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AEC RESEARCH AND DEVELOPMENT REPORT

# THE DISSIPATION OF REACTOR HEAT AT THE SAVANNAH RIVER PLANT

J. S. NEILL D. F. BABCOCK





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### THE DISSIPATION OF REACTOR HEAT AT THE SAVANNAH RIVER PLANT

by

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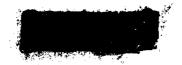


#### **ABSTRACT**

The effluent cooling water from the heat exchangers of the Savannah River nuclear reactors is cooled by natural processes as it flows through the stream beds, canals, ponds, and swamps on the plant site. The Langhaar equation, which gives the rate of heat removal from the water surface as a function of the surface temperature, air temperature, relative humidity, and wind speed, is applied satisfactorily to calculate the cooling that occurs at all temperature levels and for all modes of water flow. The application of this equation requires an accounting of effects such as solar heating, shading, mixing, staging, stratification, underflow, rainfall, the imposed heat load, and the rate of change in heat content of the body of water.

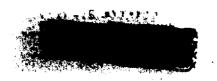
If the water is reused for reactor cooling, its temperature is reduced to within ±2°C of the natural equilibrium temperature by passage through a relatively deep 2500-acre pond, and is cooler in the summer than the natural equilibrium temperature. This temperature is defined as the temperature for a stagnant shallow pond at steady state. If the effluent cooling water is not reused, its temperature is reduced before discharge to the Savannah River, by passage through natural stream beds and swamps, to below 35°C, even under the most severe summer conditions. The discharge to the river is within 3°C of the natural equilibrium temperature; and, because of the shade in the swamp, it may be below the natural equilibrium temperature. During the summer, however, the temperature of the Savannah River itself is as much as 8°C below the natural equilibrium temperature because of cold water storage in reservoirs upstream from the SRP site, so that the river is warming by natural processes as it passes the Savannah River Plant.





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#### INTRODUCTION

The heat from the nuclear reactors at the Savannah River Plant (SRP) of the U. S. Atomic Energy Commission is dissipated to the atmosphere during passage of the effluent cooling water through many miles of canals and hundreds of acres of cooling ponds and swamps within the SRP boundaries. This report presents a quantitative assessment of this heat dissipation.







Par Pond



#### **SUMMARY**

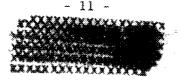
The decrease in the temperature of the effluent cooling water from the SRP reactors as the water passes through the effluent canals and a 2500-acre cooling pond (Par Pond), or through the stream beds and the swamp along the Savannah River, can be accounted for by the Langhaar equation for the surface cooling rate when proper consideration is given to the physical characteristics of the system, primarily the geometry of the water body.

The Langhaar equation gives the surface heat flux as a function of water surface temperature, air temperature, humidity of the air, and wind speed. The equation has two terms. One term gives the rate at which heat is carried away from the surface by radiation and convection. The second term gives the rate at which heat is carried from the surface by evaporation.

The physical situation determines whether the water flows by simple displacement, i.e., slug flow, or whether there is perfect mixing, or whether water at the warmer end mixes with subsurface water that flows upstream from the colder end of the pond. Such flow patterns are readily formulated into mathematical models. Using the appropriate model, the observed performance of the streams and canals is correlated by an effectiveness factor for the surface area. The observed performance of Par Pond is correlated by a temperature increment that varies with the season and is attributed to thermal stratification. The observed performance of the swamp is explained as the result of shading from the solar heat, albeit with a reduction in wind speed, and an effectiveness factor for the swamp area appears reasonable as judged by aerial photographs. The concept of the equilibrium temperature is developed for the analysis.

The analysis of the cooling process is not completely accurate, but it is adequate. The mechanism of stratification needs to be formulated and incorporated into the mathematical model. Stratified flow, mixing, and the effect of fluctuating wind stress need further study. Velocity measurements and a continuous record of the solar radiation intensity would be helpful. The apparent ability of a swamp to achieve lower temperatures than an open pond, by virtue of the effect of shading upon the equilibrium temperature, needs to be verified.

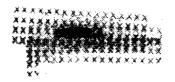
This report shows that the temperature of the effluent cooling water discharged at the river is within a few degrees of the natural equilibrium temperature. The natural equilibrium temp-





erature is defined as the temperature calculated for a stagnant shallow pond at steady state (24-hour-average conditions). However, the temperature of the Savannah River is as much as 8°C below the natural equilibrium temperature in the summertime, as a result of the cold-water storage in Clark Hill Reservoir about 75 miles upstream from SRP. Thus, the temperature of the Savannah River is generally increasing naturally as it reaches the SRP site, and it continues to increase naturally as it progresses on toward the ocean. This report also shows that the temperature of the discharge from Par Pond, which is recycled to the reactors, is within ±2°C of the natural equilibrium temperature and cooler than the natural equilibrium temperature in the summer as a result of thermal stratification effects.

From this analysis and the history of the river temperature and weather at SRP, the temperature of the SRP effluent cooling water reaching the Savannah River was calculated for the most severe summer conditions. The temperature of the SRP discharge from the swamp to the river (from C. K. and L reactors) was calculated to be 35°C. The mixed temperature in the river downstream from SRP was calculated to be 29°C, which is in agreement with independent observations of the U. S. Geological Survey. A computer program is given for calculating the temperature of the SRP effluent cooling water at the river under other conditions. The computer program can also be used to calculate the temperature of Par Pond discharge.



#### DISCUSSION

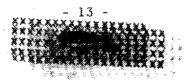
#### HOT WATER EFFLUENT FROM THE PRODUCTION REACTORS

The nuclear reactors at the Savannah River Plant of the U. S. Atomic Energy Commission are operated for the purpose of producing radioactive isotopes for both military and peaceful applications. Such reactors are called production reactors. The production is accomplished by absorbing in target materials the excess neutrons from nuclear fission in the critical lattice that makes up the reactor core. The fission process generates most of the reactor heat. The rate of heat generation, or reactor power, is directly related to the production rate.

The heat that is generated in the reactor must be removed to prevent melting of the reactor components. This is done at SRP by circulating heavy water through the reactor, since heavy water is an essential part of the reactive lattice. This heavy water then flows through the tubes of heat exchangers while ordinary water flows through the shell side, i.e., across the bank of tubes. In SRP parlance, the heavy water coolant is called "process water," and the ordinary water is called "cooling water." The reactor heat is therby transferred in the reactor heat exchangers from the process water to the cooling water.

The production reactors are operated at a pressure not much greater than atmospheric. This requires that the bulk temperature of the process water leaving the reactor and entering the heat exchangers be less than 100°C. The effluent cooling water in turn has to be at a lower temperature, generally less than 80°C, since a temperature difference of about twenty degrees between the process water and the cooling water is required in order to transfer the heat load to the cooling water.

The power of the reactor is generally limited by one or more of the temperatures that are reached at various places in the reactor system. The limiting temperature might be the effluent temperature of the process water. Or, it might be the maximum temperature of the fuel or fuel surface; or, the effluent temperature of the process water from a particular fuel channel. Regardless of the temperature limit, it is a good approximation that the reactor power is directly proportional to the difference between that limiting temperature and the temperature of the cooling water entering the heat exchangers. For example, if the temperature limit governing reactor power is 110°C and if the





temperature of the cooling water could be lowered from 20 to 19°C, the reactor power could be increased by 1.1%. Thus, the temperature of the available cooling water is important to reactor productivity.

The cooling water for the reactors comes from either the Savannah River or from Par Pond. The effluent cooling water from the reactor heat exchangers is returned either to the river downstream from the river pumphouses or to Par Pond at a point remote from the pond pumphouse. Before reaching the river or the pond, the effluent cooling water courses natural streams or man-made canals which are several miles in length. The effluent canals leading to Par Pond connect a number of artificial small ponds. The natural streams carrying effluent cooling water to the river are Four Mile Creek, Pen Branch, and Steel Creek. These streams pass through swampy regions in the flood plain before reaching the Savannah River. Lower Three Runs Creek carries the overflow, if any, from Par Pond to the river.

Studies have shown that it is not economically feasible to recover the heat in the effluent cooling water for electric power generation. Nuclear reactors for electric power generation that employ water as coolant are designed to operate at high pressure in order to achieve steam temperatures sufficiently high, not only for an acceptible thermodynamic efficiency in work recovery but also for less costly turbines. By operating at low pressure, the production reactor can employ a cladding material (aluminum) that is less costly and less parasitic with respect to the neutrons needed to produce the desired products. Finally, the low pressure reactor is more easily charged and discharged, which is an important consideration since the fuel irradiation cycle is short compared with that for the power reactor. Because no useful work is abstracted from the effluent cooling water of the production reactor, all of the reactor heat at SRP is wasted.

#### THEORY FOR THE NATURAL COOLING OF WATER

#### Energy Budget

A mathematical analysis of the cooling process is built around four quantities that are related according to the energy budget equation

$$H_{C} = H_{S} + H_{F} - H_{T}$$
 (1)

The rate of change in the heat content of the body of water  $(H_{C})$  is equal to the rate at which heat is added by the sun  $(H_{S})$  plus the rate of heat addition from the change in temperature of the water that flows through the body  $(H_{F})$  minus the rate at which heat is removed by transfer to the atmosphere  $(H_{T})$ . Equation 1





leads to a nonlinear first-order partial differential equation of first degree with variable coefficients, where time and space are the independent variables, and temperature is the dependent variable. In this report, however, the treatment of Equation 1 is simplified by variously assuming certain terms to be zero, constant, or linear, according to the situation, and by employing spot data or time-averaged data rather than the actual continuously varying data. The unit used in this report for each of these four quantities is pcu/(hr-ft²). Each of these quantities is discussed in turn below.

#### Rate of Change in Heat Content, HC

During the time interval  $d\theta$  hours between observations at a point, a change dT (°C) may occur in the average temperature over the depth h (ft). The rate of change in stored heat is then

$$H_{C} = 62.4 \text{ h} \frac{dT}{d\theta} \tag{2}$$

where the volumetric heat capacity of water is 62.4 pcu/(ft³-°C). Steady-state conditions exist when H<sub>C</sub> is zero. When either dT/dθ or h is sufficiently small, H<sub>C</sub> may be small enough in relation to the other quantities in the energy budget equation that H<sub>C</sub> may be neglected. Thus, in the analysis of the performance of the canals, shallow ponds, streams, and swamp at SRP, H<sub>C</sub> can be set equal to zero. For the deeper Par Pond at SRP, H<sub>C</sub> is an important quantity; but since it is less than 25% of the solar heat load (as shown later), it can be considered constant for the period of time that the solar heat load is considered to be constant. Thus, for Par Pond, H<sub>C</sub> is seen as diminishing or augmenting the solar heat load.

#### Solar Heat Load, Hs

The heat added to a body of water by the sun is the incident radiation minus that reflected. The incident radiation is best measured by a pyrheliometer. Alternatively, it can be estimated from the latitude, altitude, month of the year, time of day, and cloud cover. 1, 2 Tentatively, the reflected radiation is taken at 2.5 pcu/(hr-ft<sup>2</sup>). In Table I, the monthly average solar heat load observed by a pyrheliometer is shown to be about 70% of the maximum 24-hour value estimated from tables. As shown in this table, the 24-hour average value for Hg is 19 pcu/(hr-ft2) in January, increasing to 44 pcu/(hr-ft²) in May. As shown below, for Par Pond in May, the heat load imposed by the flow of reactor effluent cooling water (two reactors in operation) is only half the solar heat load. Generally, Hg is taken as the average value during the time between observations of the temperature at a point or during the transit time between points, i.e.,  $H_S$  is generally a constant in the formulations over an appreciable time interval.





TABLE I

#### Net Solar Heat Load

Month	Maximum Solar Heat Flux, <sup>a</sup> pcu/(hr-ft <sup>2</sup> )	Observed Solar Heat Flux, b pcu/(hr-ft²)	Ratio of Observed to Maximum Heat Flux, pcu/(hr-ft <sup>2</sup> )	H <sub>S</sub> = 69.5% of Maximum Minus 2.5,0 pcu/(hr-ft <sup>2</sup> )
Jan	31.1	22.3	0.717	19.1
Feb	38.3	21.1	0.551	24.1
Mar	46.7	34.4	0.737	30.0
Apr	59.5	45.5	0.765	38,9
May	66.7	47.1	0,705	43.9
June	72.2	47.1	0.652	47.7
			THE REAL PROPERTY AND ADDRESS.	
	Avg (Jan-May	)	0.69\$	

a. Reference 1: clear arid conditions, 24-hr average.

#### Heat Added by the Change in Temperature of the Flow, Hr

The heat content of the water flowing out of the body of water is subtracted from the heat content of the water flowing into the body. This difference in heat content (in pcu/hr) is then divided by the surface area for heat transfer to the atmosphere to obtain Hp in pcu/(hr-ft²). The flow is that imposed by the SRP operations plus that resulting from rainfall, which is the source of the natural stream flow. The flow from SRP operations is metered and its temperature is measured; these are generally the most significant quantities. The rainfall that enters the system, which is next in importance, depends upon the drainage area and the runoff fraction; these are discussed later in connection with Par Pond. In differential form, for the case where only one flow needs to be considered

$$H_{\rm F} = -500F \frac{dT}{dA} \tag{3}$$

where

F = flow, gpm,

A = surface area,  $ft^2$ 500 has the units pcu/(hr-°C-gpm)

b. By pyrheliometer.

c. Allow 2.5 pcu/hr-ft2) for reflected radiation.



Surface Cooling Rate, HT

The rate of cooling at the surface of a body of water is predicted by the equation of J. W. Langhaar.  $^{1,4,5}$  The equation has two parts, one part giving the surface heat flux corresponding to the evaporation rate ( $H_{\rm e}$ ) and the other part giving the surface heat flux for radiation and convection ( $H_{\rm rc}$ ), as follows:

$$H_{T} = H_{A} + H_{TC} \tag{4}$$

$$H_e = 1.63 (1.0 + 0.1W) (P - P_{air})$$
 (5)

$$H_{rc} = 1.20 (1.5 + 0.1W) (T - T_{air})$$
 (6)

where the atmospheric conditions are represented by the variables

W = wind speed, mph "above the trees"

T = water surface temperature, °C

T<sub>sir</sub> = air dry-bulb temperature, °C

P = vapor pressure of water at T, mm Hg absolute

P<sub>air</sub> = partial pressure of water vapor in air, mm Hg

The partial pressure of water vapor in the air  $(P_{air})$  is the product of the vapor pressure of water at the air dry-bulb temperature and the relative humidity. The relative humidity is a function of the air dry-bulb and wet-bulb temperatures  $(T_{WB})$ .

For given atmospheric conditions, the surface cooling rate by the above equations is a nonlinear function of the water surface temperature. Typical curves for the surface cooling rate are given in Figure 1. Over a short interval of temperature, for instance, 10°C, it is reasonable and convenient to approximate the Langhaar curve by a straight line

$$H_{T} = mT + b \tag{7}$$

Equilibrium Temperature, Te

If a stagnant body of water exists initially at some arbitrary temperature T  $^{\circ}$ C and is then exposed to constant atmospheric conditions and to a given solar heat load, the temperature of the water would approach an equilibrium temperature asymptotically with time. For this case,  $H_{\rm P}=0$ , and by Equations 1 and 2 we have

$$62.4h \frac{dT}{d\theta} = H_S - H_T$$
 (8)



## \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

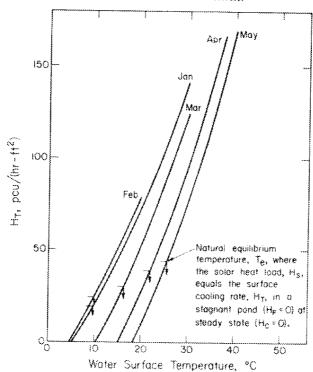


FIGURE 1. Surface Cooling Rate, H<sub>T</sub>

At the equilibrium conditions, by definition  $dT/d\theta=0$ , so the solar heat load equals the rate of surface cooling. The water temperature at equilibrium can be read from the appropriate surface cooling rate curve at the point where  $H_T=H_S$ , as shown in Figure 1. This water temperature  $(T_e)$ , calculated for equilibrium in a stagnant pond, is termed the natural equilibrium temperature.

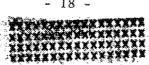
In the analysis of the cooling process throughout this report, however, the concept of the apparent equilibrium temperature is employed in conjunction with the straight-line approximation (Equation 7) to the Langhaar cooling rate curve between two temperatures. This facilitates the integration with respect to time or to surface area. Thus, taking a straight line approximation of the cooling rate curve we have, by Equations 7 and 8, for the transient temperature in a stagnant body of water

$$-\left(\frac{62.4 \text{ h}}{\text{m}}\right)\frac{\text{dT}}{\text{d}\theta} = \text{T} - \text{T}_{es}$$
 (9)

where

$$T_{eS} = \frac{-b + H_S}{m} \tag{10}$$

Here, Tes is the apparent equilibrium temperature.





Similarly, when water is flowing in a channel or shallow pond either under steady-state conditions where HC is zero, or where there is a long-term trend in the average temperature with the season such that HC can be considered as constant, the temperature of the water approaches an equilibrium temperature downstream at infinite distance. The temperature profile with distance is then as follows, from Equations 1 and 3

$$-(500F) \frac{dT}{dA} = H_T - H_S + H_C$$
 (11)

Again, taking a straight line approximation of the cooling rate curve we have, by Equations 7 and 11, for the temperature distribution with distance

$$-\left(\frac{500F}{m}\right)\frac{dT}{dA} = T - T_e \tag{12}$$

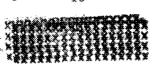
where

$$T_{e} = \frac{-b + H_{S} - H_{C}}{m}$$
 (13)

In this case,  $T_{\rm e}$  is also the apparent equilibrium temperature.

By Equations 9 and 12 the rate of change in water temperature, with time and with distance, respectively, is directly proportional to the difference between the local water temperature and the apparent equilibrium temperature for the water as defined by Equations 10 and 13. Note that, as the straight line is fitted to the Langhaar curve at an increasingly higher temperature range, the value for the apparent equilibrium temperature increases because of the increasing slope of the Langhaar curve. The apparent equilibrium temperature is the temperature that the water appears to be approaching when the cooling is viewed as the simple first-order process described by Equations 9 and 12.

The difference between the apparent equilibrium temperature and the natural equilibrium temperature for Par Pond is shown graphically by Figure 2; in this case, the difference is only about 0.3 °C. However, the difference between the apparent equilibrium temperature and the natural equilibrium temperature in the effluent canals leading from the reactors, where the water is much hotter, can be as much as 20°C (this is shown later in connection with Figure 4). Therefore, if the cooling extends over a long range in temperature, say 10°C or more, the surface cooling rate curve should be approximated by several straight-line sections. Each section then has its own apparent equilibrium temperature. Equation 9 and 12 is integrated for each section, and the time increments or the area increments for the sections are then summed.





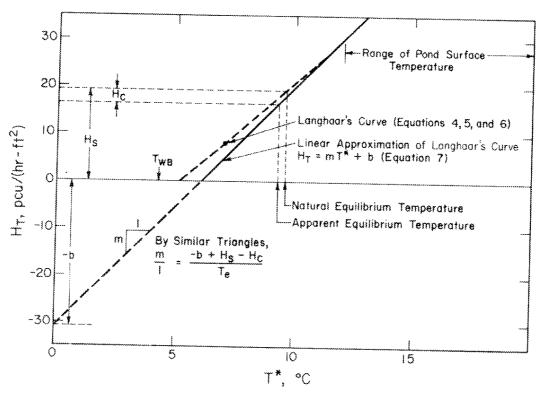


Diagram Showing Concept of the Equilibrium Temperature FIGURE 2. January 1964 Conditions (See Table VI) (The asterisk (\*) on T indicates it is specifically the temperature at the surface, not the bulk temperature of the water.)

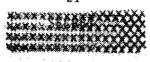


 $T_{\mbox{es}}$  by Equation 10 is the natural equilibrium temperature, as defined above, only when m and b correspond to the tangent to the Langhaar curve at that particular temperature.  $T_{\mbox{es}}$  deviates from the natural equilibrium temperature to the extent that the straight-line fit deviates from the Langhaar curve at the point where  $H_T$  is equated to  $H_S$ .

