pumps and fans, can reduce the attractiveness of closed-cycle cooling, especially when less costly mitigative measures exist for the open-cycle system at many locations.

4.11. Human Pathogens. Proper designs and good maintenance practices can reduce the potential risks to humans from pathogens stimulated by environmental conditions in cooling systems, eg, amoebae *Legionella*, to very low levels. Thermophilic protozoans that thrive in water near human body temperature that is also rich in organic matter find animal tissues similarly favorable, particularly the nasal passages, which allow easy penetration to the brain. Field evidence indicates that these organisms are most abundant in stagnant pools and roadside ditches; fatal infections have generally been traced to exposures in such environments. The rapidly flowing water in power station discharges, although quite warm in summer, generally does not provide either stable substrates or high concentrations of organic material. Additionally, plant security measures generally ensure that bathers do not use the warmest zones. Allowing water contact by the public in discharges, particularly wherever the outlet is a slowly moving canal with abundant vegetation, is risky. The Legionnaires' disease microorganism, identified as a common inhabitant of many cooling-tower systems, especially small ones used for building-temperature control, can be held in check by systematic use of biocides in recirculating cooling water. Contact with the infectious organisms can be minimized if care is taken to isolate inlets for ventilating air from the drift aerosols, which are emitted from cooling towers.

5. Maximizing the Benefits

During occasional episodes of energy scarcity, particularly in the 1970s, attention was given to finding productive uses for power plant waste heat. Potential physical applications of power plant rejected heat include industrial heating and biological applications, eg, fish culture, soil warming, heating greenhouses, and livestock shelters (38).

The most important factor determining the possible uses of such heat is the temperature of the heat source. There is a threshold between low and high grade heat for engineering uses at $\sim 100^{\circ}$C. Most waste heat from electric power stations is in the form of low grade heat. This is so low in temperature that disposal to the environment has traditionally been considered the only practical alternative. Discharges from once-through cooling systems of thermal power plants have outlet temperatures of $10{-}40^{\circ}$C, depending on the season. Circulating water in closed-cycle cooling systems is only slightly warmer ($20{-}50^{\circ}$C). These low temperatures are the result of careful engineering of power stations to extract the maximum amount of electrical energy from the fuel before the rejected heat is dumped to circulating water in steam condensers. Such engineering has produced high efficiencies compared to most other mechanical systems; 33% in nuclear plants to 40% in fossil-fueled plants is the fuel energy converted to electricity.

A more useful, higher grade heat is in a form that has not been degraded to the low temperatures of most power plant thermal discharges but which remains at $40{-}200^{\circ}$C following production of initial amounts of electricity. Low pressure steam can be extracted from the turbine system of a power plant before condensation to waste-heat temperature, thus permitting its use for functions requiring higher temperatures. Although this gives better utilization of the energy remaining in the steam, the efficiency of the low pressure turbine for producing electricity is diminished. Condensers can also be operated with smaller cooling-water flows to yield higher discharge temperatures, but with some penalty to generation efficiency because of higher turbine back pressures. The overall efficiency of fuel energy use in such multiple-purpose systems can exceed that of electricity production alone, however.

Ideally, a power station could be a potential supplier of electricity, high and low grade heat, even though electricity is the main product, and new power stations are often optimized accordingly. Depending on the desired uses at particular sites, future power stations could be designed to alter the ratios of electricity and different grades of heat to produce the most efficient total energy use. Such multiple use was common at early generating stations in the United States and is still common in Europe. Applications in North America are becoming more common.

5.1. Aquaculture. Culture of some aquatic species in essentially unmodified thermal effluents of power stations has been attempted both experimentally and commercially. The principle behind such culture is the temperature dependence of growth rates. Use of rejected heat to prolong optimal growth temperatures in cool months can significantly increase the sizes attained in a year. Even though power stations rarely provide high enough temperatures in winter for optimal rates, temperatures can usually be maintained at levels that increase growth rates. Maximum use of available temperatures has been made by culturing warm-water shrimp in summer and cool-water trout in winter, each of which can utilize the added temperature imparted by power station cooling (39). Most thermal aquaculture facilities at power stations have not been economical and have been closed. There has been interest in small-scale thermal aquaculture cogeneration facilities in which small fossil-fueled electricity generators are operated, with temperature control of fish tanks as the primary objective. Any electricity remaining after on-site use by the facility is sold to the local electrical utility.

