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IAEA-SM-146/30

CONF-700816--30

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ABSTRACT

THERMAL EFFECTS AND NUCLEAR POWER STATIONS IN THE U.S.A.

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Steam-electric stations discharging heated condenser cooling water into public waters will modify the aquatic environment. There is no question that some changes will occur, but the biological problem is to determine the degree of changes, both short-term and long-term, the extent of these changes, and to determine if they significantly affect water uses.

Pressing biological problems are identified and needed research and development are recommended. Examples of problems considered are as follows:

1. Compliance with water temperature standards.
2. Lack of definition of mixing zones.
3. Lack of approved state water temperature standards.
4. Predicting temperature distributions in receiving water.
5. Assessment of biological changes.
6. Design of intake and outfall structures to minimize biological damage -- fish protection facilities.
7. Nuisance growth of plants and algae.
8. Sublethal effects of temperature on aquatic life.

IAEA-SM-146/30

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Introduction

It is often said that our knowledge of how to protect the environment has not kept pace with our ability to pollute it. Nuclear power is a notable exception. The hazard potential of the radioactive materials associated with nuclear power has caused the movement and effects of these materials to be studied in more detail and depth than perhaps any other agent. These studies have contributed significantly to scientific knowledge of the environment and to the development of techniques for predicting and evaluating potential effects before a facility is approved for operations and for controlling the effects after the facility begins operation.

The basis of this methodology is the ability to relate quantities (or rates) of potential pollutants released to the resulting concentration of these materials in the environment. Control can then be exercised at the point of discharge once environmental limits have been established. Compliance with water quality standards can be determined by monitoring a facility effluent and the need to perform difficult environmental sampling and analysis to determine compliance can be greatly diminished. It is of some interest to note that use of this method by the atomic energy industry has

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†Work performed under the auspices of the U.S. Atomic Energy Commission.

produced detailed information about waste releases and the availability of this information has made possible informed debate concerning the industry's waste release practices.

The above methodology is beginning to be applied to the release of waste heat from nuclear power stations but not without some degree of distress. Unfortunately the state-of-the-art on thermal effects, unlike its radiological equivalent, is not, in most cases, sufficiently developed to assess the biological and ecological implications of thermal discharges for any particular situation. Field experience has shown that there seems to be little evidence pointing to the adverse effects of heated discharges in an aquatic environment while laboratory investigations sometimes indicate the opposite. It is not surprising, therefore, that disagreement exists over the limits which should be established for thermal discharges. This disagreement is currently being reflected in power plant siting and design practice and in very conservative discharge criteria. This paper presents a survey of the present situation in the United States with respect to the disposal of waste heat by nuclear power stations and includes observations and recommendations which the present authors feel to be germane to this issue.

Nuclear Power Plant Cooling Water Survey

The relative numbers of nuclear power plants that will use various methods of disposal of condenser cooling water are presented in Table I. This table lists 94 of 99 of the nuclear power plants that are either operable, being built or planned as of December 31, 1969. A closed cycle water system will be used in 26 of 94 (27.7%) of these plants. In such systems the condenser cooling water will flow from condenser to atmospheric heat exchanger (either a cooling tower or artificial lake or pond), where it will lose heat before it is returned to the condenser. In such systems there is virtually no discharge of condenser cooling water into the natural aquatic environment. Eleven of 94 (11.7%) will use a variable cycle cooling water system where some of the heat will be removed from the condenser cooling water in a cooling tower or flow-through cooling pond before this water is discharged into a natural water body. Some of these systems are capable of operating anywhere between the two extremes of closed cycle operation and once-through operation. It should be noted that there usually are economic and perhaps other penalties associated with these alternate schemes of heat dissipation. The remaining 57 of 94 (60.6%) plants will use the once-through system where the condenser cooling water is taken from nearby rivers, lakes, estuaries or the ocean and then usually returned to the same source.