The apparent equilibrium temperature Te by Equation 13 is less than the apparent equilibrium temperature Tes when HC is positive. HC is positive when the average temperature of the pond is greater at the end of the time increment than at the beginning, i.e., when  $dT/d\theta$  in Equation 2 is positive. With positive H<sub>C</sub>, more of the heat from the sun and from the imposed flow goes to another sink (the pond contents) than to the atmosphere. Hence, in approaching equilibrium at the discharge end of a deep pond having positive Hc, the surface temperature need not be so high as the natural equilibrium temperature in a shallow stagnant pond where all the solar heat must be transferred to the atmosphere. Similarly, when H<sub>C</sub> is negative, some of the heat to be transferred to the atmosphere stems from a source (namely, the pond contents) other than the sun and the imposed flow, so that the apparent equilibrium temperature is greater than the natural equilibrium temperature. It follows that, given sufficient surface area, the surface temperature at the discharge end of a deep cooling pond during the period of positive  $H_{\mathbb{C}}$  can be lower than the natural equilibrium temperature. This effect of HC on the apparent equilibrium temperature and, accordingly, on the cooling rate and the surface temperature is expounded further in connection with the two-region model for Par Pond.

#### Par Pond and Lake Colorado City Experience

If the tangent to the surface cooling rate curve is drawn at the point where the equilibrium temperature occurs, the slope m is the increment in surface heat flux corresponding to the imposed heat load (i.e., from Hr) per °C difference between the actual temperature and the equilibrium temperature. Although the slope m has the units of a heat transfer coefficient, pcu/(hr-ft2-°C), it should be noted that for a heat transfer coefficient the total heat flux is divided by the temperature difference in the direction of heat flow. Typical values of the slope m for Par Pond are given in Table II. The value ranges from 5.1 in January to 7.3 in May. Similar values have been reported for Lake Colorado City, Texas, where it is stated that "... the amount of heat disposed of in Lake Colorado City ranged from winter to summer between approximately 4 and 8 pcu per sq ft per hr per degree (Centigrade) difference in water-surface temperature. The average for the year was 6.7 pcu per sq ft per hr per degree temperature difference. The temperature difference is the rise in water-surface temperature, not the air-water temperature difference."6



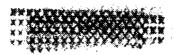


TABLE II

Slope of the Surface Cooling Rate Curve $^{\alpha}$ 

Month	Jan	Feb	Mar	$\frac{\mathrm{Apr}}{}$	May	5-Month Average
Slope, m pcu/(hr-ft <sup>2</sup> -°C)		5.5	6.2	6.8	7.3	6.2

a. From Figure 1 and Table V. Based on monthly average atmospheric conditions and solar heat load.

#### Wet-Bulb Temperature

A stagnant body of water at equilibrium with the atmosphere, but protected from solar radiation, is analogous to a hygrometer. HT by Equation 1 is then zero; hence, by Equations 4, 5, and 6, He and  $H_{\rm rc}$  are equal in magnitude but opposite in sign. The heat for evaporation is supplied by radiation and convection from the atmosphere. Thus, the temperature at the intercept of the surface cooling rate curve at  $H_{\rm T}=0$  is analogous to the air wet-bulb temperature that is obtained by the hygrometer. However, as shown in Table III and in Figure 2, the intercept temperature is higher by about 1°C than the air wet-bulb temperature. It is also shown in Table III and in Figure 2 that the apparent equilibrium temperature of Par Pond, which has not only the solar heat load but also an imposed heat load, is 5 to 7°C higher than the air wet-bulb temperature during the period January through May.

TABLE III

Air Wet-Bulb Temperature Versus Equilibrium Temperature

Month	Jan	Feb	Mar	Apr	May
Air wet-bulb temperature TwB, "C	4.3	3.8	9,4	14.2	17.2
Intercept temperature, b °C .	5.2	4.7	10.5	15.2	18.4
Natural equilibrium temperature, °°C	9.6	10.0	16.2	22.0	25.6
Apparent equilibrium temperature $T_e$ , $d$ °C	9.3	10.1	15.2	20.9	24.5
T <sub>e</sub> - T <sub>WB</sub> , °C	5.0	6.3	5.8	6.7	7.3

a. Monthly average

b. From Figure 1 at Hr = 0

c. From Figure 1 at HT = HS

d. From Equation 13 and Table VIII



#### COOLING IN THE SRP EFFLUENT CANAL SYSTEMS

Description of the Effluent Canal Systems

The canal systems for conducting the effluent cooling water from P reactor and from R reactor to Par Pond are shown in Figure 3. The P reactor effluent is conducted to the middle (or north) arm of Par Pond; the R reactor effluent, to the upper (or east) arm. The elevation drops from about 300 ft msl at the reactors to 200 ft msl at the Par Pond surface. From P reactor there are 4½ miles of canals and five ponds, the largest being 36 acres, plus a 140-acre impoundment of the middle arm of Par Pond upstream from the by-pass road embankment, which is called the "precooler"; the total surface area is 227 acres. From R reactor there are 3½ miles of canals and two ponds, 7.4 and 260 acres in size; the total surface area is 285 acres.

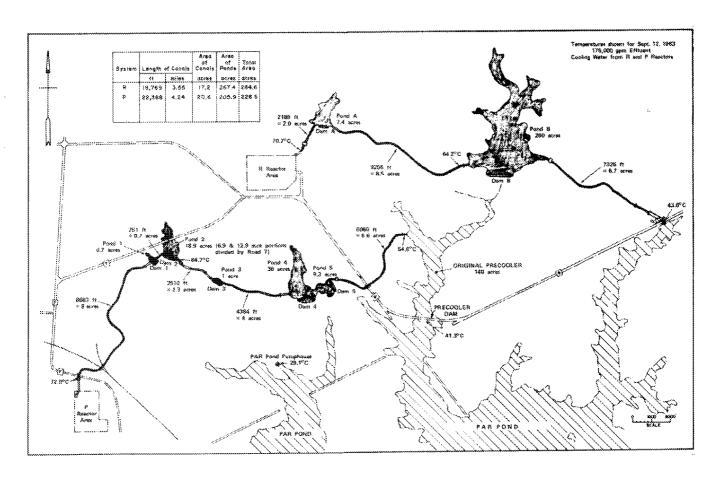
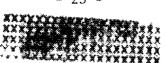


FIGURE 3. R & P Effluent Canals





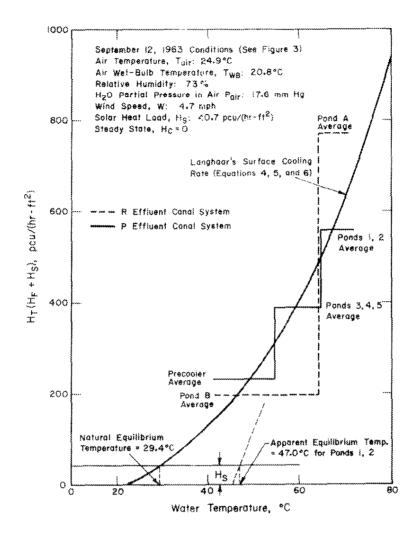


FIGURE 4. Performance of the R & P Effluent Canals



#### Nominal Performance of the Effluent Canal Systems

Typical temperatures are also shown in Figure 3 at various locations along the effluent canals for a day in September 1963. Both canal systems are seen to produce about the same reduction in temperature before reaching Par Pond. In fact, the effluent canal systems dissipate about 70% of the heat generated in the reactors. The reactor effluent temperature of 71°C was reduced to 42°C at the inlet to Par Pond; the effluent from Par Pond was 29°C.

#### Models for the Effluent Canals and Shallow Ponds

Several models for the canals, streams, and shallow ponds at SRP have been formulated: 1) single stage, 2) n equal-size stages in series, 3) n unequal-size stages in series, and 4) infinite number of stages in series. Each stage is considered to be perfectly mixed such that the surface temperature is the same at all points and is equal to the effluent temperature from that stage. An infinite number of stages in series is also known as the slug-flow model. For slug flow, integration of Equation 12 gives the effluent temperature  $T_{\text{out}}$  as a function of the inlet temperature  $T_{\text{in}}$  for a given surface area A at given cooling conditions (m, b, and  $H_{\text{c}}$ ), as follows:

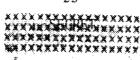
$$\int_{T_{in}}^{T_{out}} \frac{dT}{T - T_e} = -\frac{m}{500F} \int_{0}^{A} dA$$

$$\ln \left(\frac{T_{out} - T_e}{T_{in} - T_e}\right) = -\frac{mA}{500F}$$
(14)

or, 
$$T_{out} = T_e + (T_{in} - T_e) e^{-\alpha}$$
 (15)

where 
$$\alpha = \frac{mA}{500F}$$
 (16)

The quantity 500F/m is the "attenuation area"; i.e., the surface area required to reduce the temperature in excess of the apparent equilibrium temperature by a factor of e = 2.718. The models (shown on the following pages) employ a linear fit to the Langhaar equation over the temperature range that exists in the canals, or in portions of them. The models also employ the concept of an apparent equilibrium temperature. Use of the Langhaar relation itself rather than a linear fit would be better, but more tedious; this does not seem to be justified.



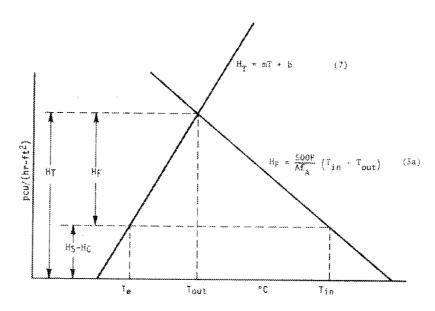


#### MODELS FOR THE EFFLUENT CANALS

MODEL: SINGLE STAGE

Assume perfect mixing in the region corresponding to surface area A  $\rm ft^2$ . Then the surface temperature everywhere is equal to the discharge temperature T<sub>out</sub>.

Let  $f_A$  = effectiveness factor on A



At  $H_F = 0$ we have from (1) and (7)  $0 = mT_e + b - H_S + H_C$ or,  $T_e = \frac{-b + H_S - H_C}{m}$  (13)

At 
$$H_F = H_T - H_S + H_C$$
  
we have from (2) and (7)

$$\frac{500F}{Af_A}$$
 ( $T_{in} - T_{out}$ ) =  $mT_{out}$  + b -  $H_S + H_C$ 

or,

$$\frac{T_{\text{out}} - T_{\text{e}}}{T_{\text{in}} - T_{\text{e}}} = \frac{1}{1 + \alpha f_{\text{A}}}$$
 (17)

where

$$\alpha = \frac{\text{mA}}{500\text{F}} \tag{16}$$

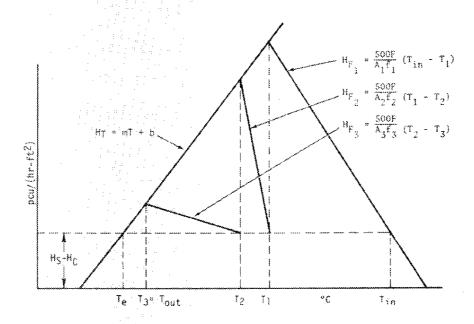


MODEL: n EQUAL-SIZE STAGES

Replace the effectiveness factor  $(f_A)$  used in the Single Stage Model with the apparent number of stages (n). The following equation is derived directly from Equation 17:

$$\frac{T_{\text{out}} - T_{\text{e}}}{T_{\text{in}} - T_{\text{e}}} = \left(\frac{1}{1 + \frac{\alpha}{n}}\right)^{n} \tag{18}$$

MODEL: UNEQUAL-SIZE STAGES



Let  $f_1$ ,  $f_2$ , etc., be the effectiveness factor applied to the surface areas  $A_1$ ,  $A_2$ , etc., respectively.

Assume perfect mixing in each stage.

The first stage overflows to the second stage, etc.

 $A_1 + A_2 + \text{etc.} = A$ , the total surface area.



Assume same linear fit to Langhaar's cooling rate curve (Equations 4, 5, 6); i.e., same Equation 7. Then,

$$\alpha_1 = \frac{mA_1}{500F} = \alpha A_1/A; \ \alpha_2 = \frac{mA_2}{500F} = \alpha A_2/A; \text{ etc.}$$

$$\alpha_1 + \alpha_2 + \text{ etc.} = \alpha = \frac{mA}{500F}$$
(16)

Two Unequal-Size Stages:

$$T_{out}(1+\alpha_1f_1)(1+\alpha_2f_2) = T_{in} + T_e[\alpha_1f_1+\alpha_2f_2+(\alpha_1f_1)(\alpha_2f_2)]$$
 (19)

Three Unequal-Size Stages:

$$T_{\text{out}}(1+\alpha_{1}f_{1})(1+\alpha_{2}f_{2})(1+\alpha_{3}f_{3}) = T_{\text{in}} + \\ T_{\text{e}}[\alpha_{1}f_{1}+\alpha_{2}f_{2}+\alpha_{3}f_{3}+(\alpha_{1}f_{1})(\alpha_{2}f_{2})+(\alpha_{1}f_{1})(\alpha_{3}f_{3})] + \\ T_{\text{e}}[(\alpha_{2}f_{2})(\alpha_{3}f_{3}) + (\alpha_{1}f_{1})(\alpha_{2}f_{2})(\alpha_{3}f_{3})]$$
(20)

When  $T_{\rm in}$ ,  $T_{\rm out}$ , F, A, m, b,  $T_{\rm e}$ , and  $\alpha$  (from above), together with the areas  $A_1$ ,  $A_2$ , etc., of each stage, are substituted into either Equation 19 or Equation 20, an equation in  $f_1$ ,  $f_2$ , etc., is obtained. If similar data were available for other days, particularly over a different range of temperature and/or flow, it should be possible to find "best fit" values for  $f_1$ ,  $f_2$ , etc., which also fit the data better than some other model. Here, however, assume  $f = f_1 = f_2 = \text{etc.}$  Equations 19 and 20 then reduce to a polynomial in f; Equation 19, to a quadratic; and Equation 20, to a cubic.

MODEL: INFINITE NUMBER OF STAGES

This is the "slug-flow" model.

Let  $f_A = effectiveness$  factor on the surface area A.



Integrate Equation 12:

$$\int_{T_{in}}^{T_{out}} \frac{dT}{T - T_e} = -\frac{mf_A}{500F} \int_{0}^{A} dA = -\frac{mf_A^A}{500F} = -\alpha f_A$$

$$\ln \left(\frac{T_{out} - T_e}{T_{in} - T_e}\right) = -\alpha f_A$$

$$\frac{T_{out} - T_e}{T_{in} - T_e} = e^{-\alpha f_A}$$
(15b)

Note: Comparison of Equation 15b with Equation 18 obtained for the model of n equal-size stages gives the identity:

$$\frac{1}{e^{\alpha f_A}} = \lim_{n \to \infty} \left( \frac{1}{1 + \frac{\alpha f_A}{n}} \right)^n$$

Note: In terms of the logarithmic mean temperature difference above  $T_{\rm e},\ {\rm Equation}\ 15b\ {\rm reduces}\ {\rm to}$ 

$$\Delta T_{l,m} = \frac{\frac{T_{in} - T_{out}}{\ln \left(\frac{T_{in} - T_{e}}{T_{out} - T_{e}}\right)} = \frac{\frac{T_{in} - T_{out}}{\alpha f_{A}} = \frac{500F(T_{in} - T_{out})}{mAf_{A}}$$

$$\frac{500F(T_{in} - T_{out})}{Af_A} = m\Delta T_{L\dot{m}}$$
 (21)

where

$$\frac{500F(T_{in} - T_{out})}{AF_A} = \text{average surface heat flux over the effective area.}$$

For an explanation of why m is not a heat transfer coefficient in the usual sense see page 22.

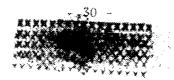


Analysis of the Effluent Canal System Performance

The average heat load over stretches of the effluent canals and ponds between the points where temperatures were measured (Figure 3) is plotted in Figure 4 versus the corresponding range in the water temperature. The average heat load is the sum of heat load imposed by the flow of hot water (HT) and the sun (HS). As shown, the R effluent canal system is divided into two steps (dashed lines); the P effluent canal system, into three steps (solid lines). On the same figure is plotted the curve for the surface cooling rate (HT) corresponding to the weather conditions for that day, by Langhaar's Equations 4, 5, and 6. The system is regarded as steady state, so  $H_{\mathrm{C}}=0$  . Now, if slug flow existed in the region between temperature measurements, the flats of the steps, which are the average heat load over that particular temperature range, would straddle, i.e., be bisected by, the cooling rate curve. If there were perfect mixing in that particular region, the tip of the step would just touch the cooling rate curve, i.e., the steps would touch the curve from the right side. Pond A in the R effluent canal system as shown in Figure 3 is cooling better than can be predicted. Also, the Precooler in the P effluent canal system is shown to be somewhat better than the infinite-stage model (the better performance might be interpreted as the surface temperature being about 1.4°C higher than the average in the cross section normal to the direction of flow everywhere in the precooler pond). The rest of the effluent canal system shows performance lying between the single-stage and the infinite-stage model.

The data of Figures 3 and 4 are analyzed two ways, as shown on the following pages. First, a superficial analysis is made based only on the effluent cooling water temperatures measured leaving the reactor area and entering Par Pond. The values for  $f_A$  or n can be used in the corresponding equation shown to predict the effect of different flows, temperatures, and weather conditions. Both systems are shown as performing better than the single-stage model, since  $f_A$  is greater than 1 for the latter model. The P effluent canal system performs better than the R effluent canal system.

The more-detailed analysis of the data in Figures 3 and 4 is preferred for making predictions. In this analysis, slug flow is assumed in the canals and in the ponds of one acre or less. The temperature of the water entering and leaving each of the larger ponds can then be calculated where they are not already available from the data. Each pond is then evaluated according to the alternative models. From the results, the slug flow model is recommended for all of these ponds using the following factors for the effectiveness of the pond surface area: Pond A,  $f_A = 1.98$ ; Pond B,  $f_A = 0.61$ ; Pond 2,  $f_A = 0.93$ ; Ponds 4 and 5.  $f_A = 0.99$ ; and Precooler,  $f_A = 1.13$ . Using the slug flow model (Equations 15 and 16), the total effective area in the R effluent canal system is  $8.30 \times 10^6$  ft<sup>2</sup>; in the P effluent canal system, it is  $10.58 \times 10^6$  ft<sup>2</sup>.





#### ANALYSIS OF DATA ON THE EFFLUENT CANAL SYSTEMS2

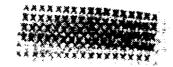
#### SUPERFICIAL ANALYSIS

Consider only the temperature of the effluent cooling water entering the canal system at the reactor area ( $T_{in}$ ) and leaving the canal system at Par Pond ( $T_{out}$ ), from Figure 3. Obtain the surface cooling rate  $H_T$  at  $T_{in}$  and  $T_{out}$  from Figure 4. Take  $H_C$  equal to zero and  $H_S$  equal to 40.7 pcu/(hr-ft²). Calculate m, b,  $T_e$ , and  $\alpha$ . Then calculate  $f_A$  or n for the alternative models.

i kanada a kanada a kuman kata da 1900 da 1900 Barangarangan kanada a kanada	Canal System		
	R	P	
Temp of water entering canals Tin, °C	70.7	72.0	
Temp of water leaving canals Tout, °C	43.6	41.3	
Flow F. gpm	175,000	175,000	
Total surface area A, 106 ft2	12.40	9.86	
m, Eq 37	17.85	17.71	
b, Eq 7, 38 : 100   100	-615.0	-593.0	
T <sub>o</sub> , °C, Eq. 13 (14)	36.8	35.8	
a, Eq. 16	2.53	2.00	
Model: Single stage (mixed), Eq 17 for f	1.57	2.79	
Model: n equal-size stages, Eq 18 for n	1.90	16.5	
Model: 2 unequal-size stages, Eq 19 for f (Divide between Pond A and Pond B: $A_1 = 0.78 \times 10^6$ ; $A_2 = 11.62 \times 10^6$ )	1.32		
Model: 3 unequal-size stages, Eq 20 for f (Divide between Pond 2 and Pond 3, and between Pond 5 and the Precooler: $A_1 = 1.23 \times 10^6$ , $A_5 = 6.10 \times 10^6$ )	en.	1.45	
Model: Infinite number of stages, Eq 15b for f <sub>A</sub> (Slug flow)	0.634	0,943	

a. Data taken 9/12/63. See Figures 3 and 4.

