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Cooling Ponds-- A Survey of The State of The Art

Hanford Engineering Development Laboratory

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Cooling Ponds-- A Survey of The State of The Art

Hanford Engineering Development Laboratory

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ABSTRACT

Since the enactment of the Water Quality Act of 1965, there has been an increasing concern over the quality of the nation's waters. Adoption of temperature standards for water bodies, combined with the economics of scale, is resulting in increased use of alternatives to once-through cooling systems, particularly ponds and towers. Approximately 60 steam-electric power plants with capacities greater than 60 electrical megawatts use cooling ponds. This report documents a review of cooling pond technology in which major emphasis was placed on examination of engineering and environmental aspects of design, mathematical and physical modeling, use of sprays, and economics.

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I. INTRODUCTION

At the present time, approximately 80% of our electric power production, estimated at 1.5 trillion kilowatt hours, is generated by thermal stations. In the future, this percentage will probably be even greater because acceptable sites for further hydroelectric generating plants are limited.

In thermal power systems, the waste heat is removed by circulating large quantities of cooling water through steam condensers. The heated water is then either discharged or cooled and returned to the system. Recent legislative action, intended to minimize environmental pollution, greatly restricts the use of natural water bodies for cooling. A number of alternative waste heat disposal systems are available to the industry--these can be divided into the two major categories of cooling towers and ponds. Within the category of ponds, a range exists which extends from essentially closed recirculating artificial ponds or lakes, to basically once-through tempering configurations, such as hold-up ponds. Lakes and reservoirs used for cooling power plants have usually been termed cooling lakes.

At present, there are between 50 and 60 power plants in the United States that are closed recirculating ponds or lakes⁽¹⁾. While the primary function of these water bodies is for cooling, on occasion they have been used for other purposes, such as recreation. Regionally, half of these systems are located in the Southwest, Texas and Oklahoma, a quarter in the Southeast, and the remainder are found primarily in the Midwest. Cooling ponds are generally considered economically attractive when land is available at a reasonable price, and the terrain is suitable.

The design of a cooling pond is still pretty much of an art, although during the last few years, there has been a resurgence of interest in a more technical approach. The difficulty, of course, is introduced by the fact that there are such a vast number of factors that influence the performance of a specific pond. At present, certain "rules of thumb" have been generally adopted by design engineers. However, much work remains to be done on defining appropriate criteria and selecting design procedures.

Cooling ponds dissipate heat by radiation, evaporation, and conduction from the free surface. Ponds, unfortunately, have relatively low heat transfer rates; therefore, extensive surface areas are required. Because they usually rely less heavily on evaporative heat transfer, ponds do not consume as much water as do towers for the dissipation of an equivalent amount of excess heat. However, the total evaporation or consumption rate (forced plus natural) from a pond is greater than would be expected from a wet tower. On the other hand, in some areas, make-up in the form of precipitation caught by the basin might be significant, and its effect on the consumption rate should be taken into account.

An extension of cooling pond technology includes the use of spray ponds. The inclusion of such features as spray systems reduces the pond surface area needed for the same degree of cooling. In principle, when the effluent condenser cooling water is sprayed into the air, it increases the surface area from which the exchange of heat from the water to the air can take place. Generally, the combined rate of water consumption is greater than for a tower, but less than for a natural pond. The inclusion of sprays is not without environmental problems. Sprays introduce a potential for drift greater than that presented by wet towers.

Oleson and Boyle⁽²⁾ list the following advantages of cooling ponds or lakes:

- 1) Ponds have reasonable construction costs where soil conditions permit.
- 2) Ponds serve as a settling basin for suspended solids.
- 3) Ponds can possibly operate for extended periods without make-up water.
- 4) Ponds can be beneficial for other purposes; e.g., recreation,
Not mentioned by Oleson and Boyle, but also possible, is river control to minimize flooding or to increase minimum flow.

The disadvantages of cooling ponds are:

- 1) They require large land area.
- 2) They require a soil basin of low permeability.
- 3) They present the possibility of fogging and icing.
- 4) They tend to concentrate dissolved solids.
- 5) They form a collecting area for wind-blown debris.

Similarly, one can state advantages/disadvantages for spray ponds as compared with cooling ponds. Spray ponds:

- 1) Require less land area.
- 2) Provide aeration of coolant.
- 3) Have lower natural, and hence total, water consumption due to reduced surface area.

However, the disadvantages of spray ponds include:

- 1) Drift.
- 2) Limited recreational or commercial usage.
- 3) Increased maintenance and icing of equipment.
- 4) Increased fogging.

The above factors include engineering, environmental, and economic aspects. The relative importance of each will, of course, vary with the specifics of the particular site under examination. Furthermore, it is conceivable for a given site that the list of items might take a totally different form, with items being exchanged between the two lists.

In the following sections, a review of cooling pond technology is presented. The report is divided into major sections in an attempt to provide an explicit review of certain aspects. While these sections are somewhat independent, the reader is encouraged to review the material with respect to its total content, since overlaps do exist.

II. ENGINEERING ASPECTS OF COOLING POND DESIGN

The design of a cooling pond is affected by the local climatic, topographic, and hydrologic characteristics of the specific site. Cooling ponds have normally been constructed by placing dikes and embankments to form an artificial water body. On occasion, floating partitions, called baffles, have been employed in an attempt to create a cooling pond within a larger water body. In other cases, existing lakes have been used⁽³⁾.

The low heat transfer rate from the surface of cooling ponds requires that cooling ponds have large surface areas. Typically, these requirements have been specified as ranging from one to two acres per megawatt of installed capacity for fossil plants, to two to three acres per megawatt of installed capacity for a nuclear plant. Heat exchange and consumption are reviewed in this section of the report.

Volume and depth of the pond are both important, since they relate to the thermal capacity of the water body, and the over-all capacity of the water body with respect to chemical composition and plant make-up requirements.

A. DIKING AND BAFFLING

In order to make cooling ponds economically attractive, their construction is normally limited to placing dikes or low dams to take advantage of the natural topography. The cost of excavating an entire pond would normally be prohibitive.

Dikes and baffles have been used in attempts to isolate or partially separate the affected zone. In the case of diking, the demarcation is obvious. However, in construction a baffled partition, this difference is much more subtle and, depending upon the particular prevailing conditions, at times might be almost non-existent.

In a series of reports (4,5,6) the effect of baffling a portion of Lake Monona, in conjunction with using the lake for cooling purposes, was reviewed. The baffled portion of the lake occupies an area of approximately 20 acres and the total capacity of the plant is 190 Mw. The depth of the baffles was 8 feet. Hoopes, et. al.⁽⁵⁾, estimated, that based upon measurements collected, during the winter the surface heat loss was only 5 to 10%, and that the

remaining portion of the waste heat flowed under the baffle. In the particular study cited, the ineffectiveness of the baffle was brought about by dilution and subsequent mixing of the effluent, creating a virtually homogeneous state.

One example of a pond which employs both diking and baffling is located at the Cholla Steam Plant in Holbrook, Arizona. Taking advantage of the local topography and soil conditions, the pond was formed by placing a dike on three sides⁽⁷⁾. The dikes have a maximum height of 14 feet and required approximately 265,000 cubic yards of fill. The natural soil was impervious enough so no core had to be constructed. The pond has a surface area of 380 acres, an average depth of 9 feet, and the plant capacity is rated at a nominal 125 Mw. Figure 1 shows the major features of the Cholla pond which is divided into two sections, one of which is a "hot pond". Flow of water is permitted to occur between the sections through the use of an inverted weir five feet deep. The feature was added to the design as an afterthought based upon a closer examination of the local wind rose. The weir helps to prevent short circuiting of the effluent from the point of release to the intake.

Colter and Lotz⁽⁷⁾ and Derrick⁽⁸⁾ also discuss construction of the cooling pond for the Four Corners Steam-Electric Station located in northwest New Mexico. This pond has a design surface area of 1080 acres, with an average depth greater than 30 feet. The pond was constructed by placing a 6,000,000 cubic yard earth fill dam at one end. While there is no inflow under normal conditions, the size of the drainage basin and the possibility of flash floods required the construction of a rather large spillway. Fill and makeup water for the pond are pumped from the San Juan River.

Krause and Woodson⁽⁹⁾ discuss a series of cooling circuits which they obtained by placing various dikes and baffles in Lake Calaveros. This lake, which has been formed by damming Calaveros and Chupadares creeks near San Antonio, is a reservoir having a surface area of between 3000 and 4250 acres, depending on the lake elevation. A total of five circuits were reviewed for cooling 3000 MW of proposed generation.

Gray and Stephenson⁽¹⁰⁾ review the use of a submerged skimmer weir and a baffled intake, inverted weir, for the Marshal Steam Plant on Lake Norman, North Carolina. The system is basically once-through. Because of the stratification pattern in Lake Norman, the use of the inverted weir, located

Figure 1. Cholla Site Development Plan

at the mouth of the intake cove, allows cold water to pass to the power station, be heated, and discharged at temperatures close to those of the lake's surface waters.

Schroeder, et. al.⁽¹¹⁾, discuss the construction of a 2000-acre cooling lake for the Baldwin Power Station in Baldwin, Illinois (ultimate capacity - 3000 Mw). This lake has been constructed by building a seven-mile dike. The lake was filled by pumping water from the Kaskoskia River. Make-up water will also be supplied by this source.

Brezina, et. al.⁽¹²⁾, discuss the use of the 1500-acre Montrose Reservoir built to cool the 525 Mw Montrose Power Plant in Missouri. The lake was formed by damming Deepwater Creek.

Braswell⁽¹³⁾ discusses using a 540-acre cooling pond to cool the 210 MWe Delta fossil-fueled power station near Cleveland, Miss. The lake was formed by constructing a 3000-ft dike. Brady, et. al.⁽¹⁴⁾, gave a description of the 600-acre Mountain Bayou Lake designed to cool the 445 Coughlin gas-fired station in Louisiana. The lake was formed by constructing two low level earth dams. The 2500-acre Smithers Lake in Texas used to cool the 1250 Mw Parish gas plant was formed by damming Dry Creek. The 650-acre Wilkes Lake used to cool the 200 Mw gas-fired Wilkes Station was formed by damming the east and west branches of Johnson Creek. Numerous other cooling ponds exist; however, little information on their specific nature was found in the open literature. A listing of ponds used to cool power stations can be found in Appendix A.

B. HEAT TRANSFER

The heat transferred to the ground is considered insignificant. The loss rate has been estimated at between 0.5 - 2.5 BTU/ft²-hr-°F⁽¹⁵⁾. Therefore, only the heat loss to the atmosphere will be discussed in detail.

The energy budget approach has been used for years to calculate the exchange of thermal energy from the surface of cooling ponds. Lima⁽¹⁶⁾, in 1936, correlated lake cooling performance to actual results. Throne⁽¹³⁾ and Langhaar⁽¹⁷⁾ extended the analysis and derived expressions for the heat exchange resulting from the processes of evaporation, conduction and radiation from the water surface.

Employing the energy budget approach, the net or total heat exchange from the surface of a body of water can be expressed as:

$$\Delta Q_T = Q_s + Q_a - Q_b - Q_e \pm Q_c \quad (\text{II-1})$$

where: Q_s = the absorbed short wave solar radiation
 Q_a = the absorbed long wave atmospheric radiation
 Q_b = the long wave back radiation from the water body
 Q_e = the heat loss by evaporation
 Q_c = the heat gained or lost by conduction.

The specific representation for each of these terms has been developed over the years. The expressions are semi-empirical in nature. The primary credit for the development of this methodology belongs to the Lake Hefner and Lake Mead studies(18,19) conducted by the U. S. Geological Survey. Since that time, a number of researchers have elaborated on the use of this technique. In the following discussion of each of these terms, it is worthwhile recalling that the first two terms on the right side of Equation II-1 are independent of the water temperature, whereas the final three are not. For a more complete discussion of the terms than that which follows, the reader is referred to reference 20 which provides an excellent treatise on the subject of heat transfer from the surface of a cooling pond.

1. Short-wave Solar Radiation

Incoming short-wave solar radiation (wave length 0.30 to 3.0 microns) is normally measured by the use of a pyrheliometer. Such data are collected by the U. S. Weather Bureau at a number of locations throughout the United States. This term can vary from 400 to 2800 BTU/ft²/day, depending on location and meteorological conditions.

Empirical formulations have also been developed to estimate this source. The formulation considered most representative has been proposed by Laevasta(21).

$$Q_s = 0.014S_{an}t_d (1 - 0.0006C_L^3) \text{ langleys/day} \quad (\text{II-2})$$

where: S_{an} = noon sun angle
 t_d = length of the day
 C_L = the average cloud cover in tenths of the total sky.

Whenever possible, the measured insolation should be employed. The actual net insolation which has been used by Jaske(22) is:

$$Q'_s = \alpha(Q_s) \quad (\text{II-3})$$

The absorbtivity coefficient, α , was obtained from the material presented by Budyko⁽²³⁾. The coefficient is a function of time and location which is summarized in Table 1.

2. Long-wave Atmospheric Radiation

The atmospheric radiation term, which is generally between 2400 and 3200 BTU/ft²-day, is a function of a number of variables. There are two empirical formulations commonly used. Brunt⁽²⁴⁾ has proposed the following formulation:

$$Q_a = 4.5 \times 10^{-8} (T_a + 460)(C_1 + 0.31 e_a) \text{ Btu/ft}^2\text{-day} \quad (\text{II-4})$$

where: T_a = air-temperature in °F measured about six feet above the water surface

e_a = air-vapor pressure in mm-Hg measured about six feet above the water surface

C_1 = a coefficient determined from the air-temperature and ratio of the measured solar radiation to the clear-sky solar radiation.

A procedure for computing Q_a suggested by Edinger, et. al.⁽²⁵⁾, is to first compare the measured short-wave radiation to the clear-sky radiation (Figure 2). Using this ratio and the air temperature, enter Figure 3 to obtain the Brunt coefficient (C_1). The long-wave atmospheric radiation can then be calculated using Equation II-4.

A second procedure was first suggested by Raphael⁽²⁶⁾ who proposed the following empirical representation:

$$\frac{Q_a}{\sigma T_a^4} = a + b e_a = \beta \quad (\text{II-5})$$

where: $a = 0.740 + 0.025 C_L \epsilon - 0.0584 Z_c$

$b = 0.00490 - 0.00054 C_L \epsilon - 0.060 Z_c$

e_a = vapor pressure of air (mb)

β = radiation factor

Z_c = cloud height in feet

σ = Stefan-Boltzmann Constant $4.5 \times 10^{-8} \text{ BTU/ft}^2\text{-day-}^\circ\text{F}^4$

ϵ = Napierian base.

Raphael concluded, since most weather observations available to engineers give the amount of cloud cover in tenths of sky obscured without distinguishing

TABLE 1
VALUES FOR THE ABSORBTIVITY COEFFICIENT AS A FUNCTION OF
CALENDAR TIME AND LATITUDE

LATITUDE	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
70 N	-----	0.77	0.84	0.89	0.91	0.91	0.91	0.90	0.87	0.85	-----	-----
60	0.80	0.84	0.89	0.92	0.92	0.93	0.92	0.91	0.90	0.86	0.81	0.79
50	0.84	0.88	0.91	0.93	0.93	0.94	0.93	0.93	0.92	0.89	0.86	0.84
40	0.89	0.91	0.92	0.93	0.94	0.94	0.94	0.94	0.93	0.92	0.89	0.88
30	0.91	0.92	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.93	0.92	0.91
20	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.93	0.93
10	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.93
0	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94

Figure 2. Clear Sky Solar Radiation

Figure 3. Brunt C Coefficient from Air Temperature, T_a , and Ratio of Measured Solar Radiation to Clear Sky Radiation

among clouds as to the height, that he could reduce the analysis by proposing that the radiation factor (β) could be related to the amount of cloud cover and the associated vapor pressure similar to the Brunt Analysis. This information is shown in Figure 4. In Reference 27, the information shown in Figure 4 was placed in functional form to facilitate its use in a digital computer program.

3. Back Radiation

Water radiates energy in the form of long wave radiation as an almost perfect black body at a rate on the order of 2400-3600 BTU/ft²-day. The rate at which heat is lost by this mechanism can be computed from the Stephan-Boltzmann fourth power law:

$$Q_b = \gamma_w' \sigma (T_w + 460)^4 \text{ Btu/ft}^2\text{-day}, \quad (\text{II-6})$$

where: γ_w' = emissivity of water (0.97).

T_w = temperature of surface water.

4. Evaporation

Heat loss from a body of water to the atmosphere through the evaporation of water occurs at a rate of a few hundred to several thousand BTU/ft²-day, depending upon water temperature and local meteorology. There have been a number of semi-empirical models proposed for the evaporative term. These expressions take the form

$$Q_e = f(u) [e_w - e_a] \text{ Btu/ft}^2\text{-day}, \quad (\text{II-7})$$

where: e_w = saturated vapor pressure at the temperature of surface water.

In this expression, the term $(e_w - e_a)$ is the driving force commonly referred to as the "Dalton Difference". The wind speed function $f(u)$ is described through a polynomial

$$f(u) = a' + b'u + c'u^2,$$

where: u = wind speed (mph)

a' , b' , c' = empirically derived coefficients.

Four of the more common models are:

Meyer formula⁽²⁸⁾

$$f(u) = 73 + 7.3u.$$

Lake Colorado City formula⁽²⁹⁾

$$f(u) = 16.8u.$$

Lake Hefner formula as expressed in⁽²⁵⁾

$$f(u) = 11.4u.$$

Brady formula⁽¹⁴⁾

$$f(u) = 70 + .7u^2.$$

Figure 4. Atmospheric Radiation Factor, β

5. Conduction

Heat can either enter or leave water by conduction, depending upon whether the air temperature is greater or less than the water temperature. Generally this transfer is small - less than 500 BTU/ft²-day. The rate at which heat is conducted between two media through molecular motion is expressed by Fourier's Law. Similarity arguments relating heat transfer and mass transfer have been used by Bowen to arrive at a proportionality between heat conduction and heat loss by evaporation.

$$B = \frac{Q_c}{Q_e},$$

where: B = the Bowen ratio given by:

$$B = C_2 \left(\frac{T_w - T_a}{e_w - e_a} \right) \left(\frac{P_a}{760} \right),$$

where: P_a = Barometric pressure (mm hg)

C₂ = experimentally determined coefficient = 0.26

Using the general form of the evaporation model, the rate at which heat is conducted to or from the surface of the water can be written

$$Q_c = 0.26 f(u)(T_w - T_a) \text{ BTU/ft}^2\text{-day.} \quad (\text{II-8})$$

C. EQUILIBRIUM TEMPERATURE CONCEPT

By definition, the equilibrium temperature is that temperature (water) at which the net exchange of energy between the water and air is zero for a given set of meteorological conditions. Although the concept has been accepted for years, it has only recently come into its own in calculating the heat flux to and from a given body of water. The equilibrium temperature concept proposed by Edinger, et. al.⁽²⁵⁾, provides a convenient way of representing the complex heat transfer process and for this reason is reviewed in this study.