The average maximum temperature rise across the condenser for nuclear plants planned, being built or operable, is approximately 10°C. On the average these plants will use approximately 50 liters per megawatt of capacity (about 180 liters per kilowatt-hour) of cooling water. Fossil fuel plants require about 115 to 150 liters per kilowatt-hour for a maximum temperature rise across the condenser of approximately 8.3°C.[1] In other words, the nuclear plants require from 20 to 60% more cooling water than fossil fuel plants and have a 20% higher maximum temperature rise across the condenser

TABLE I

Nuclear Power Plants Classified by Water Body Type and Condenser Cooling Method

**Rivers--
Variable Cycle
Cooling Towers**

1. Monticello
2. Peach Bottom #2
3. Peach Bottom #3
4. Vermont Yankee
5. Prairie Island #1
6. Prairie Island #2
7. Beaver Valley

**Bays or Ocean--
Once-Through**

1. Humboldt Bay
2. San Onofre #1
3. Millstone #1
4. Millstone #2
5. Oyster Creek #1
6. Oyster Creek #2
7. Turkey Point #3
8. Turkey Point #4
9. Pilgrim
10. Diablo Canyon #1
11. Diablo Canyon #2
12. Crystal River #3
13. Calvert Cliffs #1
14. Calvert Cliffs #2
15. Malibu
16. Hutchinson Is.
17. Shoreham

**Great Lakes--
Once-Through**

1. Nine Mile Point
2. R. E. Ginna
3. Palisades
4. Point Beach #1
5. Point Beach #2
6. Donald C. Cook #1
7. Donald C. Cook #2
8. Kewaunee
9. Zion #1
10. Zion #2
11. James A. Fitzpatrick
12. Enrico Fermi #1
13. Enrico Fermi #2
14. Davis-Besse*
15. Big Rock Point
16. Bailly

**Estuaries--
Once-Through**

1. Indian Point #1
2. Indian Point #2
3. Indian Point #3
4. Conn. Yankee
5. Surry #1
6. Surry #2
7. Maine Yankee
8. Brunswick #1[c]
9. Brunswick #2[c]
10. Salem #1
11. Salem #2

**Cooling Ponds and
Lakes (Artificial)**

1. H. B. Robinson #2
2. Oconee #1
3. Oconee #2
4. Oconee #3
5. Midland #1
6. Midland #2
7. North Anna #1
8. Unnamed
9. Unnamed

**Closed Cycle
Cooling Towers**

1. Three Mile Is. #1
2. Three Mile Is. #2
3. Fort St. Vrain
4. Edwin I. Hatch #1
5. Rancho Seco
6. Duane Arnold
7. Trojan
8. Joseph M. Farley
9. Unnamed
10. Unnamed
11. Limerick #1
12. Limerick #2
13. Newbold #1
14. Newbold #2
15. Wm. H. Zimmer #1
16. Wm. H. Zimmer #2

**Rivers--
Once-Through**

1. Shippingport
2. Yankee (Rowe)
3. Dresden #1
4. Dresden #2[d]
5. Dresden #3[d]
6. Quad Cities #1
7. Quad Cities #2
8. Browns Ferry #1[e]
9. Browns Ferry #2[e]
10. Browns Ferry #3[e]
11. Peach Bottom #1
12. Arkansas Nuclear One[a]
13. Cooper
14. Sequoyah #1[b]
15. Sequoyah #2[b]
16. Elk River
17. N-Reactor
18. Fort Calhoun
19. LaCrosse

To discharge cooling water:

[a] into Dardanelle Reservoir.

[b] into Chickamauga Reservoir.

[c] about 2000' offshore.

[d] into a 1350 acre cooling pond (for partial heat dissipation before discharge into the Illinois River).

[e] into Wheeler Reservoir.