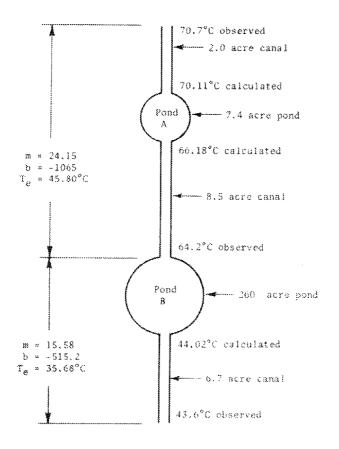




#### MORE-DETAILED ANALYSIS

Assume slug flow (Equation 15b) in the canal sections and ponds of one acre or less in order to calculate  $T_{\rm in}$  and  $T_{\rm out}$  for the larger ponds where these temperatures are not given in Figure 3. Take HC equal to zero; Hg = 40.7 pcu/(hr-ft²). Calculate m, b, and  $T_{\rm e}$  for a straight line fit to Figure 4 between the temperatures given in Figure 3. Then calculate  $f_{\rm A}$  or n according to the alternative models for the larger ponds in the effluent canal system

#### R Effluent Canal System



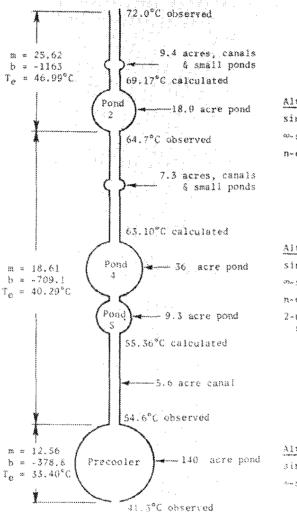
#### Alternative Models for Pond A single stage (mixed) $f_A = 2.17$ $\sim$ -stage (slug) $f_A = 1.98$

Alternative Models for Pond 8 single stage (mixed)  $f_A \approx 1.20$   $\approx$  -stage (sing)  $f_A \approx 0.61$  n-equal-size stages  $n \approx 1.34$ 





#### P Effluent Canal System



#### Alternative Models for Pond 2

single-stage (mixed)  $f_A = 1.05$   $\infty$ -stage (slug)  $f_A = 0.93$ n-equal-size stages n = 1.65

#### Alternative Models for Ponds 4 & 5

single-stage (mixed)  $f_A = 1.22$   $\Rightarrow$ -stage (slug)  $f_A = 0.99$ n-equal-size stages n = 162-unequal-size
stages  $f_1 = f_2 = 1.14$ 

#### Alternative Models for Precooler

single-stage (mixed)  $f_A = 1.92$ -stage (slug)  $f_A = 1.13$ 





#### COOLING IN PAR POND

#### Description of Par Pond

Par Pond covers 2640 acres to an average depth of 20.4 ft. A 140-acre portion is separated from the main body of Par Pond by the bypass road embankment to form the "precooler" which is considered to be a part of the P effluent canal system. The surface area of the main pond is therefore 2500 acres, or 109 million ft $^2$ . The Par watershed is 36 mi $^2$ . The greatest depth in Par Pond is about 55 ft near the dam.

The plan for Par Pond is shown in Figure 5. There are three major arms. The effluent canal from R reactor terminates at the shallow end of the east arm; the effluent canal from P reactor, at the shallow end of the north or middle arm. The pump house is located at the shallow end of the west arm. The main dam is to the south across Lower Three Runs Greek. The intake slot at the pump house, which is located along the bank, is 100 ft wide with the opening at a depth extending from 17 to 20 ft. During construction, the pond bottom was bulldozed as necessary to provide a 20-ft-deep channel 300 ft wide leading to the pump house intake from a distance of 2000 ft out, where the natural -20 ft contour was intercepted.

The rated capacity of the Par pump house is 275,000 gpm, which is about 30% of the total SRP capacity for pumping cooling water to the reactors. This flow is divided between R and P reactors (R reactor was shut down in mid-1964). With both R and P reactors in operation and with each reactor requiring about 180,000 gpm, additional cooling water was drawn from the river system. The effluent cooling water from both reactors was discharged to Par Pond through the effluent canal system. The excess cooling water then overflowed at the dam and traveled to the Savannah River via Lower Three Runs. Because the temperature of the overflow at the dam was only slightly above the equilibrium temperature, and the water was further cooled during its 18-mile flow path to the Savannah River, there was no thermal impact on the river because of the operation of R and P reactors. At the present time, with Par Pond serving only P reactor, there need be no regular overflow at the dam. In fact, it is currently necessary to add about 7500 gpm of water from the river system to maintain constant level in the pond.



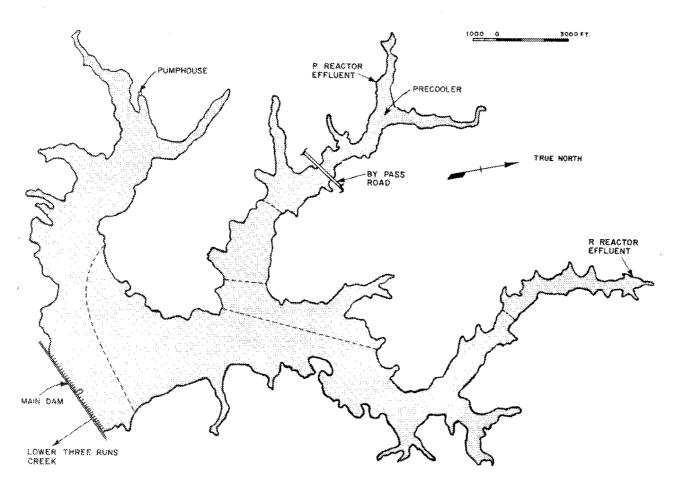


FIGURE 5. Par Pond Map





Par Pond contains about 18 billion gallons of water. At the rated capacity of the pump house this quantity corresponds to 45 days for displacement; at 180,000 pgm for P reactor only, it corresponds to 68 days.

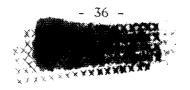
#### Nominal Performance of Par Pond

The concern with Par Pond is the extent to which the temperature of the water is cooled before being pumped back to the reactor heat exchangers. Thus, over the years the effluent temperature from Par Pond has been compared with that of the Savannah River at SRP. As shown in Table IV, the effluent temperature from Par Pond has averaged about  $3^{\circ}$ C higher than the temperature of water from the river but at times it may be as much as  $7^{\circ}$ C higher than the river. The study of Par Pond has shown that the effluent temperature is within  $\pm 2^{\circ}$ C of the natural equilibrium temperature, and the water pumped from Par Pond at a depth of -20 ft may be less than the apparent equilibrium temperature because of stratification.

TABLE IV  $\mbox{Par Pond Effluent Temperature } \\ \mbox{Compared with the River Temperature}^{\alpha}$ 

			Par Effluent Temperature			
		Effluent		Minus"		
	Temperature, °C		River Temperature, °C			
	***************************************	Maximum	Maximum			
	•	Deviation	Mean	Deviation		
Month	Mean	From Mean	Difference	From Mean		
Jan	10.6	+ 1.1 - 0.9	1.7	+ 1.2 - 0.9		
Feb	11.5	+ 1.3 - 1.7	1.8	+ 2.0 - 1.3		
Mar	13.7	+ 1.8 - 4.2	2.0	+ 1.8 - 0.9		
April	18.4	+ 1.6 - 1.8	2.6	+ 1.6 - 1.3		
May	23.5	+ 0.7 - 2.7	4.4	+ 2.0 - 1.7		
June	26.6	+ 0.5 - 0.9	5.0	+ 1.7 - 1.2		
July	28.6	+ 0.9 - 0.4	5.1	+ 1.7 - 1.4		
Aug.	28.9	+ 1.2 - 1.0	4.8	+ 1.6 - 1.7		
Sept	26.8	+ 0.6 - 0.9	3.6	+ 1.0 - 1.7		
0ct	22.7	+ 1.6 - 1.3	2,2	+ 0.8 - 1.5		
Nov	18.0	+ 2.0 - 2.1	1.7	+ 0.6 - 0.8		
Dec	12.4	+ 1.8 - 1.4	1.3	+ 0.8 ~ 0.7		
Annual Avg	20.1°C		3.0°C			

a. Monthly average values 1959 through 1965

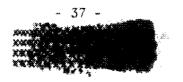




The principal reason for the difference between Par Pond effluent temperature and the river temperature arises from the fact that the river is not at its natural temperature because of the Clark Hill Reservoir. The seven-year average temperature of Par Pond effluent, which is shown in Table IV to be 20.1°C, is only 0.4°C higher than the average temperature of the Savannah River before construction of Clark Hill dam, i.e., from 1935 through 1950. The effect of Clark Hill Reservoir on the temperature of the Savannah River is discussed at more length later. Par Pond is not sufficiently large and not sufficiently deep, particularly at the pump house intake slot, for its performance to benefit greatly from thermal stratification.

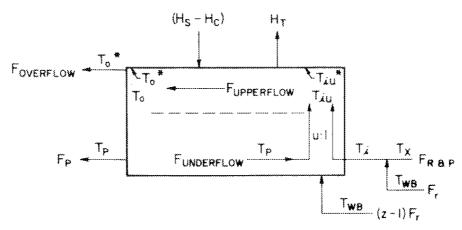
### Model of Par Pond

Observations at Par Pond, primarily by temperature traverses, have led to a model for a relatively deep cooling pond (Figure 6). The pond is conceived as a rectangular channel having two regions of flow, namely, an upper flow region, which moves in the direction of the pump house from the inflow point, and a countercurrent underflow. Warm water from the canals at temperature  $T_{f i}$  enters the pond and immediately mixes with u parts of underflow at temperature Tp to give the temperature Tiu, which is the average temperature of the upperflow at the warm end of the pond. The underflow at Tp has traveled upstream from the cool end of the pond and is at the same temperature as the water discharged from the pond through the pump house intake slot. The excess of the inflow over that withdrawn at the pump house overflows at the cool end of the pond at a temperature  $T_0^*$ . The asterisk on the temperature symbol indicates that it is a surface temperature; the average temperature of the upperflow at the cool end of the pond is To. Similarly, at the warm end the surface temperature is  $T_{iu}^{\star}$ . The flow of vapor from the pond is considered as part of the overflow. The pond receives heat from the sun at the rate Hs and experiences a gradual change in stored heat at the rate Hc: the quantity Hs - Hc is uniformly distributed over the surface of the pond. He is based on the average depth of the pond (h = 20.4 ft), not on the depth of the upperflow region, which is not specified. Because the depth of the upperflow region may be only a few feet, and because of the high internal circulation (the u effect), the transit time from the warm end to the cool end of the pond may be about a day. As the upperflow travels from the warm end to the cool end of the pond, heat is dissipated to the atmosphere at the rate HT, decreasing as the surface temperature decreases from  $T_{
m iu}^*$  and  $T_{
m o}^*$  according to the slug flow model discussed in the next section. The difference between the surface temperature T\* and the average temperature T of the upperflow in a section normal to the upperflow is considered to be constant everywhere in the pond; this difference has the symbol  $\Delta T_G$ . It is expected that this excess temperature at the





surface varies with the season depending on the extent of thermal stratification. As shown in Figure 6, part of the runoff from rainfall (which is also the source of natural stream flow into the pond) mixes with the water in the canal system, while the balance enters the pond by other routes; the runoff is at the air wet-bulb temperature,  $T_{WB}$ .

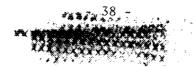


 $T_0$ \*- $T_0$  =  $T_{\dot{\alpha}\dot{\alpha}}$ \* - $T_{\dot{\alpha}\dot{\alpha}}$  = T\* -T =  $\Delta T_G$  = Constant

FIGURE 6. Model for Par Pond

# Extension of the Theory to the Par Pond Model

Consider the energy budget equation not only for the region of the upperflow but also for the region of the underflow. Only part of the solar heat load  $H_{\rm S}$  (say, the fraction x) and only part of the heat content rate-of-change  $H_{\rm C}$  (say, the fraction y) are assigned to the upper region. For the underflow there is no surface heat transfer, so 100% of  $H_{\rm T}$  is assigned to the upperflow. Also, there is no change in temperature of the underflow as it moves from the discharge point (the pump house) to the inflow point at the warm end of the pond. Thus, there is an  $H_{\rm F}$  term only for the upperflow. The two energy budget equations are consequently as follows:





Upper layer

62.4 yh 
$$\frac{\partial T_a}{\partial \theta} = xH_S - 500F_{upperflow} \frac{\partial T_a}{\partial A} - H_T$$
 (22)

Lower layer

62.4 (1-y) 
$$h \frac{\partial T_b}{\partial \theta} = (1-x) H_S$$
 (23)

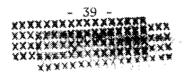
Adding these equations gives the combined energy budget equation

62.4h 
$$\left[ y \frac{\partial T_a}{\partial \theta} + (1-y) \frac{\partial T_b}{\partial \theta} \right] = H_S - 500 F_{upperflow} \frac{\partial T_a}{\partial A} - H_T$$
 (24)

The left-hand side of the combined equation is  $H_{\mathbb{C}}$  for the pond.

The quantity (1-y)  $\partial T_b/\partial \theta$  is generally more significant than the quantity y  $\partial T_a/\partial \theta$ . Consequently, since the discharge temperature  $T_b$  is also the temperature  $T_b$  of the lower layer, in the model for Par Pond, it is reasonable to measure the time rate of change in pond heat content by the time rate of change in the discharge temperature. Note that the fraction x (of the solar radiation that is absorbed in the upper layer) has dropped out of the combined energy budget equation. Thus, with the substitution of  $H_C$  for the left-hand side of Equation 24, the energy budget equation for the Par Pond model appears the same as that presented above under Theory, where only a single region was considered. All of the solar energy and all of the pond heat content is considered to be in the upper layer.

Actually, the time rate of change in the temperature of the underlayer is not determined just by the attenuation of the solar energy that occurs in that region. The quantity xHg-HT in the energy budget equation for the upper layer varies greatly between night and day, being much more negative at night. (In this report, the 24-hr average has been used for Hg and HT). The colder water produced at the surface during the night is transported to lower levels by convection in seeking stable stratification (see page 70). In effect, the solar heat that is absorbed in the lower layer is compensated by the downward transport of colder water to this region. To the extent that the solar heating in the lower layer is more than compensated by the diurnal convection,  $\partial T_b/\partial \theta$  may be negative, as in the fall. The downward transport of colder water to the lower layer is accompanied by the upward transport of





warmer water to the upper layer, in effect increasing the apparent solar heating in the upper layer. The combined energy budget equation above remains unchanged by this diurnal convection since the quantities xHs and (1-x)Hs in the separate energy budget equations were the apparent solar heat loads, by whatever mechanism; and, in the combined equation, the value of the split assigned to the two regions for the solar heating contribution is unimportant. When diurnal convection is sufficient for the average  $\partial T_b/\partial\theta$  to become negative, the average  $\partial T_a/\partial\theta$  is also expected to become negative. In fact, at the "turnover" in the early fall,  $T_a$  has managed to drop below  $T_b$  by virtue of  $\partial T_a/\partial\theta$  being more negative than  $\partial T_b/\partial\theta$ . The heat content rate-of-change Hc for the pond is negative following the fall "turnover" as the pond temperatures decrease.

At the time of the fall "turnover," the pond contents undergo extensive mixing whereby the thermal stratification that developed in the spring is largely, but not completely, destroyed. Also, a temperature gradient must still exist from the inflow point to the pump house. The Par Pond model described above should apply just as well with negative  $H_{\rm C}$  as with positive  $H_{\rm C}$ .

#### Formulation of the Par Pond Model

The total heat load per square foot of effective surface area that is imposed on the pond by the change in temperature of the flow through the pond, Hr, is derived by two independent methods (shown in Appendix A). First,  $H_{\rm F}$  is obtained by difference from consideration of the energy budget equation with Hs and Hc constant and with Langhaar's surface cooling rate averaged over the pond (Equation A-5). Second, Hr is formulated directly from its definition (Equation A-6). Hr is then eliminated between Equation A-5 and A-6 to give Equation A-7. Some of the variables in Equation A-7, however, are not directly measured; but they are readily derived by material and heat balances, from consideration of the model (Figure 6), in terms of other variables that are usually measured (except the quantity  $\Delta T_G$ ). Thus, Equation A-13a is obtained which gives  $\Delta T_G$  explicitly in terms of the average discharge temperature Tp at the pump house during the time interval of d days, the average temperature  $T_i$  of the water entering the pond from the canal systems, the average air wetbulb temperature TwB, and the apparent equilibrium temperature Te, which is calculated by Equation 13. The coefficients  $K_0$ ,  $K_2$ ,  $K_3$ ,  $K_4$ , and  $K_5$  in Equation A-13a are weighting factors applied to the five temperatures. These coefficients are functions of the average flow from R and P reactors (FREP, gpm), the average pump house flow (Fp, gpm), the rainfall (r inches during d days), the



average weather conditions expressed in terms of the slope m and intercept b (Equation 7), the solar heat load (Hg), the pond attenuation coefficient ( $\alpha$ ), and the mixing ratio at the warm end of the pond (u). Other factors are the ratio of total runoff to the runoff into the canal systems (z), the runoff fraction (f<sub>r</sub>), the pond area effectiveness factor (f<sub>A</sub>), and the pond heat content factor (f<sub>C</sub>).

In order to calculate the values for some of the coefficients in Equation A-13a and for the apparent equilibrium temperature  $T_e$  by Equation 13, it is necessary first to obtain the slope m and intercept b of the straight-line approximation to Langhaar's curve for the surface cooling rate (Equations 4, 5, and 6). The line is fitted between the extremes in surface temperature in the pond,  $T_{iu}^{\star}$  at the warm end and  $T_0^{\star}$  at the cool end using Equations A-15 and A-16. The temperatures  $T_{iu}^{\star}$  and  $T_0^{\star}$  are calculated by Equations A-11 and A-12, which use  $\Delta T_G$ ; hence, a trial-and-error solution for the value of  $\Delta T_G$  during the period of d days is required in order to place the straight line properly on the surface-cooling-rate curve.

The rate of change in stored heat  $H_{C}$  is also required in calculating the apparent equilibrium temperature  $T_{e}$  by Equation 13. The data on Par Pond performance did not include temperature traverses of the pond such as would be needed to estimate the heat content of the pond at the beginning and at the end of the interval of d days. It is therefore assumed that the change in the discharge temperature over the d days is a measure of the change in the average pond temperature, with the factor  $f_{C}$  included for purposes of obtaining a better correlation if desired. Thus  $H_{C}$  is estimated by Equations 2a and A-14.

The attenuation coefficient  $\alpha$ , used in the coefficients of Equation A-13a, is calculated by Equation 16a in terms of the slope m and the upperflow, which is calculated by Equation A-9.

The flow  $F_{\mathbf{r}}$  contributed to the discharge from the canal systems by runoff from rainfall is also needed to calculated the coefficients in Equation A-13a and the upperflow. It is calculated by Equation A-17.

Thus, data on Par Pond performance are evaluated so as to obtain a set of  $\Delta T_G$  values, say, according to the month of the year, using the correlating Equation A-13a. The data required are the weather conditions, the solar heating rate, the rainfall, the flow of effluent cooling water to the pond, the average temperature of the water discharging from the canals into the warm end of the pond, the discharge flow at the pump house, and the average discharge temperature at the pump house. Also, importantly for  $H_C$ , the data include the discharge temperature  $T_1$  at the start of the interval of d days and the discharge temperature  $T_d$  at the end of the interval.





Having determined the set of  $\Delta T_G$  values from the analysis of Par Pond performance, it is then desired to arrange the correlating Equation A-13a so as to give the average discharge temperature  $T_P$  explicitly; then  $T_P$  can be calculated for other conditions of the weather, flows, and temperatures. Now, the temperature  $T_1$  at the start of the time interval will be known, but not the temperature  $T_d$  at the end of the interval. However, for a short enough interval of time, the average discharge temperature  $T_P$  can be assumed to be equal to the average of  $T_1$  and  $T_d$  (Equation A-18). Thus,  $T_P$  is given explicitly by Equation A-21 in terms of  $T_1$ ,  $T_i$ ,  $T_{WB}$ ,  $T_{es}$ , and  $\Delta T_G$ . Here, the equilibrium temperature  $T_{es}$  is approximately that for a stagnant shallow pond at steady state, calculated by Equation 10 using m and b values from the straight-line fit to Langhaar's curve at  $T_{iu}^*$  and  $T_O^*$ .

The arguments in favor of such a complex-appearing function as Equation A-13a, together with its satellite equations for the K coefficients, for correlating the pond performance, or Equation A-21 for predicting the pond performance, are as follows: The numerous parameters must be considered if they are thought to have an appreciable effect on the pond effluent temperature. The equations that involve these parameters are the equations that express the physical phenomena according to the model envisioned in Figure 6; they are not mere empirical equations. The factors u, fr, z, fA, and for might be varied to obtain a better correlation, but the values of these factors must be reasonable; otherwise, a better model should be sought. These factors are not intended to be mere correlating constants. Moreover, the coefficients in the Langhaar Equations 5 and 6 are not legitimate areas for tampering merely to force a better fit to the data on pond performance. These equations give the heat and mass transfer rates to the atmosphere; the coefficients are determined only by consideration of these effects. Although the  $\Delta T_{C}$  value may be regarded as merely a shift (to the left) of the Langhaar cooling curve, it is tentatively believed that  $\Delta T_{\rm G}$  is related to thermal stratification and is not a correction to the surface cooling rate. In sum, the complex-appearing Equations A-13a and A-21 for Par Pond performance are a composite of the elementary considerations, such as, the rates of heat and mass transfer, energy and material balance, mixing, staging, stratification, underflow, overflow, rainfall, and heat content, and are devoid of purely empirical factors and coefficients.

