Predicting effects of power plant once-through cooling on aquatic systems

A contribution to the International Hydrological Programme

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A contribution to the International Hydrological Programme

Predicting effects of power plant once-through cooling on aquatic systems

A state-of-the-art report of IHP Working Group 6.2 on the effects of thermal discharges

Chief editors: W. Majewski and D. C. Miller

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Preface

The "Technical Papers in Hydrology" series, like the related collection of "Studies and Reports in Hydrology", was started in 1965 when the International Hydrological Decade was launched by the General Conference of Unesco at its thirteenth session. The aim of this undertaking was to promote hydrological science through the development of international co-operation and the training of specialists and technicians.

Population growth and industrial and agricultural development are leading to constantly increasing demands for water, hence all countries are endeavouring to improve the evaluations of their water resources and to make more rational use of them. The IHD was instrumental in promoting this general effort. When the Decade ended in 1974, IHD National Committees had been formed in 107 of Unesco's 135 Member States to carry out national activities and participate in regional and international activities within the IHD programme.

Unesco was conscious of the need to continue the efforts initiated during the International Hydrological Decade and, following the recommendations of Member States, the Organization decided at its seventeenth session to launch a new long-term intergovernmental programme, the International Hydrological Programme (IHP), to follow the decade. The basic objectives of the IHP were defined as follows: (a) to provide a scientific framework for the general development of hydrological activities; (b) to improve the study of the hydrological cycle and the scientific methodology for the assessment of water resources throughout the world, thus contributing to their rational use; (c) to evaluate the influence of man's activities on the water cycle, considered in relation to environmental conditions as a whole; (d) to promote education and training in hydrology; (e) to assist Member States in the organization and development of their national hydrological activities.

The International Hydrological Programme became operational on 1 January 1976 and is to be executed through successive phases of six years' duration. IHP activities are co-ordinated at the international level by an intergovernmental council composed of thirty Member States. The members are periodically elected by the General Conference and their representatives are chosen by national committees.

The "Technical Papers in Hydrology" series is intended to provide a means for the exchange of information on hydrological techniques and for the co-ordination of research and data collection. In order to co-ordinate scientific projects, however, it is essential that data acquisition, transmission and processing be conceived in such a way as to permit the comparison of results. In particular, the exchange of information on data collected throughout the world requires standard instruments, techniques, units of measurement and terminology.

It is believed that the guides on data collection and compilation in various specific areas of hydrology which have been published in the "Technical Papers in Hydrology" series have already helped hydrologists to standardize their records of observations and thus have facilitated the study of hydrology on a world-wide basis.

Much still remains to be done in this field, however, even as regards the simple measurement of basic elements such as precipitation, snow cover, soil humidity, run-off, sediment transport and ground-water phenomena.

Unesco therefore intends to continue the publication of "Technical Papers in Hydrology" as an indispensable means of bringing together and making known the experience accumulated by hydrologists throughout the world.
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Foreword

The hydrological aspects of water pollution were identified as priority study topics by the Intergovernmental Council of the International Hydrological Programme (IHP) at its first session in 1975. The Council agreed that studies should be made of the consequences of increased use of natural water bodies for industrial processes or waste discharge, including the manner that waste products are dispersed, accumulated or destroyed in different receiving environments. The Council thus established a project entitled "Hydrological and Ecological Aspects of Water Pollution". These studies are intended to contribute scientific information for pollution abatement measures and environmental protection. The project is being carried out in close cooperation with relevant UN agencies, especially the Unesco "Man and Biosphere" Programme: "The Ecological Effect of Human Activities on the Value and Resources of Lakes, Marshes, and Rivers, Deltas, Estuaries and Coastal Zones".

The IHP project, "Ecological and Hydrological Aspects of Water Pollution," is comprised of three sub-projects. The present report is the product of one of these, "Investigations of the Effects of Thermal Discharges". The study draws on the experience of industrialized countries to examine the environmental problems associated with cooling water use by electric generating plants. This sub-project has focused primarily on the tools available for forecasting (prima facie) and monitoring (post facto) the consequences of power plant cooling water use in the various aquatic environments, as well as reviewing some of the hydrological, atmospheric and ecological effects observed to date at operating power plants.

The IHP working group on the effects of thermal discharges was comprised of Dr. M.L. Heitmann, Research Institute of Hydrometerology, Berlin, German Democratic Republic; Mr. J. Jacquet, Electricité de France, Paris, France; Dr. W. Majewski, Polish Academy of Sciences, Gdansk, Poland; Dr. D.C. Miller, U.S. Environmental Protection Agency, Narragansett, R.I., U.S.A. Also, Dr. C.C. Coutant, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A., participated as a representative of Unesco/MAB. Mr. J.A. da Costa, Unesco, served as Technical Secretary of the Group through December, 1977, followed by Mr. W.H. Gilbrich, Unesco. Dr. Majewski chaired the Working Group.

The first meeting of the Working Group was held in Paris in March 1976. Papers on potential environmental problems and physical aspects of cooling water use were presented by C.C. Coutant and Mr. J.F. Janin (WMO, France). The Working Group agreed to review information on environmental impact assessment for hydrologists, ecologists and engineers concerned with power plant cooling system problems. To this end, the manual discusses physical processes at intakes and discharges and identifies the potential for direct biological damage for the entire cooling circuit. The manual should also serve as a source book, as primary methods are cited for predicting and monitoring physical and ecological changes potentially occurring with cooling water use. The primary aim of this report is to enable those charged with the preparation of environmental impact assessments to develop an ecologically sound study to evaluate power plant siting and cooling system design options.

The scope, format and general topics to be included in the manual were worked out during the first meeting of the Working Group. Chapter assignments were also agreed on. Meetings were subsequently held in April 1977 in Paris and in January 1978 in Oak Ridge to jointly review chapter drafts. The co-editors, Drs. Majewski and Miller, met in Paris in August 1978 for the final review. The chapters of the manual were contributed as follows: Chapter I, Majewski, Miller and Coutant; Chapter II, Miller and Coutant; Chapter III, Coutant; Chapter IV, Majewski; Chapter V, Heitmann; Chapter VI, Majewski; Chapter VII and VIII, Miller and Coutant; Chapter IX Coutant; Chapter X, Majewski and Miller.
I. Introduction

I.1 The Need, Objective and Scope of the Manual

Currently, many countries of the world are planning construction of new electricity generating facilities to accommodate population growth and increased industrial and domestic demand for electric energy. There is now a general tendency to shift from fossil-fuel to nuclear power plants because of possible future shortage of conventional fuels (oil, coal). These new power plants are usually large, comprised of one to four units, each reaching up to 1000 MW(e) in capacity. Increases in the size of production units and the concentration of several large units on a single site results from decreasing capital costs and increasing efficiency of large units in comparison with small ones. Present nuclear power plants have smaller overall efficiencies (30–33 per cent) than fossil-fuel (40–42 per cent). This results in a greater cooling water requirement by nuclear power plants.

Included with engineering and economic considerations of these large power plants is a concern to minimize deleterious environmental effects of their construction and operation. One important environmental problem pertains to the power plant cooling system which requires vast quantities of water and rejects waste heat created in process of converting thermal energy to mechanical and finally to electrical. Of many cooling water systems (dry and wet cooling towers, cooling ponds, and once-through systems), the best efficiencies and the lowest capital and operational costs of cooling systems are achieved with once-through cooling with the power plant sited on large natural water bodies. As these power plants withdraw and pump cooling water through the condensers, there is the potential for the entrainment of large numbers of larval fish and invertebrates. There may also be the problem of entrapment of larger fish and other organisms at water intake structures. The potential for environmental damage due to thermal addition at the discharge is dependant on the capacity of the receiving water body to dilute and eventually dissipate waste heat to the atmosphere.

It is the purpose of this manual to introduce some basic procedures to predict ecological impact of once-through cooling for proposed electricity generating plants on aquatic environments. The manual is intended to serve as a source book for the working ecologist and engineer responsible for designing, implementing or evaluating results of cooling system impact assessment studies. Potential environmental problems, impact assessment approaches, and physical and biological information needs are discussed in a general manner. Publications which provide more detailed information are cited. A chapter on beneficial uses of thermal discharges is included to encourage consideration of heat use options as an integral aspect of power plant planning.

This manual focuses primarily on once-through cooling systems. Assuming adequate water availability, this represents the first cooling option due to its low initial cost and potentially higher efficiency. Some environmental problems and limitations of closed-cycle cooling systems are included but not addressed in detail for impact assessment.

I.2 Place of Environmental Impact Assessment in Planning New Electrical Generating Plants

The potential for adverse environmental impact of power plant cooling systems can be minimized by early involvement of specialists in ecology, hydraulics, hydrology, meteorology and related fields in site selection considerations and proposed cooling system design. Studies of natural resources and ecological systems should be looked to as important input to these
decisions, and not undertaken post facto to justify choice of power plant site or cooling system designs. Environmentally unsuitable locations for a power plant can be identified early in the planning cycle; detailed studies will identify site-specific problems which can possibly be mitigated by careful engineering of the cooling systems. Many environmental problems encountered at power plants today are the direct consequence of poor siting or cooling system designs which failed to consider the biological aspects of interfacing with the natural water body. Closed-cycle cooling systems have been looked to as one recourse to reduce impact of power plants on aquatic systems. While this may be practical in some situations, closed-cycle cooling is not without its own set of environmental problems which potentially impact not only aquatic, but also atmospheric and terrestrial environments as well.

In some countries, laws require that major projects be reviewed for their environmental compatibility before construction. Such a law is the National Environmental Policy Act (NEPA) in the USA; other countries are developing similar requirements. In the USA, NEPA mandates use of a systematic, interdisciplinary planning process involving both the natural and social sciences for all major projects under the jurisdiction of Federal agencies. The preparation of environmental impact statements to evaluate the potential for significant environmental effects is one element of this process. A thorough evaluation of project alternatives is also required. Under NEPA, the environmental impact statement is not intended to be a document to support or deny predetermined objectives or decisions. Rather, it is to permit administrative planners to include environmental considerations in their decision making.

I.3 Predictive Environmental Impact Assessment

The task of predicting the potential impact of an engineering project on the environment is a difficult one. In the case of power plants, for example, we cannot predict with precision the specific stresses that a given cooling system design will impose on the biota of waterway. And we have a very limited understanding of the extent that populations of whole ecosystems can compensate for environmental change or direct loss of organisms. The difficulty of impact prediction is also compounded since assessments usually must be completed within a short time period. Rarely are more than a few years available in a planning programme before the major decisions must be made on an activity. As a consequence, it is usually not possible to undertake all the ecological studies which one might like. Also, it will not be possible to adequately measure natural ecosystem variations over time. As a consequence, it may not be possible to determine with certainty whether the data of short-term field studies are indeed typical for a given site, or to predict the extent of natural variation which may occur there over a period of years. These limitations recognized, an impact assessment team can nonetheless make a useful appraisal of potential environmental problems by drawing on existing ecological principles, on the first hand knowledge of experienced field biologists and on existing information of impacts which have occurred at similar facilities in the past.

The field of environmental assessment is a young one, with the preferable study approaches and methods still being developed. In addition to looking to ecological and planning concepts to improve impact assessment techniques, we can also draw some lessons from the problems and deficiencies of past studies. Many early environmental impact projects suffered from both inadequate procedural guidelines and poor scientific design (Andrews et al., 1977). Official guidelines have frequently been too broad and general to provide focus, define scope or clearly indicate the environmental components and relationships which should be considered in an assessment study. Clarification of such questions is important to the design and conduct of good assessment work.

The scientific design of ecological assessment projects can be improved by giving careful attention to deficiencies identified in early impact studies (Andrews et al., 1977). These include:
- absence of a clear statement of the objective of the evaluation;
- failure to ask specific ecological questions or to frame hypotheses and conduct studies to test them;
- species lists only tabulate the potential biota or the rare and endangered species;
- community descriptions primarily qualitative, with little quantitative data on biomass, spatial heterogeneity or temporal variability;
- little or no real consideration of community functional aspects, impact vulnerability and assimilative capacities, or linkages within and between the various ecolo-
gical compartments, including man;
- reliance on a single index (e.g. a species diversity index or a productivity measurement) to describe the health or condition of a community. (Multiple community indices should be used.)

Three approaches to ecological impact assessment can be distinguished at present. There are the studies which are primarily descriptive, with impact prediction highly subjective; those which also involve detailed quantitative and experimental assessment for a limited number of important ecosystem components, usually populations; and holistic studies, which focus on the function of the ecosystem as a whole.

One common descriptive approach involves listing all potentially relevant aspects of the environment, then subjectively evaluating the likelihood of impact by the proposed activity for each environmental component. The conclusions are often summarized in tabular form (e.g. a Leopold matrix), with the degree of importance of the ecological parameter and the likelihood of impact rated on a scale of 1 to 10 (Fisher and Davies, 1973). Other methods of ranking and weighting potential impacts are discussed by Bisset (1978).

The second type of study also employs an initial descriptive phase to ascertain the nature and makeup of the ecological system in the locality of the proposed project, but then selects important species and/or community components for detailed investigations. This would include experimental studies to measure vulnerability to the proposed activity. This is the approach pursued in this manual. Selection of the principal study species and species assemblages is typically based on their perceived importance to the ecological system or their economic or aesthetic value to man. Potential susceptibility to impact is also considered in the selection. If the studies indicate a high potential for appreciable loss of an important biotic component, a population model may also be developed to evaluate the long term consequences of this impact.

The holistic, or ecosystem approach seeks to assess impact potential by studying properties and requirements of the total system. As the major functional components of the system and their interdependence are identified through energy and materials flow studies and perturbation experiments, it may be possible to discern the consequences of an environmental change or of direct loss of biota resulting from an engineering project (Andrews et al., 1977).

Today, elements of each of the above three approaches are being incorporated into the design of predictive impact assessment projects. The studies usually have a preliminary descriptive phase to ascertain the types of communities and dominant populations present. With this information, the scope of the project is defined, based on the subjective judgment by biologists and engineers of the maximum plausible impact of an activity. If several populations are selected for intensive study, they are chosen in part because of their interrelationships with the larger ecosystem. Few predictive assessment studies have been purely holistic, at least for aquatic systems, although this has been long proposed by professional ecologists (Odum, 1972). To date, most workers consider the information needs simply too great to develop an aquatic ecosystem model which could reliably predict the consequences of an engineering project. Nonetheless, many holistic concepts and certain ecosystem study techniques have been shown to be valuable in developing impact assessment projects (Gilliland and Risser, 1977). And the holistic approach can be quite profitably employed in monitoring for ecological change at operating power plants (McKellar, 1977).

I.4 Steam Electric Plant Cooling Water Requirements

The production of electric energy in fossil-fuel or nuclear power plants requires the conversion of thermal energy into mechanical energy and finally into electric energy. All energy conversion processes operate at efficiencies less than 100%. The efficiency of steam electric power production is governed by thermodynamics of the heat cycle. The ideal or Carnot efficiency is determined by the temperature of the heat source (boiler or nuclear reactor) and the heat sink, which is the surrounding air or water. The ideal efficiency is given by:

\[ E = \frac{\text{usable energy produced}}{\text{energy consumed}} = \left( 1 - \frac{T_{\text{sink}}}{T_{\text{source}}} \right) \times 100 \]

where sink and source temperatures are measured on an absolute scale. Thus, by decreasing sink temperature or increasing source temperature increased efficiency may be achieved. There are,
Figure I.1  General scheme of the electricity generating station

Figure I.2  Cooling water requirements for fossil and nuclear power plants

\[ \eta_t = 33\% \quad \text{fossil} \]

\[ \eta_t = 40\% \quad \text{nuclear} \]

In-plant losses = 5%  
In-plant and stack losses = 15%

\[ \Delta T = \text{condenser temperature rise} \]

\[ \eta_t = \text{plant thermal efficiency} \]
however, limitations which restrict source temperature to certain values because of technological or protective requirements. Further, sink temperature is dependent on natural meteorological and hydrological conditions. In all mechanical and thermodynamic processes, the working or overall efficiency is much less than the ideal efficiency because of certain additional inplant and stack losses. At present, the overall efficiency for modern thermal plants is about 40-42 per cent and for nuclear power plants it ranges from 30-33 per cent. Thus, in a nuclear power plant, for every kilowat-hour (kWh) of produced electric energy, the equivalent of 2 kWh of energy is rejected to surrounding water or atmosphere. For the remainder of this century, it is expected that electric energy will continue to be produced by liquid-vapour cycles using fossil or fission fuels and the power plants overall efficiency will remain in the 30-40 per cent range. Further, it is necessary to expect that because of economical reasons the power plants will grow in size and lead to greater concentration of cooling water consumption and thermal discharges in one place.

A general scheme of a thermal power plant is shown in Fig. 1.1. Cooling water withdrawn at the intake from the water body is pumped through the condenser. Waste heat derived from low pressure steam leaving the turbine is transferred to the cooling water in condenser tubes. Here the cooling water increases its temperature by the value $\Delta T$ and returns to the original water body through the outlet. The rate of heat transfer from the power plant to the cooling water is given by

$$ H = Q \times \rho \times c_p \times \Delta T $$

where:

- $H$ - rate of waste heat transfer J s$^{-1}$ or kcal s$^{-1}$
- $Q$ - cooling water discharge m$^3$ s$^{-1}$
- $\rho$ - water density kg m$^{-3}$
- $c_p$ - specific heat capacity of J kg$^{-1}$ K$^{-1}$ or kcal kg$^{-1}$ K$^{-1}$
- $\Delta T$ - temperature rise across condensers °C

Condenser designs normally produce a temperature rise of cooling water in the range 6°-16°C. When the temperature rise (i.e. the $\Delta T$) is low, cooling water use is high. Typical cooling water requirements for fossil and nuclear power plants, based on current technology are presented in Fig. 1.2 (US Environmental Protection Agency, 1973).

### I.5 Plant Siting and Cooling System Design Options to Meet Cooling Requirements

Siting decisions for power plants are generally made primarily for reasons of load demand, availability of electricity transmission corridors and fuel transport (coal and oil). Water availability for cooling is also one of the important considerations; in arid lands it may be the most important. Choice sites for power plants, have included large rivers, natural lakes, existing reservoirs, estuaries and coastal waters.

Where a large natural water body is not available, artificial, cooling reservoirs can be built, provided sufficient amount of water and land is available. These reservoirs may range in size from small cooling ponds to large artificial lakes. All of these sites can use the once-through system, although the smaller cooling ponds, are, in fact, closed-cycles. The distinction between cooling reservoirs and cooling ponds is not very precise. Cooling ponds usually have high thermal load, small surface area and volume.

It is possible for waste heat to be transferred more directly to the atmosphere by using closed-cycle cooling, like cooling ponds, cooling canals, spray canals or cooling towers (natural draft and mechanical draft.) In these systems, evaporation is a predominant process of heat transfer. These evaporative systems require water to make up for evaporation loss, and to remove accumulated salts (blow-down). Such consumptive water use can be considerable in closed-cycle cooling. Direct transfer of waste heat from the coolant to air can be accomplished using dry cooling towers, where consumptive water use is negligible. Although very expensive to operate, dry cooling towers are used in arid areas.

Once-through cooling systems (including cooling reservoirs) have certain advantages over closed-cycle cooling. These advantages may be summarized in the following points: lower capital costs; lower consumptive use of water; lower consumption of energy for pumping of cooling water; dissipation of waste heat to the atmosphere over large area; greater thermal inertia.

Disadvantages of once-through cooling are related to the possible damage to aquatic life as large volumes of water are pumped through the power plant and by subsequent discharge of heat.
Precise economical comparisons between various cooling systems are rather difficult because each power plant site is different. Closed-cycle cooling usually involves higher capital costs, whether for construction cooling towers or to acquire land for cooling ponds. Consumptive water use in closed-cycle cooling is usually less than 10 per cent of that used in once-through cooling systems. Yet this quantity of water can still be considerable and in some cases special reservoirs may be necessary to provide the required cooling water. In closed-cycle cooling systems, additional consumption of electric energy is usually incurred. In wet cooling towers, cooling water must be pumped to the top of the tower. Forced draft cooling towers require extra energy consumption for fan operation.

Harleman (1976) presents data of overall efficiency reduction for a simulated performance of a 1000 MW(e) nuclear steam electric plant located in the temperate zone using different cooling systems. The power plant has the overall efficiency 33 per cent. Table I.1, illustrates the reduction of electric power output due to increased intake water temperature if closed-cycle cooling is employed. Once-through system is taken as the basis for comparison.

Large water bodies are well suited for once-through cooling systems. They have great thermal inertia which means that they do not react rapidly to changing meteorological conditions or varying rates of waste heat discharge from power plants due to load changes. Changes in intake water temperature for once-through systems on large water bodies are of the order of several days while in closed-cycle cooling systems, changes can occur within few hours. Rapid increase in intake water temperature results in lower overall efficiency of the power plant.

For ecological reasons, power plant sites are preferable that have low biological value — that is, they are not located on important migratory routes, spawning or nursery areas, unique habitats, etc. Careful cooling system design can minimize specific ecological problems (e.g. by considering type and length of intake or discharge conduits, configuration of discharge ports, orientation and location of intake structures and screens). Knowledge of important physical and biological processes occurring at potential sites can provide the necessary information for selecting the most appropriate designs.

One important design decision is the relationship between \( \Delta T \) and volume of cooling water (Fig. 1.2). The amount of heat to be dissipated remains constant but, within certain limits, \( \Delta T \) and water volume can be varied. The more water pumped, the lower the \( \Delta T \) will be. A large \( \Delta T \) often results in greater thermal impacts while large volumes of cooling water can cause large losses of entrained organisms through physical damages at intakes and during passage through

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**Figure 1.3** Heat exchange
the cooling system. The type of biota to be protected will determine which alternative is selected. For example, if there is a major plankton component, yet physical entrapment damages cannot be controlled, present thinking suggests that the highest ΔT that is feasible for engineering reasons is the most desirable.

**TABLE 1.1**

REDUCTION OF ELECTRIC POWER OUTPUT FOR DIFFERENT COOLING SYSTEMS

<table>
<thead>
<tr>
<th>Cooling system</th>
<th>Yearly average reduction per cent</th>
<th>Maximum summer daily reduction (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Once-through</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cooling pond</td>
<td>2.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Wet cooling tower</td>
<td>3.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Dry cooling tower</td>
<td>4.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**REFERENCES CITED**


II. Potential and observed ecological effects of once-through cooling systems

SUMMARY

This chapter surveys the sources of potential ecological damage for power plant cooling systems, with emphasis on once-through cooling. Heated discharges are only one of several sources of potential adverse ecological changes, others being physical damages of entrapment and impingement at intakes, physical, chemical as well as thermal stresses of entrainment through the cooling circuit, discharge chlorination toxicity, and hydrological and habitat changes with the construction of new intake and discharge structures. Observed evidence for these changes are detailed to illustrate that many of the impacts can be real, and not merely hypothesized.

II.1 Sources of Potential Ecological Changes

The heated discharge of a power station is only one of several sources of potential ecological change from the cooling system operations. In addition, researchers also now recognize the potential for ecological effects associated with power plant intakes and processes associated with passage of water through the power plant. Large fish and invertebrates are often impinged and killed on intake screens which are designed to keep debris out of the condenser tubes; small organisms, particularly larval stages of fish, can be mutilated or thermally killed during their transit (entrapment) through pumps, heat exchange condensers and piping. Whether screened out or entrained with the cooling water, organisms entrained in the water at the intake may fare worse than organisms which only encounter the discharge plume.

The shift in attention to include intake entrainment problems as well as discharge stresses occurred with utility industry development of estuarine sites for steam electric stations. Small, freshwater rivers generally have only limited amounts of planktonic organisms that would be susceptible to entrainment. Estuaries, however, are important spawning grounds and nursery areas for large numbers of aquatic species. Here, recirculating hydraulic patterns of fresh and salt water have encouraged evolution of drifting larvae. These drifting larvae generally do not distinguish between the patterns of water flow that provide recirculation and nourishment for them within the estuary and those that draw them into power station intakes. As power stations grow both in size of individual units and in numbers of units on a given estuary, and cooling water use increases, the probability increases that a larval fish will be entrained in a power station cooling system before it leaves the estuary (see for example, US Nuclear Regulatory Commission, 1975).

The principal engineering alternative to the traditional "once-through" cooling system is the cooling tower. Yet we now recognize that this alternative has its own potential to adversely influence the environment, with impact on the terrestrial as well as the aquatic system. These impacts are briefly addressed in this chapter to indicate some of the potential environmental problems of this alternative.

The sources of potential ecological change from once-through (open cycle) power station cooling systems are currently recognized to include the following (Fig. 11.1).

1. Change in the physical (structural) features of the intake and discharge areas by dredging, filling, change of substrate (such as placing rock jetties on sand and gravel beaches), or construction of inlet and outlet works (such as intake pumphouses
2. Changed current patterns near the intake and discharge which may extend to areas far removed from the power station and result in altered patterns of such factors as estuarine salinity, lake thermal (and biochemical) stratification or movement of nutrient and plankton concentrations;

3. Entrapment and impingement of larger organisms, principally fish, on intake screens;

4. Entrainment of phytoplankton, zooplankton, and larvae and juveniles of fish and invertebrates with the pumped cooling water during which these organisms are exposed to:
   (a) physical damage from mechanical contacts with pumps and piping, and physical effects of pressure changes and shear;
   (b) temperature shock in the condenser tubes followed by a period of exposure to that elevated temperature until the discharge reaches cooler receiving waters;
   (c) chemical exposures, principally to chlorine which is added periodically to the circulating water as a biocide to prevent accumulations of fouling materials on heat exchange surfaces and other parts of the piping system, but also including in some plants such varied materials as laundry wastes or radionuclides;

5. Plume entrainment of organisms in the discharge area through dilution of the effluent where organisms receive thermal and chemical exposures which vary according to their location in the mixing zone (physical damages may also result if pumps are used to augment effluent mixing);

6. Temperature elevation for resident and thermally attracted organisms, which is greatest in the vicinity of the discharge and is less at more remote locations, and may influence to some degree the whole of small water bodies;

7. Unnatural temperature changes, often rapid, which may occur in the vicinity of the discharge due to plant operations (e.g., sudden shutdown or start-ups) or due to environmental changes which affect rates of mixing and dispersion of the effluent;

8. Chemical (biocides and condenser metals) exposure for plume biota;

9. Changes in dissolved gas concentrations in the intake and effluent areas due to increased biochemical oxygen demand of warmed waters, to pumping of oxygen-poor hypolimnetic waters, or to gas supersaturation of discharge waters in winter;

10. Increase in nutrients in the effluent area due to kill of plant-entrained plankton;

11. Combinations of the above, which may cause effects greater than the sum of individual effects (synergism).

Cooling towers have several sources of potential ecological change, some of which are unique while some are similar to, but of lesser magnitude, than those for once-through systems. They include:

1. Impingement and entrainment of aquatic organisms at the intake where makeup water is added to the cooling loop to compensate for evaporation and dilution ("blow-down") flows;

2. Chemicals released to water bodies as the "blow-down" or dilution flow released from the "closed-cycle" loop to prevent build-up of dissolved solids, which contains materials added to the cooling loop to prevent corrosion (e.g., chromates, zinc, organophosphorous complexes) or to eliminate biological fouling (e.g., chlorine);

3. Chemical "drift" in the form of small droplets and aerosols which emerge to the terrestrial environment from the top of the tower and contain, in addition to water, chemicals used in the circulatory water system;

4. Temperature elevations or other changes due to heat in the "blow-down" releases;

5. Meteorological effects, including fogging, which affect the terrestrial environment, including man;

6. Combinations of the above (synergism).

II.2 Potential for Adverse Physical/Chemical Changes

Pollution has often been defined as a change in water or air quality that adversely affects other uses. Power plant cooling can change the physical and chemical characteristics of water and air so that other direct uses are impaired. Accelerating trends in many countries toward closed-cycle cooling, especially cooling towers, has encouraged broadened consideration of impacts on air as well as water.
II.2.1 Physical effects on water

Temperature changes are known to affect every physical property of concern in water quality management, including water density, state, viscosity, vapour pressure, surface tension, gas solubility, and diffusion (Appendix IV). Some of these changes are of importance in their subsequent effects on aquatic life. For example, temperature-induced gas solubility changes affect dissolved gas content and can create supersaturated gas conditions that cause gas bubble disease in aquatic organisms (Rolke et al., 1975). (This phenomenon is discussed further in Section II.3e.4 on biological effects.)

Vapour pressure changes can influence rates of evaporation and thus water consumption. In many regions the quantity of water which is transferred through evaporation by various types of cooling systems is becoming a major factor in the siting and design of large steam-electric power generating facilities. The amounts of water evaporated depend on the specific environmental and plant condition involved. For example, for open water surfaces such as lakes, ponds, rivers, reservoirs and estuaries, about half of the heat is dissipated by evaporation, whereas with wet cooling towers over 75% of the heat is transferred by evaporation during the summer. The magnitude of the potential water consumption problem for large power plant facilities can be considerable. Approximately 2000 m$^3$/h of water are transferred to the atmosphere through evaporation in a wet cooling tower for a 1000 MW(e) nuclear power plant (IAEA, 1974). A power station can, therefore, be in direct competition for water resources with other uses such as agricultural irrigation and drinking water supplies.

Increased temperature and the resulting decreased viscosity may also result in increased sedimentation in water bodies. This could lead to potential sludge problems, changed sediment carrying capacity of rivers or changes in riverbed.

Temperature-induced density stratification of lakes is a principal regulator of chemical water quality in deep hypolimnetic waters. Changes in thermal structure by power stations can alter the normal annual cyclic pattern. Municipal or industrial water works could be affected by such changes. Problems of a similar nature can arise in stratified estuaries where the ecosystem depends upon the complex stratification and mixing patterns of saline and freshwater.

Temperature increases in winter can reduce ice-cover. This may prolong navigation in rivers and affect biota, such as attracting overwintering waterfowl. Dingman et al., (1968) estimated that a 600 M(e) nuclear power station could keep 18-25 km of the St. Lawrence River (Canada) ice free.

II.2.2 Chemical effects on water

Power stations can influence the chemistry of natural waters by changing reaction rates through temperature changes and by direct addition of chemicals to the cooling water. Altered chemical reaction rates affect the assimilation of other wastes in water bodies, the efficacy of water treatment systems, corrosion of materials, and biological processes.

Certain chemicals are added in the operation of power plant cooling systems for protection against corrosion, scale and biogenic slime build-up on heat transfer surfaces, and biofouling of the cooling water piping or other surfaces. Chlorination of once-through cooling water is the accepted practice at most power stations, either as periodic slugs or as continuous, low-level additions. The discharge of chemical-laden "blow-down" water from cooling tower systems, used to avoid excessive concentrations of dissolved solids within the cooling system, is an essential part of plant operation. The use of oxidizing biocides such as chlorine is also periodically required in a recirculating cooling system to minimize the growth of algae.

Chlorination has recently been questioned because recent studies show formation of chlorinated organics in both polluted and natural waters (Jolley, 1975). These chlorinated organic materials can remain toxic for aquatic life for long periods, as well as being of concern to municipal water users (Gehrs et al., 1974). Chlorinated organic compounds have recently been identified from several municipal water supplies in the USA (Morris and McKay, 1975). These are believed to derive from chlorinated waste effluents.

II.2.3 Atmospheric effects

Large cooling towers, either mechanical or natural draft, and large arrays of cooling ponds represent much more rapid means of releasing heat and moisture to the atmosphere than the discharge through large natural water bodies. Accordingly, cooling towers and cooling ponds,
hold the greatest potential atmospheric effects. These include:

(a) ground level fog and icing;
(b) clouds and precipitation;
(c) severe weather effects;
(d) plume length and shadowing; (and)
(e) drift.


More attention has been given to fog and ice associated with plumes from evaporative cooling towers than to any other effects. Many cooling tower reports from the United States contain statements that mechanical and natural draft cooling towers have the 'potential' to cause or increase the frequency of ground level fog or icing. Theoretical analyses (e.g. McVehil, 1970; EG & G; Inc., 1971) all predict tower-induced ground level fog for various periods of time with a greater fog persistence existing in cold weather. In these theoretical studies maximum fog frequencies would result from mechanical draft cooling towers. Available physical observations near towers and extensive European observations indicate that the plumes usually do not cause surface fog (e.g. Decker, 1969; Aynsley, 1970; IAEA, 1974; Hanna and Pell, 1975). In these field observations the warm, moist plume enters the atmosphere at heights of 100 metres or more and evaporates before it reaches ground level. These observations indicate that theoretical models may be too pessimistic in their assumptions.

In the operation of cooling lakes or ponds local climatological changes are to be expected, such as changes in the intensity, frequency, and inland penetration of induced fog, including the creation of freezing fog near the water's edge. Observations at cooling ponds indicate that the fog over the pond is usually thin, wispy, and does not penetrate inland more than 100 to 300 metres. Because the water vapour is released slowly over large areas, ponds are not a major source of fog despite the release at ground level (IAEA, 1974). However, in weather situations producing natural fog over large areas, ponds would act to intensify and prolong fog conditions. Cooling pond site selection is important in order to assure that induced fogs (and freezing fogs) do not affect roads and bridges. Spray units, with which the effective evaporation area is greatly increased by spraying the heated water over the pond or through a canal, will also increase the frequency and intensity of dew, fog, frost, and icing conditions along the banks or downwind of the pond or canal.

Quantitative data on the effects of moist plumes from cooling towers on clouds and precipitation are very limited. Occasional observations of light drizzle or snow have been reported in the vicinity of towers (e.g. Culkowski, 1962; Federal Water Pollution Control Administration, 1968). Additional heat and/or moisture fed into a developing storm cloud might conceivably produce an imbalance that would result in intensification into a severe weather state. In view of the paucity of data available in this area, any effects are only conjecture at this time.

The psychological aspects of the shadowing effect of atmospheric plumes from cooling towers have been considered in nuclear power plant studies in Western Europe. Calculations performed in Switzerland for two natural draft cooling towers (Broehl, 1868) indicates that even if visible cooling tower plumes are assumed to be fully opaque, the reduction of sunlight in nearby areas would be insignificant (the average reduction was one minute per day corresponding to 0.35% of sunshine.) The shadowing effect of mechanical draft towers is smaller than from natural draft towers because the vapour plume, through the several ejection points, obtains a more rapid atmospheric dilution.

A problem in the operation of wet cooling towers involves a small portion of the total water circulated in the tower which enters the atmosphere without being evaporated. This physical water loss is due to droplets entrained in the air leaving the tower and is often referred to as 'drift'. Drift fall-out which occurs near the tower may cause problems such as highway icing in the winter and transmission line flash-over. Drift contains all the salts and impurities in the intake cooling water. When deposited in the area surrounding the plant site, the drift droplets evaporate and leave a solid or salt residue behind. This residue can cause vegetation to accumulate chemicals present in drift (Taylor et al., 1975; Hanna and Pell, 1975). Of particular concern is long-term build-up of potential toxicants such as chromium.

Published test data indicate drift loss rates of 0.005 to 0.0076% for mechanical draft towers and 0.0012 to 0.0025% for natural draft towers (Böhm et al., 1971). Additional operating test data are needed to validate the drift loss rates in this study. Tower equipment companies now guarantee drift rates to be limited between 0.002 and 0.005% of the circulating water flow. For a 100 MW(e) power plant, water loss due to drift can be less than one litre per second.
Up to the present time, wet cooling towers at power stations have been limited to non-saline make-up water. Evaporative towers are, however, now being installed in estuarine or coastal locations of power plants. The first hyperbolic natural draft cooling tower in the United States using brackish water is installed in conjunction with a 630 MW(e) oil-fired power plant at Chalk Point, Maryland (Pell, 1975). A comprehensive soil and vegetation research programme is planned for this site, in order to determine the potential effects that brackish water cooling towers may have on the surrounding vegetation. Additional field studies of this type will be required as salt or brackish water cooling towers are introduced into common power plant use in other regions.

In addition to the meteorological effects, cooling towers may impact the environment in other ways. For example, the synergistic effects of cooling tower plumes mixing with industrial stack effluents which contain oxides of sulphur and nitrogen require further study and evaluation. In some instances, acid rains may result due to the mixing of the cooling tower plumes with fossil-fueled power plant stack effluents. The environmental impact of noise and the aesthetic effects of large cooling tower arrays also deserve consideration.

II.3 Potential and Observed Biological Changes From Once-Through Cooling

It would be impossible for this section to comprehensively report the biological data and observations from laboratory and field studies that bear on cooling system damages to organisms and ecological systems. The scientific literature is simply too vast, and the particular locations and species too diverse. Emphasis has been placed on once-through cooling systems, as these biological problems are better documented. For each source of potential biological damage, knowledge of the circumstances and probability of damage, especially as indicated by operational power plants, is useful for estimating damages or their lack at a given site. This section will emphasize this type of information and indicate where additional information can be obtained. This section also provides an update of an early review on effects of thermal discharges (US Senate Committee on Public Works, 1973) plus the additional consideration of the broader, non-thermal effects of cooling water use.

II.3.1 Change due to physical alterations: Construction of intakes and discharges

Construction activities required to build intake and discharge structures may involve dredging, cutting or tunnelling. Normally, these impacts are of a temporary nature. Increased siltation, for example, may act only as a temporary stress through reducing oxygen content of a water body segment or reducing food uptake by filter feeding invertebrates. Yet heavy or continued siltation (e.g. from scouring by high velocity discharge) can lead to long term loss of benthic communities where suspension feeders dominate, such as oyster bars or coral reefs. Construction which cuts across a barrier dune system of an open beach could also result in long-term ecological alteration. If dune revegetation is not quickly accomplished, storms can breach the beach at this point, resulting in a new ocean inlet which may persist for some time. In inter-tidal areas, slumping of dredged canal banks will result if side slope design exceeds one on fifteen. In cut and fill operations across marsh lands, top soil will be required to achieve revegetation, as the pH of marsh soil drops greatly upon exposure to the atmosphere. These effects are not unique to power plant construction.

Submerged cooling system structures will be colonized by sessile organisms, to which fish and other motile organisms will be attracted to feed. These mobile forms will be exposed to potential intake impingement or entrainment, or at the discharge, possible entrainment in the effluent. Attraction of fish to submerged intake structures has been found to be greater at some off-shore locations e.g. off the California coast) than within large estuarine channels.

New patterns of water circulation, will develop around any cooling system structure which extends into a waterway. These may also serve to attract motile organisms. When intakes are indented into the original shore-line, currents develop which retain fish within intake bays; if protruding, end bay sections may experience greater impingement due to eddy currents which develop (e.g. Lake Norman in the USA, Edwards et al., 1976). Intake structures built flush with the shore-line can minimize these problems. Circulation will also be altered upon operation of the cooling system. Benthic scouring immediate to the intake and discharge is common. This can cause additional benthic loss downstream due to increased sedimentation (Merriman, 1976).
Figure II.1 Sources of potential ecological changes at a power plant cooling system

Figure II.2 Fish passage
In estuarine areas, problems can arise if cooling water use creates new circulation patterns which appreciably alter the local salinity regime. At the minimum, a shift in the indigenous community would occur, with a loss of intolerant species and the addition of others. Establishment of intake and discharge structures in small marsh creeks at the Oyster Creek (N.J.) Nuclear Plant resulted in movement of more saline bay water into the marsh system. Wood-boring marine shipworms moved into the creek, which resulted in loss of a local economic and recreational resource, as pilings, docks and boats at several marinas were destroyed (Turner, 1973). Knowledge of the salinity tolerance of potential deleterious species should make predictable.

Concern has been expressed whether jet discharges might affect free movement of animals past a power plant. While the thermal component of discharges may cause problems for some species, discharge currents per se have not been found to block movement of animals (Leggett, 1970; Maryland Power Plant Siting Programme, 1977).

### II.3.2 Changes from entrapment and impingement at intakes

Field experience at operating power station intakes has shown clearly that large numbers of fish and invertebrates can be killed on the screens (USEPA, 1976a). The underlying causes of entrapment and impingement remain little understood and predictability is therefore poor. Reasonably quantitative laboratory data on fish swim speeds have been obtained (e.g. Blaxter, 1969) with the initial assumption that physical stamina could be compared directly with water flow rates through screens to determine likelihood of impingement. This has not proved reliable. Current thinking relates susceptibility to impingement to:

1. behaviour patterns of fish, many completely unknown, in the vicinity of velocity accelerations and intake structures;
2. physical characteristics of the intake area which many or may not allow routes for easy return to open water following withdrawal to an intake channel;
3. environmental factors such as low water temperature, Griffith and Tomljanovich, (1975); Griffith, (1978) and high turbidity which influence normal behaviour such that an organism cannot (or does not) escape;
4. attractants, such as recirculating warm water (often for ice control) in winter, lights, shade, or presence of food organisms.

It seems that some species, particularly in the family Clupeidae, are especially susceptible to impingement.