Substituting equations II-6, II-7, and II-8 into equation II-1, the heat exchange can be expressed as

$$\Delta Q_T = Q_s + Q_a - 1801 \left[\frac{T_w}{460} + 1 \right]^4 - f(u)(e_w - e_a) - 0.26f(u)(T_w - T_a) \quad (\text{II-9})$$

Defining the exchange of energy using an average exchange coefficient.

$$\Delta Q = -K(T_w - E),$$

where: E = equilibrium temperature ($^{\circ}\text{F}$)
 K = exchange coefficient ($\text{Btu}/\text{ft}^2\text{-day-}^{\circ}\text{F}$)

Letting $T_w = E$ with the corresponding saturation vapor pressure at any equilibrium temperature $e_w = e_E$, equation II-9 becomes

$$Q_s + Q_a = 1801 \left[\frac{E}{460} + 1 \right]^4 + f(u)(e_E - e_a) + 0.26f(u) (E - T_a). \quad (\text{II-10})$$

Equation II-10 equates the incoming total radiant energy flux to the equilibrium conditions.

Edinger⁽²⁵⁾ proposed the following linearizing assumption:

$$(e_w - e_E) = \beta_1(T_w - E), \quad (\text{II-11})$$

where: β_1 = the proportionality factor ($\text{mm Hg}/^{\circ}\text{F}$).

Brady⁽¹⁴⁾ has proposed the following functional relationship for β_1 :

$$\beta_1 = 0.255 - .0085 T_w + .000204 T_w^2 \quad (\text{II-12})$$

Subtracting equation II-10 from II-9, substituting equation II-11 into the remainder, and truncating the binomial expansion of the back radiation term (retaining only the linear portions) results in the following:

$$\Delta Q = - \left[15.71(T_w - E) + f(u)\beta_1(T_w - E) + 0.26 \cdot f(u) \cdot (T_w - E) \right]. \quad (\text{II-13})$$

Simplifying equation II-13 results in the following:

$$\Delta Q = \left[15.7 + (0.26 + \beta_1) \cdot f(u) \right] \cdot (T_w - E)$$

and the exchange coefficient is defined as

$$K = 15.7 + (0.26 + \beta_1) \cdot f(u). \quad (\text{II-14})$$

An expression for the equilibrium temperature in terms of the exchange coefficient can then be obtained by substituting

$$f(u) = \frac{K - 15.7}{(0.26 + \beta_1)}$$

into equation II-10 using the following linear approximation for the vapor pressure term

$$e_E = (\beta_1)E + C(\beta)$$

and retaining only the linear and quadratic terms of E in the binomial expansion, i.e.,

$$\left[\frac{E}{460} + 1 \right]^4 = 6 \left(\frac{E}{460} \right)^2 + \frac{4E}{460} + 1.$$

and simplifying results in the following equation

$$E + \frac{0.051E^2}{K} = \frac{(Q_s + Q_a) - 1801}{K} + \frac{K - 15.7}{K} \left[\frac{e_a - C(\beta)}{0.26 + \beta_1} + \frac{0.26 T_a}{0.26 + \beta_1} \right]. \quad (\text{II-15})$$

Solution for K and E is then obtained by trial and error. For a complete discussion of the development and method of solution, the reader is referred to Reference 25. Other solution techniques have been proposed^(14,30) and once again the reader is referred to the specific work for a detailed description.

The equilibrium temperature concept is useful in that it provides a single "sink" temperature for effective simulation of the several natural sink temperatures (e.g., wet bulb for evaporation, dry bulb for convection, etc.). Similarly, the use of the exchange coefficient permits a considerable simplification of complex problems. The convenience of using the equilibrium temperature concept to simplify the analysis will become apparent in Chapter III of the report.

D. WATER USAGE

Associated with the heat exchange in evaporation is the transfer of mass in that the latent heat of evaporation is liberated by changes of water from the liquid to the vapor phase as it leaves the surface. Using models discussed in the previous section, the total heat exchanged, and, hence, mass transferred, between the water and air is, of course, a function of the exchange rate and the pond's surface area integrated over a specified period. Pond models that have been developed to simulate this interaction will be discussed in a following section. Water usage is an extremely important consideration in certain geographic locations, the most notable being the Southwest.

1. Consumption

The semi-empirical nature of the evaporative expression has been discussed. The general form of the model equates the evaporation in appropriate units to the product of the difference in pressure between the saturated vapor at pond temperature and the ambient air vapor pressure times a function related to the wind speed. In the natural state, for relatively small

bodies of water, and under the influence of reasonable meteorological conditions, it can be assumed that the surface water temperature will be approximately at its equilibrium condition.

Artificially heated ponds operate at temperatures above the equilibrium condition. Therefore, as a point of reference, the geographical and seasonal variation of the equilibrium temperature could be examined. In a study recently conducted by Vanderbilt University⁽²⁷⁾, the equilibrium temperatures for 88 stations throughout the United States were determined, based upon monthly averaged weather conditions. The calculations were used as a guide to construct equilibrium isotherm plots for different times of the year. Isopleths were also constructed for the associated exchange coefficient. The analysis was extended to include extreme weather conditions for most of the 88 sites, which are represented in a similar fashion.

It has long been recognized that ponds used for industrial cooling will have an evaporation rate greater than ponds in their natural state, provided all other factors are constant. Using an analogous "Dalton difference" representation for forced evaporation, the total (natural plus forced) evaporation is found to equal

$$Q_e = f(u) (e_H - e_a) \quad (\text{II-16})$$

where: e_H = vapor pressure at pond temperature.

To determine the total heat lost through evaporative cooling, equation II-16 has to be multiplied by the effective pond surface area. This, in turn, is equated to the conservation of mass through the latent heat of evaporation to determine the mass loss. The latent heat of evaporation varies with water temperature and can be approximated by

$$H_e = 1076 - 0.56714 (T_w - 32.0) \frac{\text{Btu}}{\text{lb}}$$

Hauser and Oleson⁽³¹⁾ compared the evaporative losses from ponds having a surface area of one acre per megawatt and two acres per megawatt. The authors examined the sensitivity of varying one of five selected independent variables while holding the remaining four fixed. These independent variables selected included: wet bulb temperature, relative humidity, cloud cover, wind speed and range. Consumption, in this case, meant the total evaporative loss (natural plus forced) per unit of energy produced.

As expected, the analysis showed a primary dependence upon the wet bulb temperature, relative humidity, and wind speed. The results were seemingly independent of cloud cover except for total cover, and totally independent of cooling range. Generally speaking, the two curves, (one for one acre/MWe, second for 2 acre/MWe) paralleled one another. For the entire analysis, rate of consumption from the 2 acre/MWe case was approximately 25% greater than the 1 acre/MWe case.

Tichenor and Christianson⁽³²⁾, using a different approach, extended the information presented in Reference 31. The authors selected six geographic locations, each characterized by different weather, and a critical design condition. The plant characteristics were fixed at 1000 MWe, coolant flow rate of 1430 cfs, temperature differential of 20°, and a sensitivity analysis was performed by varying the pond surface area. Using a slug flow model, to be discussed shortly (equation III-13), the pond condition at the inlet and outlet were simulated. Using this information, the evaporative loss expressed in terms of cubic feet per second was computed. Based on the analysis, it was indicated that the evaporative loss rate can be reduced by 50 to 100 percent by reducing the pond size by a factor of 2 to 3. This is accomplished, however, at some loss in plant efficiency. For the design conditions hypothesized, the rate of evaporation was found to range from 35-80 cfs. Figure 5 taken from Reference 32, illustrates this range.

Sefchovich⁽³³⁾ compares the consumption from various sizes of nuclear and fossil fueled power stations on a proposed pump storage facility. For a pond having a surface area of 7000 acres, the evaporation rate as a function of plant capacity and wind speed were evaluated. The results indicate that evaporation rates from a nuclear plant are from 15 to 20 percent greater than that for a comparable size fossil plant resulting from the difference in the assumed overall plant efficiencies and the heat delivered to the cooling water.

Although Reference 27 did not address itself specifically to the subject of evaporative loss, the report contains information which can be used to compute consumption. Using a completely mixed pond model (Equation III-10), the pond temperature for two ponds (of 1500 and 2200 acres) were evaluated for locations throughout the United States. The waste discharge characteristics were 1350 cfs and the temperature rise across the condenser was 15°F. Both average and extreme conditions were examined for the critical winter and summer conditions. In addition, the analysis was repeated, holding the net

Figure 5. Pond Evaporation vs Inlet Temperature

pond temperature constant at 1/2 the temperature rise, 50 percent cooling, and the surface area requirements determined. This information was presented for the same conditions mentioned above. Knowing the humidities of the air, the mixed pond temperature, and the wind speed (which is provided), the evaporation can be estimated.

In the studies discussed, make-up in the form of precipitation was not accounted for. In reality, the net consumption should equal the total evaporative loss minus the make-up, since the pond surface area would be present to intercept the precipitation and runoff. As one would expect, in some areas, this can be substantial. For example, in the southwest alone, the range in precipitation is from less than 10 in./yr to more than 40 in./yr. This converts to approximately 1.5 to 6 cfs per 1000 acres.

2. Reducing Evaporation

As suggested previously, controlling the rate at which water evaporates from the surface of a water body can be of great importance. In certain sections of the United States, the required make-up water for planned power development would tax the available water resources. This is particularly true in arid regions. As indicated previously, the total evaporation from a cooling pond can be lowered by reducing the pond surface area; which results, of course, in higher pond water temperature and lower plant efficiency. Two other methods that might be considered are providing a mechanical cover, and introducing a substance which provides a surface film.

Using a pond cover limits the amount of incoming short-wave radiation, thus reducing the temperature of the water body. The range of methodologies employed could extend from roofs to floating devices, but intuitively, it would seem that the use of physical covers would be limited to small ponds.

Two types of reflective treatments were recently examined by Winiarski and Byram⁽³⁴⁾. Using the basic heat balance equation, the effect of introducing the various reflective treatments was described by overriding the effect of the various terms. For example, if a reflective evaporative treatment is assumed, this can effectively be simulated by decreasing the amount of absorbed solar radiation. If a reflective non-evaporative treatment is assumed, the amount of absorbed solar radiation is decreased and the evaporation term is set equal to zero. For a given set of meteorological and operating conditions,

the two treatments were compared to a natural pond using both the completely mixed pond model and the slug flow model. The results are shown in Tables 2 and 3. Examples of the two types of treatments suggested by the authors were:

- 1) For the reflective evaporative effect, floating white or shiny granular material;
- 2) For the reflective non-evaporative effect, covering the pond surface with a sheet of white plastic.

Experiments were conducted to test the effectiveness of the non-evaporative methods. Comparisons were made of a pond covered with white opaque plastic, and untreated ponds. The results of the experiment agree with the predictions of the mathematical model.

While this method works satisfactorily in a small experimental pond for a short period of time, further research is needed to apply the method to cooling ponds of a few thousand acres in size. First, the plastic must stay afloat and in place; secondly, the material must be inexpensive, and must last at least five years to be economical and reliable.

Studies have also been made using chemicals to create a thin surface film. A chemical which has received considerable attention is hexadeconal⁽³⁵⁾. The material is a white, waxy, crystalline solid available in flakes or powder. Hexadeconal is a polar compound, in which one end of the molecule has a great affinity for water and the other end repels water. Consequently, when introduced to water, the molecule literally stands on end. The monomolecular film formed by hexadeconal on water surfaces is only six ten-millionths of an inch thick. Theoretically, 0.02 pound of hexadeconal is required to form a compact monomolecular film on an acre of water surface. In practice, six pounds of powdered hexadeconal (roughly worth \$2.50) were used in a seven-day period to cover a 2.8 acre pond⁽³⁵⁾. Extrapolation of this experience to large cooling ponds, which is tenuous at best because of the added effects of wind and surface turbulence, indicates a cost in excess of \$0.20/1000 gal not evaporated. For a 1000 MW_e nuclear plant, this could amount to \$130,000 annually.

TABLE 2
COMPARISON AMONG COMPLETELY MIXED PONDS

TREATMENT EFFECT	AREA (ACRES)	EVAPORATION RATE (GPM)	EQUILIBRIUM TEMPERATURE
Natural	2770	21.6×10^3	83.5
Reflective-Evaporative	1110	8.6×10^3	71.5
Reflective-Nonevaporative	3500	-----	73.5

TABLE 3
COMPARISON AMONG FLOW-THROUGH PONDS

TREATMENT EFFECT	AREA (ACRES)	EVAPORATION RATE (GPM)	EQUILIBRIUM TEMPERATURE
Natural	1140	14.0×10^3	83.5
Reflective-Evaporative	670	8.8×10^3	71.5
Reflective-Nonevaporative	2340	-----	73.5

E. POND VOLUME AND DEPTH CONSIDERATIONS

A criterion that has been used in the design of cooling ponds is that the minimum water storage capacity of a pond should be at least equal to the volume of water to be recirculated in 24 hours⁽⁷⁾. This criterion is employed to take advantage of added cooling during the cooler night hours. The depth of the pond should be sufficient to avoid channelization. A minimum of three feet has been suggested⁽¹⁷⁾.

1. Stratification

The thermal capacity of the cooling pond is characterized by its surface area and depth. The conservation of thermal energy for a unit cell or parcel of water (neglecting the exchange of energy through the processes of advection and dispersion) is expressed as:

$$\frac{\partial T_w}{\partial t} = \dot{q} / \rho C_p ,$$

where: $\dot{q}$ = rate of thermal energy added per unit volume, Btu/unit volume-time

t = time, appropriate units

ρ = density, lb/unit volume

C_p = specific heat, BTU/lb

For the particular case under examination (exchange of thermal energy through the surface only) and under conditions of uniform mixing within the vertical cell, temperature change for a given quantity of energy added can be written

$$\frac{\partial T_w}{\partial t} = Q_T / d \rho C_p ,$$

where: Q_T = flux of energy through unit surface area per unit time

d = depth in appropriate units.

The rate of temperature change is inversely proportional to the depth of the water column. For a pond having more than one day's holdup, the temperature in a completely mixed vertical cell may be expected to vary from its average by $\pm 2^{\circ}\text{F}$ for a five-foot depth, or $\pm 3^{\circ}\text{F}$ for a three-foot depth⁽¹⁷⁾.

The rate of heating and mixing in the vertical plane is an extremely complex process about which much remains to be learned, although the Lake Cayuga Study⁽³⁶⁾ provides an excellent stepping stone from which future efforts might be referenced. Basically, the principal factors underlying the process are summarized by the degree of vertical mixing, advection and diffusion, and the distribution of absorbed solar radiation. Hutchinson⁽³⁷⁾ has presented a discussion of the thermal properties of lakes. The reader is referred to the reference for a complete discussion of the subject which is beyond the scope of this report. The external heat source is summarized through the processes of incident radiation (short-wave and long-wave), radiant cooling (back radiation), convective cooling or heating, and evaporative cooling. All but the solar radiation component are normally looked upon as surface phenomena, whereas the incident solar radiation is absorbed in a decreasing exponential fashion below the water's surface. The nature of this absorbtivity depends upon the transparency and motion of the water in the vertical cell.

Dake and Harleman⁽³⁸⁾ have recently examined the absorption of radiation as a function of depth. Their studies indicated that approximately 40% of the net incoming solar radiation is absorbed at the surface; the remaining 60% is absorbed exponentially with depth. The absorption is primarily a function of the water's transmissibility. Sensitivity studies were performed by Sonnichsen and Oster⁽³⁹⁾ using a one-dimensional model containing an effective vertical thermal eddy diffusion coefficient and an effective absorption coefficient to study the two parameters. For the range of conditions studied, the absorption coefficient appeared to be the more sensitive of the two variables examined. For lakes, the range of absorption coefficients is from 0.30 - 0.05 m^{-1} .

A number of studies^(40,41,42) have been conducted to determine the depth of the euphotic zone in sewage lagoons. Under such conditions, the depth to which 1% of the surface light penetrates very seldom exceeds 4 to 5 feet.

This converts to an absorption coefficient of approximately 3 m^{-1} . The high value results from the presence of algal blooms, etc. Under such conditions, the effective depth of mixing might be reduced to a few feet.

Cooling of the surface water by evaporation, back radiation, and possibly sensible heat loss, sets in motion convective currents in the vertical plane for temperatures above 4°C . The degree of motion is amplified by external forces, such as wind, which introduce a direct stress, as well as creating surface undulation. The motion or turbulence which is generated transports momentum and heat in the vertical plane.

The interplay of these processes is manifested in the resulting temperature distribution. In lakes of sufficient depth or vertical resistance, the processes of heating and mixing give rise to a zone of warmer water near the surface, termed the epilimnion, and a relatively undisturbed region near the bottom, termed the hypolimnion. The region of rapid decrease in temperature is commonly referred to as the thermocline. The exact location and definitiveness of these regions depends upon the size characteristics and location of the water body in question. Indeed, in a flowing river, it is common to find the lateral water mass to be isothermal during the entire year. A similar condition might also be experienced for small shallow lakes, provided there is sufficient wind-generated turbulence to mix the medium. However, more commonly this is not the case, and a well defined epilimnion and hypolimnion will exist.

In the natural state, when there is insufficient turbulence or motion to mix the thermal energy absorbed by the water column, the heating cycle (increased during spring and summer) will effectively establish a stratified condition that becomes more stable. This, of course, results from the decreasing density of water above 4°C . As the degree of stratification increases, the rate at which momentum and thermal energy may be transferred to deeper waters decreases.

In cooling ponds, the addition of an artificial (man-made) heat load upon this natural condition will amplify the above situation. Consequently, the effective mixing depth and subsequent epilimnionic volume can be effectively reduced. In shallow lakes, it has been found that the water temperature down to a depth of about 10 to 15 feet will average within 2 or 3°F of the temperature at the top of the water cell. In mathematically modeling the behavior of heated discharges into lakes, it has been assumed that vertical entrainment is

non-existent below a depth of 10 feet.

Suggested depths adopted from regulations of the Heating and Power Board of the Soviet Union for cooling ponds are⁽⁴³⁾:

Depth greater than 5.0 feet at low level

Depth greater than 8.2 feet at normal water level

Depth less than 10 to 13 feet, since circulation ordinarily does not extend deeper.

These guidelines agree well with the previous comments. In the design of cooling ponds for a chemical plant having surface areas of 45 and 140 acres, an operating depth of from 8 to 9 feet was determined optimum⁽⁴⁴⁾.

2. Selective Withdrawal

Selective withdrawal from reservoir impoundments for the purposes of enhancing the downstream water quality has become a popular consideration during recent years. A recent paper⁽⁴⁵⁾ lists 90 facilities which possess features to permit selective withdrawal. As suggested by its authors, the list is probably not complete and possibly more exist.

A number of different designs have been proposed and constructed to accomplish this objective. At the present time, operating experience from the various selective withdrawal works has received limited documentation. Data which have been collected on the subject have generally been retained by the collecting agency and not disseminated for numerous reasons. Consequently, the adequacy of these various designs is still unknown to public. In terms of reservoir operation and overall optimization (of which water quality would be a primary consideration) it is an extremely complex undertaking.

With regard to designing a cooling pond, inverted weirs or baffles could be included into the design to permit selectively withdrawing dense cooler water under stratified conditions. Harleman et. al.⁽⁴⁶⁾, ⁽⁴⁷⁾, have discussed the problem of withdrawing cold water from a two-layered system possessing a discrete interface using a skimmer wall. The problem was to determine, for a given intake geometry and water density differential, the maximum amount of colder water that could be withdrawn without inducing an appreciable withdrawal from the upper layer of warm water.

A basic experimental and analytical investigation was conducted for both a plane and a radial skimmer wall. The maximum discharge for a plane skimmer

wall was found to occur when the ratio of interface elevation to skimmer wall opening was 2.5. For a radial skimmer wall, the maximum discharge occurred when the ratio equaled 1.5.