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*Announced July 31, 1970 will use natural draft cooling tower.

then fossil fuel plants. It should be noted that the comparisons between fossil and nuclear plants reflect the fact that most commercial nuclear plants existing or being built are water cooled and restricted to saturated steam cycles which are less efficient thermodynamically. In addition, the nuclear facilities do not have the thermal stack loss of approximately 12% characteristic of fossil plants; all the waste heat of the nuclear plant must be transferred to coolant water. Future generations of water cooled nuclear plants could benefit from addition of superheat while liquid metal, molten salt and gas-cooled systems show promise of equaling or exceeding efficiencies of present fossil-fueled plants.

Biological Considerations

Steam-electric stations discharging heated condenser cooling water into public waters will modify the aquatic environment. There is no question that some changes will occur, but the biological problem is to determine the degree of changes, both short-term and long-term, the extent of these changes, and to determine if they significantly affect water uses.

It is generally better to site plants where their effects are likely to be minimal and to protect biota by design measures rather than modifications resulting from afterthought. However, it appears that the knowledge and data required to permit an effective evaluation of plant sites and discharge details with the objective of minimizing effects on the biological environment are lacking or inadequate.

Increase in temperature changes physical properties of the water such as density, viscosity and gas solubility which can affect such phenomena as the vertical migration of plankton and the mobility of other species. In addition, changes in temperature and the rate of temperature change can have farther reaching biological effects. Some questions which will require answers are: What are the effects of chronic sublethal or acute exposures to artificially elevated temperatures as well as nutrients and toxic material contaminants on the nutrition, metabolism, growth, fecundity, fertility, survival and behavior of important species of different ages and sex? What are the optimum temperatures for all these factors? What are the lethal limits? To what extent is physiological adaptation or acclimation to elevated temperatures possible? How does the effect of temperature interact with that of other stresses? What species of what age and sex are most sensitive to the various stresses, and what is the most sensitive property (fertility, lifespan, behavior, etc.) of the most sensitive species to each type of stress?

One characteristic of the change in temperature in a water body is the shift in growth rates and equilibrium populations of species present. If appropriate nutrients and light are available, diatoms (Bacillariophyta) predominate in the temperature range 20 to 24°C (68-75°F) whereas the green algaes (Chlorophyta) extend over a range of 30-35°C (86-95°F). At temperatures above 35°C, the blue-green algae (Cyanophyta), which are most responsible for taste and odor problems, flourish.

Since there are reported to be 2,500 different species of Cyanophyta widely distributed in nature and capable of healthy growth under widely differing conditions, a "population explosion" of nuisance growth can be expected any time conditions are favorable. Recent studies [2], [3] have shown that higher temperatures and the presence of phosphorous are not sufficient in themselves for encouraging algal blooms. These studies have pointed to the symbiotic relation between the bacteria always associated with the Cyanophyta. These aerobic bacteria require the oxygen produced in the photosynthetic process to decompose assimilable carbon compounds. The decomposition product, CO_2, appears directly related to the algae growth.[3] Indeed, phosphorous, which has been considered a primary nutrient causing eutrophication in lakes, did not stimulate algal growth in Lange's experiments and actually showed a toxic effect when the phosphate concentration was raised above an optimal ratio of the nutrient components. Since the blue-green algae are not used in the food-web of aquatic ecosystems to the same extent that diatoms and green algae are, the increased production is lost to higher trophic levels and utilized only by bacteria.

Obviously, many nutritional and environmental requirements of a highly complex interrelationship must be met before excessive algal growth may take place. Careful study of the introduction of a natural predator, with desirable characteristics, if any exist, could lead to control of this potential problem.

It is well known that adults of arctic and tropical fish generally live in a narrow temperature range while temperate species can tolerate a relatively wide temperature range. In semi-tropical locations such as Biscayne Bay in Florida, a body of water generally runs a higher risk of damage than in northern temperate waters. The maximum summer temperatures observed in Biscayne Bay are about 32°C; nearly lethal temperatures for some species. A recent fish kill, allegedly by heated discharges from the Turkey Point Station there has emphasized the importance of changes in salinity and pH interacting with the increased water temperatures.[13]

Changes in species and species diversity can also be attributed to such factors as bottom scour by the effluent, removing food and breeding grounds. Seasonal changes in populations noted at Turkey Point indicate the ability of an area to recover after the increased stress of excessive temperatures is removed. Clearly, regional differences in aquatic flora and fauna require care to be exercised in generalizing results obtained by studying a single location.