Reports of chronic intake impingement problems experienced at operating plants can be useful to evaluating site-specific aspects contributing to the problems as well as to identify susceptible species and environmental correlates with impingement. In the USA, this information is available for nuclear plants in reports made to the Nuclear Regulatory Commission and Environmental Protection Agency. (see, for example, the Millstone Nuclear Power Station, 316b report, (Northeast Utilities Service Co., 1976); and reviews by Loar et al., 1977 and Uziel, 1978). At some power plants a direct correlation is apparent between species impinged and the abundance and seasonality of fishes present in the water body segment (Maryland Power Plant Siting Programme, 1977; Landry and Strawn, 1974; Benda and Guluas, 1976). In these cases, the power plant intake represents a non-discriminate stress on the nekton community. The same can also apply to pelagic marine macro-invertebrates, such as squid and swimming crabs. Yet scavengers, such as blue crabs, may be differentially attracted to intake bays in such abundance as to achieve nuisance proportions. Impingement susceptibility can also be species dependent and not representative of the local ichthyo-fauna at large, as seen by Edwards et al., 1976, at four freshwater sites in North Carolina, USA. Thread-fin shad was the major species impacted, especially during the late fall and winter, when this species is typically highly stressed or killed by low temperatures. With this species, there was no relationship between intake velocity and impingement, nor was a skimmer wall effective in reducing impingement. A survey of freshwater power plants in the southeast of the USA (Loar et al., 1977), pinpointed the cold sensitivity of threadfin shad as the major cause of impingement in this large region. Additional correlates between impingement and season, river flow, and water level are cited by Grimes (1975 and Mathur et al. (1977).

The numbers of animals lost due to impingement is difficult to assess. (At US nuclear plants, counts of dead animals are summarized and reported to the US Nuclear Regulatory Commission). Some impinged fish are returned alive to the waterway although the chances of their ultimate survival is questionable. For certain fragile fishes, such as the family Clupeidae,
there is little probability of survival once the screens are impacted. For other species, survival estimates should be made conservatively. The ability of impinged fish to withstand disease following loss of surface mucus or scales, or to withstand normal predator pressure following impingement stress is doubtless markedly reduced following impingement. Benda and Gulvas (1976) report signs of physical damage in over 50% of the impinged fish at a Lake Michigan power plant. They rate the chances of survival of these fish as minimal. Field or laboratory assessment of injury rate and survival suggest post-impingement survival to be better during cold winter months, with loss increasing proportionally with seasonal temperature increase (Maryland Power Plant Siting Programme, 1977; Landry and Strawn, 1974; Northeast Utilities Service Co., 1976). Relative sensitivity of eight estuarine fish species to impingement stress is reported by Burton Maryland Power Plant Siting Programme, 1977).

The significance of fish mortalities at intake structures can be placed in some perspective by distinguishing between repeated chronic kill and the very conspicuous, but infrequent major kills. Heavy fish kills due to entrapment or impingement are dramatic in nature and are always a serious problem for the power plant, possibly resulting in plant shutdown as the screens become clogged. Yet if major kills occur only infrequently, their ecological significance may be minimal. For example, loss of 50 million juvenile menhaden and blueback herring at Millstone, Conn., (Northeast Utilities Service Co., 1976) occurred as atmospheric cooling began in late summer, 1971, and the fish were leaving the estuarine nursery grounds to move south in the fall. Such an event has not reoccurred. In contrast, impingement of winter flounder occurs chronically at the same plant, with this species comprising 23% of all fish impinged over a four year period. The number of flounder impinged represented 0.3, 0.7 and 0.9% of the estimated local population during three of these years. If none of the impinged flounder survived, which is probably unlikely for this species, it is projected that the local population would be reduced by 12% after 35 years operation of three generating units, assuming present impingement experience continued. Fish troughs will be added to the screens at this plant in an attempt to minimize impingement mortalities in this species.

State-of-the-art intake technology to minimize impingement is summarized by Ray et al., 1976, and USEPA, 1976a. These reports address intake orientation (off-shore conduit, shore-line or bankside, and intake approach channel), behavioral and physical intake barriers and fish removal systems. Also discussed are potential approaches to minimize entrainment of larval fish. An extensive bibliography on fish protection at intake structures, with abstracts, has been compiled by Huber (1974). Impingement problems and intake design have also been the topics of several workshops (Jensen, 1974, 1976, 1978). At present, it is difficult to generalize on best technologies for intake structures which minimize environmental impact due to the site specific nature of the problem. For example, the louver bypass system described by Schuler and Larson (1975), was a site specific design and may not be the best technology elsewhere (Schuler, personal communication). At present, there is considerable research underway to develop better physical barriers and to perfect fish removal systems. Until new designs are proven in field tests, modifications of the standard rotating vertical screen barrier cited by Ray et al., 1976, should be explored to mitigate impingement loss. These modifications include provision for escape routes inside the intake suction pit or screen well, equipping the screens with fish troughs and continuously rotating the screens to minimize impingement time for a fish. It is usually recommended that intake velocities not exceed 0.15 m sec$^{-1}$ at the trash rack to permit fish to escape the screen wall (Boreman, 1977).

II.3.3 Change due to entrainment of small organisms with pumped cooling water

All small aquatic organisms capable of passing through the intake screens (usually 1 cm$^2$ openings) are entrainable and potentially subject to passage through power plant cooling systems. This would include planktonic and weakly swimming pelagic organisms ranging from microalgae to copepods and eggs and larvae of fish and invertebrates. Organisms entrained through the cooling system experience a combination of thermal and mechanical stress, plus exposure to a chemical biocide during periods of application. Survival of entrained organisms following plant passage is problematic and will depend on cooling system design, plant operating characteristics as well as overall tolerance of the species and life stages entrained. The larger copepods and fish eggs and larvae tend to be the more sensitive, with entrainment losses reported as ranging from 70 to 100% at several plants. More typical losses average about 30% over an annual cycle (Lawler et al., in press). Of primary environmental concern is entrainment loss of meroplankton (i.e. the eggs or larvae of fish and macroinvertebrates) since
these species can have generation times on the order of one to several years. In contrast, phytoplankton or copepods can produce replacement generations in a matter of hours to days, respectively, during favourable seasons.

The significance of meroplankton entrainment loss for the adult populations can be evaluated by biological models, such as developed for the winter flounder by Hess et al. (1975). (For additional details, see also Northeast Utilities Services Co., 1976; Van Winkle, 1977.) Similar modelling efforts are currently being conducted in the USA for the striped bass in the Hudson (discussed in chapter III), and Potomac Rivers. Enright (1977) has proposed a simple first order approach to assess maximum probable impact of larval entrainment mortalities upon the adult populations.

Our present understanding of the pumped entrainment problem is summarized in a volume edited by Schubel and Marcy (1978). Some early papers which document aspects of pumped entrainment stress include Coutant (1970, 1971) and Hess et al. (1974) (thermal shock); Marcy, (1973) and Carpenter et al., (1974b) (mechanical); and Hamilton et al. (1970) (chemical). Marcy, (1975) has written a succinct overview of the interaction of these three entrainment stresses, particularly as they pertain to fishes. Additional articles can be found in a review by Carrier, (1978) and in the proceedings of several entrainment workshops (Jensen, 1974, 1976, 1978).

The magnitude and the nature of pumped entrainment damage is plant specific, depending on the entrainable biota and hydrodynamic characteristics of the site, cooling system design and operating conditions. Beck et al. (1978) have tabulated, by species, reports of entrainment damage at 14 power plants with once-through cooling systems in the USA. Some of these studies also evaluated the relative influence of single stressors. They suggest that physical stress can be a major contributor of larval and juvenile fish mortality, accounting for 80-100% of observed losses in almost every study where cause of mortality has been partitioned. Thermal stress often contributes to mortalities during the summer, when water temperature is naturally high. Chemical biocides, most frequently used during spring and summer, can dominate as a stress during any period of application, and more so during periods of maximum thermal elevation (Hoss et al., 1977). Zooplankton appear to be more affected by chlorine than are fish larvae.

Yet it must be emphasized that the above conclusions are tenuous at best, as the data from operating power plants are sparse, and often of limited use due to sampling problems, variation in study techniques between workers, and potentially unique differences in power plant cooling systems. Ilogilcal results such as greater numbers of live organisms in the discharge than in the intake or opposite results from day to day or year to year at a single plant emphasize the inadequacy of many of the study methods used.

Problems of sampling entrained plankton have been discussed by Heinle (1976a, 1976b) and Copeland et al. (1976) (estuarine), Jude (1976) (large lake, Kind and Mancini (1976) (river) and Bowles et al. (1978) (ichthyoplankton). Numbers of larvae or zooplankton captured tend to be highly variable due to their patchy distribution (both horizontally and vertically) in the water column, diel variation in activity, possible day-time avoidance of nets, watermass changes at the intake due to tidal (in estuaries) and/or weather changes (especially in large lakes), plus unknown changes in distribution of plankton in the forebay of the intake. At the discharge sampling is usually complicated by high water velocities and changes in organism buoyancy and swimming behaviour due to the heat, which affect vertical distribution. Another problem centres around ability to detect entrainment damage. Problems of net collection, including the potential for net damage, have been addressed by some workers by use of a pump for sampling. Vital stains have been used to distinguish living from dead animals when it is not practical to make counts immediately following collection (Heinle, 1976a). The potential for latent effects, such as reduced ecological fitness and subsequent loss from the system due to differential predation, for example, has been little considered to date. Studies which simply tally mortalities immediately following discharge from the power plant are probably describing only a portion of the ultimate loss.

It is also difficult to directly document the consequences of through-plant entrainment damages on populations on the whole ecosystem in water bodies used for cooling. Many examples exist of field sampling programmes at power stations where no decreases of plankton have been seen that can be attributed to the inplant losses. (e.g. Carpenter et al., 1974 a). "Natural" variability of plankton is typically so great that only very large impacts would be directly discernable if they did exist.

**Components of Plant Entrainment Stress : Physical.**

Physical damage to entrained biota can...
result from four stresses operating in power plant cooling systems: pressure, acceleration forces, shear and abrasion or collision (Ulanowitz, 1975; Schubel and Marcy, 1978). At the pumps, organisms are exposed to sudden fluctuations in pressure and velocity shear forces, physical buffeting and abrasion. Once in the pump, there is rapid positive and negative charges in hydrostatic pressure, ranging from 0.29 to 1.6 atm. There is potential for contact with impeller blades (2-5%) or pump walls and pump shear stresses can be up to 10 times that existing near the walls of the condenser tubes. Accordingly, the pump is considered the most likely site of physical damage within an open cooling system. In the condenser water box, physical stress takes the form of negative pressures and high flow rates, which are maximum at this point. Negative pressure is considered particularly damaging to entrained fish. In the condenser tubes, shear and pressure changes also occur, but may pose a minimal physical stress at this point (Marcy et al., 1978).

The consequences for entrained biota of the combined physical forces of a power plant cooling system can be most realistically studied at an operating power plant. Plants pumping water through a cooling system without any thermal load have provided this opportunity at a few sites (e.g. Marcy, 1973). Pressure is one force that can be studied separately (Beck et al., 1975). However it is difficult at present to relate the findings of such studies to an operating power plant, where the magnitude of any one stress is hard to define and its consequences problematical due to interaction with multiple additional stresses. A scaled total cooling system simulator constructed at Oak Ridge National Laboratory (US) may permit detailed cause and effects experimental studies of the whole compliment of cooling system physical stresses which to date have not been possible at operating power plants (Costant, personal communication).

Studies to date suggest great differences exist between power plants with regards to physical entrainment damage. The primary variables regarding physical damage to entrained biota fall into two categories. Those which are a function of cooling system design and operation, and those which are dependent on the specific biota entrained. Location and design of the intake has the potential to enhance or minimize entrainment of planktonic organisms, as will volume of water pumped. Pump design and the efficiency of their operation (inefficient operation results in excessive cavitation and high biological damage) is another variable. The practice of augmentation pumping to reduce discharge water temperature, for example, is now recognized as clearly counterproductive and not a wise approach to mitigate discharge temperatures, as it increases the number of planktonic organisms exposed to damage. Indeed, the design option of a higher operating ΔT to reduce the volume of cooling water required might be considered, should plant entrainment of meroplankton pose a potentially serious environmental problem.

The biological variables influencing the probability of physical entrainment damage focus on the relative fragility of the entrained species, which is often a function of size and lifestage. Fish eggs and larvae appear to be more sensitive, among which the most fragile are larvae of the clupeids, menhaden, Atlantic silverside, sea robin, tautog, cunner and anchovy, (Marcy et al., 1978). Species with the larger respiratory apparatus have also been reported as highly susceptible to physical entrainment stress, possibly since the head area in fish is especially vulnerable to damage (Nawrocki, 1977). For other species, the yolk and post-yolk sac embryonic stages have been seen to be highly sensitive. There has also been a good correlation, for both ichthyoplankton (Marcy, 1973) and invertebrates, of increasing physical damage with organism size. Marcy et al. (1978) have proposed a generalized model which relates percent mortality to size of the entrained biota. For some fishes however there is an upper size limit for this generalization, with the largest entrainable individuals of some species showing increased tolerance to physical stress (Teleki, 1976; Nawrocki, 1977).

Thermal. The contribution of high temperature per se as a dominant entrainment stress has been best illustrated at operating plants by increased loss during the summer, the period that nature water temperature is at its maximum. If the discharge canal is long, considerable kill due to temperature will occur. (For further discussion of this topic, see Sec. 3.4). But otherwise, good estimates of the specific contribution of temperature alone to observed entrainment damage are difficult to make. This would require a good assessment be first made of the extent of damage from mechanical forces alone (i.e. damage without any heat load not chlorinated). Only a few workers, such as Marcy (1973), Carpenter et al (1974b), Alden et al. (1976) and Lauer et al. (1974) have had such an opportunity. Reviewing this literature, Schubel et al. (1978), conclude that high temperature can be the dominant entrainment stress at plants where mechanical stress is minimal and biocides are used only infrequently or not at all.
Laboratory studies can be useful in identifying entrainable organisms which clearly cannot tolerate the thermal regime of a given power plant. Yet organisms surviving a laboratory simulation of the entrainment thermal experience will not necessarily survive cooling system passage where mechanical and possibly chemical stresses are also present and probably will act in a synergistic fashion. A laboratory thermal stress simulation typically uses entrainable organisms common to the site in question and acclimation temperatures typical of the site during the seasons of occurrence of the test organism. The thermal dose (i.e. duration and magnitude of heating) should be comparable to that expected in the power plant, including the manner the elevation is experienced, i.e. as an initial instantaneous heat shock. Cooling may occur as a gradual decay if there is a surface discharge (Schubel, 1975), or a sudden drop in the case of a jet discharge (Hoss et al., 1974).

Schubel et al. (1978) suggests that fish eggs and larvae are usually significantly more sensitive to simulated thermal plant entrainment stress than are zooplankton or macroinvertebrates. Early fish embryos (i.e. early cleavage to blastopore closure) are more sensitive than later embryonic stages. Mortality is usually complete with a $20^\circ\Delta t$, while hatching success may be reduced at a $15^\circ\Delta t$, depending on species. Larval deformities can also result when the eggs are thermally stressed ($\Delta t = 10^\circ$ and $15^\circ$), markedly affecting their ability to swim normally and doubtless reducing their ability to avoid predation or feed (Koo and Johnson, 1978).

Working with larval fish, Hoss et al. (1974) found entrainment simulated temperature shock to be potentially very damaging in itself, especially the second (cooling) shock. The larvae exhibit marked initial deviations in behaviour, including complete immobilization. Those which might survive the direct effects of heat are clearly rendered more susceptible to predation at the time of discharge. Species differences in larval thermal resistance times and thermal shock effects should be considered when evaluating the potential for thermal entrainment damage at a given site. Hoss et al. (1974) observed a range in thermal tolerance among the six larval species he tested, with the flounders the more tolerant and menhaden the least. Striped bass larvae appear to have a relatively high thermal tolerance (Laurer et al., 1974).

Juvenile fish may have greater thermal tolerances than either the larval or adult stages (Otto, 1976; Brett, 1956). (The same phenomenon is frequently seen among invertebrates as well). Accordingly, Schuble et al. (1978) suggest that any damage experienced by entrained juvenile fish is probably more due to physical forces than from temperature alone.

Many of the generalizations of thermal entrainment stress made above for larval fish have also been observed with zooplankton and macroinvertebrates at operating power plants or in laboratory simulation studies. Schubel et al. (1978) cite several papers showing temperature can be the dominant entrainment stress in the summer at plants with a large $\Delta t$ (e.g. in excess of $13^\circ$-$15^\circ$), or when the excess temperature exposure is prolonged by discharge into a long canal or if plume dispersion is slow. (Fig. II.3)

Chemical Biocide Stress. Biocides, such as chlorine, are employed for the purpose of killing bacteria and algae which can build up on condenser walls, and to prevent settlement of growth of fouling invertebrates, such as mussels or barnacles. Accordingly, it is to be expected that many other entrained organisms will be similarly killed when biocides are used. Application practices vary. In the United States, application is usually intermittent. In contrast, continuous low-level chlorination is employed at estuarine and coastal plants in England between April and November in order to prevent fouling by Mytilus edulis (Coughlan and Whitehouse, 1977). Considerable research on power plant biocide use and its effects on aquatic organisms has been conducted at the Central Electricity Research Laboratories in Great Britain. (See Coughlan and Whitehouse (1977) and the review of Whitehouse (1975) for citations). Residual chlorine may persist in the cooling water following discharge from the cooling system, depending on dose level and application techniques.

Morgan and Carpenter (1978) have summarized some observed effects of chlorination at operating power plants in the USA. It appears that most entrained organisms are adversely affected by concentrations in excess of 0.5 ppm residual chlorine. Adverse effects have been most apparent with phytoplankton, perhaps due to the ease of measuring productivity. Yet Coughlan and Whitehouse (1977) also report increased sensitivity to chlorine as organism size decreases. Morgan and Carpenter cite numerous reports of 50 to 90% reduction in productivity (probably irreversible) following injection dose levels ranging from 0.1 to 2.7 ppm chlorine. Reports of zooplankton biocide entrainment damage include 50% kill in the presence of 0.25-0.75 ppm chlorine residue (Davis and Jensen, 1975), 40-80% copepod kill at two Chesapeake Bay (USA) plants in August, but negligible chlorine kill in May (Heinle, 1976b); 90% mortality of
Figure II.3  Mortality rate

Figure II.4  Composite toxicity data for freshwater organisms
Acartia tonsa at another Chesapeake Bay plant (McLean, 1973); and 50% direct or delayed kill of Gammarus sp. at the Indian Point (N.Y.) plant (Ginn et al., 1974). Loss of approximately 25% of entrained larval Morone spp. was reported by Laurer et al. (1974) during chlorination at the same plant. In contrast, Carpenter et al. (1974b) was unable to see effects on copepod survival, with or without chlorine, above that caused by mechanical stress at the Millstone (CT.) plant; likewise for larval fishes at another plant (Marcy, 1973), although there only one-fourth of the cooling system was chlorinated at one time. Potential and observed effects of chlorine in power plant discharges are discussed further in section 3.6.

Several approaches to minimize chlorination stress are suggested by Morgan and Carpenter (1978). These include intermittent low-level chlorination in preference to continuous dosage (entrained plankton are damaged even at very low-levels); investigation of site specific antifouling needs in order to minimize duration and frequency of chlorination (e.g. during some seasons, little or none may be required); use split condenser chlorination; use a higher Δt, coupled with reduced cooling water volume; and finally, consider alternative bio fouling control techniques, such as outlined by Yu, H.H.S. (1977).

II.3.4 Changes from exposure to the cooling system discharge: Near field thermal and physical effects

Cooling system effluent includes primarily heated water, biocides used to prevent slime build-up and fouling in the condensers, and metals leached from the condensers. The potential and observed consequences of exposure to these stresses will be treated and in sections 3.5 and 3.6, primarily as single entities. It should be recognized that effects observed can also result from synergistic interaction of these stress factors. The thermal component is particularly dominant due to the large volume of heated water continually discharged during plant operation. Biocides are usually used only on an intermittent basis; at some plants mechanical cleaning methods make them unnecessary. Leaching of condenser metals usually do not achieve levels of biological concern.

Temperature Related Problems of Cooling System Discharges

1. Discharge Canal and Near-field Thermal Plume. Organisms pumped through the condensers experience continued exposure to thermal stress in the discharge canal and discharge plume as the effluent enters the receiving water body. A plume which contacts the bottom will also adversely impact benthic life. Planktonic and weakly swimming pelagic organisms entrained into the discharge plume will experience thermal shock. During non-summer months, fish will move in and out of the plume and canal, attracted by the warmer water. Fish remaining in these waters for some period risk exposure to discharged biocides, and during the winter, could experience gas bubble disease, loss of physiological condition, or in the event of plant shutdown, cold kill.

A long discharge canal may be an attractive engineering design option to limit recirculation of cooling waters to the intake or reduce discharge temperatures a few degrees. Yet these long canals serve to prolong exposure of plant entrained plankton to elevated temperatures and potentially toxic biocides. Thermal death is a function of both the temperature and duration of exposure (Coutant, 1970). Ginn et al. (1974) have documented this fact in the context of the discharge canal for two species of entrainable Gammarid amphipods. Discharge canal stress on both entrained biota and organisms entering from the mixing zone can be reduced to the extent that the discharge canal is shortened or eliminated altogether. Thermal plume problems can be minimized by enhancing dilution of the discharge, potentially achieved by siting the discharge in an area with strong currents (e.g. Millstone, CT.) or by employing a jet discharge (e.g. Calvert Cliffs, MD., San Onofre, CA.).

Markedly elevated effluent temperatures close to the operating Δt of the power plant usually occur only in discharge canals and in the immediate discharge area. It is here that the most striking biological changes are seen. The consequences and underlying causes are highly site-specific. Important early reviews of power plant thermal effects include Alabaster (1963); Parker and Krenkel (1969); Krenkel and Parker (1969); Coutant (1970); Clark and Brownell (1973). Published case studies on thermal discharge effects include Hedgpath (1973) for two California (estuarine and coastal) power plants and Merriman and Thorp (1976) for a temperate zone riverine site. Coles (1977) has summarized some environmental effects of power plants in the tropics. Recent symposia include those sponsored by IAEA (1975a, 1975b), and the Savannah River Ecology Laboratory (Cibbons and Sharitz, 1974; Esch and McFarlane, 1976; Thorp...
and Gibbons, in press). Bibliographic information is catalogued and indexed in Raney, Menzel and Weller (1974) (for literature through 1971) and in annual indexed bibliographies by Coutant and his associates (1972-1977).

Early reports of biological change within discharge canals per se were reviewed by Coutant (1970). At that date, topics being addressed were canal water column productivity and the potential for "self pollution", benthic productivity, succession to thermally tolerant algae, such as the blue greens, and fish kills. Reports describing the annual dynamics of the biota in discharge canals (Merriman and Thorp, 1976; Miller et al., 1976) show the discharge canal and immediate mixing zone to be areas of extreme ecological instability at plants experiencing occasional shutdown or which operate in a peaking mode. Also, during the summer, thermal conditions in the canals typically reach stress or lethal levels for the indigenous biota. Depending on the absolute temperatures which prevail, productivity is reduced or inhibited, benthic diversity drops and the fishes move out of canal. During non-summer months, productivity of each compartment usually exceeds that of the open water body, although the persistence of this community is limited due to the instability of the canal environment.

Today we recognize two general problem areas regarding discharge canals: continued thermal and chemical stress on plant-entrained plankton (an extension of the entainment problem) and those resulting from the attraction of fishes and other motile organisms during non-summer months. Coutant (1974) suggested that fish will be attracted to heated effluent until discharge temperatures exceed the final preferendum by 2°C (±1). Then fish tend to avoid the discharge. Field and laboratory studies cited by Coutant, plus major studies by Spigarelli et al. (1974) and Neil and Magnuson (1974) show that many fish do behaviorally thermoregulate, swimming in and out of the plume to maintain body temperature close to the known preferendum. These findings correspond with the frequent literature reports of fish attraction to power plant discharge plumes during non-summer months, followed by avoidance in the summer. The behavioral and physiological aspects of temperature preference in fishes was the subject of a recent symposium (Richards et al., 1977). Included is an update of Coutant's temperature preference data summary. It is generally agreed that the final preferenda in fish closely approximates the optimum temperature for many physiological processes.

Problems associated with fish aggregations in thermal discharges are most conspicuous during the winter. Major problems include loss of condition of fish due to malnutrition (Merriman and Thorp, 1976); occurrence of gas bubble disease as cold water is heated and dissolved gases exceed 115% of saturation (Miller, 1974); and cold kill of fishes aggregated in the thermal plume when there is abrupt winter plant shutdown (Coutant, 1977). Marked loss of weight and condition of brown bullheads (Ictalurus nebulosus) overwintering in a discharge canal was reported by Massengill (1973). Three possible reasons are suggested: higher metabolic rate for fish in the warmer discharge canal water; higher metabolic requirements due to the greater swimming activity required to maintain fish in canal flows of 0.3-0.9 m s⁻¹; high population densities in the canal which result in overcrowding and increased competition for food. In white crappie, thermal stress during the winter was evidenced by reduced tissue lipid levels and gonosomatic indices in the hot water arm of a reservoir (Knox, 1973). Yet there are exceptions, suggesting that the effects of near-field thermal discharge on fish condition must be considered on a species specific or site-specific basis. Bennett (1972) found no effect on condition of bluegill fingerlings, while condition was enhanced for adult bluegills and black crappies in a heated discharge pond in St. Caroline. (This might be expected if food in not limiting). Extreme temperature stress near the discharge (ΔT = 12°-15°) can result in increased incidence of vertebral abnormalities in fish (Mitton and Koehn, 1976). Spring and fall collections of a marine fish (Fundulus heteroclitus) at a power plant on Long Island Sound, N.Y., had a 1.1 to 20% increase in vertebral abnormalities relative to two adjacent control populations. Such abnormalities would reduce fitness of the power plant population.

Animals attracted to a thermal discharge may experience increased incidence of parasitism and disease. General loss of physiological condition and crowding would contribute to this. A direct relationship between incidence of parasitism and disease and temperature per se is well documented for aquatic animals (Sinderman, 1966). DeSylva (1969) observed high incidence of fungus disease in a marine fish species at a Florida power plant, although the actual relationship between this disease and the power plant discharge was not determined. Sankurathri and Holmes (1976) found the prevalence of certain snail parasites, especially the metacercaria, to be enhanced as thermal effluent eliminated a commensal oligochaet, which normally feeds on the digenia larvae. Additional reports of parasitism and disease incidence are cited in the annual thermal effects reviews by Coutant et al. (1972-1978).

Gas bubble disease (GBD) has also occurred in fish attracted to thermal effluents.
Heat Shock; There is also the potential for loss of organisms due to heat shock following studies of salmon. Experience increased predation by unstressed prey (Coutant et al., 1974). It had earlier been shown (Brett 1956) that loss of equilibrium occurred long before actual death in cold resistance studies of salmon. A school entered the discharge canal and plume shortly after plant start-up. Some 90% of the fish in the discharge canal had external signs of gas bubble disease. The resulting kill was estimated at 43,000 fish. Dissolved oxygen levels in the canal and plume were found to range between 120 and 140% of saturation. A net was subsequently placed across the mouth of the discharge canal which has effectively minimized subsequent exposure of fishes to these conditions.

Excellent recent papers on gas bubble disease in fish include Wolke et al. (1975, Bouck et al. 1976) and a workshop edited by Fickeisen and Schneider (1976). Wolke et al., reviews the early literature, describes the physical and environmental factors contributing to gas supersaturation and details the pathological signs and general lesions common to GBD. Field diagnosis is discussed, as are rapid methods for in situ measurement of total dissolved gas pressure. Bouck et al., summarizes findings of a laboratory study on tolerance of several life stages of two salmonids and large-mouth bass to total dissolved gas pressures ranging from 110-140% barometric pressure. Times to 20% and 50% mortality were determined, with biological variables influencing time to death examined. Few papers of the gas bubble disease workshop deal with temperature or power plants, yet this publication provides an excellent summary of our current knowledge of GBD in fish, the physiological consequences of sublethal exposures, and techniques to monitor total dissolved gases. Included is a working group recommendation of 115% as the gas supersaturation criteria to protect juvenile salmonids fishes migrating through Columbia-Snake River systems (US Pacific Northwest). A lower level (110%) is suggested if shallow water invertebrate benthic food organisms are also to be protected. It is important to note that sensitivity to supersaturation varies with species, as well as life history stages (Bouck et al., 1976). Otto (1976) documents additional species differences. In the laboratory, yellow perch were unaffected at 115% total gas saturation, and the 8-day TLM occurred with 126% saturation. Trout were more sensitive. The maximum no effect level was 110% and the 8-day TLM occurred at 119% gas saturation.

From Cold Shock. Cold kills have occurred with abrupt temperature decreases after fish were attracted to warmed discharge water in winter (usually in canals) (e.g. Ash et al., 1974; USAEC, 1972; Coutant 1977). At least one cold kill has been reported due to abrupt wind changes causing a shift in a lake thermocline that introduced cold, hypolimnetic water to the power plant intake and thus a rapid decrease in effluent temperatures (Coutant, 1977). The biological basis for cold shock is well understood and death is a function of particular species, the recent thermal history or acclimation temperature, and the new cold temperature. Exposure duration is important, but generally termination of the power plant heat lasts for sufficient time that cold death results. Recent studies on susceptibility of young fish to predation following cold shock indicate that some warm-water species can tolerate only 5°-6°C drop in temperature before they experience increased predation by unstressed prey (Coutant et al., 1974). It had earlier been shown (Brett 1956) that loss of equilibrium occurred long before actual death in cold resistance studies of salmon.

Heat Shock. There is also the potential for loss of organisms due to heat shock following
sudden exposure to thermal plumes (Hoss et al., 1974). This could occur if planktonic or weakly swimming pelagic organisms are carried by currents into a discharge plume, or if fish fail to perceive acutely lethal temperatures. The latter situation was observed by Young and Gibson (1973) while SCUBA diving. A migrating school of juvenile menhaden encountered a thermal plume (maximum Δt = 15°C), experienced immediate thermal shock and sank, with most fish dying. Those which did recover swam back into the plume to subsequently sink again, die and be carried away by bottom currents. It is unknown how prevalent such fish kills may be, as they are not evident at the surface. This behaviour of menhaden is perplexing in light of many studies showing avoidance by fish of temperatures exceeding the final preferendum (Neil and Magneson, 1974; Coutant, 1974; Richards et al., 1977; Gray et al., 1977). Yet at very high temperatures, Gift and Westman (1971) have found breakdown of the avoidance response in fish. This could have occurred in the above field situation.

Organisms encountering a discharge plume can also be lost if they are thermally stunned and temporarily debilitated, becoming more susceptible to predation by fish and birds as they drift out of the plume. This is suggested by field observations and supported by laboratory studies with a number of juvenile fish species following sublethal shock (Coutant, 1973; Stober et al., 1971; Sylvester, 1972; Yocum and Edsall, 1974). Deacutis (1978) has also seen some differential predation in thermally shocked larvae of the Atlantic silversides (Menidia menidia). The potential loss of planktonic organisms, especially larval stages, which drift into thermal plumes has received little consideration to date. The potential for thermal shock can be minimized by designing and siting the discharge to assure rapid dilution in the receiving water.

Blockage of migration routes by thermal plumes has also been suggested as a potential problem at power plants. Yet extensive monitoring of salmon and trout on the Columbia River (Templeton and Coutant, 1970) and American Shad on the Connecticut River (Merriman and Thorp, 1976) have detected no modification of migratory patterns by thermal discharges. High temperatures of some natural tributaries have caused migrations into them to be delayed, however. (Major and Mighell, 1966).

Fish Harvest at Thermal Discharges. Thermal effluents, through their attraction of fish during non-summer seasons, are well known among fishermen for their ability to increase catchability. Several studies in the USA have analyzed this phenomenon in some detail. Coutant (1975) reviewed several studies on black basses. Landry and Strawn (1973) followed the annual activity of sport fishing at a thermal discharge into Galveston Bay, Texas. Marcy and Galvin (1973) characterized the intense winter fishery in the discharge canal of the Connecticut Yankee Atomic Power Plant on the Connecticut River. Moore et al. (1973) surveyed fishing near the Chalk Point plant on the Patuxent Estuary, Maryland. Allen et al. (1970) used experimental angling as a means of identifying fish movements at a marine coastal plant. The Tennessee Valley Authority publicizes the excellent fishing near its steam plants in winter (TVA, 1969).

Results of Elser (1965) have largely been upheld in these later studies. Elser identified seasonal changes in percentages of fish catch among his three test locations, two in unheated sections of the Potomac River, and one in a heated zone. The heated area had disproportionately high catches (greater than 35%) from October through mid-June. Catches declined to essentially zero in August, the warmest month of the year. Yet, the summer is the more popular fishing period, both in the Potomac and elsewhere. Catchability should be balanced with time of recreational demand in any analysis. Also, if food becomes inadequate for large aggregations of fish, a reduced quality of catch for the anglers can result.

Benthic Impact. The impact of thermal discharges on the benthos is largely dependent on the extent that the plume comes in close proximity to the bottom. If the discharge is located in shallow waters, appreciable loss of benthic life can occur, (Coutant, 1962). Limited circulation to rapidly dilute and disperse the plume can make this more acute. At semi-tropical and tropical sites, benthic kill can be particularly extensive with shallow water discharges, as summer temperatures are normally only a few degrees below the upper thermal limits for the biota. (Thorhaug et al., 1978). At all latitudes, where benthic impact has occurred, it is greatest during the summer. Some recovery of sublethally stressed populations may occur during winter and peripheral benthos can experience enhanced productivity.

The Turkey Point Power Plant in Florida provides one example of consequences of a surface discharge into shallow water (<1m) at a low latitude site. A total of 1.2 km² of benthic and epibenthic community experienced a statistically measurable decline in abundance for at least part of the year. Damage was perceptible between the +2°C and +3°C above ambient isotherms during
the summer months (Roessler and Tabb, 1974).

The prevalence of summer sublethal stress and thermal kill at other low latitude power plant sites has been reported by Blake et al. (1976) at Tampa Bay, Florida; Jokiel and Coles, (1974) at Hawaii and Kolehmainen et al. (1975) at Puerto Rico. These papers show the relationship which exists between extent of benthic impact and receiving water depth, circulation pattern and volume of thermal effluent.

Benthic impact at shallow water discharges has not been limited to the tropics. Warinner and Brehmer (1966) reported a general depression of benthic community diversity during the summer at a York River, Virginia, station some 200 to 300 m from the discharge. Depth was only 1 m at MLW. Damage further off-shore was minimal, as increased depth permitted the plume to rise off the bottom.

Discharges located in deeper water or where good circulation prevails, usually only impact the benthos immediate to the discharge. Water depth at the discharge at the Pilgrim Plant (Plymouth, Mass., Lat. 42°) ranges from 3 m near shore to 9.7 m within 0.8 km off-shore. While currents at this site are modest, water depth is sufficient to minimize benthic contact by the plume. Thermal discharge from the existing 655 MW(e) unit has eliminated Irish moss (Chondrus crispus) only within a 15 m radius of the canal; with an additional 118U MW(e) unit operating, the projected impact is a 33 m radius devoid of moss, and moss reproduction thermally excluded over a total area of 0.8 hectares. Likewise, Mytilus edulis is projected to experience some summer mortality over a 0.8 hectare area during periods of natural maximum summer water temperature. The two-unit discharge plume is predicted to rarely contact the bottom below 6 m MLW (Boston Edison Co., 1975).

Epibenthic communities dominated by one or several sessile species are particularly sensitive to thermal discharges (North, 1969; Thorhaug et al., 1978). Loss of major sessile organisms (coral, sea grasses, macroalgae, or bivalves) will also result in loss of associated motile organisms (e.g. fishes and crustacea) which depend on the dominants for food or habitat. At Turkey Point, Florida, Roessler and Tabb (1974) found a direct correlation between loss of the sea grass, Thalassia, and macroalgae (Laurencia and Digenia) and reduction in both the kinds and numbers of benthic animals and fishes collected at the thermally impacted stations. The same phenomenon was observed by Blake et al. (1976) in Tampa Bay, Florida. The animals appeared dependent on this vegetation for food and shelter. The dependence of the coral community on survival of the coral is well established. The relative susceptibility of coral to thermal discharges and thermal stress has been reported by Jokiel and Coles (1974, 1977); Coles (1975) and Jokiel et al. (in press).

Effects of thermal discharges on the mussel (Mytilus edulis) has been reported by Gonzalez and Yevich (1976). A mussel bed had become established in the discharge canal of a Massachusetts power plant during the spring. In June, as discharge temperatures reached 27°C, the mussel bed was killed. Loss of mussels near the intake subsequently also occurred in August, as ambient water temperatures reached 27°C. Laboratory studies demonstrated sublethal stress at 25°C as feeding ceased.

Reproduction and survival in oysters (Crassostrea virginica) was examined at the mouth of a long discharge canal at a Delaware power plant (Tinsman et al., 1976). Average Δt was 5°C during the seasons that an appreciable temperature differential did occur. During the first year of plant operation the primary effect was precocious gonad development in the spring, but in the second year there was high mortality and reduced gonadal development in surviving oysters, suggesting an overall loss in condition. This also occurred with the scallop, Argopectin irradians concentricus at two southern Florida power plants (Studt and Blake, 1976). One month exposure to an effluent station with 4.5°C Δt resulted in mortality and resorption of oocytes; the same was seen after five months at a 1°-2°C Δt station. These effects were not considered exclusively due to the thermal component of the discharge, but also from an increase in total suspended solids at these stations. It should be noted that this scallop is at the southern extreme of its geographic range at these two study sites, so thermal sensitivity is to be expected.

Thermal Loading of Embayments and Wetlands. At lake, estuarine and coastal sites there is the potential of wind or tidal transport of heated effluent into small bays or wetlands. Two papers document the consequences of thermal loading on the fish community in marsh creeks in Florida. Carr and Giesel (1975) found a 3-10 fold drop in summer abundance and biomass of juveniles of economic species. Thermal effects appeared as pronounced in a creek which received heated discharge for only 1 to 2 hours during flood tide periods as an adjacent creek receiving effluent directly from the power plant. Homer (1976) recorded 93% reduced abundance and 76% less fish biomass during summer in a marsh creek 360 m from a discharge canal which experienced
maximum thermal addition of 6°C. The impact of heated water on marsh systems in the summer is of concern in light of their important nursery function during this season.

II.3.5 Changes from small temperature elevations over wide areas

Direct effects of small temperature elevation on single species can potentially occur in the tropics, or during the summer, in species near the lower latitudinal extreme of their geographic range. Crossman (1969) has noted the loss of fish species near the southern limit of their range in Lake Erie due to a general increase in average water temperature of 1.1°C. The commercial clam, *Mya arenaria* is another case in point. This species reaches the southern extreme of its range in the Chesapeake Bay. A small temperature elevation (e.g. 1°C) above the natural summer maxima due to cooling system discharge can adversely impact *Mya* populations in this region. North and Adams (1969) cite examples of natural loss of cold water species in coastal bays in Southern California, and deterioration of kelp bed canopies in this region when temperatures 1.1°C or more above normal summer levels persist for several weeks.

In the tropics, coastal marine organisms commonly experience a thermal regime with maxima close to their upper thermal tolerance limit. A compilation of thermal effects data by the US EPA (1976b) suggests the range between optimum and exclusion temperatures in the tropics is around 50°C for many species, while sublethal thermal stress may be evident 2°C above optimum levels (Table II.1). It should be noted that almost all these data represent studies on semi-tropical populations (the larval fish study excepted). Optimum and upper limiting temperatures for tropical populations may be 1°C to 5°C higher, according to comparative studies by Coles et al. (1976) in the Pacific and Kolehmainen, et al. (1975) at Puerto Rico. Nonetheless, the narrow range between thermal optima and upper limiting temperatures persists, (Thorhaug et al., 1978).

It is well recognized that small temperature elevations over wide areas, if persistent, can exert sublethal stresses which can become limiting, even if lethal temperatures do not occur. Temperature has a major influence on growth and reproduction in organisms, two phenomena crucial to population success. Such thermal effects are detailed for some percoid fish by Hakanson (1977).

The influence of temperature on bioenergetics in aquatic organisms is well studied for fish (Brett, 1970; Warren, 1971), and certain marine bivalves (Thompson and Bayne, 1974; Widdows, 1978). If food supply is limited and the efficiency of any step of food procurement or energy conversion is reduced, energy available for growth and reproduction will also be reduced. Bisson and Davis (1976) reports reduced growth in fish exposed to 4°C elevation in experimental streams. Food was clearly limiting in these studies, a condition which can occur in some rivers and deep lakes. Tropical waters are also often characterized by low productivity. Modest thermal additions could reduce growth in this biome if increased metabolic demands could not be met. In estuarine environments, food usually would not be limiting in a quantitative sense, so normal or even enhanced growth may occur with low-level thermal addition. This has been reported in snails at a coastal site (Barnett, 1971), and in an artificial reservoir lake (McMahon, 1975). Yet even in a highly productive environment, such as an estuary, growth could be reduced should food become limiting in a qualitative sense for animals which have highly specific food requirements (Briand, 1975).