Sood⁽⁴⁸⁾ examined experimentally the effect of selectively withdrawing cool sub-surface water under conditions of divided flow. The main channel flow was stratified, and a lift gate was used to form the barrier on the branching side channel. Experiments were conducted for various take-off angles and lift gate openings. It was concluded that optimum discharge occurs on either side of the 90 degree take-off angle.

As indicated previously, the design of the Cholla Cooling Pond includes an inverted weir. The structure was designed to allow the coolest water to leave the hot pond. A design velocity of one foot per second was selected.

3. Pump Storage Basins

Pump storage basins might be used as cooling ponds⁽³³⁾. However, it must be recognized that not all are suitable for such usage. Some storage basins undergo tremendous stage variations and consequent variations in the surface area which would impose limitations on the waste heat that can be removed. Significant variations in the rate withdrawal from the pond could lead to the development of differing flow patterns within the basin.

III. MODELING THE PROPERTIES OF COOLING PONDS

Mathematically modeling the distribution of temperature, chemical species, or particulate matter in a cooling pond involves solving the coupled equations of continuity, motion, and energy in conjunction with appropriate equations of state and information about chemical kinetics or particle dynamics (if relevant). Solution of this set of equations would be common to the analysis of any form of pollutant discharge in a water body (i. e., release to tidal estuary, large lake, river). The differences in the mathematical models used to simulate each form of discharge are in the boundary conditions, the characteristics of the natural water body and surroundings and the accuracy required in computations.

In the sections that follow, a discussion of the system of equations which theoretically describes the response of a cooling pond is presented. This is complimented by a brief discussion of techniques used to solve similar equations in related fields. A review of cooling pond modeling in practice is then presented.

A. COOLING POND MODELING -- THEORY

The equations of change are statements of a "balance sheet" on species, Newton's law of mechanics, and the first law of thermodynamics. Leaving out discussion of systems in which centrifugal forces, Coriolis forces, etc., Dufour flux, Soret flux, etc., are prominent; and after making simplifications which virtually every cooling pond model could accommodate, the following equations result.

Continuity, total for fluid mixture:

$$\frac{\partial \rho}{\partial t} + (\nabla \cdot \rho \mathbf{V}) = 0 \quad (\text{III-1})$$

Continuity, chemical species:

$$\frac{\partial C_i}{\partial t} + (\nabla \cdot C_i \mathbf{V}^*) = (\nabla \cdot C_m D_{ij} \nabla x_j) + k C_i^n + \alpha_i \sum_m \frac{\partial N_{mi}}{\partial t} \quad (\text{III-2})$$

Continuity, two-phase mixtures:

$$\frac{\partial M}{\partial t} + \nabla \cdot M \mathbf{V}_s = \nabla \cdot D_s \cdot \nabla M$$

Conservation of motion:

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} + C_D N (\mathbf{V}_s - \mathbf{V}) - \rho \mathbf{g}. \quad (\text{III-4})$$

Conservation of energy:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = \nabla \cdot D_T \nabla T + \sum_{\ell} Q_{\ell} \quad (\text{III-5})$$

where:

- C_D = drag or lift coefficient
- C_i = individual chemical species concentration
- C_M = molar density
- D_S = transfer coefficient of sediment
- D_T = thermal diffusion coefficient
- D_{ij} = multi component diffusion coefficient
- g = gravitational acceleration
- K = chemical reaction coefficient
- M = sediment density
- n = order of chemical reaction
- N = number density of sediment particles
- N_{Mi} = number of nuclei of M^{th} radioactive isotope of chemical species i per unit volume
- P = fluid pressure
- Q_ℓ = ℓ^{th} energy source or sink
- T_n = water temperature
- V_S = average velocity of sediment
- V = average velocity of fluid
- V^* = average velocity of mixture
- X_i = mole fraction of i^{th} chemical species
- α' = conversion factor, nuclei/unit volume to molar/unit volume
- μ = viscosity of mixture

Those features which characterize a cooling pond will be described in the following section. Further, the unique properties of ponds which require analytical techniques different from the broader class of pollutant problems will be identified. Later sections will illustrate how the basic equations may be simplified, and how the assumptions implicit in the simplifications measure up to the cooling pond features delineated in the following section.

1. Pond Features to be Modeled

The operation of cooling ponds proceeds in three steps: 1) discharge of warm condenser water into the pond; 2) energy dissipation to the atmosphere; and 3) plant intake. All models must contain at least this simple description. It is implicit in such a simplified model that the entire pond is involved in the cooling process. Any short circuiting process produced by non-optimum locations of intake and outfall structures; resistance to plume spread due to local stratification, finite diffusivity, or finite buoyant forces; and/or deflection of plume due to pond boundaries are all ignored.

The features that broadly characterize a cooling pond are climatic (energy loss to atmosphere), topographic (boundary conditions), and hydraulic (circulation, stratification) in nature. Familiarity with the current state-of-the-art literature review of mathematical modeling techniques employed prior to 1969 to describe pollutant plumes in large water bodies is provided by Baumgartner and Trent⁽⁴⁹⁾. Tracor, Inc.⁽⁵⁰⁾ provided a similar assessment based upon two well attended conferences (June 1969, May 1970). A more current state-of-the-art review restricted to thermal plumes has been published by ANL⁽⁵¹⁾. A review of the unique aspects of the features that characterize cooling ponds, as cited above, will be undertaken within the framework of a comparison between ponds and large natural water bodies.

The description of the flow field contains the primary distinctions between the large flow field problems and cooling problems. The mathematically infinite (or semi-infinite) flow field problem usually involves a relatively simple description of the momentum distribution, i.e., the velocity distribution is assumed uniform or is given through measurement, and certain mechanisms such as wind-driven circulation in the far field and jets in the near field are dominant. Circulation is usually absent, secondary flows are usually neglected and boundaries usually play at most a passive role in the fluid motion within the problem domain.

In contrast, the cooling pond problem frequently involves circulation, or at least boundary influenced currents existing within the problem domain. All the forcing functions and mechanisms present in the infinite (or semi-infinite) flow field problem may be present, but their range of influence can be exaggerated due to the presence of boundaries. For example, a jet discharge may be deflected and partially dissipated by a boundary.

A feature which may be present in a cooling pond is the ability of the pond to create its own atmosphere⁽⁵²⁾. The pond may interact with a portion of its surroundings to create a transition or boundary layer which manifests itself in the mathematical description by altering the mass transfer coefficient and the wind speed at the water surface. The evaporation rate is thereby influenced and, hence, the rate of energy loss to the atmosphere is also affected.

In sum, it would appear that the largest hindrance to the construction of an adequate model for cooling pond analysis is the multidimensional character of the system. Difficulties also experienced in the modeling of large natural water bodies are compounded by the introduction of more complex boundaries.

In the following paragraphs, the least complicated models for the transport of various field quantities are presented, and their adequacy is analyzed. These models are commonly employed in pollution analysis, though not necessarily on the cooling pond problem. The probable direction of development of mathematical modeling for pond application is then hypothesized.

The remainder of this section will be devoted to the development of very simple models to predict the transport of a field quantity in a cooling pond. Identification of the assumptions implicit in the mathematical model and, thereby, the adequacy of the formulation, is sought. It will be found that considerable similarity exists between the dispersion of the various field quantities.

1.1 Thermal Energy Transport

The dissipation of thermal energy of large heat sources is the central objective of cooling pond technology. The temperature variable is usually transformed into an "excess temperature" (equilibrium temperature concept) in order to simplify the mathematics of an atmospheric loss (or gain) term (see Chapter II, Section B). Typical of the thermal energy transport problem is the two-dimensional mathematical model in a semi-infinite domain as employed by Edinger and Polk⁽⁵³⁾. They use Equation III-5 in the form

$$u \frac{\partial T_w}{\partial x} = \frac{\partial}{\partial y} \left(D_y \frac{\partial T_w}{\partial y} \right) - \frac{K}{\rho C_p d} T_w, \quad (\text{III-6})$$

where the fluid which possesses a uniform velocity diffuses normal to the direction of convection. The ultimate loss of energy from the system is through transfer to the atmosphere by evaporation and radiation.

Direct application to the cooling pond problem is limited. An infinite domain, two-dimensional thermal model is inadequate since the internal circulation is not known. Some form of a two-dimensional model might describe internal circulation, but limitations on prevailing current, convection, and system domain generally preclude this feature. For high temperature gradients at the outfall, buoyant spread of the thermal plume would require a coupling of the energy and momentum equations.

1.2 Radionuclide Transport

Concern for the movement of radioactive materials in cooling ponds arises from the potential for local concentration. Two types of problems may be defined: 1) secular equilibrium of isotopes (or concern only with net radioactivity and not individual isotopes), sorption-desorption by sediments and dilution by diffusion; and 2) relatively short elapsed time, parent-daughter decay of short half-lived isotopic species and dilution by diffusion.

Typical of the methods to describe the secular equilibrium problem is the general one-dimensional mathematical model developed by White and Gloyna⁽⁵⁴⁾ for the routing of radionuclides in a river. They employ only equation III-2 in the form

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} + \sum_{i=1}^n S_i, \quad (\text{III-7})$$

where the last term on the right is a sorption term for plants and bottom sediments (each of the i sorption phases).

An auxiliary condition computes S_j using a form similar to the Freundlich isotherm for sorption reactions. This model would not be adequate for the description of cooling ponds possessing internal circulation. Circulation within a pond could be driven by the outflow momentum source, wind and/or temperature gradients in a completely bounded basin. The velocity field resulting from this circulation would thus be complex and would require coupling with the momentum equation (Eq. III-4) and, if a density current were present, the energy equation (Eq. III-5). Further, circulation implies Equation III-6 must involve at least two dimensions.

By analogy with the secular equilibrium model, an expression similar to Equation III-7 for each radioactive isotope can be developed. In place of (or in addition to) the sorption term would be a decay term. The complex coupling of the chains of radionuclides result in the source in one relation being the sink in another. Thus, an extensive set of equations is required when the concentration of each isotope is to be followed. The total activity would be the sum of the activities of the individual species. When the radioactivity of a single isotope predominates, the parent-daughter decay relations can be simplified. Furthermore, by defining a pseudo-decay constant which includes local advection, as Harward did⁽¹²⁸⁾, the phenomena can be described by a single expression.

1.3 Suspended Sediment Transport

Pick-up and deposition of sediment allows a potential change of the bottom contours and shoreline topography of cooling ponds. It is conceivable that a pond designed to possess optimum heat transfer properties (i.e., minimum dead water) could be reshaped to lose this property by local scour and refill. The sediment itself would be unlikely to influence the fluid properties, but would alter the boundary conditions imposed on energy and radionuclide dissipation problems, and would influence the mass transfer coefficient

in the latter problem. This would constitute a problem only in regions possessing a large momentum transport.

Typical of the sedimentation problem is the two-dimensional mathematical model employed by Jobson and Sayre⁽⁵⁵⁾. They employ Equation III-3 in the form

$$u \frac{\partial M}{\partial x} = Ds_x \frac{\partial^2 M}{\partial x^2} + \frac{\partial}{\partial y} \left[Ds_y \frac{\partial M}{\partial y} + V_s M \right] \quad (\text{III-8})$$

where the vertical convection term, a result of the sedimentation velocity, is combined with the vertical diffusion term on the right-hand-side. Variation of diffusion coefficient and fluid velocity with depth are based upon empirical relations. Because only the continuity relation is imbedded in this model, it suffers from the same shortcomings experienced in the one-dimensional radio-nuclide transport problem.

2. Advanced Transport Models

Invariably, to some extent, the entire cooling pond participates in the cooling process. Thus, adequate simulation of the cooling pond transport problem necessarily involves either a three-dimensional or pseudo-three-dimensional mathematical model. Presently available mathematical models and computational techniques, and present-day computers are inadequate to deal with complex three-dimensional calculations of the cooling pond variety. Relaxation of some rigor does admit approximate simulations to the problem.

A coarse layering scheme has been employed by Pritchard⁽⁵⁶⁾ for the treatment of problems possessing regular boundaries. Except for provisions for some integral empiricism, this method is a standard three-dimensional technique, but with the vertical direction limited to two (or a few) layers of elements in order to conserve computer storage. Vertical integration may also be employed to reduce the problem to a two-dimensional one, as accomplished by Leendertse⁽⁵⁷⁾. This pseudo-three-dimensional model is particularly interesting due to its provisions for irregular boundaries. Both Pritchard and Leendertse's methods may experience difficulty in applying physically plausible boundary conditions to the computational mesh. For example, finite elements cannot be made small enough, so that a uniform field variable can be justified over the element domain without correction. Shoreline physical boundaries correspond to element shape.

B. COOLING POND THERMAL MODELING--IN PRACTICE

As inferred from the previous section, cooling pond analysis is still regarded as an art. Adequate mathematical models which encompass the entire range of features that the complete class of cooling ponds could possess are not available. Hence, experience and simplified analysis provide the primary basis for practical engineering design, although, during recent years, in responding to water quality standards, the analysis has become more sophisticated.

In practice some ponds may be adequately described by simplified temperature and flow distributions. Two uncomplicated models, which employ the conservation of thermal energy, used in cooling pond analysis will be reviewed. If internal circulation exists, these simplified models by themselves are inadequate for the purposes of analysis. However, they should bracket the solution, provided the total pond surface area participates in the cooling process. Generally, the circulation or flow field is provided using one of several techniques which include physical models or in situ prototype studies. A discussion of internally circulating pond models and the use of physical models is presented. Finally, comments on specific applications and comparisons with data are discussed.

1. Completely Mixed Pond

By definition, a completely mixed pond has a nearly uniform temperature distribution throughout. The drop in temperature from the plant discharge temperature to the pond temperature takes place over a small portion of the pond. For such a condition to exist in ponds other than spray ponds, the resistance within the pond for mixing would have to be relatively small, the pond would have to be extremely large and the mixing of the outfall with the surrounding waters would have to be extremely efficient. The condition could also exist if artificial mixing devices, including sprays, were added to the pond.

The temperature of the pond would be above the equilibrium by an amount such that the net rate of heat transferred to the atmosphere, on the average, equaled the rate at which heat was being added to the pond. Under such a

condition, the steady-state representation for predicting the temperatures within the pond is summarized by the basic conservation relationship

$$\text{Heat in} - \text{Heat out} = \text{Heat dissipated}$$

which can be expressed as

$$\rho C_p Q_p T_i - \rho C_p Q_p T_o = KA(T_o - E),$$

where:

A = pond area

Q_p = plant pumping rate

T_i = temperature into the pond

T_o = temperature out of the pond

Simplifying

$$\rho C_p Q_p (T_i - T_o) = KA(T_o - E),$$

or

$$\frac{T_i - T_o}{T_o - E} = \frac{KA}{\rho C_p Q_p}.$$

(III-9)

The convenience of employing the equilibrium temperature concept is evident in the above expression, since it leads to a simplified heat budget with the various transport mechanisms lumped into a single transport coefficient (K), referenced to a single sink temperature (E).

As indicated by Edinger⁽²⁵⁾, the depth of the pond enters into the analysis in a very subtle manner. Letting V equal the volume of the pond, the average detention time of the pond is given by

$$t_d = \frac{V}{Q_p}$$

Solving for Q_p and substituting into Equation III-9, leads to

$$\frac{T_i - T_o}{T_o - E} = \frac{KA}{\rho C_p} \frac{t_d}{V}.$$

(III-10)

Letting V/A = mean depth, d, Equation III-10 becomes

$$\frac{T_i - T_o}{T_o - E} = \frac{K t_d}{\rho C_p d}.$$

In other words, the ratio (t_d/d) is a constant as long as all other parameters are constant.

Equation III-10 indicates that the temperature drop increases with time and increases as the depth decreases. However, as indicated previously, as the depth decreases, the diurnal variation of background pond temperature increases.

The addition of heat by the operating power plant equals

$$H_p = (\Delta T) \rho C_p Q_p , \quad (\text{III-11})$$

where: $\Delta T = T_i - T_o$.

Substituting Equation III-11 into Equation III-9 and simplifying results gives the following

$$T_o = \frac{H_p}{KA} + E . \quad (\text{III-12})$$

Equation III-12 is a very convenient way of solving for the average pond temperature based upon a given plant load and pond surface area once the equilibrium temperature and exchange coefficients has been determined from the meteorological conditions.

2. Slug Flow

Possibly a more realistic representation of cooling pond behavior is depicted by a slug-flow or flow-through pond. As such, the temperature of a water parcel will decrease in an exponential manner from plant outlet to inlet. Under this condition, higher rates of heat rejection occur near the inlet than occur in the vicinity of the outlet.

Using the approach suggested by John⁽⁵⁸⁾ for an element of length dx and surface area dA (assuming no longitudinal mixing), the flux of energy dissipated from the surface is equal to the decrease in the energy of the flow crossing the element. The mathematical model is

$$\rho Q_p C_p dT = -KdA (T - E) ,$$

$$\frac{dT}{T - E} = \frac{KdA}{\rho Q_p C_p} .$$

Integrating over the pond surface area

$$\frac{T_o - E}{T_i - E} = e^{-KA/\rho Q_p C_p} . \quad (\text{III-13})$$

Once again, the depth of the pond can be related as before, and equation III-13 can be written

$$\frac{T_o - E}{T_i - E} = e^{-\frac{Kt_d}{\rho C_p d}} \quad (\text{III-14})$$

Edinger and Geyer(25) have compared the results obtained using Equations III-10 and III-14 for the similar temperature reductions. Table 4 summarizes the findings, and indicates that, for a reduction in temperature of 70%, approximately twice as much area is required for the completely mixed pond.

TABLE 4
RATIO OF AREA REQUIRED FOR COMPLETELY MIXED POND TO THAT OF A FLOW-THROUGH
POND TO PRODUCE THE SAME TEMPERATURE EXCESS UNDER SIMILAR LOADING
AND COOLING CONDITIONS

Temperature Excess Ratio $\frac{T_o - E}{T_i - E}$	Ratio of Areas, Completely Mixed Over Flow-Through A_m/A_f
0.8	1.12
0.7	1.20
0.6	1.30
0.5	1.44
0.4	1.64
0.3	1.95
0.2	2.47
0.1	3.87

3. Internally Circulating Pond

As defined by Edinger⁽²⁵⁾, "Internally circulating ponds are those which exhibit a temperature structure between the plant discharge and plant intake that is more complex than the slug flow pond." (See Section 2, above.) Conceptually, the circulation pattern might be assumed to be principally in the horizontal or vertical plane.

For the case where the circulation pattern lies in the vertical plane, the heated effluent is assumed to flow from the discharge point across the surface of the pond, returning to the intake as an underflow. Such a model is discussed in Reference 25.

For the case where the circulation pattern lies in the horizontal plane, the heated effluent is assumed to flow from the point of discharge to the plant intake, occupying only a fraction of the pond's usable volume and surface area. In the extreme, this has been called channelization. Edinger⁽⁵⁹⁾ has proposed a technique to account for the presence of these relatively stagnant zones on the heat exchange process and evaluate the effectiveness of changing the location of the intake and discharge. Edinger divides the body of water into a "main flow path" and associated "tributary sidearms". Advective exchange with the sidearms are assumed to be negligible. The heat balance within each sidearm is summarized by the basic conservation relationship

$$\text{Heat Spread By Mixing} = \text{Heat Dissipated.}$$

Solution of these ordinary differential equations and matching boundary conditions on temperature at the main flow path produces correction "shape factors" which modify Equations III-10 and III-14. The authors are not aware of any successful implementation of the shape factors to cooling pond design.