5.2. Open-Field Agriculture. Use of warmed water for field crops and orchards has been tested in several studies. Buried pipes can convey thermal-discharge heat to soils where warming aids plant growth and extends the growing season. Soil warming with open irrigation water has also been studied. There are advantages of spraying thermal-effluent water on crops and orchards to prevent freezing of buds and blooms. Whether or not the heat is used, power plant cooling water can conveniently be combined with irrigation water systems to provide multiple uses of the water. An extensive demonstration project has been established by Electricité de France at their St. Laurent des Eaux power station.

5.3. Greenhouse Agriculture. Greenhouse agriculture is well known for its many advantages over open-field agriculture for certain crops. Yields are greater per land area and year-around culture is possible, which allows matching of crop harvest with high demand and price. One drawback is high expense for heating in winter, which can be the most costly part of greenhouse operation. The use of waste heat from steam-electric power plants therefore appears promising as a source of low cost heat for use in greenhouses, especially if the power stations have cooling towers with wintertime operating temperatures of 16°C or higher. The economic analysis is favorable (40).

Experimental greenhouses based on waste heat for temperature control have been operated at several sites and have demonstrated the principle that cooling water can be used to heat a greenhouse in winter. Some have also been based on power plant effluent for cooling in summer; inexpensive porous packing through which the heated water drips and air circulates is used (Fig. 8).

Evaporation provides cooling in summer and sensible heat transfer warms the air in winter. Additional heat and humidity control can be provided with a finned-tube heat exchanger. The French have used pipes and plastic tubes laid in the floor of the greenhouse; warm thermal effluent or water warmed further with heat pumps operating from thermal discharge waters circulates through the pipes and tubes. As with aquaculture systems, greenhouses should affiliate with multiple-unit power stations to ensure continuous warm water supplies.

5.4. Animal Shelters. The advantages of temperature control for maximizing weight gain and avoiding animal losses in livestock and poultry are well known. Low grade heat from power station cooling offers the possibility of low cost heating of animal shelters, although few demonstration projects have been developed. Heating animal shelters is a special case of space heating, although capital costs generally must be lower for the system to be economical. The greatest potential for heating animal shelters appears to be in continental climates where exceedingly cold winters can lead to deaths of livestock (41).

5.5. Space Heating. A large percentage of the energy requirements of most countries in temperate zones is for heating and cooling of living and working spaces and for hot water. The historical use of dual-purpose power plants for electricity generation and central district heating in the United States and their extensive use in such countries as the Russia, Sweden, and Germany suggests that expansion of this form of waste-heat utilization can contribute significantly to energy conservation and control of concentrated thermal discharges worldwide.

The most economical form of long-distance transport of thermal energy for space heating and cooling by adsorption methods is by heated water rather than steam. Steam had been used from early dual-purpose power plants prior to development of modern water-cooled condensers. It is still used in areas of dense loads, but its range of effective distribution is small because of large pressure drops in distribution systems. Modern experience with dual-purpose power plants (mostly in Europe) and new district heating systems in the United States, eg, in colleges, institutions, and shopping centers, has shown hot water to be superior for dispersed loads, including single-family residences. These dual-purpose stations operate at high thermal efficiency; the Swedish Malmo Plant is researching new technologies for distribution pipes in order to expand economical district heating to dispersed single-family residences.

Economic analyses for the United States indicate that supplying thermal energy to the commercial–residential sector from dual-purpose power stations is more economically competitive in new applications than in cases where existing buildings are to be serviced (42). There is little difference for supplying industrial heating. Such a thermal grid is most competitive with new fossil fuels where there is a high heat-load density and expensive fuel costs.

