EXPERIMENTAL AND ANALYTICAL STUDY OF THE
DESIGN OF SHALLOW COOLING PONDS

by

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ABSTRACT

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Submitted to the Department of Civil Engineering on 19 May 1977 in partial fulfillment of the requirements for the degree of Master of Science.

Cooling ponds for the dissipation of waste heat from steam-electric generation are frequently of the shallow, vertically well-mixed type. The desirable configuration of such shallow ponds is defined as one which will maximize surface heat transfer while damping fluctuations in plant intake temperature and minimizing construction and maintenance cost. An experimental and analytical study of shallow pond behavior is conducted with the goal of establishing pond design criteria which maximize the desired objectives.

Different internal baffle designs and two types of discharge structures, radial and rectangular, are tested with regard to steady-state heat transfer. In addition, transient laboratory studies of shallow ponds with a small deep reservoir section and a skimmer-wall intake are carried out to determine the damping effect on fluctuations in intake temperature.

All laboratory experiments are schematic, but care has been taken to assure that the thermal structure, as indicated by the vertical temperature gradient, is similar to actual shallow field cooling ponds. It is shown that an important scaling requirement is similarity of a non-dimensional parameter, the "pond number" which includes the effects of pond shape, depth, the circulating water flow rate and temperature rise, entrance mixing and interfacial friction. The experimental results are compared on the basis of a deficiency parameter which puts the actual pond performance on a relative scale of pond performance between the plug flow and the completely mixed pond.

An analytical model which describes the role of recirculating eddy zones in shallow cooling ponds has been formulated. For certain parameter conditions, the model indicates that recirculating eddies, caused by the entrance jet and internal baffle design, can reduce the pond performance below the completely mixed pond, which is usually taken as
the extreme case of cooling pond performance.

Based on the results of this investigation, the recommended pond configuration consists of a radial discharge structure, a moderate amount of baffling arranged to form a U-shaped flow path, and at the downstream end, a deep reservoir section combined with a skimmer-wall intake.

Thesis Supervisor: Gerhard H. Jirka

Title: Lecturer in Civil Engineering
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CHAPTER 1
INTRODUCTION AND OBJECTIVES OF STUDY

1.1 Introduction

In the production of useful electrical energy, all steam electric generating plants, both nuclear and fossil fueled, produce waste heat which must be disposed of in an environmentally acceptable manner. One method of effecting this disposal is the closed-cycle cooling pond or lake in which continuously circulating water receives waste heat in the condensers of the power plant, flows through the pond, thereby dissipating the heat to the atmosphere, and then back to the plant.

The efficient operation of a power plant depends not only on the capability of the pond to dissipate waste heat, however. A cooling pond should also damp out transient temperature fluctuations which arise due to diurnal cycling or other changes in meteorological conditions. These fluctuations in ambient conditions are an important factor in power plant operation, especially during peak loading conditions. In many U.S. utility systems, peak power demands occur in the late afternoon or early evening and thus during the same period in which ambient conditions may cause the cooling facility to be least effective in dissipating heat. The capability of a pond to damp out these transient conditions is highly desirable and is known as "thermal inertia".

Generally, the economics of pond construction and the available water supply dictate that the pond should be built as small as possible. Thus the designer of a cooling pond facility is faced with the problem of
maximizing the heat transfer from the pond surface, damping transient fluctuations and building a pond as small and as cheaply as possible.

1.2 Objectives of Study

A number of factors may affect the performance of a cooling pond—that is the extent to which the pond meets the aforementioned objectives of maximizing heat transfer while minimizing transient fluctuations and construction costs. Among the most important design parameters are the areal extent and depth of the pond, the placement and configuration of the discharge and intake structures, the use of internal dikes and baffles to direct the flow, and the power plant operating scheme (that is the combination of cooling water flow rate and its associated temperature rise incurred in the steam condensers). Judicious incorporation of the above factors can improve the performance of a pond of fixed surface area, but adequate, verified design criteria for shallow ponds are presently lacking. The objective of this study is to develop, through laboratory experimentation and analytical studies, specific guidelines for cooling pond design and to specify those factors which will combine to form the cooling pond which will best meet the aforementioned design objectives at a given location. The investigation is aimed at shallow ponds of the offstream or "perched" type and primary emphasis is placed on assessing the effect of varying discharge structures, baffle configurations, intake designs, and operating schemes.
CHAPTER 2

CLASSIFICATION OF PONDS

2.1 Deep Ponds (Well Stratified)

Cooling ponds may generally be classified as "deep" or "shallow" (Harleman, Jirka, Stolzenbach 1977). This classification is dependent not only on the actual pond depth, but upon pond shape and size, the temperature rise and flow rate of coolant through the condensers, and the degree of mixing at the pond entrance.

Deep ponds or lakes are distinguished by thermal stratification in which a thin buoyant layer of heated effluent floats upon a cooler deep reservoir. The heated upper layer is vertically isothermal and exhibits only horizontal temperature gradients due to surface cooling while in the deep reservoir the temperature gradients, if any, are vertical and the isotherms horizontal. An example of a deep stratified pond is given by the laboratory temperature profiles in Figure 2.1.

The degree of pond stratification and, hence, the distinction between deep and shallow may be quantified in several ways.

A simple measure of stratification is the normalized temperature gradient $\frac{\Delta T_v}{\Delta T_o}$ where $\Delta T_v$ is the average temperature difference between the surface and bottom of the pond and $\Delta T_o$ is the temperature difference between the pond inflow and outflow.

It is possible to correlate $\frac{\Delta T_v}{\Delta T_o}$ with a parameter made up of independent variables describing the cooling pond dynamics. This parameter called pond number, $P$, is defined (Harleman, et. al. 1977).
Figure 2.1 Vertical Isotherms of a Deep Stratified Pond

Figure 2.3 Vertical Isotherms of a Partially Stratified Pond
\[ IP = \frac{f_i}{\beta \Delta T_0 g H^3 W^2} \left( \frac{D_v}{H} \right)^{1/4} \]  

(2-1)

where \( f_i \) is an internal friction factor, \( Q_o \) is the condenser flow rate, \( D_v \) is the vertical dilution involved in the entrance mixing, \( L \) is the length of the flow path, \( H \) is the pond depth, \( \beta \) is the coefficient of thermal expansion of water at the appropriate temperature, \( \Delta T_0 \) is the difference in pond inflow and outflow temperatures, \( g \) is the gravitational constant, and \( W \) is the channel width. A correlation between pond number \( IP \) and the normalized temperature gradient \( \Delta T_v / \Delta T_0 \) is shown in Figure 2-2.

Vertical dilution, \( D_v \), may be calculated as a function of the modified discharge densimetric Froude number, \( F'_o \) (Jirka, Wood, and Harleman, 1976).

\[ D_v = 1 + 1.2(F'_o - 1) \]  

(2-2)

\[ F'_o = \frac{u_o \sqrt{\beta \Delta T_0 g (h_o b_o)^{1/2}}}{\Delta T_v} \]  

(2-3)

where \( u_o \) represents the velocity of the effluent at the discharge channel outlet, \( h_o \) is the depth of the discharge channel and \( b_o \) its half-width. Generally, a value \( D_v = 1.5 \) is taken as the minimum which can be attained in a deep pond (Ryan and Harleman, 1973).

For a pond to be classified as "deep", it must obey the criterion

\[ IP \leq 0.3 \]  

(2-4)
Figure 2.2 Correlation Between Pond Number, IP, and Normalized Temperature Gradient, $\frac{\Delta T_v}{\Delta T_0}$
The deep pond is a desirable configuration in two respects. First, the buoyancy of the surface layer spreads heated water to all parts of the pond, insuring that the entire surface area is effectively utilized for heat dissipation. Secondly, the deep reservoir is isolated from diurnal and short-term surface temperature fluctuations and responds only to long term meteorological variations with time scales on the order of the cooling pond residence time. The deep pond therefore exhibits high thermal inertia and a power plant withdrawing from the deep reservoir through a submerged skimmer-type inlet is isolated from temperature extremes which may affect efficiencies during periods of peak power demand.

Deep ponds or lakes are usually constructed by damming a river or stream creating an artificial impoundment. Sites for such a deep pond are not always available, however, and environmental regulations regarding the temperature and water quality of onstream impoundments may restrict power plants located on them to operating in an inefficient mode. Thus modern cooling ponds are often constructed as off-stream and "perched" ponds, i.e. the elevation of the pond surface is above the surrounding land and the pond is contained within artificial dikes. In order to minimize the cost of raising these dikes, most off-stream ponds are also of the "shallow type".

2.2 Shallow Ponds (Partially Stratified or Vertically Fully Mixed)

Shallow ponds, defined as having a pond number

\[ IP \geq 0.3 \]  

(2-5)
have the advantage of being free from temperature regulations if constructed off-stream. They do not, however, exhibit the distinct stratification of deep ponds and the thermal inertia effect is, hence, minimal. This lack of distinct stratification may be illustrated by contrasting Figure 2-3 showing temperature profiles for a partially stratified shallow laboratory pond with Figure 2-1. Based on the degree of stratification, shallow ponds may be further subdivided into partially stratified or vertically well-mixed. Partially stratified ponds exhibit slanted isotherms in a longitudinal cross-section and are characterized by having surface temperatures warmer than the underlying water as illustrated in Figure 2-3. Vertically well-mixed ponds exhibit vertical isotherms and are characterized by uniform temperatures from surface to bottom at any location as shown in Figure 2-4.

Buoyancy currents do not predominate in shallow ponds as in deep lakes and frequently internal baffles are used in an attempt to direct the throughflow to all portions of the pond. If not properly placed, however, currents created by these baffles or eddies set up by the discharge jet may cause short-circuiting of the flow and actually prevent efficient use of the pond surface area with a deterioration of pond performance.

Figure 2-5 showing the surface isotherms of a shallow cooling pond at Powerton, Illinois illustrates the use of baffling and the formation of eddies. In contrast, Figure 2-6 illustrating the deep pond at Maitland, Australia shows minimal eddy formation and uniform spreading of effluent across the main section of the pond.
\[ T_0 = 102.7 \]
\[ T_1 = 86.9 \]
\[ \frac{\Delta T_V}{\Delta T_0} = 0.013 \]
\[ IP = 1.0 \]

**Figure 2.4 Vertical Isotherms of a Vertically Well-Mixed Pond**
Figure 2.5  Surface Isotherms of Shallow Pond at Powerton, Illinois

Figure 2.6  Surface Isotherms of Deep Pond at Maitland, Australia
CHAPTER 3

CONCEPTUAL MODELS FOR STEADY-STATE COOLING POND PERFORMANCE

In order to understand the basic hydrodynamics of various cooling pond configurations as well as to provide preliminary information to the designer of a cooling pond on the effects of pond size, entrance mixing, and condenser flow rate, some simple, steady-state pond models are reviewed here. Before the analytical models can be utilized, however, an understanding of the concepts of equilibrium temperature and of linearized surface heat flux is necessary.