4. Physical Models

The use of physical models to study engineering problems has long been recognized as an acceptable means of qualitatively studying various physical phenomena. Because of the difficulties and complexities of analysis mentioned previously, it is not surprising to find physical models applied to cooling pond studies.

It must be recognized that, in order to obtain exact similarity between model and prototype, the geometry, kinematics, dynamics, and thermodynamics

must be accounted for. Although much knowledge has been gained on the subject, our insight into the problem is still very limited. The general subject matter has recently been reviewed quite extensively by Silberman and Stephan⁽⁶⁰⁾. A brief examination of the subject is provided herein. However, the reader should see Reference 56 for a complete discussion of the subject.

Geometric similarity is obtained by expressing a sufficient number of length variables and relating them through appropriate ratios. Kinematic similarity usually involves the consideration of flow patterns and the distribution of flow fields. Once again, normalization is through the selection of appropriate ratios. Hydrodynamic similarity is obtained by modeling the various forces; i.e., the ratio of inertial to gravitational forces is given by the Froude number, inertial to viscous forces by a Reynolds number, and the ratio of buoyancy to the inertial force gradient through the Richardson number.

At the present time, sufficient criteria have not been established to model the entire phenomenon of thermal plume dispersion in both the near and far field using a single model. This results primarily from our present incomplete understanding of modeling turbulent mixing and cooling thermodynamics. It has been accepted for many years in river modeling work, that it is essential to maintain the Froude number relationship between model and prototype. Since it has generally been accepted that buoyancy is an aspect of flow which should be considered, the densimetric Froude number is the one normally employed. As it is almost impossible to satisfy the Reynolds number criterion at the same time as the Froude number criterion, the effect of turbulence is normally retained by introducing a distortion of scales. A distortion of 10 between the horizontal and vertical scales is fairly common.

Modeling of the thermodynamic characteristics in plumes and ponds has received some attention during recent years. It has generally been accepted that the exchange of energy is particularly important in the far field. (Near field effects are dominated by dilution through entrainment.) The major problem, of course, is due to the difference in surface heat transfer rates between model and prototype to obtain the proper thermal balance. To compensate for this factor, variable depth factors have been occasionally introduced, as have artificial laboratory environments^(61,62).

In the near field, physical models are particularly useful. They help to define the entrainment and trajectory of plumes. Physical models can be used for both surface and submerged buoyant jets. Modeling in the near field requires only that the scale be undistorted, that the Reynolds number be large enough to create turbulent flow, and that the Froude number be specified⁽⁵⁶⁾. The primary forces would be either inertial or buoyancy.

The difficulty of using physical models increases as one moves into the intermediate and far field. In the intermediate region, plume behavior is governed by interfacial shear between the fluid layers, the intrusion of fluid due to density disparity, large scale natural turbulence, and, of course, the exchange of thermal energy at the surface. At the present time, we do not have enough knowledge to favor either a purely physical or a mathematical approach.

Analysis within the far field lends itself more to the mathematical approach. However, insight into certain phenomena can best be obtained through empirical observation. An example would be the effect of wind shear and the extent of vertical mixing. Analysis within the far field is largely governed by the exchange of thermal energy at the free surface. Convective and diffusive transport are governed by the natural motion of the pond.

5. Application of Cooling Pond Models

As a result of the National Environmental Policy Act, considerable effort has recently been placed on evaluating, a priori, the effect of cooling pond operation on the surrounding environment. However, to a large extent, the adequacy of these endeavors is unknown, since the vast majority of these cooling ponds and power stations are presently under construction.

Brady et. al.⁽¹⁴⁾ used data from three cooling ponds: Mountain Bayou (Coughlin Station); Smithers Lake (W. A. Parish); and Wilkes Lake (Wilkes Station); to evaluate the surface heat exchange. The lakes were monitored with a number of recording thermometers. Average pond temperatures were computed using weighted averages based upon the relative surface areas around each.

Knowing the prevailing meteorology and waste heat load of the power plants, the exchange coefficient was computed using weekly averaged quantities assuming steady-state conditions. Cooling pond models were not used to simulate pond behavior.

Jaske and Drew⁽⁶³⁾ discuss using the COLHEAT simulation system⁽⁶⁴⁾ to simulate the temperature distribution in Lake Arlington serving the Handley Steam Electric Station. The coolant flow field was determined using measurements collected in situ. Knowing the flow geometry and the plant pumping rate, the model was used to calculate the heat exchange and to estimate the surface temperature distribution within the lake. Comparing measured to observed quantities indicated an agreement to within 0.2°C. Normalization to the 10°C differential from outfall to intake suggests an agreement to within a few percent.

Krause and Woodson⁽⁹⁾ discuss sizing the Calaveros Cooling Lake to accommodate various heat loads. Pond performance or heat dissipation per unit surface area was determined using a model similar to the slug flow model (equation III-13). A number of cooling circuits are compared. A horizontal baffle will be used to withdraw the lower colder water.

Riesbol et. al.⁽⁶¹⁾ discuss using both a physical model and field current measurements to estimate the dissipation of heat from the 850 MW Arkansas Nuclear Inc. plant to be cooled by the Dardanelle Reservoir. The heat dissipation was determined analytically using the energy budget approach and the concept of equilibrium temperature between various cross sections once the flow pattern has been estimated. The flow patterns were based upon natural circulation plus a superimposed discharge momentum jet. A physical hydraulic model was then constructed. Operation of the hydraulic model generally confirmed the analytical approach.

By far the most comprehensive investigation regarding the application and adequacy of cooling pond models is found in Reference 20 where the two basic approaches (Equations III-10, III-14) are expanded to include a linear vertical temperature gradient and effects of transient conditions. For example, the mixed pond case can be studied in either a steady-state or a transient condition, and for each of those the effect of a linear vertical temperature gradient can be included, if desired. Thus, a total of eight possible models were then applied to the five cooling ponds, (Wilkes, Kincaid, Cholla, Mt. Storm, and Four Corners) where data had been collected for verification.

The steady-state slug flow representation was found to best represent the temperatures from the Wilkes Cooling Pond. Temperatures from the Kincaid Lake were found to generally lie between the curves representing solution to the steady-state slug and mixed models. Temperatures for the Cholla Cooling Pond were simulated using the steady-state mixed pond model, assuming that only one-third of the pond's surface area is effectively engaged in the cooling process. Both the Mt. Storm and Four Corners cooling lakes were simulated using the transient slug flow representation. Generally, each of the models was found to calculate the inlet temperature to within $\pm 5^{\circ}\text{F}$ of the measured value. However, the difficulty experienced in applying these models was in knowing before hand which model was suited for a particular pond.

As suggested previously, the completely "mixed-pond model" should be best suited for a condition where the resistance within the pond for mixing is small and/or the pond is relatively large. The "slug-flow model" should be best suited where the geometry causes the mixing to be inefficient (i.e., long and narrow). In Reference 20, a rule of thumb for using the steady-state analysis (III-10, and III-14) is developed as:

$$\Delta t \geq 0.5 \rho C_p \left(\frac{V}{A} \right)$$

where Δt = the time duration (in days) over which conditions are averaged. This can be reduced to the following:

$$\Delta t \geq 3.11d$$

Using this rule and monthly averaged data suggested the following behavior:

<u>Pond</u>	<u>d</u>	<u>Behavior</u>
Wilkes	15	Steady State
Kincaid	12	Steady State
Cholla	5	Steady State
Mt. Storm	40+	Transient
Four Corners	40+	Transient

Figures 6 and 7 show the fit obtained for the Wilkes and Four Corners cooling ponds. Notice that the Wilkes Pond is best simulated using the steady-state slug flow model, as is suggested by using relationship III-14 and examining the pond geometry. The transient model used in simulating the Four Corners pond helps to properly set the phase.

Figure 6. Comparison of Measured and Computed Temperatures at the Wilkes Pond.

Figure 7. Comparison of Measured and Computed Temperatures at the Four Corners Cooling Pond.

IV. ENVIRONMENTAL CONSIDERATIONS

Cooling ponds can interact with the environment in three different ways:

- 1) The infiltration or seepage losses may affect the surrounding groundwater reservoir
- 2) Evaporation and heat exchange may create a condition suitable for the formation of fog
- 3) Make-up demands may be sufficient to overtax the available water supply, thus affecting the other planned water usage.

In this section, a brief discussion of these three aspects is presented. A complete discussion of these aspects is, of course, beyond the scope of the report.

A. INFILTRATION

Infiltration concerns the entry and movement of water in soil. This factor may be an important consideration in the design and location of cooling ponds for the following reasons:

- 1) The effect of recharge to the local groundwater structure may be sufficient to raise the water table elevation, thereby affecting the surrounding land use.
- 2) The potential for contamination of the groundwater reservoir exists.

The importance of groundwater use to total water use in the United States is presented in Figure 8⁽⁶⁵⁾.

A cooling pond can be located either above or within the saturated zone (the saturated zone being the zone below the water table). Furthermore, natural fluctuations of the water table might create a condition where the cooling pond is located within both the saturated and unsaturated zones during different periods of the year. The distinction is important in analyzing the environmental impact of any cooling pond under consideration.

1. Flow Rate

The flow of water through saturated porous media has been studied for many years. In 1856 Henry Darcy (d'Arcy) in a treatise on water supply, reported on experiments of the flow of water through sands. The Darcy law is formulated as

$$v = Q/A = kdh/dL, \quad (IV-1)$$

where: v = velocity (units determined by k)

k = coefficient of permeability or the hydraulic conductivity

dh/dL = hydraulic gradient.

Figure 8. Groundwater Use Relative to Total Water Use

Equation IV-1 is valid, provided the soil column under examination is saturated and the flow regime is laminar. Fortunately, Darcy's law can be applied to most natural groundwater motion⁽³⁵⁾. The coefficient of permeability has been measured for a number of soils. The range of permeability coefficients determined in the laboratory is from 10^6 gal/day/ft² for clean gravels to 10^{-3} gal/day/ft² for impervious clays⁽³⁵⁾. Because of the great range and the heterogeneous nature of natural soil deposits, assessing the flow of groundwater is difficult.

The problem of analyzing the rate of infiltration is further complicated if the pond is above the groundwater table in the unsaturated zone. In saturated flow, the coefficient of permeability, k , depends solely on the porosity of the medium. In unsaturated flow, the problem becomes more complex due to the variation in the coefficient of permeability with moisture content. In treating flow in the unsaturated zone, allowances for this behavior must be included before Darcy's law can be applied. The problem has recently received considerable attention because of the interest in recharging groundwater reservoirs.

It was initially assumed in the analysis of the saturated-unsaturated interface that a uniform infiltration rate causing the recharge was transmitted unchanged through the unsaturated zone. Assumptions of infiltration rates were either based upon the soil composition or measured in test ponds. The effect of this influx was then superimposed or blended into the existing groundwater reservoir. Bouner⁽⁶⁶⁾ investigated groundwater mounds beneath a recharge area by using a resistance network analog.

Only during the last five years has an integrated saturated-unsaturated approach to groundwater recharge problems been attempted. A number of papers, both theoretical and experimental, have been written by soil physicists on one-dimensional, vertical, unsteady, unsaturated flow. Most of the recent theoretical techniques have employed the use of finite differences.

Freeze⁽⁶⁷⁾ has tabulated a number of techniques with respect to the type of formulation, boundary condition and the form of solution. Under the category of problem type (upper boundary condition) it is indicated that five papers treat the case of ponded water. Freeze goes on to propose a model which accounts for both variations in the location of the water table and the elevation head of the pond. The soil is assumed to be isotropic.

Two conclusions reached by Freeze using a sensitivity analysis pertinent to this discussion are:

- 1) The surface head or depth of ponding had a considerable effect on the relative surface infiltration rate. (However, it should be noted that in a study conducted on the Hanford Reservation using a gravel medium, this relationship was found to hold only below some limiting head above which the flow rate remained constant.)
- 2) Estimates of the infiltration and recharge properties of a soil based on a knowledge of the saturated hydraulic conductivity of the soil and its textural classification can be misleading.

More recently, Freeze⁽⁶⁸⁾ describes a numerical model for predicting the transient and steady-state subsurface flow in two and three dimensions, including consideration of both saturated and unsaturated zones. The model considers only convective transport and does not consider dispersion or hydrochemical reactions. Freeze compares the effect of infiltration from a pond by varying the boundary conditions.

In a more comprehensive sense, Cearlock⁽⁶⁹⁾ has discussed a systems approach to the management of the Hanford groundwater basin. This system is composed of three major models, one of which is the hydraulic model. The hydraulic model predicts the flow of groundwater in saturated and unsaturated soils.

Although seepage loss depends upon a number of factors, a rough idea of the magnitude of the situation can be obtained by considering a few specific design seepage loss rates. No attempt will be made to include the details of the individual sites. Estimated seepage loss rates for the Delta Station cooling pond in Cleveland, Mississippi were 4 cfs/1000 acres (35 in./yr)⁽¹³⁾. The estimated seepage loss rate at the Cholla Station cooling pond in Holbrook, Arizona was 5 cfs/1000 acres (44 in./yr)⁽⁷⁾. In a recent study performed for the 1100 MW Hanford Number Two Nuclear Power Station to be located on the AEC Hanford Reservation, equilibrium loss rates of 10 cfs/1000 acres (88 in./yr) were computed⁽⁷⁰⁾.

If it is determined that the seepage loss will have either a detrimental effect on the surrounding environment or that the planned water use is not compatible with the existing regional water use plan, consideration might be given to lining the pond. Depending upon the local soil conditions, the alternatives could range from simply compacting the on-site soil to the selection of an artificial lining, perhaps made from a highly impervious soil. A

pertinent characteristic of clay soils is that some soak up moisture initially, then swell, becoming a dense waterproof layer that will shed water. If as few as 10% of the particles are smaller than 0.074 mm in diameter (No. 200 sieve size), which classifies them as silt and clay, the soil may be virtually impervious, especially when the coarse grains are well graded⁽⁷¹⁾.

2. Linings

In some situations, it might be desirable to add clay to the existing soil; this normally calls for a clay such as bentonite (montmorillonite) to be added to the soil and mixed or tilled into the top few inches. The required quantities can be determined from specifications set with respect to the conditions which make the soil impervious. Bentonite clay can be purchased for \$50/ton. This converts to a few cents per treated square foot of pond surface.

Artificial liners include butyl rubber, polyvinyl chloride, polyethylene, asphalt and concrete. Butyl rubber was recently selected as the liner for the Kualapur Reservoir on the island of Molokai (Hawaii)⁽⁷²⁾. One-hundred-ten acres of 1/32-inch butyl rubber sheets were installed at a unit cost of 23 cents per square foot.

Asphalt has been used to line canals and reservoirs⁽⁷³⁾. The procedure calls for first placing a continuous asphalt membrane, then covering the membrane with a layer of local soil, gravel, or asphalt macadam to hold the layer in place. At least 1.5 gallons of asphalt/square yard are required to assure a continuous waterproof layer. Asphalt has also been used to prevent erosion of pond banks resulting from wave activity. Seemingly, concrete could be used in a similar manner. Aside from the high cost, the difficulty in using either asphalt or concrete would be the apparent irreversible commitment of the resource.

B. FOGGING

A drawback to using cooling ponds and towers is the potential increase in fog formation. Although cooling ponds are less of a problem in this respect than towers, fogging is still undesirable and, in some instances, can be dangerous.

Fog results from the condensation of atmospheric water vapor into water droplets that remain suspended in the air in sufficient concentration to reduce visibility. Saturation of the air and the presence of sufficient conden-

sation nuclei are usually a necessary precondition for fog formation. However, if proper condensation nuclei are present in sufficient quantity, fog may form when the relative humidity is below 100 percent.

There are several ways that fog may be formed. Two types most common to the air-water interface are advective and steam fog. Moist air flowing over cold water frequently creates conditions suitable for the formation of advective fog. The exchange of heat from the air to the water reduces the temperature of the air, thereby reducing the atmospheric capacity to hold water vapor. If the process continues long enough, the air will eventually approach saturation and condensation will occur. The vertical structure of the fog layer is stable since the cold, dense air is located at the bottom of the air column.

Steam fog, on the other hand, is initially unstable. This type of fog is produced by intense evaporation from a water surface into relatively cold air. The condition of water vapor to the air mass creates a relatively buoyant plume. In the presence of a stable layer aloft, the fog will become stable and persist. If there is no layer inhibiting vertical motion, the fog will dissipate rapidly.

It has been mentioned that ponds dissipate heat primarily through the processes of evaporation and back-radiation. Since cooling ponds generally operate at temperatures 5 to 10°F above the equilibrium temperature, the type of fog most common to cooling ponds would be steam fog. However, it must be recognized that, under conditions where cooling ponds are sited close to and upwind of large water bodies, the potential for the formation of advective fog may be significant. Therefore, when planning a cooling pond, particular attention should be given to the topographic features of an area and the effect upon local meteorology of the proposed pond. Valleys with valley-induced inversions⁽⁷⁴⁾ that create relatively stagnant air pockets could significantly increase the potential for fog. In addition, where cold temperatures dominate for extended periods of time, the potential for fog will also be high. A qualitative feel for adverse effects resulting from fog formation over cooling ponds can be obtained through examination of Figure 9 which depicts the potential for fog formation. Statistically, these potentials are defined as⁽⁷⁶⁾:

High Potential - Region where heavy fog is observed over 45 days per year, where during October through March, the maximum mixing depths are low (400 to 600 m), and the frequency of low level inversion is at least 20 to 30%.

Figure 9 Geographic Distribution of Potential Adverse Effects from Cooling Towers, Based on Fog, Low-Level Inversion and Low Mixing Depth Frequency (Ref. 75)

Moderate Potential - Region where heavy fog is observed over 20 days per year, where during October through March the maximum mixing depths are less than 600 m, and the frequency of low-level inversion is at least 20 to 30%.

Slight Potential - Region where heavy fog is observed less than 20 days per year, and where, October through March, the maximum mixing depths are moderate to high (generally greater than 600 m).

Fog formation and persistence depends on the following factors: wind speed, vertical air stability, relative humidity, air temperature and water temperature. No models used specifically for predicting the formation of steam fog in the vicinity of cooling ponds are available, although there are some allusions to techniques employing diffusional analysis⁽⁷⁴⁾.

It is assumed that one procedure employed to compute fog formation and persistence for ponds is similar to the technique suggested to compute fog formation in the vicinity of evaporative cooling towers^(75,76). Such a technique normally consists of applying Pasquill's Diffusion Equation in the form

$$\bar{c} = \frac{Q^*}{2\pi\sigma_y\sigma_z u'} \exp \left[-\frac{z^2}{2\sigma_z^2} - \frac{y^2}{2\sigma_y^2} \right] \quad (\text{IV-2})$$

where:

Q^* = rate of release of the effluent

u' = ambient wind velocity

σ_y = variance of the horizontal concentration distribution

σ_z = variance of the vertical concentration distribution.

Equation IV-2 assumes an infinite diffusion medium in the y and z direction. The diffusion relationship is assumed to govern once the buoyant convective motion of the plume is sufficiently suppressed due to the entrainment and mixing with the ambient air. In the case of tower plume rise, this is commonly applied at the point where the vertical rise diminishes. The plume diffuses downwind in accordance with this equation. Estimates of the variance in the horizontal and vertical directions can be obtained using Figures 10 and 11. The stability is based upon the prevailing wind conditions⁽⁷⁷⁾.