Thermal Water Quality Standards

All states have submitted water quality standards to the Secretary of the Interior for approval pursuant to the Water Quality Act of 1965. In establishing these standards, five general areas of water use were to be considered: public water supplies, propagation of fish and wildlife, agricultural, recreational and industrial. The temperature criteria of most states reflect to some extent the guidelines set forth in the National Technical Advisory Committee (NTAC) Report, "Water Quality Criteria."[4] The guidelines recommend no more than a 5°F artificial increase above "natural" ambient (at the expected minimum daily flow for that month) for streams classified for either warm or cold water fish. In lakes and reservoirs, a 3°F increase limit (in the epilimnion) is suggested based on the monthly average of the maximum daily temperatures. The NTAC report did not recommend the practice of withdrawing from or discharging into the hypolimnion. For estuarine and marine waters, a 1.5°F limit was advised during the summer months and 4°F limit for the rest of the year based on the monthly means of the maximum daily temperatures. The ΔT limits were established to preserve the natural daily and seasonal temperature variations. The NTAC report, in addition, recommended maximum temperature criteria for various species of fish ranging from 9° to 34°C.

The NTAC report also discussed the concept of mixing zones. It was recognized that certain areas of mixing are unavoidable in the vicinity of pollutional outfalls and that these zones could be harmful to the biota. In such cases it was recommended that adequate passageways, in which at all times the water quality is to be favorable to the biota, should be provided to allow for the movement or drift around these potentially harmful mixing zones. For estuaries and streams it was recommended that the passageways be preferably 75% of the cross-sectional area and/or volume flow. Numerical mixing zone limitations were not delineated for coastal, lake or reservoir situations. However, the report did recommend keeping the mixing zones as small as possible -- 'Mixing should be accomplished as quickly as possible through the use of devices which insure that the waste is mixed with the allocated dilution water in the smallest possible area."

As of January 1970, 18 states have not had their thermal criteria fully approved by the Secretary of the Interior. In particular, the following states have important portions of their temperature criteria not as yet approved and in which nuclear plants are operating, being built, or planned: California, Illinois, Maine, Michigan, New Jersey, North Carolina, South Carolina and Virginia. Thus, at any time in the near future, changes in their water temperature criteria may have a serious effect on nuclear plant design or operation. Even for those states with approved temperature standards, changes are being made or contemplated. For instance, in May 1970, an Interior Department policy statement read before the Lake Michigan Enforcement Conference stated that no more than a 1°F temperature rise above ambient be allowed for any effluent discharged into Lake Michigan. At the moment the policy statement is a recommendation which must be acted upon by the states of Illinois, Indiana, Michigan and Wisconsin and their deliberations then appropriately negotiated and approved. Of these states, only Michigan does not have approved thermal criteria for Lake Michigan. There are eight nuclear power units under latter stages of construction and one under operation on Lake Michigan at the present time. Thus, the 1°F limitation, if accepted by the states, would necessarily predicate reliance on alternate forms of cooling for these facilities such as cooling ponds or towers. If alternate cooling methods can be accommodated by these nuclear facilities, it is highly likely that extensive turbine and condenser modifications would have to be made should near original design efficiencies be desired.

While meeting temperature requirements can be difficult because of evolving standards as indicated above, even the uncertainty in existing criteria poses problems. For instance, unless specific dimensions are specified for mixing zones, it is difficult to interpret where the maximum temperature and temperature rise above ambient should be enforced. While most states recognize the necessity for mixing zones, only a few have stipulated actual numerical limitations as to its size.