5.6. Industrial Process Heat. Many industries use process heat at 77–110°C. Much of this heat is supplied by combustion of oil and natural gas. Equipment manufacturers are developing industrial heat pumps to capture free industrial plant waste heat and regenerate it to the desired process heat temperature, thereby greatly reducing energy costs associated with direct heating. Operations that use heat in the 88–110°C range that can be supplied by new high efficiency heat pumps based on rejected heat sources are washing, blanching, sterilizing, and cleaning operations in food processing; grain drying; metal cleaning and treating processes; distilling operations in the food and petrochemical industries; and industrial space heating. Power plant rejected heat could be valuable for developing industries that perform these processes.

5.7. Cooling Reservoirs. The most extensively developed productive use for power plant cooling is in multiple-purpose cooling reservoirs. Small impoundments built especially for heat dissipation have been managed for extensive recreational uses as well. Highly productive fisheries for warm-water species, eg, largemouth bass (*Micropterus salmoides*) and channel catfish (*Ictalurus punctatus*), have made cooling reservoirs highly popular. Such reservoirs have been extensively developed in lake-free areas, eg, Texas and Illinois. Broad-scale ecological research on some of these cooling reservoirs has documented the valuable synergistic relationship between cooling-lake fisheries and power station heat dissipation (43).

6. Summary

Thermal pollution from energy generation is not viewed today as the threat to the environment that it appeared to be in the 1960s and 1970s. This is not because the potential environmental hazards of power station cooling are necessarily any less. The change in perspective has arisen because the hazards have been recognized, biological and other environmental constraints (and benefits, in some cases) have become understood, and good engineering practice has devised methods to minimize risks. Where location-specific controversies remain, multidisciplinary teams of biologists and engineers can usually design appropriate, site-specific studies to develop the most suitable solutions. Nonetheless, there are still pressures to eliminate once-through power plant cooling and to substitute closed-cycle cooling systems.

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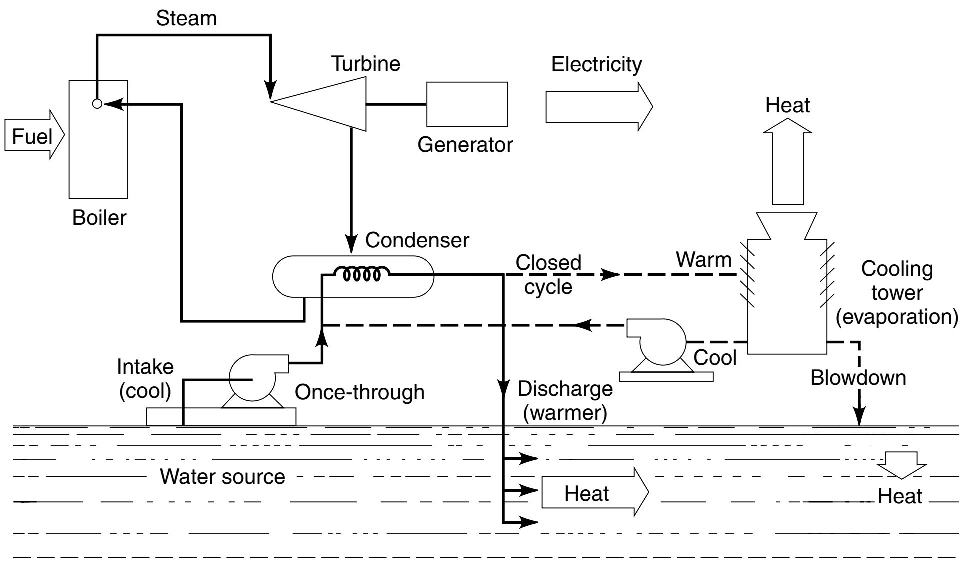


Fig. 1. The energy cycle of a thermal electric generating station having two alternative cooling systems: (—) the open-circuit or once-through system and (– – –) a representative closed-cycle, cooling-tower system. [Reproduced by permission from (3).]