The occurrence or non-occurrence of fog (condensed vapor) can be determined using a method suggested by Taylor⁽⁷⁸⁾ which is based upon a plot of mixing ratio (mass of water vapor to mass of dry air) versus temperature, such as Figure 12. The area below the saturation curve represents unsaturated air, whereas the area above the curve represents an excess of water vapor and, as a result, condensation. To use Figure 12 in this sense, let point A represent

Figure 10 Horizontal Dispersion Coefficient as a Function of Downwind Distance from the Source (from Ref. 77)

Figure 11. Vertical Dispersion Coefficient as a Function of Downwind Distance from the Source (from Ref. 77)

Figure 12. Taylor Graphical Method for Calculating Liquid Water Content (Ref. 78)

the mixing ratio and temperature of the ambient air. As this air mass moves into the zone directly above the pond, the humidity of the air increases. This is accompanied by a small change in temperature due to the transfer of sensible heat and the release of latent heat in the process of condensation. The air mass is now at point B. The line B-C represents the mixed state. The location of C depends upon the relative amounts of the two mixtures. The length of line, C-D, gives the amount of liquid matter in the mixture (provided that all the excess water vapor condenses). As the air mass is carried away from the pond, its mixing ratio is decreased through the process of diffusion until the air parcel once again becomes unsaturated. If the process continues unchecked, eventually the air parcel will return essentially to its original state.

The concentration of condensed water vapor can then be related to the reduced visibility through Figure 13. Reduced visibility in fogs is a function of both liquid water content and droplet size. The droplet size depends on a number of factors and will not be discussed herein. A discussion of the interaction of droplet size and liquid water content on reduced visibility has been presented by Eldridge⁽⁷⁹⁾ for stable fogs. Assuming a droplet radius of 5 microns, Table 5 summarizes visibility as a function of liquid water content⁽⁷⁶⁾.

TABLE 5 (ref. 76)

VISIBILITY AS A FUNCTION OF WATER CONTENT

Visibility (mi)	Liquid Water Content (g/Kg)
1	0.007
3/4	0.009
1/2	0.013
1/4	0.026
1/16	0.053

In practice, however, the graphical analysis presented previously will not permit distinction between such small quantities. Therefore, it should be assumed that fog will persist, inhibiting visibility to the point at which the mixture line crosses the saturation line. Using this as the governing criterion, the zone of influence can then be determined, based on the local meteorological condition for the particular cooling system under examination. The frequency of occurrence, of course, is based on the particular probabilities assigned.

Figure 13. Visibility as a Function of Liquid Water Content in a Stable Fog (modified from ref. 79).

The zone of influence should be reviewed with respect to the surrounding land usage such as highways, airports, and population centers.

As suggested, the application of the diffusional technique follows from the point at which the source momentum has become sufficiently suppressed. It has become common to employ entrainment techniques to analyze plume behavior in the region where momentum dominates plume behavior. To our knowledge, this type of analysis, or, for that matter, any other type of analysis, has not been employed to analyze the convective motion from the surface of a cooling pond. Although these techniques have been employed to analyze the behavior of cooling tower plumes^(75,80), both of these studies employ the basic cumulus model equation presented by Weinstein and Davis⁽⁸¹⁾.

It would be advantageous to be able to localize fogging to the vicinity of the pond. In the case of cooling towers, burners and heating coils have

been used successfully to dissipate fog^(82,83). Application of a similar technique to cooling ponds would be difficult, if not impossible. One means of containing the fog is to plant a belt of trees around the perimeter of the cooling pond. The trees could enhance precipitation of the fog which would, in turn, serve as a source of moisture for the trees⁽⁸⁴⁾. In certain regions, this might be a worthwhile consideration.

It is typical of some northerly arid regions to have fog in the winter but an over-all shortage of water to sustain tree growth. From information contained in a feasibility report concerning raising sycamore on a commercial basis at Hanford, Washington⁽⁸⁵⁾, it was determined that the irrigation requirements during the month of July of a 200-foot wide forest belt surrounding a cooling pond sized for a 1000 MWe nuclear plant would be 0.25% of the coolant flowrate. The water consumption would not differ greatly for a coniferous tree belt, which would be a more suitable precipitating agent in the winter months.

It has been shown that, by introducing hygroscopic materials to a stable liquid water cloud, the distribution of drop size can be modified and, under certain conditions, this may lead to an improvement in the visibility⁽⁸⁶⁾. Although primary attention has been directed to using sodium chloride, experiments have been conducted using phosphates and urea. In theory, the hygroscopic particles are introduced into the top of the fog layer and allowed to fall through. A simulation model of this process has been proposed by Silverman and Kunkel⁽⁸⁷⁾. The model predicts the growth of the hygroscopic particles from condensation, lowering the ambient vapor pressure as they consume water vapor. The falling hygroscopic particles also grow by coalesce as they remove liquid water from the fog. The remaining fog droplets evaporate in response to the vapor pressure deficit created. Using the model, Kunkel and Silverman⁽⁸⁶⁾ compared the clearing capabilities of some hygroscopic materials. A summary of their findings is shown in Table 6. As indicated, the hydroxides appear to be the most effective materials in removing fog, followed by chlorides, bromides, nitrates, iodides, and sulfates. In practice, considerations of cost and corrosiveness of some of these materials would override effectiveness. The hydroxides and chlorides tend to be either caustic or corrosive; therefore, urea and ammonium nitrate are the most

TABLE 6

THE TEN MOST EFFECTIVE WARM FOG SEEDING MATERIALS
Taken from (Ref. 86)

Constant Volume 2000 part/cm ²		Constant Mass 2.834 gm/m ²	
Material	Visibility Improvement %	Material	Visibility Improvement %
LiOH	26.8	LiOH	56.2
NaOH	24.6	NH ₄ Cl	28.2
LiCl	23.2	LiCl	25.7
LiBr	16.7	NaOH	25.3
NiCl ₂	14.8	KOH	18.0
KOH	14.6	NaCl	13.7
NaCl	13.7	Urea	12.8
CoCl ₂	13.6	Na ₂ HPO ₄	11.7
MgCl ₂	13.1	NH ₄ NO ₃	11.5
LiNO ₃	12.7	KCl	11.3

practical, since they are neither corrosive nor caustic and are relatively inexpensive⁽⁸⁰⁾.

Another way in which fog might be retarded is by treating the condensation nuclei with a surface film. The use of long-chain alcohols for the prevention of fog formation was suggested by Jinsto⁽⁸⁸⁾. In a study conducted by Warner and Warne⁽⁸⁹⁾ cetyl alcohol was used; these authors suggest that a small amount of cetyl alcohol (few tens of kilograms) could prevent the formation of a fog for some ten minutes over airports. However, there is the danger that, if cooling continued, the fog which eventually did form would be worse than if no cetyl alcohol had been added.

C. HYDROLOGIC CONSIDERATIONS

The evaporative make-up requirements for a power reactor cooling pond ranges from approximately 0.01 cfs/acre to 0.07 cfs/acre. In other terms, this suggests a consumption ranging from approximately 0.5 to 3.5 gal./Kw-hr. Cooling water make-up must be obtained from either the surrounding hydrology, surface and groundwater reservoir, or reclaimed from other uses. Of primary consideration when planning for the operational make-up water needs of a steam-electric power plant, is to assure that the over-all water use scheme is compatible with the surrounding water use plan.

Make-up water requirements have been obtained directly from surface runoff, surface water reservoirs, groundwater reservoirs, coastal waters, and, on a few occasions, reclaimed from other industrial and domestic uses. In water-deficient areas, sewage treatment plant effluents have been used to provide make-up requirements⁽⁹⁰⁾.

The Nichols Power Plant in Amarillo, Texas uses sewage effluents for make-up tower losses. The effluent is first treated to reduce concentrations of trouble-making chemicals. Initial treatment costs run about 22 cents/1000 gallons; these are expected to decrease in the future⁽⁹⁰⁾. Normally, the cost of providing domestic water ranges from approximately 5 to 40 cents/1000 gallons. To our knowledge to date, sewage effluent has not been used directly for cooling pond make-up water.

The total volume or capacity of the system should be designed with the appropriate limiting factors clearly in mind. The designer must be cognizant

of such factors as: those systems which obtain their make-up water from surface runoff; the demand must be compatible with downstream usage; when public lakes and reservoirs are employed, attention must be given to drawdown and its possible effect on recreation; when salt water is used, care should be given to infiltration and its potential effect upon the surrounding potable water supplies, etc.

D. RECREATION

According to the 1960 and 1962 reports of the Outdoor Recreation Resources Review Commission, 90% of Americans who seek outdoor recreation do so in some association with water. Presently, swimming is the second most popular outdoor recreational activity, and by the year 2000, trends indicate that it may be first. Boating and fishing are also in the top ten. In some states, it is strongly recommended that cooling lakes become recreational areas open to the public. In such cases, the quality of the water must meet the state water quality standards⁽⁹¹⁾ for that specific recreational use.

If the water is to be used for swimming, it must meet temperature and pH standards. For any swimming, the water should be no hotter than 90°F, and for prolonged swimming, 85°F. The pH of the water should be between 6.5 and 8.3. Table 7 shows environmental conditions for a typical cooling lake⁽⁹³⁾. The surface water pH of this "typical" pond does not meet these pH standards.

TABLE 7
TYPICAL COOLING LAKE ENVIRONMENTAL FACTORS ⁽⁹³⁾

Depth (ft)	Temp (°F)	Dissolved Oxygen (ppm)	pH
60	67	2.9	7.8
50	74	4.8	8.4
40	76	5.8	8.4
30	77	6.0	8.4
20	77	6.4	8.4
10	78	6.7	8.4
Surface	81		
Intake	75		
Discharge	93		

Fish raising on a recreational basis has been tried at the cooling lake of the 1200 MW Commonwealth Edison Kincaid Plant. The lake has been donated to the State of Illinois as a State Park. Initially stocked with bass, the

lake now successfully supports 12 species of fish⁽⁹²⁾. On a recreational level, the pollution problem is no greater than that in any natural lake. Problems might develop with fish screens, but this problem also exists in the typical once-through system.

In order to ensure the survival of the fish and to meet the requirements set up in the Water Quality Criteria report of the Federal Water Quality Administration⁽⁹¹⁾, temperature and oxygen content specifications have to be met. Table 8 defines maximum temperatures recommended for raising various species of fish. These values can be compared with the temperatures calculated for average pond conditions during January and July in Miami, Florida and Seattle, Washington as shown in Table 9. Utilizing such a comparison indicates that the species of fish listed in Table 8 could not be raised in Miami in a pond allowing one acre/MWe. In certain regions of the remaining three cases, some species of fish could be raised. However, further research should be undertaken to determine the need to restrain fish from entering regions that are too warm for proper development. G. J. Eicher⁽⁹³⁾ suggests that, in deep ponds, only the surface will be hot and varieties of fish can be raised in the cooler, deeper portions of the lake. On the other hand, Nakatani⁽⁹⁴⁾ notes that fish have been observed to congregate in temperature regions which are barely tolerable, such as in power plant out-flow structures. It has been observed at the Cholla cooling pond that fish migrate between the hot and cold portions of the pond with relative ease⁽⁹⁵⁾.

TABLE 8 (91)

PROVISIONAL MAXIMUM TEMPERATURES RECOMMENDED AS COMPATIBLE WITH THE WELL-BEING OF VARIOUS SPECIES OF FISH AND THEIR ASSOCIATED BIOTA

93°F	- Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.
90°F	- Growth of largemouth bass, drum, bluegill, and crappie.
84°F	- Growth of pike, perch, walleye, smallmouth bass, and sauger.
80°F	- Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.
75°F	- Spawning and egg development of largemouth bass, white and yellow bass, and spotted bass.
68°F	- Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.
55°F	- Spawning and egg development of salmon and trout (other than lake trout).
48°F	- Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

TABLE 9
COOLING POND TEMPERATURE DIFFERENCES
GIVING INLET AND OUTLET TEMPERATURES IN °F

	Miami	Seattle
1 acre		
January	96 to 76	75 to 55
July	112 to 92	101 to 81
2 acre		
January	90 to 70	64 to 44
July	107 to 87	94 to 74

In addition to pH, Table 7 also lists the probable temperature distribution and oxygen content of a typical deep cooling lake, as a function of depth. The Water Quality Criteria report⁽⁹¹⁾ states that warm water biota require 5 ppm and cold water biota, 7 ppm of oxygen. Therefore, the typical pond described in Table 7 would be inadequate for cold water biota not only because of temperature level but also because of oxygen content. Spray systems, including the rotating disc cooling method developed by Cherne Industrials⁽⁹⁶⁾, placed at the plant outfall, have been recommended as a means of increasing the dissolved oxygen content.

One source⁽⁹⁷⁾ predicts a 50% increase in the number of fishermen (and related expenditures) between 1980 and 2000. While the desire for this recreational activity is increasing, the available locations have been decreasing. Cooling lakes, stocked with fish, could reverse this situation. In addition to increasing the potential for fishing, cooling lakes can also serve as new locations for water fowl and other game. Montrose Lake, used as a cooling pond for a steam plant operated by Kansas City Power and Light Company in Missouri, has been leased to the Missouri Game Commission which rents duck blinds to a limited number of hunters⁽⁹³⁾.

Further recreational possibilities have been proposed; these include permanent and temporary lake shore dwellings and marinas, as well as bathing, fishing and hunting facilities surrounding power plant cooling ponds. While offering these opportunities to the public may serve to improve the image of the utility, difficulties may arise from requirements of stricter safety standards and, perhaps, in convincing the public of the safety of using such recreational facilities.

V. SPRAY PONDS

There are two major reasons for considering the use of a spray pond. First, the land required for the spray pond is far less than that required for a cooling pond; secondly, the total rate of evaporation is less. While these advantages are important, they have apparently been overshadowed by disadvantages, since there are few plants using spray ponds, and the existing ones are used in conjunction with other cooling methods. In 1969, only nine utilities specified spray ponds as a means of cooling water⁽¹⁾. Six of these plants were constructed prior to 1930 and five have power ratings under 100 MWe.

The important feature of a spray system is the increased heat transfer rate per unit of pond surface area. For relatively small areas, the transfer rate is given as 2,600 to 5,500 Btu/hr/ft² by a Russian source⁽⁹⁸⁾ and 4,000 to 10,000 Btu/hr/ft² by Western data⁽⁹⁹⁾. In comparison, this is about 20 times greater than the rate associated with a normal cooling pond.

A. SPRAY POND CALCULATIONAL MODELS

In general, calculational methods for evaluating spray pond performance or for spray pond design are based either on overall mass and energy balances, or on consideration of the resistance of the film to heat transfer with inclusion of experimentally determined film coefficients. These two methods can be applied to a variety of specific situations involving different spray techniques and layouts, either alone or in conjunction with other cooling methods.

The overall mass and energy balances for a spray pond can be written as follows:

$$Lh_i - (L - E_v)h_o = G(H_o - H_i) , \quad (V-1)$$

$$E_v = G(r_o - r_i) \quad (V-2)$$

where: E_v = evaporative loss rate
 L = water flow rate, lb/ft²-hr
 h_i = enthalpy of water in
 h_o = enthalpy of water out
 G = airflow rate

H_o = enthalpy of air out

H_i = enthalpy of air in

r = humidity ratio.

Simultaneous solution of these equations is complicated by the fact that the enthalpy of moist air is not a linear function of temperature or of water content. As a result, some form of iterative technique is commonly employed. Scofield and Frazzolare⁽¹⁰⁰⁾ approach the problem by first recasting the energy balance to permit a solution for the exit air enthalpy:

$$H_o = H_i + \frac{L}{G} (h_i - h_o) + \frac{E}{G} h_o. \quad (V-3)$$

The exit air enthalpy can then be used to find the corresponding wet-bulb temperature and correction factors applied to determine the cooled water temperature. The iterative process involves assumption of the cooled water enthalpy, and its subsequent calculation using the method just outlined. When the assumed and calculated values agree, the evaporation can be computed from the mass balance. Subsequent iterations may be used to establish the evaporation more precisely; however, it has been found that the result is relatively insensitive to this term and that further iteration is generally not needed.

Scofield and Frazzolare do not describe in detail the methods used to relate exit air enthalpy to cooled water temperature. A number of approaches, each with its own assumptions, could be used. As an example, one might assume that the cooled water temperature is equal to the exit wet bulb temperature. This would produce a generally conservative result.

The alternative approach is to consider the resistance to heat flow presented by the air-water interface. First, the heat transferred by conduction and convection is given by:

$$dQ_c = K_e (T_w - T_a) A' dV,$$

where: A' = surface area

K_e = exchange coefficient

V = volume

The mass transfer due to evaporation is given by:

$$dL = K_x (r' - r) A' dV,$$

where: r = humidity ratio

r' = saturation humidity ratio at water temperature

K_x = exchange coefficient, similar to K_e , but in appropriate units for use with humidity ratios.

Since the water evaporated carries with it an enthalpy, H_v , the heat transferred by evaporation is

$$dQ_e = K_x H_v (r' - r) A' dv$$

It is convenient to relate the energy and mass exchange coefficients through the Lewis Number.

$$Le = \frac{K_e}{CK_x}$$

Substituting for the humid heat, C , and rewriting, one obtains:

$$K_e = Le K_x (C_a + C_v r),$$

where: C_a , C_v = specific heat of air and vapor

Now, combining the two heat transfer equations to obtain the total heat transferred and substituting the exchange coefficient, the total heat transferred can be expressed as

$$dQ = K_x A' dV H_v (r' - r) + Le (C_a + C_v r) (T_w - T_a). \quad (V-4)$$

After considerable rewriting, this may be expressed as

$$dQ = K_x A' dV (H' - H + \delta)$$

$$\delta = K' (H_v - H') + Le C_v (T_w - T_a) - (1 - Le) (T_w - T_a) C_a,$$

where H' = enthalpy at saturation value

The quantity δ may be neglected, as it is quite small. A simple heat balance gives

$$dQ = LC_p dt.$$

Equating this to the previous expression for total heat transferred yields, after some rearrangement and integration

$$\frac{K_x A' V}{L} = C_p \int_{T_w \text{ out}}^{T_w \text{ in}} \frac{dt}{H' - H} = N_1. \quad (V-5)$$

The integral gives the number of times the average potential, or driving force, may be divided into the total heat transfer required. It is therefore the number of "transfer units" (more appropriately diffusion units) in the process, where the concept of a transfer unit is analogous to that introduced by Colburn⁽¹⁰⁾ as a measure of the number of interphase equilibrium changes required to effect a given amount of diffusion.

Experimental evidence indicates that the quantity $K_X A'$ may be approximated by $C_1 G^n$. Furthermore, for cooling tower packings it has been found that $(K_X A'/L)$ may be approximated by $C_2 (G/L)^n$. In either case, the value for n lies between roughly 0.45 and 0.65. The value of this fact is that a measured value of $K_X A'$ may be used under substantially different climatic conditons provided the ratio G/L does not change. Kelley⁽¹⁰²⁾ capitalizes on this by approximating the integral as

$$N_i = \frac{t_i - t_o}{H'_w - H_i},$$

so that

$$\Delta t = t_i - t_o = N_i (H'_w - H_i).$$

Then, Kelley uses this in an arrangement where the water is cooled in stages by spraying a portion and mixing the cooler, sprayed water with the rest before passing to the next spray device.