Status of Thermal Plume Modeling

The ultimate objective in thermal plume modeling is to obtain spatial and temporal temperature and velocity distributions within the affected receiving water which in turn could be used to make biological and ecological predictions. The bodies of water receiving the discharge can be categorized by their unique characteristics. Ponds are shallow and generally quiescent except for wind-driven flows. Lakes are deeper than ponds and show stratification as well as currents driven by winds. Larger lakes have internal currents due to air pressure variation and Coriolis forces. Rivers are characterized by unidirectional flows with a velocity profile. Their flow volume shows short-term fluctuations due to weather as well as seasonal trends. In deep rivers some stratification is possible. Estuaries are characterized by the cyclic flows due to tidal flushing and stratification due to salinity. Because of the cyclic movement, recirculation of the heated water can be a problem. Oceans are characterized by the good mixing due to currents and waves and stratification due to temperature effects. Each of these receiving environments presents special design requirements and simplifications.

Except for horizontally mixed cooling ponds and thoroughly mixed streams, reliable predictions in complex receiving water situations continues to be a distant goal. Current design methods use retrofits to model studies or conservatively bracket expected eddy diffusivities.

The classical analytical approach to such problems involves solving the basic equations of continuity, momentum and energy with the appropriate boundary conditions and transport coefficients. Since mass, momentum and heat transport within any large body of water can be assumed to be governed by turbulent mechanisms, the needed transport coefficients are not simple properties of the water alone as they would be in laminar flows but are dependent on the geometric and environmental characteristics of the flow.

The functional relationship of the transport coefficients to these geometric and environmental characteristics is complex and not yet well defined. To provide solutions to turbulent problems recourse is generally made to "turbulent equations of state"[5] which relate the turbulent coefficients to local or global mean flow properties. Analytical solution of complex turbulent flows by necessity becomes a "trial and error" process in which simplifications are made to the governing equations, boundary conditions, and transport coefficients in order to obtain solutions.

Hydraulic modeling is also used for delineating the temperature and velocity distributions within a plume. It requires relations between the hydraulic model and a prototype. These relations take the form of dimensionless geometric, kinematic, hydrodynamic, and thermodynamic parameters.

Exact modeling requires identically valued dimensionless numbers in the model and prototype. In practice this is seldom achieved and several models must be used, each emphasizing separate considerations to produce the desired results.[6]

For convenience in modeling, the plume is separated into regimes in which dominating parameters can be isolated. Since this procedure is followed for analytical modeling it would be worthwhile to review these regimes.

A plume can be considered to consist of three regions -- the near field, the joining region, and the far field. In the near field (immediately adjacent to the outfall) entrainment of the ambient fluid, at the expense of the heated effluent's initial kinetic energy, is most important. From a biological point of view this region may be important because the highest temperatures are present even though this region represents a small fraction of the total plume. Few analytical models for this regime are available because of the free surface and bottom effects. A solution is available for vertical axisymmetric discharges into a stagnant medium. For horizontal discharges with boundaries, the problem becomes difficult because of additional complicating factors such as stratification and cross-currents. This regime is more suitably treated by hydraulic modeling. The Reynolds number, densimetric Froude number and the ordinary Froude number are to be matched between model and prototype. Some consideration of boundary conditions is required.

The joining region is where entrainment is important along with buoyancy, advection, and surface cooling. This regime has received some analytical attention. References [7] through [11] offer excellent reviews of this subject matter. This region is characterized by the attainment of a critical value, greater than 0.8, of the bulk Richardson number [11] defined as

$$Ri = \frac{gh}{V^2}\frac{\rho_a - \rho}{\rho_a} \qquad (1)$$

where g is the gravitational acceleration and h, V and ρ are average values of the thickness, velocity and density of the plume at a given position, while ρ_a is the ambient density. The densimetric Froude number, also used as a stability criterion, is given by

$$Fr_d = \frac{V}{\sqrt{gh\frac{\Delta\rho}{\rho_a}}} \qquad (2)$$

where $\Delta\rho = \rho_a - \rho$. It can be seen that Fr_d is the reciprocal square root of Ri.