Reproduction is commonly one of the most sensitive life-cycle processes to elevated temperature. Production of eggs is energy expensive, especially when eggs are heavily yolked. Obviously if food is not sufficient to meet basic metabolic requirements, fecundity is reduced. Brungs (1971) found egg production to be the most sensitive parameter in response to experimentally increased temperature in the fathead minnow. He recorded a 29% reduction in fecundity with a 2.5°C elevation, while egg hatchability and fish growth was only affected by 6.5°C and 8.5°C elevations. Reduced fecundity was also seen by McMahon, (1975) in the snails at a power plant site. In an experimental study with corals, Jokiel et al. (in press) saw a very narrow (1°C-2°C) optimum for reproductive success; a 10°C elevation above this resulted in reduced success by 10 to 100 times. In contrast, growth of these corals was only reduced 10 to 20% by 1°C elevation above optimum. Timing of the reproductive season can also be altered by thermal additions, Barnett (1971, 1972) observed the breeding season begin and end some two months earlier in a few marine molluscs living near a thermal effluent. For species having planktonic larvae, probability for successful development to metamorphosis would be low with an early spawn, as water temperatures distant from the plant would be too low.

Low-level thermal addition also has the potential of altering community structure and important species interactions. The most conspicuous examples of this, involve loss of habitat forming species at semi-tropical and tropical sites (see section 3.4). This potential is also
### TABLE II.1
A COMPARISON BETWEEN OPTIMUM AND SUBLETHAL AND LETHAL UPPER LIMITING TEMPERATURES FOR SEMI-TROPICAL AND TROPICAL BIOTA

(After EPA 1976b)

<table>
<thead>
<tr>
<th>Biotic group</th>
<th>Optimum temperature (°C)</th>
<th>Thermal stress/limiting temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molluscs</td>
<td>26.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>31.4 50% species exclusion</td>
</tr>
<tr>
<td>Echinoderms</td>
<td>27.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>31.8 50% species exclusion</td>
</tr>
<tr>
<td>Coelenterates</td>
<td>25.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>29.5 50% species exclusion</td>
</tr>
<tr>
<td>Porifera</td>
<td>24.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>31.2 50% species exclusion</td>
</tr>
<tr>
<td>Fouling community</td>
<td>25.4-27.8</td>
<td>28 50% reduction</td>
</tr>
<tr>
<td>Lytechinus variegatus</td>
<td>27</td>
<td>29.9 50% reduction</td>
</tr>
<tr>
<td>growth and gonadal</td>
<td></td>
<td>gonadal vol.</td>
</tr>
<tr>
<td>development</td>
<td></td>
<td>32.0 86 hr. TL 50</td>
</tr>
<tr>
<td>Thallasia testudinum</td>
<td>30</td>
<td>31 (daily av.) long</td>
</tr>
<tr>
<td>productivity</td>
<td></td>
<td>term decreased growth</td>
</tr>
<tr>
<td>Survival of larval fish</td>
<td>28.30</td>
<td>30.32 tolerance limit</td>
</tr>
<tr>
<td>12 hrs. post-hatch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Temperature for high species diversity.
illustrated by changes in structure of a fouling community experiencing 3°C elevation above ambient (McCain, 1975). Community changes would be expected during the summer when maximum ambient temperatures were 29°C, yet shifts also occurred in February (ambient 24°C), with a dominant bryozoan sparse or lacking on the +3°C panels.

II.3.6 Changes from power plant chemicals

The effects of cooling water chlorination on aquatic life has received considerable attention recently. Yet laboratory studies predominate, with field assessments of the problem limited in number. Important literature reviews on this topic include those by Brungs (1973, 1976), Whitehouse (1975), and Mattice and Zittel (1976). An abstracted bibliography has been prepared by Mattice and Pfuderer (1976). Recent conference proceedings which detail our current understanding of chlorine related problems in aquatic systems include those edited by Jensen (1977), Jolley (1976, 1978), Block and Helz (1977).

The biocidal effects of chlorine on productivity within discharge canals have been quantified at a few plants. Hamilton et al. (1970) observed a 91% reduction of primary productivity during periods of chlorination at the Chalk Point (Md.) plant. Considering chlorination practices at that time and the magnitude of cooling water usage from the river, these authors projected a maximum loss of 6.6% of the primary productivity of the affected section of the river due to chlorination. Fox and Mayer (1975) reported a 57% drop in productivity in cooling water following chlorination at Crystal River, Fla. The reduction following plant passage was only 13% during periods of no chlorination. Reduced productivity of periphytic algae was observed downstream of a power station at a riverine site (Eiler and Defiro, 1974).

The response of caged fish exposed to chlorinated power plant discharge water has been examined by several workers. Trucken (1977) reported mortalities only for brown trout, non for brown bullheads or various sunfish. He reports IL50 (intermittent median lethal concentration) values of 0.14 - 0.19 mg/l for fish held for 43 hours following either two or four intermittent chlorinations of 30 min. duration each. The 96-hr. IL50 values were more variable, ranging from 0.02 - 0.05 mg/l (3 intermittent chlorinations) to 0.17 - 0.18 mg/l (6 chlorinations). In contrast to these findings, Liden and Burton (1977) failed to see significant effects of discharge canal water on survival of caged juvenile Atlantic menhaden and spot at the Morgantown (Md.) plant. Salinity here ranged from 0.5 to 10% varying with river flow. These fish experienced halogen concentrations of 0.020 - 0.080 mg/l total residual chlorine and 0.014 - 0.062 mg/l chlorine during 19 and 20 day study periods. Similarly, Marcy (1973) observed no adverse chlorination effects on fish at the Connecticut Yankee plant, possibly since only 1/4 of the condensers were chlorinated at a time, assuring good dilution at the discharge.

Drawing on existing chlorine toxicity data, Mattice and Zittel (1976) proposed zero mortality curves for acute chlorine exposures (0.0015 mg/l chlorine for freshwater; 0.02 mg/l for marine) (Fig. II.4). Certain sublethal effects of chlorination may fall within these suggested protection levels and some may not. For example, the lowest level of total residual oxidant found by Meldrim and Fava (1977) to elicit behavioral avoidance response in a marine fish was 0.03 mg/l. Cherry et al. (1977) determined the avoidance threshold for two freshwater fishes to be 0.1mg/l TRC or 0.03 mg/l FRC in a complimentary set of field and laboratory studies. Avoidance of near-threshold concentrations was most pronounced in winter. Low temperature (e.g. ≤12°C) contributes to a high concentration of the more toxic free chlorine radicles. Capuzzo et al. (1977) observed significant metabolic stress in stage I lobster larvae at 0.01 mg/l, the lowest total chlorine residual concentration tested. Clearly additional research is necessary to more fully assess the consequences of chlorination on aquatic systems. There are several unknowns concerning potential toxicity of bromate formed when sea water is chlorinated (Macalady et al., 1977); potential health problems regarding chlorinated fresh waters which may be reused for drinking has been addressed by Morris and McKay (1975) and Stevens et al. (1976).

Metals leaching from condenser tubes can also comprise a detectable chemical addition to discharged cooling waters. Highest levels of metals release have been reported at marine sites after a period of plant shutdown, during which non-circulating sea water was in contact with copper-nickel tubing. At a California plant, Martin et al. (1977) report 1,800 μg Cu/l in this water upon initial discharge, with rapid dilution following with flushing. Yet even after 30 days, copper concentration in the effluent water was 20 μg/l while intake water only contained 1 μg/l. These authors report 1500 abalone killed at this plant following testing of the cooling system. Their laboratory study shows 50 to 65 μg/l Cu is lethal to adults after 96-hours for the two species tested. Copper accumulation by the American oyster (Crassostrea virginica), in the vicinity of a power plant has been documented by Roosenburg (1969). Copper
body burdens measured as high as 1.28 mg/g dry wt. within the effluent canal. Oyster condition index corresponded inversely with oyster copper body burden over a four year period. At high levels of copper accumulation, greening of the meats and a bitter taste results. At a Florida power plant, Grimes (1971) reported summer high values of 482 ppm zinc and 80 ppm copper in oysters from the discharge. Intake canal body oyster burdens were 138 ppm Zn and 9 ppm Cu. Zinc is high here as zinc ingots had been placed at all metal structures of the intake and discharge to retard electrolysis. Additional metals data are provided by Gilmore et al. (1975) for oysters cultured in power plant cooling ponds. In contrast, metals accumulation was not conspicuous in eels raised in power plant discharge water and cooling ponds (Romeril and Davis, 1976). Indeed, growth was so rapid, due to thermal addition and supplementary feeding, that no increase in metal was seen on a weight specific basis, except for iron, which accumulated in the livers. It is probable that metals body burden data obtained from filter feeding bivalves would represent the higher levels of bioaccumulation likely to occur in discharge waters due to their propensity to concentrate and retain metals.

II.3.7 Changes from total combined stresses

It is well recognized that a once-through cooling system poses a number of potential stresses and perhaps certain enhancing effects on the natural system. Circulation of an appreciable volume of water and addition of heat can enhance productivity. Yet the biota associated with this water mass may be altered as certain populations experience immediate or latent mortalities due to impingement, through-plant entrainment or discharge canal and plume stresses (Brand, 1975). The impact of the total cooling system on the biota can be assessed only in the field. Laboratory multivariate studies simply cannot include the full spectrum of positive and negative conditions, nor attain a scale adequate to realistically simulate cooling water use by a power plant. The consequences of total cooling system operation of a single power plant may be apparent on a waterway which is devoid of other pollution inputs and semi-enclosed, such as a coastal embayment, or on a small river where appreciable river flow is used for cooling. A shift from a benthic of planktonic dominated ecosystem has been seen by McKellar (1977) in the outer portion of an estuarine bay at the Crystal River (Florida) plant. The thermal component of the discharge was fairly dilute in this portion of the bay, but phosphorous levels were elevated. Plankton production increased 4 to 6 fold during the summer relative to a control bay, with turnover time decreasing from 6 to 5 days. In addition to this change in system structure, total system biomass was 15-20% lower in the outer discharge bay, even though total community gross primary production and metabolism was very similar to the coastal bays. This study illustrates the simultaneous stimulating and degrading effects of cooling water use.

Changes in a large oligotrophic lake which received cooling water pumped from an eutrophic lake for 10 years was described by Koschel and Mothes (1976). The consequences of nutrient enrichment are apparent: phytoplankton productivity increased and water transparency decreased, resulting in a decrease of macrophyte depth limit from 20 to 12 m. Macrozoobenthos productivity increased 3 fold. Much of the observed changes can be explained simply by the pumping of cooling water from the eutrophic lake. Damage to entrained plankton and release of orthophosphate was apparent above 27°, although this would contribute to lake enrichment only in a minor way.

The impact of power plants on the fish community has been much studied. If the plant is small or is located on a large open water body, such as the Great Lakes, the primary consequences are local shifts, in the spatial distribution of fish fairly close to the discharge (Nugent, 1970; Neill and Magnuson, 1974; Stauffer et al., 1976; Yoder and Gammon, 1976; White et al., 1977). The fish community of waterways receiving discharges from one large or multiple power plants has been assessed on the Potomac River (Maryland) (O'Conner and McErlean, 1975) and a segment of the Wabash River in Indiana (Tepper and Gammon, 1976; Gammon, 1976). O'Conner and McErlean found a downward trend in diversity, number of species caught, species richness and evenness over the study period; biomass remained relatively stable. They concluded that a general degradation of the Potomac River had occurred, but could not relate this specifically to power plant operations. In the Wabash River, Tepper and Gammon found primarily only local shifts in distribution of several species around power plants. There was a 40°C increase in temperature over the 161 km river section studied, but chemical and municipal discharges into the river precluded identification of any community effects of this thermal rise or of cooling water use in general.

Should a power plant be sited on a polluted waterway, one potential negative consequences is further deterioration of water quality, particularly dissolved oxygen content.
Considerable study of this effect has been undertaken in Europe (Wunderlich and Müller, 1976). A study in Poland showed only local elevation of nitrite levels and depression of dissolved oxygen at a 1600 MW(e) power plant on the Vistual River, a waterway which also received industrial and municipal wastes (Dojlido, 1977). However, during this study, no extreme or "worst case" conditions occurred (such as full generating load or low river flow). A formula was developed to predict the consequences of river water temperature rise and pollution loading on dissolved oxygen concentration. At a proposed power plant, this problem would have to be evaluated on a site specific basis, considering the nature and extent of waterway pollution and volume and Δt of cooling water used.

II.4 Potential Changes Due to Cooling Towers From Entrainment in Cooling Tower Makeup Water

Entrainment in cooling tower ("closed-cycle") makeup water can be assumed to cause 100% mortality. Repeated cycles through both tower and condensers, with biocides and anti-corrosion chemicals added periodically, make any survival doubtful. While cooling towers may reduce water use at a power station, negligible survival in the "closed system" may cause more plant entrainment deaths than would a well-designed once-through system that allows nearly complete survival. Detailed comparisons are needed, however.

From Chemical Releases in Cooling Tower Blow-down. Toxic effects of chromates and chlorine are reasonably well established in the literature for many species (see Becker and Thatcher, 1973). Effects of newer cooling tower chemicals, often mixtures of complex organic and inorganic compounds for which the composition is held proprietary by the manufacturer, are not well understood. Phosphate compounds may contribute to eutrophication. Phosphate released from one cooling tower system for a 715 MW(e) nuclear station was estimated to be equivalent to sewage phosphate from a city of 75,000 population (USAREC, 1972). In arid areas, the concentrated dissolved solids may affect aquatic life detrimentally.

From Cooling Tower Drift. Drift affects mostly the terrestrial environment, where cooling tower chemicals can accumulate in foliage and soils and damage may ensue (Taylor et al., 1975). Runoff of accumulated drift chemicals in the vicinity of towers may also create toxic levels in small streams for short periods. Little work has been done in this area.

From Blow-Down Heat. Heat of blow-down is generally too small in magnitude to create problems, unless discharged to very small streams.

From Meteorological Changes. Available evidence from existing cooling towers and ponds suggests that biological effects of meteorological changes would be minimal. There has been little critical study, however.
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III. A conceptual format for cooling system environmental impact assessment projects

SUMMARY

A general procedure is presented for the conduct of predictive impact assessment for proposed power plants with once-through cooling. The first step considers relevance of listed sources of potential damage for specific site and cooling design options. Next, studies must be designed which quantitatively determine probability of hydraulic involvement of the biota with the power plant. Those species (or species assemblages) which are representative and important to the natural system or to man are selected for definitive biological study to establish the probability of direct damage by the plant. Population modelling is introduced to illustrate techniques to assess consequences of direct damage to single species. The importance of considering implications of direct damage for the community and ecosystem is also cited.

III.1 Introduction

Current perspectives on power plant impacts are increasingly aimed at assessing probabilities of risk for aquatic populations, communities and ecosystems. The field of pollution control has matured beyond the phase of simply demonstrating that there can be effects of potential pollutants on the organisms of the biosphere. We have entered the more difficult and demanding phase of assessing implications of these effects for a local ecosystem or natural resource, in order to evaluate risks and benefits associated with specific human activities. This maturation of approach intensifies the need for well designed scientific and social assessments.

III.1.1 The conceptual assessment format

A conceptual framework for impact analyses of power stations of power stations on aquatic life has evolved in the USA which encompasses several steps (Fig III.1) and requires expertise in many scientific disciplines (Coutant, 1974). Determining the likelihood of direct biological damage to exposed organisms is merely one step involved in assessment of risk to the ecosystem or the larger biosphere. The analysis must begin with (1) careful attention to all sources of potential ecological damage (or change) from the facility, both during the operating and earlier construction phases. These have been described in Chapter II. Then (2) information on the distribution and abundance of organisms in the ecosystem must be coupled with (3) hydrologic and hydraulic assessments to determine the likelihood that key organisms or life stages will come in contact with the sources of potential damage. Next (4) probable damage to these key organisms must be estimated, based on quantitative effects data (both lethal and sublethal) from laboratory or field studies. This information must then (5) be translated into changes in population dynamics of each key species (particularly as yields to fisheries or possible declines to extinction are concerned). And (6) at the community and ecosystem level, risk assessments to normal structure and function should be sought (e.g. changes in diversity and types of species and of functional aspects such as energy flow and nutrient cycling). Mathematical modelling is one approach to evaluate long-term population, community and ecosystem effects. The last stage (7), often beyond the realm of the ecological analyst, is the assessment of the probability for social impact.
The relative importance of the several sources of potential ecological change, whether from a once-through or close cooling system, will differ depending on the engineering design of the power station cooling system and the biota and environmental characteristics of the site. It becomes the job of the environmental analyst to determine which are relevant and which warrant detailed study or early remedial attention in cooling system design.

III.2 Probability of Hydraulic Involvement of the Biota: Site Description, Hydrographic Modelling and Preliminary Field Studies

Knowledge of local conditions of the water body and surrounding environment used by the power station is now seen to be as important in assessing ecological risks as are data on the direct biological effects of cooling water use per se. The likelihood that a species (or community) will be exposed to particular sources of potential damage at a power station can only be evaluated with knowledge of (1) cooling system engineering design, including location and type of intake and discharge, and (2) the hydrodynamics of the water body relevant to withdrawal of water and organisms at the intake and dispersion of the discharge. Such hydrodynamic processes are addressed in Chapter IV.

As the zones of influence of a cooling system are identified for both the intake and discharge (see Chapter VI for methodology) it is possible to enumerate those components of the local biota which could be impacted. Elaborate mathematical models of hydraulic patterns have, for example, been utilized to estimate the likelihood that eggs and larvae of anadromous fishes in an estuary would be entrained with power station cooling water before they successfully pass from the affected zone (Hess et al., 1975, Eraslan et al., 1976) (Fig III.2). With some simplifying assumptions one can calculate the probability of entrainment for randomly distributed planktonic organisms passing the power plant (Table III.1) or the probability that organisms drifting at a certain location in the water body will be withdrawn (Fig III.3). Similarly, the likelihood that organisms in the discharge area will receive thermal exposures of a given magnitude and duration can be estimated if the thermal effluent dispersion and flow rates in the discharge area can be accurately modeled (Fig III.4).

Hence, this second phase of the impact analysis serves to define the volumes of water to be used, the specific areas potentially influenced by water withdrawal and discharge, certain physical characteristics of this water use (flow rates at and rates and spatial patterns of temperature decay upon discharge) and identify amounts and frequency of any chemical biocide use. This type of information is mandatory for the design of laboratory studies which are to simulate the full range of thermal and other stresses which the local biota could experience during cooling system operation. Further, the biological field surveys conducted during this phase will specifically identify those organisms which occur (whether permanently, seasonally, or only as migrante) within the zone of influence at the intake and discharge. It is the task of the ecologist to subsequently select from this list those species or communities which represent economically or ecologically important aquatic resources, for which risk assessment must be undertaken.

Assessment of risk implies that we have some clear notion of what we could be putting at risk. Thus, the specific resources which we believe to be at risk should be clear. Chronic effects of power stations on an estuary, for example, can hardly be evaluated against vague notions of the "proper functioning" of the estuary ecosystem. The essence of quantifying "probabilities of involvement" is to explicitly draw the relationship between these ecological resources which we deem valuable and their interaction with the power station.

An accurate understanding of the life patterns of potentially affected organisms is essential to estimating the probability of their involvement with the power plant system. Distribution and abundance of each species, including their developmental stages, will almost certainly vary with location and time of year. The annual movements of mobile organisms and their spawning and nursery grounds must be known in relationship to the intake and discharge of the power station to assist in visualizing places and times of probable interaction (Fig. III.5). Consideration of reproductive strategies of the organisms may be especially crucial when predicting impacts because the life stages most often affected are larvae or juveniles.

Resource maps of water bodies, which indicate relative biological values of different locations, are particularly useful for locating power stations or their inlet and outlet works at points where there will be minimal ecological damage. To create such maps, habitats of importance for key species (e.g. spawning areas, migration routes, wintering grounds, etc.) or location of sensitive or important communities can be indicated by appropriate shading,
Figure III.1 Analytical steps that are important for estimating risk to aquatic organisms from power plant cooling systems (after Coutant, 1974)

Figure III.2 Schematic representation of a discrete element of an estuary with tributary (right) and power plant (left) that forms the conceptual basis for a computer simulation model of the geometry hydraulic flow and larval fish population density that is used to estimate probability of entrainment (after Eraslan et al., 1976)
Figure III.3  Idealized flow field from a river into a power station intake (adapted from Dresner et al., 1973). In practice there is not a clear dividing line between the entrained zone and the bypass zone, rather there are isopleths of decreasing probability of entrainment as one progresses towards the centre of the river.

Figure III.4  Thermal dispersion pattern observed by infra-red imagery for a discharge plume in the Columbia River (after Jaske et al., 1970).
Figure III.5  Schematic diagram of the life cycle of the alewife (Alosa pseudoharengus) in relation to the Palisades power plant on Lake Michigan, USA (after U.S. AEC 1972).
colouring or other designations. The biological resources of the Chesapeake Bay (USA) are currently being mapped in this fashion (Maryland Power Plant Siting Programme 1975). Overlays depicting the extent and nature of water body utilization by a service of key species, can aid in identifying the role of the water body in maintaining these populations.

III.3 Probability of Direct Biological Damage

This phase of the impact assessment involves definitive evaluation of the potential of direct damage to the biota which occur within the cooling system zones of influence. The investigation at this point is largely autecological in nature, focusing on damage potential for single species selected on the basis of literature reports of damage susceptibility, for their importance to the ecological system (e.g. community dominants) or their importance to society because of their economic or aesthetic value. The selected representative and important species (RIS) will be evaluated in part by laboratory studies of thermal tolerance, chlorine toxicity, physical frailty and tests which simulate combined cooling system stresses. Test conditions representative of the site and power plant in question would be employed (e.g. local base temperature regimes for acclimation purposes and the proposed degree rise and exposure durations in the case of a temperature study). Experimental material would be drawn from the local population, if possible. Otherwise, literature data may be satisfactory. For additional details on this approach, see Chapter VII, Coutant (1970) and Schubel and Marcy (1978); also Carter et al. (1977) for illustrations of laboratory studies coupled with hydrographic modelling for a large lake, river and sound.

Data on the hydraulic and biological involvement of organisms with the power station will be used to perfect and finally validate the ecological relevance of experimental data and designs. The field studies will be subsequently expanded for those key species or communities which one found to have high potential for direct damage in order to provide data to evaluate the consequences of this damage at the population and community levels.

The selection of the primary study species for both this and subsequent phases of the analysis must be done with great care and only after preliminary studies have been completed. These indepth investigations of the representative and important species are a crucial data set for estimating the cooling system impact on the remainder of the ecosystem. The rationale for using selected species, and criteria for selecting them have been outlined by Coutant (1977) as follows:

1. It is impossible to adequately study every species that may exist at a site of pollution or other impact - there isn't enough time, enough money, enough expertise, or (most important) the state of knowledge of aquatic ecology isn't adequate to predict all eco-system interactions that may be relevant to the particular source of impact. Since all species cannot be adequately studied in the time-frame for making an impact evaluation, some smaller number is to be chosen.
2. The species of primary concern are those causally related to the sources of impact. Although there may be repercussions throughout an ecosystem if certain elements are destroyed, the most obvious change will generally be on the species directly affected. If we are to correct design or siting mistakes, we must also be most concerned with causal relationships.
3. Some species of fish and invertebrates at a site will be economically important in their own right, e.g. commercial and sports fishes, regardless of connections to the ecosystem as a whole. Some others may be nuisance species and thus important to society in the negative sense.
4. Some species are known to be critical for the structure and function of their ecosystem, either as habitat formers (e.g. corals) or through food chain relationships. These would be "important" in an ecological sense.
5. Some species which we can term "representative" will be either particularly vulnerable to the source of potential damage (based upon our prior knowledge from laboratory or field studies), or they are truly representative of other local species in their biological requirements. If these species are protected, there is some assurance for protection of the other species at the site.
6. Often, the list of organisms that might be considered "important" or "representative" is still too long to be practical and a smaller list, perhaps greater than 5 but less than 15, may have to be chosen. Yet at a minimum, we would want the reduced list to include a diversity of the more sensitive fish, shell fish, or other species of direct use to man or
important for the structure and functioning of the ecosystem.

Finally, there is a category of organisms termed endangered species (e.g. the US Endangered Species Act of 1973 (PL 93-205) which are automatically "important" by legal definition and which must be carefully considered in any environmental impact evaluation.

The limited scope of ecological analyses inherent in the RIS approach is acceptable in many cases because decisions regarding water resource use are often required before all pertinent ecosystem information can be obtained. Knowledge continuously builds - sometimes to reveal our successful predictions, sometimes to reveal our mistakes. We may minimize the mistakes within practical limitations of today's environmental sciences if we concentrate our initial efforts on those species that we feel are either particularly important or are representative indicators of the rest. Whether the ecosystems be designated as wild or managed (most freshwater bodies are actually managed for certain harvestable species), knowledgeable scientists and managers should be able to compile a list of key species based upon the water body use objectives. These species can then receive more than haphazard attention. The detailed information developed on them will provide clearer decision criteria for the planner and regulatory authorities and clearer standards for later judging any changes in the integrity of natural water bodies.

Probability of Population Effects. For species having a high potential for direct cooling system damage, detailed population dynamics analyses may be desirable to quantitatively predict the significance of direct power plant affects. Two excellent examples of such analyses are: (1) the Hudson River striped bass (DeAngelis et al., 1978; USNPC, 1975); (2) winter flounder in Niantic Bay (Hess et al., 1975). Brief discussion of one case study bass, will indicate the type of analysis which has proven useful for power plant effects analyses.

Striped bass, Morone saxatilis, occupies the lower Hudson River where there are seven existing power plants and one propose project, the Cornwall pumped-storage facility (Fig III.6). The concentration of power plants between mile points (MP) 38 and 65 is of particular concern, due primarily to the large cumulative water withdrawal from the Hudson River by these plants. From 1950 through 1972, there was a steady but gradual increase in water withdrawal as Indian Point Unit 1 and the various relatively small units at Lovett and Danaskammer came on line. Since 1972 there has been a rapid and large increase in the cumulative water withdrawal as relatively large units at Bowline, Roseton and Indian Point have come on line. Water withdrawal in future years is in question and depends on the fate of the proposed Cornwall pumped-storage facility, the installation of closed-cycle cooling at Bowline, Roseton and Indian Point Units 2 and 3, and the construction of additional power plants in this middle region of the lower Hudson River.

Although the cumulative effects of thermal and chemical discharges from these plants clearly require monitoring because of potential habitat alteration, the primary concern has been the direct cropping impact on fish populations due to impingement on the intake screens and entrainment in the water passing through the plants. In response to this concern, the three utilities involved have supported a steadily escalating research programme that somewhat parallels the water withdrawal curve and that now involves expenditures exceeding $5 million per year.

Entrainment and impingement data indicate that the fish species having the greatest potential for being adversely affected by the operation of the power plants are striped bass, white perch, tomcod, alewife, blueback herring and anchovy (USNRC, 1975). For several reasons, however, the impact assessment has concentrated on one of these species, the striped bass. The striped bass in a "representative and important species" in that it is the object of an intensive sport and commercial fishery, it is a representative anadromous species (returning to fresh water to spawn), and it is one of the top carnivores in the fish community in the Hudson River Estuary. Secondly, the spawning distribution of striped bass in the Hudson River is in and immediately above the region in which the plants are concentrated while the major nursery area for young-of-the-year striped bass is in Haverstraw Bay and Tappen Zee Bay immediately below Bowline, which is below most of the other plants. Data indicate that the majority of young-of-the-year striped bass which survive to reach this major nursery area move past these power plants at an entrainable size (i.e. less than 50 mm long) (USNRC, 1975). Finally, considerably more field data are available for striped bass than for any of the other five fish species of concern, thus permitting a more detailed and accurate assessment.

Although this assessment was carried out in the course of the licensing procedure
Figure III.6  The Hudson River (USA) north of New York City showing major existing and planned power generating plants. A heavy concentration of plants between Tarrytown and Poughkeepsie withdraws cooling water from a zone of the river that is important for spawning and early development of the striped bass, a fish that is important for sports and commercial fisheries.
for a single power plant (Indian Point Unit 3), young-of-the-year striped bass are subjected to entrainment and impingement impacts from the entire complex of power plants on the Hudson River. Consequently, a multiplant or regional assessment of the impact was necessary. As an aid in determining the significance of the entrainment and impingement impact on the Hudson River striped bass population, two models were developed: a young-of-the-year population transport model (Eraslan et al., 1976) and a life-cycle population model (DeAngelis et al., 1978). Other simulation models for the Hudson River striped bass population have been developed by Clark (1972), and Lawler, Matusky and Skelly Engineers (1973).

The young-of-the-year model (Eraslan et al., 1976) considers six life stages (egg, yolk-sac larva, post yolk-sac larva, and three juvenile stages), and includes dependence of spawning rate, mortality rates, growth rates, apparent survival probabilities and maximum swimming speeds on temperature, salinity and population densities. The transport of each of these life stages in the Hudson River is formulated in terms of a daily transient (tidal-averaged), longitudinally one-dimensional (cross-section-averaged) hydrological transport scheme. Major features of the hydraulic model were discussed earlier in this chapter (Section 2, Probability of Involvement) and represented schematically in Fig. III.2. The validation procedure for this model involves comparing simulated and observed weekly standing crop values in the Hudson River for each of the young-of-the-year life stages.

From the striped bass young-of-the-year population model, we obtain forecasts of the percent reduction in the number of striped bass surviving their first year, due to mortality at the power plants. This percent reduction value provides input to the striped bass life-cycle population model (Fig III.7) (Van Winkle et al., 1974, DeAngelis et al., 1978). The life-cycle model is designed to evaluate the long-term impact on the striped bass population of changes in mortality in the youngest age class. The general question concerns what happens to a fishery when new density-independent sources of mortality which act on the young-of-the-year are added to already existing sources of mortality. This model considers all age classes of striped bass from young-of-the-year to fifteen-year-olds and older. The model is strictly time-dependent and, unlike the young-of-the-year model, does not include spatial considerations. In the model, the striped bass population is presently assumed to be regulated in the long-term time frame by fishing in a compensatory (density-dependent) manner.

Typical (but hypothetical) results from the life-cycle model are illustrated in Fig III.8 for two situations. Situation 2 involved an annual reduction of 50% for each of the first 35 years in the number of striped bass surviving their first year, due to mortality at the power plants, and then no power-plant impact for the next 65 years, followed by an annual reduction of 10% for the next 30 years following installation of cooling towers, and then no power-plant impact for the next 65 years. Relative yield is defined as the ratio of the yield to the fishery with a power-plant impact to the yield with no power-plant impact. The hatched area in Fig III.8 represents an index of the difference in the expected impact on the striped bass fishery from the two power plant designs and can serve as a basis for calculating an index of risk of irreversible damage to the striped bass population (Christensen et al., 1976). This index takes into account both the number of years and the extent that the relative size of the population is depressed below 0.5 of its original steady-state size.

Public policy decisions regarding use of cooling towers or other off-stream cooling devices for future power plant developments on the Hudson River can presumably be made from a clearer understanding of the impacts on this one important species. Alternative models and assumptions provide critical guidance for needed field research, as can be seen in the licensing proceedings for one new power station (USNRC, 1975).

Probability of Community and Ecosystem Changes. Except for the zones near power station discharges, effects at the community and ecosystem level have received little attention. This is regrettable, for the high costs of many alternative cooling systems and mitigating devices are raising questions about the broad ecological significance of power station impacts as opposed to "the killing of a few fish". An important indication that society as a whole recognizes the importance of protecting aquatic populations and the higher levels of ecological organization is the United States' Water Pollution Control Act Amendments of 1972 (PL 92-500) which state that closed-cycle cooling shall be used at power stations unless it can be shown that the power station has no effect on the balanced, indigenous populations of the water body. As a result of this law, electric utilities in the USA are currently gathering data at many power stations in an effort to demonstrate lack of community and ecosystem damage.

There are basically two approaches to estimate community and ecosystem effects:
Figure III.7  Schematic diagram of a striped bass life-cycle population model used to determine the impact on the species' population of reducing numbers of eggs, larvae and first-year young by entrainment and impingement. Natural and induced mortality reduces numbers of individuals in each year class. Fish four years old or more produce eggs to replenish the cycle (after Van Winkle et al., 1974).
### TABLE III.1 Attributes of ecosystems (from Reichle 1975)

<table>
<thead>
<tr>
<th>STRUCTURAL</th>
<th>DYNAMIC</th>
<th>STRATEGIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>Homeostasis</td>
<td>Optimization</td>
</tr>
<tr>
<td>Organization</td>
<td>Circulation</td>
<td>Efficiency</td>
</tr>
<tr>
<td>Diversity</td>
<td>Stability</td>
<td>Adaptation</td>
</tr>
<tr>
<td>Connectivity</td>
<td>Sensitivity</td>
<td>Perpetuation</td>
</tr>
</tbody>
</table>

### TABLE III.2 Results of a mathematical perturbation of an ecosystem model of a reservoir cove by adding a 3°C constant rise to the normal temperature pattern. The biomass predictions are given both in grams per square metre and as percentage deviations (increase (+) or decrease (-)) from predictions for the normal temperature cycle (after stabilizing to the third year). Energetic variables (production, respiration and their ratio) are also shown. (From Patten, 1975, with kind permission of American Fisheries Society).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Predicted Biomass (Third year nominal mean g m(^{-2}))^a</th>
<th>Change in Biomass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State variables:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small phytoplankton</td>
<td>1.53 x 10(^{-2})</td>
<td>-1.1</td>
</tr>
<tr>
<td>Medium phytoplankton</td>
<td>1.32 x 10(^{0})</td>
<td>-2.3</td>
</tr>
<tr>
<td>Large phytoplankton</td>
<td>1.47 x 10(^{-2})</td>
<td>-3.5</td>
</tr>
<tr>
<td>Blue-green crusts</td>
<td>1.77 x 10(^{-2})</td>
<td>+2.0</td>
</tr>
<tr>
<td>Floating mats</td>
<td>2.44 x 10(^{-1})</td>
<td>+8.8</td>
</tr>
<tr>
<td>Attached algae</td>
<td>5.52 x 10(^{0})</td>
<td>-4.2</td>
</tr>
<tr>
<td>Aufwuchs</td>
<td>4.90 x 10(^{-1})</td>
<td>-2.2</td>
</tr>
<tr>
<td>Submergent plants</td>
<td>2.63 x 10(^{0})</td>
<td>-1.0</td>
</tr>
<tr>
<td>Emergent plants</td>
<td>1.86 x 10(^{0})</td>
<td>-11.9</td>
</tr>
<tr>
<td>Small zooplankton</td>
<td>2.95 x 10(^{-3})</td>
<td>0.0</td>
</tr>
<tr>
<td>Large zooplankton</td>
<td>3.76 x 10(^{-2})</td>
<td>+0.6</td>
</tr>
<tr>
<td>Larval fishes</td>
<td>4.52 x 10(^{-2})</td>
<td>-27.5</td>
</tr>
<tr>
<td>Fingerlings</td>
<td>6.44 x 10(^{-2})</td>
<td>+1.5</td>
</tr>
<tr>
<td>Filter feeding fishes</td>
<td>4.23 x 10(^{-1})</td>
<td>+7.7</td>
</tr>
<tr>
<td>Bottom feeding fishes</td>
<td>9.85 x 10(^{-1})</td>
<td>+13.5</td>
</tr>
<tr>
<td>Minnow-like fishes</td>
<td>7.78 x 10(^{-1})</td>
<td>+58.1</td>
</tr>
<tr>
<td>Carnivorous fishes</td>
<td>1.14 x 10(^{-1})</td>
<td>+29.5</td>
</tr>
<tr>
<td>Turtles</td>
<td>5.95 x 10(^{-2})</td>
<td>+17.2</td>
</tr>
<tr>
<td>Plant harvesters</td>
<td>2.02 x 10(^{-2})</td>
<td>+5.7</td>
</tr>
<tr>
<td>Animal harvesters</td>
<td>2.59 x 10(^{-2})</td>
<td>+43.2</td>
</tr>
<tr>
<td>Suspension feeders</td>
<td>5.78 x 10(^{-2})</td>
<td>-4.3</td>
</tr>
<tr>
<td>Deposit feeders</td>
<td>1.74 x 10(^{0})</td>
<td>+1.2</td>
</tr>
<tr>
<td>Predators</td>
<td>1.53 x 10(^{-1})</td>
<td>+15.6</td>
</tr>
<tr>
<td>Dissolved organic</td>
<td>2.42 x 10(^{1})</td>
<td>+3.7</td>
</tr>
<tr>
<td>Particulate organic</td>
<td>2.49 x 10(^{0})</td>
<td>-5.7</td>
</tr>
<tr>
<td>Plant carcasses</td>
<td>1.51 x 10(^{0})</td>
<td>-4.9</td>
</tr>
<tr>
<td>Animal carcasses</td>
<td>5.20 x 10(^{-4})</td>
<td>+78.3</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>9.09 x 10(^{-2})</td>
<td>+42.8</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>2.90 x 10(^{-2})</td>
<td>+8.6</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.44 x 10(^{2})</td>
<td>+0.5</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>1.72 x 10(^{1})</td>
<td>-7.2</td>
</tr>
</tbody>
</table>

| **Output variables:** | | |
| Gross production | 2.87 x 10\(^{6}\) | -3.5 |
| Respiration | 2.66 x 10\(^{6}\) | +5.5 |
| P/R ratio | 1.08 x 10\(^{6}\) | -8.6 |

\(\text{a g m}^{-2} \text{ wk}^{-1}\) for gross production and respiration; unitless for P/R ratio.
The figure shows hypothetical curves of relative annual yield to the striped bass fishery in the Hudson River modelled by the striped bass life-cycle population model. Design 2 illustrates a result when once-through cooling is used by a power plant; design 1 illustrates the result when cooling towers are installed after the plant begins operation. The hatched area represents a quantitative estimate of the resource that could be protected over the lifetime of the power plant by a regulatory requirement to install cooling towers.
(1) develop predictive models based on the expected consequences of altered mortality or other direct species responses (metabolism, growth, reproduction, disease, parasitism, predation, competition, etc.) to total cooling system stress, or (2) seek to model changes in the emergent attributes of ecosystems, i.e. the structural characteristics and dynamic properties which govern the flow of energy and cycling of elements in the biosphere. Reichle (1975) tabulated important attributes of ecosystems which do not derive directly from lower levels of organization (Table III.1); Cairns (1976) identified other attributes which relate directly to an ecosystem's tolerance of human perturbation.

We know that small temperature differences applied over long periods can cause differences in aquatic ecosystems based on well known latitudinal differences and in changes in the distribution and abundance of species when there are slight climatic changes. Latitudinally, the geographic distribution of many species is limited by climate. Populations at the extreme southern limits of a species range can be reduced or eliminated following a slight temperature rise (Kennedy and Mihursky, 1971, Dickie, 1958), while species with southern affinities can increase. The abundance of many species, especially commercially important species, has been shown to vary over a wide geographic range within a relatively short period of time (1 decade) in response to climatic changes of 4°C in seawater temperature (Dow, 1964, 1969, Southward and Crisp, 1954; Taylor, Bigelow and Graham, 1957, Welch, 1968). Climate elevation of 1°C have been correlated statistically with major shifts of commercial catch of several species (Johnson and Schneider, 1976).

Unfortunately for the impact analyst, most changes at the community and ecosystem level require several years to become evident and may not be practical to consider in adequate detail for a predictive environmental impact assessments. By that time, however, power plant impacts may have progressed to the point where mitigation is either not possible or would itself require a long time. Gradual eutrophication is an example. Extreme cases of eutrophication have been reported for cooling ponds in the USSR (IAEA, 1974). They have been caused by gradual accumulation of nutrients in closed water bodies, and gradual changes in the biotic communities which have been supported. The annual changes were probably small, however, and the ecosystem change was not evident until the long-term damage had been done.

Because of the inherent time lag with large biological systems, ecosystem modelling has been developed as a predictive tool. Its use corresponds with population dynamics modelling discussed earlier, but it focuses on different interactions, i.e., those which pertain directly to ecosystem structure and function. Patten (1975) described a reservoir cove ecosystem model and the changes in its steady state when the cove was, through mathematical simulation, given a 12 month perturbation of a 3°C elevation above the annual temperature cycle. This rise increased the rates of virtually all biological processes in the model since most coefficients were temperature dependent. The results (Table III.2) showed highly variable changes from the normal third year mean values among the different ecosystem components. Gross production declined 3.5%, while respiration increased 5.5%. The P/R ratio, often used as an index of ecosystem "health", declined in the model prediction by 8.6%. As with population models, however, validation remains a difficult if not insurmountable problem.

Probability for Social Impacts. Damages to particular aquatic species by power plant cooling systems should be reviewed in different perspectives based on the social importance of the species. Effects on a highly prized sports or commercial fishery will have much larger social impact than damage to a little-known microorganism. Social impacts will also be highly dependant on local or regional values. Aquatic species that are highly favoured in some regions may be considered undesirable in others, and vice versa. The impact analyst should keep this social perspective in mind as he judges the severity and significance of changes in aquatic ecosystems.

Analysis of the long term social impacts of changes in the composition of aquatic environments due to "pollution" is a complex task that should include more expertise than that of aquatic ecologists. Some social impacts are quantifiable (e.g. economic effects of loss of a fishery) but others are not. Many relate more to social values of aspects of the human environment deemed important than they do to quantitative economic criteria. As the social costs of damaging technologies increase and the economic burdens of mitigating these damages also increases (often at rates faster than the reduction in social costs), we can expect increasing social debate over costs vs benefits of our actions.
REFERENCES CITED


Clark, J.R. 1972. Effects of Indian Point Units 1 and 2 on Hudson River aquatic life. Testimony before the Atomic Safety Licensing Board, Indian Point Unit No. 2 USAEC Docket No. 50-247, October 20, 1972.