Pita⁽¹⁰³⁾ has attempted a similar approach, giving considerable attention to the exchange coefficients. The energy exchange by evaporation is also given by

$$dQ = H_v K_T (e_w - e_a) A' dV = LC_p dt.$$

This can be approximated by the expression

$$\Delta h K_T A' (e_w - e_a) = LC_p \Delta t$$

or

$$\Delta t = \frac{\Delta h (e_w - e_a)}{C_p} \frac{K_T A'}{L}.$$

This is the basic expression used by Pita. His work has led to a relationship for $K_T A'/L$ that is related to the geometry of the system. The relationship is

$$K_T A'/L = B(Re)^m \left(\frac{\ell}{D}\right)^r \left(\frac{P}{p}\right)^s, \quad (V-6)$$

where P = ref. pressure

P_w = water supply pressure

Re = Reynolds number

ℓ = geometric length of trajectory of spray

D = drop diameter

K_T = exchange coefficient in units appropriate to vapor pressure

and experimental evidence indicates that the appropriate values for m , r , and s are -0.55, 0.45, and 0.50, respectively.

B. SPRAY POND CONCEPTS

A recent resurgence in the interest regarding the use of spray ponds to cool steam electric power stations has resulted in a number of new concepts.

Moore⁽¹⁰⁴⁾ discusses using a 10 acre spray pond to temper the cooling water from the 450 MWe Canadys Power Station in Canadys, South Carolina. The spray pond was constructed entirely of earth sides and bottom and occupies an area formerly used for ash disposal. The water is discharged from the bottom of the spray pond at a temperature within 5°F of the ambient Edisto River temperature. The cooling water is aereated to increase the dissolved oxygen content before its return. The system has also been discussed by Malkin⁽¹⁰⁵⁾.

Kelley⁽¹⁰²⁾ discusses the application of a central system which operates the spray pumps based upon meteorologic and hydrologic data. The spray units consist of a number of floating spray pump modules which form droplets with a mean size ranging from 0.38 to 0.50 in. The larger drop size provides adequate cooling without causing objectionable drift. Detroit Edison and Pacific Gas and Electric are presently considering installing such units.

Spinning discs have been proposed by Cherne⁽⁹⁶⁾ as a means of forming spray droplets. A variable-flow hydraulic system is used to control the cooling rate, i.e., droplet size, and trajectory. Measurements and calculations indicate the droplet approach to wet bulb temperature was about 6°F and the cooling rate was about 300,000 Btu/hr/disc. It is estimated that a 42-acre cooling pond could serve a 500 MW nuclear unit. A demonstration unit has been installed at the Allen King Power Plant in Minnesota.

VI OPERATIONS

As suggested in the introduction, two advantages of cooling ponds over other closed systems are: 1) cooling ponds serve as a settling basin for suspended solids; and 2) cooling ponds can operate for extended periods of time without requiring make-up water. A disadvantage listed was that ponds tend to concentrate dissolved solids. By performing mass and energy balances on the overall system, the requirements for make-up water can be easily estimated. If the degree of deposited solids becomes extensive, it is conceivable that the pond would require some form of dredging. However, the authors are unaware of such practice in the operation of cooling ponds. The concentration of dissolved solids might require special control through the use of chemicals.

To avoid pumping over-cooled water through the condenser, a bypass is frequently constructed. The bypass allows for a portion of the heated discharge to re-enter the intake water, thus maintaining a more constant condenser temperature.

The cooling pond bypass is also used for keeping the cooling system free from the formation of ice during winter overhauls. On these occasions, an auxiliary pump is used to keep the water circulating through the system. Heaters might also be added, if required.

The major concern, however, in operating cooling ponds, as the case for using any industrial cooling water, is to provide cooling water of the proper quality. In Chapter III of this report, the problems associated with mathematically describing the multi-dimensional characteristics of a cooling pond were discussed. As indicated in Appendix A, the different sources for cooling water are numerous. In practice, the program outlined for water treatment normally consists of performing an analysis on the particular water utilized to hopefully establish the least expensive and most effective means of treatment⁽¹⁰⁶⁾. A program for water treatment is then prescribed and periodically reviewed.

Treatment of cooling water in general is designed to prevent the following two problems:

- 1) Deposits - which can form on the surfaces over which it flows interfering with the transfer of heat and impeding circulation.

2) Corrosion - which can destroy equipment.

It is difficult to identify what type of water causes one or the other of these two problems. In fact, one problem usually brings on the other⁽¹⁰⁶⁾. In the secondary cooling cycle, primary attention has been directed towards preventing deposits formed by the growth of micro-organisms. However, on occasion, corrosion inhibitors, such as phosphates, have been introduced. Controlling the pH has also been undertaken on occasion; this has a significant effect upon the corrosion rate⁽¹⁰⁷⁾.

Laboratory and in-plant analyses are essential for preventing deposits due to microbiological growths. The important steps for microbiological control are:

- 1) Systematic cleaning and plant sanitation
- 2) Elimination of stagnant areas
- 3) Proper use of a biocide material, including "slug" or shock treatments.
- 4) Use of an antifoulant
5. Variation according to fluctuations in season, cooling load,⁽¹⁰⁶⁾ water acidity, etc.

The growth of organisms on the surfaces of water cooling system components ranges from scaling by biological slimes to system blockage by larger organisms such as mussels. Slime-forming micro-organisms include bacteria, algae, fungi and diatoms. Besides forming scale, some of these organisms release acids and gas which change the pH, leading to possible corrosion⁽¹⁰⁶⁾.

To date, the most popular form of microbiological control has been through the use of chlorine. The chlorine is normally introduced at the intake of the cooling system.

The larger organism can, at times, be screened. About 95% of the plant growth that becomes uprooted and floats to the surface is removed by the intake screens at the Cholla Power Station.

Larger organisms, such as mussels, have been removed through the use of chlorine. When dealing with mussels, the process becomes more effective as the temperature of the cooling water is increased.

Table 10 summarizes the annual amount of chemicals added to ~ 40 cooling ponds as reported to the Federal Power Commission⁽¹⁰⁸⁾. As indicated, chlorine

is by far the most important chemical added. On the average, the dosage ranges from approximately 0.2 ppm to less than 0.01 ppm. In some instances, it is evident that an occasional "slug" of chlorine used is used only as a biocide. For a few of the cooling ponds, no treatment was listed. On occasion, alum, which is normally looked upon as a flocculant, was employed.

TABLE 10
ANNUAL CHEMICAL USE BY SELECTED STEAM ELECTRIC POWER STATIONS
OPERATING COOLING PONDS AND LAKES

Plant	Flow (cfs)	Chlorine (lb)	Phosphate (lb)	Alum (lb)	Caustic Soda (pH) (lb)	Sulfuric Acid (lb)	Lime (lb)
Cholla	180	76,700					
4-Corners	1082	108,000					
H. F. Lee	346	62,000					
Asheville	200	6,000*					
Roxboro	870	24,000					
Coffeen	325	112,000					
Coughlin		6,600	7,300	33,000			
Braunig	445	145,500					
Kincaid	535	86,826					
Dallas		30,000	14,300				
Mountain Crk	980	46,000					
North Lake	900	4,000					
Parish	1660	320,000					
Baldwin	720	50,000					
Fox Lake		2,950					
Montrose	765	65,900					
Comal	200	54					
Sim Gideon	500	32,000					
Aurora	186	9,230					
Delta	308	8,000					
Rex Brown	354	2,000					
Horseshoe Lake	1175	30,250				3,581,380	
Cameo **	75	892*					
Valmont	467	3,783					
Ft. Churchill	103	3,650					
Canadys	600	120,000					
Knox Lee	435	3,800					
Lieberman	416	600					
Lone Star	122	8,000					
Wilkes	490	16,000			30,000		
Eagle Mt.	323	34,000					
Graham	753	57,808					
Handley	755	74,000					
Morgan Creek	276	66,000					
Lake Creek		20,000					
Lake Pauline	556	12,000					
Oak Creek	90	4,400	500	150			600
Paint Creek	183	6,000					
San Angelo	174	13,000					

* gal Sodium Hypochloride

** Cameo plant is essentially once-thru 90 of the time

VII. ECONOMICS

The interest in cooling pond costs (as in all alternate cooling systems) is in the incremental costs over those of a once-through cooling system. The costs normally discussed include capital costs, operating costs, and combination of the two, such as additional plant capacity to account for capability loss in the turbine resulting from operating at higher water temperatures. More recently, interest in the environmental and commercial cost factors of cooling ponds has been voiced. However, these costs are extremely difficult to quantify at the present time.

In the discussion that follows, we will not discuss the costs associated with transporting fuel, nor will we discuss variations in local construction costs or the cost of shipping components.

A. CAPITAL COSTS

As mentioned in the introduction, cooling ponds are generally considered attractive when land is available at a reasonable price and the terrain is suitable. The incremental cost associated with the construction and use of a pond is less than the cost of constructing a wet tower in these cases.

Table 11 summarizes the material presented in References 109, 110, 111 and 97. In most cases, comparison of seven different cooling systems were presented. As indicated from Table 11, the range in cooling pond incremental cost is from 0 to 4 \$/KWe for a nuclear fueled reactor. Costs for a fossil fueled plant would be approximately one-third less. The range in costs results primarily from the different assumptions regarding the availability of land. Kolflat⁽⁹⁷⁾ allows the possibility of a zero capital cost increment, which implies the use of a pre-existing reservoir or natural lake for the cooling pond. Jameson⁽¹⁰⁹⁾, on the other hand, defines a cooling pond as a structure, constructed by diking and/or damming for the use of the facility requiring purchase of the land. Another factor which might have affected the analysis was the size of the power plant selected.

For a comparison, the land and land rights costs published in Reference 1 for power plants which use cooling ponds, lakes, and reservoirs were reviewed. Table 12 summarizes the capital cost of 26 steam electric power stations which utilize cooling ponds⁽¹⁰⁸⁾. Unit cost of \$/KWe and \$/acre are provided.

TABLE 11
CAPITAL COSTS, COOLING SYSTEMS

Cooling System	Estimates, \$/KWe, Nuclear			
	Hauser	Woodsen	Jimeson +	Kolflat ++
Once-Through:				
Fresh	Base	Base	Base	Base
Salt	1.68	-0.25°	----	----
Recirculated:				
Cooling Pond:	1.65	2.8	3.- 4.*	0**- 3.
Wet Tower:				
Mechanical	3.93	2.5	5.- 6.	2.9- 4.
Natural	6.18	8.3	6.- 8.	6.2-10.
Dry Tower:				
Mechanical	21.9	21.3	23.	20.5-27.
Natural		53.4	25.-27.	37.0-55.0
Date of Publication	1-70	5-71	6-71	4-71

- + Does not include condenser differences costs.
- ++ Initial lower range, taken to be fossil, has been raised to reflect higher cooling costs for nuclear facilities.
- ° Includes cost differences of condensers.
- * Assumes construction of dikes or dam to provide pond capable of cooling a 1200 MW plant.
- ** Allows use of existing reservoirs.

These units costs can, of course, be misleading for a number of reasons, one of which can be that additional units may be planned. Figure 14 shows land rights costs in dollars per KWe plotted against the year of plant start-up. The land and land rights costs range from approximately 0.01 to 10.5 for the forty plants surveyed. Aside from the one outlier, the range is from 0.01 to approximately 6, which compares well with the summary provided in Table 11. It is interesting to note that, in some cases, even when a reservoir existed for use, the land costs for the plant alone and land rights for access to the reservoir ran into several millions of dollars.

Table 13 gives a breakdown of the average costs associated with the various components of a cooling pond^(97,110). As indicated, approximately 2/3 of the cost is associated with the cost of the condenser auxiliary pump

Figure 14. Power Plant Land and Land Rights Costs, versus year in which Operation Commenced

TABLE 12
CAPITAL COSTS OF SELECTED COOLING PONDS

PLANT	1970 CAPACITY (MWe)	SURFACE AREA (ACRES)	CAPITAL COST OF COOLING POND (\$)	UNIT COST		COMMENTS
				\$/KWE	\$/ACRE	
ASHEVILLE	206	320	1,366,000	6.631	4269	Unit 3 Only 1971 Capacity
H. F. LEE	252	575	1,308,000	5.190	2275	
H. B. ROBINSON	906	2145	4,800,000	5.298	2238	
ROXBORO (a)	1067	3750	4,831,000	4.528	1288	
BRAUNIG	885	1250	4,717,000	5.330	3774	
KINCAID	1319	2400	3,819,000	2.895	1591	
MT. CREEK	990	2710	4,333,000	4.377	1599	
NORTH LAKE	709	800	3,555,000	5.014	4444	
BALDWIN (a)	584		3,000,000	5.137		
VALMONT	273	531	978,000	3.582	1842	
FT. CHURCHILL	110	100	273,000	2.482	2730	Units 3 and 4 Units 1 - 7
SIM GIDEON	250	906	3,650,000	14.600	4029	
DELTA	220	640	995,500	4.525	1555	
REX BROWN (b)	304	382	1,166,000	3.836	3052	
HORSE SHOE (b)	500	300	2,151,000	4.302	7170	
WILKES	160	651	1,112,000	6.950	1708	
LAKE CREEK	322	490	1,009,000	3.134	2059	
RIVERCREST	120	560	781,350	6.511	1395	
VALLEY	725	1000	918,209	1.266	918	
MT. STORM (a)	1140	1120	6,523,000	5.722	5824	
COFFEEN (a)	389	1100	1,790,000	4.602	1627	
SPRAY PONDS						SPRAY PONDS
CAMEO (b)	66	2	53,000	0.803	26.500	Units 1 and 2 Units 2 and 3
CANADYS (b)	490	10	1,631,250	3.329	163,125	
DALLAS (b)	224		495,000	2.210		
NEOSHO	40	180	812,000	7.186	4511	
DRESDEN	1430	1300	25,000,000	17.483	19,231	

(a) - Future expansion at site contemplated.

(b) - Cooling Towers also used.

and conduits of the secondary cooling system. The remaining costs were associated with the purchase of land, clearing and construction. In comparing costs of ponds and lakes with other once-through cooling systems (rivers and oceans) costs of the former are approximately 10% lower in the areas of pumps and conduits. This results primarily from the fact that the station can be located nearer to the water body. For the case of rivers, allowance must be made for flooding; in the case of oceans, a similar arrangement must be made for tide and wave activity. The cost of the condenser and auxiliary, for all intents and purposes, is the same.

TABLE 13
BREAKDOWN OF CAPITAL COSTS OF COOLING PONDS

Items	% of Capital Costs
Condenser and Auxiliaries	24.
Pumps and Conduits	41.
Cooling Pond:	
Land Purchase	14.
Clearing & Diking	14.
Other	7.

A point to be considered in arid regions, where water consumption is an important parameter, is if there is no local water supply sufficient to satisfy the make-up demand, a pond will be required that possesses a sufficient reserve. In the case of the Four Corners power plant, an evaluation of the alternate cooling methods showed that the operation of a tower would require a pond large enough to provide make-up water for possibly six months. The size of the storage pond for a cooling tower would be approximately that of a spray pond, and would require the same excavation and diking cost.

As suggested previously, a spray pond will require only about 5% of the local area needed for a cooling pond without sprays. Where land costs are high, this may be a decisive factor in deciding on a cooling system. On the other hand, when the land is leased for a nominal amount, there would be little savings. For the 42-acre spray pond discussed by Papamarcos⁽⁹⁶⁾ the estimated installed cost was \$2.5 million. The capital cost associated with adding the spray system to the Canadys Station is estimated at \$3.65/Kw⁽¹⁰⁴⁾.

B. OPERATIONAL COSTS

As indicated previously, cooling ponds operate at temperatures from 5 to 10°F above the equilibrium state. In turn, this means operating the system at a higher condensing temperature, causing a slightly higher back-pressure and reducing the capability of the turbine. Hauser⁽¹¹¹⁾ relates this capability loss as an incremental kilowatt capacity loss which must be replaced by additional plant capacity. To obtain the required power, added plant capacity is required; hence additional capital and increased fuel cost.

Hauser estimates the total increase over once-through cooling as 0.054 mils/Kwh, of which 0.03 mils/Kwh are in additional capital costs. Added to an initial capital cost increment of 0.0331 mils/Kwh for land, etc., the total capital cost increment becomes 0.0871 mils/Kwh, which might be converted very roughly to \$5.40/Kw for a 1000 MW system. Hauser further concludes that this incremental cost equates to the cost associated with transmitting power approximately 35 miles. In other words, if a source of cooling water for once-through cooling is further than about 35 miles from the load center, it is more economical to construct a facility with a cooling pond at the load center.

Although several authors mentioned have attempted to give single value definitions of cooling pond costs, it is obvious that the cost will vary greatly, depending on location. This includes not only variations in capital costs, but in annual costs as well. For each plant to be built, parametric studies must be made to determine the most economic cooling means and the most economic site. An interesting site selection report by Ebasco Services, Inc.⁽¹¹²⁾ for the Four Corners location compares three site locations for cooling ponds and, in one case, for a cooling tower as well. Table 14 is a comparison of expected investment costs for two of the pond sites and one tower site. (The third pond site was obviously more expensive and is not included here.) The biggest difference is in dam construction costs. While the sites are not on flowing streams, they are in terrain requiring a dam. The area drained determines the size of required spillways. Site 1 requires a small dam, but a large spillway. Site 2 requires a large dam with a small spillway. The other major capital expense is in the cost of the tower.

The annual operating expenses are listed in Table 15. The pond at Site 2 is slightly more expensive to operate than the pond at Site 1, as it is

TABLE 14
COMPARATIVE EXPECTED INVESTMENT COSTS - 700 MW PLANT - \$10³ (63)

	Pond Site 1	Tower Site 1	Pond Site 2
Dam	550	560	3,900
Relocation	10	10	190
Intake Canal	208		125
Discharge Canal	125		125
Dikes	175		20
River Intake	200	190	200
Make-Up Pipe Line to Reservoir	80	80	250
Make-Up Pipe Line to Discharge	15	15	15
Plant Area Grading	400	150	150
Access Roads	75	125	180
Circulating Water Intake & Conduits	1,000	1,000	1,000
Condenser Plant	2,900	3,000	2,900
Ash Disposal	120	150	70
Cooling Tower		2,000	
Cooling Basin Intake		400	
Cooling Make-Up Pipe		350	
Cooling Make-Up Pumps		75	
Total	5,858	8,105	9,125

TABLE 15
COMPARATIVE EXPECTED ANNUAL OPERATION-MAINTENANCE COSTS - 700 MW PLANT - \$10³

	Pond Site 1	Tower Site 1	Pond Site 2
Make-Up Pump from River	12	8	24
Make-Up Pump to Tower		16	
Circulating Water Pump	56	112	56
Cooling Tower Fans		50	
Total	68	186	80
Operating Labor	Same for all Possibilities		
Cooling Tower Maintenance		70	
Total Comparative Annual Costs	68	256	80

further from the make-up water source. The tower is far more expensive than either.

From these data, the pond at Site 1 would be the obvious choice. However, it had to be discarded, as the pond would submerge 8 million tons of minable coal. The pond at Site 2 was selected. It should be noted that land purchase is not a factor. In this instance, the land is leased from the Navajo Indians.

A thorough economic study would include parametric studies involving various turbine designs, pond sizes, various land costs and consequent temperature ranges of the cooling water. Such a parametric study has been reported by Littleton Research and Engineering Corp.(20) for a 2000 MWe plant to be located near Philadelphia. This exercise allows variations of all parameters, except turbine design, to arrive at the optimum economic design. The variables are:

- 1) Mixed flow vs plug flow
- 2) Five temperature rises
- 3) Variable pond areas
- 4) Three land prices

From their study, it is obvious that, in general, land costs and lost capacity due to increased back-pressure are the important items contributing to the capital and operating costs of a cooling pond facility. As this study is more an exercise than a real situation (the water cooling choice for this plant was cooling towers), specific variations such as diking or damming costs are not included. Table 16 lists various optimum designs for given situations. With respect to annual costs, the most economic combination is a slug flow pond. At \$500/acre, using a 25°F temperature rise, this results in a need for 2.6 acres/MW.