3.1 Equilibrium Temperature and Surface Heat Flux

Equilibrium temperature is the theoretical temperature of a natural body of water at which incoming heat fluxes due to solar and atmospheric radiation are exactly balanced by outward fluxes due to evaporation, back radiation, and conduction. Equilibrium temperature, \( T_{E,\text{in}}^{\text{OF}} \) may be calculated iteratively by the method of Ryan and Harleman (1973) as

\[
T_{E} = \frac{\phi_{r} + f(w)[\beta^{*} T_{d}^{\text{w}} + 0.255 T_{a}^{\text{w}}] - 1600}{23 + f(w)(\beta^{*} + 0.255)}
\]  

(3-1)

where \( \phi_{r} \) is the radiative flux into the pond, \( T_{d} \) is the ambient dew point temperature in \( F^{o} \), \( T_{a} \) is the ambient air temperature in \( F^{o} \), \( \beta^{*} \) is a proportionality factor and \( f(w) \) is a wind speed function used in calculating evaporation. The factor \( \beta^{*} \) may be calculated

\[
\beta^{*} = 0.255 - 0.0085 \left( \frac{T_{E} + T_{d}}{2} \right) + 0.000204 \left( \frac{T_{E} + T_{d}}{2} \right)^{2}
\]  

(3-2)
and \( f(w) \) for a natural water surface is given as:

\[
f(w) = 14W_2 \quad (3-3)
\]

where \( W_2 \) is the windspeed in mph measured at two meters above the water surface.

Equilibrium temperature is obtained recursively by assuming a value \( T_E \), calculating \( \beta^* \) by Eq. (3-2), and then calculating a new \( T_E \) via Eq. (3-1). The new value of \( T_E \) is used to obtain a new \( \beta^* \) until the \( T_E \) obtained from Eq. (3-2) matches the value used in the previous iteration.

Once equilibrium temperature is obtained, the surface heat loss from a pond, \( \phi \), (in BTU/ft\(^2\)-day) may be calculated

\[
\phi = -K(T_s - T_E) \quad (3-4)
\]

where \( K \) is a surface heat loss parameter and \( T_s \) is the pond surface temperature. The parameter \( K \) is a non-linear function of surface temperature which itself varies throughout the pond. Thus heat loss from the pond surface is a non-linear, non-uniform process. To make analytical models tractable, however, \( K \) is assumed to be linear and is calculated at an average pond surface temperature, \( \overline{T_s} \). The value of \( K \) is obtained as

\[
K = \frac{(\phi_{in} - \phi_{out} - \phi_{e+c})}{\overline{T_s} - T_E} \quad (3-5)
\]

where \( \phi_{in} \) is the sum of short and long wave radiation into the pond, \( \phi_{out} \) is the long wave radiation out of the pond, \( \phi_{e+c} \) is the sum of evaporative and conductive heat flux out of the pond, and \( \overline{T_s} \) is the average pond
surface temperature. Formulas for evaluating $\phi_{in}$, $\phi_{out}$, and $\phi_{e+c}$ in
the field and in the laboratory are given in Appendix II.

3.2 Traditional Models

Utilizing the concepts of equilibrium temperature and linearized
surface heat flux reviewed in Section 3.1, a number of analytical steady
state models may be formulated. Two of the simplest models are the
plug-flow and completely mixed ponds.

In a plug-flow pond, there is no mixing between the heated dis-
charge and the receiving waters and no dispersion along the flow path.
The governing heat conservation equation is

$$\frac{Ud(T-T_E)}{dx} = -\frac{K}{\rho c d} (T-T_E)$$  \hspace{1cm} (3-6)

where $U$ is the cross-sectional average velocity of the pond, $T$ is the
surface temperature at any distance $x$ from the inlet, $d$ is the pond depth
and $\rho$ and $c$ are the density and specific heat of water, respectively.
The solution of Eq. (3-6) is the classic exponential decay equation

$$T^*_i = e^{-r}$$  \hspace{1cm} (3-7)

where $T^*_i$ is a normalized intake temperature

$$T^*_i = \frac{T_i-T_E}{T_o-T_E}$$  \hspace{1cm} (3-8)
and \( r \) is the pond cooling capacity

\[
    r = \frac{KA_p}{\rho cQ_o}
\]  

(3-9)

In Eq. (3-8), \( T_1 \) is the intake temperature of the flow into the power station (and out of the pond) and \( T_o \) is the discharge temperature of the flow out of the power station (and into the pond). In Eq. (3-9), \( A_p \) is the pond surface area and \( Q_o \) is the condenser flow rate.

In contrast to the plug-flow pond is the fully mixed pond in which the inflow is immediately mixed and dispersed throughout the pond, corresponding to infinite entrance mixing and dispersion. For the completely mixed pond, \( T^*_1 \) is given

\[
    T^*_1 = \frac{1}{1+r}
\]  

(3-10)

Neither the plug-flow nor completely mixed models are realistic since some entrance mixing and dispersion is always present, but infinite mixing is unlikely. Although they were much used in the past, reflecting on incomplete understanding of cooling pond hydrodynamics and surface heat transfer, the present usefulness of these models is limited to providing theoretical limits on cooling pond performance. The plug flow pond provides a best case, lowest estimate of \( T^*_1 \) and the completely mixed pond provides a worst case, highest estimate, assuming the entire pond surface is utilized.

A number of improved analytical models which include more realistic descriptions of entrance mixing, dispersion and eddy formation have been developed and are described in Section 3.3 and 3.4.
3.3 Shallow Pond Models

Entrance mixing in cooling ponds is generally a three-dimensional process with receiving water entrained into the discharge jet from both the sides and bottom. For a shallow pond in which the depth of the discharge jet is on the order of the pond depth, however, vertical mixing will be greatly inhibited by interference of the jet and the pond bottom. The amount of lateral mixing will then be determined by the pond and discharge jet geometry allowing two shallow pond models to be formulated; a dispersive pond in which lateral mixing is negligible and a recirculating pond in which lateral mixing is predominant.

3.3.1 The Dispersive Pond

For shallow ponds with long, narrow flow paths as in the Collins Pond of Fig. 3.1, lateral mixing as well as vertical mixing will be suppressed and a dispersive model is appropriate. The dispersive model is similar to the plug-flow model except a dispersion term, $E_L$, is incorporated to account for the heat dispersion caused by cross-sectional velocity non-uniformities likely to be encountered in a shallow, relatively narrow pond. The governing equation, including the dispersive term becomes

$$\frac{Ud(T-T_E)}{dx} = \frac{E_L d^2(T-T_E)}{dx^2} - \frac{K}{pcd} (T-T_E) \tag{3-11}$$

where $E_L$ is the longitudinal dispersion coefficient for the pond. A solution, adapted from Wehner and Wilhelm (1956) is

$$T_1^* = \frac{4a \exp\left[\frac{1}{2E^*}\right]}{(1+a)^2 \exp\left[\frac{a}{2E^*}\right] - (1-a)^2 \exp\left[-\frac{a}{2E^*}\right]} \tag{3-12}$$

where $a$ is given as
\[ a = 1 + 4rE^* \]  

(3-13)

E is a dispersion number defined

\[ E^* = \frac{E_L}{uL} \]  

(3-14)

and L is the length of the flow path through the pond.

Fischer (1967) gives a method for evaluating longitudinal dispersion in channels with a large width to depth ratio as

\[ E_L = 0.3 \frac{u* \ell}{K^2 R_h} \]  

(3-15)

where \( u^* \) is shear velocity, \( \ell \) is a characteristic length (the distance from maximum surface velocity to the most distant bank), \( K \) is von Karman's constant, and \( R_h \) is hydraulic radius.

3.3.2 The Recirculating Pond

As the width of a cooling pond increases relative to its length and relative to the width of the discharge channel, the potential for lateral mixing and dilution increases. This is especially so if the discharge is oriented perpendicular to the longitudinal axis of the pond creating a large eddy. In this case, a recirculating pond model may be schematized as in Fig. 3.2. The recirculating model features a forward jet zone and a return or entrainment flow zone with the jet zone occupying a fraction \( b \) of the total pond area. Flow in the forward zone is given as \( D_s Q_0 \) and in
Figure 3.1 Example of a Dispersive Pond at Collins, Illinois
Figure 3.2 Schematic Plan View of Shallow Recirculating Pond

Figure 3.3 Schematic Elevation of Deep Pond
the return zone as \((D_s - 1)Q_o\) where \(D_s\) is a dilution factor.

Using plug-flow relationships for the forward and return zones, and appropriate entrance mixing relationships, an analytical predictive model for the recirculating pond may be developed.

The governing equation of the jet flow region is

\[
\frac{U_{\text{jet}} d(T + T_E)}{dx} = \frac{-K}{pcd} (T - T_E) \tag{3-16}
\]

In this case the velocity, \(U_{\text{jet}}\), is given by

\[
U_{\text{jet}} = \frac{Q_o D_s}{bWd} \tag{3-17}
\]

where \(W\) is the total pond width. Noting that \(bWdx = dA_{\text{jet}}\) leads to

\[
\frac{d(T - T_E)}{dA_{\text{jet}}} = \frac{-K(T - T_E)}{pcQ_o D_s} \tag{3-18}
\]

The temperature into the jet zone, \(T_m\), is the mixed temperature of the flow leaving the return zone, \(T_p\), and the flow into the pond, \(T_o\).

\[
T_m = \frac{T_o + (D_s - 1)T_p}{D_s} \tag{3-19}
\]

Using \(T_m\) as a boundary condition yields the solution to (3-18)

\[
\frac{T_i - T_E}{T_m - T_E} = e^{-r_1} \tag{3-20}
\]

where
\[ r_1 = \frac{KA_{jet}}{\rho c D_s Q_o} \]

In a similar fashion to the jet zone, the temperature of the flow in the return zone is given by

\[ \frac{T_p - T_E}{T_i - T_E} = e^{-r_2} \]

where

\[ r_2 = \frac{KA_{return}}{\rho c (D_s - 1) Q_o} \]

Combining equations (3-19), (3-20), and (3-21) yields the final solution for the recirculating pond

\[ T^*_i = -\frac{rb/D_s}{e^{r(D_s - b)/(D_s^2 - D_s)}} \]

\[ D_s - (D_s - 1) e \]

This model differs from the less realistic model of Ryan and Harleman in that the flow in the forward and return zones need not be proportional to their respective flow rates. For ponds with more than one recirculating compartment this newer model may be applied consecutively to each segment as in modelling the Powerton Pond of Fig. 2.5.

Use of the recirculating model requires estimation of two parameters, \( D_s \) and \( b \). Inspection of experiments on circulations in closed tanks by Iamondi and Rouse (1969) and Abramovich (1963) indicate values of \( b = 0.25 \) to 0.40, i.e., the jet zone is smaller than the return zone. Lateral entrance mixing in a shallow pond without significant stratification may
be evaluated using the formula of Albertson (1950)

$$D_s = 0.62 \sqrt{\frac{L_{jet}}{2b_o}}$$ (3-23)

where $L_{jet}$ is the length of the jet path and $b_o$ is the jet half width. Typical values of $D_s$ are 1.5 to 2.5.

3.4 The Deep Pond

In a deep pond, as determined by Eq. (2-4), vertical entrance dilution is predominant and lateral dilution generally negligible. This pond may be schematized as in Fig. 3.3. Plug-flow, exponential decay is assumed in the surface layer, the dilution, $D_v$, is calculated from Eq. (2-2) and the dilution water is assumed to be at the temperature of the flow leaving the pond. In the absence of preliminary information, use of the minimal entrance mixing for a well-designed pond, $D_v = 1.5$, is advised. A solution to this model, given by Ryan and Harleman (1973), is

$$T_i^* = \frac{-r/D_v}{e^{\frac{-r/D_v}{D_v-(D_v-1)e}}}$$ (3-24)

The cases of plug-flow ($D_v = 1$) and complete mixing ($D_v \gg 1$) result as limiting cases of Eq. (3-24).