IV. Physical aspects of intake and discharge of cooling water

SUMMARY

General information is presented about once-through cooling systems using natural water bodies: rivers, lakes, reservoirs, estuaries and coastal waters. The characteristics of these water bodies, including dynamic, hydrological, morphometric and meteorological information are briefly outlined. Functions of intake and discharge are described from both the technical and the environmental points of view. Withdrawal of cooling water through the intake structure changes natural velocity and water temperature distribution, thus affecting environmental conditions. Examples of existing intake structures are given, together with practical recommendations and methods of investigation. Discharge of heated water is considered in the near and far-field region in the form of buoyant surface discharges, submerged buoyant jets and stratified flow.

IV.1 Introduction

Once-through cooling systems present real advantages for thermal (fossil fuel and nuclear) power plants from both the economic and the operational points of view. Therefore they are always the first cooling system option to be considered. A once-through cooling system carries off waste heat from the power plant by means of water flowing through the condenser and discharges it to the natural water body. There, waste heat is transferred to the atmosphere which is the ultimate heat sink.

Once-through systems consist of the intake, an internal (inplant) part, the outfall, and a large external part including the natural water body. Typically, water discharged at the outfall either does not return to the intake again, or returns after a long time when its temperature has reached the natural level. One of the important advantages of these systems is their large thermal inertia, assuming that the natural water body has a large surface and volume. As a result, hydrological and meteorological changes, as well as load changes of the power plant, do not result in rapid variations of cooling water temperature - a favourable condition for plant efficiency (Harleman, 1976).

Present power generating capacities of the order of 3000-4000 MW(e) installed at a single site demand large quantities of cooling water (Fig.I.1), thus restricting once-through systems to large water bodies. The majority of inland waters are either too small, or are already dedicated to other water uses. Consequently coastal waters are more and more frequently used for cooling purposes, although the salt contents of sea water presents some additional technological complications. Off-shore nuclear power plants located 4 to 5 km from the shore-line have been proposed as one answer to the cooling water supply problem (Fisher, 1975; Jirka et al. 1977).

The cooling water system is an important part of the power plant and its proper operation has a significant influence on the overall efficiency. Therefore cooling system design must take into account all the technical aspects which will provide the greatest efficiency. Nevertheless, the ecological aspects of cooling water use must also be considered in order to minimize any deleterious effects on the natural water body. The design of once-through systems should also take into account all present and prospective users of a given water body such as hydro-energy, navigation, industrial and municipal use, recreation, etc. (US Environmental Protection Agency, 1973).

A general solution for the design of once-through cooling systems would be difficult
because of the different characteristics of individual power plant sites and water bodies. Therefore each case must be considered separately, taking into account all the technical, economic and ecological aspects (Hauser, 1971).

The intake and discharge of cooling water bring about important changes in the aquatic environment. In the vicinity of the intake, due to the withdrawal of large quantities of water, a change in the local velocity field is observed. This may influence the existing currents pattern, the transport of suspended and bottom sediment, and the existing stratification. Much larger changes are observed near the outlet due to the discharge of cooling water at a temperature of 6° to 11°C above the natural water temperature. This will not only cause changes in the existing velocity field, but will result in thermal stratification and the formation of areas of increased water temperature. Moreover, the intake and discharge of cooling water may affect large-scale circulation in natural water bodies, possibly leading to changes in the environmental conditions.

Consumptive water use in once-through cooling systems is of the order of 1 to 2 percent of total circulating discharge and is caused mainly by increased evaporation from the artificially heated water surface. In most situations this does not present a problem, although in the case of lakes with small inflows the additional evaporation may disturb the natural water balance. Methods of calculating the additional evaporation rate due to increased temperatures are presented in Chapter V.

IV.2 Intake and Discharge (Outlet) of Cooling Water

The flow of cooling water through the internal part of the system is induced by pumps and can be controlled precisely. In contrast, the flow of cold water into the intake, and the dissipation of the warm water near the outlet depend predominantly on morphometric, hydrological and meteorological conditions which may show significant temporal and spatial variations at a specific site. The size, construction, and relative positions of intake and discharge have also an important effect on flow conditions in the whole system. Further, the hydrodynamics associated with the intake and discharge of cooling water is complicated in comparison with other flow situations by the simultaneous occurrence of two factors, namely: the buoyancy, and the considerable volume and momentum of the discharge. The buoyancy is associated with the temperature change which occurs as the water passes through the condensers. Thus heated discharge cannot be treated as a passive discharge into ambient flow.

A cooling system having a short distance between intake and outlet is advantageous from the economic and technical points of view, because it permits the use of short inflow and discharge channels or conduits. However, locating the intake and outlet close together, creates the danger of recirculation, i.e. the withdrawal of discharge water which has not returned to the natural temperature (Bata, 1957). In this case, water temperature may build up in the area close to the intake and cause both a decrease of overall plant efficiency and intolerable environmental conditions. One solution is the construction of separating dikes. The other possibility is the construction of bottom intakes which will selectively withdraw only deeper, cooler water (Harleman, 1960). In shallow water bodies, where the construction of a bottom intake is not possible and a greater distance between intake and outlet is necessary to meet technical and environmental requirements, it is advisable to have longer inflow channels (conduits) rather than to lengthen the outlet ones. The reason for this is that the aquatic organisms entrained at the intake will be exposed to the unfavourable discharge water temperature during only a short time in the outlet channels.

Several examples of the location of intakes and outlets of cooling water are shown in Fig. IV.1. Fig. IV.1a., represents a typical intake for a river with an average discharge of 400 m³/s. The intake structure is equipped with a skimmer wall, and a surface discharge rejects heated water in the downstream direction. When river flows are smaller than 400 m³/s, the warm water will spread in the upstream direction and form an arrested thermal wedge.

Fig. IV.1b., represents a cooling water intake from a reservoir formed by damming a river with an average flow of 30 m³/s. Discharge of all warm condenser water is downstream from the dam, thus excluding any risk of recirculation.

Fig. IV.1c., shows the use of a lake for cooling purposes. The surface area of the lake is 14.2 km² and the depth is 18.0 m in the vicinity of the bottom intake. Heated water is rejected through a surface discharge which induces the spread of warm water over nearly the whole surface area of the lake.

Fig. IV.1d., shows a typical scheme for intake and discharge in coastal waters. A bottom intake is situated 300 m from the shore-line where the depth is 15 m, and the dis-
Figure IV.1  Location of intake and discharge of cooling water
charge in the form of a submerged diffuser is 100 m from the shore-line. This type of discharge causes a limited temperature rise in the area close to the intake, and thus minimizes recirculation.

IV.3 Water Bodies Used for Once-through Cooling

The availability of a continuous water supply, adequate in quantity for the cooling system of a steam-electric power plant has recently become one of the most important factors in power plant site selection. Concern about the environmental effects of excess temperature, and flow field changes in natural water bodies considerably restrict the possibilities of once-through cooling. It is, however, expected that good engineering design of the intake and discharge structures, based on an accurate knowledge of the characteristics of the water body, together with precise predictions of the temperature and velocity field will make it possible to satisfy environmental and technical criteria and thus permit retention of the once-through system as a cooling option. The following water bodies may be used for once-through cooling: rivers, lakes, reservoirs, estuaries, and coastal waters.

IV.3.1 Rivers

The large quantities of cooling water required for modern steam-electric power plants restrict the possibility of once-through cooling to rivers with a considerable discharge. A river affected by cooling water effluents has a water temperature regime in which a man-made component is superimposed on natural fluctuations, (Stefan and Chau, 1976).

Rivers usually exhibit considerable variation of stage and discharge with time (Henderson, 1966). Therefore the required cooling water volume must be carefully compared with the hydrological characteristics of the river. Suspended sediment or bed load movement which accompany high stages in rivers also presents difficulties for cooling water use and in some cases requires the construction of settling basins.

The operation of cooling water withdrawal and discharge can interfere with navigation, and the resultant velocity field in the river must also be considered. Discharge velocities perpendicular to the river bank should be low. This may be achieved by means of discharge structures having a large cross-sectional dimension of an appropriate direction of discharge in relation to the river flow.

Most rivers have no stratification because turbulence maintains a uniform temperature and chemical distribution. However, in some instances e.g. deep, slow-running rivers, stratification may exist during some periods of the year. River ice conditions must be considered, especially in cold climates. (Baily et al., 1974).

Moreover, all present and prospective users of a river section, including the potential influence of cooling water use on hydrobiological conditions, must be considered.

IV.3.2 Lakes

Under natural conditions lakes are stagnant water bodies in which the presence of currents is primarily due to wind-driven circulation and not to inflows and outflows. Small variations of water depth usually occur during the hydrological cycle. Hydrological and meteorological conditions determine the thermal structure of the lake and its seasonal variations (Stefan and Ford, 1975). Sedimentation processes in natural lakes are relatively small and appear mainly in the vicinity of natural tributaries. A once-through cooling system will change both water balance and thermal balance of the lake, due to cooling water discharge and increased evaporation (Stefan et al., 1972).

Shallow or medium-size lakes may be used for cooling purposes if the intake and discharge are located some distance apart so as to avoid recirculation. This requires the construction of intake or discharge channels and sometimes also dikes to ensure the continued circulation of warm water and hence increase the cooling surface. In large and deep lakes, intake and outlet may be located near each other at different depths.

IV.3.3 Reservoirs

Reservoirs are usually man-made lakes created for special purposes (flood protection, hydroenergy, irrigation, etc.), mostly by damming rivers. Therefore they are confined to river valleys and have very irregular characteristics. The water balance and thermal regime of reservoirs depend on their morphological, hydrological and meteorological conditions, as well as the
hydraulic regime resulting from their operational conditions (Huber et al., 1972).

Especially in mountain regions, the tributaries of reservoirs may carry a considerable sediment load in periods of heavy rainfall. Part of the coarse sediment is deposited in the vicinity of the inflow area, but fine sediment may be carried through the reservoir in the form of a bottom density current (Harleman, 1960). Sediment problems must be taken into account when the design of a bottom intake is considered. Construction of a once-through cooling system demands a detailed analysis of the new hydrodynamic and thermal conditions which may considerably influence aquatic life. Under certain conditions, a once-through cooling system may improve water quality in the reservoir by bringing deep hypolimnion water to the surface where it can be aerated. Reservoirs are usually deep, and this opens up many possibilities for location of the intake and discharge of cooling water.

IV.3.A Estuaries

Considered solely from the physical standpoint, estuaries are suitable for once-through cooling purposes because they usually provide large volumes of water. However, estuaries are much more complicated than rivers from the hydrodynamic point of view because of rapidly varying water levels, changes of flow direction, discharges, velocities and water density (salinity) gradients. Sediment transport and all sedimentation processes in estuaries are much more complex than in river channels. Depending on the magnitude of river discharge, tidal characteristics, estuarine basin morphology, and salt concentration in the coastal waters, estuaries may be fully mixed, partly mixed or stratified. Each of these situations demands a fresh analytical approach when evaluating the possibility of using the estuary for cooling purposes.

IV.3.5 Coastal waters

Recently, coastal waters have been increasingly used for cooling purposes (Golden, 1975) because of the decreasing availability of inland waters. The possibility of cooling water intake and warm water dispersion is complicated in coastal waters by the action of tides, along-shore currents and undulation. Sediment movement and salinity may bring about additional complications for the operation of once-through systems. In shallow coastal waters it is often necessary to construct off-shore bottom intakes or discharges in order to reach appropriate depths. If the coastal area is rich in aquatic life, special attention is required in the location and design of a once-through cooling system.

Quite recently, the first off-shore nuclear power plants were designed. These power plants are located 4 to 5 km from the shore-line, in deep water which provides a practically unlimited cooling water supply and, in a physical sense favourable conditions for waste heat disposal.

IV.4 Cooling Water Intake

IV.4.1 Some intake design requirements

The intake should be designed to ensure a constant supply of low temperature cooling water with small temporal variations. The cooling water should also be free of any floating material, trash, debris, sediment, weeds, and aquatic organisms which may impair the proper operation of the cooling system. The intake design should also protect fish and other aquatic organisms from impingement or entrapment within the intake structure. Several intake designs have been developed which successfully fulfill both these functions.

There are two general types of intake design. In the first type, water withdrawn is a homogeneous water body (i.e. one without vertical stratification due to temperature, salinity, or turbidity); in the second, water is withdrawn selectively from a depth at which the water is found at an appropriate temperature. The second category of intakes operates under complicated hydrodynamic conditions and the design should be based on detailed hydraulic model investigations or theoretical analysis. Skimmer walls and underwater dams are often used to selectively withdraw water from the bottom layer of lower temperature.

Log booms are used to protect the intake from large floating material and debris. Trash racks hold back medium size trash, weeds, and large fish. The wire-mesh screen prevents the passage of coarse sediment and small fish. It should be noted that the rack and wire-mesh protect the power plant but not the fish, which may be impinged on the screens. Therefore fish bypasses or deflectors should be located before the screens.

If there is very fine sediment which will not be stopped by the wire mesh, a settling basin may be employed. This design may be used for power plants where the circulating discharge
Figure IV.2  Scheme of river cooling water intake and discharge

Figure IV.3  Surface intake
Figure IV.4  Bottom intake

Figure IV.5  Bottom intake
is not very high (in the range 20 - 30 m³/s).

The risk of intake icing should also be considered as this could cause flow restrictions or even structural damage. De-icing procedures include the discharge of warm condenser water in the vicinity of the intake.

Intake design depends very much on the morphometric conditions of the water body. The following types are often used: shore-line surface or bottom intakes, intake chammels, and off-shore submerged intakes.

The following general criteria are suggested for intake design and location (US Environmental Protection Agency, 1973):

1. Place the intake at a proper distance from discharge to avoid recirculation which will cause increased temperatures, dangerous to aquatic organisms, and reduction of plant efficiency.
2. Avoid location of the intake in the area of high biological value.
3. Reduce intake velocities, by enlarging inlet dimensions, to below 0.15 m/s at the trash rack to protect fish and other aquatic organisms from entrainment and impingement. This will also reduce the amount of entrained bottom sediment.
4. In shore-line intakes, avoid breaks in the natural shore-line which may act as fish traps.
5. Avoid location of the intake in areas used for recreation or in the vicinity of already operating intakes.
6. Avoid placing of the intake in the area of intensive sediment transport (river or coastal zones).

IV.4.2 Examples of intake structure

A typical scheme for the intake and discharge structure on a river having uniform temperature $T_r$ and depth $h_r$, is shown in Fig. IV.2 (Harleman, 1969). Cooling water $Q_i$ is withdrawn through bottom opening $h_i$ at intake temperature $T_i = T_r$. The upper part of the intake is closed by means of a skimmer wall which prevents warm water in the surface layer from entering the intake channel. This water, after passing through the condensers is discharged through the outlet channel at the temperature $T_o$, greater than the intake temperature by temperature difference $\Delta T$, which reduces water density by $\Delta \rho$. This warm, less dense water spreads in the surface layer in both downstream and upstream directions. Upstream it forms an arrested thermal wedge which, depending on flow conditions in the river and density difference, may move upstream beyond the intake. An intake with a skimmer wall will prevent recirculation in such cases. The depths of the warm water layer and the cold water layer are $h_1$ and $h_2$ respectively. Average velocity in the warm upper layer upstream from the outlet is practically zero.

Two examples of surface intakes from a river, lake or reservoir are shown in Fig.IV.3. Here the main emphasis is placed on fish protection against entrainment or impingement. Smooth-faced screens or a recessed screen with a fish bypass are the best solutions.

An example of a bottom intake is shown in Fig.IV.4. It is located on a rocky bottom where sediment movement does not exist. The intake withdraws water from the bottom layer through a radial structure directed towards the sea (Grunwaldsen et al., 1971).

Another bottom intake of the radial type is represented in Fig. IV.5. Intake openings are above the bottom to avoid the entrainment of sediment. A velocity cap reduces the possibility of fish entrainment, and the entrainment of trash floating on the water surface. The supply of cooling water to the power plant is accomplished by means of 2 horizontal pipes.

An intake designed for a coastal site with high sediment movement is shown in Fig.IV.6. It extends 220 m into the sea to reach a suitable depth. Water is withdrawn through the intake tower and then flows gravitationally through 2 concrete conduits to a settling basin where fine sediment is deposited. The settling basin has 2 chambers which may be closed alternately for cleaning.

IV.4.3 Velocity and temperature fields near the intake

All natural water bodies have their own velocity and temperature regimes which are governed by the hydrological cycles and meteorological conditions. These in turn govern other physical processes such as sediment transport, stratification, turbulence and turbidity which have an important influence on aquatic life. Withdrawal of cooling water through the intake
Figure IV.6  Bottom intake with settling basin
changes these conditions near the intake. The rate of change depends on the intake size, geometry, location and orientation in relation to the water body, and the local geometry of the water body. In order to predict physical changes in the water body after intake construction, a detailed knowledge of the natural hydrodynamic and thermal conditions is required. Prediction of velocity and temperature changes in stratified water bodies is very difficult. Changes caused by the withdrawal of cooling water are usually restricted to a small area near the intake and are reflected in velocity and temperature distribution, which are both of prime importance for the proper functioning of the intake.

In hydroelectric reservoirs, turbine intakes are usually located near the bottom and therefore withdraw cold water from the reservoir. If at the same time this reservoir were used for the cooling of a steam-electric power station, it would be advantageous to discharge warm surface water through the hydraulic turbines and keep the cold water taken from the bottom layer for condenser cooling. This can be achieved by the construction of a submerged dam in front of the hydroelectric power plant and a channel intake with a skimmer wall situated some distance upstream from the dam (Fig.IV.7). Thus, the submerged dam holds back cooler water but allows the discharge of surface water, while the bottom intake with a skimmer wall withdraws water from the bottom layer for the condensers (Gray and Stephenson, 1969).

IV.4.4 Studies of selective withdrawal

The ability to withdraw water from a region in which the density varies in the vertical direction is a significant advance brought about by an understanding of the mechanics of stratified flow. Control structures are used to provide cooler water at the condenser intakes of steam-electric power stations. Generally, lakes, artificial reservoirs or coastal waters used for cooling purposes require an intake design which withdraws the low-level cold water and discharges the warm water near the surface. In the case of thermal stratification induced by thermal discharges, temperature differences range from 5°C to 10°C. These result in density differences of the order of 1 kg/m³ which provide the conditions for selective withdrawal.

The aim of a selective withdrawal study is to assess the maximum flow which may be withdrawn from the bottom layer of lower density without entraining warm water from the upper layer, for a given intake and water body geometry, as well as the density difference between the two layers. Several investigations employing hydraulic model tests and theoretical analysis have been carried out by Craya (1949), Gariel (1949), Huber (1960), Harleman and Elder (1965), and Senshu (1968) who presented several bottom intake designs.

The most common solution of this problem is a hydraulic study using a two or three-dimensional model in undistorted scale. Simulation of stratification in such models is achieved by means of temperature difference or salinity. A combination of hydraulic model study, theoretical analysis and field measurements has recently been applied to the problem of selective withdrawal: Ho and Monkemeyer (1975), Slotta and Charbeneau (1975), Jirka et al (1977).

IV.5 Discharge of Heated Water

The ultimate heat sink for waste heat removed from a steam-electric power plant by the cooling water is the earth's atmosphere. In once-through cooling systems, water is circulated through the system and waste heat is discharged into natural water bodies. Transfer of waste heat to the atmosphere occurs by evaporation, radiation, and conduction/convection at the water surface. The use of water bodies for disposal of waste heat must take into account all the technical aspects of heat release, and the effects upon the environment of the flows and temperature rises produced in the receiving water.

Heated discharge can directly affect all biochemical processes and potentially impair the biological functions of aquatic life. Indirect thermal effects are difficult to measure and evaluate, but include the possibility of increased susceptibility to disease and predation or attraction of undesirable species. It is generally accepted that water temperature increases that induce sublethal effects should be avoided.

Protection of the natural aquatic environment requires the establishment of restrictive standards for temperature and mixing zone size. Specific standards usually take into account the size and nature of the receiving water body, seasonal effects, water use, etc. These standards are usually given in one or both of two categories: (1) maximum water temperature not to be exceeded, and (2) a maximum water temperature rise above natural ambient temperatures not to be exceeded. Such permissible increases outside the mixing zone usually vary between 1°C and 3°C. The size of the mixing zone may be specified either as an absolute surface area or as a percentage of total water surface or volume of the water body.
Powerhouse, dam, and submerged (underwater) dam

Cross-section

Intake with skimmer wall

Figure IV.7 Submerged dam and intake channel with skimmer wall

<table>
<thead>
<tr>
<th>NEAR-FIELD ZONE</th>
<th>TRANSITION</th>
<th>FAR-FIELD ZONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Diffusion</td>
<td>Buoyant</td>
<td>Ambient Diffusion</td>
</tr>
<tr>
<td>and Advection</td>
<td>Spreading</td>
<td>Surface Heat Loss</td>
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<td></td>
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<td>Advection by Ambient Currents</td>
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Spatial scale (m)

Time scale (s)

Figure IV.8 Physical processes in water body near warm water discharge
Such a low temperature rise can be accomplished only by intensive mixing of warm discharged water with the natural water body. Various types of diffusers are used for this purpose. Design possibilities for the heated water discharge range from complete stratification to full mixing of the heated effluent. In the case of stratification, the heated water flows into the receiving water body in a relatively thin layer from a surface discharge. In this case heat is transferred to the atmosphere at a maximum rate and there are negligible temperature changes at/or near the bottom of the receiving water (given adequate depths). Thermal discharge regulations usually prohibit highly stratified surface discharge with high surface temperature. To achieve a lower surface temperature, the velocity at the exit of the surface discharge must be increased, thereby entraining more of the colder receiving water into the heated discharge.

Complete mixing of the heated discharge with the available ambient water is the other extreme possibility. In this case, the condenser water flows through a diffuser pipe and is discharged through nozzles or ports near the bottom of the water body. Entrainment of surrounding water into the high velocity jets produces considerable dilution and rapid temperature reduction within a small area. In this situation, however, more heat is stored in the water body and the rate of heat dissipation from the water surface, is reduced.

It is generally possible to distinguish, in relation to the discharge point, two areas with different hydrodynamic characteristics, namely near-field and far-field zones (Jirka, 1976). The near-field zone is adjacent to the discharge point in which turbulence and receiving water entrainment is created by the shearing action of the discharge with respect to the ambient water. Within this zone the heated discharge initially mixes rapidly with the receiving water, with velocities and temperature diminishing in an expanding region until jet-induced mixing is no longer effective in entraining surrounding water. This jet diffusion process is also affected by the buoyancy of the discharge and interaction with ambient currents. The far-field zone exists beyond the near-field and occupies a considerably larger area in which the heated discharge is distributed mainly through buoyancy-driven currents and by advection and diffusion caused by the ambient current system. Because of the relatively large area of far-field processes, surface heat transfer and wind affect the temperature distribution considerably. The physical processes occurring in the near- and far-field, together with length and time scales, are summarized in Fig. IV.8.

The prediction of temperature distribution and velocity in the near- and far-field regions involves an understanding of a variety of fluid mechanics phenomena. In the near-field region the turbulent mixing of submerged buoyant jets or heated surface jets are the most important phenomena. In the far-field region the phenomena of stratified flow, heat advection and excess heat transfer to the atmosphere are of primary importance.

Heated water discharges may be classified in two different types: (1) Buoyant surface discharges, and (2) buoyant submerged discharges.

IV.5.1 Buoyant surface discharges

The discharge of heated condenser water into a natural water body will always include mixing of the discharge and ambient water. In the mixing region, usually regarded as the near-field zone, the heated discharge may be considered as a turbulent buoyant jet. Buoyancy is induced by the temperature difference between discharged and ambient water. The temperature and velocity distributions in the jet may, in certain cases, be found by using results from turbulent non-buoyant jets and taking into account additional complexities introduced by the buoyancy of heated discharge.

Buoyant surface discharges commonly empty from a large diameter pipe or an open channel terminating at the shore-line of the water body. The dominant transport processes in such surface discharges or jets are advection along the trajectory of the jet, lateral turbulent diffusion normal to the jet trajectory through irregular eddy motion within the jet and entrainment of ambient water (Ellison and Turner, 1959). The advective mechanisms due to the initial discharge momentum and buoyancy result in a horizontal spread of the warm water (Turner, 1973). An additional effect due to buoyancy is the damping of vertical turbulence, thereby reducing vertical spreading and entrainment. The buoyant effect is given by the local densimetric Froude number:

$$ F = U_c \left( \frac{\Delta \rho c}{\rho a} g h \right)^{-1/2} $$

where $U_c$ and $\Delta \rho c$ are velocity and density difference at a given point of the jet centreline on the-water surface, $\rho a$ is ambient water density, $g$ is acceleration due to gravity and $h$ is a
measure of vertical thickness of the jet.

Fig. IV.9. illustrates the problem under consideration. A dimensionless formulation of the heated surface discharge is given by

\[
\frac{T - T_a}{T_0 - T_a} = f \left( \frac{\Delta T}{C_p V_a}, \frac{K}{c_p U_0 \rho_a}, S_z, \frac{V_a}{U_0} \right)
\]

where: 
- \(T\) is water temperature in the warm jet,
- \(T_a\) is ambient water temperature,
- \(F_o\) is the discharge densimetric Froude number,
- \(U_0\) is the discharge velocity,
- \(\Delta \rho\) is the density difference due to temperature difference between ambient and discharged water,
- \(\rho_a\) is the density of ambient water,
- \(g\) is acceleration due to gravity,
- \(h_0\) is the depth at the discharge,
- \(K\) is the heat transfer coefficient (water-atmosphere),
- \(S_z\) is the bottom slope,
- \(V_a\) is the ambient water velocity,
- \(C_p\) is the specific heat capacity of water,
- \(A = h_0/b_0\) is the discharge channel aspect ratio,
- \(b_0\) is the width of the discharge.

Several investigations have been carried out to assess the effect of each parameter in equation (2) on surface temperature distribution. In particular, it is known that the theoretical critical limit for \(F_o\) is unity. For \(F_o < 1\) a stagnant wedge of ambient water will intrude into the discharge channel. For \(F_o > 1\) thermal discharge behaves like a turbulent jet. In the near-field region, temperature decrease is mainly due to the dilution of heated water with the ambient water body and heat transfer to the atmosphere has an insignificant effect.

More information about buoyant surface discharges is given by Hayashi and Shuto (1967), Harleman and Stolzenbach (1972), Harleman (1975), Jirka et al. (1975).

IV.5.2 Submerged discharges

Because of the increasing quantities of warm water discharged from steam-electric power plants, more effective means of dilution than is achieved with surface discharges is often necessary. Underwater discharges in the form of single or multiport diffusers have been commonly used for sewage disposal where a high degree of mixing was required. In view of restrictive temperature standards, submerged diffusers have also been used for heated water discharges. Their construction is more expensive than surface heated discharges but in many cases they present the only solution to meet temperature standards. Furthermore, for large quantities of heated water discharge, a single buoyant submerged jet is generally impractical since the dilution is rather small. Therefore the submerged discharge is often arranged as a multiport diffuser from which many single jets are issued. In this way, much greater dilution and temperature decrease may be achieved than for a single jet. The multiport diffuser consists of a pipeline laid on the bottom of the water body with many nozzles attached at regular intervals.

The dominant transport processes for submerged jets are convection along the trajectory of the jet and lateral turbulent diffusion normal to the jet trajectory through irregular eddy motion. The convective mechanism is due to the initial discharge momentum and vertical acceleration due to buoyancy. The water body into which a jet discharges has a strong influence on the behaviour of the jet (i.e. on its trajectory and dilution characteristics) and will vary from one water body to another. Even small currents in the receiving water can affect the trajectory and dilution of the buoyant jet and the important factor is water body stratification. A problem commonly encountered in predicting submerged jet behaviour concerns water bodies which are shallow with respect to the vertical dimensions of the discharge. The limited vertical distance over which the jet can rise and the effect of bottom friction can considerably change the jet behaviour in comparison with that at a deep water site. Effects of relative buoyancy, submergence and angle of the discharge are shown in Fig. IV.10a. for a submerged buoyant jet. Zones of stratified flow for a two-dimensional submerged buoyant slot jet are presented in Fig. IV.10b. Studies on these types of discharges have been carried out by Abraham (1965), Harleman (1975) and Jirka et al. (1975). High buoyancy (large temperature difference) in deep water results in a stratified flow which spreads uniformly in all directions in the surface layer. This occurs for both vertical and non-vertical discharge. A low buoyancy of submerged thermal discharge in shallow water will always produce unstable stratification in the near-field and lead to high entrainment and full vertical mixing. One of the primary aims of a submerged buoyant jet physical analysis is to determine the limiting conditions for a stable flow field and the degree of dilution.

The four regions associated with a buoyant jet (Fig. IV.10b) represent different hydrodynamic properties and must be considered separately. The behaviour of the submerged buoyant
Figure IV.9 Buoyant surface jet

T - Temperature Distribution
U - Velocity Distribution

Figure IV.10 Submerged buoyant jets

1 buoyant jet region
2 surface impingement region
3 hydraulic jump region
4 stratified counterflow region
Figure IV.11 Multiport diffuser

\[ j_{o} = \text{function of outlet densimetric Froude number:} \]

\[ F_{o} = \frac{U_{o}}{D_0} \left( \frac{\Delta \rho}{\rho_{a}} \times gD_0 \right)^{-1/2} \]  

where \( U_{o} \) is discharge velocity, \( \Delta \rho \) the initial density difference between warm and ambient water, \( \rho_{a} \) the density of ambient water, \( g \) the acceleration due to gravity, and \( D_0 \) the initial jet diameter.

Fig. IV.11 illustrates the operation of a multiport horizontal bottom diffuser in a non-stratified shallow water body with ambient current. Fully mixed flow is obtained over a relatively short distance.

A comparison of temperature distribution in shallow coastal water due to various forms of heated discharge is given by Harleman (1972). Results were obtained from calculations for two types of heated discharge: (1) Multiport diffuser, and (2) surface discharge from an open channel. The depth of the receiving water body is 9.15 m. Heated discharge from a 500 MW(e) steam-electric power plant is 28.3 m³/s with temperature difference \( \Delta T_0 = 8.3^\circ \text{C} \). The results are presented in the form of isotherms of excess (above ambient) temperature for the water surface and in cross-section along the plume centreline (Fig. IV.12).

In the case of the submerged diffuser, discharging in the off-shore direction, the increase of temperature occurs throughout the whole water depth but the surface area of the +0.5°C excess temperature isotherm is about 50 per cent smaller than for surface discharge. In the case of surface discharge, a thermally stratified flow results, leaving half the depth near the discharge at the natural ambient temperature.

IV.5.3 Stratified flow.

When a surface-heated discharge or a submerged buoyant discharge are controlled to minimize mixing between heated effluent and receiving water, a thermally stratified flow will be obtained. This can result in flow in all directions from the outlet. Heat dissipation to the atmosphere in this case is maximized since the surface temperature is at its maximum. The physical analysis of this type of discharge is based on the theory of two-layered stratified
Figure IV.12  Temperature distribution for submerged diffuser and surface discharge
flow, as illustrated by Fig. IV.13. For simplification, the flows are assumed to be steady in homogeneous layers with a density difference across the interface. An average velocity over the whole depth of each layer is also assumed. The direction of flow in the two layers may be in the same, opposite, or either layer may have zero velocity. The equations of motion and continuity for each layer may be combined into one differential equation for the slope of the interface (Harleman, 1960):

$$\frac{d h_2}{dx} = \frac{(\tau_b - \tau_1) / \rho g h_2 - \tau_1 / \rho g h_1}{(\Delta \rho / \rho) \times (F_2^2 + F_1^2 - 1)}$$

(4)

where $F_1$ and $F_2$ are densimetric Froude numbers of the upper and lower layers given by

$$F_1 = \frac{V_1}{\sqrt[2]{\frac{\Delta \rho}{\rho} \times g x h_1}} \quad \text{and} \quad F_2 = \frac{V_2}{\sqrt[2]{\frac{\Delta \rho}{\rho} \times g x h_2}}$$

(5)

the bottom $\tau_b$ and interfacial $\tau_1$ shear stresses are given by

$$\tau_b = \frac{f_b}{8} \times \rho x (V_2) \times |V_2| \quad \text{and} \quad \tau_1 = \frac{f_1}{8} \times \rho \times (V_1 - V_2) \times |V_1 - V_2|$$

(6)

where $f_b$ and $f_1$ are dimensionless friction factors for the bottom and the interface.

Equation (4) makes it possible to calculate the location of the interface for various flow situations and density differences, thus describing the water body characteristics necessary for the design and location of a stratified flow cooling water intake and discharge.

IV.5.4 Methods of investigation

The introduction of restrictive standards for temperature rise in natural water bodies and mixing zones, the increasing capacity of steam-electric power plants, and the limited sites for new power plants have brought about a rapid development of predictive methods for temperature distribution in natural water bodies. These predictive methods involve the use of physical (hydrothermal) models, mathematical models, and field measurements. Data from field measurements are necessary for the formulation of physical and mathematical models and their verification. In these models, velocity and temperature fields must be simultaneously reproduced, a major complication in comparison with a simple hydraulic model (Ackers, 1969). Moreover, all physical processes which occur under natural conditions and with heated discharges are unsteady and have a stochastic character (Gras and Henry, 1971; Mesarovic, 1975). The necessity of employing simplifying assumptions has the result that, in many presently used models, only steady conditions can be simulated with a deterministic approach. Models of unsteady conditions or models with a stochastic approach are in the state of development. Methods for the prediction of the temperature and velocity fields of discharges are described in Chapter VI.
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V. Heat exchange between water and atmosphere and water loss by evaporation

**SUMMARY**

Heat budget of a water body is controlled by several processes which supply or remove energy. The dominant factor influencing this budget is heat exchange between water surface and atmosphere. It includes solar radiation, atmospheric radiation, long-wave radiation emitted from the water body and evaporative and conductive heat fluxes. Values of surface heat exchange components may be determined by means of empirical formulae, however, better accuracy is obtained from direct measurements. This chapter presents methods for evaluation of these components and the concept of the overall heat exchange coefficient and equilibrium temperature. Water losses by evaporation may significantly increase when heated water from a power plant is discharged into a water body. In some cases these additional losses may influence existing water balance. Fog formation due to increased evaporation is briefly outlined. The chapter concludes with recommendations for practical use.

The heat exchange between a water body and the environment is controlled by processes which supply or remove energy. In the natural state, the heat balance of a water body is established by heat transfer within surface and ground waters, precipitation, heat exchange through the banks and the bottom, heating due to chemical and biological processes, transformation of kinetic energy into thermal energy, and heat exchange between water surface and atmosphere. The last component is usually the dominant factor influencing the heat balance and is discussed in detail in this chapter.

When an artificial heat source, such as heated water from a power plant, is supplied to an aquatic system, a new heat balance is established between combined heat input and heat losses. A warm water discharge predominantly affects the heat exchange between water surface and atmosphere. This process is extremely complex and depends upon a variety of hydrodynamic and meteorological factors (Budyko, 1958; Timofeev, 1963). Comprehension of surface water heat fluxes is fundamental to the prediction of the effects of heated discharges on natural water bodies.

V.1. Components of Surface Heat Exchange

The natural heat input from the sun includes all direct and diffuse short-wave radiation reaching the water surface, plus the incoming long-wave radiation from the atmosphere. This heat is dissipated from the water surface by three main processes, namely, long-wave radiation emitted from the water surface, evaporation and a combined process of conduction and convection. These predominant components of flux densities are indicated schematically in Fig. V.1. where:

- \( R_s \) - incident solar radiation (short-wave radiation).
- \( R_r \) - reflected short-wave solar radiation.
- \( R_a \) - atmospheric radiation (long-wave radiation from the atmosphere).
- \( R_{ar} \) - reflected long-wave atmospheric radiation.
- \( L_b \) - long-wave radiation emitted from the water surface.
- \( H_e \) - evaporative (latent) heat.
Net heat flux \((H_s)\) through the surface of a water body may be described in terms of these components of surface heat exchange. The basic energy budget or heat balance of the water surface can be expressed by the equation (1)

\[
H_s = R_{sn} - R_{sr} + R_{an} - R_{ar} - L_b - H_e \pm H_c
\]

In equation (1) net solar radiation \(R_{sn} = R_s - R_{sr}\) and net atmospheric radiation \(R_{an} = R_a - R_{ar}\).

Net radiation \(R_n = R_{sn} + R_{an}\) depend predominantly on meteorological variables which change with time, \((t)\). Heat loss fluxes \(L_b\), \(H_e\), and \(H_c\) depend on meteorological variables and water surface temperature \((T_s)\) both varying with time. Equation (1) may therefore be presented in the following functional relationship.

\[
H_s(T_s, t) = R_n(t) - L_b(T_s, t) - H_e(T_s, t) \pm H_c(T_s, t)
\]

This representation has to be made taking into account the availability of meteorological variables which are related to the different processes. The practical problems which arise at this point are:

1. Choice of formulae describing different components of energy budget valid for local conditions, the quality of available meteorological information, and the time step chosen for integration of the temperature differential equation.

2. The spatial representativity and adequacy of the available meteorological data used for estimating the different components of the energy budget.

The net heat flux density \((H_s)\) acting on a given volume of water \((V)\) over its water surface area \((A)\) will change the amount of heat stored. Uniform temperature \((T_s)\) is assumed for the whole water volume. This relation is given by equation (2).

\[
H_s \times A = \rho c x V \frac{dT_s}{dt}
\]

Each term in equation (1) may be measured in situ or evaluated by empirical formulae. All components are considered in following sections.

V.1.1 Net solar radiation \((R_{sn} = R_s - R_{sr})\)

Net solar radiation is the net flux density of downward and upward short-wave radiation \((< 4 \mu)\) emitted by the sun. The downward short-wave radiation called also global radiation \((R_g)\) arrives at the earth's surface partly as direct solar radiation (sky radiation).

Global Radiation \((R_g)\): The heat input by global radiation depends on elevation of the sun, cloudiness, content of water vapour and dust in the atmosphere. Typical daily averages of global radiation range from 60 to 300 W m\(^{-2}\). Global radiation should be measured at a site near the water body with a pyranometer and the output continuously recorded. Considerable care and attention must be taken for selection and exposure of pyranometer and accuracy of measurements (WMO, 1971).

When direct measurements of the solar radiation are not available, empirical formulae may be used to estimate this component. These use the solar radiation with a cloudless sky, or a clear, dry Rayleigh atmosphere to take into account the sun altitude, and a function to express cloud cover \((n)\) or the percentage of possible sunshine \((A_s - \text{ratio of actual to astronomically possible duration of sunshine})\). (For example see: Bernhardt and Philips, 1958; Braslavskij and Vikulina, 1954; Black, 1956; Collmann, 1953; Klein, 1948).

Generally, the indirect methods cited above yield satisfactory results for monthly values. The global solar radiation can be calculated by an empirical formula with an error of \(\pm 15\%\). If data of the solar radiation are required for shorter periods (days), it is recommended to perform direct measurements. Likewise, special conditions, such as a superelated...
TABLE V.1
Reflected short-wave solar radiation of water surface $R_{SR}$ for
different months as a function of geographical latitude $\varphi$
(mean values in per cent of global radiation $R_{S}$)

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<th>$\varphi$</th>
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</table>

(Kirillova, 1970, tab. 3. p. 22)
horizon, cannot be accounted for calculation, but require direct radiation measurements. In this case it is advantageous to measure net radiation, since all components of radiation are influenced by local conditions.

Reflected Global Radiation ($R_{sr}$): Upward short-wave radiation is the reflected global radiation by the earth's surface, including water surfaces. The reflected global radiation $R_{sr}$ may be expressed as a fraction of the global radiation, called albedo. The albedo of a surface may be defined as the ratio of the global radiation reflected by the surface to that incident upon it. Albedo ($r$) is a function of the sun amplitude, cloud cover, and type of clouds.

The local albedo of a surface is determined with a pyranometer. The reflected solar radiation is not changing in a wide range. Therefore, the albedo of water surface can be calculated by empirical equations with good results. Values of albedo are presented in tables, usually given in per cent of the global radiation (Table V.1.) Mean values of albedo range from 5 to 20 W m$^{-2}$.

V.1.2 Net atmospheric radiation ($R_{an} = R_a - R_{ar}$)

Net atmospheric radiation is the net flux density of long-wave radiation mainly emitted by the atmosphere, minus the upward long-wave radiation reflected by the earth's surface or including water surface with wave-lengths greater than approximately 4 microns.

Incident Atmospheric Radiation: Atmospheric radiation is a function of several atmospheric variables, especially cloudiness, vapour pressure and air temperature. Typical values of incident atmospheric radiation can range from 200 to 450 W m$^{-2}$. Downward atmospheric radiation together with downward solar radiation should be measured at a site near the water body with a radiometer. Care must be taken as mentioned above (WMO, 1971).