#### Correlation by the Par Pond Model

Data on Par Pond performance were available for the period January through May in 1964 in sufficient detail for evaluation by Equation A-13a. These data and details of the analysis are presented in Table V. The  $\Delta T_G$  values by months were found to be as follows:





	Jan	Feb	Mar	Apr	May
$\Delta T_G$ , °C	1.2	1.1	1.7	2.6	1.9

where  $\Delta T_G$  is the difference between the surface temperature and the average temperature of the upperflow. The trend is toward increasing  $\Delta T_G$  as summer is approached, as expected.

TABLE V  $\label{eq:Analysis} \mbox{ Analysis of Par Pond Data According to the Model $^{2}$ }$   $\mbox{ 1964 Data }$ 

North	January	February	March	April	May
Time interval d. days	31	29	31	30	31
Monthly Average Conditions					
Air dry-bulb temp Tair, °C Air wet-bulb temp TwB, °C Wind speed W, miles/hr	7.01 4.28 7.8	8,61 3,76 9,0	13.16 9.41 8.6	18.04 14.15 7.8	22.22 17.21 7.3
Solar heat flux Hg, pcu/(hr-ft*) Rainfall r, in. Canal effluent temp T <sub>1</sub> , *C	19.1 7.52 37.57	24.1 5.08 30.61	30.0 6.32 33.03	38.9 5.22 35.16	43.9 4.10 38.41
Pumphouse effluent temp, °C At beginning of month T <sub>1</sub> Average for month T <sub>p</sub> At end of month T <sub>d</sub> Flow from R&P canals FR&P, 10° gpm Flow from pumphouse Fp, 10° gpm	10.06 10.67 11.67 0.3182 0.1847	11.67 11.79 13.23 0.3373 0.1927	12,23 15,48 16,43 0,3344 0,1998	16,43 19,34 21,05 0,3267 0,1821	21.05 23.60 25.88 0.3343 0.2029
Calculating ATG					
H <sub>C</sub> , Eq 2a, A-14 E <sub>T</sub> , Eq A-17 Fupperflow, Eq A-4 T <sub>10*</sub> , Eq A-11 T <sub>2*</sub> , Eq A-12 H <sub>T</sub> , iu, Eq 4, 5, 6 H <sub>T</sub> , 0, Eq 4, 5, 6 H <sub>T</sub> , 0, Eq A-15 b, Eq A-16 T <sub>e</sub> , Eq 13 0, Eq 16 T <sub>e</sub> , Eq 13 0, Eq 16 K <sub>2</sub> , Eq A-13 K <sub>3</sub> , Eq A-13 K <sub>3</sub> , Eq A-13	2.75 0.0097 1.099 16.80 12.06 54.22 5.06 -30.7 9.31 1.002 2.506 0.367 0.019	1.02 0.0070 1.148 18.41 13.03 68.99 39.15 5.54 -33.1 10.14 1.052 2.531 0.349 0.012	7,19 0,0082 1,145 22,32 17,41 66,72 36,40 6,17 -71,0 15,21 1,174 2,630 0,309 0,013	8,17 0,0070 1,113 26,64 22,40 69,84 41,25 6,75 -110,1 20,86 1,321 2,722 0,267 0,010	8,26 0,0053 1,150 29,94 25,85 75,25 45,16 7,31 -143,4 24,50 1,409 2,765 0,244 0,007
Ke, Eq A-13 -Ks, Eq A-13 AT <sub>G</sub> , Eq A-12a	2.121 2.691 1.19	2,170 2,724 1,06	2,308 2,838 1,67	2,445 3,020 2,61	2,514 3,007 1,94
Calculate Check Tp					
Tes, hq 10 K1, hq A-21 k0, hq A-21 k1, hq A-21 k2, hq A-21 k3, hq A-21 k4, hq A-21 k4, hq A-21 check Tp, hq A-21	9,85 1,435 3,947 0,364 0,093 0,005 0,538 0,683 10,74	10.32 1.431 3.965 0.361 0.088 0.003 0.548 0.687 11.85	16.36 1.280 3.910 0.327 9.079 0.005 0.590 0.726	22.07 1.281 4.003 0.320 9.067 0.002 0.611 0.754	25.63 1.177 3.942 0.299 0.062 0.003 0.638 0.763 23.36
Deviation = Tp - Check Tp	-0.07	-0.06	+0.38	+0.19	+0.04
Calculate Check T <sub>d</sub>					
Check Td (use Check Tp), Eq. A-18	11.42	12,03	17.97	21.87	26.07
Deviation = Td - Check Td	<b>*0.2</b> \$	+0.20	-1.54	-0.82	-0.19

 $<sup>\</sup>alpha$ , Assume u=2.3, z=2.71, h=20.4 ft,  $f_{T}=0.25$ ,  $f_{A}=1.0$ ,  $f_{C}=1.0$ 



For the analysis in Table V the following parameters were specified as being reasonable values: the runoff factor,  $f_{\mathbf{r}}=0.25;$  the ratio of the total runoff to the runoff into the canals, z=2.71; the pond area effectiveness factor,  $f_{A}=1.0;$  and the pond heat content factor,  $f_{C}=1.0.$  The mixing ratio u at the warm end of the pond was taken to be 2.3, which is the average of 13 values estimated from temperature traverses made in 1959.

The  $\Delta T_G$  values calculated above from the 1964 data are consistent with observations made in 1959 of the thermal stratification in Par Pond, as shown in Figure 7. The difference between the surface temperature and the average temperature over a 20-ft depth, calculated from these 1959 data, are given in Table VI. These differences should be greater than  $\Delta T_G$ , since the depth of the underflow is not thought to be as great as 20 ft; but the values are seen to be remarkably similar. Thus, for the months in 1959 in which temperature profiles in depth were taken, the difference between the surface and the average temperature over a 20-ft depth was as follows:

	Jan	Apr	May	June	July	Aug
Observed	0.4	0.6	2.2	1.4	2.6	2.0

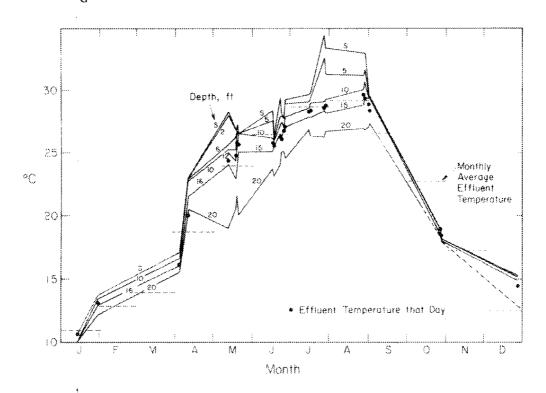


FIGURE 7. Stratification in Par Pond

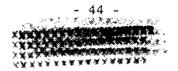




TABLE VI Stratification in Par Pond

Date	Surface Temp (T <sub>S</sub> ),°C	Avg Temp at 20-ft depth (Tav),°C	Pumped Temp (Tp), C	Pumped Avg Temp for month,	Tav - Tp,	Observed $ \begin{array}{c} \Delta T_{G} = \\ T_{S} - T_{av}, \end{array} $
1/14/59	10.6	10.2	10.6	10.9	-0.4	0.4
1/29/59	13.7	13.2	13.1		0.1	0.5
4/3/59 4/10/59	17.1 23.0	16.5 22.3	16.1 20.0	18.7	0.4	0.6 0.7
5/12/59	28.2	24.5	24.3	23.9	0.2	3.7
5/18/59	26.8	24.6	24.7		-0.1	2.2
5/19/59	27.2	25.5	25.7		-0.2	1.7
5/20/59	26.5	25.3	25.6		-0.3	1.2
6/16/59 6/17/59 6/22/59 6/23/59 6/25/59 6/26/59	28.3 26.3 29.3 28.1 27.7 29.2	26.2 25.5 27.0 27.0 27.0 27.6	25.7 25.5 26.2 26.0 26.7 27.0	26.4	0.5 0.0 0.8 1.0 0.3	2.1 0.8 2.3 1.1 0.7 1.6
7/15/59	29.6	28.4	28.2	28.6	0.2	1.2
7/16/59	29.7	28.5	28.3		0.2	1.2
7/27/59	34.5	30.0	28.5		1.5	4.5
7/28/59	33.3	29.6	28.7		0.9	3.7
8/27/59	32.9	29.9	29.6	29.1	0.3	3.0
8/28/59	32.9	30.3	29.2		1.1	2.6
8/30/59	29.6	29.1	28.8		0.3	0.5
9/1/59	29.3	29.0	28.3	26.5	0.7 	0.3.

<sup>7.</sup> The temperature of the water withdrawn at the pump house (Tp) averaged 0.5°C lower than the average temperature from the surface to a 20-ft depth ( $T_{av}$ ). This may have been due to selective withdrawal from the stratified reservoir, or it may be the result of wind stress (in view of the wide variation in  $T_{av}$  -  $T_p$ ).

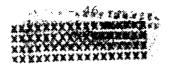


The period of appreciable thermal stratification is shown in Figure 7 to be from April through August. In the light of the results obtained by application of Equation A-13a to the 1964 data and the observations in 1959, it is suggested tentatively that  $\Delta T_{G}$  be taken as 1°C from September through March and as 2°C from April through August.

The correlation in terms of these ATG values is given with some reservations. First, the variation in  $\Delta T_G$  is substantial. As shown in Equation A-21 the average discharge temperature Tp depends linearly on  $\Delta TG$  with a coefficient k5; Table V shows ks to be about -0.7. Thus, an uncertainty of  $1^{\circ}$ C in  $\Delta T_{\rm C}$  means an uncertainty in Tp of 0.7°C, which is substantially greater than what is hoped for in the prediction of pond performance. Of greater concern, however, are the fluctuations that are observed in the pond discharge temperature. The fluctuation in the discharge temperature from Par Pond recorded daily from January through May in 1964 is shown in Figure 8. The fluctuation is attributed more to fluctuating wind stress at the surface of the stratified pond than to the fluctuations in the weather and in SRP operating conditions. More is said about wind stress later under "Areas for Further Investigation." For the analysis given in Table V, the data were averaged for one-month intervals. The temperatures T<sub>1</sub> and T<sub>d</sub> were the average of the three days preceding and the three days following the start of the month, in order to iron out some of the fluctuation. These temperatures are the circled points joined by dashed lines on Figure 8. average discharge temperature Tp for the month is shown in Figure 8 by the horizontal dashed lines. It is seen that the difference between  $T_{
m p}$  and average of  $T_{
m l}$  and  $T_{
m d}$  is as follows by months:

	Jan	Feb	Mar	Apr	May
T <sub>p</sub> , °C	10.67	11.79	15.48	19.34	23.60
$\frac{1}{2}(T_1 + T_d), ^{\circ}C$	10.86	11.95	14.33	18.74	23.46
Difference, °C	-0.19	-0.16	+1.15	+0.60	+0.14

The difference is greatest in March and April. As shown in Table V, the check value for  $T_P$  by Equation A-21 and the check value to  $T_d$  by Equation A-18, when using the  $\Delta T_G$  values calculated in Table V, show the greatest deviations for March and April.





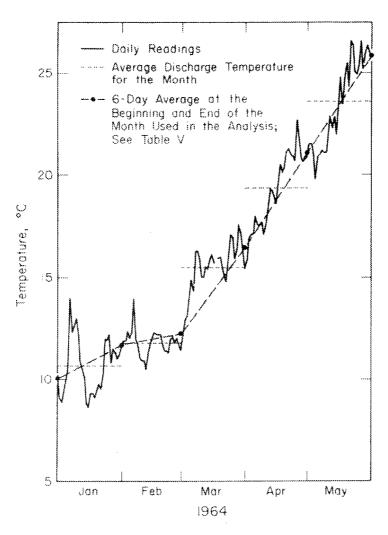


FIGURE 8. Par Pond Temperature, January Through May 1964





The Energy Budget for Par Pond

The average values for the quantities  $H_{\text{S}}$ ,  $H_{\text{C}}$ ,  $H_{\text{F}}$ , and  $H_{\text{T}}$  in the energy budget for Par Pond for the months of January through May 1964, from the analysis given in Table V, are as follows:

$$H_S - H_C + H_F = \overline{H}_T$$

Jan 19.1 - 2.7 + 23.9 = 40.3

Feb 24.1 - 1.0 + 28.4 = 51.5

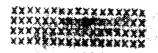
Mar 30.0 - 7.2 + 25.8 = 48.6

Apr 38.9 - 8.2 + 21.7 = 52.4

May 43.9 - 8.3 + 21.3 = 57.0

 $\rm H_S$  and  $\rm H_C$  come directly from Table V;  $\rm H_F$  is calculated by Equation A-6 and HT by Equation A-4. The imposed heat load Hp from the flow is relatively constant while the solar heat load Hp more than doubles as summer is approached. The imposed heat load Hp exceeds the solar heat load in winter, but is only about half the solar heat load as summer is approached. The heat load HC from the change in stored heat varies 8-fold, but does not exceed 25% of the solar heat load.

The energy budget diagram for the month of May 1964 is given in Figure 9. The diagram shows the variation in surface heat flux HT as the surface temperature varies from  $T_{iu}^*$  to  $T_0^*$ . The important effect of the mixing ratio u in reducing the canal effluent temperature  $T_i$  to the pond temperature  $T_{iu}$  at the warm end is evident. Note also the effect of  $\Delta T_G$  in shifting to a higher surface heat transfer rate, and note the differences between  $T_P$ ,  $T_e$ , and  $T_0$ . This information has been translated in Figure 10 to show the variation in the pond heat transfer rate over the surface area.



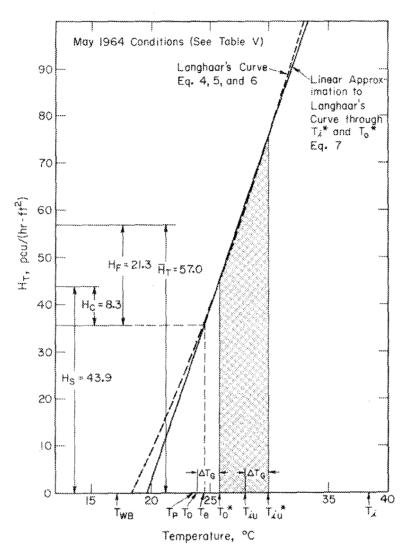


FIGURE 9. Energy Budget Diagram for Par Pond

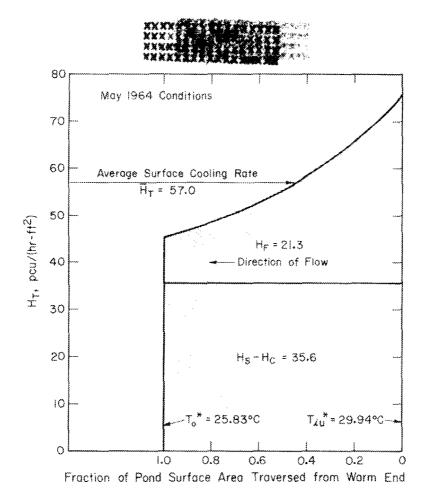


FIGURE 10. A Variation of the Energy Budget Diagram

The Approach to Equilibrium Temperature in Par Pond

The surface temperature  $T_0^*$  calculated for the cool end of Par Pond in Table V exceeded the natural equilibrium temperature for those months (Figure 1), but barely in April (0.4°C) and in May (0.2°C). The surface temperature  $T_0^*$  compares with the natural equilibrium temperature and with the apparent equilibrium temperature as follows:

	Jan	Feb	Mar	Apr	May
Surface temperature To*, °C	12.1	13.0	17.4	22.4	25.8
Natural equil temp (Figure 1), °C	9.6	10.0	16.2	22.0	25.6
Apparent equil temp (Table V), To, °C	9.3	10.1	15.2	20.9	24.5

The natural equilibrium temperature was defined above as the steadystate temperature for a shallow stagnant pond. The apparent equilibrium temperature may be greater or less than the natural equilibrium temperature depending on the magnitude and sign for



the rate of change in stored heat  $H_C$  and on the deviation of the straight-line fit to Langhaar's curve in the vicinity of  $H_T = H_S - H_C$ . In April and May, the apparent equilibrium temperature was lower than the natural equilibrium temperature by about 1.°C. Remember that the surface cooling rate in Par Pond is proportional to the difference between the water surface temperature and the apparent equilibrium temperature, according to Equations 12 and 13. It is possible, as explained above in connection with the concept of an apparent equilibrium temperature, for the surface temperature of a deep cooling pond to be less than the natural equilibrium temperature.

#### Selective Withdrawal from Par Pond

Selective withdrawal from a stratified reservoir is claimed if the discharge temperature is lower than the average temperature to the depth of the intake slot at the pump house. Data taken on occasion in the vicinity of the pump house (i.e., in the "intake channel") to relate the discharge temperature to the vertical profile of temperature in Par Pond have been inconclusive. The analysis of Par Pond performance, however, does infer selective withdrawal. Thus, by Equations A-1b and A-12, the difference between the average temperature of the upperflow at the cool end of the pond and the discharge temperature realized at the pump house is formulated to be

$$T_{O} - T_{P} = \left(\frac{F_{REP} + zF_{r} - F_{p}}{u(F_{REP} + F_{r}) + F_{p}}\right) \Delta T_{G}$$
 (25)

From the data in Table V the values of  $(T_o-T_p)$  are as follows (for 1964):

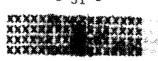
Jan Feb May Apr May 
$$(T_o-T_p)$$
, °C 0.20 0.18 0.26 0.45 0.29

For comparison, the 1959 data given in Table VI showed the discharge temperature to average 0.5°C below the average temperature over a 20-ft depth.

# COOLING IN THE SRP STREAMS

Description of the SRP Effluent Streams

A map of the streams on the SRP site that are used to conduct the effluent cooling water from the reactors - specifically, C, K, and L reactors - to the swamp in the Savannah River flood plain is given in Figure 11. Four Mile Creek can be followed from C reactor



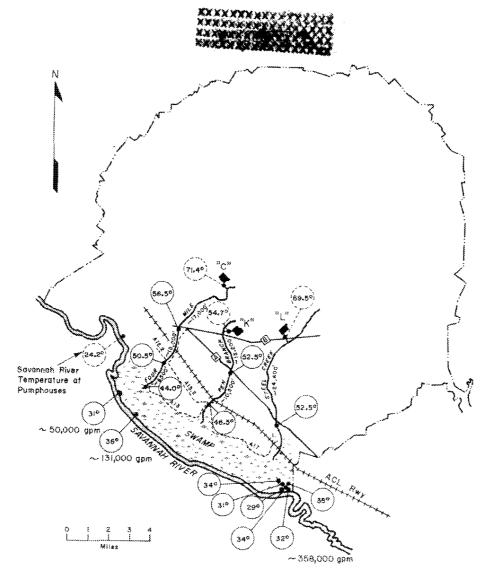


FIGURE 11. Temperatures Along C, K, and L Effluent Streams to the Savannah River

for a distance of about 6.7 miles, at which point it disappears into the swamp. Pen Branch can be followed from K reactor for a distance of about 4.5 miles to the swamp, at which point it is still about 3 miles from the river. After penetrating the swamp about 1.5 miles, the main portion of Pen Branch appears to make a right-angle turn and to more-or-less parallel the river for a distance of about 5 miles until it joins Steel Creek about 0.5 miles from the outlet at the river. Steel Creek can be followed from L reactor for a distance of about 4.6 miles to the swamp, at which point it is about 3.4 miles from the river. The width of these streams is about 150 ft in the vicinity of the reactors, widening to about 400 ft as the swamp is approached, with numerous islands. The natural flow in these three streams during the summer is small compared to the imposed flow of effluent cooling water from the reactors.



## Performance of the SRP Effluent Streams

Temperatures observed along the three effluent streams in August 1966 have been spotted on the map (Figure 11). The surface cooling rate predicted by Equations 4, 5, and 6 for the weather conditions are given in Figure 12. Assuming slug flow and a zero rate of change in stored heat, as was done above the SRP effluent canals, the effective areas of the stream between any two points where the temperature is known can be calculated by Equation 14. The effective areas between temperature points from Figure 11 are given in Table VII. These areas, together with Equation 14, constitute the correlation for the cooling process in the SRP effluent streams. Using these areas, the temperature of the C, K, and L effluent water at the points shown in Figure 11 along the streams leading to the swamp can be calculated for other combinations of reactor power, river temperature, cooling water flow, air temperature, humidity, and wind speed.