3.5 The Deficiency Parameter

In an experimental study of cooling pond configuration and design alternatives, a measure is needed by which to compare the performance of the different ponds tested. The normalized intake temperature alone, $T_i^*$, is not a good measure due to its strong dependence on the cooling capacity,
In comparing ponds at different $r$ values, it is difficult to discern changes in $T_1^*$ due to varying $r$ from changes due to different pond configurations. Thus a measure of pond performance independent of $r$ is needed.

A second measure which is only weakly dependent on $r$ has been adopted in this study; the deficiency, $D$, defined as

$$D = \frac{T_1^* - T_p^*}{T_m^* - T_p^*}$$  \hspace{1cm} (3-25)

where $T_1^*$ is the normalized intake temperature of the pond in consideration, $T_p^*$ is the normalized intake temperature of an ideal plug-flow pond of the same cooling capacity $r$ (obtained from Eq. (3-7)) and $T_m^*$ is the normalized intake temperature of a completely mixed pond also of the same cooling capacity $r$ (obtained from Eq. (3.10)).

The deficiency indicates how closely a pond approaches ideal plug-flow performance. Lower values of deficiency indicate better pond performance with the limiting value, $D = 0$, denoting ideal performance. A deficiency value, $D = 1.0$, indicates performance equivalent to a fully mixed pond, which is usually the worst case except for ponds with strong recirculation patterns which may exhibit deficiencies greater than unity.

The superiority of the deficiency parameter over $T_1^*$ is shown in Figs. 3.4 and 3.5. Fig. 3.4 is a plot of $T_1^*$ vs. $r$ for each model described in this chapter using typical parameters for dilution, dispersion, and short-circuiting. It illustrates both the relative performance of these ponds and the strong dependence of $T_1^*$ on $r$. Fig. 3.5 is a plot of deficiency vs. $r$ for the same models. Deficiency is seen to be almost independent of the cooling capacity. These figures also illustrate the potential for a recirculating pond to have a deficiency greater than one.
Figure 3.4 $T_1^*$ vs $r$ for Conceptual Pond Models

Symbols are the same as Figure 3.4

Figure 3.5 Deficiency vs $r$ for Models Illustrated in Figure 3.4
CHAPTER 4

LABORATORY EXPERIMENTS

4.1 Scaling Parameters

There are two objectives towards which laboratory studies of cooling ponds may be oriented: direct scale modelling and diagnostic modelling. With a direct scale model, an attempt is made to reproduce, in a predictive sense, the three dimensional temperature field of a prototype. In contrast, diagnostic models attempt to reproduce only the general thermal structure of a prototype rather than its exact temperature field and are useful for isolating and examining the parameters governing pond behavior and for analyzing the effects of varying design parameters such as discharge and intake orientation, baffle configuration, and depth. Thus the object of diagnostic models is a schematic representation of cooling ponds.

4.1.1 Application of Direct Scale Models

For a model to be an exact replica of a prototype cooling pond, it must obey several similitude requirements formulated by the modeler who must discern the physical processes most important in determining prototype behavior and select similarity parameters which will insure corresponding physical processes in the model.

In a direct scale model, a functional relationship of the three-dimensional steady state temperature field with the following physical variables may be postulated.
\[ T - T_E = f(A, L, H, Q_o, a_o, K, T_o - T_E, g, \beta, \rho, c, f_i) \]  \hspace{1cm} (4-1)

where \( T \) is the pond temperature at any point, \( T_E \) is the equilibrium temperature, \( A \) is the pond surface area, \( L \) is the length of the through-flow path, \( H \) is the pond depth, \( Q_o \) is the condenser flow rate, \( a_o \) is the characteristic width of the discharge channel, \( K \) is the surface heat loss coefficient, \( T_o \) is the condenser discharge temperature, \( g \) is gravitational acceleration, \( \rho \) is the coefficient of thermal expansion of water, \( \beta \) and \( c \) are the density and specific heat of water, and \( f_i \) is an interfacial friction factor for stratified flows.

Eq. 4-1 includes eleven physical variables and a non-dimensional variable involving five basic dimensions: length, time, mass, heat, and temperature. Thus using the Buckingham theorem, the functional variables of Equation 4-1 may be arranged into seven non-dimensional independent parameters

\[ \frac{T - T_E}{T_o - T_E} = f\left(\frac{A^{1/2}}{L}, \frac{L}{H}, \frac{Q_o}{a_o^{3/2}(g\beta(T_o - T_E))^{1/2}}, \frac{Q_o}{LH(g\beta(T_o - T_E)H)^{1/2}}, \frac{Q_o}{LH(gH)^{1/2}}, \frac{KA}{\rho c Q_o}, \frac{f_i L}{H}\right) \]  \hspace{1cm} (4-2)

The first two parameters are shape factors. The third parameter is a discharge densimetric Froude number; the fourth is a pond densimetric Froude number and the fifth is a free-surface pond Froude number. The sixth parameter is the cooling capacity, \( r \), and the last one is a measure of friction forces in the pond.
For the model to be perfectly scaled, equivalence between model and prototype of each dimensionless parameter of Equation 4-2 is required. This equivalence is not possible, however, since certain physical parameters, i.e. \( g, c, \) and \( \rho \) cannot be reduced from prototype to model as can length, dimensions and flow rate. Thus some similitude requirements must be relaxed and the model distorted. Jirka, Abraham and Harleman (1975) have shown that the distortion and scaling requirements of different model regions, e.g. the discharge jet and heat loss region, are not compatible, however, limiting the applicability and accuracy of a direct scale model. In addition, features of concern in prototype design such as variable meteorological conditions cannot be accurately reproduced in the laboratory placing further limitations on the usefulness of this modelling approach. Thus the application of predictive mathematical models in conjunction with diagnostic experiments, as described below, appears to be a better approach to modelling prototype behavior.

### 4.1.2 Application of Diagnostic Models

Diagnostic models are much less rigorous in their similitude requirements than direct scale models. In a diagnostic model it is desired to reproduce only the pond thermal structure as measured by the parameter \( \Delta \overline{T}_v/\Delta T_o \) where \( \Delta \overline{T}_v \) is the average temperature difference between the surface and the bottom of the pond and \( T_o \) is the temperature difference between the pond inflow and outflow. In Chapter 2, it has been shown that this measure of thermal structure is dependent on pond number, \( \Pi_p \) (Equation 2.1) and the dependence can be expressed
\[
\frac{\Delta T_v}{\Delta T_o} = f \left[ \frac{f_i D_v Q_o^2}{g \beta \Delta T_o H^A A^{1/2}} \right]^{1/4}
\] (4-3)

Thus, equivalence of thermal structure between model and prototype can be assumed to be guaranteed by equivalence of the pond number, IP.

In diagnostic modelling, no attempt is made to exactly model any prototype. Some preliminary prototype data for scaling the laboratory pond is useful, however. Using field data in the form of the vertical temperature distribution of the prototype, it is possible to construct a schematic laboratory pond by ensuring similarity of the pond number. Pond number similarity, in turn, is ensured through similarity of vertical dilution, of geometry, and of buoyancy forces.

(a) **Similarity of Entrance Mixing**

To insure similarity of thermal structure, similarity of the entrance mixing characteristics of model and prototype is needed. This requirement may be stated that the ratio of vertical dilution in model and prototype be unity

\[
D_{v_r} = 1
\] (4-4)

Vertical dilution is a function primarily of discharge densimetric Froude number (Equation 2-3) and of pond geometry

\[
D_v = f(F_o^*, \text{geometry})
\] (4-5)

In a deep pond, however, the effect of geometry on a well-designed discharge structure is minimal and dilution may be assumed to be a function of \( F_o^* \) alone. Similarity in dilution between a deep prototype and model
can then be achieved by designing the model discharge such that the discharge densimetric Froude number is less than one

\[ F'_o < 1 \] (4-6)

and a cold entrance wedge is formed guaranteeing minimal mixing as in a well-designed prototype. For a review of this design procedure, see Ryan and Harleman (1973).

In a shallow pond, vertical mixing is inhibited by the pond bottom and dilution is primarily a function of geometry. Similarity is thus achieved by constructing a model with the same entrance geometry, i.e., discharge orientation and shape, as the prototype.

(b) **Geometric Similarity**

The laboratory model need not be shaped exactly as the prototype. It is desirable to roughly preserve the geometry, however, by maintaining in the model the prototype ratio of surface area to length. This criteria may be stated

\[ \left( \frac{A^{1/2}}{L} \right)_{r} = 1 \] (4-7)

and should be satisfied by the initial design and construction of the model.

(c) **Similarity of Buoyant Forces**

The degree of pond stratification may be considered to be the result of a balance between a driving head force, \( \beta \Delta T_o \), and a counter-acting friction force, \( f_{zL/H} \). Similarity of stratification between model
and prototype is crucial to the modelling effort and is guaranteed by setting the ratio of the governing forces between model and prototype equal to unity

\[(\beta \Delta T_o) = 1 \quad \text{(4-8)}\]

\[(f_1L/H)_r = 1 \quad \text{(4-9)}\]

It is difficult to specify these forces in the model a priori, however, and instead an empirical approach which compares the structure of preliminary laboratory models with the prototype is necessary.

The simplest method of achieving equivalence of the term \(\beta \Delta T_o\) is to run the model in the prototype range of \(T_o\) and \(\Delta T_o\). The coefficient of thermal expansion, \(\beta\), is a function of the pond temperature and setting the lab pond temperature approximately equal to the characteristic prototype temperature should guarantee equivalence of \(\beta\). The appropriate value of \(\Delta T_o\) is obtained by running the laboratory experiment with different combinations of discharge and equilibrium temperature until a value of \(T_o - T_E\) which results in the desired temperature difference \(\Delta T_o\) across the pond is obtained.

(d) Similarity of Frictional Forces

The modeller must also assure equivalence of the friction term \(f_1L/H\). Rearranging (Equation 4-9) yields

\[(f_1)_r = (H/L)_r \quad \text{(4-10)}\]
indicating the friction ratio is a function of the depth to length ratio.

Maintenance of the prototype proportions of depth and length in the model would result in an unreasonably shallow model with strong laminar friction. Generally, the model must be distorted such that

\[
\frac{L}{H}_{\text{model}} = \frac{1}{\Delta} \frac{L}{H}_{\text{prototype}} \tag{4-11}
\]

where \(\Delta\) is the distortion given by

\[
\Delta = \left( f_i \right) \frac{1}{r} \tag{4-12}
\]

Equation (4-12) shows the distortion should be chosen as the ratio of internal friction factors of the model and prototype. While some knowledge exists of prototype values of \(f_i\) (Jirka, et al, 1975) a priori specification of \(f_i\) in the model is uncertain and an iterative process is undertaken in which a value of \(\Delta\) is selected and experiments performed to verify that the thermal structure \(\frac{\Delta T}{\Delta T_o} \frac{V}{V_o} \) observed in the model does, indeed, replicate the thermal structure of the prototype \(\frac{\Delta T}{\Delta T_o} \frac{V}{V_o} \). If the thermal structure is not replicated, new values of \(\Delta\) should be chosen until a satisfactory agreement is reached.

4.1.3. Calibration and Verification of the Lab Model

The objectives of this study suggested the use of diagnostic laboratory experiments. The Powerton cooling pond of Fig. 2.5 was selected as a typical shallow, partially stratified pond and used to provide preliminary data for scaling the lab pond. The Powerton pond has an area \(A = 1426\) acres, an average depth \(H = 10\) ft, and services two 893 \(\text{MW}\) generating units.
each with a condenser flow rate of \( Q_o = 769 \text{ ft}^3/\text{sec}. \)

The laboratory pond available for this study had a surface area of approximately 650 ft\(^2\), fixing the area ratio of the model to prototype as

\[
A_r \approx \frac{1}{9 \times 10^4}
\]

and the horizontal length ratio as

\[
L_r = \sqrt{A_r} = \frac{1}{300}
\]

The lab pond was shaped such that the geometry requirement of (Equation 4-7) was roughly satisfied. The laboratory pond was divided into compartments to resemble Powerton and a discharge structure was constructed and oriented so as to obtain equivalence of dilution.