When the value of Ri exceeds the critical, there will be no further significant vertical entrainment and no significant change in plume depth until the decrease in $\Delta\rho$ leads to a decrease in Ri below the critical value.

Differences in density as little as one percent lead to stable stratified flows in which momentum is easily transmitted to the lower region but heat and matter transport is inhibited, as if by an elastic membrane, at the lower plume boundary. The principal mechanism of temperature reduction in this region is by lateral entrainment of surrounding fluid.

It is sufficient to state that these models are by necessity heavily semi-empirical in nature relying on assumed similarity conditions; Gaussian or other distributions of momentum, mass and heat; spread coefficients; entrainment coefficients; eddy diffusivities of heat, mass and momentum; etc. Hydraulic modeling of this regime is seldom done by itself; it is modeled accurately with the near field it is important that existing currents, wind, heat transfer, stratification, and boundary conditions be included with the near field parameters.

The far field represents that portion of the plume where advection, entrainment, and surface cooling dominate; momentum and buoyancy forces are no longer considered important. Of the three plume regions this one is particularly amenable to analytical approaches; however, empirical values or relationships for the horizontal and vertical eddy diffusivities are required. The initial conditions for this regime must also be specified. Except for river and estuary situations, physical boundaries need not be considered as they would be generally remote to the plume.

There is evidence alluding to the fact that the bulk of the thermal energy is dissipated to the atmosphere within this regime of the plume. For hydraulic modeling it would be extremely important to provide techniques for reproducing the surface cooling phenomena. It would also be necessary to provide for the influence of wind which, to a large extent, governs the eddy diffusivities present. It is highly probable that these two conditions alone represent antagonistic goals. Further, it has not been established whether eddy diffusivities in a generally distorted far field hydraulic model are equivalent to actual field values. Thus, far field hydraulic modeling is beset with many uncertainties and technical difficulties.

Calculations of energy exchange between the various regions and the atmosphere by mechanisms of evaporation, radiation, convection and conduction have been made by many authors. This energy budget approach has been successful in predicting trends for periods longer than a week. Models are available for rivers, lakes and estuaries which appropriately consider the special characteristics of each.

General Observations and Recommendations

Summary statements describing the planning, design and procedures for waste heat release were obtained for most of the nuclear power plants.[13] These statements, together with information obtained from personal plant visits and information obtained from other sources, were used to arrive at the following rather broad set of observations and recommendations.

General

1) The design and operation of nuclear power stations is strongly influenced by water quality standards which are derived from a paucity of research. Nevertheless, and seemingly contrary to actual field experience, water thermal quality standards are becoming increasingly stringent.[14-15]

2) Fish kills caused by the release of waste heat from steam electric plants are rare and their severity limited. From June 1960 through December 1968, eleven incidents of fish kills that may have been caused by the release of heated water from steam electric generating have been identified. The total number of incidents from all causes during the same period was 2,830. The eleven incidents involved an estimated 81,000 fish out of a total of 103,380,000 fish killed from all pollution incidents during the period. Thus, the importance given in the popular literature to fish kills by heat discharges from steam electric generating stations is unwarranted.

3) Large water systems such as the Great Lakes, the Chesapeake Bay, Long Island Sound, Puget Sound and the whole Pacific Coast represent valuable national resources. Wise and informed use of these systems for receiving waste heat could contribute significantly to this country's need to minimize the environmental impact of meeting its power demands.

Accelerated and intensive studies of the short- and long-range movement and effects of heat should be undertaken at power stations operating in distinctively different physical-biological systems. These studies should involve all appropriate state resource agencies, state regulatory agencies, nuclear utilities, federal agencies, universities and private research laboratories.

Biological

4) The ultimate objective in predictive modeling is the prediction of biological damage. At this time, very little is known about the sublethal effects of heat except that a great deal of heat is currently being released at many locations with no obvious adverse environmental effects. However, a two-part effort to acquire knowledge of the sublethal effects of releasing heat should be undertaken viz. (a) the acquisition of short-range, short-term information through the observation of operating power plants and (b) the study of long-term ecological changes. The short-range information is needed to determine how individual generating stations must be designed to protect the environment. The latter information is needed to make long-range decisions concerning the effects of regional power growth.