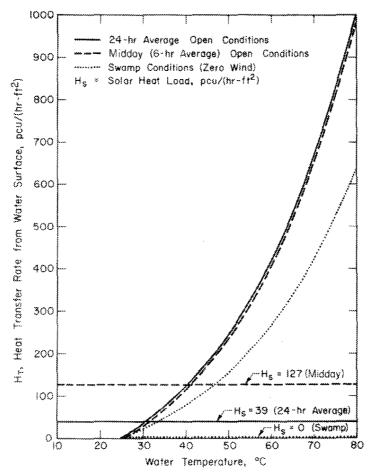
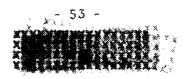
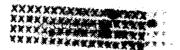


FIGURE 12. Surface Cooling Rate, August 1966
(The difference between open conditions and swamp conditions is described on page page 60.)





#### TABLE VII

# Effective Area of the Effluent Streams

August 1966 Data

Effluent Stream	Observed Temperature at Sampling Point, °C	Calculated Effective Area Between Sampling Points, ft <sup>2</sup>	Estimated Length of Stream, ft	Calculated Effective Width of Stream, ft	Estimated Width of Stream at Sampling Point, ft
Four Mile	71.4 56.5 50.5 44.0	2.89 x 10 <sup>6</sup> 2.11 x 10 <sup>6</sup> 3.56 x 10 <sup>6</sup>	17,000 10,000 8,500	170.0 211.0 419.0	∿150+ >150 ∿400
	Subtotal	$8.56 \times 10^6$	(197 acres)		
Pen Branch	54.7 52.5 48.5	$0.78 \times 10^6$ $1.75 \times 10^6$	13,200 10,500	59.0 166.0	250 <sup>a</sup> ∿400 <sup>a</sup>
	Subtotal	$2.53 \times 10^6$	(58 acres)		
Steel Creek	69.5 52.5	3.68 x 10 <sup>6</sup>	24,400 (84 acres)	151.0	250-300 <sup>α</sup>

a. This estimated width did not allow for the numerous islands.

From the effective area and the estimated length of the stream between temperature points, the effective width of the stream can be calculated for that reach. The comparison of the effective widths with rough estimates of the width of the streams is also given in Table VII. Considering that the actual streams have numerous islands, the comparison is satisfactory.

# COOLING IN THE SRP SWAMP

Description of the SRP Swamp

A swampy region lies in the flood plain along the Savannah River for a distance of about 10 miles, averaging about 1.5 mi in breadth, for a total area of about 15 mi<sup>2</sup>. The location of the swamp in relation to the SRP boundaries and to the three streams that conduct reactor effluent water into the swamp is shown in Figure 11. Aerial photographs of the swamp are given in Figures 13, 14, and 15. They show a mottled region of wet areas and areas of forest and other vegetation.





FIGURE 13. Aerial View of Four Mile Creek Outlet into the SRP Swamp

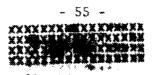






FIGURE 14. Aerial View of Pen Branch Outlet into the SRP Swamp



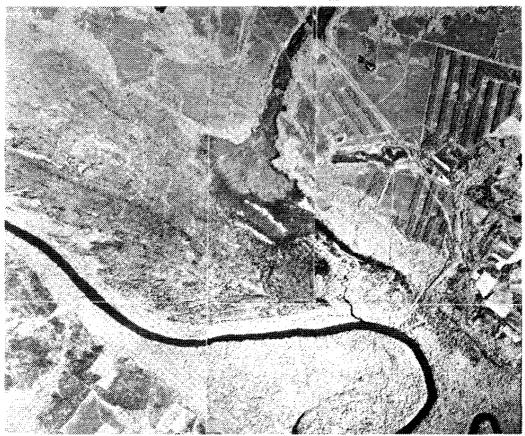
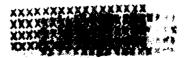


FIGURE 15. Aerial View of Steel Creek Outlet into the SRP Swamp

The swamp is separated from the river by a relatively high bank (90 ft ms1) which has only three significant openings to the river. When the river reaches the 90-ft stage, which corresponds to a flow of about  $11,000 \text{ ft}^3/\text{sec}$ , the swamp becomes flooded. Normally, the reactor effluent water emerges from the swamp and enters the river through the three openings.

Thus, water discharges from the swamp at three points along the Savannah River. The flow from two of these points, which are opposite Four Mile Creek, accounts for the C reactor effluent. The discharge point farther downstream, which is considered to be Steel Creek outlet, accounts for the K and L reactor effluent. The temperatures and estimated flows of the water discharging into the river, observed in August 1966, are shown in Figure 11. The temperatures and flows observed in the exploration up Steel Creek from the outlet at the river are shown on Figure 16; note the two forks found in this stream. Thus, it was observed that: (1) the effluent water from C reactor reached the river at temperatures of 31°C (28% of the flow from C) and 36°C (72% of the





flow from C) for an average temperature of 34.6°C; (2) the effluent water from K and L reactors reached the river at a mixed temperature of 32°C; (3) up Steel Creek from its outlet at the river substantial flows were found having temperatures of 29°C, 31°C, 34°C, and 38°C; (4) the coolest water was flowing from the direction of Pen Branch (K reactor), which was farthest away; and (5) the hottest water was flowing from the direction of Steel Creek (L reactor). The distribution of the flow conjured from these observations is given in Figure 17.

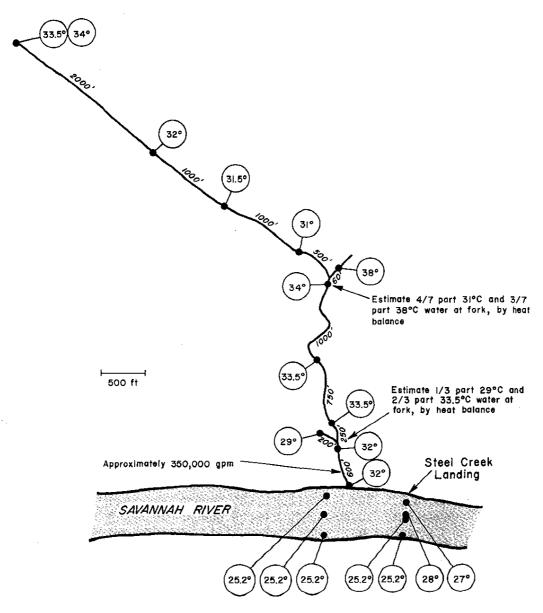
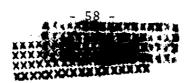


FIGURE 16. Temperatures Up Steel Creek from the Savannah River





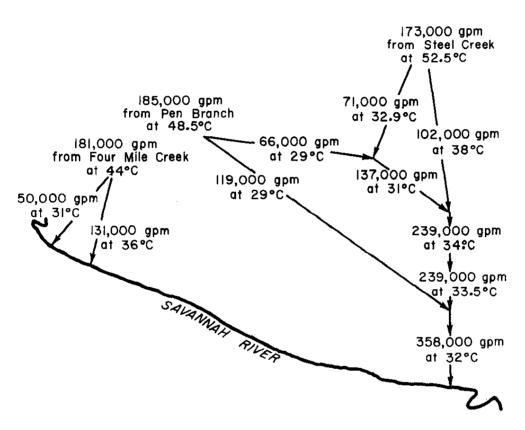
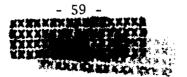
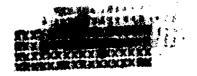


FIGURE 17. Flow of C, K, and L Effluent Cooling Water Through the SRP Swamp





# Performance of the SRP Swamp

The water cooling process in the swamp differs from that described above for the streams, canals, and ponds. The clue is that a substantial flow of water was found in the swamp in the August 1966 survey at a temperature of 29°C. As shown in Figure 12, the natural equilibrium temperature for the effluent streams at this time was 30.5°C. According to Equation 15 it takes an infinite surface area to cool water down to the equilibrium temperature. The explanation is that the equilibrium temperature in the swamp is lower than in streams, canals, and ponds because the water is shaded by the vegetation. Admittedly, this vegetation causes a lower surface cooling rate, by Equation 5 and 6, because the surface is sheltered from the wind. But given enough shaded surface area, a lower temperature can be obtained for the water from the swamp than is possible with an infinite surface area in open streams, channels, and shallow ponds that are heated by the sun.

In the application of the theory to the swamp, the solar heating rate and the wind speed were taken to be zero. The lower wind speed causes the lower surface cooling rate shown in Figure 12 for the August 1966 conditions than the surface cooling rate for open conditions. However, as shown in Figure 12 at the intersection of the curve with the horizontal line at  $H_S=0$ , the water in the swamp approaches a natural equilibrium temperature of 26°C rather than 30.5°C which occurs for "open" conditions.

The effective cooling area in the swamp can be calculated by Equation 15, which is for the slug flow model, from the flows and temperatures shown in Figure 17 as entering and leaving the swamp, together with Figure 12 for the surface cooling rate under swamp conditions. These effective areas for the swamp regions are shown in Figure 18; also posted are the effective areas for the open regions, i.e., the effluent streams which were discussed in the preceding section. Thus, the effective cooling area in the swamp is  $58.4 \times 10^6$  ft<sup>2</sup>, or 1341 acres, or  $2.1 \text{ mi}^2$ . The effective cooling area calculated from the observed performance of the swamp cannot be readily compared with actual measurements of the wet areas in the swamp. However, an effective cooling area of  $2.1 \text{ mi}^2$  is about 14% of the  $15 \text{ mi}^2$  swamp region, which is consistent with the percentage wet area apparent from the aerial photographs.

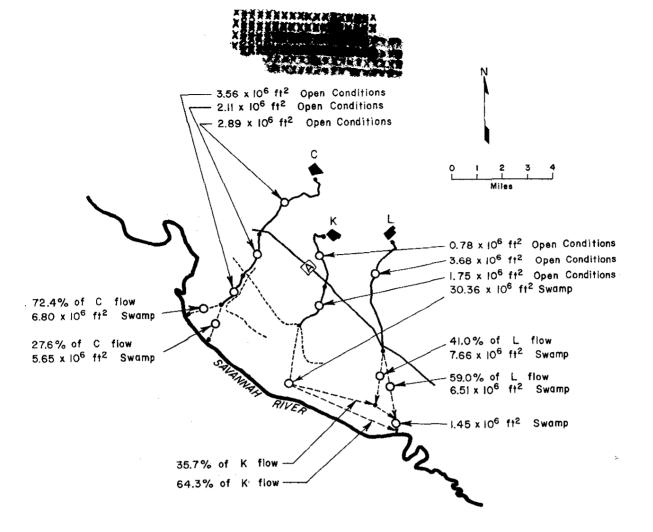


FIGURE 18. Effective Cooling Surface and Flow Split for the C, K, and L Effluent Streams and SRP Swamp

The assumptions of zero wind speed and zero solar heating in the SRP swamp are an exaggeration. However, they have opposite or compensating effects on the effective area that is calculated from the observed temperatures and flows, or, on the effluent temperature predicted for other conditions once the effective area has been determined. Moreover, the calculated effective surface area in the swamp increases exponentially as the estimated equilibrium temperature increases toward the observed 29°C water temperature; the calculated area can become unreasonably large.

# SRP DISCHARGE TO THE SAVANNAH RIVER

The temperature of the effluent cooling water emerging from the SRP swamp and entering the river at the three major cuts in the river bank, as shown in Figure 11, averaged 32.9°C for a typical day in August 1966. From the analysis of the cooling process in the SRP effluent streams and swamp, given in the



preceding sections, it is possible to calculate the effluent temperatures entering the river under what is regarded as the most severe summer conditions encountered at SRP according to the records of prior years. These most severe conditions occurred in August 1959. The temperature of the SRP effluent cooling water entering the river under the severe summer conditions was calculated to be 34.6°C. The details of the comparison are given in Table VIII.

TABLE VIII
SRP Effluent From the Swamp Entering the Savannah River

		Typical August (Observed)	Severe August (Calculated)
Date		8/18-19/66	8/25-26/59
Air dry-bulb temperature		27.3°C	30.9°C
Relative humidity		78%	65%
Wind speed		6 mph	3.8 mph
Solar heat load		39 pcu/(hr-ft <sup>2</sup> )	60 pcu/(hr-ft <sup>2</sup> )
Natural equilibrium temperature		30.5°C (Fig. 12)	35.5°C (Fig. 19)
River temperature at SRP intake		24.2°C	27.8°C ~
River flow at SRP intake		7368 ft <sup>3</sup> /sec	6850 ft³/sec
	S K L	2256 MW/181,000 gpm 1494 MW/185,000 gpm 2062 MW/173,000 gpm	2250 MW/180,000 gpm 2100 MW/180,000 gpm 2100 MW/180,000 gpm
Effluent temperature at river			
Four Mile Creek outlets (C reactor Steel Creek outlet (K & L reactors		34.6°C 32.0°C	36.7°C 33.5°C
C, K, L mixed effluent		32.9°C	34.6°C
River temperature downstream of C, K, L effluent at actual river flow from above		25.6°C	29.0°C
River temperature downstream of C, I effluent at minimum river flow of 6100 ft <sup>3</sup> /sec	K, L	25.9°C	29.1°C

The river temperature upstream of SRP during the severe conditions in August 1959 was 27.8°C, the highest observed in recent history. The weather conditions governing atmospheric cooling at the water surface were also more severe at that time, i.e., higher air temperature and lower wind speed, although the relative humidity was somewhat lower than in the August 1966 case. The surface cooling rate under these severe conditions is given in Figure 19. When Figure 12 is compared with Figure 19, the surface cooling rate is seen to be lower under the severe conditions for the same water temperature. Moreover, for the



calculation of the SRP effluent temperature under the most severe conditions, a solar heating rate of 60 pcu/(hr-ft²) was taken because this high rate [compared with 39 pcu/(hr-ft²) for the typical August 1966 conditions] has a relatively frequent occurrence in the summer months. Also, the reactor power levels for the case with severe conditions were somewhat higher than for the typical conditions; the reactor powers were the actual ratings for the cooling water temperature of 27.8°C, which existed at the time of the severe conditions.

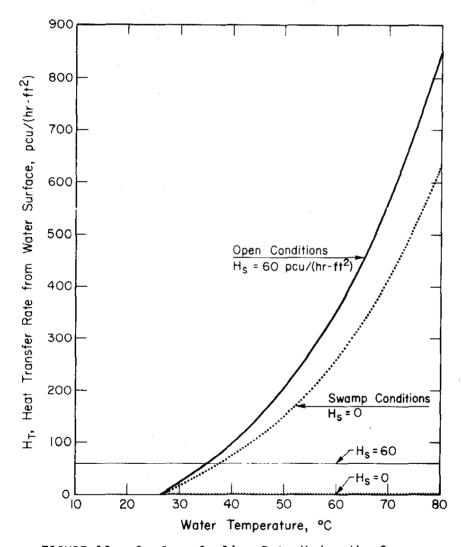


FIGURE 19. Surface Cooling Rate Under the Severe Conditions That Existed in August 1959



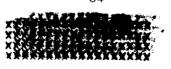


Thus, the mixed effluent from C, K, and L reactors reached the river at a temperature of 32.9°C under typical midsummer conditions and 34.6°C under severe summer conditions. These temperatures are warmer than the river temperature by 8.7°C and 6.8°C, respectively. The temperature of the river after mixing with the warmer SRP effluent water depends on the river flow, which is discussed next.

The flow in the Savannah River is regulated by the U. S. Army Corps of Engineers through their operation of the Hartwell, Clark Hill, Stevens Creek, and Augusta dams. Additional dams above SRP are under construction or in planning. It is the stated intent of the Corps of Engineers, since October 30, 1963, to provide not less than 6100 ft<sup>3</sup>/sec at SRP and to exceed 6300 ft<sup>3</sup>/sec 75% of the time. This intent must necessarily be qualified to cover circumstances beyond their control, such as a major drought. Since 1954 the lowest river flow recorded is 3850 ft<sup>3</sup>/sec (February 1956). The lowest river flow since October 1963 is 6200 ft<sup>3</sup>/sec. The improvement is attributed to the advent of Hartwell For the cases shown in Table VIII, SRP drew 1200 ft<sup>3</sup>/sec from the river for C, K, and L reactors; L reactor has been shut down since early 1968. Thus, the increase in temperature of the Savannah River in passing by SRP is less than one-fifth of the increase in temperature of the SPP cooling water from the intake point at the river pump houses to the discharge points from the SRP swamp. Mixing of the SRP effluent with the river water is essentially complete about two miles downstream.

The river temperature downstream of SRP after mixing is shown in Table VIII to be  $25.6^{\circ}$ C under the observed August 1966 conditions, when the river flow was 7368 ft $^{3}$ /sec, and  $29.0^{\circ}$ C under the severe August 1959 conditions, when the river flow was 6850 ft $^{3}$ /sec. This corresponds to an increase in the temperature of the river passing SRP of  $1.4^{\circ}$ C for the typical August conditions and  $1.2^{\circ}$ C for the severe August conditions, respectively. At the minimum 6100 ft $^{3}$ /sec flow in the river, the increase in river temperature would have been  $1.7^{\circ}$ C and  $1.3^{\circ}$ C, respectively. Note that the increase in the temperature of the river in passing SRP is less under the more severe summertime conditions. The higher temperature of the river under the severe conditions is the more important consideration, however.

Independent observations, with the SRP operation as a black box, are available from the records of the U. S. Geological Survey. These records show that, for the fiscal years 1959 through 1965, the maximum increase in the Savannah River temperature attributable to SRP operations ranges from 1.9 to 3.2°C from year to year and more importantly, as a confirmation of this study, that the maximum yearly river temperature downstream of SRP ranges from 25.3°C to 29.4°C.





Temperatures above 31°C are considered to be deleterious to fish and algae. Thus, by virtue of the natural cooling within the SRP boundaries and the operation of Clark Hill Reservoir, SRP has not caused an objectionable increase in the river temperature.

# WARMING IN THE SAVANNAH RIVER

As the Savannah River flows past SRP on its way to the Atlantic Ocean, its temperature is generally increasing, regardless of the SRP thermal contributions. This is because, throughout two-thirds of the year and particularly during the summer months, the Clark Hill Reservoir upriver discharges water that is colder than the temperature in natural streams and ponds. The reservoir has about a 4-month inventory of water, and the water is released from a depth of 60 to 80 ft. The water released in the summer is collected in early spring and is stored in the deeper regions by virtue of thermal stratification. The temperature of the discharge at Clark Hill Reservoir is about 8°C cooler in the summer months, than the natural river temperature in prior years. At SRP, the temperature of the river during the summer is about 4°C lower than it was before the advent of the reservoir, and about 2.5°C lower on an annual average basis. 5 Thus, the river temperature is generally approaching the equilibrium temperature from the cold side as it flows past SRP.

The formulation for the warming process in the river is the same as that outlined above for the SRP effluent canals and streams. By Equation 15, the difference between the river temperature at some point downstream from SRP and the equilibrium temperature is the fraction  $e^{-\alpha}$  of the difference from equilibrium that exists in the river after mixing with the SRP effluent. The exponent  $\alpha$  is given by Equation 16 in terms of the slope m of the Langhaar cooling rate curve near the equilibrium temperature, the area A of the river, and the river flow F. From Figure 12, m = 8.0 pcu/(hr-ft²-°C) for typical August conditions. At the minimum guaranteed flow of 6100 ft³/sec in the river, the "attenuation area" - that is, the river surface area required to reduce the temperature in excess of the equilibrium by a factor of e = 2.718 - is therefore

$$\frac{500 \times 6100 \times 60}{8 \times .1337} = 171 \times 10^{6} \text{ ft}^{2}$$

Since the width of the river is about 330 ft, which corresponds to 1.74 x  $10^6$  ft  $^2/\text{mi}$ , the "attenuation distance" is

$$\frac{171 \times 10^6}{1.74 \times 10^6} = 98 \text{ miles}$$





Thus, the difference from equilibrium at a point 98 miles down-stream from SRP will be 1/e of the difference that exists at SRP. This applies whether the river temperature is above or below the equilibrium temperature; the difference must be in the same sense. At higher river flows than 6100 ft<sup>3</sup>/sec, the attenuation distance is greater than 98 miles. (The probable chilling effect of rainfall runoff below SRP has been neglected here.)

The two-day average weather conditions and solar heating rate in Table VIII is used for calculating the rate of heat transfer to the atmosphere ( $H_T$ ). The velocity in the river is about 2 ft/sec at 7000 to 8000 ft $^3$ /sec. Distances by river from the SRP boundary are roughly 23 miles to Millhaven (Route 301 crossing), 81 miles to Clyo (Route 110 crossing), and 120 miles to Savannah (Route 17 crossing). The transit times are 17, 59, and 88 hours, respectively.