The model calibration procedure consisted of selecting a temperature rise, \( T_o - T_e \), and distortion, \( \Delta \), iteratively until similarity of thermal structure of Powerton and the laboratory pond was obtained.

The depth of the laboratory pond corresponding to the specified distortion was obtained via the relationship

\[
\frac{H_{\text{model}}}{H_{\text{prototype}}} = \Delta \cdot \left[ \frac{A_{\text{model}}}{A_{\text{prototype}}} \right]^{1/2}
\]

and the flow rate was obtained by assuming equivalence of pond number in model and prototype

\[
F_r = 1
\]
Using the relationships \( f_r = \Delta, (D_r) = 1, (\Delta T_v) = 1, (H_r) = \Delta A_r^{1/2} \)
and (Equation 4-16) the following is obtained

\[
Q_r = \Delta^{3/2} A_r^{5/4} 
\]  

(4-17)

Satisfactory results were obtained for a distortion

\[
\Delta = 7.5
\]  

(4-18)

yielding \( H_{model} = 0.25 \) ft and \( Q_{model} = 0.02 \) ft\(^3\)/sec for two unit operation of the pond.

This distortion and selection of parameters is verified by comparing the surface isotherms and vertical profiles for the schematic three compartment laboratory pond with the Powerton Pond. Figure 4.1, illustrating the surface isotherms for a laboratory pond, compares well with the isotherms of the Powerton Pond (Fig. 2.5) verifying the similarity of surface circulation patterns. Figure 4.2 showing the vertical isotherms of the Powerton Pond is one method of illustrating the stratification of the prototype. Figure 4.3 is a similar plot for the model showing the same partial stratification as the prototype. The model and prototype also show a correspondence in pond number and in \( \Delta T_v/\Delta T_o \) confirming the success of the model in duplicating the Powerton thermal structure.

4.2 Facilities and Instrumentation

4.2.1 Physical Facilities

Laboratory investigations conducted in the course of this study were carried out in a 17.7' by 35.7' by 1.0' basin in the Ralph M. Parsons laboratory of M.I.T. The basin walls were constructed of 9" thick cinderblocks while the floor was of 1.5" cinderblocks resting on one inch of
Figure 4.1 Surface Isotherms for a Shallow Laboratory Pond Corresponding to Powerton Pond
Figure 4.2 Vertical Isotherms of Powerton Pond,
\( \Pi^2 = 0.48, \frac{\Delta T_V}{\Delta T_o} = 0.18 \)

Figure 4.3 Vertical Isotherms of a Laboratory Pond,
Corresponding to Powerton Pond \( \Pi^2 = 0.46 \)
\( \frac{\Delta T_V}{\Delta T_o} = 0.28 \)
styrofoam insulation and sand to minimize heat loss to the concrete floor. A vinyl swimming pool liner sandwiched between the styrofoam and cinderblocks and mounted to the basin walls insured the pond was waterproof.

Hot water to simulate the power plant effluent was supplied by a steam heat exchanger capable of supplying a flow of up to 28 gallons per minute at a temperature up to 150°F. Tap water supplied through a mixing valve was used to dilute water from the heat exchanger to desired temperatures. The heated influent was then introduced to the pond through a Brooks rotameter of 3 to 27 gal/min capacity allowing continual measurement and control. A .75 horsepower pump was used to provide withdrawal which was monitored through another rotameter. By regulating the inflow and outflow, it was usually possible to maintain the pond level within 0.01 ft of the desired depth as measured with a fixed point gauge. A schematic of this set-up is provided in Figure 4.4.

Flow was introduced into the pond via a rectangular plywood entrance "canal" approximately 18" long, 11" wide, and 11" deep with provisions for a variable width orifice (See Fig. 4.5). The orifice dimensions were usually fixed at 11" wide by 2" deep. Alternately, a radial discharge of 2 ft radius inscribing a 90° arc and provided with vanes to direct the flow was employed (Fig. 4.16). In both discharges, flow was forced through gravel and "horsehair" filters to reduce momentum and insure uniform flow distribution.

Outflow was withdrawn from the pond through a 1 ft wide by 1 ft long outlet structure separated from the pond by a skimmer wall 1.5 ft wide having a 0.5" bottom opening. Both inlet and outlet structures were
Figure 4.5 Rectangular Discharge Structure

Figure 4.6 Radial Discharge Structure
connected to the rotameters via 1" hose allowing the inlets and outlets to be located in any portion of the pond.

4.2.2 Instrumentation

Temperatures throughout the pond were measured by approximately 60 Yellow Springs Instruments Series 708 temperature probes. The probes were spaced throughout the pond (a plan of a typical configuration is shown in Figure 4.7) and mounted in a horizontal plane on a motorized frame capable of traveling in a vertical direction allowing temperatures at any depth of the pond to be measured. (Figures 4.8 shows the frame set up in the lab basin.) In addition to probes mounted on the frame, two probes each were permanently situated in the discharge hose, intake structure, and equilibrium tank. All probes were scanned via a Data Entry Systems Console-Premier scanner producing both a printed record of temperatures and punched paper tape for computerized data analysis.

Equilibrium temperatures were measured directly using a shallow insulated tank filled with approximately 1 inch of water. The tank, measuring 3.5' x 3.5' x 0.25' was constructed of plywood lined with plastic sheet for waterproofing and insulated with 0.25' of fiberglass to prevent heat loss through the sides and bottom (see Figure 4.9). A YSI Model 91 Dew Point Hygrometer was used to measure both air temperature and dew point.

4.2.3 Dye Studies

Insight into the behavior of experimental pond configurations, independent of temperature measurements, was gained through the instantaneous
Figure 4.7 Plan View of Temperature Probe Locations
Figure 4.8  Motorized Frame in Laboratory Basin

Figure 4.9  Equilibrium Tank and Intake Structure
injection of 50 cc of fluorescent Rhodamine WT dye (10 ppt concentration) into the heated influent. The highly visible red dye provided visual studies of the flow pattern and stratification of the pond as well as a Unit Impulse Response Curve for each configuration. The curves were obtained by periodically sampling coolwater outflow for analysis in a Turner Model III Fluorometer calibrated to detect concentrations in the range of 0 to 500 parts per billion. The results of the analyses were then converted into plots of concentration in the outflow vs. time elapsed since injection. In addition to instantaneous injections an apparatus was also available to provide continuous dye injections for further visual analysis.

4.3 Run Procedure

Experiments were initiated by specifying the type of discharge to be used (rectangular or radial), the location of discharge and intake structures, the internal baffle configuration and flow rate. The internal baffles were constructed from 1.5" thick cement blocks fastened to the floor and each other with a sealing compound. The seal was non-permanent and the baffles were easily removed or relocated.

Next, the basin was filled from an indoor reservoir and the equilibrium temperature monitored. The inflow temperature for the run was decided as a function of the equilibrium temperature. Experience showed an inflow temperature approximately 40 to 45°F above equilibrium provided the desired temperature difference of 20 to 30°F between inflow and outflow.

The experiment was run and outflow temperature monitored until a steady-state condition was reached - usually 8 to 24 hours. Steady state was judged to occur when no change was observed in outflow temperature
between hourly readings. Frequently, due to changes in laboratory
equilibrium temperature no steady outflow temperature was observed. In
this case, steady-state was judged to occur when no change in the differ-
ence between outflow and equilibrium temperatures was observed over an
hourly period. Figure 4.10 is a plot of a typical temperature history
for a run and illustrates conditions adjudged to be steady-state.

At the occurrence of steady-state, measures of inflow temperature,
outflow temperature, and equilibrium temperature were taken as well as
readings of air temperature and dew-point. Simultaneously, the tempera-
ture probes throughout the pond were scanned and recorded while the
probes were lowered, at half-inch intervals from the surface to the bottom
of the pond.

Steady outflow temperatures were interpreted to mean steady
physical conditions in the pond as well and at this point the Rhodamine
was injected via a 50 cc syringe into the hose immediately upstream of
the discharge structure. This procedure was followed to insure uniform
mixing of the dye solution in the influent. When the dye was observed
to be approaching the pond outlet, samples of outflow were withdrawn
from a siphon in the hose downstream of the outlet structure. Samples
were withdrawn at 3 to 30 minute intervals until the dye appeared to be
flushed from the system - usually three to six hours. At this point,
the experiment was terminated.

4.4 **Data Reduction**

Data from the experiments consisted principally of temperature
records and dye analyses. The punched tape temperature records were
read onto a computer disc pack and converted via a data reduction program
Figure 4.10 Temperature History of an Experiment Illustrating the Occurrence of Steady State
into planar isotherms at recorded depths. A data reduction program also provided records of the parameters of each experiment and computed deficiency and other measures. Temperature records were also converted into vertical profiles at selected locations providing information on the vertical structure of the pond.

The results of the dye analysis were converted into plots of dye concentration vs. time elapsed since injection. These plots, known as Unit Impulse Response Curves, provided information for each configuration on the effective residence time, and the presence of short-circuiting and dead zones.

4.5 Sensitivity Analysis of Experimental Parameters

In any experimental study, there will be uncertainty regarding the values of some experimental parameters. An effort is made in this section to quantify the uncertainty involved in this study and to analyze the possible effects on the reported results.

Experimental uncertainty was judged most likely to occur in the parameters $T_o$, $T_i$, $T_E$, and $K$. Uncertain values of $T_o$ arise due to fluctuations in the performance of the steam heat exchanger and to variations in the pressure and temperature of the local water supply used to feed the heat exchanger and to mix with the heated water. Figure 4.11 shows this variation of $T_o$ (as well as $T_E$ and $T_i$) within one hour. The inflow temperature was regularly monitored and usually kept within $\pm 0.5F^\circ$ of the desired value and the reported values are averages of hourly readings commencing three to four hours before completion of the experiment.
Figure 4.11 Variation of $T_o$, $T_i$ and $T_E$ Within One Hour

Figure 4.12 Calculated vs Measured Equilibrium Temperatures
Uncertain values of $T_1$ arise as a reflection of variations in $T_0$ and as a result of changes in ambient laboratory conditions. The determination of steady state as defined in Section 4.3 should be understood to mean that no change in the average value of $T_1$ occurred over a hourly period or that the change in the average value of $T_1$ relative to the change in $T_E$ was zero. Reported values of $T_1$ are thus time averages and it is felt errors as large as ±0.3°F may be involved in their determination.

Uncertainty in the evaluation of $T_E$ and $K$ are linked to each other. Figure 4-11 shows equilibrium temperature did not fluctuate in a random fashion about a mean but changed monotonically as a result of changing laboratory conditions. Thus the measurements of $T_E$ involve little error yet the measured values often differ from the values of $T_E$ as calculated by Equation 3-1, occasionally by 1°F or more. Figure 4-12 illustrates this difference.

The discrepancies in the measured and calculated values of $T_E$ are probably due to drafts in the laboratory which enhance heat transfer and to changes in ambient air temperature and dew point not immediately reflected in the damped reponse of the equilibrium tank.