TABLE 16
OPTIMUM RESULTS OF PARAMETRIC ECONOMIC STUDIES
FOR A 2000 MWe PLANT COOLING POND (20)

Land Costs - \$/Acre		Optimum Range - °F	Resulting Acreage Acres/MW	Annual Costs \$10 ³ /MW
Mixed Pond:	500.	20	3	1.2
	2000.	20	2	1.7
	5000.	20	1.5	2.3
Slug Flow:	500.	25	2.6	1.0
	2000.	25	1.5	1.3
	5000.	20	1.0	1.8

A review of data submitted to the FPC⁽¹⁰⁸⁾ showed that operating and maintenance costs can vary considerably. However, some very general statements summarizing the data can be made. In the Southeast, annual operating and maintenance costs (other than chemical additives) for cooling ponds tend to be in the \$0.1 to 0.2/KWe range. In Texas, these costs seem to be near \$0.02/KWe or in the \$0.06-0.085/KWe range, and in Illinois, costs range from \$0.01 to 0.05/KWe. Chemical additives generally contribute from \$0.003 to 0.007/KWe annually in Texas. In the Southeast, this factor is quite variable, ranging from a low of \$0.0005/KWe to a high of \$0.015/KWe. Illinois and other areas are generally in the neighborhood of \$0.05 to 0.1/KWe.

Combination facilities utilizing sprays or towers generally have higher costs. Chemical additions may range from \$0.05 to 0.075/KWe for such plants and operating and maintenance costs generally run from \$0.2 to 0.6/KWe.

C. COMMERCIAL AND RECREATIONAL ASPECTS

The commercial use of cooling ponds that has received the most attention is fish farming. Further, catfish are the most intensively studied species in the U. S. The reason for this is two-fold. First, catfish are hardy and grow well in warm water. Secondly, there already exists a good market for this fish in certain regions of the country, particularly the South. Experiments have been performed in which catfish were grown in conjunction with power plant heated effluent in Texas^(113, 114, 115) at Lake Colorado City, at Hyco Lake, Jackson, Mississippi⁽¹¹⁶⁾, and a TVA site⁽¹¹⁶⁾. These experiments apparently have been successful; catfish can be raised from fingerlings to marketable size in the nine months of the year that excludes the summer. In the South, in summer, conditions in a cooling pond would generally be too warm for successful growth. Normally, during winter months, fish are dormant; hence feed less and have little growth. The use of warm water in winter months extends the growing season. The advantages to catfish culture of using thermal effluent are:

- 1) Yields could be doubled by doubling the growing season in more northern climates;
- 2) Food conversion is optimized by having fish continuously at optimum temperatures; and
- 3) Disease problems are reduced by eliminating the winter dormant period.

A further enhancement is the use of "running water culture" which has recently been studied in the United States⁽¹¹⁷⁾, but is practiced in Japan. Using slightly more than 50 cfs of heated effluent per acre, it is feasible to raise two, 200-ton/acre, crops of catfish annually. The return on investment in raising catfish is about 25 percent/crop. This includes the cost of feed and maintenance⁽¹¹⁸⁾.

Intensive studies have been made of the possibilities of fish farming using power plant heated effluent but little work has been done on the negative aspects. One author⁽¹²⁴⁾ has pointed out that, if the cooling pond is, in fact, a holding pond in a once-through system, the fish will increase the BOD content, lower the dissolved oxygen level, and possibly lower the nutrient level. If the water is returned to the source without the proper treatment this could present a potential problem. The obvious problems which will

occur in a recycled system are filtration of the water before it enters the condenser, re-aeration of the water before it is returned to the fish ponds and chemical incompatibilities between the two systems. Further, the fish pond system may require a higher frequency of blowdown to maintain suitable environment.

Consideration has been given to other forms of aquatic culture farming. In northern states, the possibility of farming salmon and trout exists(117,120). On seacoasts, the possibility of inland salt water shrimp farms is being studied(123). The reports on the studies are written from a viewpoint of promotion rather than objective criticism, and once again, there is little reported on the drawbacks of these commercial possibilities.

As has been mentioned, a utility choosing to use a cooling pond for condenser cooling may be pressured into making a recreational facility of this pond, which for large utilities, will, indeed, be a lake. Designers are proposing not only the utilization of the pond for recreation, but are designing the structure for profitable recreational usage. Eicher(93) has suggested such possibilities as cabin rentals on the lake front, restaurants, apartments, seaplane and boat ramps, swimming areas, water skiing facilities,...in general, a typical for-profit resort. No drawbacks were offered by this author; however, drawbacks to use of a cooling pond as a recreational facility have been dealt with elsewhere in this report.

A very rough estimate of the potential economic gains due to recreational uses of cooling ponds or lakes may be determined by applying a net annual gain (value less cost) of \$20 to 40/acre in a manner similar to that used to estimate the approximate feasibility potential of hydroelectric projects in the Southeast.(129) For a moderate size cooling pond, this would yield a gain on the order of 0.01 mill/kwh. Of course, extensive development of the lake could increase income, but with greater expense.

D. ENVIRONMENTAL COST FACTORS

An available, inexpensive site for a cooling pond may have hidden economic costs. The construction of the pond may result in the actual destruction of a unique ecosystem or of the habitat of endangered species. The environmental concern may be real or imagined; nevertheless, it involves a cost to the utility in image and ill will which is difficult to define in monetary units. A case in point is the 2600-acre pond for Houston Lighting and Power Company's Cedar Bayou gas-fired generating plant⁽¹²⁵⁾. Work has been currently halted on this project by the EPA on the grounds that the proposed pond would cover a "biologically productive marshland" which is also the habitat of three "rare or endangered species".

VIII. CONCLUSIONS AND RECOMMENDATIONS

As indicated by this report, cooling ponds have been under review for some time. However, the design and operation of cooling ponds must still be regarded as an art, and probably will remain as such for some time to come. It is our intent at this time to discuss some areas where we feel additional research should be undertaken to advance the art.

In the area of heat transfer, additional work remains. The relationships are semi-empirical in nature and, as a result, reflect the manner in which data were collected and interpreted. At the present time, data sampling and reduction techniques have not been totally standardized. For example, it has been suggested by Jobson⁽¹²⁶⁾ that the time period over which data are averaged can strongly influence the results. In dealing with the mass transferred through evaporation, Jobson suggests a maximum duration of one day for averaging. In comparison, for the formula proposed by Morton⁽¹²⁷⁾ and Meyer⁽²⁸⁾, monthly average wind speeds were used to compute the mass transfer coefficient, whereas Brady⁽¹⁴⁾ obtained reasonable correlations using weekly averaged values. Present and future work should address this problem.

The effect on the heat transfer mechanisms when operating at temperatures well above equilibrium should be more thoroughly reviewed. Research by Harbeck⁽⁵²⁾ suggests the mass transfer coefficient is dependent on surface area. The heat flux may be of sufficient magnitude to modify the properties of

overlying air masses, thereby creating a condition in which the actual heat sink possesses properties that differ from the ambient air. Furthermore, it must be recognized that the condition of the water surface is a function of the pond's surface area, prevailing meteorological condition, and surrounding topography. The several studies currently underway should attempt to include the effect of this variable in their analyses.

The geometry of the cooling pond should be considered during design. The specific geometry of a pond will promote a particular hydraulic response. In turn, this will affect the temperature distribution. Similarly, a number of analytic cooling pond models have been proposed; however, few have been tested, at least in the open literature. The models should be tested with the intent of establishing criteria from which the designer will know, a priori, which model, or procedure, as the case may be, should be employed under a given set of conditions. Conceivably, a set of dimensionless variables that characterize the pond's geometry and effective transfer properties could be developed.

More research should be conducted on examining materials that might possibly be used as surface films. Providing such surface films might both decrease background water temperatures by reflecting incoming radiation and by reducing the loss through evaporation. For example, a chemical might be introduced which changes the properties of the water, lowering the transmissivity and effective vapor pressure, while maintaining a high capacity for absorbing heat. Particular attention must be directed to the effects of surface turbulence and wind.

In the design of the Cholla cooling pond, a portion of the pond was diked off, creating a "hot pond". An inverted weir was used to selectively remove the cooler hypolimnetic water from the hot pond. Similarly, additional work should be performed on the effect of varying pond geometry to improve pond performance and to reduce consumption. The aspects of selective withdrawal from a stratified water body should be explored in more detail. Several studies are currently underway which should add to our knowledge in this area.

Studies are also in progress to examine the adequacy of heated ponds to support various ecosystems for purposes of recreation and commercial use. In addition to the direct use of the cooling pond for such purposes, efforts should be expended to factor the cooling pond into comprehensive land use plans.

The heated water might be used to increase the yield from various forms of agriculture and aquaculture.

Recently, there has been a renewed interest in the use of spray devices to help cool condenser cooling water. Several manufacturers have marketed various concepts, with some utilities showing considerable interest. Attention should be given to both their effectiveness in removing heat and their effect on the environment. Water droplets, drift and fog could conceivably limit their use. With respect to fog, models should be developed and tested which simulate the formation and persistence of fog in the vicinity of ponds. An understanding of mechanisms will shed considerable insight into the manner in which the fog might be either contained or dispersed. The aspect of fog containment or interception is important if the pond is situated near transportation corridors or populated areas.

IX NOMENCLATURE

a = relationship defined in text
 a' = empirically derived coefficient
 A = surface area of pond
 A' = surface area of drop

 b = relationship defined in text
 b' = empirically derived coefficient
 B = Bowen ratio

 c' = empirically derived coefficient
 C_j = concentration of individual chemical species
 C_p = specific heat of water
 C_a = specific heat of air
 C_M = molar density
 C_v = specific heat of vapor
 C_L = average cloud cover in tenths
 C_1 = coefficient defined in text
 C_2 = empirically derived coefficient
 C_D = drag or lift coefficient
 d = depth of water
 D_{ij} = multi-component diffusion coefficient
 D_S = transfer coefficient of sediment
 D_T = thermal diffusion coefficient
 D_L = longitudinal mixing coefficient
 D = geometric length, diameter

 e_a = air vapor pressure
 e_w = saturated vapor pressure at temperature of surface water
 E_v = evaporative loss rate

 $f(u)$ = wind speed function

 g = gravitational acceleration
 G = air flow rate

h_i = enthalpy of water in
 h_o = enthalpy of water out
 dh/dL = hydraulic gradient
 H_E = latent heat of evaporation
 H_P = heat discharged from power plant
 H_O = enthalpy of air out
 H_i = enthalpy of air in
 H_V = enthalpy of evaporated water
 H' = enthalpy at saturated value

 K = chemical reaction coefficient
 K' = coefficient of permeability or hydraulic conductivity
 K = surface heat exchange coefficient
 K_e = energy exchanged coefficient
 K_X = mass exchange coefficient (units appropriate to humidity ratio)
 K_T = mass exchange coefficient (units appropriate to vapor pressure)

 ℓ = geometric length trajectory of water drop
 L = water flow rate
 L_e = Lewis Number

 M = sediment density

 n = order of chemical reaction
 N = number density of sediment particles
 N_{mi} = number of nuclei of m th radioactive isotope of species i /unit volume
 N_T = number of transfer units

 P_a = barometric pressure
 P = fluid pressure
 P = reference pressure
 P_w = water supply pressure

 q = rate of thermal energy added/unit vol
 Q_T = total heat flux
 Q_S = absorbed short wave solar radiation
 Q_a = absorbed long wave atmospheric radiation

Q_b = long wave back radiation
 Q_e = heat loss by evaporation
 Q_c = heat gained or lost by conduction
 Q_ℓ = energy source vs sink
 Q_p = plant pumping rate
 Q^* = rate of release from tower

 Re = Reynolds number
 r = humidity ratio
 r' = saturated humidity ratio

 S = sorption term
 S_{an} = noon sun angle

 t = time
 t_d = length of day
 t_d' = retention time
 T_a = air temperature
 T_w = temperature of surface water
 T_i = temperature of coolant flow into pond
 T_o = temperature of coolant flow out of pond
 u' = wind speed
 u = velocity in the x-direction

 v = average velocity of fluid
 V_s = velocity of sediment
 V^* = average velocity of mixture
 V = volume

 x = cartesian coordinate

 y = cartesian coordinate
 Y_i = mole fraction of i^{th} species

 Z = cartesian coordinate
 Z_c = cloud height in feet

α = absorbtivity coefficient used in conjunction with Q_s
 α' = conversion nuclei/unit volume to moler/unit vol
 β = radiation factor
 β' = proportionality factor
 γ_w = emissivity of water
 μ = viscosity of mixture
 σ = Stefan - Boltzmann constant
 σ_y = variance in the horizontal direction
 σ_z = variance in the vertical direction
 ρ = density of water
 ϵ = 2.718

X REFERENCES

1. Steam-Electric Plant Construction Cost and Annual Production Expenses-Twenty-Second Annual Supplement - 1969, FPC S-209 Jan, 1971
2. Oleson, K. A., R. R. Boyle, "How to Cool Steam Electric", Chemical Engineering Progress, July, 1971
3. Throne, R. F., "How to Predict Lake Cooling Action", Power, Sept, 1951
4. Zeller, R. W., "Cooling Water Discharge into Lake Monona", Ph.D Thesis Dept. of Civil Engineering, U. of Wisconsin, 1967
5. Hoopes, J. A., R. W. Zeller, G. A. Rohlich, "Heat Dissipation and Induced Circulations from Condenser Cooling Water Discharges Into Lake Monona", College of Engineering, U. of Wisconsin, Report No. 35, Feb, 1968
6. Niemeyer, J. A., "Modeling of Power Plant Cooling Water Discharges into Lake Monona", M. S. Thesis Dept of Civil Engineering, U. of Wisconsin, 1969
7. Cotter, T. J., A. W. Lotz, "Cooling Pond Design in the Southwest", ASCE Journal of Power Division, July, 1961
8. Derrick, A. E., "Cooling Pond Proves to be the Economic Choice at Four Corners", Power Engineering, Nov, 1963
9. Krause, G. G., R. D. Woodson, "Maximum Utilization of Calaveras Cooling Lake for Electric Generation", Vol 31 Proceedings of the American Power Conference, 1969
10. Gray, R. F., J. B. Stephenson, "Cooling Water Studies at Electric Power Station", ASCE Journal of Power Division, Oct, 1969
11. Schroeder, T. W., E. E. Connon, H. M. Sroka, "Baldwin Power Station Takes Advantage of Mine-Mouth Coal with a Cooling Lake", Vol 31 Proceedings of the American Power Conference, 1969
12. Brezina, E. R., R. S. Campbell, J. R. Whitley, "Thermal Discharge and Water Quality in a 1,500-Area Reservoir", Journal Water Pollution Control Federation, Vol 42 No. 1, Jan, 1970
13. Braswell, R. W., "A Cooling Pond Proves Cheaper", Electric World, Nov, 1953
14. Brady, D. K., W. L. Graves, J. C. Geyer, "Surface Heat Exchange at Power Plant Cooling Lakes", Edison Electric Institute, Pub. No. 69-901, Nov, 1969
15. "A Survey of Alternate Methods for Cooling Condenser Discharge with Large-Scale Heat Rejection Equipment", EPA Project No. 16130, DHS July, 1969
16. Lima, D. O., "Pond Cooling By Surface Evaporation", Power, 80, 1936
17. Langhaar, J. W., "Cooling Pond May Answer Your Water-Cooling Problems" Chemical Engineering, 60, 1953

18. Water-Loss Investigations: Lake Hefner Studies. Technical Report, U. S. G. S. Prof. Paper 269, 1954
19. Water-Loss Investigations: Lake Mead Studies. U. S. G. S. Prof. paper 298, 1958
20. An Engineering-Economic Study of Cooling Pond Performance, EPA 16130 DFX05, 1970
21. Laevastu, T., "Factors Affecting the Temperature of the Surface Layer of the Sea", Commentiones Physico-Mathematicae XXV 1, Helsinki, 1960
22. Jaske, R. T., "An Evaluation of the Use of Selective Discharges from Lake Roosevelt to Cool the Columbia River", BNWL-208, Feb, 1966
23. Budyko, M. I., "Heat Balance of the Earths Surface", Leningrad, 1956
24. Brunt, D., Physical and Dynamical Meteorology, Cambridge University Press, 1944
25. Edinger, J. E., J. C. Geyer, "Heat Exchange in the Environment", Electric Institute Pub. No. 65-902, June, 1965
26. Raphael, J. M., "Prediction of Temperature in Rivers and Reservoirs", ASCE Journal of Power Division, July, 1962
27. "Effect of Geographical Location on Cooling Pond Requirements and Performance", EPA Project No. 16130 FDQ, March, 1971
28. Meyer, A. F., "Computing Runoff from Rainfall and Other Physical Data", Trans. ASCE, Vol 79, 1915
29. "The Effect of the Addition of Heat From a Power Plant on the Thermal Structure and Evaporation of Lake Colorado City, Tex.", U.S.G.S. Prof. paper 272-B, 1959
30. "Industrial Waste Guide on Thermal Pollution", FWPCA Pacific Northwest Water Lab. Corvallis, Oregon, Sept, 1968
31. Hauser, L., K. Oleson, "Comparison of Evaporative Losses in Various Condenser Cooling Water Systems", presented at American Power Conference Chicago, Ill., April, 1970
32. Tichenor, B. A., A. G. Christianson, "Cooling Pond Temperature versus Size and Water Loss" ASCE Journal of Power Division, July, 1971
33. Sefchovich, E., "Condenser Cooling and Pumped Storage Reservoirs", ASCE Journal of Power Division, July, 1971
34. Winiarski, L. D., K. V. Byram, "Reflective Cooling Ponds", ASME 70-WA/PWR-4
35. Chow, V. T., Handbook of Applied Hydrology, McGraw Hill, 1964
36. Sundaram, T. R. et al., "An Investigation of the Physical Effects of Thermal Discharges into Cayuga Lake", Cornell Aeronautical Laboratory Inc. Cal No. VT-2616-0-2, Nov, 1969
37. Hutchinson, G. E., A Treatise on Limnology, Vol 1, John Wiley & Sons, 1957