If measured radiation data are not available, empirical relations are used. The basic equation for the atmospheric radiation $R_a$ is usually given as:

$$R_a = \sigma T_a^4$$ (W m$^{-2}$) (3)

where:

$\sigma$ - Stefan-Boltzmann constant

$T_a$ = $5,669.6 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$

$T_a$ - air temperature absolute (°K)

$\epsilon$ - average emittance of the atmosphere, i.e. ratio of emitted radiant flux to that from a black body at the same temperature.

Emittance $\epsilon$ is actually a marked function of wave-length and varies from about 0.7 for low temperatures and a clear sky to almost unity for higher temperatures and heavy low overcast conditions. Formulae modified for effects of clouds and using values of the air temperature and of the vapour pressure take the form:

$$R_a = \sigma T_a^4 \times f(\beta)$$ (4)

where:

$f(\beta)$ = atmospheric radiation function, which depends on vapour pressure of the water in the air ($e_a$) and cloudiness temperature gradients.

The atmospheric radiation function may be determined using:

$$f(\beta) = a - \beta \times 10^{-\gamma e_a}$$

or Brunt's formula:

$$f(\beta) = a + b \sqrt{e_a}$$

where $a$, $\beta$, $\gamma$, $a$, $b$, are empirical coefficients with different values for several places (Table V.2.) Therefore the use of these relations makes the assumption that the structure of the air mass corresponds with that at the original observation point where coefficients of the
TABLE V.2
EXAMPLES OF COEFFICIENTS OF ATMOSPHERIC RADIATION FORMULAE FOR VARIOUS COUNTRIES

a/ for Brunt's formula

<table>
<thead>
<tr>
<th>Place</th>
<th>a</th>
<th>b</th>
<th>Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td>0.53</td>
<td>0.065</td>
<td>Dines</td>
</tr>
<tr>
<td>Sweden</td>
<td>0.43</td>
<td>0.082</td>
<td>Asklüf</td>
</tr>
<tr>
<td>Algeria</td>
<td>0.48</td>
<td>0.058</td>
<td>Angström</td>
</tr>
<tr>
<td>Austria</td>
<td>0.47</td>
<td>0.063</td>
<td>Eckel</td>
</tr>
<tr>
<td>France</td>
<td>0.60</td>
<td>0.042</td>
<td>Bontaric</td>
</tr>
<tr>
<td>India</td>
<td>0.62</td>
<td>0.029</td>
<td>Raman</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>0.68</td>
<td>0.036</td>
<td>Anderson</td>
</tr>
</tbody>
</table>

b/ for Angström's formula

<table>
<thead>
<tr>
<th>Place</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>0.806</td>
<td>0.236</td>
<td>0.115</td>
</tr>
<tr>
<td>Virginia</td>
<td>0.80</td>
<td>0.326</td>
<td>0.154</td>
</tr>
<tr>
<td>Austria</td>
<td>0.71</td>
<td>0.24</td>
<td>0.163</td>
</tr>
<tr>
<td>India</td>
<td>0.79</td>
<td>0.273</td>
<td>0.112</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>1.107</td>
<td>0.405</td>
<td>0.022</td>
</tr>
</tbody>
</table>

(Anderson, 1954, p.93, tab. 9,10)

TABLE V.3
SELECTED RELATIONS OF THE WIND SPEED FUNCTION F(u)

<table>
<thead>
<tr>
<th>f u</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.131 u_z</td>
<td>WMO, 1966</td>
</tr>
<tr>
<td>0.13 (1 + 0.72 u_z)</td>
<td>WMO, 1966</td>
</tr>
<tr>
<td>0.104 (k_0^+ u_z)</td>
<td>Valdaj, 1966</td>
</tr>
<tr>
<td>0.225 (1 + u_z)^0.5</td>
<td>Jaworski, 1973</td>
</tr>
<tr>
<td>0.17 + 0.20 u_z 0.53</td>
<td>Richter, 1973</td>
</tr>
<tr>
<td>0.148 u_z</td>
<td>Harbeck, 1962</td>
</tr>
<tr>
<td>0.210 + 0.103 u_z</td>
<td>Rymsha and Donchenkow, 1958</td>
</tr>
<tr>
<td>0.128 + 0.094 u_z</td>
<td>McMillan, 1973</td>
</tr>
<tr>
<td>0.243 + 0.012 u_z^2</td>
<td>Brady et. al., 1969</td>
</tr>
</tbody>
</table>
function $\beta$ were deduced [climatological dependence]. The dependence of atmospheric radiation ($R_a$) on the vapour pressure is illustrated in Fig. V.2. (Krodnatjew, 1969).

**Reflected Atmospheric Radiation:** Reflected atmospheric radiation at the water surface ($R_{ar}$) for temperatures ranging from 0° to 30° is 0.03. Since reflected atmospheric radiation at the water surface is nearly constant through the year, a figure of 3% of the atmospheric radiation is usually accepted as reflectance of a water surface. Small errors are insignificant here in view of the inaccuracies in estimating the atmospheric radiation.

**Net Atmospheric Radiation:** Net flux density of atmospheric radiation $R_{an} = R_a - R_{ar}$ may be estimated from:

$$R_{an} = 0.97 R_a \quad (W \cdot m^{-2})$$  

Braslavskij and Vikulina (1954) present tables of long-wave radiation for different geographical regions for cloudless sky. As a result of extensive investigations, Kirillova (1970), developed a formula for estimating the net radiation for several reservoirs using factors of cloud cover and level of cloudiness. For a rough estimation of long-wave radiation, a modified Swinbank's formula (1963), was used by Stolzenbach (1976) giving a linear approximation for $R_{an}$:

$$R_{an} = 233 + 6.6 T_s \quad (W \cdot m^{-2})$$

**V.1.3 Long-wave radiation emitted from the water body, $L_b$**

Long-wave radiation from the water surface ($L_b$) is usually a large value in the energy budget of a water body. The long-wave radiation from the water surface can be calculated applying the Stefan-Boltzmann law of back-body radiation, corrected by the emissivity factor $\varepsilon$ (ratio of emitted radiant flux to that from a black body):

$$L_b = \varepsilon \sigma T_s^4 \quad (W \cdot m^{-2})$$  

According to the data given by several authors, $\varepsilon$ ranges from 0.90, to 0.98 (cf. Kirillova). According to other investigations (cf. Anderson) $\varepsilon$ amounts to 0.970 ± 0.05, independent of temperature, and salt and colloidal concentrations. Water carrying an oil film yielded a value of $\varepsilon = 0.956$.

Using $\varepsilon = 0.97$ long-wave radiation from the water body can be calculated

$$L_b = 5.5 \times 10^{-8} T_s^4 \quad (W \cdot m^{-2})$$

However use of $\varepsilon = 0.97$ probably involves an over-estimation of the long-wave radiation from the water surface. A simple linearized form has been used by Stolzenbach, 1976.

$$L_b = 307 + 5.4 T_s \quad (W \cdot m^{-2})$$

**V.1.4 Evaporative heat flux $H_e$**

Evaporative heat flux is the component of heat loss due to the change of phase during the evaporation process. The main factors affecting this heat flux from any water surface are solar radiation, temperature of the air and water surface, wind speed, the difference between the saturation vapour pressure of the air at the water surface and the actual vapour pressure of the air. Evaporation from free water surfaces is further affected by the state of the surroundings and the morphometry and shape of the water body as well as by impurities and any vegetation in it.

The heat flux consumed by evaporation:

$$H_e = LE' = \rho LE \quad (W \cdot m^{-2})$$  

is of special importance in determining the heat exchange of artificially heated water bodies.
Figure V.1   Components of heat transfer at the water surface

Figure V.2   Dependence of the atmospheric radiation on the vapour pressure (in per cent)

Figure V.3   Variation of heat exchange coefficient $K$ with surface water temperature $T_s$. 
A large number of empirical equations have been derived to calculate the amount of water lost by evaporation \((E)\). These can be reduced to the simple form as:

\[
E' = \rho E = f(u_z) \times (e_s - e_a)
\]

(8)

where:

- \(E'\) - mass flux (kg m\(^{-2}\) s\(^{-1}\))
- \(E\) - amount of water loss by evaporation (m s\(^{-1}\)) or (mm d\(^{-1}\))
- \(\rho\) - density of evaporated water equal to 1000 kg m\(^{-3}\)
- \(u_z\) - wind speed at height \(z\) (m s\(^{-1}\))
- \(e_s\) - saturated vapour pressure in the air at temperature of the water surface \((T_s)\) (mbar)
- \(e_a\) - vapour pressure in the air at height \(z\) (mbar)

Empirical evaporation formulae have been developed for natural water bodies without waste heat discharge. Evaporation from artificially heated water surface have often been calculated using also these formulae, but as will be shown in Section V.3., there are discrepancies. Special formulae for estimating evaporation losses from artificially heated surfaces are also given there.

V.1.5 Conductive (sensible) heat flux \(H_c\)

The energy conducted from a body of water as sensible heat \((H_c)\) cannot be measured directly; it is evaluated indirectly by use of the Bowen ratio \((B)\). The Bowen ratio, which is the ratio of energy conducted to, or from the water surface as sensible heat to the energy utilized for evaporation, is expressed in a simple form:

\[
B = 0.61 \frac{\rho (T_s - T_a)}{1000 (e_s - e_a)}
\]

(9)

and \(H_c\) can be derived from:

\[
H_c = H_e \times B
\]

(10)

where:

- \(T_s\) - water surface temperature (°C)
- \(T_a\) - air temperature (°C)
- \(\rho\) - atmospheric pressure (mbar)

The term \((\rho)\) is influenced by the elevation of water body above sea-level, but is usually considered constant. The simplest way of computing \(B\) is to use average values of air temperature, water surface temperature and vapour pressure for the period for which the heat fluxes are being computed. The Bowen ratio is dimensionless.

V.2 Heat Exchange Coefficient and Equilibrium Temperature

The total heat flux \((H_S)\) is established by the incoming solar energy and the outgoing heat losses (Equation 1)

\[
H_s = R_n - L_b - H_e - H_c
\]

(11)

\(H_s\) is a function of wind speed, water temperature, air temperature, and vapour pressure:

\[
H_s = (T_s, T_a, u_z, e_a)
\]

The net flux of solar and atmospheric radiation \((R_n)\) is independent of \((T_s)\). Only three terms on the right-hand side of equation (11) depend on the water surface temperature \((T_s)\). These three heat exchange components will be changed for an artificially heated water body resulting from power plant discharge. The total heat loss flux \(H_1\) is expressed by
Figure V.4 Heat exchange coefficient, $K$, for a heated water surface \([T_s - T_a = 5.5^\circ C (10^\circ F)]\) units for $K$ \([W \text{ m}^{-2} \text{ K}^{-1}]\)

Figure V.5 Heat exchange coefficient $K$, for a heated water surface \([T_s - T_a = 11^\circ C]\) units for $K$ \([W \text{ m}^{-2} \text{ K}^{-1}]\)
The components of $H_1$ are nonlinear functions of water surface temperature. A linearized approximation of $H_1$ has been developed by Edinger and Geyer (1965) who defined the relation between heat exchange and surface water temperature. This approximation has been practically used by other authors (e.g. Brady et al., 1969; Jaworski, 1973 (a); Ryan et al., 1974; Sweers, 1975).

Preliminary estimates of incremental water temperature increases caused by waste heat are facilitated by introducing a surface heat exchange coefficient $K$ defined by:

$$
K = \frac{\partial H_S}{\partial T_s} = - \frac{\partial H_1}{\partial T_s}
$$

where $K$ is in (W m$^{-2}$ K$^{-1}$).

The surface heat exchange coefficient is the increase in surface heat loss resulting from a rise of one degree in water surface temperature for a specified condition, i.e. for particular values of air temperature $T_a$, water surface temperature $T_s$, wind velocity $u_z$, and vapour pressure $e_a$. Fig. V.3 illustrates these relationships.

In practice, a slightly different form is used:

$$
K' = \frac{H_1}{T_N - T_s}
$$

and

$$
K'' = \frac{H_1}{T_E - T_s}
$$

where:

- $H_1$ - total heat loss from the water surface (W m$^{-2}$)
- $T_N$ - natural temperature of the water (°C)
- $T_E$ - equilibrium temperature of the water (°C)

The equilibrium temperature ($T_E$) is defined as the temperature that would ultimately be reached by the water surface under stationary environmental conditions. The net exchange of heat between air and water is zero when $T_s = T_E$. Depending on the depth of water and intensity of mixing it takes several days to weeks before the water temperature actually approaches $T_E$. Daily cycles in the meteorological conditions therefore preclude that $T_E$ will ever be reached.

The natural temperature $T_N$ is defined as the temperature attained by the water surface under the influence of natural conditions only. If there was no measuring programme for water temperature prior to the operation of a power plant, $T_N$ can be measured directly in a water body of similar morphology (area, shape, depth) which is not artificially heated. The mean value of $T_N$ approaches the mean value of $T_E$ for periods when the mean water temperature remains stationary. Fig. V.4 and V.5 give $K$ as a function of $T_s$, $u_z$, and $T_a$. The figures were calculated for a relative humidity of 75% in $K$ for a relative humidity range of 50 - 100%.

The errors resulting from the linearization of the heat loss formula may be minimized by evaluating $K$ by means of a temperature $T_{sk}$ midway between $T_N$ and $T_s$, i.e. $T_N + \Delta T_s/2$, Fig. V.3.

Surface heat loss coefficients derived by linearizing the total heat flux $H_S$ may be used in a variety of applications in cooling ponds, lakes, reservoirs, and rivers. However, considering the capability of computers to handle the full expression for heat loss, the linearized approach should only be used for preliminary calculations.

Better results, without the application of linearization of particular components of heat balance equation (1), has been obtained by Wunderlich (1962) by application of the square approximation:
Figure V.6  Relation between additional evaporation loss $\Delta$He due to thermal discharge by power plant and heat input by thermal discharge of power plant, Q in per cent.

Figure V.7  Heat exchange coefficient as function of water temperature and wind speed.
V.3. Evaporation Losses

Evaporation is of special importance for the heat exchange of water bodies having thermal discharges because evaporation is responsible for transferring most of the additional heat to the atmosphere. In addition, evaporation results in increased water consumption. In certain water bodies, such as relatively small reservoirs or rivers during low water period, water losses from heated water surfaces due to evaporation can become critical.

Methods to determine the evaporation losses of artificially heated water surfaces as well as water surfaces under natural conditions involve mainly balance of heat exchange or mass-transfer methods. Different types of water bodies (rivers, lakes, reservoirs, estuaries, oceans) can be treated similarly.

In using of the heat balance method to estimate evaporation, the heat balance equation (1) can be expressed in the following form (WHO 1966) with aid of the relationships expressed in equations 7,10,11.

\[ H_s = \alpha + \beta T_s + \gamma T_s^2 \]  

(17)

where \( H_s \) is the heat flux density of the water body. This equation can be used to calculate the heat loss from the water body.

In the mass-transfer method, the evaporation rate can be calculated using the equation:

\[ E' = \frac{R_n - L_n - H_s}{L (1 + B)} \]  

(Kg m\(^{-2}\) s\(^{-1}\))

(18)

where \( E' \) is the mass flux of water vapour by a free surface of water, \( R_n \) is the net radiation at the water surface, \( L_n \) is the latent heat of vaporization, \( H_s \) is the sensible heat flux, \( L \) is the latent heat of vaporization, \( B \) is the Bowen ratio, \( T_s \) is the surface temperature, and \( \alpha \), \( \beta \), and \( \gamma \) are empirical coefficients.

Evaporation from water surfaces is more frequently calculated by means of simple empirical relations, so-called mass-transfer relations.

The relations employed are generally in the form of equation (8):

\[ E = f(u_z) \times (e_s - e_a) \]  

(mm d\(^{-1}\))

(19)

where \( f(u_z) \) is function of wind speed, often called the wind function, and has usually a structure:

\[ f(u_z) = a + b \times u_z^d \]  

(20)

where \( a \), \( b \), and \( d \) are empirical coefficients. As a result of many different types of studies, several independent values of this wind speed function have become available.

The magnitude of these coefficients can differ widely. In addition to climatic influences, local conditions such as height of wind speed measurement are of decisive importance. In a number of papers, the formula (20) is reduced by omitting coefficient \( -a \) or setting \( d = 1 \). In the case of calm \( (u_z = 0) \), the evaporation loss is described by the term \( (a) \). Empirical equation (8) has been used to calculate evaporation loss for both artificially heated and unheated water bodies. Some authors moreover have tried to take into account the magnitude of the area of the water body or the influence of the thermal stratification of air above it, or the simultaneous influence of both these factors together.
A number of selected, frequently used relations of the wind speed function (20) are listed in Table V.3 (E is expressed in mm d$^{-1}$). These formulae are based on mass-transfer principle.

Most of these formulae have the basic form of equation (8) and (20). A different structure is given in the formula of Valdaj (1966), where the factor $K_0 = f (T_s - T_a)$ is added. Several Soviet authors have proposed formulae that explicitly include the air-water temperature difference, but only Shulyakovskij (1969) used a theoretical base for the free convection term. Ryan et al., (1974) recommended a formula which is equivalent to Shulyakovskij's.

A comparison of the performance of evaporation formulae made by Stolzenbach (1976, Table 2.8) are of special relevance here. A good performance for evaporation of heated water surface was found by using the formula of Ryan and Harleman (1973). The fact that the formula is slightly more complex than many is not a serious disadvantage since most heat transfer calculations are done by using a digital computer.

Sweers (1976) has given critically evaluated wind speed functions such as used in the formulae of Table V.3. He found the wind speed functions determined by various authors to be in reasonable agreement if only recent investigations are considered and when the underlying measurements have been extensive.

Using the data for a given lake as the baseline, the relation between the wind speed functions $f_1$ and $f_2$ for the two lakes with areas $A_1$ and $A_2$ can be expressed in the form $R_{1,2} = (A_2/A_1) \exp(0.0)$. $R$ has been applied to account for variations in lake size in order to compare the results of various authors. The area ratio may be a useful tool to reduce the variability between the various investigations, but the evidence is not conclusive. This approach would not be applicable when the wind speed is measured over land.

The wind speed functions have been defined using different expressions of wind speed and vapour pressure difference.

The results tend to diverge as wind speed values change from small (<1.5 m s$^{-1}$) to large (> 6 m s$^{-1}$). Usually, however, these observations cover only a relatively narrow wind speed range. In this range, agreement is generally good; outside this range predicted differences are irrelevant since they are not based on observational material.

Sweers concluded that McMillan's wind speed function yielded the best results for practical application in a temperate climate. For water bodies differing significantly in size from Lake Trawsfynydd ($\lambda = 5 \text{ km}^2$), the wind speed function should be corrected with the area ratio. The expression then becomes:

$$f = \left( \frac{5 \times 10^6}{A} \right) \times (3.6 + 2.5 \ u_3)^{0.05}$$

where $A$ is the representative area of the water body under consideration. The representative area is equal to the total surface area for regularly shaped lakes, but may be smaller in irregularly shaped lakes. In canals, rivers or elongated lakes, it can be taken as equal to the square of the mean width.

V.4 Fog Formation

Waste heat, whether discharged into water or air can cause fog formation, and in the winter, icing of surfaces near the discharge. These effects should also be taken into account in site selection and cooling system design. Fog is often observed within a few hundred metres downwind of cooling reservoirs (often less than 100 m or 200 m), but mainly occurs when atmospheric conditions favour the formation of natural fog, especially in cold, humid climates (e.g. on cold, calm mornings).

Whether the extra water vapour from cooling water discharge will condense wholly or partly to form fog, and where, for how long, and in what thickness, depends on the atmospheric temperature, moisture, and wind conditions near warm water discharge. Both physical laws and observations of natural situations show that thick, persistent fog will form near a cooling water body when the environmental air is humid, calm, and some degrees cooler than the water in the heated water body. If dry, windy, warm conditions prevail the extra water, vapour will not condense and fog will not form. These sets of conditions represent the two ends of a spectrum relevant to fogging. The potential for fog formation at operating power plants also depends on other factors such as configuration of the heated discharge, currents and/or tides,
salt content and upland topographic conditions, as well as power plant operating characteristics and capacity.

Studies necessary to systematically assess waste heat effects on the atmosphere are difficult to perform. Atmospheric conditions are typically quite variable over time, making it extremely difficult to distinguish between natural and man-made changes. Special methods for assessing the severity of fogs caused by a heated water body are given by several authors (for example: Technical Note, 1973; Tschirhart, 1974; Currier et al., 1974; Hicks, 1977).

V.5. Recommendations For Practice

Considering order of magnitude, the most important components of the heat exchange between the water surface and the temperature are, global solar radiation, long wave atmospheric radiation, and long-wave radiation from water surface. The empirical relations used in calculating long-wave atmospheric radiation and global solar radiation give an accuracy of ±15%. Larger errors may occur if these relations are applied in regions where the validity of the empirical constants have not been checked. Generally these radiation components can be more accurately determined by direct measurement. Direct measurement is by all means recommended in cases where the expected calculation errors are > 15%. Direct site measurements are especially necessary where the radiation conditions are influenced by an elevated horizon, since all radiation equations were derived for the conditions of a free horizon. The influence of the horizon elevation on the radiation balance is very complex. While the short-wave radiation is reduced, the long-wave atmospheric radiation increases because of temperature radiation of the objects projecting from the horizon, which in most cases, have a higher temperature. The gain of long-wave radiation energy may possibly compensate for the loss of short-wave radiation. Therefore radiation measurements should determine both components, or totally the radiation balance. Measurements of the radiation balance have to be carried out above the water surface at a sufficient distance from the shore. Moreover, in fixing the measuring point, care should be taken to measure representative values of the water-surface temperature. Since the installation of measuring instruments above the water surface raises technical problems, it may be preferable to separate measurements of the long-wave and the short-wave radiations, respectively, above the land surface. In arid regions, spatial variations of these quantities are small. Their reflected part can be determined with sufficient accuracy by means of formulae and tables since it averages only 6% in the short-wave range and 3% in the long-wave range.

In calculating evaporation according to traditional empirical formulae, errors in excess of 20 - 40% may occur. From the great variety of empirical evaporation formulae an accurate check of its applicability to the water body investigated will be required. Direct measurements by means of raft-mounted evaporation pans or the derivation of an empirical formula for the given location are the most accurate methods of calculating evaporation rates. But the difficulties of operating such experimental devices must not be underestimated (WHO, 1973). Choosing a representative position of the raft in the temperature field over the water surface is of critical importance in estimating evaporation parameters. Floating evaporation pans on small lakes or reservoirs should be placed in the central open part of the water body. On larger water surfaces, they should be placed at a distance of up to 1 km from the shore, though not nearer than 200 m. If there are capes, spits and flat open islands, the floating evaporating installation can be set up in their vicinity, but never nearer to the shore than 200 m. The depth of the water body where the raft is installed must as a rule be not less than 2 m, or if the water bodies are very shallow, not less than 1 m. Direct measurements with evaporation pans on water surfaces are unsuitable if there are strong winds.

In estimating evaporation from artificially heated water surfaces, the following recommendations should be taken into consideration. Changes in evaporation cannot be determined by direct measurement but can only be deduced by comparing thermal behaviour simulations of the considered water body operated under natural and disturbed thermal conditions. Another experimental approach could be based on the different evaporation rates of a set of evaporation pans operating in natural and artificially heated conditions at the site being considered. Meteorological data to be used in empirical calculations of evaporation should be obtained above the water surface, not the land. Transfer of data measured over land require reconsideration, especially for artificially heated water bodies. And in each case, the method selected for empirical calculation of evaporation must be tested for its general application.

In estimating the occurrence of fog, a quantitative evaluation should be made to determine the number of days per year with moist air, low air temperatures and calm in the
vicinity of the heated body. In order to quantitatively observe ground fog, a measurement programme should be initiated around existing electric production facilities with cooling reservoirs. There are several instruments available for sensing fog, most of which operate on the principle of attenuation of a light beam. It is necessary to install a network of these instruments and operate them for several years in order to determine a statistically significant climatology.

In view of the marked diurnal cycles for most meteorological and hydrological elements and possibly also in power plant operation it is reasonable to take the day as the smallest time unit. The mean period for observations should be at least equivalent to the time of cooling water flow through the water body segment being investigated so that stationary conditions can be assumed to exist.

For details of instruments used for measuring meteorological and hydrological parameters and observing techniques, the basic guides compiled by WMO (WMO, 1971; WMO, 1974) should be used.
REFERENCES CITED


VI. Prediction and monitoring of water velocity and temperature fields

SUMMARY

Methods for the prediction of water velocity and temperature fields in water bodies used for once-through cooling of steam-electric power plants are outlined. Predictive techniques include mathematical models and physical laboratory-scale models. The physical basis for analysis is formed by the hydrological and dynamic characteristics of the natural water body, the amount of cooling water circulated, the way it is withdrawn and discharged into the water body and the meteorological conditions which influence plume pattern and heat exchange between the water surface and the atmosphere. These data provide basic information for model formulation, the definition of initial and boundary conditions, and model verification. The application of mathematical and physical models is also described.

VI.1 Introduction

Prediction of the water velocity and the temperature fields set up in natural water bodies by the withdrawal of cooling water and the discharge of warm water is necessary both for efficient design and operation of power plants and also for the assessment of their effects on aquatic ecosystems (Sundarm and Daugard, 1974). The spatial and temporal distribution of temperature and velocity depends on the hydrodynamics of the receiving waterway, the meteorological conditions prevailing in the disposal area, and the mode of water withdrawal and discharge (Harleman, 1972).

The specific hydrological and hydrodynamic characteristics of different receiving water bodies (e.g. rivers, estuaries, lakes, reservoirs, and coastal waters) significantly influence the pattern of warm water dispersion. The mode of discharge can be surface or submerged (Harleman, 1969); the design employed depends on the volume of cooling water required, the water body available and the thermal standards established for a given type of water body. Meteorological conditions influence the flow pattern of the heated plume and heat exchange between the water surface and the atmosphere (Silberman, 1972).

Predictive techniques for thermal discharges include mathematical models and physical models (laboratory hydrothermal scale studies - Matchett, 1974). A combination of the two models often produces good results. The reliability of the results depends on the quality of the basic information needed for model formulation and the definition of initial and boundary conditions. Basic information may be collected through an appropriate pre-operational monitoring programme and operational surveys at existing power plants. Extensive field data are necessary for the verification of both mathematical models and physical laboratory-scale models. The ranges of applicability and accuracy of each technique must be considered in view of the problem to be solved. Temperature standards for a waterway usually require a very high accuracy of the prediction method (e.g. within 10% of the permissible increase of water temperature outside the mixing zone area). Evaluation of the accuracy and reliability of existing predictive techniques is complicated by the fact that only limited laboratory and field data are available to check the results obtained from various models (Neale and Hecker, 1972). The majority of physical phenomena associated with thermal discharges have an unsteady and random character, hence considerable experience is necessary to solve this problem properly.

In predicting thermal changes, results are usually given as the increase above ambient or natural temperature. In many circumstances it is difficult to define the ambient temperature
if a power plant is already operating or when the given water body is already influenced by other discharges. Further complication arises from the fact that water bodies show natural daily and seasonal temperature variations thus making it difficult to define which temperature to take as the ambient value (Burd, 1968, Churchil, 1969).

A very good review and state of the art in predictive techniques is given by Jirka et al. (1976).

VI.2 Predictive Techniques

The available techniques for hydrothermal predictions are mathematical models and physical laboratory-scale models.

VI.2.1 Mathematical models

Mathematical models are based on the governing equations of fluid motion and heat conservation. These equations for specific initial and boundary conditions may be solved by means of analytical and numerical methods. Mathematical models usually present a general solution which may be applied to different prototype situations. Several limitations stem from the difficulty of establishing the exact specifications of turbulent transport as well as from the simplification of some physical phenomena, the reduction of dimensions through averaging, and the dropping of secondary terms. Therefore a comparison of mathematical model results with basic laboratory experiments and field data is absolutely necessary. The mathematical model does offer to the user a quick and efficient evaluation technique, but it gives very little insight into the physical problem, and this may be regarded as a disadvantage.

VI.2.2 Physical models

Hydraulic scale models used for temperature prediction are based on similarity laws which can be derived from the governing equations. It is never possible to satisfy all the similarity requirements for hydraulic models, and therefore a choice of the dominant physical processes is required (Ackers, 1969). As a result of scaling, a hydraulic model can be developed for only a limited area, usually the near-field zone. Hydraulic scale models must also be verified by testing with field data (Fisher and Holley, 1971). The advantages of physical modelling techniques lie in the possibility of including complicated boundary conditions, and the good insight they provide into the problem. Physical models are more expensive than mathematical models and are also much more time-consuming to construct and run.

A valuable extension of hydraulic model studies for larger areas can be achieved through field dispersion tests. Such tests will also furnish valuable data for hydraulic and mathematical models (Fisher, 1967, 1972).

VI.3 Criteria For The Choice Of Predictive Technique

The following criteria are of primary importance in selecting an appropriate predictive technique for hydrothermal processes in natural water bodies influenced by heated discharges (Jirka et al. 1976).

Physical validity: The mathematical model must be examined to determine whether dominant physical processes are included and whether the mathematical formulations describe each process adequately. Criteria for physical models primarily concern the degree to which similitude laws are satisfied.

Verification: Model results must be compared with available field or laboratory data to determine their ability to predict other situations over a wide range of conditions in a reliable and consistent fashion.

Utility: For mathematical models it is necessary to consider the amount and accuracy of data input and the computation requirements (computer size and run time). For physical models this question concerns the feasibility of constructing and operating the model (e.g. laboratory area required, necessary apparatus, and measuring and recording equipment).

Limits of applicability: The range of applicability of each model is an important factor for the model user. This may be estimated by inspection of mathematical properties and the model formulation, or by comparison with field or experimental data. This especially concerns zone
models which are already limited. In physical models this problem mainly concerns model distortion and heat exchange between the water surface and the atmosphere.

VI.4 Physical Basis For Hydrothermal Analysis

Two basic physical processes are involved in the temperature decrease of warm water discharge, namely mixing of the warm water with the cold water of the recipient water body, and surface heat transfer to the atmosphere. Mixing and surface heat transfer cannot be considered separately as there is a close relation between these two processes.

The ratio and patterns of thermal dispersion depend on the warm water discharge design, the characteristics of the water body, and atmospheric conditions.

Warm Water Discharge: The physical characteristics of warm water discharge include flow rate, density differences between the warm water and ambient water, and its velocity at the outlet. It may be generally assumed that higher density differences and lower discharge velocities restrict mixing (Macagno, 1972).

Important characteristics of discharge structure are the type (e.g. free surface or submerged), location in relation to water body and the intake, orientation to the shore-line, and its shape and size. These characteristics can considerably influence warm water dispersion. Two extreme possibilities of near-field temperature distribution from surface discharge are shown schematically in Fig. VI.1. In Fig. VI.1a, due to a low discharge densimetric Froude number (small discharge velocity \(u_0\)) there is little entrance mixing and small initial temperature decrease. Further temperature decrease is due to high water surface temperature resulting in intensive heat exchange with the atmosphere. In this figure \(T\) is water surface temperature, \(T_o\) = discharge temperature, \(T_a\) = ambient water temperature, \(A_T\) = water surface area with increased temperature, \(A\) = total surface area of the water body. In Fig. VI.1b a rapid temperature drop of the heated discharge is due to high initial velocity \(u_0\) and ambient-water entrainment. Further temperature reduction due to heat exchange with the atmosphere is slow because of the small temperature difference between the water surface and the atmosphere.

Natural Water Body: Natural water bodies, including rivers, estuaries, lakes, reservoirs and coastal waters, are characterized by:
- geometry - shape, surface area, volume, bottom configuration, and roughness,
- hydrodynamic conditions - flow velocities (magnitude and direction), currents, waves, changes of water level, and turbulence, and
- stratification - natural stratification due to temperature, suspended solids, or salinity.

Atmosphere: The main atmospheric parameters include wind velocity, direction and duration; air temperature and humidity; solar and atmospheric radiation, and cloud cover. These atmospheric parameters can strongly influence the hydrodynamics of a water body and heat exchange between a water surface and the atmosphere.

VI.5 Mathematical Models

Predictive hydrothermal models can be classified in two general groups:
1. Complete models, and
2. Zone models.

Complete models are based on the general solution of governing equations over the whole region of interest. These models promise a significant advance through the use of modern computers. However, many simplifying assumptions and averaging processes are necessary in fluid flow and heat fluxes. Moreover, the flow and temperature field induced by a heated discharge present different and distinct hydrodynamic zones. Therefore simplifying assumptions and averaging of a general model are not uniformly valid in all regions of interest and this may lead to considerable errors. Other problems are related to the proper assessment of boundary conditions.

In zone models the whole region of interest is divided into several areas with distinct hydrodynamic properties. For each zone it is possible to simplify the governing equations by dropping unimportant terms, which is a considerable advantage in the mathematical treatment. The main problems which arise in zone modelling are the division of the whole region of interest into zones, transition conditions between zones, and combining the zone predictions.
Figure VI.1  Near-field temperature distribution
### VI.5.1 Governing equations

The spatial and temporal distribution of temperature in water bodies due to warm water discharge is described by the equation for heat conservation. For a turbulent flow, this equation can be written in the following form:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u_i \frac{\partial T}{\partial x_i} = \rho C_p \frac{\partial^2 T}{\partial x_i \partial x_j} - \rho C_p \frac{\partial}{\partial x_i} \left( u_i' T' \right) + \frac{\partial}{\partial x_i} \left( \rho C_p u_i u_j \right)
\]

where: \( t \) = time, \( T \) = temperature, \( x_i \) = co-ordinate axis \((i = 1, 2, 3,)\), \( \rho \) = density, \( C_p \) = specific heat, \( u_i \) = velocity in direction \( x_i \), \( D \) = molecular heat diffusion coefficient, \( Q_H \) = internal heat adsorption rate, \( u_i' T' \) = time-averaged turbulent eddy transport of heat in the direction \( x_i \); \( u_i' \) = velocity fluctuation, and \( T' \) = temperature fluctuation. In this equation, heat transport by convection \( u_i' T \) and by turbulent diffusion \( u_i' T' \) depend on the flow character, and must be evaluated by simultaneous solution of the hydrodynamic equations.

Heat transport by molecular diffusion is usually negligible in comparison to turbulent diffusion. Internal heat sources are represented by adsorption of short-wave radiation which penetrates into the water body.

The hydrodynamic equations are the continuity equations

\[
\frac{\partial u_i}{\partial x_i} = 0
\]

and 3 turbulent (time-averaged) momentum equations (\( j = 1, 2, 3 \)).

\[
\frac{\partial u_j}{\partial t} + u_i \frac{\partial u_j}{\partial x_i} = - \frac{1}{\rho} \frac{\partial p}{\partial x_j} - g K_i + \frac{\partial^2 u_j}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_i} \left( u_i' u_j' \right)
\]

where: \( p \) = pressure, \( g \) = gravitational acceleration, \( K_i \) = unit vector in the direction of \( g \), \( u_i' u_j' \) = time-averaged turbulent eddy transport of momentum.

The equation of state defines the relation between temperature and density

\[
\rho = \rho (T)
\]

These equations represent a set of 6 equations for 6 variables \( u_i, p, \rho \) and \( T \), for which initial and boundary conditions must be specified. The turbulent eddy transport terms \( u_i' u_j \) and \( u_i' T' \) are essentially unknown at this point and must be related to the mean parameters \( u_i \) and \( T \).

The equation system is very complex due to its time dependence and 3-dimensional nature. No general solution to the above system of governing equations can be formulated directly. It is therefore necessary to reduce, on the basis of scaling experiments, the complexity of the governing equations by the elimination of insignificant terms. The problem is complicated by the considerable source of mass, momentum, and buoyancy. A warm water discharge and its interaction with the ambient water environment produces a high degree of spatial inhomogeneity which restricts the simplification of governing equations. In this situation two possible solutions exist, namely: direct numerical integration and zone modelling. With direct numerical integration, several problems arise depending on the choice of solution domain and grid size, turbulence closure, and specification of boundary conditions. Zone modelling will greatly simplify the computation effort, but one must remain cognizant of the limits of applicability and of problems in combining the solutions for near and far-field zones (Jirka and Harleman, 1974).
VI.5.2 Application of mathematical models to different water bodies

Near-Field Surface Discharges - Where cooling water is discharged into a large receiving water body, e.g., a river, estuary, lake, reservoir, or coastal waters, a form of near-field analysis may be considered. The water body is assumed to be unstratified, either stagnant or with cross-flow of various magnitudes parallel to the shore-line. A steady heated water discharge is characterized by constant outflow velocity and temperature difference between the ambient and warm water. Receiving water conditions, usually assumed to be steady, include water depth, cross-current magnitude and direction, and temperature. Estuaries and coastal waters must be regarded as unsteady, which considerably complicates the analysis. If a water body can be regarded as deep, the influence of shore and bottom is neglected. In the case of shallow water bodies, bottom configuration may considerably change thermal discharge patterns. Analyses of the near-field region have to be linked to the far-field to predict unsteady temperature distributions beyond the transition line.

In all near-field zone models, surface discharges are dominated by jet diffusion. Hence temperature reduction is due to discharge-induced turbulence, and surface heat transfer may be neglected. Jet diffusion processes are highly complex due to the effect of buoyancy, ambient cross-flow, and ambient geometry.

A near-field analysis for buoyant surface discharges is given by Stolzenbach (1976). Three types of zone models are distinguished: (1) jet models with integral formulation, (2) semi-empirical correlation models, and (3) three-dimensional numerical models. A number of each type have been developed. Useful summaries of various model formulations are presented by Policastro and Tokar, (1972) and Dün et al., (1975).

Near-Field Submerged Discharges - Submerged discharges of condenser water create a dynamic instability in the discharge vicinity, resulting in re-entrainment of heated water. As a consequence, highly complicated flow patterns can be induced (Abraham, 1972). No exact models exist which give a detailed description of surface isotherms resulting from submerged discharges. Available models are restricted to stagnant water with negligible shore-line interference. Application of these models is closely related to the particular design of the diffuser (Jirka, 1976).

For submerged shallow discharges, only experimentally derived guidelines are available. They are summarized by Jirka et al. (1976). More exact definition of the mixing characteristics of any submerged discharge requires hydraulic model studies.

Models for Rivers and Estuaries. In many cases full vertical and lateral mixing is assumed downstream of the warm water discharge into the river. In this situation, one-dimensional far-field models can be successfully applied (Raphael, 1962; Garrison and Elder, 1965; Goubet, 1969). One major problem in using these models is accurate specification of surface heat flux. While simple steady models are used for rivers and channels, unsteady numerical models are applied to estuaries or elongated through-flow reservoirs (Brocard and Harleman, 1976; Bowels et al. 1977). An important problem in these models is the detailed computation of the flow field to avoid ambiguous dispersion concepts.

The problem of heat disposal in rivers under winter conditions is of special importance in cold climates. This has been addressed by Paily et al. 1974.

Zone Models for the Far-Field. Mathematical models of the far-field involve significant simplifications, arrived at by neglecting some physical phenomena and averaging over time and space. Far-field effects can be of major importance under the following conditions: (1) presence of unsteady reversing currents, (2) interaction between power plant cooling systems, and (3) recirculation of heated water into the intake (Stolzenbach, 1976b).

Distribution of heat in the far-field is governed by the following processes: (1) advection by ambient currents, (2) buoyancy, induced advection, (3) diffusion due to ambient turbulence, and (4) heat exchange between water surface and atmosphere.

The application of existing models is discussed by Jirka et al. (1976). These models are also applicable for the prediction of natural temperature distribution without an artificial heat input.
VI.6 Physical Models

Hydraulic scale models are analogues, i.e., a physical analogue of the actual prototype is investigated and the results are transferred to the prototype by appropriate relationships. In many respects, the application of physical models faces problems which are similar to those of mathematical models, namely: identification of the dominant physical process, choice of the modelling domain, and determination of initial and boundary conditions.

The hydraulic scale modelling of warm water movement is much more complicated than a standard hydraulic model in which a flow of water of uniform density is reproduced. Changes of water temperature result in density differences (Appendix 4) which form new physical phenomena: stratification, buoyant spread, entrainment of ambient water into the warm stream, mixing between warm and ambient water, and heat exchange between water surface and atmosphere. These physical phenomena must be correctly reproduced in the model.

Hydraulic models rely on the premise of similitude of dynamic and heat transfer between model and prototype. Similarity of the reproduced physical process requires geometric similarity between model and prototype and equality of non-dimensional parameters which characterize various physical processes. These parameters can be obtained directly from basic differential equations of momentum, continuity and heat conservation. Sometimes it is also convenient to use more simplified and specialized equations, such as for stratified flow, to obtain these non-dimensional parameters.

Hydraulic modelling is especially useful in studying the near-field region because mathematical modelling cannot be readily applied there. A hydraulic model is also useful in cases where lateral or bottom boundaries are irregular and complicated. Even in situations in which mathematical models can be applied with confidence it is sometime desirable to operate a hydraulic model. The effects of changing certain parameters become directly visible in these models. They can also be useful to provide estimates of certain parameters required by mathematical models. Disadvantages of hydraulic models usually lie in their high costs, the time required to construct and operate a model, and their inflexibility to evaluate other designs.

Basic information about physical models applied to thermal discharges is given by Ackers (1969), Jirka et al., (1976), and Stolzenbach (1976c).