Factors resulting in errors in the calculation of $T_E$ may also cause errors in the calculation of $K$, the surface heat transfer coefficient which is needed to obtain the parameters $T^*_p$ and $T^*_m$ used in calculating deficiency. It is difficult to determine the magnitude of uncertainty in $K$, but for the purposes of sensitivity analysis, a variation of 5% is assumed.
Uncertainty in the values of $T_0$, $T_1$, $T_E$ and $K$ can greatly affect the determination of deficiency, a parameter of prime importance in this study. To estimate this effect, a sensitivity analysis was performed by singly varying $T_1$, $T_0$, $T_E$ by $0.25F^0$ and $K$ by $5.0\%$. The deficiency obtained using the modified values was then compared to the reported value. Some typical and extreme sensitivities are given in Table 4-1. The reported value of deficiency was found sensitive primarily to variations in $T_1$ and $K$. A $0.25F^0$ change in $T_1$ produced a typical change of 10\% in deficiency while a 5\% change in $K$ produced a typical change of 15\% deficiency. As Table 4-1 shows, changes in deficiency of a larger magnitude are also possible.

Table 4-1  Sensitivity Analysis of Deficiency to Uncertain Parameters

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<th>Run</th>
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<th>% Change for $0.25F^0$ Change in $T_0$</th>
<th>% Change for $0.25F^0$ Change in $T_1$</th>
<th>% Change for $0.25F^0$ Change in $T_E$</th>
<th>% Change for 5% Change in $K$</th>
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CHAPTER 5

STEADY-STATE LABORATORY INVESTIGATIONS

5.1 Types of Ponds Investigated

Approximately 50 experiments were performed assessing five basic pond configurations:

The unbaffled pond,
The S-shaped pond,
The U-shaped pond,
The highly baffled longitudinal pond, and
The highly baffled lateral pond

Each of these basic configurations, illustrated and given a symbolic notation in Figure 5.1 was tested with a low and a high discharge and with various orientations of rectangular and/or radial discharge. A complete listing of the parameters for each experiment, including geometry, inflow temperature, outflow temperature, equilibrium temperature, cooling capacity, surface heat transfer coefficient, normalized intake temperature, and deficiency is given in Table 5-1 (low flow rate) and Table 5-2 (high flow rate).

5.2 Low Reynolds Number Effects

In this experimental series, several experiments were run in one compartment of the S-shaped pond to test the Reynolds number dependence of the laboratory studies. An understanding of the potential effects of this parameter is necessary before proceeding with the experimental analysis.
Figure 5.1 Pond Configurations and Notation
U-shaped Pond with Rectangular Discharge in Center

Geometry Discharge

U RE_c

U-shaped Pond with Radial Discharge in Corner

U RA

U-shaped Pond with Radial Discharge in Center

U RA_c

Highly Baffled Pond, Longitudinal Baffles, Rectangular Discharge

HLN RE

Highly Baffled Pond, Lateral Baffles, Rectangular Discharge

HLA RE

Figure 5.1 (Cont'd) Pond Configurations and Notation
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<th>$T_i$ ($^\circ$F)</th>
<th>$T_E$ ($^\circ$F)</th>
<th>$K$ (BTU/ft$^2$-day-$^\circ$F)</th>
<th>$r$</th>
<th>$T_i^*$</th>
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The ratio of inertial to viscous forces in a body of water may be characterized by the Reynolds number, \( Re \). For wide, open channels

\[
Re = \frac{4uH}{v}
\]  

(5.1)

where \( u \) is the cross-sectional average velocity, \( H \) is the channel depth, and \( v \) is the kinematic viscosity of the fluid.

In a model study, it is generally impossible to reproduce the high Reynolds numbers typical of prototype conditions. Instead it is deemed sufficient to operate the model in the turbulent range in which the role of viscous-inertial forces in model and prototype should be similar. For the model to be in this turbulent range, it should have a Reynolds number

\[
Re > 3000
\]  

(5.2)

In a pond receiving heated discharges and/or containing a three-dimensional flow field, however, there are a number of sources of turbulence not reflected in the Reynolds number. Jet entrainment and velocity non-uniformities created by flow constrictions and counterflows result in velocities much higher than the cross-sectional average and turbulent mixing will occur as heated, buoyant surface water cools and mixes with subsurface water. These conditions may allow the criterion of Equation (5.2) to be relaxed while still providing sufficient turbulence in the model.

For sufficiently high Reynolds numbers, the distribution of relative velocities in the current and the relative size of the main flow and eddy zones should be independent of \( Re \). As a result, the non-dimensional residence time of a particle in the pond should be independent of the flow
rate and normalized Unit Impulse Response (UIR) curves for a variety of flow rates will superimpose upon each other. Lack of superposition indicates low Reynolds number effects are present in the flow field.

Figure 5-2 shows the UIR results of fluorescent dye injections into unheated non-buoyant inflows with $Q_o = 2.5, 4.5, 9.0, \text{ and } 18.0 \text{ gpm}$, corresponding to $Re_e = 280, 500, 1000, \text{ and } 2000$. The reported values of $Re_e$ are obtained by considering the lab pond to be a recirculating pond (Section 3.3.2) with $D_s = 2.0$ and $b = .33$ and are calculated for the forward jet region.

It can be seen that the dye responses for $Q_o = 9 \text{ gpm (}Re_e = 1000)$ and $Q_o = 18 \text{ gpm (}Re_e = 2000)$ superimpose well indicating the runs were effectively in the turbulent region. The curves for $Q_o = 2.5 (Re_e = 280)$ and $Q_o = 4.5 (Re_e = 500)$ do not match the curves for the higher flows, however, indicating the experiments were not fully in the turbulent region.

These results compare favorably with the report of Tatinclaux, Jain and Sayre (1973) who found, in a model study of the LaSalle, Illinois cooling pond involving unheated discharges, that normalized UIR dye curves for experiments with $Re_e = 1000$ and $Re_e = 730$ superimposed well with each other but failed to match the normalized UIR curve for an experiment with $Re_e = 420$.

It should be noted that the buoyant spreading and thermally generated turbulence caused by a heated discharge will result in markedly different UIR curves for the heated than the unheated case. Figure 5-3 illustrates this difference.
Figure 5.2  UIR Curves of Unheated Discharges in a Single Recirculating Compartment

Figure 5.3  UIR Curves for Heated and Unheated Discharges in a Single Recirculating Compartment
In Figure 5.4, UIR curves for heated discharges at low and high flows are shown. It can be seen that in the presence of heat addition the thermally generated turbulence causes the UIR for the low flow rate experiment to approach the UIR for the high flow case. The UIR curves for the full pond experiments in Appendix I also show this approach. Some difference remains but it cannot be stated with certainty that low Reynolds number effects cause this discrepancy since in a pond receiving buoyant discharges, different flow rates will result in different degrees of stratification and eddying which will be reflected in the unit impulse response curves.

In the following discussion, both high and low flowrate experiments are considered as guidelines for pond design and performance. This decision incurs a tradeoff since the low flowrate experiments involve potential laminarity effects but allow better measurement accuracy (due to lower \( r \) values and associated higher temperature drops across the pond) while the high flowrate experiments eliminate laminarity effects at the expense of decreased accuracy.

5.3 Results of Thermal Studies

Preliminary analysis of the experimental results consisted of a comparison of the average deficiencies for each basic configuration. The configuration with the lowest deficiency would be most efficient at dissipating heat under steady-state conditions. A summary of average deficiencies and a ranking of configurations is presented in Table 5-3.

A qualitative analysis of the cooling pond thermal structure was also provided by examining the surface isotherms and vertical temperature
Figure 5.4 UIR Curves for Heated Discharges in a Single Recirculating Compartment
Table 5-3  Average Deficiencies for Each Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\bar{D}$</th>
<th>$Q = 4.5$ gal/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-LA (runs 17, 19, 71)</td>
<td>0.310</td>
<td></td>
</tr>
<tr>
<td>H-LN (runs 55, 69)</td>
<td>0.359</td>
<td></td>
</tr>
<tr>
<td>N-RA (runs 8, 9, 10)</td>
<td>0.390</td>
<td></td>
</tr>
<tr>
<td>S-RE (runs 2, 22, 40, 60)</td>
<td>0.466</td>
<td></td>
</tr>
<tr>
<td>U (runs 48, 51, 64, 67, 68)</td>
<td>0.480</td>
<td></td>
</tr>
<tr>
<td>S-RA (runs 58, 62)</td>
<td>0.531</td>
<td></td>
</tr>
<tr>
<td>N-RE (runs 5, 6, 7)</td>
<td>0.597</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\bar{D}$</th>
<th>$Q = 9.0$ gal/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>U (runs 49, 50, 65, 66)</td>
<td>0.438</td>
<td></td>
</tr>
<tr>
<td>S-RA (runs 14, 59, 63)</td>
<td>0.449</td>
<td></td>
</tr>
<tr>
<td>H-LN (run 54)</td>
<td>0.490</td>
<td></td>
</tr>
<tr>
<td>S-RE (runs 24, 41, 42, 61)</td>
<td>0.514</td>
<td></td>
</tr>
<tr>
<td>H-LA (runs 16, 18, 72)</td>
<td>0.597</td>
<td></td>
</tr>
<tr>
<td>N-RA (runs 46, 79)</td>
<td>0.631</td>
<td></td>
</tr>
<tr>
<td>N-RE (runs 44, 78)</td>
<td>1.019</td>
<td></td>
</tr>
</tbody>
</table>
profiles for each run. Surface isotherms and temperature profiles for each basic configuration tested are included in Appendix I of this report.

5.4 Results of Dye Studies

The instantaneous injections of Rhodamine WT dye provided Unit Impulse Response (UIR) curves for each run. These curves, along with visual studies of the dye flow field, provided information on short-circuiting and residence time for each configuration. Typical UIR's for the basic configurations tested are included in Appendix I. Loss of dye due to adsorption and non-recovery due to dye which remained in dead zones and eddies long beyond the sampling period (usually 1 to 2 residence-times) made computation of the centroids of mass difficult. Instead, quantitative analysis of the dye curves was made using two parameters: \( \hat{t}_a = tQ_o/V \) - the time until the first arrival of the dye patch of the intake, and \( \hat{t}_m = tQ_o/V \) - the time for the peak concentration of dye to arrive at the intake. Ponds with longer times to first arrival and times to peak may be considered to exhibit less short circuiting and longer effective residence times. The parameters \( \hat{t}_a \) and \( \hat{t}_m \) are tabulated and ranked in Table 5-4.

5.5 Analysis of Experimental Results

5.5.1 Analysis of Baffle Configuration

Table 5.3 shows that for the low flow case, deficiency is inversely correlated with the density of the baffles. With the exception of the unbaflled, radial configuration, increasing the number of baffles decreases the deficiency. For the high flow case, however, the relationship is different. There is a tendency for moderately baffled ponds - that is the
| Configuration | $Q_o = 4.5 \text{ gpm}$ | | | $Q_o = 9.0 \text{ gpm}$ | |
|---------------|----------------|----------------|----------------|----------------|
| | $t_a$ | $t_m$ | $t_a$ | $t_m$ |
| HLN-RE | 0.444 | 0.648 | 0.614 | 0.851 |
| HLA-RE | 0.333 | 0.574 | 0.370 | 0.740 |
| U-RA$_C$ | 0.222 | 0.407 | 0.333 | 0.518 |
| U-RA | 0.240 | 0.444 | 0.370 | 0.481 |
| U-RE$_C$ | 0.203 | 0.425 | 0.296 | 0.518 |
| U-RE | 0.185 | 0.481 | 0.148 | 0.629 |
| S-RA | 0.203 | 0.259 | 0.222 | 0.444 |
| S-RE | 0.133 | 0.222 | 0.148 | 0.370 |
| N-RA | 0.166 | 0.214 | 0.244 | 0.311 |
| N-RE | 0.066 | 0.074 | 0.066 | 0.081 |

* Time of arrival for second peak
S-shaped and U-shaped ponds - to be less deficient than either the highly baffled or unbaffled ponds. (Note the U-shaped ponds with various discharge configurations are grouped together in this section since it is felt individual analysis would unfairly weight configurations tested by only one experiment).