38. Dake, J., D. R. F. Harleman, "Thermal Stratification in Lakes: Analytical and Laboratory Studies", Water Resources Research, April, 1969
39. Sonnichsen, J. C., C. A. Oster, "Examination of the Thermocline", Journal of Sanitary Engineer, April, 1970
40. Stahl, J. B., D. S. May, "Microstratification in Waste Treatment Ponds", Journal of Water Pollution Control Federation, Jan, 1967
41. Bartch, A. F., M. O. Allum, "Biological Factors in Treatment of Raw Sewage in Artificial Ponds", Limnology and Oceanography 2, 77, 1956
42. Copelane, B. J., et. al., "Chlorophy ll and Suspended Organic Matter in Oil Refinery Effluent Holdup Ponds", Limnology and Oceanography, 1964
43. Parker, F. L., P. A. Krenkel, "Thermal Pollution: Status of the Art", Report Number 3, Dept. of Environmental and Water Resources, Vanderbilt University, Dec, 1969
44. Wright, R. L., P. K. Kirsopp, "Pond Surface Cooling of a Chemical Plant Cooling Water", Vol 23, Proceedings of the American Power Conference, 1960
45. "Register of Selective Withdrawal Works in United States", ASCE Journal of Hydraulics Division, Vol 84 HYD4, July, 1965
46. Harleman, D. R. F. et. al., "Submerged Sluice Control of Stratified Flow", ASCE Journal of Hydraulics Division, Vol 84 HYD2, April, 1958
47. Harleman, D. R. F., R. A. Elder, "Withdrawal From Two-Layer Stratified Flows" ASCE Journal of Hydraulics Division, Vol 91 HYD4, July, 1965
48. Sood, M. N., "Efflux From a Thermally Stratified Flow", College of Engineering Bulletin No. 325, Washington State University, 1972
49. Barmgartner, D. J., D. S. Trent, "Ocean Outfall Design, Part I, Literature Review and Theoretical Development", FWQA Northwest Region, April, 1970
50. "Estuarine Modeling: An Assessment", EPA Project No. 16070 DZV, Feb, 1971
51. Policastro, A. J., and J. V. Tokar, "Heated Effluent Dispersion in Large Lakes; State of the Art of Analytical Modeling. Part 1. Critique of Model Formulations", ANL/ES-11, January, 1972
52. Harbeck, G. E., "Estimating Forced Evaporation from Cooling Ponds", ASCE Journal of Power Division, Oct, 1964
53. Edinger, J. E., E. M. Polk, "Initial Mixing of Thermal Discharges into a Uniform Current", Report No. 1, Hydrologic and Hydraulic Aspects of Water Pollution Control, Vanderbilt University, Dec, 1969
54. White, A., E. F. Gloyna, "Radioactivity Transport in Water; Mathematical Simulation", Tech. Report 19, Dept. of Civil Engineering, U. of Texas, 1969
55. Jobson, J. E., W. W. Sayre, "Predicting Concentration Profiles in Open Channels", ASCE, presented at Water Resources Meeting, Memphis, Tenn. Jan, 1970
56. Pritchard, D. W., "Dispersion and Flushing of Pollutants in the Estuarine Environment", ASCE Congress on Water Resources Reprint No. 566, Oct, 1967

57. Leendertse, J. V., "A Water-Quality Simulation Model for Well-Mixed Estuaries and Coastal Seas: Vol 1, Principles of Computation", Memorandum RM-6230-RC, Rand Corp., Feb, 1970
58. John, J. E., "The Use of Cooling Ponds to Dissipate Thermal Pollution", Seminar of the Institute of Environmental Sciences, Oct, 1970
59. Edinger, J. E., "Shape Factors for Cooling Lakes", ASCE Journal of Power Division, Dec, 1971
60. Silberman, E., H. Stephan, "Physical Hydraulic Modeling of Heat Dispersion in Large Lakes", ANL/ES-2, Aug, 1970
61. Riesbol, H.S., et.al, "Thermal Hydraulic Study: Arkansas Cooling Reservoir", ASCE Journal of Power Division, Jan, 1971
62. Harleman, D.R.F., K.D. Stolzenbach, "A Model Study of Proposed Condenser Water Discharge Configurations from the Pilgrim Nuclear Power Station at Plymouth Mass," M. I. T. Hydrodynamics Laboratory Tech. Report No. 113, May, 1969
63. Jaske, R. T., H. R. Drew, "Simulation of Evaporation From a Cooling Lake With a Comparison to a Real Case and the Alternative Use of Cooling Towers", presented at 70th National Meeting, AIChE, Houston, Texas, March 4, 1971
64. "The COLHEAT River Simulation Model", HEDL-TME 72-103, Oct. 1972.
65. MacKichan, K.A., "Estimated Use of Water in the United States 1955," Journal of American Water Works Association, Vol 49, 1957
66. Bouwer, H., "Analyzing Ground Water Mounds by Resistance Networks, ASCE Journal of Irrigation and Drainage, 1962
67. Freeze, R.A., "The Mechanism of Natural Groundwater Recharge and Discharge 1. One-dimensional, Vertical, Unsteady, Unsaturated Flow above a Recharging or Discharging Groundwater Flow System ", Water Resources Research, Feb, 1969
68. Freeze, R.A., "Subsurface Hydrology at Waste Disposal Sites", Subsurface Hydrology, March, 1972
69. Cearlock, D.B., "A Systems Approach to Management of the Hanford Groundwater Basin", Presented at National Groundwater Quality Symposium Denver, Colorado, Aug, 1971
70. Study performed by R. W. Beck and Associates for Washington Public Power Supply System, June, 1971
71. Design of Small Dams, U. S. Dept. of the Interior, Bureau of Reclamation, 1960

72. Chuck, R.T., "Largest Butyl Rubber Lined Reservoir", Civil Engineering, May, 1970
73. Smith, W., "Canal and Reservoir Lining with Asphalt", Civil Engineering, May 1962
74. De Harpporte, D. R., "Cooling Tower Site Considerations ", Power Engineering, Aug, 1970
75. "Potential Environmental Modifications Produced by Large Evaporative Cooling Towers", EPA Program 16130, Jan, 1971
76. "Final Report on a Meteorological Evaluation of the Effect of the Proposed Cooling Towers at the Hanford Number Two "C" Site or surrounding areas", Battelle Northwest Report prepared for Burns and Roe, Sept, 1971
77. Meteorology and Atomic Energy 1968, published by the U. S. AEC, July, 1968
78. Pilie, R. J., "Investigation of Warm Fog Properties and Fog Modification Concepts", Project Fog Drops, NASA CR-368, Jan, 1966
79. Eldridge, R.G., "The Relationship Between Visibility and Liquid Water Content in Fog", Journal Atmospheric Sciences, Oct, 1971
80. Hanna, S. R., "Meteorological Effects of Cooling Tower Plumes", presented at Cooling Tower Institute Winter Meeting, Houston, Texas, Jan, 1971
81. Weinsten, A. I., "A Numerical Model of Cumulus Dynamics and Microphysics" Journal Atmospheric Sciences, March, 1970
82. Hall, W. A., "Elimination of Cooling Tower Fog from a Highway", presented at Air Pollution Control Association Meeting, Chicago, Ill., May, 1962
83. Hall, W. A., "Cooling Tower Plume Abatement", Chemical Engineering Progress, Vol 67, No. 7, July, 1971
84. Geiger, R., Climate Near the Ground, Harvard University Press, 1966
85. Cone, B. W., "The Economic Feasibility of Establishing an Irrigated Forestry Enterprise on the Hanford Reservation", Battelle Northwest, Nov, 1970
86. Kunkel, B. A., B. A. Silverman, "A Comparison of the Warm Fog Clearing Capabilities of Some Hygroscopic Materials", Journal of Applied Meteorology, Vol 9, No. 4, Aug, 1970
87. Silverman, B.A., B. A. Kunkel, "A Numerical Model of Warm Fog Dissipation by Hygroscopic Particle Seeding", Journal of Applied Meteorology, Vol 9, No. 4, Aug, 1970
88. Jinsto, J.E., "Nucleation Factors in the Development of Clouds", Ph.D. Thesis, Dept. of Meteorology, Penn. State University, 1967
89. Warner, J., W. G. Warne, "The Effect of Surface Films in Retarding the Growth by Condensation of Cloud Nuclei and their Use in Fog Suppression", Journal Applied Meteorology, Vol 9, Aug, 1970
90. Robinson, E.E., "Reclaimed Water Cools Station", Electrical World, Jan, 1961

91. Water Quality Criteria, Federal Water Pollution Control Administration, U. S. Govt. Printing Office, 1968
92. Edison Electric Institute Committee on the Environment Newsletter, Vol IV, No. 8, Oct, 1971
93. Eicher G. J., "Cooling Lakes can be a Pleasant Solution", Electrical World, April, 1969
94. Sonnichson J. C., B. Bentley, R. E. Nakatani, "A Review of Thermal Power Plant Intake Structure Designs and Environmental Considerations", to be published
95. Engstrom, S. L., with O. L. Thornburg, Personal Communication (Arizona Public Service Co.), Jan, 1972
96. Papamarcos, J., "Spinning Discs", Power Engineering, Sept, 1971
97. Kolflat, T. Statement Before the Subcommittee on Air and Water Pollution of the Committee on Public Works, U. S. Senate, Wash D.C., Feb. 6, 1968, U. S. Govt. Printing Office
98. Berman, L.D., "Evaporative Cooling of Circulating Water", Pergamon Press, 1961
99. McKelvey K. K., M. Brooke, "The Industrial Cooling Tower", Elsevier, Amsterdam, 1959
100. Scofield, F.C., R.A. Fazzolare, "Nuclear Power Plant Heat Rejection in an Arid Climate", presented Aug. 1971 ANS Winter Meeting, Miami, Oct 21, 1971
101. Colburn, A.P., Trans. AICHE 35, 211, 1934
102. Kelley, R.D., "Large Scale Spray Cooling", Industrial Water Engineering, Aug, 1971
103. Pita, E.G., J. John, "The Effect of Forced Convection on Evaporative Cooling of Sprays in Air", paper presented at Fourth International Heat Transfer Conference, Versailles, Sept, 1970
104. Moore, W.E., "Spray Pond Keeps River Within 5°F Rise Limit", Electrical World, April, 1968
105. Malkin, S., "Converting to Spray Pond Cooling", Power Engineering, Jan, 1972
106. "Controlling Contaminants in Cooling Water" Chemical Engineering Aug 9, 1971
107. Donohoe, J.M., "Making Cooling Water Safe for Steel and Fish, Too", Chemical Engineering, Oct 4, 1971
108. Steam-Electric Plant Air and Water Quality Control Data for the Year Ended December 31, 1970, Federal Power Commission Form 67
109. Jameson, R.M., G. G. Adkins, "Waste Heat Disposal in Power Plants", Chemical Engineering Progress, July, 1971
110. Woodson, R.D., "Cooling Towers", Scientific American, May, 1971

111. Hauser, L.G., "Cooling Water Sources for Power Generation", presented ASCE Water Resources Eng. Meeting, Memphis, Tenn., Jan, 1970
112. "Coal Reserves Water Availability and Site Selection for Four Corners Project for Arizona Public Power Service", Vol II, by Ebasco Services, Inc., 1959
113. Tilton, J. E., and J. F. Kelley, "Experimental Cage Culture of Channel Catfish Ictalurus punctatus in the Heated Discharge Water of the Morgan Creek steam Electric Generating Station, Lake Colorado City, Texas," presented at the Second Annual Workshop, World Mariculture Society, Baton Rouge, Louisiana, Feb 9, 1970
114. Lewicki, C. K., "Thermal Pollution in Uncharted Waters", Environmental Science and Technology, Vol 5, No. 12, Dec, 1971
115. Communication, C. W. Long (National Marine Fisheries Service) with J. E. Tilton (Texas Electric Service Co.)
116. Pickering, C.W., "Catfish Farming-Beneficial Use of Waste Heat", Proceedings Conference on the Beneficial Uses of Thermal Discharges, New York State Dept. of Eng. Conservation, Sept 17-18, 1970, Albany, N. Y.
117. Brown, E.E., "The Fresh Water Cultural Fish Industry of Japan", Research Report 41, University of Georgia College of Agriculture Experiment, March, 1969
118. U. S. Bureau of Commercial Fisheries, "A Thermoquaculture Research Proposal-- Channel Catfish", Pasco Biological Field Station
119. Boersma, L., "Warm Water Utilization", Proceedings Conference on the Beneficial Uses of Thermal Discharges, New York State Dept. of Env. Conservation, Sept 17-18, 1970, Albany, N. Y.
120. McNeil, W.S., "Heated Water from Generators Presents Fish-Culture Possibilities", The American Fish Farmer and World Aquaculture News, Vol 1, No. 6, May, 1970
121. "Nuclear Thermal Waste Brings New Northern Catfish Farm Possibilities", Farm The American Fish Farmer and World Aquaculture News, Vol 1, No.6, May, 1970
122. "Thermal Effluent Woe Studied", The American Fish Farmer and World Aquaculture News, Vol 1, No. 10, Sept, 1970
123. "Aquaculture Comes to Turkey Point", The American Fish Farmer and World Aquaculture News, Vol 1, No. 8, July, 1970
124. Garton, R.R., A. G. Christianson, "Beneficial Uses of Waste Heat - An Evaluation", Proceedings Conference on Beneficial Uses of Thermal Discharges of New York State Dept. of Eng. Conservation, Sept 17,18, 1970, Albany, N. Y.
125. Electrical World, Vol 176, No. 10, Nov 15, 1971
126. Jobson, H. E., "Effect of Using Averaged Data on the Computed Evaporation", Vol 8, Number 2, Water Resources Research, April, 1972

127. Morton, F.I., "Potential Evaporation and River Basin Evaporation", ASCE Journal of Hydraulics Division, Vol 91, No. HY6, Nov, 1965
128. "Environmental Effects of Producing Electric Power", Hearings before the JCAE, 91st Congress (First Session), Part 1, p. 760-767, 1969
129. "The 1970 National Power Survey, Part II", Federal Power Commission, 1971

APPENDIX A

LISTING OF STEAM ELECTRIC POWER PLANTS
USING COOLING PONDS OR COOLING LAKES

TABLE A-1
LISTING OF STEAM ELECTRIC POWER PLANTS
USING COOLING PONDS OR COOLING LAKES

POWER PLANT			COOLING POND OR LAKE CHARACTERISTICS					
Utility	Power Plant	1970 Cap	Source Makeup	Consump cfs	Surf acres	Volume acre-ft	Depth ft	Comments
Assoc Electric Co	Thomas Hill	483	Thomas Hill Res		4700			On Thomas Hill Res
Arizona Public Service Co	Cholla 4-Corners	114 575	Wells San Juan R	5 24	380 1200		5 40	Cap now 1370 MWe
Brazos Electric	R W Miller Nor Texas	75 75						
Carolina Power & Light	Asheville H F Lee H B Robinson Roxboro	206 402 206 1067	French Broad R Neuse R Black Cr Hyco Cr		320 575 2145 3750	9000 4600 43000 77000		Cap now 906 MWe
Central Louisiana Electric	Coughlin	483	Mountain Bayou Lake		~650			
Central Illinois Public Service	Coffeen	389	Lake Coffeen		1100	22000		On Lake Coffeen
City Public Service Board, San Antonio	V H Braunig	885	River	3 4	1250	26500		
Commonwealth Edison	Kincaid	1319	Natural Rain		2400	30000		
Dallas Power & Light	Mountain Cr North Lake	989 709	Mountain Cr City Dallas	5 4	800	17100		
Duke Power	Allen Buck Marshall River Bend	1155 443 1350 631	Lake Wylie Yadkin R Catawba R Catawba R		12500 10000 33000 3235	~82000 140000 300		On High Rock Lake On Lake Norman
Florida Power Corp	Avon Park	61	Lake Lotella		2500			On Lake Lotella
Georgia Power	Harlee Branch	1540	Lake Sinclair		15300	334000		
Houston Power & Light	W A Parish	1255	Dry Creek	15 5	2480	18700		Consumption Calc
Gulf States Utility Co	Sabine	952	Sabine R		44600			On Sabine Lake
Illinois Power	Baldwin	584	Kaskaskia R		2000	27000		
Interstate Power	Fox Lake	104	Fox Lake		~2500			On Fox Lake
Kansas City Power & Light	Montrose	563	Deep Water Cr		1700	25000		
Kansas Gas & Electric	Neosho	113	River	1	180	2160		
Lower Colorado River Auth	Sim Gideon	250	Colorado R	3 4	906	16593		
Madison Gas & Electric	Blount St	195	Lake Monona		~3500			On Lake Monona
Minnesota Power & Light	Aurora	116	Colby Lake					St Louis County
Mississippi Power & Light	Delta Rex Brown	220 383	Sunflower R Pearl R		640 382	6400 4000		
Oklahoma Gas & Electric	Horseshoe L	945	N Canadian R	6 7	300	900		
Public Service Comp Colorado	Valmont	273	Boulder R	5 5	531	11235		
Sierra Pacific Power Co	Ft Churchill	110	Wells	2 2	100	1500		
South Carolina Public Service Authority	Granger	163	Waccamaw Creek		330	2 5		Used to Temper Discharge
Southern Illinois Power Coop	Marion	99	Crab Orchard Creek		7500			On Crab Orchard Lk
Springfield Water Light & Power Co	Dallman Lakeside	80 146	Springfield L		3000			Both on Springfield Lk
Southwestern Electric Power	Knox Lee Lieberman Lone Star Wilkes	174 276 44 531	Cherokee Lake Caddo Lake Ellison Creek Johnson Creek		3500 31000 1516 651	150000 25000 10100		On Cherokee L On Caddo Lake On Ellison Res
Texas Electric Service	Eagle Mt Graham Handley Morgan Cr	310 615 523 846	Creeks	2 4 3 6	8500 2525 2200 1700	183000 52500 46000 32000		On Eagle Mt Lake On Lake Graham On Lake Arlington
Texas Power & Light	Lake Creek River Crest Stryker Valley	322 120 703 725	Brazos R Sulphur R Lake Stryker Red River	3 5	490 560 1000	7400 8300 15000		On Lake Stryker
Virginia Electric Power	Mt Storm	1140	Stony R	1	1120	47600		
West Texas Utilities	Lake Pauline Oak Creek Paint Creek San Angelo	44 81 126 105	Lake Pauline Oak Creek L Lake Samford Lake Nasworthy	22 74 74 1	625 2350 5450 1470	3750 39200 60250 10700		

TABLE A-2
LISTING OF STEAM-ELECTRIC POWER PLANTS
USING SPRAY COOLING

Utility	Power Plant	Capacity	Comments
Arkansas City Water & Light	Jonesboro	28	Combined with towers
Colorado-Ute Electric Assoc.	Nucla	39	Source make up wells
Commonwealth Edison	Quad-Cities*	1618	Closed spray-canal system to be ready in 1974-75. 1300 acre pond auxilliary spray units, closed system since Oct, 1971
	Dresden 2,3	1430	
Dallas Power & Light	Dallas	224	Combined with towers, wells provide makeup
Lower Colorado River Auth.	Comal	60	Combined with towers
Public Service Co. of Colorado	Cameo	66	Used only ~10% of time, otherwise once-thru cooling
Public Service Board San Antonio	Mission Road	164	Combined with towers
South Carolina Electric & Gas	Canadys	490	Used to temper before release in Edisto R.
Southwestern Public Service Co.	East	71	Both combined with towers
	Riverview	70	
Vineland Municipal	Vineland	55	12 MWe cooled by spray, rest with cooling tower
*with Iowa-Illinois Gas & Electric			

TABLE A-3

LISTING OF NUCLEAR POWER PLANTS NOT YET OPERATING
FOR WHICH POND OR LAKE COOLING IS INTENDED

Utility	Power Plant	Capacity	Comments
Carolina Power & Light	Shearon Harris	3600	Four units, startup 1977-80
Commonwealth Edison	LaSalle	2244	Two units, startup 1975,76
Consumer's Pwr.	Midland	1325	Two units, startup 1974,75
Duke Power	Oconee	2622	Three units, startup 1972-73
	McGuire	2360	Two units, startup 1975,77
Florida Power & Light	Turkey Point	1520	Two units, startup 1972-73
So. Carolina Elect. & Gas	Virgil C. Summer	918	Two units, startup 1976,81
Virginia Elect. & Power Co.	North Anna	3664	Four units, startup 1973,75,77, 78

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