Thus, the temperature in the river may continue to increase downstream of SRP or it may decrease depending on whether or not the boost that it gets from SRP takes it to a temperature below or above the equilibrium temperature. For the situations presented in Table VIII, the equilibrium temperature was higher than the mixed temperature in the river below SRP. The natural equilibrium temperature for the typical conditions in August 1966 was calculated to be 30.5°C, whereas the effluent from SRP (∿1200 ft<sup>3</sup>/sec) was calculated to be 32.9°C, and the river temperature, 24.2°C. Under these conditions the temperature of the Savannah River would continue to increase downstream from SRP as long as the river flow was greater than 1700 ft<sup>3</sup>/sec. Under the severe conditions seen in August 1959, the calculated natural equilibrium temperature was 35.5°C, whereas the calculated effluent from SRP was 34.6°C, which was actually less than the natural equilibrium temperature because of the contribution of 29.9°C water from K reactor via the swamp. The river temperature on that severe day in August 1959 would have continued to increase downstream from SRP even if SRP had taken the entire river flow.

#### APPLICATIONS AT SRP

Questions arise regarding the effect of changes in SRP operations or of the diurnal and seasonal variations in the atmospheric conditions on the temperatures in the canals, ponds, streams, and swamp. In order to answer such questions, the correlations presented above have been composited in a single computer program LIMN, which is given in Appendix B. This program is written in FORTRAN IV for the IBM System/360 computer. The independent variables are the reactor power levels (in megawatts), the respective flows of cooling water (in 10 gpm), the weather conditions, the solar heat load, the river temperature, and the





initial temperature of the discharge from Par Pond. The time interval is also specified; this time is needed only for Par Pond. The temperature of the effluent cooling water is computed for the points shown on the map (Figure 20). The evaporation that occurs along the way is also computed. Any combination of reactors can be selected for evaluation by LIMN.

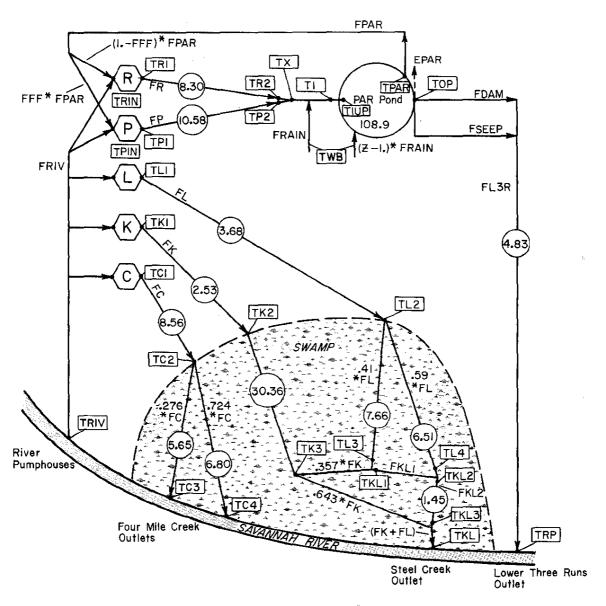


FIGURE 20. SRP Map for Computer Program LIMN





This program first calculates the surface cooling rate by Langhaar's Equations 4, 5, and 6 at temperatures in 10°C intervals from 5 to 95°C for the particular set of weather conditions that are read into the computer. A straight-line approximation (Equation 7) is then made for each 10°C segment of Langhaar's curve. The slope m, intercept b, and equilibrium temperature To (by Equation 13) are calculated for each segment and stored (as well as printed out), first for the open conditions that exist in the canals, ponds, and streams, and then for the shaded conditions of the swamp. The rate of change in heat content  $H_{\mbox{\scriptsize C}}$ needed to calculate the equilibrium temperature is zero except for Par Pond. For Par Pond, HC depends on the pond discharge temperature at the end of the specified time interval; this temperature is found by trial values for the average discharge temperature during the time interval. The equilibrium temperatures for Par Pond corresponding to the segments of the Langhaar curve are therefore tabulated separately.

The map (Figure 20) is systematically evaluated by LIMN. temperature of the water entering a particular region shown on the map, and the related flow, are supplied to the subroutine JWL, which then calculates the temperature at the downstream end of that region, and also the evaporation that occurs. JWL considers slug flow (Equations 15 and 16) to occur in the canals, small ponds, streams, swamp, and the upperflow region of Par Pond; the effective areas (in 10<sup>6</sup> ft<sup>2</sup>) by this model for the various regions are the numbers given on the map (Figure 20). The subroutine JWL first finds the segment on Langhaar's curve that contains the input temperature. It then calculates the surface area required for the water to cool to the upper boundary of the next lower segment; then, it calculates the surface area required to cool over that segment; and so on, until the total surface area equals or exceeds the effective surface area prescribed for that region. Only part of the last segment is traversed in reaching the prescribed effective surface area, which then gives the temperature at the downstream end of the region. With each increment of surface area there is an increment of evaporation, which is accumulated for that region by JWL. The main program LIMN then picks up the downstream temperature and the evaporation for that region and proceeds to the next region on the map. Note that for Par Pond the average discharge temperature for the prescribed time interval is calculated in LIMN by trial-and-error, rather than analytically as in Table V, in order to utilize the particular segments of Langhaar's curve that are initially set up in LIMN.

The LIMN Printout 1 in Appendix B gives the case for Par Pond in May 1964 when both R and P reactors were in operation. The average discharge temperature is calculated to be 23.4°C, as compared with 23.6°C given in Table V. Printout 2 gives the hypothetical case for Par Pond in May 1964 if only P reactor were





in operation. Shutting down R reactor resulted in a calculated discharge temperature of  $22.7^{\circ}\text{C}$ , or  $0.7^{\circ}\text{C}$  lower than with both reactors in operation. The water balance in Printout 2 shows that, with an estimated seepage loss of 2800 gpm, about 7500 gpm makeup water from the river is needed to maintain the level in Par Pond, i.e., for zero overflow at the dam, since the shutdown of R reactor. (Actually, the seepage loss is estimated from the observed makeup water requirement.) Note that as a result of the lower temperature of the Par Pond overflow at the dam, since the shutdown of R reactor, the temperature of the overflow increases  $0.9^{\circ}\text{C}$  before reaching the river via Lower Three Runs Creek.

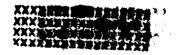
Printout 3 gives the temperatures and evaporation of the effluent cooling water for C, K, and L reactors in August 1966 for comparison with the observations given in Figure 11. Printout 4 gives the temperatures and evaporation for the CKL effluent cooling water calculated for the severe August 1959 conditions for comparison with the hand calculations in Table VIII.

# AREAS FOR FURTHER INVESTIGATION

The Langhaar equation for the rate of heat transfer to the atmosphere, equated to the rate of heat input minus the rate of heat accumulation, was applied to a model of the apparent flow pattern to provide a mathematical description of the cooling process extant in the SRP canals, ponds, streams, and swamp. A correlation of the SRP performance was then readily obtained using relatively few data on water temperatures, water flow, and atmospheric conditions; the correlation was in terms of only a few derived factors, such as, the effective surface area and the excess temperature at the surface attributed to thermal stratification. The factors obtained by substituting the plant data into the mathematical description of the cooling process have physical significance; they are not simply empirical terms in a correlation. The factors are subject to the requirement that they have a reasonable correspondence to the actual system. The simple description of the cooling process and the derived correlating. factors are adequate for most purposes at SRP. The effect of variations in SRP operating conditions and in the weather conditions on the temperature of the SRP effluent at the Savannah River or from Par Pond can be readily evaluated by this description using the computer program LIMN.

One might proceed to evaluate more of the same kind of data by the above formulations, for instance, to find the standard deviation from actual performance or to improve on the derived factors in order to reduce the standard deviation. Such a step at this time would be largely an exercise, however, in view of the stated adequacy of the present description for practical purposes at SRP. Rather





than to engage in obtaining a better fit to this simple model with more extensive data, efforts might better be devoted to certain fundamental investigations which offer the possibility of extending our understanding and of refining the mathematical description of the cooling process.

The Partial Differential Equation for Natural Cooling

The energy budget Equation 1 together with Equations 2, 3, 4, 5, and 6 and the vapor pressure relation (Reference 9) lead to the following partial differential equation:

$$\frac{\partial T}{\partial \theta} = \frac{H_S - 1.63(1 + 0.1W)(P - P_{air}) - 1.2(1.5 + 0.1W)(T - T_{air}) - 500F}{62.4h}$$
(26)

where

$$\log_{10}\left(\frac{E}{P}\right) = \left(\frac{X}{T + 273.16}\right) \left(\frac{A + BX + CX^3}{1 + DX}\right) \tag{27}$$

X = 374.11 - T

A = 3.2437814

B = 0.00586826

 $C = 0.011702379 \times 10^{-6}$ 

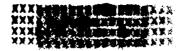
D = 0.0021878462

E = 165807.0

In Equation 26 the parameters  $H_S$ ,  $P_{air}$ ,  $T_{air}$ , W, and F vary with time  $\theta$ . It would be constructive to develop the finite difference form of Equation 26 for solving by computer with data input for short time intervals. The computer program would calculate the temperature T as a function of time  $\theta$  and space A.

# Stratification Algorithm

A computer code is needed that can take the hourly data on atmospheric conditions and solar radiation intensity at the pond site and calculate the vertical temperature profile as a function of time. Consider a natural pond, i.e., neglect any imposed thermal load. Consider the pond as a rectangular parallelepiped having a depth equal to the average depth. Divide it into horizontal slabs. This is then a one-dimensional model in space, with time as another independent variable. The solar radiation is attenuated, for instance, by Lambert's Law:  $dI = -\mu I dz$  where  $\mu$  is the attenuation coefficient. Surface cooling occurs according to Langhaar's equation. Start with a uniform temperature in the early spring. The input data are the air dry-bulb and wet-bulb temperatures, the wind speed, and the solar radiation intensity



at the pond surface. Except for the solar radiation intensity, these data are available in three-hour intervals from the National Climatic Center. 10 Regarding solar radiation, see the following section. At the end of each time interval, calculate the new temperature in each slab, ignoring conduction and convection effects other than from the surface of the top slab. Then, interchange the slabs so as to have a stable temperature distribution. That is, the density must increase with depth. The convection mechanism that physically accomplishes this restructuring need not be formulated.

Such an algorithm should reproduce the observed stratification in a pond. It should also predict the inversion that occurs in the fall when the pond temperature again becomes relatively uniform. Integrating over the vertical temperature profile will give an estimate of the pond heat content at that particular time, which is important for the energy budget equation. The predicted stratification can be the basis for the  $\Delta T_G$  term that was used in the Par Pond model above, and it can be the basis for predicting the mixed temperature of the underflow in the intake channel to the pump house (see section on Stratified Flow below).

#### Solar Radiation Measurements

A continuous record at SRP of the solar radiation intensity, measured by a pyrheliometer, is highly desirable. A way of calibrating the instrument should be available. Hourly readings should be tabulated. Since the solar radiation intensity for clear arid conditions is known as a function of latitude and altitude, the actual radiation intensity might be estimated from the "sky cover" which is available from the records of the National Climatic Center. The rate of evaporation of water from an open pan exposed to the atmosphere, which is obtained at some meteorological stations, might be converted to solar radiation intensity by using Langhaar's equations to estimate the ratio of total heat transfer to heat transfer by evaporation. Some study should be made of the extent that solar radiation is reflected from the water surface and of the attenuation of the solar radiation as a function of water quality and depth, particularly, for the stratification algorithm discussed above.





### Stratified Flow

The existence of an underflow in the stratified pond was postulated in the model described above for Par Pond. The underflow was the source of cool water for mixing with the hot influent at the warm end of the pond and for the discharge at the pump house at the cool end. An improved model for a cooling pond requires consideration of the conditions needed for stratified flow. A theory for the selective withdrawal of water from a stratified reservoir has been developed recently. This theory needs to be verified by observations of the temperature of water withdrawn through a submerged intake slot from a deep reservoir in relation to the thermal stratification and to the discharge rate.

# Mixing of the Influent to the Pond

It is desirable to spread the hot influent onto the surface of a cooling pond with as little mixing as possible in order to benefit from a higher surface temperature for a greater rate of heat transfer to the atmosphere. The structure at the bypass road embankment at the warm end of Par Pond was designed with this objective in mind. Still, temperature surveys in the pond have shown that there is considerable mixing. The mixing factor u, which was employed in the model for Par Pond, was calculated from these data as the ratio of the underflow of cool water to hot influent. The values for u ranged from 1.0 to 4.5; the value u = 2.3, which was used in the correlation, was the average of 13 surveys. The variation seen for the given structure might be caused by the variation in stratification and in the wind. The variation may also have been the result of an inadequate temperature survey. A better understanding of the mixing process should enable a better design of the inlet structure for future cooling ponds.

### Wind Stress

The fluctuation of Par Pond discharge temperature, shown in Figure 8 for the daily readings from January through May 1964, was attributed in large measure to the action of the wind. Subsequent to those data, other observations of the pond discharge temperature have been taken, such as is shown in Figures 21 and 23. The effluent temperature was observed to change by several degrees centigrade in a period of one hour up to three days; the maximum amplitude (minimum to maximum) observed for such fluctuations has been about 5°C.





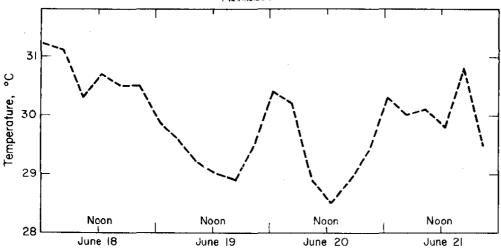


FIGURE 21. Fluctuation in Pond Effluent Temperature

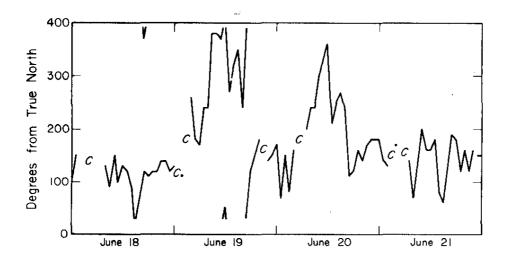
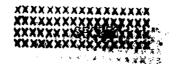


FIGURE 22. Fluctuation in Wind Direction

The simultaneous fluctuation in wind direction is shown in Figure 22 for the temperature fluctuations shown in Figure 21. Superposition of the two figures shows that the peaks in the wind direction correspond to the valleys in the pond effluent temperature. A wind direction of 120° from north in Par Pond corresponds to the wind flowing directly toward the pump house along the axis of the pump house arm of the pond. Similarly, a wind direction of 300° from north corresponds to the wind blowing directly away from the pump house. In Figure 22, the wind direction is plotted from 30° to 390° rather than from 0° to 360° from north; thus,



below the median direction of 210° from north, which corresponds to the wind blowing directly across the pump house arm, there is a positive component of the wind from the pond toward the pump house. Above the median direction of 210° from north, there is a positive component of the wind away from the pump house. The relation between the component of the wind velocity vector along the axis of the pump house arm and the pond discharge temperature is shown in Figure 23 from data taken at another time than that for Figures 21 and 22.

The temperature fluctuation in the pond as a result of the wind is well known to limnologists. As observed along the shore, colder water is found in the upwind (windward) direction; warmer water is found in the downwind (leeward) direction. That is, when the wind blows during the period of thermal stratification, the warmer water congregates downwind, and the colder isotherms break the surface at the upwind end. The action of the wind is shown in Figure 24 for a two-zone body of water. The interface between the two zones is like the thermocline in an actual body of water. When the wind blows steadily in one direction across

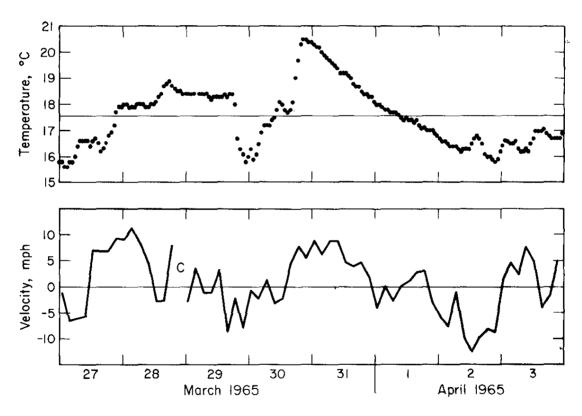


FIGURE 23. Fluctuation in Wind Vector and Pond Effluent Temperature





the pond, the drag force of the wind on the surface is counterbalanced by the difference in hydrostatic head at one end of the pond from that at the other end as a result of the different vertical temperature profiles. When the wind stops, the thermocline does not immediately come to rest in a horizontal position, but, due to the inertia of the flow that occurs in returning to the horizontal, the thermocline proceeds to about the same maximum gradient in the opposite direction; then the flow reverses. Thus, the action of the wind on the pond is analogous to the compression of a spring. Damped harmonic motion occurs when the compressing force is released. If the wind velocity component is a function of time, the case is analogous to forced harmonic motion. If the wind blows and then stops, when there was initially a uniform temperature gradient in the pond, a sinusoidal-like variation in the temperature occurs at any given point in the pond except at the node. The wave in the isotherm surface as a result of the wind action is called an internal seiche. Since the wind takes all directions over a period of time, the crisscrossing of the internal seiches can be expected to produce a complex isotherm surface.

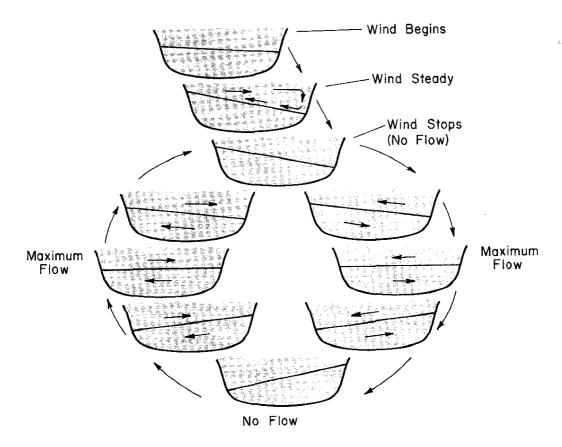
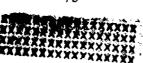


FIGURE 24. Wind Stress and Internal Seiche<sup>12</sup>





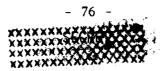
The action of the wind is seen to result in short-time variations in the effluent temperature from a pond that are large compared to the deviations that can be expected in the predicted effluent temperature by the theory and application sections above. The effect of the wind action was smeared over, in the evaluation of the Par Pond model, by taking monthly average data. When dealing with shorter time intervals, which is required for a better description of the cooling process in the pond, the action of the wind must be accounted for. Therefore, it is desirable that a program be instituted to collect data on Par Pond discharge temperature and on the wind direction and speed at frequent time intervals. These dates can then be used to calculate the component of the wind velocity acting along the axis of the pump house arm of the pond, and to seek a correlation between the component velocity and the discharge temperature.

### Velocity Measurements

The study of Par Pond has been deficient in that there have been no measurements of the local velocity of the water. Traverses in the vicinity of the inflow structure at the warm end of the pond for the velocity field as well as the temperature distribution would enable a better understanding of the mixing process (for the u factor in the Par Pond model, for example). Traverses in the intake channel to the Par pump house for the vertical velocity profile would help to demonstrate the existence of an underflow; the vertical profiles for velocity and temperature might be related so as to verify the theory of stratified flow. A periodic variation in the velocity at a point out in the reservoir would corroborate the existence of an internal seiche. In general, the circulation pattern in a pond or in the vicinity of structures and restrictions, such as a culvert, might better be observed by velocity measurements than inferred from temperature measurements.

#### Swamps

The cooling process in a swamp ought to be studied further, particularly because the swamp region at SRP might be modified at a reasonable cost to effect a further reduction in the temperature of the SRP effluent to the river. The lower cooling rate expected in a swamp is not of concern so long as compensating surface area is available at low cost. The lower equilibrium temperature expected in a swamp makes the swamp potentially as effective as an expensive cooling tower.