A number of hypotheses may be formulated to explain the anomalies between the low and high flow results. As shown by their UIR curves, the highly baffled ponds exhibit longer effective residence times than their less densely baffled counterparts. Intuitively, better performance for the ponds with longer residence times is expected as verified by the results for the low flow rates. For the high flow runs, however, increased dispersion in the narrow channels and mixing at the bends in the flow path may cause the deficiency of the highly baffled configurations to rise relative to the more moderately baffled S- and U-shaped ponds.

A second hypothesis is that low Reynolds number effects are responsible for the discrepancy between the low and high flow results. As discussed in Section 5.2, the results of the high flow runs seem more reliable due to minimal laminarity effects. Considering in addition the extra costs associated with constructing dense prototype baffle configurations, the U-shaped and S-shaped ponds appear to represent desirable baffle configurations.

5.5.2 Analysis of the Radial Discharge

The radial discharge can be expected to enhance cooling pond performance in two ways. First, the wide cross-sectional area of the radial discharge should result in a lower flow velocity and hence, a lower discharge
Froude number and less entrance mixing. Secondly, the fan-shape should direct the effluent in a more even distribution across the pond than a rectangular structure.

The radial discharge is best evaluated by comparing the results of the unbaffled rectangular vs unbaffled radial configurations. The thermal data shows conclusively that the radial runs are less deficient than their rectangular counterparts and the surface isotherms in Appendix I illustrate that the radial discharge does indeed distribute the effluent more evenly across the pond surface. Examination of the UIR curves also shows a difference in pond behavior. UIR's for the unbaffled rectangular ponds (Figure A.21) show two peaks - the first occurring when the discharge plume short-circuits directly across the pond into the intake and the second occurring when effluent which has passed to the recirculating regions of the pond is reentrained and arrives at the discharge for the second time. UIR's for the radial configuration (Figure A.22) show only one peak which arrives later than the short-circuited peak of the rectangular discharge.

Results for the radial discharge in the U-shaped pond are more difficult to interpret. Two comparisons are possible for each flowrate - U-RE vs. U-RA and U-RE_C vs U-RA_C. Of the four total comparisons, three show the radial discharge to be superior and one shows it to be inferior - the comparison of U-RE_C vs U-RA_C at the low flowrate. Judging by this weight of evidence and considering the possibility of laminarity effects, the radial discharge appears to be of benefit in the U-shaped pond.

To ascertain the potential effect of the radial discharge independent of experimental error, analytical calculations were made. Using the actual values of $T_o$, $T_e$ and atmospheric parameters from the U-shaped pond
experiments (Runs 48-51 and 64-68) the lab pond was modeled as consisting of a completely mixed zone (Equation 3-10) comprising 25% of the pond area followed by a plug flow zone (Equation 3.7). This was considered to schematize the entrance mixing followed by uniform flow patterns produced by a rectangular discharge. The results of this model were compared to a purely plug flow model schematizing a pond with a radial discharge capable of completely eliminating entrance mixing. The difference in deficiency of these two extreme cases was in the order of 0.10, with variations depending on the value of r. (An improvement of this magnitude, even if fully realized, could easily be masked by experimental errors). Thus entrance mixing and short-circuiting are seen not to have a large influence on the performance of a U-shaped pond yet even this limited potential gain from a radial discharge may be important in prototype design.

The results of using the radial discharge in the S-shaped ponds were inconclusive. In the high flow cases, the radial discharge was superior to the rectangular discharge. In the low flow cases, it was inferior. While the radial discharge did produce less pronounced eddies in the first compartment of the pond it did not eliminate the eddy zones of the second and third compartments and the improvement, if any, gained by using the radial discharge is probably smaller than the magnitude of experimental errors.

In summary, the radial discharge is seen to influence deficiency chiefly in the unbaffled pond and its use in such ponds seems necessary. The use of a radial discharge is also advisable for the U-shaped (and even the S-shaped) pond as it reduces the entrance eddying zone with beneficial effects on pond deficiency. The use of radial discharges in highly baffled
ponds seems superfluous, however, since the baffling density alone is likely to constrain any potential discharge eddy.

5.6 Applicability of Laboratory Data to Steady-State Conceptual Models

The data provided by the steady-state experiments conducted in this study formed an excellent basis for verification of the shallow pond models of Chapter III and for estimation of their parameters.

The dispersive pond model (Equation 3.12) was applied to the highly baffled ponds denoted HLN-RE and HLA-RE with a value of $E^* \gamma \approx 0.1$ calculated from Equation (3-15). Table 5.5 which compares the predicted values of $T_4$ with the measured data shows the model underpredicts $T_4$ somewhat, probably due to the failure of Fischer's formula to account for the additional dispersion caused by flow reversals. (A value of $E^*\approx 0.2$ gives improved results).

A more rigorous test of the capacity of the dispersive model is provided by comparisons of predicted vs. measured values of surface area enclosed by each isotherm. Figures 5.5 and 5.6 show an example of these comparisons for each flowrate and the agreement is good.

The recirculating pond model was verified by applying it in series to each compartment of the S-shaped pond with rectangular discharge (S-RE). Parameter values $DS = 1.7$ and $b = 0.3$ were found to give the best results although the comparison of predicted and measured values of $T_4$ in Table 5-5 shows the model overpredicts $T_4$ slightly. Figures 5.7 and 5.8 show that the analytical predictions also differ from the laboratory results of temperature vs surface area although the insufficiency is minor since a predictive knowledge of $T_4$ is most important and this aspect of the analytical model is satisfactory.
<table>
<thead>
<tr>
<th>Run</th>
<th>Geometry</th>
<th>$T_1$ (Measured)</th>
<th>$T_1$ (Predicted)</th>
<th>$T_1$ (Measured - Predicted)</th>
<th>$({}^\circ F)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>HLN-RE</td>
<td>86.9</td>
<td>85.7</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>HLN-RE</td>
<td>81.8</td>
<td>79.8</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>HLN-RE</td>
<td>77.9</td>
<td>77.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>HLA-RE</td>
<td>84.4</td>
<td>82.3</td>
<td>2.1</td>
<td>Math. Mod.</td>
</tr>
<tr>
<td>17</td>
<td>HLA-RE</td>
<td>82.7</td>
<td>81.6</td>
<td>1.1</td>
<td>Long. Dis.</td>
</tr>
<tr>
<td>18</td>
<td>HLA-RE</td>
<td>96.7</td>
<td>95.0</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>HLA-RE</td>
<td>76.1</td>
<td>75.8</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>HLA-RE</td>
<td>77.0</td>
<td>76.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>HLA-RE</td>
<td>87.9</td>
<td>86.2</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S-RE</td>
<td>71.0</td>
<td>74.1</td>
<td>-2.9</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>S-RE</td>
<td>85.6</td>
<td>86.6</td>
<td>-1.0</td>
<td>Math. Mod.</td>
</tr>
<tr>
<td>24</td>
<td>S-RE</td>
<td>93.2</td>
<td>94.2</td>
<td>-1.0</td>
<td>Long. Dis.</td>
</tr>
<tr>
<td>40</td>
<td>S-RE</td>
<td>87.0</td>
<td>88.0</td>
<td>-1.0</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>S-RE</td>
<td>96.1</td>
<td>96.7</td>
<td>-0.6</td>
<td>Rec. Zone</td>
</tr>
<tr>
<td>42</td>
<td>S-RE</td>
<td>101.9</td>
<td>102.4</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>S-RE</td>
<td>78.2</td>
<td>79.2</td>
<td>-1.0</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>S-RE</td>
<td>90.8</td>
<td>91.5</td>
<td>-0.7</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.5 Predicted and Measured Values of Temperature vs. Area for Run 69, $Q_o = 4.5$ gpm

Figure 5.6 Predicted and Measured Values of Temperature vs. Area for Run 54, $Q_o = 9.0$ gpm
Figure 5.7 Predicted and Measured Values of Temperature vs. Area for Run 22, $Q_o = 4.5$ gpm

Figure 5.8 Predicted and Measured Values of Temperature vs. Area for Run 24, $Q_o = 9.0$ gpm
CHAPTER 6

TRANSIENT EXPERIMENTS

6.1 Introduction

The experiments and analysis of Chapter V were directed primarily towards finding the pond configuration which would maximize steady-state heat transfer to the atmosphere. The desirable pond, however, has been defined as one which will damp out transient fluctuations in intake temperature as well as maximize heat transfer. In this chapter, an experimental analysis of the effect on transient fluctuations of a small deep reservoir added to a shallow pond is detailed.

6.2 Temperature Fluctuations and the Deep Intake

In a vertically fully or partially mixed cooling pond, diurnal fluctuations in the temperature of the pond including condenser intake are caused by the daily cycling of meteorological parameters, especially air temperature and incoming solar radiation. Depending on pond depth, the total daily change of temperature is in the order of 2 to 5 °F, with the highest temperatures occurring during late afternoon and the lowest during early morning.

Withdrawal of this warm intake water into the condensers of a power plant can result in marked decreases in plant efficiency during the afternoon hours, the same time of the day at which peak power demand occurs. It is thus advantageous to reduce or eliminate these transient fluctuations in the temperature of the condenser intake water.
Plants located on deep, stratified ponds and withdrawing through submerged skimmer-type inflow structures usually eliminate the effects of diurnal cycling since the deep reservoir portion of a lake is insulated from short-term phenomena affecting the surface temperature. Deep ponds are therefore said to exhibit high thermal inertia, as opposed to shallow ponds with low thermal inertia.

In this chapter, experiments are performed to test the hypothesis that it is possible for a plant located on a shallow pond to experience the benefits of high thermal inertia while avoiding the costs and potential environmental restrictions associated with deep ponds by adding a small deep reservoir to the shallow pond immediately in front of the skimmer wall intake. During the period in which adverse meteorological conditions and peak power demands coincide, some stratification will exist in the deep portion of the pond allowing the power plant to selectively withdraw cool water from the deep reservoir. As the cool water supply in the lower layer of the deep reservoir is exhausted and replaced by warmer surface water, enhanced surface cooling during the evening hours will cause vertical overturn in the deep reservoir. In principle, the combined action of stratification and overturn on a daily cycle will have a damping effect on cooling pond behavior, minimizing fluctuations in the intake temperature. Similarly, the deep portion can also act to minimize transient effects caused by changes in power plant operation typical for non-base load plants.
6.3 Design of a Deep Intake Structure

The intake structure of a shallow pond with a deep reservoir section is schematized in Figure 6.1. The pond is of depth = d with an additional deep reservoir of depth = h. The interface between the warm surface water, at uniform density ρ, and the cool reservoir water at uniform density ρ+Δρ is assumed to be at height h above the reservoir bottom and the skimmer opening is of height b.