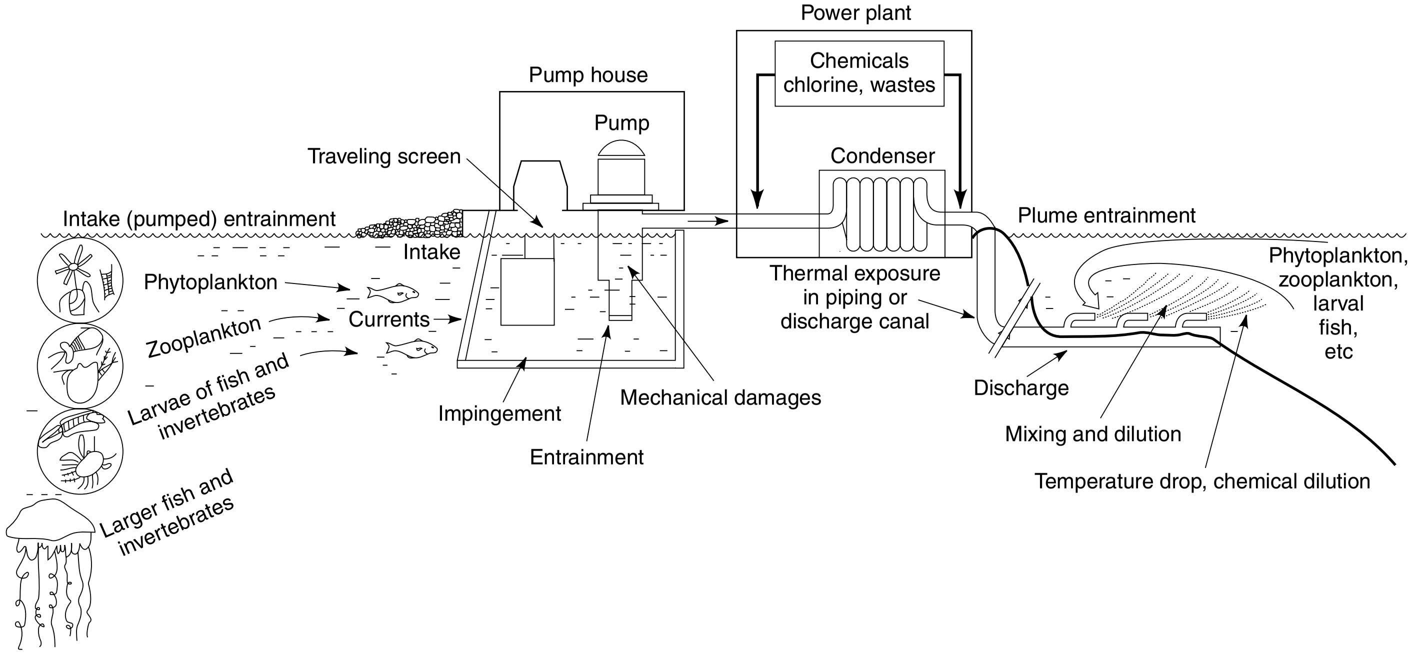
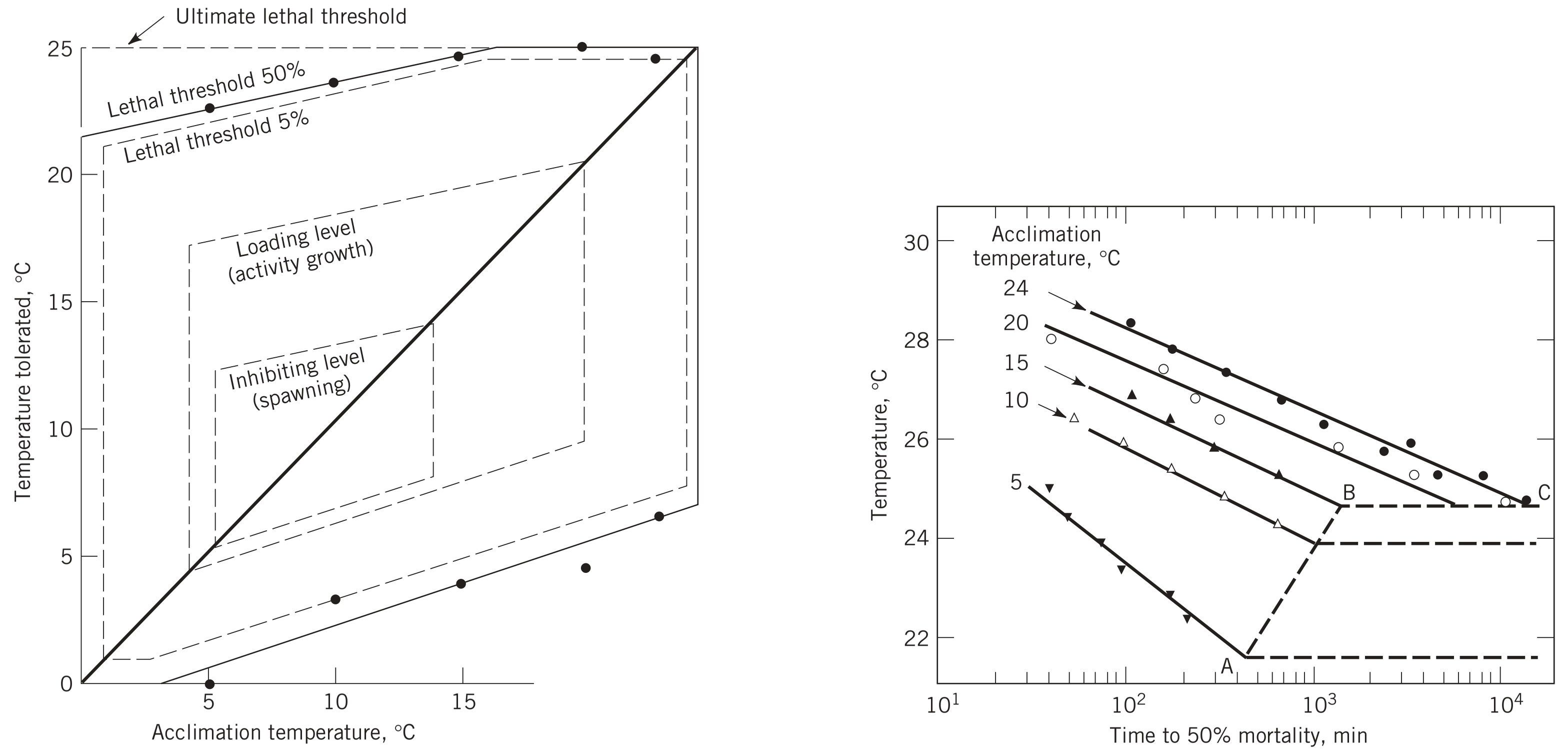