Modelling of heated water discharge is complicated by the fact that the effluent may disperse by several different mechanisms, and more than one such mechanism may exist at a given site. It has to be admitted that it is impossible to design and operate a hydraulic model of a situation in which several types of warm water dispersion occur. The main forms of warm stream dispersion in an ambient waterway are:

- Turbulent entrainment at the efflux jet. Close to the discharge point, inertial forces of the jet predominate while density differences are of minor importance.
- Buoyant rise of the submerged jet. Jet trajectory depends on initial inertia and boundary forces. Mixing is due to entrainment at the jet boundary.
- The convective spread over the surface of the receiving water. This process is dependent on the density difference. Whether or not mixing will occur at the interface depends on the densimetric Froude number.
- The mass transport of the effluent by ambient currents which impose additional velocity vectors on previous stages.
- Diffusion and dispersion due to turbulence in the ambient waterway.
- Heat exchange between water surface and atmosphere and heat conduction into solid surroundings.

VI.6.1 Scale requirements

Basic scale requirements for water flow with a free surface and with heat transport are obtained through non-dimensionalizing of general, or the specialized governing equations. The following fundamental symbols will be used in further considerations:

- l length dimension
- L characteristic horizontal dimension
- Z characteristic vertical dimension
- t time
- T temperature
- AT characteristic temperature difference
\[ \rho \] density of water
\[ \Delta \rho \] characteristic density difference (related to \( \Delta T \))
\[ \frac{\Delta \rho}{\rho} \] relative density difference
\[ \nu \] kinematic viscosity
\[ R_h \] hydraulic radius

Prototype values are designated by a subscript (p) and model values by (m). The scale ratio between model and prototype quantities is designated by the subscript (r).

**Geometric Similarity** - Strict geometric similarity implies that the ratio of all corresponding lengths (horizontal and vertical) in model and prototype is the same:

\[ l_r = L_r = Z_r \]

In free surface flows, very often the ratio between horizontal dimensions of water bodies and the depth is very large. This situation frequently requires distortion (D) of the vertical scale (i.e., larger than the horizontal) in order to obtain sufficient depths on the model within the limited laboratory area.

\[ D = \frac{L_r}{Z_r} < 1 \]

**Froude Law** - All free surface flows are influenced by gravitational acceleration and the fundamental law in modelling of these flows is the Froude law.

\[ Fr_m = Fr_p \]

\( Fr = \frac{u}{\sqrt{gZ}} \) - Froude number

\[ u = \text{flow velocity}; \quad g = \text{acceleration due to gravity}; \quad Z = \text{characteristic vertical dimension} \]

The Froude number is the ratio of inertial (convective) to gravitational forces which are present in free surface flows. Equality of Froude number in model and prototype with \( g_r = 1 \) (the same gravitational acceleration in model and prototype) implies

\[ u_r = Z_r^{1/2} \]

If density differences are present within the fluid, then the ratio of inertial to buoyant forces is characterized by the densimetric Froude number

\[ Fr_A = \frac{u}{\sqrt{\frac{\Delta \rho}{\rho} gZ}} \]

Equality of densimetric Froude numbers for model and prototype is the fundamental law for modelling flows with density differences.

If density differences in model and prototype are arranged to be the same \( (\frac{\Delta \rho}{\rho})_r = 1 \), densimetric Froude law is reduced to standard Froude law. This is a common procedure in hydraulic laboratory practice.

The fluid motion in the prototype is always turbulent, and the parameter which defines the state of turbulence (ratio of inertial and viscous forces) is the non-dimensional Reynolds number,

\[ Re = \frac{u R_h}{\nu} \]

If the same fluid (water) is used in model and prototype it is never possible to obtain the same value of \( Re \) for model and prototype. In order to maintain turbulent flow in the model, which exists in the prototype, it is sufficient that the model Reynolds number should exceed a certain critical value, \( Re_c \).

\[ \left( \frac{U R_h}{\nu} \right)_m > Re_c \]

For free surface flows, \( Re_c = 750 \)
In shallow water models with stratified flow, distortion of the vertical scale is usually necessary. In order to simulate frictional resistance correctly, artificial bottom roughness is required in the model. This can be evaluated from the formula

$$n_r = D^{1/2} \cdot \left( \frac{Z_r}{n_r} \right)^{1/6}$$

where $n_r$ is the scale of Manning roughness coefficient.

Surface Heat Loss - For far-field processes, surface heat flux represents a boundary condition at the water surface and should be included as a scaling requirement. It is usually defined in a form which implies different horizontal $L_r$ and vertical $Z_r$ scales:

$$L_r = \frac{Z_r^{3/2}}{K_r}$$

where $K_r$ is the scale of surface heat exchange coefficient. It usually varies between 0.5 and 0.8.

VI.6.2 Model construction and equipment

Hydraulic scale models in which warm water discharges are studied require an additional circuit for warm water. This circuit should have a precise control of flow and temperature. A fast scanning temperature system is necessary to measure the transient temperature field. Some fast response probes, installed at selected points on the model, may be useful for detecting the turbulent structure of the flow.

For three-dimensional determination of the steady temperature field, probes should be arranged either in an appropriate spatial fashion or mounted on a traversing platform. The time constants of the probes should be long enough to eliminate short-term turbulent fluctuations, but short enough to detect the transient thermal behaviour.

In far-field models, surface heat exchange is an important factor which depends on the laboratory environment. In these studies, ambient water temperature must be recorded and should remain relatively constant throughout the model experiment. Also, the equilibrium temperature should be measured in specially arranged pans during the tests. A laboratory with temperature and humidity control is very useful to maintain a stable model environment.

VI.6.3 Recommendations

Near-field models for surface and submerged discharges can be used with good reliability and accuracy provided that the model employs accurately reproduced boundary conditions and a reasonable turbulence level. These models should be undistorted and operated according to densimetric Froude Law. The scales of these models usually vary from 1 : 50 to 1 : 150.

Models with vertical scale distortion give significant overprediction of mixing zones and may provide only qualitative results. Physical models are not recommended for far-field studies and cooling prediction because of scaling inconsistencies and operational restrictions.

VI.7 Monitoring Of Water Velocity And Temperature

Assessment of the impact of once-through cooling systems on natural water bodies and their subsequent control requires detailed information during the planning, design and operation stages of steam-electric power plants. Physical information required includes morphometric and hydrological data of the water body, meteorological data of the local region, and basic technical data of the proposed power plant. Existing and prospective users of the water body should also be tabulated. With so many variables, no single monitoring programme can be described which would have general validity for all areas, regions, and types of cooling systems.

Knowledge of the potential thermal and hydrodynamic consequences of heated discharges into, and cooling water withdrawal from a given water body will provide the basis for initial planning of field measurements. As field data collection is expensive and time consuming, a monitoring programme which is too extensive in scope will simply cause unnecessary expenditure of money. On the other hand, the lack of certain data, improperly planned sampling stations or frequency of measurements can appreciably decrease the value of the field measurements which are performed.
The aim of a monitoring programme for these physical features is as follows:
- to collect data and information necessary for siting and design of the power station,
- to collect data for the formulation, operation and verification of predictive physical and mathematical models,
- to form a basis for comparison between the pre-operational natural state of the water body and conditions with the cooling system in operation,
- to provide information that the cooling system is operating properly, from both the technical and the environmental standpoints, or alternatively to document the need to modify the cooling system design or to change the operating procedure.

This monitoring programme is usually arranged in two stages: (1) Pre-operational measurements, and (2) Post-commissioning measurements.

Initial monitoring efforts must be extensive in order to determine the detailed physical characteristics of the water body. The second stage of the programme is usually limited to selected important hydrological and meteorological parameters and is very often restricted to the near-field region (e.g. the thermal plume). For every project, the procedure of measurement should have a precisely determined aim and scope.

Useful information concerning hydrological field measurements is included in a guidebook: Water Quality Surveys (1978). The following definitions are suggested in this guidebook in connexion with field measurements:

- Monitoring: Continuous, standardized measurement and observation of the environment.
- Survey: A series of finite duration, intensive programmes designed to measure and observe the environment in more detail for a specific purpose.
- Surveillance: Continuous specific observation and measurement of the environment relative to control and management.

VI.7.1 Pre-operational monitoring and surveys

Pre-operational physical data should be collected in the following ways:

1. Collection and analysis of existing information (maps, plans, cross-sections, and data from existing sources).
2. Planning and installation of measuring stations and continuous standardized measurements over predetermined periods of time. The new network should be in conformity with the hydrometric network in that area. The extent of data required on hydrological measurements and water characteristics will differ from one water body to another.
3. Surveys limited to selected characteristic parameters, and organized for a defined period of time.

The instruments and techniques used should be as in relevant hydrological and meteorological monitoring and should be compatible with the guidance provided by the World Meteorological Organization (WMO-1971, WMO-1974) or as recommended in the recent literature for special techniques (e.g. Infra-red Remote Sensing: Dinelli, 1976; Hadding, 1974; International Symposia on Remote Sensing 1974, and 1975.)

Meteorological and hydrological data should represent sufficiently long periods of time to provide local extremes and mean values. Data from a network of previously existing measuring stations should be analysed to assist in answering this question.

The following three types of physical information are needed to characterize a power plant site.

(a) Morphometric Information

Basic documents are maps and cross-sections with topographic and hydrographic characteristics. They should indicate the geometry of the water body, its surface area, volume, depths, and temporal variations of these parameters. The preliminary location of cooling water intakes and discharges, as well as the location of other users of the water body, with their characteristic operation parameters, should be identified. This information indicates the actual situation, and recent aerial photographs are very useful.
(b) **Meteorological Information**

The following average daily data for the region near the water body, including also monthly means and seasonal extremes, should be collected: short-wave solar radiation, long-wave atmosphere radiation, air temperature, wet bulb temperature, wind speed and direction (at 2 m height), cloud cover, precipitation and evaporation. If some of these parameters are not available in the given region from direct measurements, they can be calculated or obtained from analogue areas. Such information should be checked, however, against direct measurements.

(c) **Hydrological Information**

Characteristics of the following parameters is necessary: stages, discharges, tidal variations, tidal and wind currents, sediment transport (bed load and suspended load, water temperatures, wave patterns, salinity, and ice conditions. These data should extend over sufficiently long periods in order to identify expected extreme values of a given probability.

The various water bodies used for once-through cooling (rivers, lakes and reservoirs, estuaries and coastal waters) present special requirements concerning morphological, meteorological and hydrological information. These are outlined in the following paragraphs.

**Rivers** - Cross-sectional and longitudinal profiles of a river upstream and downstream of the intake and discharge should be measured at half-year or yearly intervals to evaluate existing morphometric conditions and their changes. Distances between cross-sections should be set to reflect local conditions. Cross-sections should include the main river channel and floodplains.

River discharge should be estimated for a given cross-section in the form of a rating curve (stage-discharge relation). Direct measurement of discharge is necessary to check and correct the existing rating curve. If discharge measurements near the site are not possible, they must be performed for the cross-sections upstream and downstream of the power plant.

Stages, however, must be regularly recorded at the site of the power plant, indicating daily averages and extreme values (maximum and minimum).

Sediment transport should be assessed by means of direct measurements of bed load and suspended load at or near the site of the power plant. Measurements should be performed for different water stages and discharges.

Water temperatures should be recorded over a reach of the river several kilometres upstream and downstream of the power plant. Daily averages, with seasonal extremes are necessary.

Ice condition data must document the beginning and the end of ice appearance, duration of ice cover, and its thickness. Standard meteorological data are necessary (VI.7.1b).

**Lakes and Reservoirs** - Morphometric information should include: topography of the lake or reservoir, including islands, bays and side-arms, indication of shore-line length, and the surface area and volume as a function of depth, and characteristic cross-sections. Daily and seasonal changes of water levels due to natural conditions and the operation of hydropower plants should be recorded. Characteristics of the catchment area with discharges, including tributaries and outflows, should be documented. The exact water balance should be evaluated if all data are available.

Water temperatures should be measured regularly at selected stations, with less frequent observations of the deeper basins, to describe vertical temperature distribution and its seasonal variations.

Flow velocities and wind-induced currents should be estimated from temporary measurements and be related to wind velocities and directions.

Wave characteristics of the lake or reservoir should be based on temporary measurements and be sufficient to allow wave prediction for maximum wind velocities.

In cold climates, ice conditions must be determined on the basis of direct observations and measurements, or comparisons with similar water under similar meteorological conditions.

Meteorological information for a lake or reservoir must be collected at a local station. Most accurate results can be obtained from meteorological stations located over the water surface (pier, or floating station on a raft.) The rate of evaporation is an important parameter for lakes and reservoirs with small inflows and should be determined from direct measurements.

**Estuaries** - Physical data for estuaries should include all the information listed for rivers, with the addition of salinity measurements and wave pattern. It must be recognized that all
tidal phenomena in estuaries are non-stationary and non-uniform along its length. This will influence the location of monitoring stations, the time of data collection, and the manner of summarising these data.

Coastal Areas - Morphometric information must include the topography of the shore-line and bathymetry of the area adjacent to the shore-line up to 1 km in the off-shore direction. Temporal measurements are necessary to assess changes due to waves, tides and currents.

Hydrodynamic conditions of the coastal area include depth changes, currents and wave regimes. Depths should be recorded continuously at the site, while currents and waves should be assessed on the basis of series measurements and related to wind direction and velocity to predict extreme values.

Along-shore sediment transport and suspended load should be estimated by means of direct measurements and related to extreme hydrodynamic conditions. Salinity must also be estimated from direct measurements. Standard meteorological characteristics of the area should be assessed from a meteorological station installed on the site or in the vicinity.

VI.7.2 Post-commissioning measurements

The aim of post-operative measurements is to determine actual changes in the natural water body which result from the withdrawal and discharge of cooling water. The major changes may be observed near the intake structure and near the discharge. Withdrawal of cooling water changes the actual velocity field and stratification, if such existed, in the natural water body. Discharge of heated water changes water temperatures and velocities mainly in the near-field region.

Typically, standards have been established for excess temperature at the discharge and/or outside the mixing zone. Post-commissioning measurements will indicate whether these standards are being met.

The temperature field near the discharge depends on power plant load, meteorological conditions, ambient water temperature, and wind action. All these factors are variable over time. Therefore temperature measurements of the thermal plume should be performed within a short time interval.

Further changes in water bodies due to once-through cooling may be of a long-term character and may be reflected in the water balance due to increased evaporation, or in the thermal balance due to additional heat load; cooling may also change the chemical composition of water, or alter ice conditions. These changes may be detected only if sufficient information is available from the pre-operational period or if suitable reference stations have been established (see Ch. VIII).

It is recommended that a special programme of hydrological and meteorological measurements be put into operation during the early design stage of a power plant. A meteorological station installed near the site of the power plant should operate continuously during the construction period and during operation of the power plant. Post-commissioning hydrological measurements should be performed periodically and include water stage and discharge, bottom configuration and sediment transport, especially near the intake and discharge. Permanent stations for water-temperature measurements should be installed at intake and discharge, plus 3 to 4 off-shore stations in a deeper area to measure vertical temperature distribution. Location of these stations depends on the character of the water body. Measurements of water surface temperature distribution near the discharge may be performed from boats; this method is, however, not very reliable because of the unsteady character of the thermal plume. Best results are obtained by means of infra-red aerial photographs, although this requires special equipment and measuring instruments (Dinelli, 1976).
REFERENCES CITED


VII. Preoperational cooling system impact assessment: physical and biological information requirements

SUMMARY

Preoperational impact assessment is required for decisions regarding siting, design and operational procedures. A preliminary site survey and accumulation of existing knowledge from the literature, forms the basis for initial decisions regarding plant siting and design, and for decisions regarding the need to develop additional detailed information. The detailed preoperational studies collect selected data from the field and laboratory, to answer site-specific questions for siting and engineering decisions and to obtain background information for monitoring plant impacts following commissioning. This chapter outlines general information requirements for impact assessment. These will be subject to modification depending on the environmental situation at a proposed site. (Detailed physical information requirements are discussed in Chapter IV, V and VI). Methods for summarizing and interpreting the collected data are introduced. Useful reference documents for detailed methodology are identified.

VII.1. Introduction

There are many ways to organize the information that is valuable for predicting and assessing the probable impact of power plant cooling systems on the environment and for using this information to implement ecologically desirable changes in plant siting, design and operation. This section summarizes the framework for organizing needed physical and ecological information as viewed by joint working groups of two regulatory agencies in the USA (US Environmental Protection Agency, 1977 a,b). Frameworks developed in other countries may be equally appropriate for addressing the same environmental considerations. No given assessment approach and methodology is directly or entirely applicable to every site and proposed power plant cooling system. The USA approach is offered as general guidance. As applied in the USA, the actual format and definitive assessment studies to be undertaken at a specific site are developed jointly by the electrical generating authority and regulatory agency representatives for the site and plant in question.

Preoperational environmental assessment is viewed as a two-phase process: preliminary field studies are needed to determine the important local environmental questions, to be followed by a set of specific site-related laboratory and field studies to address these questions (Fig.VII-1). Decisions on the need for specific detailed environmental studies are made only after completion of the preliminary investigation. The preliminary studies will survey the general physical and biological features (e.g. hydrography, habitat types and locations, dominant species and communities) of the site and document their general relationship to the project region. These studies will determine, for a given set of plant design options, which topics deserve further indepth study and which do not.

The detailed biological and physical studies will generally have both laboratory and field components. Controlled laboratory tests are often required to define the biological boundary conditions (e.g. thermal tolerance, critical swimming speeds) that must be met by engineering designs so that damages can be prevented. Physical and mathematical models are often used to simulate alternative intake and discharge designs. Field studies will document the physical and biological dynamics in the natural environment. Also, the preoperational field studies should include reference stations some distance from the power plant site to permit comparative evaluation of unaffected sites during the operational monitoring programme.
Figure VII.1 Surveys
A. Preliminary survey (cooling systems tentative)
B. Detailed environmental studies
C. Post-commissioning monitoring
(see Chapter VIII). Both the preliminary surveys and detailed studies will usually prove to be contributions to scientific knowledge of developing regions as well as provide information for purposes of siting and designing an environmentally acceptable power station.

Data synthesis should also be tailored to making engineering decisions regarding power plant siting, design and operation. Biological and physical data need to be synthesized to describe the practical limiting conditions (i.e., relevant to the site and proposed plant during the early phases of project development if environmental protection is to be assured. Design changes in the power station can be made readily, for example, if pertinent biological information is available before construction, but changes may be excessively costly if conflicting environmental requirements are not known until after the plant is built. Some engineering decisions which require environmental data include, for example, length of the discharge conduit, types of outlet ports, specific location for the outlet ports, $\Delta t$ and time of transit for cooling water, intake location, water velocity at the intake screens, amount of dredging required for intake or effluent channels, and chlorination schedules. It is essential that environmental and engineering staffs maintain close communication throughout the development of the project.

All potential studies discussed here will not deserve extensive assessment investigations at every site, rather, these sections are included to illustrate items for consideration in designing a specific impact assessment study.

VII.2 Site and Receiving Water Description and Preliminary Power Plant Design Information.

The following information is generally adequate to describe the potential experiences of organisms which may be entrapped within intake structures, impinged on parts of the structure, entrained in the water mass circulated through the condensers or exposed to heated water at the discharge. The full range of resultant physical, chemical, and biological conditions, which could be encountered throughout the annual cycle should be described. Information on daily and seasonal fluctuations is of special importance in those waters subject to wide variation in water quality at the specific site. Plant cooling water characteristics can be summarized using a format similar to Table VII-I. Additional data may be found pertinent to the evaluation of environmental impact of a power plant the location or intake structure in question and should be included, even if it is not specifically listed below.

VII.2.1 Site location and Layout (proposed).

Using maps and navigational charts showing topographic and hydrographic features identify specific location of the proposed power plant and its cooling water structure(s). Data should include topographic details, water body boundaries, hydrological features, including depth contours and delineation of the affected water body segment. In addition, show the location and type of other existing cooling water intakes and discharges in the water body segment, plus other pollutant discharges or large water intakes (e.g., sewage or industrial outfalls, city water intakes). Finally, indicate for the proposed site, details of the topographic and hydrological features potentially subject to change by construction and operation of the proposed cooling system.

VII.2.2 Hydrodynamic and Meteorological Information.

Basic hydrodynamic and meteorological information is necessary for adequate assessment of physical impacts and the ecological consequences of physical changes. These topics are discussed in detail in Chapter IV-VI. In general, the needed hydrodynamic information includes water flow rates and volumes (both outside and through the plant), tidal fluxes and salinity patterns (for estuaries and coastal sites), release schedules (for reservoirs), and thermal regimes. Meteorological information includes wet and dry bulb temperatures, wind conditions, radiation levels, cloud cover data, and rainfall.

VII.2.3 Sediment Transport.

The stability of shorelines and bottom sediments are very important in development of power station cooling systems. Cooling system structures can interrupt alongshore sediment
TABLE VII.1

COOLING WATER CHARACTERISTICS 1,2,6

<table>
<thead>
<tr>
<th>% Capacity</th>
<th>% Time at Fractional Load</th>
<th>Intake Velocity</th>
<th>Rate of Circulating Cooling Water Flow(^3)</th>
<th>Condenser Rise (\Delta T)</th>
<th>Discharge (\Delta T)(^4)</th>
<th>Rate of Discharge Cooling Water</th>
<th>Rate of Discharge Non-Cooling Water</th>
<th>Discharge Velocity(^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40% &amp; Less</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>40-50</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>50-60</td>
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<td>60-70</td>
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<tr>
<td>70-80</td>
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<td></td>
<td></td>
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<tr>
<td>80-90</td>
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<td></td>
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<tr>
<td>90-100</td>
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<td></td>
</tr>
</tbody>
</table>

1. A separate table should be prepared for each generating unit and for all units combined.

2. If seasonal variations occur, this should be indicated.

3. Variations of intake velocity with changes in ambient conditions (e.g. river flow, tidal height, water level) should be noted.

4. Discharge \(\Delta T\) = Discharge temperature - Intake temperature (in many cases, condenser \(\Delta T\) is equivalent to discharge \(\Delta T\); however, this is not the case for plants with supplemental cooling).

5. Discharge velocity should be provided at the point where cooling water leaves the discharge structure. Variations in discharge velocity, with changes in ambient conditions (e.g. river flow, tidal height, water level) should be noted.

6. From US, EPA, 1977b
transport resulting in build-up or erosion around the facilities and cause both environmental alterations and possible detriment to the facilities. Susceptibility of bottom sediments to erosion will influence location and design of inlet and outlet works, especially when high-velocity discharges are to be used. Pertinent features of the sediment should be determined in the early phases of study.

VII.2.4 **Plant operation data (proposed).**

Basic operational data for the facility can provide insights into probable environmental impacts. Information should be provided for the expected lifetime of the power plant, plant electrical capacity, number of units, fuel type and anticipated percent of time that the plant will operate at fractional levels, given daily and seasonally.

VII.2.5 **Cooling system description.**

**VII.2.5.1 Intake structures.**

The location of the intake structures can influence the withdrawal of organisms and should be described, with maps and drawings, to indicate their location with respect to the power plant and in the water body (including both horizontal and vertical aspects). The design of all major components of the intake, including canals and channels, screening devices and fish by-pass and handling devices, should be similarly detailed. Data are also needed on design water-flow capacity, planned operational flow rates and their frequency of occurrence (which correlate with load characteristics); also location; amount and duration of water recirculation for deicing or intake tempering and average and minimum approach and through-screen velocities at different depths.

**VII.2.5.2 Pumps.**

Information is needed on details of pump design to estimate physical damages to entrained organisms. Useful information includes location within the intake structure, configuration of blades and housing, revolutions per minute, number of pumps and their capacities, the planned operating schedule (especially if there is to be seasonal reduction in flow) pressure regimes in water subjected to pumping, velocity shear stresses in pumping (if determinable), sites of potential turbulence and physical impacts and discharge velocity.

**VII.2.5.3 Heat exchangers.**

Details of design and composition of condensers can be important for assessing biological damages. Diameter and length of tubes, their configuration and number should be indicated. The alloys used should be specified and any information regarding the expected rates of erosion or corrosion should be given. Design of heat exchange piping should be given, especially leader boxes, siphon pits or other sites of unusual turbulence.

**VII.2.5.4 Biofouling control.**

Controls for biofouling can extend to the environment outside the plant and cause damages there if not carefully planned. Indicate location of biocide (chlorine or alternative) introduction into the cooling system, describe the type of biocide used, the timing and duration of use (summarize on daily and monthly basis), expected concentrations of biocide in various parts of the cooling water system and receiving waters during fractional generating loads and chlorine demand of the receiving waterbody. Mechanical or thermal cleaning systems that may be used as an alternative to biocides should be described.

**VII.2.5.5 Entrainment thermal experience.**

Initial water temperatures and details of the thermal shock expected are needed to assess thermal impacts of entrainment. Tabulate annual ambient water temperature for the proposed intake site, plus expected thermal addition to cooling water at various operating capacities.
Graph resultant time-temperature experience of organisms subjected to entrainment in the cooling water system, until return to +1°C above ambient for worst case, anticipated average conditions, and minimum time/temperature impact conditions.

VII.2.5.6 Other relevant data on cooling water circulation system, intake and receiving water.

Estimate concentration and percent of atmospheric saturation of dissolved gases in intake and discharged water and tabulate existing dissolved oxygen vertical profiles in the vicinity of the intake, discharge and, should recirculation occur, such as in a reservoir, downstream for average and worst case conditions.

Also document water quality at the intake with regards to suspended solids, turbidity, problem wastes and chemical species, determine for each point source which discharges into the water body segment their discharge frequency, duration, pollutant type and maximum discharge concentration. Intake maintenance procedures should also be indicated, such as annual draining, heat treatments, or physical cleaning.

VII.2.5.7 Outfall configuration and operation.

A detailed description of the discharge system can assist in determining whether a given discharge volume and thermal elevation may be damaging or not. Describe, with drawings, the length of discharge pipe or canal, the area and dimensions of discharge port(s), number and spacing of discharge port(s), the exit velocity, discharge depth (mean and extremes) and angle of discharge as a function of the horizontal axis, vertical axis and current directions.

VII.3 Hydrological and Meteorological Information to Assess Cooling System Impact.

VII.3.1 Intake structure and pumped entrainment considerations.

Knowledge of the physical interaction of the intake and the adjacent water body forms a base for assessment of certain biological impacts (entrainment and impingement) by relating the behaviour and motion of local organisms to the flow of water around the site and into the intake structure. To determine the involvement of organisms with the intake, it is desirable to identify the types of circulation which will be dominant in the water body by establishing a programme of monitoring currents and other relevant hydrological and physical parameters of the system. Hydrodynamic data collection, analysis and modelling at intakes are discussed in detail in Chapters IV and VI.

A map of probability of plankton entrainment, showing both horizontal and vertical fields, would be useful to delineate the area of potential intake-organism involvement by a rational analytical method. A hydrographic computer model, for example, could simulate the flow fields in the region and indicate varying probabilities that organisms in a certain location would be entrained. Likelihood of impingement can also be estimated by delineating existence of zones in intake channels where fish may be trapped by water velocities in excess of about 0.3 m/sec. Specific attention should be given to probable velocity differences among the several intake screens or across the faces of individual screens. (Some screens are in hydraulic eddies where fish seek refuge and are weakened by long exposures).

VII.3.2 Cooling water discharge considerations.

Ecological analyses and predictions of impacts require accurate prediction of discharge water temperature and plume configuration in the affected water body. This necessarily involves consideration of meteorological conditions in the atmosphere over the water body as well as modelling discharge plume dispersion. For biological assessments, representative plumes, sizes and locations (e.g. to the +2°C isotherm) are important for predicting near-field of rivers, reservoirs, lakes and coastal zones should be known for predicting chronic, low-level impacts. Seasonal occurrence and extent of thermal or salinity stratification should be determined where important to the ecosystem. These topics are considered in detail in Chapters IV-VI.
VII.4 Preliminary Biological Information

VII.4.1 Information needed

Preliminary biological studies must be conducted to provide information on the biota occurring within the intake and discharge zones of influence. This site specific information will be utilized, along with published reports of observed ecological change at operating power plants (Chapter II) to delineate the important assessment questions for subsequent detailed study. This preliminary biological information is also crucial in the selection of the representative and important species (RIS) and sensitive communities to be investigated further.

Preliminary biological information required for site-specific impact assessment includes enumeration of all dominant species occurring in or near the intake and discharge zones of influence, plus data on their relative abundance, spatial distribution, seasonal occurrence, local breeding seasons, modes of early development (brooding or planktonic), habitat requirements and general patterns of movement for each life history stage. Information should also be included for important transient species, such as seasonal migrants or planktonic larvae. Maps and quantitative descriptions should be developed to clearly indicate the types of aquatic communities both within and near the zones of influence. Information on the adjacent areas is important for selection of reference (unaffected) sampling sites for operational monitoring. In addition, general features of ecosystem structure and function should also be elucidated in a preliminary fashion.

As studies are initiated to obtain the above information, it is assumed that much of the physical information cited in the preceding sections will be available or is being gathered simultaneously. Power plant cooling water usage should be characterized and sufficient hydrological and meteorological modelling of the site completed to identify the source and extent of water involvement (for both the intake and discharge) for several design alternatives. At the discharge, for example, prediction of the maximum annual location of the 2°C (above ambient) isotherm will serve to identify the study area of principal concern for thermal effects.

Further, it is desirable that a regional biological survey has already been completed for the larger waterway in question. This would aid in eliminating localities clearly unsuitable for power plant siting from the present site-specific considerations. Such a regional survey would map the distribution of important species and communities. Areas which are unique or critical to ecosystem function or population maintenance (e.g. spawning areas, nursery grounds, and migratory routes) would also be indicated. Such a survey has been compiled for the Chesapeake Bay (Maryland Power Plant Siting Programme 1975). While regional surveys cannot provide sufficient detailed biological information to make definitive siting decisions, they can provide a preliminary indication of potentially suitable power plant sites based on lowest concentrations of important populations and communities or the absence of zones critical for ecological functions. In the absence of a systematic regional survey, reports from the literature can often be used to compile a preliminary picture of the aquatic resource near a proposed power plant site.

VII.4.2 Identification of topics for detailed site-specific studies.

The next task is to identify the specific biotic components and ecosystem functions which could be appreciably altered by power plant cooling system construction and operation. The information to be drawn upon includes the semi-quantitative preliminary description of the biota at the site (summarized above), hydrological and meteorological information available at this point (Chapter VII, Sect.3) and a tabulation of problems associated with cooling water use at existing plants (Chapter II). In making up the list of possible ecological problems, special cognizance should be given to reports from plants on similar types of waterways and at comparable latitudes. Yet other reports should not be hastily discarded as not relevant. Some observed problems are generic to cooling water use and can be relevant to many kinds of sites.

The resulting list of potential cooling system impacts must be scrutinized by the biologists and hydrologists of the assessment team, and ideally by other investigators who have previously studied impacts at operating plants. Their objective is to reduce the list to a set of topics highly relevant to the proposed plant and the site in question. The relevant topics should then be ranked in order of probability of occurrence and relative importance of
each potential change for the existing aquatic populations, communities and the ecosystem as a whole. Hopefully, questions of marginal ecological and social importance can be recognized at this point and be dropped from the study. This will allow greater focus of technical expertise and funds on the more substantive.

VII.4.3 Identifying low risk biota.

One step in identifying major cooling system impact questions is elimination of topics of minimal importance at the study site. It will be noted that a biotic category may have a low potential of experiencing significant impact if it comprises only a very minor portion of the system (both structurally and functionally) or if the impacted species have very short reproductive cycles or ubiquitous distribution and good dispersal mechanisms, so replacement renders mortalities inconsequential. Yet as with all generalizations it must be recognized that there will be exceptions to these observations. Hence, conclusions of potential low impact at a given site must be made carefully. Further, the observations cited below must not be a substitute for adequate preliminary field studies.

Phytoplankton. Areas of low potential impact for phytoplankton may include open ocean areas; lake hypolimnia or other systems where phytoplankton is not abundant and does not represent the primary food material for the system. (Embaysments bordered by mangrove swamps, salt marshes, fresh water swamps, and most rivers and streams, may be in this latter category). Also, aquatic systems having phytoplankton-based food chains, yet which can rapidly replace power plant losses through high productivity, may experience minimal impact on the phytoplankton compartment.

Zooplankton. Plants with cooling water intakes located in zones known to be free of zooplankton (e.g. lake hypolimnia) would be expected to have low impact on these organisms. Also, at sites with characteristically high reproductive rates for true zooplankton (cladocerans, copepods), such that losses, if any, are replaced in a matter of a few days, overall impact may be very low, despite initial losses.

Most estuarine areas would not be considered areas of low potential impact for zooplankton, particularly for the meroplankton. However, where a logarithmic gradient of zooplankton abundance exists, those areas with the lowest level of abundance might be found to be low potential impact areas, but will require further definitive study of both food chain dynamics and of the spatial and seasonal occurrence of meroplankton to substantiate such a conclusion.

Habitat Formers. In some situations, the aquatic environment at a proposed site will be devoid of habitat formers. This condition may be caused by low levels of nutrients, inadequate light penetration, sedimentation, scouring by high stream velocities, substrate character, or toxic materials. Or the zone of influence of the intake or discharge may be restricted to the pelagic zone, whereas habitat formers are benthic. Under such conditions the site may be considered a low potential impact area for this biotic category. However, if there is some possibility the limiting factors (especially man-caused limiting factors, such as pollution) may be removed and habitat formers may become established within the area, it would be necessary to determine whether the heated discharge would restrict reestablishment.

Macroinvertebrates. A low potential impact area for the macroinvertebrate faunal component may include those zones of cooling system influence with insignificant occurrence of pelagic and benthic macroinvertebrate species. Lakes and large rivers generally have few drifting macroinvertebrates that would be of concern. Strictly benthic macroinvertebrates represent a low potential impact category when there is assurance that neither the intake or the thermal discharge will have near-bottom contact, alter near-bottom circultation or cause shifts in detrital or mineral sedimentation processes.

Fish. An intake or discharge zone may be considered to be in a low potential impact area for fishes if the occurrence of sport, commercial, and important forage species of fish is rare, even during migratory periods (e.g. open waters of many lakes) and the intake or discharge site is not located in a spawning or nursery area. Further, there should be a low probability that the thermal plume (bounded both horizontally and vertically by the +2°C isotherm) will occupy a large portion of the zone of passage which would block or hinder fish
migration (adult and juvenile), nor will ichthyoplankton be exposed to lethal or debilitating sublethal thermal shock under the most restrictive environmental conditions based on 7-day, 10-year low flow or water level and maximum water temperature. Likewise, the plume and discharge canal (if any) configuration would not be expected to attract fish which will then become vulnerable to cold shock, malnutrition or disease and the intake has a low velocity relative to the swimming abilities of local species at all seasons.

Other Vertebrate Wildlife. Power plants can be considered to pose low potential impact for other vertebrate wildlife where no large or unique (i.e. threatened or endangered) populations of wildlife are present. Sites in cold continental areas (such as the North Central United States) would not be predicted to be of low potential impact if geese and ducks are encouraged by plant operations to stay through the winter, unless these wildlife could be protected through a wildlife management plan from potential sources of harm.

VII.5 Detailed Preoperative Ecological Studies

Having determined the major impact topics to be pursued, the next task is to carefully design the detailed preoperational studies to assure that necessary information for impact assessment is provided. The focus at this point will be on a set of representative and important species (RIS) and communities considered particularly sensitive to cooling system construction or operation, or which are representative of potentially sensitive components not amenable to direct evaluation. It is expected that preoperative ecological studies will have field, laboratory and modelling components. Some of the questions which can be pursued through laboratory and field studies (plus literature reviews) are enumerated here. As these studies proceed, it is expected that the investigation will further narrow in focus and take on increasing complexity (e.g. to develop information for a population model for an important entrainable species). The detailed field studies must be designed to both obtain information for impact prediction and to describe the reference stations to be utilized in operative monitoring.

VII.5.1 Selection of representative and important species potentially receiving significant impact.

The preliminary survey of a waterway will identify those species which could potentially experience significant adverse cooling system impact. It is generally most useful for predictive impact assessment studies to select a modest number of these species (or species assemblages), possibly not exceeding 12 to 15, for intensive investigation of tolerance to all potential cooling system stresses. The limited resources of time, personnel and money can then be devoted to detailed study of these indicative components. In general, the species selected as representative or important (RIS) may include those which are:

1. representative, in terms of their biological requirements, of an indigenous aquatic community;
2. commercially or recreationally valuable (e.g. among the top ten species landed in a local fishery - by monetary value);
3. threatened or endangered by extinction;
4. critical to the structure or function of the ecological system (e.g. habitat formers);
5. potentially capable of becoming a localized nuisance species;
6. necessary, in the food chain, for the well-being of species determined in 1-4;
7. one of 1-6 and have high potential susceptibility to entrapment, impingement and/or entrainment;
8. particularly sensitive to temperature, biocides, synergistic effects of cooling system stresses, etc;

In selecting the RIS, two specific questions should be considered:
1. Is the potential for problems with this species or species assemblage credible (e.g. documented as a problem elsewhere or a good predictor of impact on other species or communities which are not amenable to study)?
2. Is the problem likely to be significant (ecologically or for man)?

It will be recalled that the impacts associated with the intake (impingement of fishes and entrainment of eggs and larvae of fishes and invertebrates) can be of equal or greater significance than those associated with the discharge. Therefore, species susceptible
to intake damage and entrainment should be included with those examined for possible RIS status. Experience has shown, however, that phytoplankton and true zooplankton (copepods, cladocera) are usually at low risk at the population and ecosystem scale, and thus are usually not included.

Impacts at the discharge may be predicted by investigating major components of the local aquatic community which are considered (through the literature or preliminary study) to be the more sensitive to discharge stresses. Some species are known to have a narrow range of thermal tolerance and are classified as stenothermal. In others, their potential thermal sensitivity at a given site might be suggested by natural summertime losses or by the nearness of the southern limit of a species geographic range.

Species or communities that occur distant from the power plant site, yet which could be influenced indirectly, should also be considered for RIS or other detailed studies. For example, power plants on rivers may warm the headwaters sufficiently to raise the entire river temperature and exclude cold-water fishes such as salmon from downstream zones. In this case, the salmon could be an RIS.

VII.5.2 Laboratory studies to predict direct biological damages.

Accurate predictions of impacts are often impossible without detailed knowledge about direct biological effects of heat, chlorine, water flow rate, etc. on the key species (RIS). This detailed knowledge usually cannot be obtained under uncontrolled field conditions. This section outlines types of experiments and sources of information which can be particularly useful for determining direct biological effects. In many regions, single-species information on biological responses to temperature, chlorine, pressure and other factors may be available in the scientific literature from both laboratory studies or field investigations at other sites. When not available already, laboratory information can be obtained experimentally using standardized methods.

Laboratory studies and literature reviews undertaken for each RIS should focus on specific topics relevant to site-specific cooling system questions. Table VII.2 cites several thermal indices which might be considered. Some methods for their determination are also included. The results of such laboratory studies can be related to a specific power plant by taking into account its cooling system operational characteristics, such as illustrated in Table VII.3. Table VII.2 does not provide a comprehensive summary of all thermal effects studies potentially useful for thermal impact assessment. For example, there will be interacting influences (e.g. temperature, chemicals, scouring) that are not included in the studies tabulated, but which still should be considered. Normally, the thermal requirements of distinctly different life stages should be separately studied as indicated. Comparable studies should also be developed to explore the probability of damage to local RIS due to intake impingement and entrainment and through-plant entrainment.

Some comments on methods for several laboratory RIS studies (including thermal, impingement, biocide and gas supersaturation studies, and notes on their applications to impact assessment are provided below.

1. High temperature survival for juveniles and adults:
   Method: Determine 48 hr. TL50 (a ultimate incipient lethal temperature) for juveniles and non-breeding adults. Acclimation temperatures should approximate the natural field maximum and the highest temperature at which the species can be held. Expose animals to elevated temperatures in an acute (instantaneous) manner.
   Application of Results: The TL50 value can be used to estimate the upper non-lethal limit for the life-history stage in question (48-hr. TL50 minus 2°C). The TL50 value also can be used with the optimum growth temperature to estimate the upper temperature limit for appreciable growth (National Academy of Sciences, 1973.)