The maximum flow rate which can be achieved without withdrawing from the surface layer is given by the critical flow equation of Harleman and Elder (1965)

\[ Q_c = B \sqrt{g \frac{\Delta \rho}{\rho} \left( \frac{2}{3} h \right)^3} \]  

(6.1)

where \( Q_c \) is the critical flowrate and B is the width of the skimmer opening. Harleman and Elder also specify the design height of the skimmer wall to be

\[ b \leq \frac{2}{3} h \]  

(6.2)

By setting \( Q_c \) equal to the plant flow rate, \( Q_o \), using the known value of \( \Delta \rho/\rho \) (obtainable from the characteristic temperature difference of 2-5 \( F^o \) generated by atmospheric heating of the upper layer) and choosing a depth h of the deep reservoir it is possible to determine the required skimmer wall width, B. The volume of the deep reservoir should be sufficient to provide a residence time one half the length of the cycles in temperature.
Figure 6.1 Shallow Pond with Deep Intake
For daily temperature fluctuations the required deep reservoir volume is then

\[ V_{\text{deep}} = Q_o \cdot \frac{24 \text{ hrs}}{2} \]  
(6.3)

6.4 **Experimental Simulation of a Deep Reservoir**

Two separate sets of laboratory experiments were performed in a U-shaped pond with radial discharge (designated U-RA and shown in Figure 5.1) to assess the effect of adding a deep reservoir to a shallow pond. The first set of experiments was intended to demonstrate the ability of a skimmer located in a deep reservoir to selectively withdraw cool, deep water thereby reducing and delaying fluctuations in intake temperature. The second set of experiments was designed to compare intake temperatures as a function of time for shallow ponds with and without a deep reservoir during one cyclic increase and decrease in discharge temperature.

The deep pond, when needed, was created by removing the flooring from a 12' portion of the basin immediately in front of the intake creating an excavation approximately 12' by 8.5' and 2.5" deeper than the rest of the basin. The deep reservoir lay under approximately 15% of the surface area of the pond and increased pond volume and residence time by 13%. A skimmer width \( B = 2' \) was adopted and the height, \( b \), varied from 0.5" to 2.0". Figure 6.2 shows the revised experimental configuration.

6.4.1 **Selective Withdrawal Experiments**

Initially a group of experiments was run at both high and low
Figure 6.2 Schematic of Shallow Pond with Deep Intake (vertically distorted)
flowrates to simulate the action of a skimmer wall in a conventional shallow pond. The depth of the pond, \(d\), was set at three inches and the skimmer height, \(b\), at 0.5". The experiments were run at an isothermal temperature \((T_o = T_i)\) until hydraulically steady conditions were reached. Then stratification was produced at the intake by raising the discharge temperature approximately 50 °F causing a typical temperature difference of 10 °F between surface and bottom at the intake. Three minutes after the temperature increase, 50 cc of 10 ppt Rhodamine dye was injected into the discharge. The intake was periodically sampled for dye and the intake temperature continuously monitored until the peak of dye concentration had passed at which point the experiment was terminated.

After the shallow experiments were completed, the deep reservoir was excavated and the skimmer height increased to 2". The experiments were then repeated for the pond with a deep reservoir. Experimental parameters and results for this series are presented in Table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>(Q_o)</th>
<th>(T_{o\ (low)})</th>
<th>(T_{o\ (high)})</th>
<th>(\Delta T)</th>
<th>(\hat{e}_a)</th>
<th>(\hat{e}_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without</td>
<td>4.5</td>
<td>66</td>
<td>116</td>
<td>50</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>Deep Reservoir</td>
<td>9.0</td>
<td>66</td>
<td>116</td>
<td>50</td>
<td>0.20</td>
<td>0.31</td>
</tr>
<tr>
<td>With</td>
<td>4.5</td>
<td>68</td>
<td>118</td>
<td>50</td>
<td>0.18</td>
<td>0.38</td>
</tr>
<tr>
<td>Deep Reservoir</td>
<td>9.0</td>
<td>68</td>
<td>118</td>
<td>50</td>
<td>0.28</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Figures 6.3 and 6.4 compare the UIR curves and normalized intake temperatures for ponds with and without the deep reservoir at the low flow rate. Figures 6.5 and 6.6 are the same comparisons for the high flow rate. The intake temperatures, $T_i$, are normalized as $\hat{T} = \frac{T_i - T_i^0}{T_i^0 - T_i^0}$ (low) and the time, $t$, was normalized as $\hat{t} = Q O t/V$ where $V$ includes the volume increase of the deep reservoir. Dye concentrations are normalized by dividing the actual concentration by the concentration resulting if the initial injection were completely mixed throughout the pond, $\hat{c} = c/c_m$.

Figures 6.3 and 6.5 show that the dye patches arrive later in the ponds with a deep reservoir indicating the residence time (and thus the time necessary for fluctuations in $T_i^0$ or in ambient conditions to be reflected in the plant intake) is increased for these ponds. Figures 6.4 and 6.6 show that the intake temperature at any time is lower for a pond with a deep reservoir than for a pond without one. Thus the potential of the deep reservoir to both delay and damp variations in intake temperature is verified.

6.4. Simulation of a Complete Temperature Cycle

It was impossible to reproduce in the laboratory pond a vertical temperature gradient due to diurnal cycling and instead, a cycling plant discharge, which also produces transient effects, was simulated by alternately raising and lowering the temperature of the discharge into the pond.

Two experiments were performed at the high flow rate ($Q_0 = 9$ gpm) - one run with a deep reservoir and one without. The pond depth was $d = 3"$ and the skimmer height was $b = 0.5"$ for the pond without a deep
Figure 6.3 UIR Curves for a Shallow Pond With and Without a Deep Reservoir, $Q_o = 4.5 \text{ gpm}$

Figure 6.4 Normalized Intake Temperature vs. Time Curves for a Shallow Pond With and Without a Deep Reservoir, $Q_o = 4.5 \text{ gpm}$
Figure 6.5  UIR Curves for a Shallow Pond With and Without a Deep Reservoir, \( Q_o = 9.0 \) gpm

Figure 6.6  Normalized Intake Temperature vs. Time Curves for a Shallow Pond With and Without a Deep Reservoir, \( Q_o = 9.0 \) gpm
reservoir and \( b = 1.7'' \) for the pond with a deep reservoir.

In both experiments, the pond was run in an isothermal condition for approximately 1 hour to achieve hydraulically steady conditions. The discharge temperature was then raised by 20 \( F^0 \) for a period of 3.5 hours and then returned to the original lower value of \( T_o \) for another 3.5 hours simulating a cycling of pond temperature. (This magnitude of increase produced a 9 to 12 \( F^0 \) change in \( T_1 \), higher than the 2 to 5 \( F^0 \) prototype value, but the 3 \( F^0 \) characteristic vertical temperature difference in the model reproduced the prototype value well.) Measurements of \( T_o, T_1 \) and \( T_E \) were taken every 20 minutes throughout the 7 hour cycle. Table 6.2 gives the experimental parameters for each experiment.

<table>
<thead>
<tr>
<th></th>
<th>( T_o ) (low)</th>
<th>( T_o ) (high)</th>
<th>( T_E ) (average)</th>
<th>( T_1 ) (average)</th>
<th>( T_1 ) (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Deep Reservoir</td>
<td>71.4 ( F^0 )</td>
<td>91.7 ( F^0 )</td>
<td>68.4 ( F^0 )</td>
<td>80.2 ( F^0 )</td>
<td>83.6 ( F^0 )</td>
</tr>
<tr>
<td>With Deep Reservoir</td>
<td>72.7 ( F^0 )</td>
<td>92.5 ( F^0 )</td>
<td>69.9 ( F^0 )</td>
<td>77.8 ( F^0 )</td>
<td>81.1 ( F^0 )</td>
</tr>
</tbody>
</table>

Figure 6.7 is a plot of \( T_o \) and \( T_1 \) vs. time for one temperature cycle with and without a deep reservoir. Once again, temperatures are normalized with respect to \( \Delta T (= T_o \) (high) - \( T_o \) (low) \). It can be seen from both Table 6.1 and Figure 6.7 that the pond with a deep reservoir exhibited a lower average intake temperature over the cycle and a delayed response to changes in \( T_o \).

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Figure 6.7 Normalized Temperature vs. Time for a Cyclic Temperature Change in a Pond With and Without a Deep Reservoir
A successful deep reservoir would be expected both to delay and reduce in magnitude transient fluctuations in intake temperature. The results of these studies demonstrate the laboratory pond with a deep reservoir exhibits the desired effects. Although these experiments are only schematic, they still demonstrate the effect and the potential benefits of incorporating a deep reservoir in a shallow cooling pond.
CHAPTER 7

RECOMMENDATIONS FOR A WELL-DESIGNED PROTOTYPE POND

7.1 Introduction

The ideal cooling pond configuration has been defined as one which will maximize surface heat transfer while minimizing transient fluctuations in intake temperature. In addition, construction and operation costs should be kept as low as possible. While a single pond design which will guarantee ideal conditions for all possible combinations of local topography, climate, and imposed heat load cannot be specified, a number of design guidelines based on the results of this study can be formulated for shallow, perched, off-stream ponds with an approximately rectangular shape.

7.2 Guidelines for Pond Geometry

Guidelines for cooling pond geometry cannot be based solely on deficiency and residence time. Consideration must be given to non-quantifiable parameters including eddy formation and uniformity of flow distribution. The cost of construction and maintainance of the prototype must also influence the decision.

In a shallow prototype pond, some baffling is needed to insure a reasonably uniform flow distribution and to prevent wind driven short circuiting not present in the laboratory. Thus the unbaffled ponds are removed from consideration even though, for the low flow case, the unbaffled laboratory pond with radial discharge (N-RA) exhibited a low
deficiency.

Of the remaining designs, both the U-shaped and S-shaped ponds provide good performance without dense, expensive baffle configurations. Of the two, the U-shaped pond would be more economic to construct and, based on the experimental results, provides a longer residence time and smaller amount of eddying with reduced intake temperatures. Therefore, the U-shaped pond seems the most desirable pond geometry, providing uniform flow distribution and reduced construction costs while minimizing eddying and wind driven short-circuiting.

Based on this study it appears that the baffling density should be such as to obtain a length to width ratio for the flow path of about 5 to 10. Higher values will not result in significant additional improvements and carry large construction cost penalties.

7.3 Guidelines for Discharge Configuration

A well-designed discharge should minimize entrance mixing while distributing the effluent evenly across the pond surface. In a shallow pond, proper discharge design and orientation can also minimize the formation of eddies and short-circuiting of the throughflow.

In this study, attention is directed primarily at the use of a radial discharge to achieve the above mentioned effects. Other discharge configurations with the potential for minimizing entrance mixing and eddying by effectively distributing the effluent such as elaborate pipe manifolds or channel branchings are not considered due to their high construction costs and potential maintenance problems.
Compared with a conventional rectangular discharge, the experimental results of Section 5.5.2 show the radial discharge to be most successful at improving the performance of the unbaffled ponds with some improvement for the U-shaped ponds also noticeable. Little or no verifiable improvement was noted for the S-shaped pond and the radial discharge was considered superfluous for the highly baffled configurations.

In general, it is always desirable to take some measures to prevent or minimize entrance mixing and eddying. This is most effectively and simply done with a radial discharge and its use is recommended in all but the most densely baffled prototypes.

7.4 Guidelines for Intake Design

Chapter VI reviews a series of experiments aimed at establishing the effect of adding a small deep reservoir to a shallow pond. The experiments show that the deep reservoir can significantly delay and reduce the magnitude of fluctuations in intake water temperature and its use, together with a well-designed skimmer wall, is desirable. If excavation of a deep reservoir is economically unfeasible or if the topography of the pond bottom is uneven, some of the advantages of the deep reservoir can be obtained without additional excavation by locating the plant intake in the deepest naturally occurring portion of the pond.