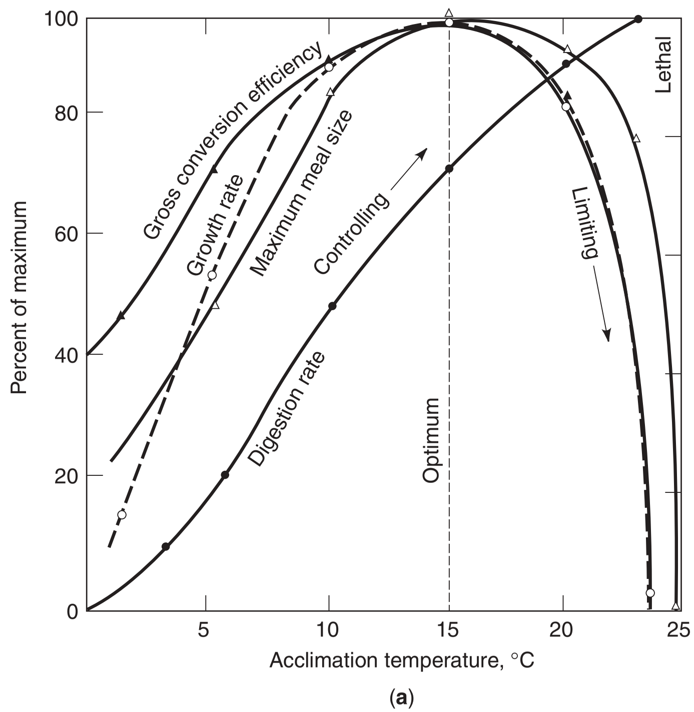