5) At certain locations, particularly in estuaries, sensitive larval forms are present and may be killed as they are drawn through generating plant condensers. The capability for determining the significance of these organisms to their total populations does not exist. A strong effort should be undertaken to develop that capability.

6) Comparison of biological sampling results among investigators is virtually impossible because of a lack of standardized equipment and methods. Top priority should be given to improving sampling techniques for fish, periphyton, benthos and plankton and recommending these for practical standardization.

7) The digital simulation of aquatic ecosystems appears to hold the most promise for optimum resource management, particularly with regard to the manner and method of waste heat dissipation. Biological rate equations are needed.

8) Most pre- and post-operational ecological surveys lack "control" areas. Without such areas it is difficult to differentiate variations caused by heated water discharges from other variations, especially natural ones.

9) Much of the past laboratory work on the effects of heated water upon aquatic life cannot be directly applied to predict the effects of the discharge of waste heat from a power plant.

10) More can be done to reduce mortalities at the intakes of steam electric power plants with emphasis on improved fish screening and diversion techniques. For example, after velocity caps were installed at offshore intakes for the El Segundo power plant near Los Angeles, the fish mortalities in the intakes were reduced from 272 tons during the year preceding installation to 15 tons the following year.[21]

Physical

11) A variety of analytical models which employ empirically evaluated parameters and hydraulic scale model studies are currently being used to predict temperature patterns associated with heated water discharges into various receiving bodies of water. To date these analytical and hydraulic models remain relatively untested.

Field data suitable for making model-prototype comparisons are difficult to find and in most situations are not available. It is imperative that such data be available for the different types of receiving waters and further that the data should be thoroughly synoptic lest some missing information render the information less useful.

12) Alternate methods for releasing waste heat into an aquatic environment are currently being used to design generating station outfalls to minimize possible biological damage. One method minimizes the temperature increase near the outfall by achieving rapid dilution of the cooling water with the receiving water. The other minimizes initial dilution and allows the heated effluent to float to the surface thereby maximizing the surface heat loss to the atmosphere. Calculations show that a floating plume one foot or greater in thickness, dissipates a greater fraction of its heat by lateral dilution rather than by direct surface heat losses. The fraction of heat lost from the surface for temperatures greater than one degree above ambient is small simply because the surface areas associated with these areas are small.[16]

The relative biological merits of the two heat release methods should also be delineated. For instance, diurnal vertical plankton migrations may be retarded by a modestly high temperature surface layer while fish may be able to swim under or around the heated water.

13) Observations of plume behavior show it to meander, with parts of the plume occasionally detaching and dissipating by themselves. Over a significant portion of the plume a sharp lateral boundary exists, particularly at the upstream edge in the presence of a current. The meandering implies a need for stochastic analytic models such as that of Gifford [17] or that a deterministic model be a suitably averaged presentation. One hypothesis which allows for a sharp boundary in the presence of entrainment and mixing is that of a gravity-driven "head" flow;[18] other models assuming "Gaussian like" temperature distributions cannot account for these phenomena although they give satisfactory predictions of long time changes.

14) Further development of numerical modeling thermal plumes should be considered. Numerical techniques have the potential capacity to account for nonlinear features and complex boundary conditions which often have to be ignored for purely analytical approaches.[19] Recent advances in the theory of turbulence and computation of effects,[20] encourage application to modeling of plumes.

15) Some alternatives for minimizing the impact of condenser cooling water on natural water bodies are:

a) dilution with additional cooler water before discharge;

b) use of jet and multiport diffusers to reduce the mixing zone;

c) use of cold water, where possible, from intakes 20-70 feet deeper than the discharge; and

d) release of colder water from upstream reservoirs.

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