7.5 Guidelines for Power Plant Operating Characteristics

Cooling pond performance is a function not only of pond design, but of power plant operation, specifically the combination of coolant flow-rate and associated temperature rise employed to remove the required
amount of waste heat from the plant steam condensers. The rejected heat can be equated to the condenser flow rate and temperature rise by the expression

\[ J_o = \rho c Q_o \Delta T_o \]  

(7.1)

where \( J_o \) is the rate of plant heat rejection, \( Q_o \) is the condenser flow rate, and \( \Delta T_o \) is the temperature rise of the coolant incurred in the condensers. Different combinations of \( Q_o \) and \( \Delta T_o \) can be chosen to reject the plant heat; power plants located on cooling ponds are usually designed to operate in the range \( 20 \, ^oF < \Delta T_o < 40 \, ^oF \). The exact specification of \( \Delta T_o \) should be based on an overall economic optimization of the plant and cooling system.

The selection of a large value of \( \Delta T_o \) and a correspondingly small value of \( Q_o \) will enhance both pond stratification and the rate of surface heat dissipation but the resulting high value of plant discharge temperature, \( T_o \), may result in decreased plant efficiency negating the beneficial effects on the cooling pond.

Power plant efficiency is defined

\[ E_p = \frac{\text{Electrical Output}}{\text{Electrical Output} + \text{Waste Heat}} = \frac{\text{Electrical Output}}{\text{Heat Rate}} \]  

(7.2)

The heat rate, reflecting the total energy input needed to produce useful electrical output is a function of turbine back pressure as shown in Figure 7.1 (adapted from United Engineers, 1974); higher back pressures result in an increased heat rate. By use of standard steam tables, turbine
back pressure may be converted into exhaust steam temperature, TS, which may be further converted into plant discharge temperature, $T_o$, through employment of the terminal temperature difference, TTD, which exists across the condenser surface. Harleman, et. al., 1975 give this difference for a once through cooling system as

$$TTD = TS - T_o \approx 8 F^0$$ (7.3)

Thus turbine back pressure can be related to plant discharge temperature and increased values of $T_o$ are seen to result in an increased heat rate (see Figure 7.1).

An analytical model was employed to investigate the effects of $Q_o$ and $\Delta T_o$ on plant efficiency. An LWR nuclear plant of capacity 1096 mw\textsubscript{e} obeying the heat rate relationship of Figure 7.1 was assumed to operate on a lake of 1000 acres extent. The lake was considered to be a shallow dispersive pond described by Equation (3.11) with $E^* = 0.2$.

Two operating schemes were hypothesized: a low temperature scheme with $\Delta T_o = 20 F^0$ necessitating $Q_o = 1.33 \times 10^8 ft^3$/day (for a plant operating at full capacity with a heat rate equal to unity) and a high temperature scheme with $\Delta T_o = 40 F^0$ and $Q_o = 6.69 \times 10^7 ft^3$/day.

The plant was assumed to operate at full capacity under climatic conditions typical for Richmond, Virginia during July, i.e. an air temperature of 77.2 $F^0$, relative humidity of 70%, wind of 5.5 mph, solar radiation of 1800 BTU/ft$^2$-day, cloud cover of 60%, and an equilibrium temperature of 81.5 $F^0$. (The heat flux for prototype conditions was computed using the relations given in Appendix II).
Figure 7.1 Exhaust Pressure vs. Heat Rate for a Typical Turbine
Separate computer runs were made in an iterative search for a discharge temperature, \( T_o \), which would result under steady state conditions, in an intake temperature, \( T_1 \), such that \( T_o = T_1 + \Delta T_o \). Once \( T_o \) was known, the heat rate could be obtained via Equation (7.3) and Figure 7.1.

The analysis showed that a plant operating with the low temperature scheme, \( \Delta T_o = 20 \ F^\circ \), would discharge at 111.5 \( F^\circ \) corresponding to a heat rate of 1.013. A plant operating with the high temperature scheme, \( \Delta T_o = 40 \ F^\circ \), would discharge at 128.5 \( F^\circ \) and a heat rate of 1.045. (Complete results of the analysis are summarized in Table 7.1). The high temperature scheme would operate at a back pressure (\( \approx 5 \) inHg) which is the upper limit for conventionally designed turbines (Giaquinta, et. al., 1976) and the power plant would probably have to be derated (i.e. operate at less than full capacity) for periods of extreme ambient conditions. Thus the low temperature - high coolant circulation scheme is seen to favor plant efficiency.

<table>
<thead>
<tr>
<th>( \Delta T_o ) ( (F^\circ) )</th>
<th>( Q_o ) ( (ft^3/day) )</th>
<th>( T_o ) ( (F^\circ) )</th>
<th>( T_1 ) ( (F^\circ) )</th>
<th>( TS ) ( (F^\circ) )</th>
<th>Back Pressure ( (in.Hg.abs.) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.33x10^8</td>
<td>111.5</td>
<td>91.1</td>
<td>119.5</td>
<td>1.013</td>
</tr>
<tr>
<td>40</td>
<td>6.69x10^7</td>
<td>128.5</td>
<td>87.8</td>
<td>136.5</td>
<td>1.045</td>
</tr>
</tbody>
</table>

This analysis indicates only the average effect on pond performance and plant efficiency of relatively high and low temperature operating schemes. The exact rate of prototype heat rate would differ from these
averages due to continuously varying meteorological conditions. Neither is any consideration made of the construction and operating costs of the condenser-pump configurations warranted by the different flow rates. Optimization of cooling system characteristics under unsteady conditions and analysis of economic factors is beyond the scope of this report and is currently the topic of research here at M.I.T. (see for example: Ralph M. Parsons Laboratory, 1976).

7.6 Summary

In this chapter, guidelines for efficient cooling pond and power plant operation are formulated. The recommended pond has a U-shaped geometry with radial discharge, and a skimmer-type intake located in an excavated deep reservoir or the deepest naturally occurring portion of the pond. The combination of condenser flowrate and condenser temperature rise which is chosen to reject the plant heat must be evaluated through a total optimization accounting for efficiency losses, costs for condenser and cooling water pumping circuits. As regards the efficiency losses, designs with low flowrate and high temperature rises appear to carry higher penalties.
APPENDIX I

Typical Surface Isotherms, Vertical Temperature Profiles, and Unit Impulse Response Curves for Each Pond Configuration
Figure A.1 Surface Isotherms and Temperature Profiles for Run 43, N-RE, $Q_o=4.5$. 

$T_o=115.4$ 

$T_1=90.3$
Figure A.3 Surface Isotherms and Temperature Profiles for Run 47, N-RA, Q_o=4.5.
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$T_1=75.4$

$T_o=101.8$
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Figure A.23 Normalized UIR Curves for Pond Configuration S-RE.

Figure A.24 Normalized UIR Curves for Pond Configuration S-RA.
Figure A.25 Normalized UIR Curves for Pond Configuration U-RE$_c$.

Figure A.26 Normalized UIR Curves for Pond Configuration U-RE.
Figure A.27 Normalized UIR Curves for Pond Configuration U-RA$_c$.

Figure A.28 Normalized UIR Curves for Pond Configuration U-RA.
Figure A.29 Normalized UIR Curves for Pond Configuration HLA-RE.

Figure A.30 Normalized UIR Curves for Pond Configuration HLN-RE.
APPENDIX II

FORMULAS FOR EVALUATION OF SURFACE HEAT FLUX

In Chapter III, the surface heat loss coefficient, $K$, is defined

$$K = \frac{(\phi_{in} - \phi_{out}) - \phi_{e+c}}{T_s - T_E}$$

(3-5)

where $\phi_{in}$ is the radiative heat flux into the pond, $\phi_{out}$ is the radiative flux out of pond, $\phi_{e+c}$ is the conductive and evaporative flux out of the pond, $T_s$ is the average pond surface temperature and $T_E$ is the equilibrium temperature. In this appendix, formulas for evaluating $\phi_{in}$, $\phi_{out}$, and $\phi_{e+c}$ in BTU/ft$^2$-day are given.

Evaluation of $\phi_{in}$

In a prototype pond, incoming radiation is the sum of net short-wave solar radiation and of long-wave atmospheric radiation. Ryan and Harleman (1973) give $\phi_{in}$ as

$$\phi_{in} = 0.94\phi_s + 1.16 \times 10^{-13}(460 + T_a)^6(1 + 0.17C^2)$$

(A.1)

where $\phi_s$ is daily solar radiation (in units of BTU/ft$^2$-day), $T_a$ is air temperature ($^\circ$C) and $C$ is cloud cover expressed as a decimal. When exact measurements of $\phi_s$ are unavailable, daily average values given by Hamon, et. al. (1954) may be used.
In the laboratory, short wave radiation is negligible and long wave radiation from the surroundings is assumed to obey the Stefan-Boltzmann Law with the emissivity of the lab equal to 0.97. Thus, for the laboratory

\[ \phi_{in} = 4 \times 10^{-8} (T_a + 460)^4 \]  \hspace{1cm} (A.2)

**Evaluation of \( \phi_{out} \)**

In both the prototype and the laboratory, outgoing radiation from the water surface is also deemed to obey the Stefan-Boltzmann Law with the emissivity of water equal to 0.97. Thus

\[ \phi_{out} = 4 \times 10^{-8} \left( \frac{1}{T_s + 460} \right)^4 \]  \hspace{1cm} (A.3)

Note that care must be used in specifying the average water surface temperature, \( \bar{T}_s \). It is preferable to use an average of the actual temperature distribution, for example the exponential temperature decline of the plug flow pond, rather than an arithmetic average of \( T_o \) and \( T_i \).

**Evaluation of \( \phi_{e+c} \)**

The sum of evaporative and conductive heat fluxes out of the pond is given by Ryan and Harleman (1973) as

\[ \phi_{e+c} = f(w)[(e - e_a) + 0.255(\bar{T}_s - T_a)] \]  \hspace{1cm} (A.4)

where \( e_s \) is the saturated vapor pressure, in mmHg, of air at the water surface temperature \( \bar{T}_s \), \( e_a \) is the actual vapor pressure of the ambient air at temperature \( T_a \) and \( f(w) \) is a function of windspeed.
For a heated water surface (e.g. a cooling pond) evaporation is the sum of wind driven forced convection and buoyant free convection and \( f(w) \) is evaluated

\[
f(w) = 14W_2 + 22.4(T_{sv} - T_{av})^{1/3}
\]  \( (A.5) \)

where \( W_2 \) is windspeed in mph measured two meters above the water surface, \( T_{sv} \) and \( T_{av} \), in \( \circ\text{F} \), are the virtual water surface and air temperatures:

\[
T_{sv} = \frac{T_s}{1 - 0.378e_s/p}
\]  \( (A.6) \)

\[
T_{av} = \frac{T_a}{1 - 0.378e_a/p}
\]  \( (A.7) \)

and \( p \) is atmospheric pressure in \( \text{mmHg} \).

For an unheated water surface, the evaluation of \( f(w) \) is simply

\[
f(w) = 17W_2
\]  \( (A.8) \)

For an unheated water surface in the absence of wind (e.g. a laboratory equilibrium tank) Equation (A.8) would result in a value of zero for \( \phi_{e+c} \). Therefore, Brocard (1976) suggests a minimum value

\[
f(w) = 15
\]  \( (A.9) \)

be imposed.
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(10) "Heat Sink Design and Cost Study for Fossil and Nuclear Power Plants", United Engineers and Constructors, Inc., 1974


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