Fig. 2. Sources of potential biological damage in the immediate vicinity of a power station cooling system where the condenser cooling may result in mechanical damage or thermal shock. [Reproduced with permission from (4).]



(**a**) (**b**)

Fig. 3. Lethal temperature thresholds for aquatic species. Patterns are general for all species, but exact temperatures are species specific. (**a**) Tolerance polygon of upper and lower lethal (50%) temperatures for 1-week exposures of an example species (juvenile sockeye salmon) that has been held at the acclimation temperature, with more restrictive thresholds indicated as dashed lines; (**b**) time-dependent mortality (50%) of an example species (juvenile chinook salmon) at temperatures above the 1-week lethal threshold after holding at different acclimation temperatures. The dashed line ABC indicates transition to $< 50\%$ mortality at lower temperatures and coincides with the upper lethal threshold of this species' tolerance polygon. [Reproduced by permission from (15).]



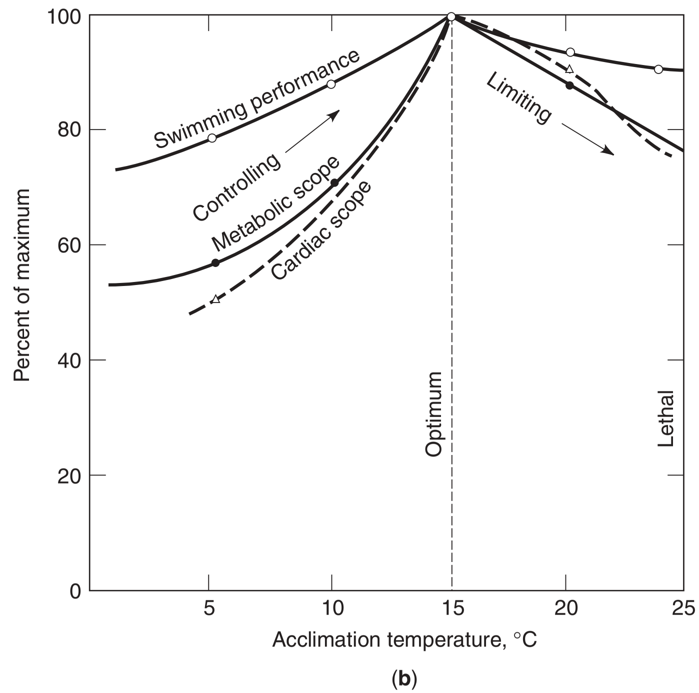


Fig. 4. Convergence of numerous physiological functions, (**a**) and (**b**), including overall growth rate, at an optimum acclimation temperature that is specific for the species (juvenile sockeye salmon). [Reproduced by permission from (15).]

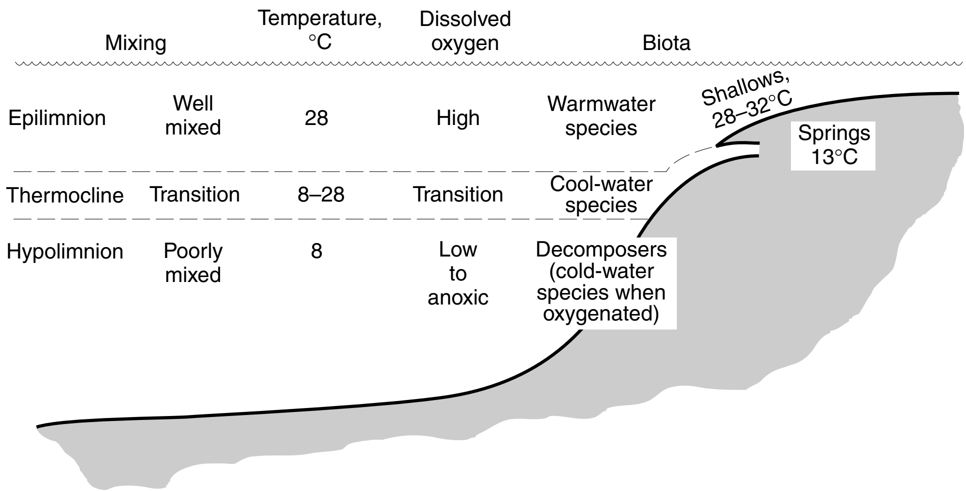


Fig. 5. Typical thermal stratification of a lake, reservoir, or poorly mixed estuary in summer which, because of density differences, establishes discrete zones with differing thermal, water quality, and biotic characteristics.