In the application of the theory for natural cooling to the SRP swamp, the solar heat load and the wind speed were taken to be zero. Admittedly the vegetation in a swamp is not uniformly distributed, nor is it completely effective in shading the water and in screening out the wind. The reduction in the rates of convection and evaporation to the atmosphere because of the sheltering from the wind acts to increase the equilibrium temperature, depending on the magnitude of the solar heat load, whereas the reduction in the solar radiation intensity by the vegetation acts to decrease the equilibrium temperature. Thus, as a first step, the equilibrium temperature in a stagnant swamp might be compared with the equilibrium temperature in a stagnant open pond at the same time and in the same locale. The rate of heat transfer to the atmosphere from the water in the swamp environment might better be determined under flow conditions at temperatures substantially above the equilibrium temperature. The average intensity of the solar radiation reaching the swamp waters should be measured and compared with simultaneous measurements taken in the open. The type and extent of the vegetation in the swamp should be investigated as a factor governing the performance of the swamp for cooling.



## FORMULATION OF THE MODEL FOR PAR POND

Consider the energy budget equation

$$H_{F} = H_{T} - H_{S} + H_{C}$$
 (1)

Take  $f_A$  as the effectiveness of the surface area, then Equation 3 becomes

$$H_{F} = \frac{-500F_{upperflow}}{f_{A}} \left(\frac{dT}{dA}\right)$$
 (3a)

Take a linear fit to the Langhaar cooling rate curve, as in Equation 7

$$H_{T} = mT^* + b \tag{7a}$$

where  $T^*$  is the surface temperature, which differs from the local value of the average temperature of the upperflow (T) by a constant amount  $\Delta T_G$  °C everywhere over the pond

$$T^* - T = \Delta T_G$$
, constant (A-1)

Hence

$$\frac{dT}{dA} = \frac{dT^*}{dA} \tag{A-2}$$

The quantity  $H_S$  -  $H_C$  is considered to be constant during the time interval of d days over which temperature, flows, and atmospheric conditions are averaged.

From Equations 1, 3a, 7a, and A-2

$$-\frac{500F_{upperflow}}{f_A}\left(\frac{dT^*}{dA}\right) = mT^* + b - H_S + H_C \qquad (A-3)$$

Introducing the apparent equilibrium temperature

$$T_{e} = \frac{-b + H_{S} - H_{C}}{m}$$
 (13)

with Equation A-3 gives

$$-\frac{500F_{upperflow}}{mf_{\Delta}}\left(\frac{dT^*}{dA}\right) = T^* - T_e$$





which is integrated

$$\int_{\text{Tin}}^{\text{T*}} \frac{d\text{T*}}{\text{T*} - \text{T}_{e}} = -\frac{\text{mf}_{A}}{500\text{Fupperflow}} \int_{0}^{\text{A}} dA$$

to give

$$T^* = T_e + (T_{iu}^* - T_e) \exp\left(-\frac{mf_A^A}{500F_{upperflow}}\right) \quad (15a)$$

Equation 15a gives the surface temperature profile over the pond.

Thus, the local value for the rate of heat transfer to the atmosphere, by Equations 7a and 15a, is

$$H_{T} = m \left[ T_{e} + (T_{iu}^{*} - T_{e}) \exp \left( -\frac{mf_{A}A}{500F_{upperflow}} \right) \right] + b$$

and the average value over the surface of the pond is

$$\overline{H}_{T} = \frac{1}{A_{\Sigma}} \int_{0}^{A_{\Sigma}} H_{T} dA$$

or

$$\overline{H}_{T} = mT_{e} + b + \frac{500F_{upperflow}}{f_{\Lambda}A_{\Sigma}} (T_{iu}^{*} - T_{e}) \left(1 - e^{-\alpha f_{A}}\right) \quad (A-4)$$

where

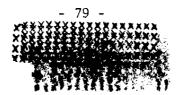
$$\alpha = \frac{\text{mA}_{\Sigma}}{500\text{F}_{\text{upperflow}}}$$
 (16a)

From Equations 1, 13, and A-4

$$H_{F} = \frac{500F_{upperflow}}{f_{A}A_{\Sigma}} (T_{iu}^{*} - T_{e}) (1 - e^{-\alpha f_{A}}) \qquad (A-5)$$

The total heat load per square foot of effective surface area,  ${\rm H_F}$ , can also be derived independently by its own definition by reference to the model for Par Pond, Figure 6

$$H_{F} = \frac{500}{f_{A}A} \left[ (F_{REP} + F_{r})T_{i} + (z-1)F_{r}T_{WB} - F_{overflow}T_{0}^{*} - F_{p}T_{p} \right]$$





Now eliminate  $H_{\rm F}$  between Equations A-5 and A-6

$$F_{\text{upperflow}}(T_{\text{iu}}^{*}-T_{\text{e}})(1-e^{-\alpha f_{\text{A}}})$$

$$= (F_{\text{RSP}} + F_{\text{r}})T_{\text{i}} + (z-1)F_{\text{r}}T_{\text{WB}} - F_{\text{overflow}}T_{\text{o}}^{*} - F_{\text{p}}T_{\text{p}} \qquad (A-7)$$

Some of the variables in Equation A-7 are not measured directly, so proceed with the analysis of the model as follows:

From Equation A-1

$$T_{iii} * = T_{iii} + \Delta T_{G}$$
 (A-1a)

$$T_o^* = T_o + \Delta T_G \tag{A-1b}$$

From the definition of u

$$F_{underflow} = u (F_{REP} + F_r)$$
 (A-8)

Thus, by flow balance,

$$F_{\text{upperflow}} = \left[ u + 1 + (z-1) \left( \frac{F_r}{F_{R + F_r}} \right) \right] (F_{R + F_r}) \quad (A-9)$$

and

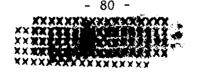
$$F_{\text{overflow}} = F_{R \in P} + zF_{r} - F_{p} \tag{A-10}$$

By heat balance at the upstream (warm) end of the pond, using Equations A-8, A-9, and A-la

$$T_{iu}^{*} = \frac{uT_{p} + T_{i} + (z-1)\left(\frac{F_{r}}{F_{R\xi P} + F_{r}}\right)T_{WB}}{u + 1 + (z-1)\left(\frac{F_{r}}{F_{R\xi P} + F_{r}}\right)} + \Delta T_{G}$$
 (A-11)

By heat balance at the downstream (cool) end of the pond, using Equations A-8, A-9, A-10, and A-1b

$$T_{O}^* = T_{P}^* + \left[1 + \frac{F_{R\xi P}^* + zF_{r}^* - F_{P}^*}{u(F_{R\xi P}^* + F_{r}^*) + F_{P}^*}\right] \Delta T_{G}^*$$
 (A-12)





Substituting from Equations A-9, A-10, A-11, and A-12 into Equation A-7 gives

$$K_0^T P + K_2^T i + K_3^T WB + K_4^T e + K_5^{\Delta T} G = 0$$
 (A-13)

where

$$K_{0} = -\left[u\left(1-e^{-\alpha f_{A}}\right) + \frac{F_{R\xi P} + zF_{r}}{F_{R\xi P} + F_{r}}\right]$$

$$K_{2} = e^{-\alpha f_{A}}$$

$$K_{3} = \left(\frac{F_{r}}{F_{R\xi P} + F_{r}}\right)(z-1)e^{-\alpha f_{A}}$$

$$K_{4} = \left(1-e^{-\alpha f_{A}}\right)\left[u + 1 + (z-1)\left(\frac{F_{r}}{F_{R\xi P} + F_{r}}\right)\right]$$

$$K_{5} = -\left\{K_{4} + \left[\frac{F_{R\xi P} + zF_{r} - F_{P}}{F_{R\xi P} + F_{r}}\right]\left[1 + \frac{F_{R\xi P} + zF_{r} - F_{P}}{u(F_{R\xi P} + F_{r}) + F_{P}}\right]\right\}$$

or

$$\Delta T_{G} = \frac{1}{-K_{5}} (K_{0}T_{P} + K_{2}T_{i} + K_{3}T_{WB} + K_{4}T_{e})$$
 (A-13a)

To calculate  $T_{\mbox{\scriptsize e}}$  by Equation 13 for use in Equation A-13a, it is necessary to know HC

$$H_{C} = 62.4 \text{ h} \left( \frac{\overline{T}_{d} - \overline{T}_{1}}{24d} \right) f_{C}$$
 (2a)

Assume that the change in the average pond temperature  $(\overline{T}_d - \overline{T}_1)$  is the same as the change in the discharge temperature

$$\overline{T}_{d} - \overline{T}_{1} \stackrel{\sim}{=} T_{d} - T_{1} \tag{A-14}$$

where  $T_1$  is the discharge temperature observed at the pump house at the start of the time interval, and  $T_d$  is the discharge temperature observed at the end of the interval (d days). Both  $T_1$  and  $T_d$  are available from the data on Par Pond performance.

Further, in calculating  $T_{\rm e}$  by Equation 13 take



$$m = \frac{H_{T,iu} - H_{T,0}}{T_{iu}^* - T_0^*}$$
 (A-15)

$$b = H_{T,iu} - mT_{iu}^*$$
 (A-16)

where  $H_{T,iu}$  and  $H_{T,0}$  are calculated by Equations 4, 5, and 6 and the known vapor pressure of water. Since both  $T_{iu}^*$  by Equation A-11 and  $T_0^*$  by Equation A-12 require knowing  $\Delta T_G$ , a trial-and-error solution of Equations A-13a, 2a, A-14, 4, 5, 6, A-11, A-15, A-16, 13, 16a, and A-12 is entailed. The results of such an analysis of Par Pond data are given in Table V.

The contribution from runoff, z and  $F_{\rm T}$ , are calculated as follows: If 13.3 square miles drains through the R and P effluent canal systems, and the total drainage area for Par Pond is 36 square miles, then

$$z = 36/13.3 = 2.71$$

and, for r inches of rainfall in d days with runoff fraction fr

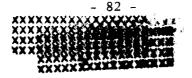
$$F_{r} = 160,500 \frac{rf_{r}}{d}$$
 (A-17)

where

$$160,500 = \frac{13.3 \times 5280^2}{12 \times .1337 \times 24 \times 60}$$

Thus, the correlation of the pond performance is presented as the function for  $\Delta T_G$  versus the season of the year. Once the  $\Delta T_G$  function has been determined, the correlation can be used to calculate the discharge temperature at other conditions of imposed flow, canal effluent temperature, and atmospheric conditions. In this case, the discharge temperature  $T_1$  at the start of the time interval will be known. To solve for the average discharge temperature  $T_p$  during the time interval by Equations A-13 and 13, which uses  $H_C$ , it is necessary to choose a time interval small enough that it is a good approximation to say

$$T_{p} \stackrel{\sim}{=} \frac{1}{2} (T_{1} + T_{d})$$
 (A-18)





Then from Equations 2a, A-14, and A-18

$$H_{C} = 5.2 \left(\frac{hf_{C}}{d}\right) (T_{p} - T_{1}) \tag{A-19}$$

where

$$5.2 = \frac{2 \times 62.4}{24}$$

From Equations A-19, 13, and 10

$$T_{es} = \frac{-b + H_S}{m} \tag{10}$$

$$T_{e} = T_{es} -5.2 \left(\frac{hf_{C}}{md}\right) (T_{p} - T_{1})$$
 (A-20)

From Equations A-20 and A-13

$$T_{p} = k_{1}T_{1} + k_{2}T_{i} + k_{3}T_{WB} + k_{4}T_{es} + k_{5}\Delta T_{G}$$
 (A-21)

where

$$K_{1} = 5.2 \left(\frac{hf_{C}}{md}\right) K_{4}$$

$$k_{0} = -(K_{0} - K_{1})$$

$$k_{0}k_{1} = K_{1}$$

$$k_{0}k_{2} = K_{2}$$

$$k_{0}k_{3} = K_{3}$$

$$k_{0}k_{4} = K_{4}$$

$$k_{0}k_{5} = K_{5}$$

where  $K_0$ ,  $K_2$ ,  $K_3$ ,  $K_4$ , and  $K_5$  are the coefficients in Equation A-13.

Starting with the discharge temperature  $T_1$  at time zero, the average discharge temperature  $T_P$  for the first interval of d days is calculated by Equation A-21. Then the discharge temperature  $T_d$  at the end of that time interval, which is calculated by Equation A-18, becomes the new value for  $T_1$  at the start of the next time interval.



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#### APPENDIX B

### COMPUTER PROGRAM LIMN

```
SEE SRP MAP FOR COMPUTER PROGRAM LIMN, FIGURE 24 IN DP- REPORT
C GLOSSARY OF NAMES
C.
C
       PR,PP,PL,PK,PC
                         REACTOR POWER (R,P,L,K,C RESPECTIVELY), MEGAWATTS
C
       FP.FP.FL.FK.FC
                          REACTOR COOLING WATER FLOW (R,P,L,K,C RESP.),
           MILLION GALLONS PER MINUTE
             FLOW FROM PAR PUMPHOUSE, MILLION GALLONS PER MINUTE
               MAKEUP FLOW FROM RIVER TO PAR POND VIA R AND P REACTORS.
       FRIV
            MILLION GALLONS PER MINUTE
                RUNDER FROM RAINFALL INTO THE R AND P EFFLIENT CANAL
       FRAIN
          SYSTEM, M LLION GALLONS PER MINUTE
IN TOTAL RUNGEF FROM RAINFALL INTO PAR POND (INCLUDING FRAIN),
MILLION GALLONS PER MINUTE
       FRUN
                SEEPAGE LOSS FROM PAR POND, MILLION GALLONS PER MINUTE
       FS EEP
               OVERFLOW AT PAR POND DAM, MILLION GALLONS PER MINUTE
       FDAM
             THE UPPERFLOW IN PAR POND, MILLION GALLONS PER MINUTE
C.
       FUP
              FSEEP + FDAM + EPAR , MILLION GALLONS PER MINUTE FLOW IN LOWER THREE RUNS CREEK FROM PAR DAM TO THE RIVER,
       FOV ER
           MILLION GALLONS PER MINUTE
       FK+FL
                FLOW IN STEEL CREEK AT THE DUTLET TO THE RIVER (FROM K AND
           L REACTORS), MILLION GALLONS PER MINUTE
            FLOW IN FOUR MILE CREEK (TWO DUTLETS AT THE RIVER) FROM C
           REACTOR, MILLION GALLONS PER MINUTE
       FKL1, FKL2 PARTIAL COMBINED FLOWS FROM K AND & REACTORS IN THE
          SWAMP, MILLION GALLONS PER MINUTE
             AIR WET-BULB TEMPERATUPE, DEGREES C
           R AIR TEMPERATURE, DEGREES C
R PARTIAL PRESSURE OF HZO IN AIR, MILLIMETERS OF MERCURY
WIND SPEED, MILES PER HOUR (ABOVE THE TREES)
       TAIR
       PAIR
C
           INCHES OF RAINFALL IN D DAYS
           TIME INTERVAL, DAYS
TIME RA E DE CHANGE IN HEAT CONTENT DE PAR POND, PCU PER HOUR
C
           PER SQUARE FOOT
            RATE OF HEAT TRANSFER FROM THE WATER SURFACE TO THE
           ATMOSPHERE UNDER OPEN CONDITIONS, POU PER HOUR PER SQUARE FOOT PATE OF HEAT TRANSFER FROM THE WATER SURFACE TO THE
           AT MOS PHERE UNDER SHELTERED (SWAMP) CONDITIONS, PC11 PER HOUR
           PER SQUARE FOOT
            SOLAR HEAT LOAD, PCU PER HOUR PER SQUARE FOOT
           RATIO OF THE UNDERFLOW IN PAR POND TO THE INFLOW FROM THE R
С
           AND P EFFLUENT CANALS
           FRUN/ FRAIN
          AVERAGE DEPTH IN PAR POND, FEET
             FRACTION OF THE RAINFALL THAT GOES TO PUNDER
             FRACTION OF THE SURFACE APEA THAT IS EFFECTIVE IN
           TRANSFERRING HEAT TO THE ATMOSPHERE
FACTOR TO APPLY TO HC IF DESIRED
N TEMPERATURE OF GOOLING WATER ENTERING R REATOR AREA,
C
       TRIN
           DEGREES C
                 TE PERATURE ENTERING AND LEAVING, RESP., REACTOR
           EFFLUENT CANAL, DEGREES C
              TEMPERATURE OF COOLING WATER ENTERING P REACTOR AREA,
           DEGREES C
                  TE PERATURE ENTERING AND LEAVING, RESP., P REACTOR
      TP1.TP2
           EFFLUENT CANAL, DEGREES C
C
C
            TEMPERATURE UPON MIXING THE EFFLUENT FROM R AND P CANALS,
           DEGREES C
            TEMPERATURE AFTER MIXING THE PUNDEF (FRAIN) WITH THE EFFLUENT
           FROM R AND P CANALS, DEGREES C
THE SURFACE TEMPERATURE AT THE WARM END OF PAR POND,
      DEGREES C
             THE SURFACE TEMPERATURE AT THE COOL END OF PAR POND,
           DEGREES C
C
      TPAR CKTPAR
                      THE DISCHARGE TEMPERATURE FROM PAP POND PUMPHOUSE,
           AVERAGE OVER THE INTERVAL OF D DAYS, DEGREES C
            THE DISCHARGE TEMPERATURE FROM PAR POND AT THE BEGINNING DE
           THE D-DAY INTERVAL, DEGREES C
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THE DISTHARGE TEMPERATURE FROM PAR POND AT THE END OF THE
            D-DAY INTERVAL, DEGREES C
V TEMPERATURE OF THE SAVANNAH RIVER AT THE RIVER PUMPHOJSE,
C
C
            DEGREES C
C
                            TEMPERATURES OF C EFFLUENT COOLING WATER AS IT
       TC1, TC2, TC3, TC4
            TRAVERSE FOUR MILE CREEK AND THE SWAMP ON ITS WAY TO THE
            RIVER. DEGREES C
            TEMPERATURE OF C EFFLUENT COOLING WATER WHEN IT REACHES THE SAVANNAH RIVER VIA FOUR MILE CREEK (TWO DUTLETS), DEGREES C
       TK1, TK2, TK3 TEMPERATURES OF K EFFLUENT COOLING WATER AS IT
            TRAVERSES PEN BRANCH AND THE SWAMP, DEGREES C
                            TEMPERATURES OF L EFFLUENT COOLING WATER AS IT
       TL1,TL2,TL3,TL4
            TRAVERSE STEEL CREEK AND THE SWAMP, DEGREES C.,TKL2,TKL3 TEMPERATURES OF PARTIALLY MIXED EFFLUENT WATER
       TKL1, TKL2, TKL3
            FROM K A PO L REACTORS, AS FOUND IN THE SWAMP, DEGREES C
TEMPERATURE OF THE MIXED K AND L EFFLUENT COOLING WATER WHEN
C
C
            IT REACHES THE SAVANNAH RIVER VIA THE DUTLET FOR STEEL CREEK,
C
            DEGREES G
C
              TEMPER TURE OF THE OVERFLOW AND SEEPAGE FROM PAR POND (R AND
            P REACTORS) WHEN IT REACHES THE RIVER VIA LOWER THREE RUNS
            CREEK, DEGREES C
            THE DIFFERENCE BETWEEN THE SURFACE TEMPERATURE AND THE AVERAGE TEMPERATURE OF THE UPPERFLOW IN PAR POND, DEGREES C
C
             APPARENT EQUILIBRIUM TEMPERATURE UNDER OPEN CONDITIONS.
C
C
            DEGREES C
C
              APPARE T EQUILIBRIUM TEMPERATURE UNDER SHELTERED (SWAMP)
            CONDITIONS, DEGREES C
APPARENT EQUILIBRIUM TEMPERATURE (SUBROUTINE JWL)
       EM, EMS, EMQ
                      SLOPE OF THE STRAIGHT-LINE FIT TO THE LANGHAAR
            COOLING RATE CURVE FOR OPEN CONDITIONS, SHELTERED CONDITIONS,
            AND SUBREUTINE, RESPECTIVELY
, BQ INTERCEPT OF THE STRAIGHT-LINE FIT TO THE LANGHAAR
Č
           COOLING RATE CURVE FOR OPEN CONDITIONS, SHELTERED CONDITIONS,
            AND SUBROUTINE, RESPECTIVELY
С
            FLOW IN SUBROUTINE JWL, MILLION GALLONS PER MINUTE
¢
C
       ATOT - EFFECTIVE SURFACE AREA IN SUBPOUTINE JWL, MILLION SQUARE
            FEFT
C
       TIN.TOUT
                    TEMPERATURES ENTERING AND LEAVING, RESP., A REGION
C
            HAVING ATOT (FOR SUBROUTINE JWL), DEGREES C
            VAPORATION BETWEEN TIN AND TOUT OVER ATOT (FOR SUBROUTINE JWL), MILLION GALLONS PER MINUTE
              EVAPORATION BETWEEN TRI AND TRE IN THE R EFFLUENT CANAL,
С
           MILLION GALLONS PER MINUTE
              EVAPORATION BETWEEN TPL AND TP2 IN THE P EFFLUENT CANAL.
           MILLION GALLONS PER MINUTE
C
             EVAPORATION FROM PAR POND, MILLION GALLONS PER MINUTE
C
               TOTAL EVAPORATION FROM PAR POND AND R AND P EFFLUENT
Ċ
            CANALS. MILLION GALLONS PER MINUTE
Ċ
       CL3R
               EVAPORATION IN LOWER THREE RUNS CREEK BETWEEN PAR POND AND
            THE SAVANNAH RIVER, MILLION GALLONS PER MINUTE
С
            EVAPORATION IN FOUR MILE CREEK ( C EFFLUENT COOLING WATER) BETWEEN TC1 AND TC2, MILLION GALLONS PER MINUTE
¢
            EC4 EVAPORATION OF C EFFLUENT COOLING WATER IN THE SWAMP BETWEEN TC2 AND TC3 AND BETWEEN TC2 AND TC4, RESP.,
       EC3,EC4
            MILLION GALLONS PER MINUTE
C
             TOTAL EVAPORATION OF C EFFLUENT COOLING WATER IN TRAVERSING
            FOUR MILE CREEK AND THE SWAMP TO THE SAVANNAH RIVER.
C
Č
            MILLION ALLONS PER MINUTE
C
                   EVAPORATION OF K EFFLUENT COOLING WATER IN PEN BRANCH
       EK 2, EK 3
            AND THE SWAMP BETWEEN TK1 AND TK2 AND BETWEEN TK2 AND TK3.
C
C
            RESP., MILLION-GALLONS PER MINUTE
                       EVAPORATION OF L EFFLUENT COOLING WATER IN STEEL
       EL2,EL3,EL4
            CREEK AND THE SWAMP BETWEEN TL1 AND TL2, TL2 AND TL3, AND
            TL 2 AND TL4, RESP., MILLION GALLONS PER MINUTE
EVAPORATION OF L EFFLUENT COOLING WATER AND PART OF K
Ç
       FK13
            EFFLUENT COOLING WATER IN THE SWAMP ( NEAR STEEL CREEK OUTLET)
            BETWEEN TKL2 AND TKL3, MILLION GALLONS PER MINUTE
              TOTAL EVAPORATION FOR K AND L EFFLUENT COOLING WATER BEFORE
           REACHING THE SAVANNAH RIVER, MILLION GALLONS PER MINUTE LATENT HEAT OF EVAPORATION FOR WATER, PCU PER POUND POUND-CENTIGRADE HEAT UNIT, I.E., THE AMOUNT OF HEAT NEEDED
C
            TO RAISE THE TEMPERATURE OF ONE POUND OF WATER BY ONE DEGREE C
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С

C

C

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ISN 0002
                      DIMENSION TT410), VP(10), HT(10), EM(9), B(9), TE(9), HTS(10), EMS(9), BS(
                     19), TES(9), EMQ(9), BQ(9), TEQ(9), TEP(9)
ISN 0003
                      COMMON TIN, TOUT, F, AT OT, TT, EMQ, BQ, TEQ, ESUM, IJK, GB, TAIR
ISN 0004
                      READ(5,101) (TT(J),J=1,10)
                 PEAD(5,101) (VP(J),J=1,10)
101 FORMAT(10F8.3)
ISN 0005
LSN 0006
                 7 READ(5,100,END=810) IR,IP,IL,IK,IC
100 FORMAT (5117)
ISN 0007
ISN 0008
                 READ (5,110) PR,PP,PL,PK,PC
110 FORMAT (5F10.G)
ISN 0009
ISN 0010
ISN 0011
                      READ (5,120) FP, FP, FPAR, FSEEP, FFF
ISN 0012
                 120 FORMAT (4F12.6,F10.4)
ISN 0013
                      READ (5,130) FL, FK, FC
ISN 0014
                  130 FORMAT (3F12.6)
                      PEAD (5,140) TRIV, T1, DTG
ISN 0015
ISN 0016
                 140 FORMAT (3F10-2)
ISN 0017
                      READ (5,150) TAIR, TWB, PAIR, W, HS, P, D
ISN 0018
                 150 FORMAT (2F10.2,F10.3,F10.1,2F10.2,F10.4)
ISN 0019
                      READ (5,160) U,Z,H,FFR,FFA,FFC
                 160 FORMAT (6F10. 2)
ISN 0020
TSN 0021
                      EK2=0.
ISN 0022
                      EK3=0.
ISN 0023
                      EL2=0.
ISN C024
                      EL3=0.
ISN 0025
                      FL4=0.
ISN 0026
                      EP 2= ).
ISN 0027
                      EP2 =0 .
                 WPITE (6,170)
170 FORMAT (1H1,5HINPUT)
ISN 0028
ISN 0029
                      WRITE (6,171)
TSN 0030
                  171 FORMAT (1H0,50H
ISN 0031
                                                 IR
                                                            TΡ
                                                                        11
                                                                                    ΙK
                                                                                                103
ISN 0032
                      WRITE (6,100) IR, IP, IL, IK, IC
ISN 0033
                      WRITE (6,172):
ISN CC34
                  172 FORMAT (1HO,49H
                                                            PΡ
                                                                       PL
                                                                                   PΚ
                                                                                               PC)
                      WPITE (6,110) PR, PP, PL, PK, PC
TSN: 0035
                 WRITE (6,173)
173 FORMAT (1HC,57H
ISN CG36
ISN 0037
                                                ΕŖ
                                                              FP
                                                                           FPAR
                                                                                          FSEEP
                        FFFI
ISN 0038
                      WPITE (6,120) FR, FP, FPAP, FSEEP, FFF
ISN 0639
                      WRITE (6,174)
ISN 0040
                  174 FORMAT (1HC+33H
                                                                            FC)
ISN 0541
                      WRITE (6,130) FL, FK, FC
ISN 0042
                      WRITE (6,178)
ISN 2043
                  178 FORMAT (1HC+30H
                                               TRIV
                                                                       DTG)
                                                            Τī
ISN 0044
                      WRITE (6,140) TRIV, T1, DTG
ISN 0045
                      WRITE (6,175)
                 175 FORMAT (1H0.66H
ISN CC46
                                              TAIR
                                                          TWR
                                                                      PAIR
                                                                                               HS
                            Ð
                                      0.3
                      WEITE (6,150) TAIR, TWB, PAIR, W, HS, R, D
ISN 0047
ISN 0948
                      WEITE (6,176)
ISN 0049
                  176 FORMAT (1H0,60H
                                                                                   FFR
                                                                       н
                                                                                               FFA
                             FFC)
                      WFITE (6,160) U,Z,H,FFR,FFA,FFC
ISN 0050
                 WEITE (6,177)
177 FORMAT (1H0,6HDUTPUT)
ISM 0051
ISN 0052
ISN 0053
                      GA=1.63*(1.+.1*W)
ISN 0054
                      GB=1.20*(1.5+.1*W)
ISN 0055
                      GA5=1.63
ISN 0056
                      GBS = 1.8
ISN 0057
                      DC 185 [=1,10
                 HT([]=GA*(VP([)-PAIR)+GB*(TT([)-TAIR)
185 HTS([)=GAS*(VP([)-PAIR)+GBS*(TT([)-TAIR)
ISN 0058
ISN 0059
ISN CC60
                      DG 190 J=1,9
ISN 0061
                      I = J + 1
ISN 0062
                      EM(J) = (HT(J) - HT(I)) / (TT(J) - TT(I))
ISN 0063
                      B(J)=HT(J)-EM(J)*TT(J)
ISN 0064
                      EMS(J) = (HTS(J) - HTS(I))/(TT(J) - TT(I))
                      BS(J) =HTS(J) -EMS(J)*TT(J)
ISN C065
                      TE(U)=(-B(U) HS)/EM(U)
ISN 2066
ISN 0067
                 190 TES(J) =-BS(J)/EMS(J)
ISN 0068
                      WEITE (6,191)
```