2. Thermal shock tolerance of selected life-history stages:
   (a) Heat Shock - For meroplankton, simulate temperature shock upon traversing a thermal plume or passing through the power plant condenser system.
   Method: Expose eggs, embryos, and larvae, or other life stages to abrupt temperature shocks of rapid temperature elevations, followed by a rapid drop in temperature at a series of exposure times and temperature gradients reflecting transit times and temperatures to be found at the power plant.
   Application of Results: The TL50 value can be used to estimate the upper non-lethal limit for the life-history stage in question (48-hr. TL50 minus 2°C). The TL50 value also can be used with the optimum growth temperature to estimate the upper temperature limit for appreciable growth (National Academy of Sciences, 1973.)
TABLE VII-2
SOME THERMAL EFFECTS PARAMETERS APPLICABLE TO AQUATIC ORGANISMS EMPLOYED AS RIS

<table>
<thead>
<tr>
<th>THERMAL EFFECTS PARAMETERS</th>
<th>POSSIBLE METHODS FOR DETERMINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. High Temperature Survival</td>
<td></td>
</tr>
<tr>
<td>Aquatic Adult</td>
<td>$T_{L50}$, 24 hours</td>
</tr>
<tr>
<td>Juvenile (Immature)</td>
<td>$T_{L50}$, 24 hours</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Thermal Shock Tolerance (Heat and Cold)</td>
<td></td>
</tr>
<tr>
<td>Aquatic Adult</td>
<td>single shock to simulate plant shutdown</td>
</tr>
<tr>
<td>Juvenile (Immature)</td>
<td>double shock (up and down) in traversing plume</td>
</tr>
<tr>
<td>Early Developmental Stages (incl. meroplankton)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Optimum Temperature for Performance and Growth</td>
<td></td>
</tr>
<tr>
<td>Non-breeding Adult</td>
<td></td>
</tr>
<tr>
<td>Juvenile</td>
<td>length, weight changes; DNA/RNA Ratio$_2$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Maximum Temperature Regime Allowing Early Development Completion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Normal Spawning Dates and Temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Special Temperature Requirements for Reproduction</td>
<td></td>
</tr>
</tbody>
</table>

2. Also indicated by final preferendum for fish (NAS, 1973).
3. Only amenable to species readily reared or held in the laboratory.
### Table VII-3

**Sample Table to Summarize Thermal Effects Data for Each Representative Important Species (RIS)**

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Common Name</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Thermal Effects Parameters</th>
<th>Temperature Limit OR Reference (°C)</th>
<th>Literature Reference (lf Appropriate)</th>
<th>Mean and Maximum Area Unavailable for Function (m²) b</th>
<th>Mean and Maximum TimeUnavailable for Function (Days) b</th>
<th>Is Effect, If Any Expected To Affect the Population of the RIS? (Yes or No)</th>
</tr>
</thead>
</table>

a. From US, EPA, 1977a

b. That area or time under average and worst case conditions that will not permit biological function to occur satisfactorily

**Summary Conclusion of Effect of Heat on the Representative Important Species (RIS):** ____________________________
Application of results: Lethal time-temperature stress regime minus 2°C can be used to estimate upper temperature limits of survival to thermal stresses of short duration in entrainment or in thermal plumes, including prey avoidance behaviour (National Academy of Sciences, 1973).

(b) Cold Shock - For juveniles and adults, simulate winter plant shutdown stress to fishes and motile macro-crustaceans that are attracted to heated areas.
Method: Expose organisms to acute temperature drops equal to the range of expected discharge Δts, using maximum winter plume temperature as the acclimation temperature. Indicate temperature test regimes which produce equilibrium loss of 50% of the sample within 4 hours and causes mortality after 24 hours.
Application of Results: Identifies the winter thermal differential between heated discharge water and cold receiving water which could result in thermal shock in the event of plant shutdown and an ensuing high loss of organisms due to death or increased susceptibility to predation (National Academy of Sciences 1973; Coutant 1977a).

3. Estimation of optimum temperature for growth:
   (a) Fish and macroinvertebrates - Determine the rate of growth of test groups (length or weight increase per unit time) when maintained at a series of temperatures and at otherwise near-optimum environmental conditions, with food provided in abundance. Identify the temperature yielding highest growth rate. For fish, determinations of final behavioral temperature preferendum may closely correspond to the temperature which is optimal for many physiological processes, including growth (Brett 1971). Coutant (1977b) has compiled data on fish thermal preferences.
   (b) Macrophytes - Determine the temperature producing maximum growth rate or net photosynthesis for at least a 24-hour period, using an appropriate photoperiod and nutrients.
Application of Results: Optimum temperature for growth can be combined with ultimate incipient lethal temperature limit to give an estimate of the upper limit for acceptable growth of desirable fish and invertebrates. This is usually applied to the far-field zone, but may also be used in the plume (National Academy of Sciences 1973). Growth rate data for nuisance species of macrophytes indicates conditions in which they can be expected to proliferate.

4. Minimum, optimum and maximum temperatures allowing completion of early development:
Method: For RIS which are capable of being reared in the laboratory, maintain fertilized eggs under a series of temperature regimes to determine minimum, optimum and maximum conditions permitting greater than 80% survival to completion of development, (i.e. post-larval metamorphosis); in fish, to the point of successful initiation of feeding. Note that diurnally cyclic temperature regimes with a 5°C total range can be more adaptive for enhanced thermal tolerance than is a constant, non-cyclic temperature regime. For species not amenable to laboratory study, field observations may be adapted to yield similar information.
Application of Results: Temperature ranges can be identified that must be maintained during periods of egg incubation and early larval development. This period may last for only brief periods (hours to days) for some species, but can extend over several months for cold-water species which spawn in the fall.

5. Estimation of preferred temperature (final preferendum) of motile organisms:
Method: There are a number of experimental systems that are suitable for determining behaviorally selected temperatures (McCauley 1977). The method chosen should suit the behaviour patterns of the subject organism. In principal, the organism should be offered a thermal gradient and allowed to select its position in it over a period of several days. (Short-term temperature selection may be confounded by effects of immediate or prior thermal acclimation). The final preferendum is the statistical mode of a frequency distribution of records of many fish or of multiple records of a single fish (Coutant 1975). If the frequency distribution is reasonably normal (Gaussian), then the mean (average) can be used. Upper avoidance temperatures are usually distinguishable in the frequency distribution and sometimes there is a lower avoidance temperature. Field data are useful for determining preferenda, but are usually less precise than laboratory experiments (Gammon 1971, Coutant 1975, Stauffer et al., 1975). Thermal preferenda of fishes in North America have recently been summarized (Coutant 1977b).
Application of Results: Movements of many fishes near thermal outfalls can be predicted if
thermal preferences are known (Coutant, 1975; Gift, 1977). This is especially true for attraction of fish to thermal areas in winter and repulsion in summer. Final preferenda of most fish studies match closely the optimum temperature for growth. Thus, final preferendum may be used to estimate this parameter.

6. Normal dates and temperatures for reproduction:
Method: Cite range of dates and threshold temperatures which initiate and inhibit gametogenesis and spawning, as reported in the literature for areas closely related to the water body segment in question. Some laboratory studies may also be available, but field observations may be more reliable here. Special temperature requirements for reproduction should be identified to the extent that they are known. For example, a minimum of 10°C must be experienced before gametogenesis can be initiated in two boreal barnacles and a winter chill seems to be required for successful early development of yellow perch (at least for stocks in northern latitudes).

7. Swimming speeds for fishes and invertebrates subject to impingement:
Method: Using a test flume or other apparatus which allows expression of normal behavioral responses (searching, turning, schooling, etc.) determine the water velocities which cause the organisms to fail to maintain themselves in the current over both short time periods (burst swimming speeds) and long periods (cruising speeds). Tests should be conducted at conditions of temperature, turbidity, etc., that the fish would experience at the power plant site. (Some species, such as threadfin shad, have much reduced swimming speeds at low temperatures which results in high impingement rates in winter.) For additional examples, see Blaxter (1969).
Application of Results: Swimming speed data can provide initial estimates regarding the abilities of mobile organisms to avoid being impinged on intake screens. This subject involves many aspects of behaviour that are little understood, however, so estimates may prove inadequate for poorly studied species.

8. Chlorine toxicity:
Method: Determine the relationship between residual chlorine concentration and time to 50% mortality for the species in question over a range of concentrations from the highest to be used in the power plant to those allowing indefinite survival (>96-hr). Compare with accumulated data in Fig. II.4 to see if RIS sensitivity is truly representative.
Application of Results: Chlorine toxicity data for RIS can be used to design plant chlorination and discharge mixing schemes that will assure chlorine toxicity for within-plant control of fouling organisms, yet protect non-target organisms in the outlet plume and receiving water-body. Protection of the community is most assured when the toxicity boundary conditions of Fig. II.4 are not exceeded (Mattice and Zittel 1976).

9. Gas supersaturation:
Method: TL50 values are determined for the RIS exposed to a range of supersaturated total gas pressures, as measured by the Weiss Saturometer or equivalent methods (Wolke et al., 1975). Tests are conducted at temperatures found in the discharge after warming air-saturated ambient intake water in winter.
Application of Results: These results will indicate whether supersaturated gases in discharge areas (caused by warming air-saturated cool water, especially in winter when gas concentrations are at saturation levels) will be likely to cause fatal gas embolisms ("gas bubble disease") in tissues of resident organisms. Fish are most likely to be resident in discharges during cool months where temperatures are closer to their thermal preferences. Levels above about 110% of saturation have been found lethal to certain fish species (National Academy of Sciences 1973).

10. Cooling Tower Biocides and Corrosion Inhibitors (and other chemicals used in power plant operation):
Method: Tests for acute and chronic toxicity should be conducted according to standard methods to determine the chemical toxicity of materials added to circulating waters of closed-cycled cooling systems, that can be released to the environment through blow-down or drift. There may be other chemical discharges from the power plant for which toxicity should also be determined (see Becker and Thatcher 1973).
Application of Results: Blow-down and the chemical discharges can be regulated using such toxicity data to prevent acute or chronic toxicity to aquatic organisms, or to determine needs for effluent treatment systems. Note that drift to the terrestrial environment can also cause toxicity in aquatic systems when long periods of dry weather
are followed by heavy runoff to streams.

VII.5.3 Detailed field studies.

Detailed field studies will be pursued for two general purposes. One is for impact assessment, to provide information on selected RIS or sensitive communities to evaluate specific major potential impact questions. Secondly, studies will be conducted to describe ecosystem components (both biotic and physical) at a set of reference stations to be utilized in operational monitoring. The latter studies are discussed in Chapter VIII. In some cases, the same field data could be used for both purposes. Yet the basic purposes and questions of these two projects differ, a distinction should be maintained between them. Clear definition of purpose for each field project is crucial to assure appropriate project design, implementation, evaluation and termination.

In developing the field studies, the same criteria established for the detailed laboratory studies should be adopted: each set of data collected must have a clear purpose or use with regards to the larger assessment or monitoring questions. A distinction must also be made between those field studies which are mandatory to impact assessment and operational monitoring and those of a "desirable" nature, yet are not clearly necessary. As the information demand of most impact assessment field studies will be considerable, limits of time, funds and expertise will probably preclude investigating the latter topics.

The detailed field studies for impact assessment should provide: (a) general autecological data on local RIS populations required for the major impact assessment questions (e.g. descriptions of spawning seasons, seasonal patterns of occurrence and movement for all life history stages, food and habitat preferences, and species associations, as relevant), (b) quantitative descriptions of the structure of each potentially impacted community and determination of the roles of the dominant species in community function, (c) quantitative estimation of the numbers of organisms which occur within the zones of probable impact of the intake and discharge (e.g. for the intake, estimate the number of animals, by species, which may experience entrainment, impingement or entrapment, and (d) and estimation of population dynamics parameters should population modelling be required to evaluate the consequences over a number of years of cooling system damages on a critical local population. See section 6.2 of this chapter for further details and information requirements for population modelling.

When developing detailed field studies for a given RIS, care must be taken that data will be obtained on all life history stages potentially experiencing cooling system impact. A study species may spend the early portion of its life in the pelagic phase and be susceptible to entrainment, then as juveniles or adults be subject to other cooling system stresses. Winter flounder larvae, for example, are found in the plankton during their pelagic larval phase and are susceptible to being entrained. Later, as juveniles and adults, they are vulnerable to impingement and thermal effects. Knowledge of the organism's life cycle and the distribution of each stage relative to the power plant is essential to fully estimate a species' potential involvement.

Each detailed field study should be designed with the assistance of a biostatistician to resolve questions of appropriate sampling techniques, selection of study stations, and the number and frequency of sampling. A statistical model or hypothesis must be developed for each field study question and a study design developed adequate to address the question at the confidence level desired. The design will take into account temporal (diel and seasonal) and spatial variability in distribution and abundance of the species or community of interest as well as the limitations of the sampling technique employed. See Eberhardt (1976), for a more comprehensive discussion of quantitative field studies for impact assessment. Additional references on field study design and survey techniques useful at power plant sites are given in Chapter VIII.

One serious limitation of power plant assessment field studies is the inability to obtain a good measure of the year to year variations which can occur at the site. A period of 15 to 25 years is needed to document many cyclic, physical and biological phenomena, but this is out of the question for predictive assessment studies, except as this information can be gleaned from historical data. A study period of three years is suggested as minimal to obtain some comprehension of year to year variation in population, community or total ecosystem characteristics. A one-year pre-operational study will generally be of value only for preliminary descriptions of community types, their distribution and species composition. Caution must be exercised in drawing inferences from these short-term field studies.
The remaining tasks in impact assessment involve reduction of all biological data to a form easily conceptualized and understood, then its final analysis and interpretation. Data reduction is achieved through statistical treatment of all observations to summarize means, modes, trends and the observed variance of each parameter. Final data analysis would involve statistical tests to document the probability that a series of observations are similar or significantly different from each other or to quantitatively express the probability of occurrence of given phenomena. An excellent and comprehensive discussion of biostatistical analyses useful in reducing impact assessment data can be found in the AIF Monitoring Source Book (1975). For an introduction to elementary biostatistics, consult Mather (1967); for a more general treatment, see Zar (1974).

Final interpretations of the biological data will be partially, and perhaps largely, made on a subjective basis, drawing on the expertise of the entire impact assessment team. Simulation models may be developed, employing both biological and physical (hydrodynamic and meteorological) data, to aid in predicting the consequences of cooling system construction and operation on the local water resource. The output of simulation models can be useful to suggest possible consequences, but should not be expected to provide a highly precise prediction of events. Input data for many important biological and physical parameters may be incomplete or missing entirely and hence the model will only partly describe the natural system. The same limitations apply when worst-case alternatives are being examined over the lifetime of a hypothetical power plant design. Also a model must be utilized with care until it has been verified in the field. This probably will not be possible in the limited time available for an impact assessment study.

### VII.6.1 Data reduction and analysis

At the minimum, reduced raw data should include the arithmetic mean, the standard error (or the standard deviation), and the sample size from which these calculations were made. If a large number of measurements or counts of a variable (e.g. species) are made, the data may be summarized as a frequency distribution in tabular form. However, results may be more evident in a diagramatic presentation, such as a histogram (i.e., a graph in which the frequency in each class is represented by a vertical bar). The shape of a histogram describes the underlying sampling distribution and facilitates comparison with expected frequencies from known models.

The spatial distribution of individuals in a population should be summarized in quantitative terms. In general, there are only three basic types of spatial distribution: random, regular or uniform, and contiguous or aggregated distribution. The spatial dispersion of a population may be expressed by the variance and the mean, as well as by other methods. In a random distribution, the variance is equal to the mean. Variance is less than the mean in a uniform distribution, and it is greater than the mean in a contiguous distribution. In general, a Poisson distribution is a suitable model for a random distribution, a positive binomial is an approximate model for a uniform distribution, and a negative binomial is probably the most often used, among possible models, for a contiguous distribution.

Temporal and spatial changes in population density should be compared statistically. Significance tests for comparisons of groups of data may be parametric when the distributions of the parent populations are known to be normal, or nearly normal, based on previous experience or by deduction from the samples. Often, non-normal data may be transformed into data suitable for such testing. Otherwise, nonparametric tests for significance should be applied.

Community classification techniques can be utilized in data summaries to identify natural groupings of species. This includes both discrimination and clustering. In general, discrimination techniques begin with a priori conceptual distinctions or with data divided into a priori groups. Then proceed to develop rules to separate data into these a priori categories. Clustering techniques, on the other hand, use a priori selection of a measure of similarity, a criterion, and a class description to find inherent empirical structure in data, i.e., clusters. Clustering does not depend on an externally supplied label, but involves finding derived data groups which are internally similar. A good review and summary of clustering procedures is provided in Anderberg (1974).
The aquatic environment can usually be stratified in some way, such as by depth, substrate composition, etc. One technique to summarize species distribution data is by using tables showing the frequency, or density, of each species at each environmental stratum. These tables are analogous to distribution curves made in a gradient analysis, and are considered natural and useful descriptors for species association data. These tables can be the basis for certain multivariate methods of data analysis for spatial and temporal variability such as canonical variate analysis described in Pielou (1977). In addition, for data which now contain a priori groupings, the linear discriminant function may also be successfully utilized for testing differences among environmental strata using multiple measurement of counting data.

VII.6.2 Predictive biological models

The essence of impact assessment is making good predictions. The complexity of natural systems often makes this difficult, however. Modelling, ranging from "box and arrow" diagrams on paper to sophisticated and complex mathematical simulations run on a computer, can aid in organizing information from surveys and laboratory experiments in such a way that predictions are possible. Impact assessment can be detrimentally subjective, and modelling, reduces subjectivity in making predictions by forcing the explicit definition of terms, functions, quantities and assumptions. Being explicit clarifies the need for information for improvement of the model or its application. Well conceived models can identify potential trends or outcomes of alternative actions (e.g. effects on fishery catches of various levels of larval fish entrainment due to several alternative intake locations) and be distinct aids to making decisions about power plant siting, design and operation. Yet the results of complex biological models, such as population models, must be used with care in light of our incomplete understanding of the controlling factors (see Eberhardt, 1976).

Modelling in some form has been used at each stage of the conceptual framework for impact evaluation given in Chapter III. For example, predictions of thermal death (or lack thereof) of organisms exposed to time-temperature patterns during entrainment have been made in nuclear power plant impact statements in the USA (e.g. USAEC, 1972a) using thermal resistance time data for the species (Coutant, 1970, 1972; National Academy of Sciences, 1973). Recent improvements of this technique have involved direct coupling of hydraulic plume models with thermal resistance data (Carter et al., 1977). In another project, expected wintertime lake temperature patterns with and without the power plant thermal discharge have been coupled with laboratory determined hatching times at various temperatures to predict hatching dates for winter-incubating fishes in the Great Lakes (USAEC, 1972b) (see also USAEC, 1974). For an example a striped bass population model developed to evaluate the consequences of potential loss of eggs and larvae at a power station on the Chesapeake - Delaware Canal USA. Additional population and ecosystem models relevant to cooling system assessment have also been cited in Chapters II and III.

Modeling is not a simple solution for organizing masses of data but can be a useful tool to project possible consequences of complex hydrodynamic events. It is inappropriate to simply "run a model" developed for another power plant location. Many models have generic (or universal) attributes that can be applied elsewhere, but such application should be done with considerable thought. Attempts are currently underway by the electric utility industry in the USA to compile descriptions of useful models and modelling techniques applicable to power station assessment (Lawler, Matusky and Skelly, Engineers in prep.)
REFERENCES CITED


VIII. Operational monitoring of cooling system impacts

SUMMARY

Monitoring of physical and biological phenomena is needed after the power station begins operation to detect changes. This surveillance provides assurance that there are no significant problems, allows for changes in design or operation if problems are found, and provides the basis for improving the predictive ability of the analyst. Structural and functional aspects of the community and ecosystem, as well as presence and abundance of key species in the vicinity of the plant can be monitored and compared with reference stations not influenced by the power station. Monitoring effort is expected to decrease with time after start-up, as environmental problems are identified and solutions found. Principal questions to be addressed in monitoring for direct and indirect effects (hydrodynamics, physical/chemical and biological) are presented, along with references for more detailed guidance for setting up the studies.

VIII.1 Introduction

"Monitoring" is the relatively routine taking of environmental measurements - physical, chemical, and biological - to direct changes in the ecosystem caused by power station operation. The measurements may range from qualitative indices to detailed quantitative analyses, depending upon the site-specific questions being investigated and the history of previous study at the site.

The post-commissioning monitoring programme is the final phase of a sequence of ecological studies and analyses carried out at the power plant site throughout the processes of site selection and plant design. Monitoring should be reviewed as the logical culmination of the assessment process discussed in previous chapters. Monitoring serves two principal purposes: (1) to provide continuing assurance that the cooling system operation is not having a significant environmental impact, or, alternatively, to document the need to modify the cooling system design or operating procedures to correct observed effects, and (2) to evaluate (hopefully to verify) the assessment techniques employed to predict cooling system impact relative to actual operating experience, with the goal of perfecting these techniques for future decisions regarding power plant cooling systems. Monitoring may also show that anticipated problems (based on studies elsewhere) do not occur and environmental constraints can be relaxed. Monitoring must be related to the continuing assessment of environmental risks or it is unnecessary and wasteful of resources. The scope of a monitoring programme will normally become reduced over time as the primary environmental questions are answered.

Cooling system monitoring programmes will be most effective if they consider the potential for impact from each of the major sources of potential damage discussed earlier (Chapter II). These include physical changes at intakes and discharges, entrapment and impingement of organisms at intakes, through-plant entrainment of plankton (phytoplankton, zooplankton, eggs and larvae), chlorination toxicity, thermal effects in discharge canals, thermal plume (mixing zone) effects, thermal effects on the water body after mixing, and combined cooling system stresses which may affect populations, communities, and ecosystem at large. Both direct and indirect effects of these stresses should be considered. Effects of construction should be distinguished from operating effects. Corrections can be made in the cooling
system engineering design only by relating an observed effect to its principal cause.

VIII.2 The Question of Significance of Observed Impacts

It is likely that some ecological change and loss of biota will be documented through post-commissioning monitoring. Typical impacts may include partial to total damage to benthic and epibenthic communities in the immediate proximity of the discharge, and possibly also at the intake; major changes in any small natural waterway utilized as a discharge canal; a shift in the abundance and speciation of fishes present near the discharge; kill of some small fishes due to impingement and loss of much of the through-plant entrained zooplankton. The potential for other impacts is dependent on the characteristics of the particular site and power plant.

Distinguishing whether observed impacts are within the range of acceptability is basically a social decision, but for which the environmental biologist must contribute crucial information (Van Winkle, et al., 1976). Decisions of acceptability or non-acceptability of an impact are often made relative to established waterway use designations and the water quality standards developed to meet the intended use. Use designations may call for protection of the whole aquatic ecosystem, or of populations of commercial importance to man (e.g. fish and shell fish) or for other special human use (e.g. drinking, swimming, or industrial). Eberhardt (1976) also focuses on "desirable use" in his suggestion that "significant ecological damage ensues when there is a reduction of the productivity of an ecosystem in terms of qualities perceived 'desirable' by mankind".

Questions of acceptability of localized impact immediate to a power plant, namely at the intake and discharge, are commonly resolved on a site specific basis. The nature of the resources and spatial area involved must be evaluated against potential economic and ecological impact of alternative modifications to existing cooling system design or plant operational characteristics.

Questions of the significance of fish kill due to impingement, loss of meroplankton or planktonic food organisms (copepods) due to through-plant entrainment, and exclusion or kill of certain fish species at the discharge may be evaluated in light of the potential impact on the populations and community, both near the power plant and far field. For commercial fish species, losses can also be evaluated relative to the size of the local catch of that species. The potential of important shifts in energy flow or nutrient cycling due to any of the above losses should also be considered. Entrainment loss of meroplankton may be evaluated by conservatively assuming 100% kill upon plant passage (i.e. "worst-possible case"), then estimating through a biological model the consequences of this loss for local populations.

The scale on which "significance" is measured will vary among economic regions of the world. Some developing countries may have insufficient economic resources available to be able to place high priority on protection of all aquatic environments from power station impacts. The demarcation line of acceptability of a given single impact may, thus, be at a less protective level there than in the industrialized nations, where environmental degradation is a greater problem. Also, the resources that can be committed to determining the impacts in detail may be less. Greatest protection may, thus, focus primarily on natural systems producing populations of economic value.

VIII.3 Approaches for Biological Monitoring

VIII.3.1 The holistic approach

Holistic or whole ecosystem concept provides a good format from which to develop a post-commissioning monitoring programme. And recommended previously for the predictive assessment studies (Chapter III), it is also imperative here to develop an initial set of hypotheses regarding potential changes which the monitoring programme will specifically address. As a first step, the important ecological features of the aquatic system should be identified. Using data from the preliminary field studies and published work on structure and function of comparable aquatic systems, it should be possible to outline in a preliminary fashion the basic functional compartments (producers, herbivores, carnivores, decomposers) and identify the dominant species in each. Seasonal differences in compartment speciation and their relative contributions to total system function should also be known. (See Odum (1971) for an excellent introduction to ecosystem trophic dynamics).
The ideal approach in monitoring for ecological change would involve measuring biological parameters for each major system compartment, plus selected total system characteristics (e.g. productivity, biomass, turnover times, nutrient levels) before and after plant operation has started. This has been done at a Florida power plant site by H.T. Odum and his associates (McKellar, 1977). Yet it may not always be practical to undertake a monitoring programme of this scale. But even should the financial resources or expertise required for total ecosystem monitoring not be available, there is considerable merit in starting with this concept for programme development. This will assure evaluation of the water body as a functional entity, with each representative and important species and unique habitat being considered as an integral part of the system. The holistic approach is particularly valuable if we are to have some comprehension of the ecological consequences of observed changes in the dominant species or communities of interest.

Should it not be practical to monitor all compartments of the aquatic system, then key ecosystem components must be selected. Some subset must be identified based on such criteria as habitat availability, spatial and temporal use of habitat by species, area of intake influence and effluent dispersion characteristics, etc. For efficient use of monitoring resources, monitoring should attempt to look at critical or governing species, system properties or events which may be most susceptible to perturbation by the power plant. These "key" components then are the minimal set of system characteristics which must be monitored to provide an ecologically integrated evaluation of ecological impact.

VIII.3.2 Reference stations

In field assessment work, there are no true experimental controls due to spatial and temporal variability of ecological systems. Rather, the magnitude of a perturbation, such as power plant impact, must be inferred through comparison with one or more sets of reference data obtained on sites not influenced by the plant, (Eberhardt, 1976). This approach stands in contrast to that taken by some early power plant studies which only collected pre-operational baseline data from stations within the zone of cooling system influence for evaluating post-commissioning effects. Pre-operational "baseline" data from the plant site alone are of limited value for operational monitoring. Even if the baseline studies had been conducted at the site for a number of years, they would only depict the short-term range for local population and community characteristics. Whether the observations for a given post-commissioning year should be expected to fall within the observed range of the original data set becomes highly conjectural, as normal temporal variation of biological systems can be considerable.

A monitoring programme should provide for near-simultaneous collections of data from nearby ecologically comparable stations outside the influence of the power plant. Several specific reference stations can be selected some distance from the power plant (Bennett, 1971, 1972) or monitoring can be conducted along gradients of expected power plant influence, with the more distant stations serving as the reference stations (Maryland PPSP, 1977). In either case, extensive pre-operational surveys are required at all potential reference sites as well as the plant site to document their extent of ecological compatibility. The main problem encountered in making between-station comparisons is spatial variability. This can result from local variations in circulation patterns, contrasting runoff or tributary inputs, or subtle differences in the physical or biological makeup of the benthic system. This limitation, plus the likelihood for environmental variability over time, requires that conclusions of plant induced changes of the aquatic system be made cautiously.

VIII.3.3 Monitoring direct effects

The first objective of post-commissioning monitoring is to determine the existence and magnitude of direct cooling-system impact on the local biota. Field sampling must determine diel and seasonal occurrence of organisms at each of the potential stress points and estimate the per cent of these populations which experience plant-induced damage. Considerations should include entrainment and impingement of fish and swimming invertebrates at the intake, plus any benthic intake effects; through-plant entrainment of plankton, especially meroplankton; and effects of the discharge on both water column organisms and the benthos. Should total losses for a given species or system compartment appear to be serious, it may be necessary to undertake more extensive monitoring studies of an entire local population or total ecosystem.

Details on methods to monitor direct effects can be obtained from manuals on field methods.
Several are cited in section IV of this chapter.

Physical data are required to delineate the hydrodynamics, and hence the zones of cooling system influence, near the intake and discharge structures (including discharge canal). Physical and chemical water quality parameters (e.g. temperature, salinity, dissolved oxygen, turbidity, and relevant chemical species) must also be monitored to spatially identify the discharge plume for each constituent. These data are required to accurately describe effects of the cooling system discharge on the local water quality per se as well as on the biota. Hydrodynamic and water quality measurements should be made for a representative array of operational levels and under a variety of environmental and water level conditions.

Cooling system effects on the benthos in the vicinity of the plant can usually be measured with some precision, since this community is comprised of sessile or only slightly motile organisms. Benthic stations at the intake, discharge and reference sites, should be monitored seasonally to determine the areas of obvious community destruction and appreciable modification (e.g. through major shifts in structure or function, or impairment of growth of community dominants). The potential for uptake of discharged chemicals by benthic biota, especially filter feeding bivalves, should also be monitored. Bivalves can also serve as good indicators of the physiological stress which a benthic community could be exposed to at a power plant site (Kennish and Olsson, 1975; Widdows, 1978).

Direct cooling system effects on water column organisms (plankton, fishes and swimming invertebrates) will be evaluated by intensive sampling near the intake, discharge and reference stations to identify diel and seasonal occurrence and document their behaviour with regards to the cooling system structures and the intake and discharge water.

The magnitude of losses due to entrapment and impingement can be estimated by sampling the intake screen backwash material. This will provide only a relative indication of annual loss by species, as it will not record delayed mortalities of organisms damaged, but not impinged long enough to be killed. If impingement is found to be highly variable in occurrence, intensive daily sampling (24-hour counts) may be required for the first year. Sampling once every four days for the first year may be the lowest sampling effort which will permit reliable loss projections. After the first year, sampling frequency should be reevaluated based on an overall evaluation of the importance of impingement and entrapment as an ecological problem.

Accurate measurements of plankton lost, (especially zooplankton) due to through-plant entrainment, are very difficult to obtain. One approach to evaluate the potential magnitude of this problem is to estimate the numbers of organisms which are entrained by species, then assume total loss of all these organisms due either to direct kill or damage which contributes to death after their return to the water body. The possible consequences of this loss for the local populations must then be evaluated. The assumption for 100% loss of entrained animals may hold for certain fragile fish larvae, but be unrealistic for hardy species. The validity of this assumption can be partially evaluated by sampling (by plankton pump) for survival in the discharge, followed by observations during a post-entrapment period, with the plankton held in "flow-through" containers in the field or under field-simulated conditions. (The potential for differential predation on these organisms will not be considered in such a test.)

Yet even when "worst case" assumptions of complete entrainment loss are made, there remain serious sampling problems in obtaining good estimates of the zooplankton species and numbers actually entrained at the intake. The problem of high spatial and temporal variability of plankton has already been discussed (Chapter II); see also section 3.4 of this chapter. To evaluate through-plant entrainment of meroplankton, sampling should be conducted continuously over 24-hour periods. Meroplankton density can change rapidly due to patchiness or temporal variations, such as spawning events. During the first year, sampling should be undertaken at least every fourth day of plant operation; more frequently during peak spawning seasons. Samples are typically collected from the forebay water immediately ahead of the travelling screens at three depths. Any post-entrapment sampling should also be at three depths at a point close to the point of discharge and possibly another point more distant, but where appreciable dilution in the receiving water has not yet occurred.

In the discharge canal, the principal monitoring questions concern fin-fish and swimming invertebrates, assuming they are not excluded by some artificial barrier, such as louveres or nets. Monitoring surveys should provide data to describe seasonal patterns of animal aggregations in the canal, the species involved, their abundance and nutritional and reproductive condition and how long individual animals remain in the canal. Monitoring should also include a sampling programme to assess actual impact of acute temperature declines or elevations on resident macrofauna. The diel and seasonal occurrence of "nuisance" species within the canal
should also be described.

The same questions cited above for pelagic organisms should be addressed also in both the near-field discharge area (i.e. within the maximum area of the 2°C annual isotherm) and far-field. In addition, monitoring should determine what ichthyoplankton (by species and abundance) are subjected to lethal or sublethal thermal shock due to passive drift into the discharge plume. The potential that the discharge plume could block or impede free movement of organisms within the water body should also be evaluated.

VIII.3.4 Evaluating population consequences of cooling system damage

Loss of organisms due to cooling system operation should be placed in some perspective relative to their abundance in the local waterway. There should be some estimate of the percentage of a population which is being damaged and some evaluation of the long-term consequences of this loss. Impact on benthic populations at a given point in time can usually be measured directly due to their sessile or only slightly motile mode of life. The consequences of cooling system loss for highly motile populations (e.g. fishes, crabs or lobsters) is more difficult, with extensive sampling required seasonally to determine population size, plus other basic parameters of population dynamics. Most difficult is evaluation of population significance of loss of planktonic larvae due to through-plant entrainment. Natural mortality rates of these early developmental stages are believed to be high. The impact of added larval mortality on recruitment success is speculative. It could be additive, reducing numbers of organisms which entered the population as juveniles, or this loss may be compensated for with greater survival of the later developmental stages or by immigration.

For many species, unless damages are of considerable magnitude, a shift in their local population size due to cooling system operation may not be directly detectable by present field sampling techniques. For example, Carpenter et al., (1974) found sampling variability such that they could not document a change which was small (up to ± 20%) for the copepod population near a coastal power plant. McErlean et al., (1977) report that sampling variation can range from 20 to 300% of the probable population size for aquatic organisms. Such problems of sampling for power plant monitoring were discussed by several workers (Heinle, Copeland, and Jude) in a recent entrainment workshop (Jensen, 1976).

Population models have been developed for a few species to evaluate the consequences of observed power plant damage (e.g. Hess et al., 1975) (see also Chapter III). The data requirements for population modelling are considerable, requiring extensive life history information to estimate fecundity, recruitment, growth and mortality rates. These data are coupled with an estimate of population size and with data describing the probability of damage by the various power plant cooling system stresses. Usually adequate biological information will only be available for species of major commercial or recreational importance, such as flounder or striped bass, which have been studied for many years. The published proceedings of a conference on assessing population impact of power plants provides a good statement of the current state-of-the-art of the approach (Van Winkle, 1977). Case studies are included. In the final chapter, the editor seeks to place some perspective on the feasibility of undertaking population modelling by balancing the potential gains with the reality of important gaps in our understanding of fish population dynamics. Eberhardt (1976) should also be consulted on this point.

VIII.3.5 Monitoring community and ecosystem impact

Both the direct and the more subtle indirect consequences of cooling system operation can also be evaluated through measuring certain community and whole ecosystem characteristics. It is commonly agreed that biological systems possess holistic properties which will only be discerned when biotic communities are studied as units. A set of system characteristics has been suggested as potential indices to measure stress in aquatic systems (FAO, 1976). At the community level, these include such structural features as species grouping, space and time patterns, diversity, stress succession and one functional index, total yield. At the ecosystem level, ratios of production/respiration, structure/maintenance, producer/consumer are suggested. It is hypothesized that total system stress may be identified by shifts in the above indices.

Community Structure  Sophisticated methods have been developed to describe community struc-
ture by identifying species groups in space and time. Multivariate methods are used to reduce data to groups using principal component analyses, principal coordinate analyses, and factor analyses. Clifford and Stephenson (1975) explain and evaluate these methods and give a partial bibliography. Classification and ordination techniques are also used to group data so that stress effects can be seen as shifts among the groups of species, sample locations and time. Stephensen et al., (1976) have reviewed these methods. A drawback to these methods is their requirement for highly trained computer specialists and expensive computing facilities that may not be available for the post-operative monitoring project.

Species diversity indices are also commonly used to describe community structure. These indexes are a function of the number of species (richness) and the distribution of individuals among the species present (evenness or equitability). Some indices are employed which represent each of these two components of diversity, while others are integrated measures, reflecting both patterns of richness and evenness. Several common diversity indices are briefly summarized in FAO (1976), which gives the original references.

The value of diversity indices in identifying cooling system impacts is presently considered to be low. The FAO (1976) paper states: "There is no clear relationship between diversity patterns and environmental alteration. Human and natural perturbations may increase, decrease, or not affect diversity... Because of this uncertainty a diversity index value cannot be established as an environmental quality standard..." Diversity indices, may however, be usefully employed to give a descriptive index of biological conditions when combined with other community, population and physiological criteria of stress. For some recent studies and additional discussion of the relative sensitivity and limitations in employing diversity indices in pollution studies, see Smith and Greene, 1976; Cook, 1976; Logan and Mauzer, 1975; Start, et al., 1974; Godfrey, 1978; and Livingston, 1976).

Community and System Function

Indices of community and total system function are also utilized to identify environmental change. Such holistic data may also provide some indication of the significance of observed changes from the ecosystem standpoint. Production and respiration are two indices frequently used, with rates determined for major compartments (autotrophs, benthos, nekton) or for the whole system. Other indices include rate of net degradation of a major detrital component and shifts in water column nutrient level over time. The use of ratios of functional indices was cited above (FAO, 1976).

Difficulties in Community and Ecosystem Impact Monitoring

Several limitations of total system indices to monitor anthropogenic influences are cited by the FAO (1976) paper on this topic. These include the problem of making hypotheses of the consequences of observed changes. For example, how will an observed system change affect the persistence or the population size of a species of particular interest? We often do not understand the details of system function sufficiently to make projections at the population level. Also cited is the problem of long time lags involved in the community to an environmental change. A perturbation may indeed by disruptive initially, but given time, a new equilibrium should become established in response to a persistent stress, such as an operating power plant. Periods of 5 to 25 years may be required for populations to come to a new equilibrium following an ecological change; much longer time periods would be expected for a community (an assemblage of populations) or ecosystem to achieve a new equilibrium.

Other difficulties encountered in seeking to monitor change at the community or ecosystem level...
level can be traced to measuring too few indices. Problems associated with only using a diversity index as the indicator of community pollution stress have already been discussed. Certain single functional indices may also fail to reflect important community or population changes. Livingston (1976) reports stability in total system productivity over a year, although species composition showed extreme variations due to regular seasonal shifts in occurrence. McKellar (1977) observed little change in community metabolism in an outer bay at a power plant site, although marked shifts in other system characteristics were evident. Clearly, if community and ecosystem monitoring is to be undertaken, data must be collected for an array of ecologically related indices.

Finally, in communities where few species dominate all facets of the community, it is possible that population level indices can serve as an economical and effective means of monitoring the community. Some population indices suggested as potential indicators of community or system condition are mathematical growth models for individual species, recruitment-related indices, and the elimination or recovery of indicator species.

VIII.4 Reference Material on Methods for Power Plant Impact Monitoring

It is beyond the scope of this guide to provide detailed methodology for power plant monitoring. Some reference documents which provide this information are listed here. One (AIF, 1975) has been written specifically as a detailed guide to power station monitoring and contains chapter on physical/chemical water quality measurements, aquatic ecology, and biostatistics. Others are broader in scope. Published post-operational case studies are also listed, including several well synthesized monitoring reports (316 demonstrations) filed with US Environmental Regulatory authorities.

A. Major Source Books and Methods Manuals


B. Published Case Studies


5. Representative US. 316 Demonstration Post-operational Reports (Available from In Forum (Appendix 5)).

   b. Pilgrim Nuclear Power Station, Plymouth, Massachusetts (Boston Edison Co. 1975)
   c. Kewana Nuclear Power Station, Wisconsin (Wisconsin Public Services Corp. 1976 a,b)
the effects of nuclear power plant site preparation, plant and transmission facilities
construction. Prepared by Hittman Assoc. In. AIF N.Y.


Barnett, P.R.O. 1971. Some changes in intertidal sand communities due to thermal pollution.

Barnett, P.R.O. 1972. Effects of warm water effluents from power stations on marine life.

Boston Edison Co. 1975. 316 Demonstration, Pilgrim Nuclear Power Station Units 1 and 2.
Prepared by Stone and Webster Engineering Corp, Boston.

Carpenter, E.J.; Anderson, S.J.; and Peck, B.B. 1974. Copepod and chlorophyll concentra-
tions in receiving waters of a nuclear power station and problems associated with their


Cook, S.E.K. 1976. Quest for an index of community structure sensitive to water pollution.

Vol. 4. p. 27-70.

Food and Agriculture Organization of the United Nations. 1976. Indices for measuring responses

Godfrey, P.J. 1978. Diversity as a measure of benthic macroinvertebrate community response to

Hess, K.W.; Sissenwine, M.P.; and Saila, S.B. 1975. Simulating the impact of the entrainment
of winter flounder larvae. In: S.B. Saila (ed.) Fisheries and energy production:


Jacobs, F.; and Grant, C.C. 1978. Guidelines for zooplankton sampling in quantitative base-
line and monitoring programmes. US Environmental Protection Agency, Washington, D.C. EPA-
600/-78-026. (PB 279 151/AS).


Livingston, R.J. 1976. Diurnal and seasonal fluctuations of organisms in a north Florida


McKellar, H.M. Jr. 1977. Metabolism and model of an estuarine bay ecosystem affected by a


Maryland Power plant Siting Programme. 1977. Summary of current findings: Clavert Cliffs
Nuclear Power Plant aquatic monitoring programme. Prepared by Martin Marietta Corp.,
Baltimore. 57 p.

Northeast utilities Service Co. 1976. Millstone Nuclear Power Station Units 1, 2 and 3. - Environmental assessment of the condenser cooling water intake structures (316 (b) demonstration). Hartford, Conn.


IX. Beneficial uses of discharge heat

SUMMARY

There are a number of potential uses for reject heat that can extend the productive efficiency of electric power plants. These range from space heating to heating fields for agriculture and ponds for aquaculture. Some industrial processes can also use the low-grade heat. The principal problem is the large volumes of low-temperature heat that result from the need to maintain a thermal differential in the power station for efficiency of the energy conversion cycle. Power stations designed for multiple purposes can produce more useful high-temperature heat, with the combined efficiency of electricity production and the other purposes given a high efficiency of fuel conversion.