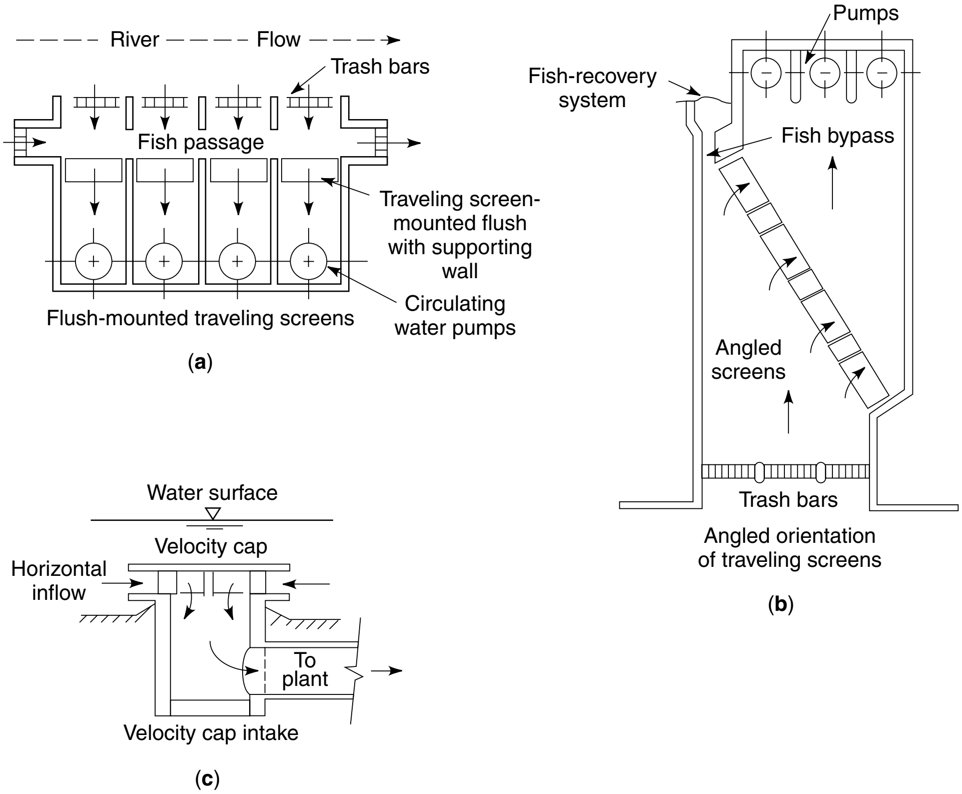


Fig. 6. Approaches to minimizing entrapment and impingement of fish and large aquatic invertebrates, eg, blue crabs, on trash screens at intakes. (**a**) An inlet pump house with vertical traveling screens mounted flush with a river shoreline to minimize obstructions to animal movements; (**b**) parallel flow to direct fish to a recovery chamber that returns to the water body; (**c**) a velocity cap atop a vertical, offshore inlet; induces a horizontal flow that fish avoid instead of a vertical flow that they do not. [Reproduced by permission from (30).]

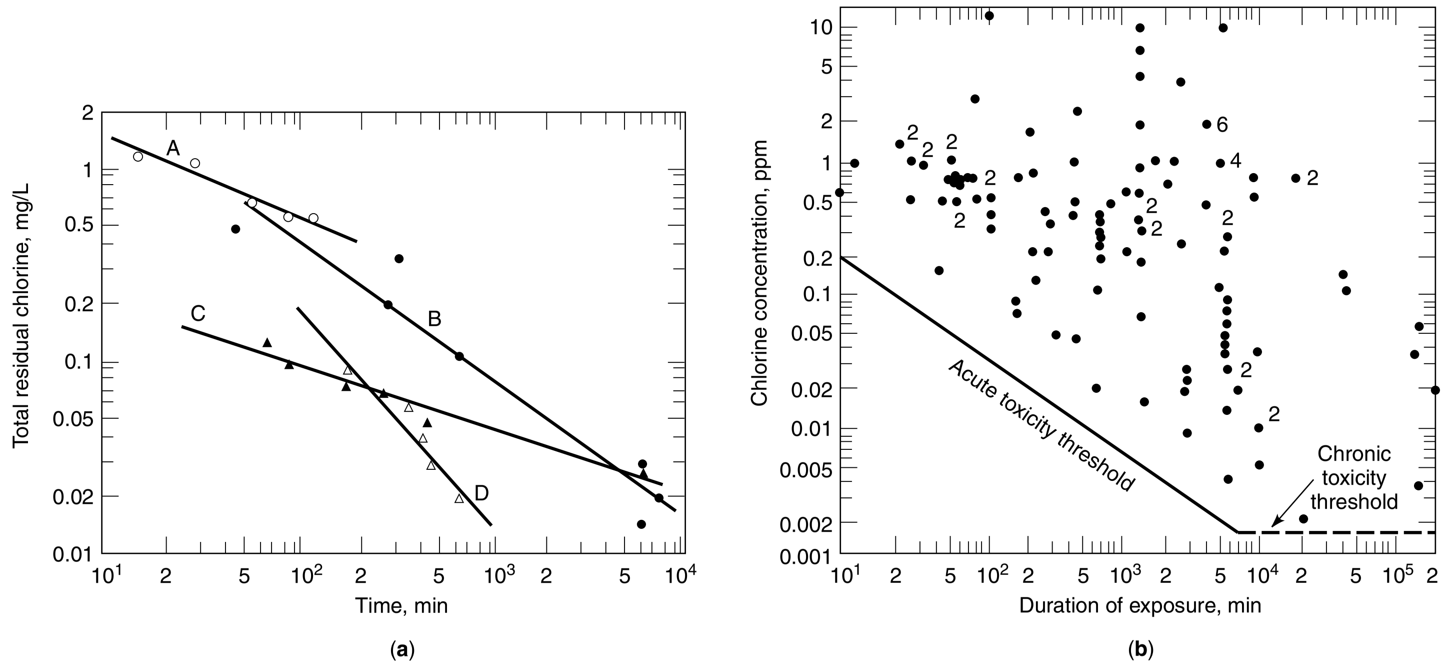


Fig. 7. Toxicity of chlorine to aquatic organisms. (**a**) Time-dependent mortality (50%) of four example species in various levels of total residual chlorine in the laboratory, where for A, *Alosa aestivalis*, and B, *Oncorhynchus mykiss, r* (correlation coefficient of the curve) = −0.96; and for C, *Pleuronectes platessa*, and D, *Salmo trutta*, $r = -0.98$. (**b**) A summary of chlorine toxicity to freshwater species, indicating overall no-effect thresholds for acute and chronic exposures. Numbers indicate where more than one test yielded the same result. A different summary figure applies to marine organisms because of differences in the chemistry of chlorine in seawater. Reproduced by permission from (33).]

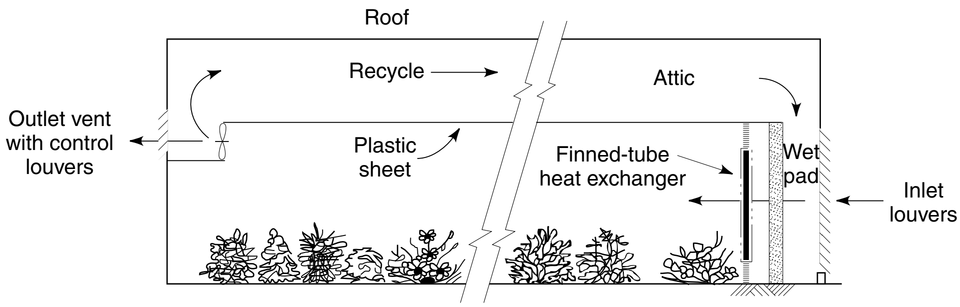


Fig. 8. Longitudinal section of an experimental waste-heat greenhouse in which temperature control in all seasons is provided by evaporation and heat transfer as air passes through a fiber pad soaked with power station cooling water or by heat transfer as air passes through a finned-tube heat exchanger that carries cooling water. A false ceiling provides for recycle of air through the heat-transfer medium. [Reproduced by permission from (41).]