IX.1 Potential Uses for Low-Grade Heat

Increasing attention is being given to finding productive uses for power plant waste heat. The waste of approximately 2/3 of the fuel energy during conversion of fossil or nuclear fuels to electricity is increasingly viewed as extravagant. There are rising demands for energy (particularly by developing countries), recognized environmental hazards from uncontrolled energy supply and use, scarcity of some fuels, and high cost of both traditional fuels and new energy technologies. Methods are being developed for converting the "thermal pollution" from power stations into useful heat resources that can substitute for other energy supplies.

There are potential physical applications of power plant reject heat such as industrial heating and biological applications such as fish culture, soil warming, and heating greenhouses and livestock shelters (Beall et al., 1977). Both types of uses have been discussed at several conferences in the USA (Mathur and Stewart, 1971, Yarosh, 1972, Lee and Sengupta, 1977) and in state-of-the-art reports (e.g., Yarosh et al., 1972). A summary of beneficial uses of waste heat is given by IAEA (1974). Beall (1970) tabulated a number of uses (Table IX-1).

The most important factor determining the use of such heat is the temperature of the heat source. There is a threshold between low-grade and high-grade heat for engineering uses at about 100°C (IAEA, 1974). 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°C depending upon the season. Circulating water in closed-cycle cooling systems is only slightly warmer (20-50°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 reject heat is dumped to circulating water in steam condensers. Such engineering has produced high efficiencies compared to most other mechanical systems: 33% (nuclear plants to 40% (best fossil-fueled plants) of the fuel energy is 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°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. While there is better utilization of the energy remaining in the steam, the efficiency of the low pressure turbine for producing elec-
tricity is diminished. Condensers can also be operated with smaller cooling water flows in order to yield higher discharge temperatures, but this is done with some penalty to generation efficiency due to higher turbine backpressures. 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 seen as a potential supplier of electricity, high-grade heat and low-grade heat, even though today electricity is the main product and most new power stations are optimized accordingly. Depending upon 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 in common practice at early generating stations in the USA, and is still common in Europe. (Olszewski, 1977a)

IX.2 Aquaculture

Culture of some aquatic species in essentially unmodified thermal effluents of power stations has been attempted both experimentally and commercially. For example, Guerra et al. (1977) describe experimental aquaculture of rainbow trout (Salmo gairdneri) in winter and freshwater shrimp (Macrobrachium rosenbergii) in summer at the Mercer Generating Station near Trenton, New Jersey, USA. Goss and Ray (1974) conducted experimental catfish culture at the Tennessee Valley Authority's Gallatin Steam Plant (Cumberland River) in Tennessee, USA. Lobster culture has been attempted by Van O1st et al. (1976). American oysters have been cultured in their early stages at the Northport power station on Long Island Sound (Vanderborgh 1972). Experiments at the Hunterston power station in Scotland demonstrated warm-water culture of marine fish (Richardson 1971) and the Central Electricity Generating Board in the UK has explored culture of freshwater species (Aston et al.,1976). Similar experiments have long been practiced in Japan (Yang,1971). Watts (1972) described mariculture at the Crystal River power plant in Florida. Some recent efforts have been aimed at warm-water culture of algae for production of organic fuels and raw materials for the chemical industry. Additional studies are described in Lee and Sengupta (1977). Olszewski (1977b,c,) has concluded that aquaculture may be the most economically feasible use for power plant reject heat.

Several conclusions have resulted from thermal aquaculture studies which would guide further efforts.

1. Species must be carefully selected to benefit from warming of the water. Some facilities have chosen two species, one for winter culture and another for summer culture. The thermal requirements for growth must be known, such as Fig. IX.2.
2. Feeding rates or availability of natural food must be matched with temperatures to assure good growth since organisms usually require more food at higher temperatures. Studies of food conversion efficiency as a function of temperature and ration are desirable for the selected species (Fig. IX.3).
3. At least three power plant units are advisable at any culture facility to assure continuous supply of warm water. This is especially important when temperature rise in the condensers is large, in order to avoid cold shock during a unit shutdown.
4. Reproduction and rearing of larval stages can be the most biologically sensitive parts of the culture system.
5. A system for blending ambient and discharge water is important for avoiding excessively high summer temperatures in mid-latitude zones.
6. Chlorination of condensers at the power plant may cause toxicity and loss of organisms. This can be avoided by providing isolation of the culture system during chlorination, and oxygenation of the culture facility.
7. High density culture can be limited by supplies of dissolved oxygen and build-up of waste products. High flow rates can be made available to prevent this, or aeration can be used.
8. A market for the product determines the economic feasibility of commercial aquaculture. Species should be selected for their market value as well as biological compatibility with culture systems. Some thermal aquaculture projects have not been economically viable, while others have predicted economic viability based on experimental data.
9. There are many institutional barriers to use of thermal effluents for aquaculture, as discussed by Vanderborgh (1972).
Figure IX.1 Effects of temperature and level of ration (percent of body weight fed per day) on growth of 7-12 month old sockeye salmon, Oncorhynchus nerka. Aquaculture would be most successful at temperatures where maximum growth rates can be obtained (after Brett et al., 1969).

Figure IX.2 Efficiency of food conversion to fish flesh in relation to temperature and level of ration, drawn as solid isopleths overlying the dashed growth curves of Figure IX.1 (after Brett et al., 1969).
10. Cost of prepared food (such as commercial fish meal or pellets) is high, and is often a limiting factor for successful economics. Systems which grow natural foods in polyculture systems are the most economical (Olszewski et al., 1977).

IX.3 **Open-field Agriculture**

Use of warmed water for field crops and orchards has been tested in several studies. Boersma (1971) used buried pipes to convey thermal discharge heat to soils in Oregon, USA, where warming aided plant growth and extended the growing season. Soil warming studies have been carried out in France for conifer and deciduous trees using open irrigation water, and for other crops using buried pipes (Balligand, 1975). Miller (1971) and Price (1972) showed the advantages of spraying thermal effluent water on crops and orchards in Oregon 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 (Carter, 1969; Jaske et al., 1970). Yarosh et al. (1972) reviewed other studies of soil warming, and indicated several reviews of research on effects of soil temperature on crops (Richards et al., 1952; Neilsen and Humphries, 1966). An extensive demonstration project has been established by Electricité de France at their St. Laurent des Eaux power station (Fig. IX.4).

IX.4 **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 (Yarosh 1972). Current energy shortages have made fuel not only costly but often unavailable. 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 plants have cooling towers with wintertime operating temperatures of 16° C or higher. Economic analysis are given by Yarosh et al. (1972) and Olszewski et al. (1976).

Experimental greenhouses using waste heat for temperature control have been operated at several sites including Oak Ridge National Laboratory (Tennessee, USA) (Beall and Samuels, 1971), the Tennessee Valley Authority (Alabama, USA), the University of Arizona (Jensen et al., 1971), Grenoble, France (Balligand et al., 1975) and at St. Laurent des Eaux, France (Electricité de France 1976). These experimental systems have demonstrated the principle that heated water can be used to heat a greenhouse in winter. Some have also used power plant effluent to cool it in summer using inexpensive porous packing through which the heated water drips and air circulates (Fig. IX.5). Evaporation provides cooling in summer while sensible heat transfer warms the air in winter. Additional heat and humidity control can be provided with a finned-tube heat exchanger. The French studies have used pipes and plastic tubes laid in the floor of the greenhouse which circulate warm thermal effluent or water warmed further with heat pumps operating from thermal discharge waters. As with aquaculture systems, greenhouses should affiliate with multiple unit power stations to ensure continuous warm water supplies.

IX.5 **Animal Shelters**

The advantages of temperature control for maximizing weight gain and 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 (Yarosh, 1972) although few demonstration projects have been developed. Demonstration of a finned-tube heat exchanger in a greenhouse at Oak Ridge National Laboratory suggests its suitability for heating animal shelters as well (Beall and Samuels, 1971). Heating animal shelters can be considered just a special case of space heating (discussed below) 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 actual deaths of livestock on open ranges. Heated feedlots could prevent such costly losses.
Figure IX.3 Greenhouse with temperature control provided by evaporation and heat transfer as air passes through a fiber pad soaked with power station cooling water and/or by heat transfer as air passes through a finned tube heat exchanger that carried cooling water. A false ceiling provides for recycle of air through the heat-transfer media. (after Beall and Samuels, 1979).

Figure IX.4 Relation between temperature and density of water
A large percentage of the energy requirements of most countries in the temperate zones is for heating and cooling of living and working spaces and for hot water (22% for the USA according to the Olszewski 1977a). The historical use of dual purpose power plants for electricity generation and central district heating in the USA and their current extensive use in such countries as the USSR, Sweden, and the Federal Republic of Germany (Olszewski 1977a) suggests that expansion of this form of waste heat utilization can contribute significantly to energy conservation and control of concentrated thermal discharges world-wide.

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 due to large pressure drops in distribution systems. Modern experience with both dual-purpose power plants (mostly in Europe) and new district heating systems in the USA (colleges, institutional developments and shopping centers) has shown hot water to be superior for dispersed loads; including single-family residences.

The Soviet Union is the world's leader in dual-purpose heat and electric generating stations. Over 1,000 such stations supply heat to 800 cities, industrial districts and population centres (Sakolov, 1974). Most of these stations are of relatively high electrical capacity - in 1970 there were 169 plants with unit ratings of 100 MW(e) or more, averaging 208 MW(e). The 1971-1975 five-year plan called for ratings of individual dual-purpose plants to exceed 1,000 MW(e). By 1970, over 50% of the domestic heat demand was supplied by dual-purpose installations which represented 85% of the installed electrical generating capacity.

Sweden has installed district heating systems in urban areas, with the larger systems, which each serve 3,000-4,000 customers, utilizing combined heat/electric power stations (Olszewski, 1977a). These dual-purpose stations operate at high thermal efficiency - the Malmo plant, probably the most efficient, has achieved an operating thermal efficiency of 88%. Sweden is researching new technologies for distribution pipes in order to expand economical district heating to dispersed single-family residences.

Economic analyses for the USA 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 (Olszewski, 1977a). 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.

Many industries use process heat at temperatures between 77° and 110°C. Much of this heat is currently supplied by combustion of oil and natural gas. Equipment manufacturers are now developing a new generation of industrial heat pumps to capture "free" industrial plant waste heat and regenerate it to the desired process heat temperature, greatly reducing energy costs associated with direct heating.

The Westinghouse Electric Corporation (1976) has conducted a detailed industrial survey to determine where and how process heat or steam is used, the type and cost of fuels consumed, and the temperatures, pressures and flow rates required. Major industries which use heat in the 77-110°C range that can be supplied by new high-efficiency heat pumps 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;
- Industrial space heating.

Power plant reject heat could be valuable for developing industries which perform these processes. Current engineering literature in waste heat reuse should be consulted (e.g. Brown et al., 1976). Technical assistance for energy conservation is now being offered by many governmental energy agencies (e.g. US Department of Energy).
Figure IX.5  Relation between water density (kg/m$^3$) and salinity (g/l) for temperatures from 0°C to 30°C.
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Temperature (°F)</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>300</td>
<td>CENTRAL HEATING AND COOLING</td>
</tr>
<tr>
<td>138</td>
<td>280</td>
<td>INDUSTRIAL CHEMICALS</td>
</tr>
<tr>
<td>127</td>
<td>260</td>
<td>PETROCHEMICALS</td>
</tr>
<tr>
<td>116</td>
<td>240</td>
<td>SNOW AND ICE MELTING</td>
</tr>
<tr>
<td>104</td>
<td>220</td>
<td>FOOD PROCESSING</td>
</tr>
<tr>
<td>93</td>
<td>200</td>
<td>DRYING: GRAIN, MINERALS, LUMBER, ETC.</td>
</tr>
<tr>
<td>82</td>
<td>180</td>
<td>HOT WATER HEATING</td>
</tr>
<tr>
<td>71</td>
<td>160</td>
<td>LNG EVAPORATION</td>
</tr>
<tr>
<td>60</td>
<td>140</td>
<td>ELECTRICITY GENERATION (BOTTOMING CYCLES)</td>
</tr>
<tr>
<td>49</td>
<td>120</td>
<td>OUTDOOR AGRICULTURE: SOIL HEATING, SPRAY IRRIGATION</td>
</tr>
<tr>
<td>33</td>
<td>100</td>
<td>SPA'S, TROPICAL GARDENS</td>
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<td>27</td>
<td>80</td>
<td>ENCLOSED AGRICULTURE: VEGETABLES, FLOWERS, POULTRY, SWINE</td>
</tr>
<tr>
<td>16</td>
<td>60</td>
<td>AQUACULTURE - MARICULTURE: ALGAE, FISH, SHELLFISH, CRUSTACEANS</td>
</tr>
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</table>
REFERENCES CITED


Olszewski, M. 1977b. The potential use of power plant reject heat in commercial aquaculture. ORNL/TM-5663 Oak Ridge National Laboratory, Oak Ridge, Tenn. 43 p.


X. Conclusions and research needs

X.1 Conclusions

Predictive ecological assessment studies must be an integral part of the planning for new power plants in order to assure selection of environmentally acceptable sites and cooling system designs. These studies will initially be of a preliminary reconnaissance type, followed by more detailed evaluation of a number of specific site options and finally extensive studies at one or several primary sites to resolve final siting questions and identify special cooling system design needs.

An ecological assessment addresses two distinct questions, namely estimation of environmental changes and direct biological damages, then evaluation of the consequences of these changes and losses for important populations and the total aquatic system. The steps involved in direct damage assessment include identifying, through hydrodynamic modelling, the probable zone of influence of the cooling water intake and discharge, then identifying the types of communities, dominant species and important biological functions which occur there. A group of species or specific assemblages (communities) are selected for further field and laboratory impact assessment based on their perceived importance for total system function, their economic and/or aesthetic importance, or due to problems previously observed at operating power plants. The potential for direct ecological loss is estimated from literature reports and experimental studies which measure tolerance limits and debilitating sublethal effects of simulated cooling system stresses. The possible consequences of direct losses are commonly addressed by population or ecosystem modelling. Perturbation studies have also been suggested.

The information needed to predict the hydrodynamic and thermodynamic changes in natural water bodies due to once-through cooling systems include the size and character of a natural water body, the volume and \( \Delta T \) of the circulated cooling water, the manner that cooling water is withdrawn at the intake and heated water rejected at the discharge, and a description of the atmospheric conditions. Either mathematical or physical models are employed to predict water velocity changes and temperature fields associated with cooling water use. These models can give accurate and reliable predictions provided necessary morphometric, hydrological, meteorological and technical information is available. The particular predictive technique used depends on the characteristics of the site.

The ultimate sink for waste heat is the earth's atmosphere. In certain localities heat exchange between water surface and atmosphere is of special importance for once-through cooling systems. For example, evaporative water loss due to additional heat load can have a significant influence on water balance of water bodies located in dry areas. In cold climates special attention must be given to ice conditions which may be considerably changed by heat discharges.

Efforts to locate, design and operate cooling systems in an environmentally compatible manner can significantly reduce direct biological damage. A first step to achieve this is identification of the biota which would be particularly susceptible to damage at the intake, upon through-plant entrainment and at the discharge. With this information, it may be possible to design intake structures which minimize entrainment and impingement damage to local species. Further, given an understanding of the distribution of the local biota, it may be possible to locate the cooling system structures away from areas of high biological value. If there is a potential for recirculation of cooling water, a deep water intake or extension of the intake canal is preferable. Length of the discharge canal should be kept at a minimum. Discharge design options include a buoyant surface discharge, which maximizes the rate of heat transfer.
to the atmosphere and minimizes the likelihood that the benthos will experience a temperature rise. Should such a discharge exceed temperature standards, the heat can be more rapidly reduced by employing a surface jet which will entrain cooler receiving water. A submerged discharge will provide even more rapid dilution by the receiving water. At sites where mechanical damage of plant-entrained meroplankton is expected to pose an ecological problem, a high design temperature should be given to a balancing discharge $\Delta t$, and the volume of cooling water pumped, for environmental reasons, as well as for plant efficiency. Approaches to reduce discharge water by pumping large volumes of water through the plant, or cooling by augmentation pumping, can be ecologically counter-productive if this subjects additional plankton to through-plant entrainment stress. Anti-fouling methods other than chemical biocides should also be incorporated into the design of the system.

The possibility of alternative use of the waste heat produced by power generating plants should be addressed at regional or national policy level. Potential uses range from space heating and industrial use to heating ponds for aquaculture or heating greenhouses and fields for agriculture. Considerable advanced planning is required to develop multipurpose power generating centres. This not only involves appropriate siting for both power plant and the heat consuming activity, but major engineering design of the generating units will also be required if the low grade heat (10-40°C) presently produced by power plants is not adequate.

After a power station becomes operational, it is necessary to monitor certain physical and biological parameters to detect changes and ecological problems which may develop. Monitoring will provide information for changes in cooling system design or operation if problems are found. It will also provide a basis to evaluate the predictive methods employed by the ecological assessment team. The monitoring programme must be designed to address specific questions of cooling system impacts at each major point of potential damage. The nature and extent of direct biological loss will be determined. In addition, the ecological consequences of plant-related physical and biological changes must be evaluated by monitoring potentially impacted populations and parameters of the total aquatic system. It is important that the monitoring programme be designed to test whether the observed changes are due to the power plant, and, if so, to relate these changes to the principal causes so corrections can be made.

X.2 Research Needs

Basic Science Topics

A better understanding of population dynamics, especially compensation and stock recruitment relationships is imperative if we are to model population effects of direct cooling system damages. At present, it is believed most fish populations are regulated by phenomena occurring during reproduction and the early life stages, with the influence of some of these controlling mechanisms varying with population size (i.e. density-dependent mechanisms). Hence, loss of fish eggs or larvae at a power plant may not cause a proportional recruitment loss for the population if compensation in the form of reduced natural mortality subsequently occurs. At present we do not understand population regulation sufficiently to develop reliable models for population impact evaluation. While compensatory capabilities are not amenable to direct measurement, several research approaches have been suggested (Eberhardt, 1976; Van Winkle, 1977). Briefly, these include field and laboratory studies on the occurrence, mechanisms and timing of compensatory responses in relevant species, especially during early development. Models could then be used to evaluate the effects of timing and various degrees of compensation in response to given levels of cooling system mortality.

At the community and total system levels of organization, studies are needed to elucidate the relationship between the structure of a community (i.e., the species present and their relative abundance) and ecosystem function for various types of water bodies. This information would assist in evaluating the ultimate consequences of expected environmental changes and direct loss of biota. It would also facilitate identification of important species and compartment which should be investigated in detail when making an ecological assessment.

In hydrography, there is a need for better understanding of the interrelationship between representative hydrographic conditions and basic physical processes, such as sediment transport, stratification, evaporation and internal turbulent exchange of mass, momentum and heat. This information is needed for various types of water bodies including lakes and reservoirs,
estuaries and coastal waters. Basic studies are also needed to better understand the influence of atmospheric conditions on the hydrodynamics of different water bodies and on their heat exchange processes. And research is needed to determine the extent that synoptic meteorological data can be used to define parameters of energy and momentum transfer to natural water bodies.

Field Measurement Techniques

There is a need to further develop and evaluate biological census techniques for use in power plant ecological assessment studies. This pertains to perfecting both sampling design and sampling technique. A more quantitative approach is clearly needed in ecological assessment. Census designs which address specific statistical models are crucial to determine the type and amount of data necessary to rigorously evaluate an assessment hypothesis.

Improved methodology for collecting physical data is also called for, including developing and perfecting continuous recording equipment and development of techniques for quantitative synthesis of physical field data, especially remote sensing data.

Hydrodynamic Modelling Research

For mathematical modelling, research is needed on the influence of turbulent scales on diffusive conditions for different water bodies; for improved numerical models for stratified flows, especially when influenced by dynamic interaction of the water body and atmosphere; and for improved models for unsteady conditions. Work is also needed on the application of stochastic modelling to hydrodynamic questions at power plants. Two needs for physical hydro-thermal modelling include improving models for near-field prediction where stratified conditions exist and for predicting turbulent flow characteristics of the discharge.

Studies of Ecological Impact at Operating Power Plants

A comparative analysis should be undertaken of monitoring studies at operating plants. This would include evaluating data of direct biological damage, plus information from comprehensive field programmes designed to determine whether population or large-scale ecological changes have occurred. Given adequate intensity of the field sampling programme and the adoption of similar sampling designs and monitoring techniques, such a comparative evaluation could contribute in two important ways: further elucidate the nature and sources of environmental change and direct cooling system damage to the biota and secondly, identify the consequences of these changes and losses for the total system. At present, we often do not know the extent that observed environmental changes and damage stems from biological or physical characteristics unique to the site, or if they are specifically due to cooling system design and/or certain operational practices. It may only be at operating plants that we will develop a good understanding of the relationships between the more readily observed biological effects (i.e. direct damage) and altered physical environmental conditions and the implications of these changes for important populations and overall system function and structure. Such comparative studies of monitoring data should also demonstrate the assimilative capacities (whether resistance or resiliance) of natural aquatic systems to cooling water stresses. These studies will also provide the opportunity to validate previously developed hydrodynamic and biological models.

Environmental Management and Regulatory Problems

Ecological impact assessment can also be enhanced as a tool for environmental planning and management as regulatory procedures and assessment guidelines are improved. Bio-legal research is needed to develop legislation and regulations which will assure a high degree of objectivity for the study, will provide some indication of the intensity of investigation expected and provide for clear procedural guidelines with flexibility for site-specific design of assessment projects. To assure objectivity, it may be necessary that the assessment work be funded and conducted by an agency independent of the parties proposing and financing the engineering activity. The size or intensity of an assessment study is typically a function of the potential for adverse environmental change. Clearly, this question can only be resolved when there is a definition of the types of environmental change which are unacceptable. Finally, better guidelines should be developed for reporting the findings of an impact assessment project. For an ecological assessment to be useful as a planning and management tool, the study must be summarized in a succinct form which can be comprehended by all parties.
having a voice in decision making. This often includes the public. The present long, technical
narratives and often little-interpreted tables of data which comprise environmental impact
statements should be reduced and clarified, with this information synthesized to produce a
short summary report citing the principal findings in non-technical language, with graphic
techniques which condense and illustrate the supportive data.

REFERENCES CITED

Vol.4 p. 27-70.

Van Winkle, W. 1977. Conclusions and recommendations for assessing the population-level
effects of power plant exploitation: The optimist, the pessimist, and the realist.
In: Van Winkle, W. (ed.). Proceedings of the Conference on Assessing the Effects of
Appendixes
APPENDIX 1

Abbreviations used

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEC</td>
<td>United States Atomic Energy Commission</td>
</tr>
<tr>
<td>EPA</td>
<td>United States Environmental Protection Agency</td>
</tr>
<tr>
<td>ERDA</td>
<td>United States Energy Research and Development Agency</td>
</tr>
<tr>
<td>CBD</td>
<td>Gas Bubble Disease</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>Md. PPSP</td>
<td>Maryland Power Plant Siting Programme</td>
</tr>
<tr>
<td>NAS</td>
<td>National Academy of Sciences (U.S.A.)</td>
</tr>
<tr>
<td>NEPA</td>
<td>National Environmental Policy Act (U.S.A.)</td>
</tr>
<tr>
<td>NRC</td>
<td>United States Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
</tr>
</tbody>
</table>
Glossary of symbols used in Chapters IV, V, and VI

Symbols are defined whenever they appear in the text. Symbols which are used repeatedly in various parts of the text are included in this glossary.

### Superscripts:
- turbulent fluctuating quality
- time or space mean quality

### Subscripts:
- \( t \), \( h \): upper and lower layers in stratified flow
- \( a \): ambient value
- \( c \): centreline or critical value
- \( i \): interface in stratified flow
- \( o \): initial value
- \( m \): model
- \( p \): prototype
- \( r \): model prototype ratio
- \( z \): vertical direction

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Symbol for unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ( )</td>
<td>( m^2 )</td>
<td>surface area cross-sectional area</td>
</tr>
<tr>
<td>( A_s )</td>
<td>( )</td>
<td>ratio of the actual duration to the astronomically possible duration of sunshine</td>
</tr>
<tr>
<td>B</td>
<td>dimensionless</td>
<td>ratio of flux densities of convective and latent heat ( H_c/H_e )</td>
</tr>
<tr>
<td>( c_p )</td>
<td>( J/kg ) ( K ) ((4.182 \times 10^3))</td>
<td>specific heat capacity at constant pressure</td>
</tr>
<tr>
<td>b</td>
<td>( m )</td>
<td>local jet or plume width</td>
</tr>
<tr>
<td>D</td>
<td>( m )</td>
<td>diameter</td>
</tr>
<tr>
<td>( D )</td>
<td>dimensionless</td>
<td>model distortion</td>
</tr>
<tr>
<td>( e )</td>
<td>( kg/m^s )</td>
<td>flux density of water vapour in evaporation from water surface</td>
</tr>
<tr>
<td>( e_a )</td>
<td>( Pa, mbar )</td>
<td>partial pressure of water vapour in air</td>
</tr>
<tr>
<td>( e_s )</td>
<td>( Pa, mbar )</td>
<td>saturation water vapour pressure at water surface temperature</td>
</tr>
<tr>
<td>( Fr )</td>
<td>dimensionless</td>
<td>Froude number</td>
</tr>
<tr>
<td>( Fr_A )</td>
<td>dimensionless</td>
<td>densimetric Froude number</td>
</tr>
<tr>
<td>f</td>
<td>dimensionless</td>
<td>friction coefficient</td>
</tr>
<tr>
<td>g</td>
<td>( m/s^2 )</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>( h, h )</td>
<td>( m )</td>
<td>depth of water</td>
</tr>
<tr>
<td>( H_c )</td>
<td>( W/m^2 )</td>
<td>flux density of convective heat</td>
</tr>
<tr>
<td>( H_e )</td>
<td>( W/m^2 )</td>
<td>flux density of latent heat</td>
</tr>
<tr>
<td>( H_l )</td>
<td>( W/m^2 )</td>
<td>heat loss flux density per unit area</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>H₁N</td>
<td>W/m²</td>
<td>total heat flux density from natural water surface</td>
</tr>
<tr>
<td>Hₙ</td>
<td>W/m²</td>
<td>flux density of the total net radiation (net radiation balance)</td>
</tr>
<tr>
<td>Hₛ</td>
<td>W/m²</td>
<td>flux density of the total net heat</td>
</tr>
<tr>
<td>L</td>
<td>J/kg (2.454 × 10⁶)</td>
<td>latent heat of vaporization of water</td>
</tr>
<tr>
<td>Lₙb</td>
<td>W/m²</td>
<td>flux density of long-wave-radiation from the water surface</td>
</tr>
<tr>
<td>n</td>
<td>dimensionless</td>
<td>amount of cloud cover (in tenths)</td>
</tr>
<tr>
<td>n</td>
<td>s/m¹/³</td>
<td>Manning's roughness coefficient</td>
</tr>
<tr>
<td>K</td>
<td>W/m² K</td>
<td>heat transfer coefficient</td>
</tr>
<tr>
<td>KᵥC</td>
<td>dimensionless</td>
<td>factor of the nature of cloud</td>
</tr>
<tr>
<td>p</td>
<td>Pa</td>
<td>pressure</td>
</tr>
<tr>
<td>Q</td>
<td>m³/s</td>
<td>water discharge</td>
</tr>
<tr>
<td>r</td>
<td>dimensionless</td>
<td>albedo (ratio of the global radiation from sun and sky reflected by the water surface)</td>
</tr>
<tr>
<td>Re</td>
<td>dimensionless</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>Rₑₙ</td>
<td>m</td>
<td>hydraulic radius</td>
</tr>
<tr>
<td>Rₑₙa</td>
<td>W/m²</td>
<td>flux density of atmospheric radiation (long wave)</td>
</tr>
<tr>
<td>Rₑₙₐn</td>
<td>W/m²</td>
<td>flux density of net atmospheric radiation</td>
</tr>
<tr>
<td>Rₑₙₐr</td>
<td>W/m²</td>
<td>flux density of reflected long-wave atmospheric radiation</td>
</tr>
<tr>
<td>Rₑₙ₁ₙ</td>
<td>W/m²</td>
<td>flux density of solar and atmospheric radiation</td>
</tr>
<tr>
<td>Rₑₛ</td>
<td>W/m²</td>
<td>incident solar radiation flux density to the water surface (global radiation)</td>
</tr>
<tr>
<td>Rₑₛₐr</td>
<td>W/m²</td>
<td>flux density of reflected short-wave solar radiation</td>
</tr>
<tr>
<td>T</td>
<td>K, °C</td>
<td>temperature</td>
</tr>
<tr>
<td>t</td>
<td>s, hr, d</td>
<td>time</td>
</tr>
<tr>
<td>Tₑₙ</td>
<td>°C</td>
<td>air temperature</td>
</tr>
<tr>
<td>Tₑₙₑ</td>
<td>°C</td>
<td>equilibrium temperature</td>
</tr>
<tr>
<td>Tₑₙₑ</td>
<td>°C</td>
<td>natural water surface temperature</td>
</tr>
<tr>
<td>Tₑₙₑ</td>
<td>°C</td>
<td>water surface temperature</td>
</tr>
<tr>
<td>Tₑₙₑ</td>
<td>°C</td>
<td>water surface temperature at which K is evaluated</td>
</tr>
<tr>
<td>u</td>
<td>m/s</td>
<td>velocity in x direction (horizontal)</td>
</tr>
<tr>
<td>v</td>
<td>m/s</td>
<td>velocity in y direction (horizontal)</td>
</tr>
<tr>
<td>w</td>
<td>m/s</td>
<td>velocity in z direction (vertical)</td>
</tr>
<tr>
<td>wₑₙ</td>
<td>m/s</td>
<td>wind velocity at the height z above water surface</td>
</tr>
<tr>
<td>Symbol</td>
<td>Dimensionless</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>x, y, z</td>
<td>dimensionless</td>
<td>cartesian coordinate direction</td>
</tr>
<tr>
<td>β</td>
<td>dimensionless</td>
<td>atmospheric radiation function depending on vapour pressure, cloudiness, and air temperature</td>
</tr>
<tr>
<td>c</td>
<td>dimensionless</td>
<td>emittance ratio of emitted radiant flux to that from a black body at the same temperature</td>
</tr>
<tr>
<td>ΔT</td>
<td>°C</td>
<td>temperature difference</td>
</tr>
<tr>
<td>ν</td>
<td>m²/s</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>ρ</td>
<td>kg/m³</td>
<td>water density</td>
</tr>
<tr>
<td>Δρ</td>
<td>kg/m³</td>
<td>density difference</td>
</tr>
<tr>
<td>Δρ/ρ</td>
<td>dimensionless</td>
<td>relative density difference</td>
</tr>
<tr>
<td>σ</td>
<td>W/m²K⁴</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>σ</td>
<td>N/m</td>
<td>surface tension</td>
</tr>
<tr>
<td>τ</td>
<td>N/m²</td>
<td>shear stress</td>
</tr>
</tbody>
</table>
### APPENDIX 3

**SI System**

Names and symbols for base SI units

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Name of unit</th>
<th>Symbol of unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>length L</td>
<td>metre</td>
<td>m</td>
</tr>
<tr>
<td>mass M</td>
<td>kilogram</td>
<td>kg</td>
</tr>
<tr>
<td>time t</td>
<td>second</td>
<td>s</td>
</tr>
<tr>
<td>thermodynamic temperature T</td>
<td>kelvin</td>
<td>K</td>
</tr>
<tr>
<td>plane angle a, β, etc.</td>
<td>radian</td>
<td>rad</td>
</tr>
</tbody>
</table>

Special names and symbols for derived SI units

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Name of unit</th>
<th>Symbol for unit</th>
<th>Dimensions of unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>force</td>
<td>Newton</td>
<td>N</td>
<td>kg.m/s²</td>
</tr>
<tr>
<td>energy</td>
<td>Joule</td>
<td>J</td>
<td>N.m</td>
</tr>
<tr>
<td>power</td>
<td>Watt</td>
<td>W</td>
<td>J/s</td>
</tr>
<tr>
<td>pressure</td>
<td>Pascal</td>
<td>Pa</td>
<td>N/m²</td>
</tr>
</tbody>
</table>

Names and symbols for derived SI units

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Name of unit</th>
<th>Symbol of unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>area A</td>
<td>square metre</td>
<td>m²</td>
</tr>
<tr>
<td>volume V</td>
<td>cubic metre</td>
<td>m³</td>
</tr>
<tr>
<td>density</td>
<td>kilogram per cubic metre</td>
<td>kg/m³</td>
</tr>
<tr>
<td>speed, velocity u</td>
<td>metre per second</td>
<td>m/s</td>
</tr>
<tr>
<td>acceleration a, g</td>
<td>metre per second squared</td>
<td>m/s²</td>
</tr>
<tr>
<td>specific heat (cₚ)</td>
<td>Joule per kilogram and Kelvin</td>
<td>J/kg K</td>
</tr>
<tr>
<td>heat flux</td>
<td>Watt</td>
<td>W = J/s</td>
</tr>
<tr>
<td>heat flux density</td>
<td>Watt per square metre</td>
<td>W/m²</td>
</tr>
<tr>
<td>surface tension</td>
<td>Newton per metre</td>
<td>N/m</td>
</tr>
<tr>
<td>kinematic viscosity</td>
<td>Square metre per second</td>
<td>m²/s</td>
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## Temperature scales

<table>
<thead>
<tr>
<th></th>
<th>Absolute</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kelvin</td>
<td>Rankin</td>
<td>Celsius</td>
<td>Fahrenheit</td>
</tr>
<tr>
<td>Boiling of water</td>
<td>373.15</td>
<td>671.67</td>
<td>100</td>
<td>212</td>
</tr>
<tr>
<td>Freezing of water</td>
<td>273.15</td>
<td>491.67</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>Absolute zero</td>
<td>0</td>
<td>0</td>
<td>-273.15</td>
<td>-459.67</td>
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## Conversion table

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<tr>
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<th>To Obtain</th>
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<tbody>
<tr>
<td><strong>Length</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inches</td>
<td>2.54</td>
<td>Centimetres</td>
</tr>
<tr>
<td>Feet</td>
<td>30.48</td>
<td>Centimetres</td>
</tr>
<tr>
<td>Feet</td>
<td>0.3048</td>
<td>Metres</td>
</tr>
<tr>
<td>Miles</td>
<td>1.609344</td>
<td>Kilometres</td>
</tr>
<tr>
<td>Centimetres</td>
<td>0.3937</td>
<td>Inches</td>
</tr>
<tr>
<td>Centimetres</td>
<td>0.0328</td>
<td>Feet</td>
</tr>
<tr>
<td>Metres</td>
<td>3.2808</td>
<td>Feet</td>
</tr>
<tr>
<td>Kilometres</td>
<td>0.6241</td>
<td>Miles</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Square miles</td>
<td>640</td>
<td>Acres</td>
</tr>
<tr>
<td>Acres</td>
<td>43,560</td>
<td>Square feet</td>
</tr>
<tr>
<td>Acres</td>
<td>0.001563</td>
<td>Square miles</td>
</tr>
<tr>
<td>Acres</td>
<td>4,047</td>
<td>Square metres</td>
</tr>
<tr>
<td>Acres</td>
<td>0.004047</td>
<td>Square kilometres</td>
</tr>
<tr>
<td>Acres</td>
<td>0.4047</td>
<td>Hectares</td>
</tr>
<tr>
<td>Square kilometres</td>
<td>247.1</td>
<td>Acres</td>
</tr>
<tr>
<td>Hectares</td>
<td>2.471</td>
<td>Acres</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cubic feet</td>
<td>7.481</td>
<td>US gallons</td>
</tr>
<tr>
<td>Cubic feet</td>
<td>28.32</td>
<td>Litres</td>
</tr>
<tr>
<td>Cubic feet</td>
<td>0.02832</td>
<td>Cubic metres</td>
</tr>
<tr>
<td>US gallons</td>
<td>0.1337</td>
<td>Cubic feet</td>
</tr>
<tr>
<td>US gallons</td>
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<td>To Obtain</td>
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<td>Miles/hr</td>
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<td>Centimetres/sec²</td>
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<tr>
<td>= 980.7 cm/s²</td>
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<td>= 9.807 m/s²</td>
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<td><strong>Volume Rate of Flow</strong></td>
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<td>Cubic feet/sec</td>
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<tr>
<td>Cubic metres/sec</td>
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<td><strong>Energy (work, heat)</strong></td>
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<tr>
<td>Btu</td>
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<tr>
<td>Btu</td>
<td>3.930 x 10⁻⁴</td>
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<td>Joules (watt-sec)</td>
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<tr>
<td>Btu</td>
<td>0.2931</td>
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<tr>
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<td>Btu</td>
<td>0.2520</td>
<td>Kilogram-calories</td>
</tr>
<tr>
<td>Multiply</td>
<td>By</td>
<td>To Obtain</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------</td>
<td>--------------------</td>
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<tr>
<td>Horsepower-hours</td>
<td>2544</td>
<td>Btu</td>
</tr>
<tr>
<td>Horsepower-hours</td>
<td>$1.98 \times 10^6$</td>
<td>Foot-pounds</td>
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<tr>
<td>Horsepower-hours</td>
<td>$2.685 \times 10^6$</td>
<td>Joules</td>
</tr>
<tr>
<td>Horsepower-hours</td>
<td>0.7457</td>
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<td>Joules</td>
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<td>Joules</td>
<td>0.7376</td>
<td>Foot-pounds</td>
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<tr>
<td>Joules</td>
<td>$3.725 \times 10^{-7}$</td>
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<td>Kilowatt-hours</td>
<td>3412</td>
<td>Btu</td>
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<tr>
<td>Kilogram-calories</td>
<td>3.968</td>
<td>Btu</td>
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<td>3088</td>
<td>Foot-pounds</td>
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<tr>
<td>Kilogram-calories</td>
<td>$1.560 \times 10^{-3}$</td>
<td>Horsepower-hours</td>
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<tr>
<td>Kilogram-calories</td>
<td>$1.163 \times 10^{-3}$</td>
<td>Kilowatt-hours</td>
</tr>
</tbody>
</table>

**Intensity of Heat Flow Rate**

- **Btu/square foot hour**: 2.712 kilo-calories/square metre hour
- **Kilo-calories/square metre hour**: 0.3687 Btu/square foot hour

**Temperature**

- Degrees Kelvin: 1.8 Degrees Rankline
- $^\circ C = \frac{5}{9} (^\circ F - 32)$
- $^\circ F = 32 + 1.8^\circ C$
APPENDIX 4

1. Water properties as a function of temperature
2. Relation between temperature and density of water
3. Relation between water density and salinity for water temperatures from 0° to 30°C
4. Comparison of heat rejection to natural environment by steam-electric power plants of different types

WATER PROPERTIES AS A FUNCTION OF TEMPERATURE

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Vapour pressure (mb)</th>
<th>Kinematic viscosity ($10^{-6}$ m²/s)</th>
<th>Density (kg/m³)</th>
<th>Surface tension (N/m)</th>
<th>Oxygen solubility (mg/1)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>6.12</td>
<td>1.789</td>
<td>999.84</td>
<td>0.0756</td>
<td>14.6</td>
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<tr>
<td>5</td>
<td>8.75</td>
<td>1.516</td>
<td>999.97</td>
<td>0.0749</td>
<td>12.8</td>
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<td>10</td>
<td>12.32</td>
<td>1.306</td>
<td>999.70</td>
<td>0.0742</td>
<td>11.3</td>
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<td>15</td>
<td>17.10</td>
<td>1.142</td>
<td>999.10</td>
<td>0.0735</td>
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<td>20</td>
<td>23.45</td>
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<td>998.20</td>
<td>0.0728</td>
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<td>25</td>
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<td>30</td>
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<td>0.802</td>
<td>995.65</td>
<td>0.0712</td>
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<td>35</td>
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<td>994.06</td>
<td>0.0714</td>
<td>7.1</td>
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<td>40</td>
<td>74.00</td>
<td>0.658</td>
<td>992.24</td>
<td>0.0696</td>
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</table>

1 mb (millibar) = $10^{-3}$ bar; 1 bar = $10^5$ N/m²; 1 N (Newton) = 1 kg x 1 m/s²

COMPARISON OF HEAT REJECTION TO NATURAL ENVIRONMENT BY STEAM-ELECTRIC POWER PLANTS OF DIFFERENT TYPES

<table>
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<tr>
<th>Type of power plant</th>
<th>Electric capacity (E)</th>
<th>Thermal capacity (T)</th>
<th>Ratio E/T (%)</th>
<th>Heat disposal to the atmosphere (Direct-stack)</th>
<th>Heat disposal through the condenser</th>
<th>Thermal capacity discharged through condenser (%)</th>
<th>Increase of heat disposal (%) of nuclear power plants in comparison with fossil-fuel</th>
</tr>
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<tbody>
<tr>
<td>Fossil-fuel</td>
<td>1000 MWe</td>
<td>2650 MWe</td>
<td>38</td>
<td>265 MW</td>
<td>1385 MW</td>
<td>52</td>
<td>0</td>
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<tr>
<td>Nuclear-light water reactor</td>
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<td>3100 MW</td>
<td>32</td>
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<td>2100 MW</td>
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<td>1440 MW</td>
<td>60</td>
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