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191 FORMAT (1HC, 49HLANGHAARS CODLING RATE CURVE FOR OPEN CONDITIONS')
ISN 0069
                WRITE (6,192% (TT(I),I=1,10)
192 FORMAT (1H0,9HDEGREES C,4X,10F10.2)
ISN 0070
ISN 0071
                 WRITE (6,193) (HT(1),1=1,10)
193 FORMAT (1H0,2HHT,11X,10F10.2)
ISN 0072
ISN 0073
ISN 0074
                     WRITE (6,194) (EM(I), I=1,9)
                 194 FORMAT (1H0,2HEM,21X,9F10.4)
ISN 0075
                     WRITE (6, 195) (B(I), I=1, 9)
ISN 0076
ISN 0077
                195 FORMAT (1HO,1HB,22X,9F10.2)
                     WRITE (6,196) (TE(I), I=1,9)
ISN 0078
                196 FORMAT (1HG,2HTE,21X,9F10.4)
ISN 0079
ISN 0980
                    WRITE (6,197)
                197 FORMAT (1HO,50HLANGHAARS COOLING RATE CURVE FOR SWAMP CONDITIONS!)
ISN 0081
ISN 0082
                     WP ITE (6,198) (TT(I), I=1,10)
                198 FORMAT (1H0,9HDEGREES C,4X,10F10.2)
ISN 0083
                WRITE (6,199) (HTS(1),1=1,10)
199 FORMAT (1H0,3HHTS,10x,10F10.2)
ISN 0084
ISN 0085
                     WPITE (6,200) (EMS(I), I=1,9)
ISN C086
                200 FORMAT (1H0,3HEMS,20X,9F10.4)
ISN C087
                WRITE (6,201 (BS(I), I=1,9)
201 FORMAT (1H0,2HBS,21X,9F10.2)
ISN 0088
ISN 0089
                     WRITE (6, 202) (TES(1), I=1,9)
ISN 0090
                202 FORMAT (1H0,3HTES,20X,9F10.4)
ISN 0091
              C.
ISN 0092
                     IF (IC.LT.1) GD TO 250
                     TC1=TRIV+1.897*PC/500./FC
ISN 0094
                     IF (TC1.GT.TT(1)) GD TO 797
ISN 0095
ISN 0097
                     DO 210 L=1.9
                     TEQ(L) =TE(L)
ISN 0098
                     EMQ(L)=EM(L)
ISN 0099
                210 BQ(L)=B(L)
ISN 0100
                     TIN=TC1
ISN 0101
ISN 0102
                     F=FC
                     ATCT=8.56
ISN 0103
ISN 0104
                     CALL JWL
                     IF (IJK.GT.0) GO TO 797
ISN 0105
                     TC 2= TO UT
ISN 0107
                     EC2=ESUM
ISN 0108
ISN 0109
                     DO 220 L=1.9
                     TEQ(L)=TES(L)
ISN 0110
                     EMO(L)=EMS(L)
ISN 0111
                220 BQ(L) =BS(L)
ISN 0112
                     TIN=TC2
ISN 0113
                     F=.276*FC
ISN 0114
                     ATOT=5.65
ISN 0115
ISN C116
                     CALL JWL
ISN 0117
                     IF (IJK.GT.0) GO TO 797
                     TC 3=TOUT
ISN 0119
                     EC3=ESUM
ISN 0120
ISN 0121
                     F=.724*FC
ISN 0122
                     ATOT=6.80
ISN 0123
                     CALL JWL
                     IF (IJK.GT.OK GO TO 797
ISN 0124
                     TC4=TOUT
ISN 0126
                     FC4=FSUM
ISN C127
                     TC=.276*TC3+.:724*TC4
ISN 0128
ISN 0129
                     EC=EC2+EC3+EC4
ISN 0130
                     WRITE (6,230.
                230 FORMAT (1HO, 46HTHE C EFFLUENT CW TEMPERATURES ARE AS FOLLOWS')
ISN 0131
                     WRITE (6,231) TC1,TC2,TC3,TC4
ISN 0132
                 231 FORMAT (1HO, 5HTC1 =, F6.2, 6X, 5HTC2 =, F6.2, 6X, 5HTC3 =, F6.2, 6X, 5HTC4
ISN 0133
                    1=,F6.2)
                     WRITE (6,232) TC
ISN 0134
                 232 FORMAT (1HO, 105HTHE MIXED TEMPERATURE OF THE TWO OUTLET STREAMS AT
ISN 0135
                    1 THE RIVER FOR FOUR MILE CREEK, FROM C REACTOR, IS TO =.F6.2)
                     WRITE (6,233) EC
TSN 0136
                 233 FORMAT (1HO,59HTHE EVAPORATION IN FOUR MILE CREEK, FROM C REACTOR,
ISN 0137
                    1 IS EC =, F12 6)
ISN 0138
                 250 IF (IK.LT.1) GO TO 300
                     TK1=TRIV+1 .897*PK/500./FK
ISN 0140
                     IF (TK1.GT.TT(1)) GO TO 797
ISN 0141
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ISN 0143
                     DO 260 L=1,9
ISN 0144
                     TEO(L) =TE(L)
                    ENQ(L)=EM(L)
ISN 0145
                260 BQ(L) = E(L)
ISN 0146
ISN 0147
                     TIN=TKI
ISN 0148
                     F=FK
ISN 0149
                     ATOT=2.53
ISN 0150
                    CALL JWL
                     IF [ IJK.GT.0 ] GO TO 797
ISN 0151
ISN 0153
                     TK2=TOUT
ISN 0154
                    EK2=ESUM
                     DO 270 L=1.9
ISN 0155
ISM 0156
                     TEQ(L)=TES(L)
ISN 0157
                     EMQ(L)=EMS(L)
ISN 0158
                270 BO(L) =BS(L)
ISN 0159
                     TIN=TK2
ISN 0160
                     F≖FK
ISN 0161
                    ATOT=30.36
ISN 0162
                     CALL JWL
ISN 0163
                     IF (IJK.GT.0) GO TO 797
ISN 9165
                     TK 3 = TO UT
ISN 0166
                     EK3=ESUM
ISN 0167
                     WPITE (6,280)
                280 FORMAT (IHO, 46HTHE K EFFLUENT CW TEMPERATURES ARE AS FOLLOWS!)
ISN 0168
ISN 0169
                     WRITE (6,281) TK1,TK2,TK3
ISN 0170
                281 FORMAT {1H0,5HTK1 =,F6.2,6X,5HTK2 =,F6.2,6X,5HTK3 =,F6.2}
              C
ISN 0171
                300 IF (IL.LT.1) GO TO 350
ISN 9173
                     TL1=TRIV+1.897*PL/500./FL
                     IF (TL1.GT.TT(1)) GD TO 797
ISN 0174
                    DO 310 L=1,9
ISN 0176
ISN 9177
                     TEQ(L)=TE(L)
ISN 0178
                     EMC(L) =EM(L)
ISN 9179
                310 BQ(L)=8(L)
ISN 0183
                    TIN=TL1
ISN 0181
                    F=FL
                    ATOT=3.69
ISN 0182
                     CALL JWL
ISN 0183
ISN C184
                    If (IJK.GT.O) GO TO 797
ISN 9186
                     TL 2=TOUT
ISN 0187
                     EL2=ESUM
ISN 0188
                     DO 320 L=1,9
ISN 0189
                     TEG(L)=TES(L)
ISN 0190
                    EMO(L) =EMS(L)
                320 BQ(L)=B$(L)
ISN 0191
ISN 0192
                     TIN=TL2
                    F=.41*FL
ISN 0193
                     ATOT=7.66
ISN C194
ISN C195
                     CALL JWL
ISN C156
                     IF (IJK.GT.0) GO TO 797
                     TL 3=TOUT
ISN 0198
ISN 0199
                     EL3=ESUM
ISN C20G
                    F=.59*FL
ISN 0201
                    ATCT=6.51
ISN 0202
                    CALL JWL
                    IF (IJK.GT.0) GO TO 797
ISN 0203
ISN 0205
                     TI 4=TOHT
ISN 0206
                    EL4=ESUM
ISN 0207
                     WRITE (6,330)
ISN 0208
                330 FORMAT (1HC,46HTHE L EFFLUENT CW TEMPERATURES ARE AS FOLLOWS!)
ISN 0209
                     WPITE (6,331) TL1,TL2,TL3,TL4
                331 FORMAT (1HG,5HTL1 =, F6.2, 6X, 5HTL2 =, F6.2, 6X, 5HTL3 =, F6.2, 6X, 5HTL4
ISN 0210
                   1 = . F6.2 )
ISN 0211
                350 IF (IK.LT.1) FK=0.
                     IF (IL.LT.I) FL=0.
ISN 0213
ISN 0215
                    FKL 1= . 357*FK+ . 41*FL
ISN 0216
                     IF (FKL1 . LE.O . ) GO TO 400
ISN 0218
                     TKL 1=(.357*FK*TK3+.41*FL*TL3]/FKL1
                     FKL2=FKL1+.59*FL
ISN G219
                     TKL2=(FKL1*TK11+.59*FL*TL4)/FKL2
ISN 0220
ISN 0221
                     TIN=TKL 2
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ISN 0222
                    F=FKL2
ISN 0223
                    AT0T=1.45
                    CALL JWL
ISN 0224
                    IF (IJK.GT.0) GO TO 797
ISN 0225
ISN 0227
                    THE RESTRICT
ISN 0228
                    EKL3=ESUM
                    TKL=(.643*FK*TK3+FKL2*TKL3)/(FK+FL)
ISN 0229
ISN 0230
                    EKL=EK 2+EK3+DL2+EL3+EL4+EKL3
ISN 0231
                    WRITE (6,355)
ISN 0232
                355 FORMAT (1HO+62HTHE TEMPERATURES IN STEEL CREEK NEAR THE RIVER ARE
                   1AS FOLLOWS')
                    WRITE (6,356) TKL1,TKL2,TKL3,TKL
ISN 0233
ISN 0234
                356 FORMAT(1HO.61TKL1 = F6.2.6X,6HTKL2 = F6.2.6X,6HTKL3 = F6.2.6X,5HTKL
                   11 = . F6 . 2)
                WPITE (6,360) TKL
360 FORMAT (1HC.83HTHE TEMPERATURE OF STEEL CREEK OUTLET AT THE RIVER.
ISN 0235
ISN 0236
                   1 FROM K AND L REACTORS, IS TKL = . F6.2)
                    WRITE (6,365) EKL
ISN 0237
                365 FORMAT (1HO, 79HTHE EVAPORATION IN PEN BRANCH AND STEEL CREEKS, FRO
ISN 0238
                   1M K AND L REACTORS, IS EKL =,F12.6)
ISN 0239
                400 IF ((IR+IP)-LT-1) GD TO 800
                    DO 403 L=1.9
ISN 0241
                    EMQ(L)=EM(L)
ISN 0242
ISN 0243
                403 BQ(L)=B(L)
ISN 0244
                    FRIV#FR+FP-FPAR
ISN 0245
                    M≖Ω
ISN 0246
                    TPAR =T1
ISN 0247
                405 TD=2.*TPAR-T1
ISN 0248
                    HC=62.4*H*(T -T1)*FFC/24./D
                    DO 408 J=1,9
ISN 0249
ISN 0250
                408 TEP(J)=(-B(J)+HS-HC)/EM(J)
ISN 0251
                    IF (IP.LT.1) GO TO 420
                    TPIN=(FFF*FPAR*TPAR+(FP-FFF*FPAR)*[RIV]/FP
ISN 0253
                    TP1=TPIN+1.897*PP/500./FP
ISN 0254
                    IF (TP1.GT.TT(1)) GO TO 797
ISN 0255
                    00 410 L=1,9
ISN 0257
ISN 0258
                410 TEQ(L)=TE(L)
                    TIN=TP1
ISN 0259
                    F=FP
ISN 0260
ISN 0261
                    ATCT=10.58
ISN 0262
                    CALL JWL
                    IF (IJK.GT.0) 30 TO 797
ISN 0263
ISN 0265
                    TP2=TOUT
ISN 0266
                    EP 2=E SUM
                420 IF (IR.LT.1) GD TO 430
TRIN=((1.-FFF)*FPAR*TPAR+(FR-(1.-FFF)*FPAR)*TRIV)/FR
ISN 0267
ISN 0269
                    TR 1=TR IN+1.897*PR /500./FR
ISN 0270
                    IF (TR1.GT.T 1(1)) GO TO 797
ISN 0271
                    TIN=TR1
ISN 0273
                    F= FR
ISN @274
                    ATOT=8.30
ISN 0275
ISN 0276
                    CALL JWL
ISN 0277
                    IF (IJK.GT.C) GO TO 797
                    TR 2=TOUT
ISN 0279
ISN 0280
                    EP 2= ESUM
                430 IF (IP.LT.1) FP=0.
ISN 0281
                    IF (IR.LT.1) FR=0.
ISN 0283
                    IF ((FR+FP).LE.O.) GO TO 800
ISN Q285
                    TX = (FR * TR2 + FF F* TP2) / (FR + FP)
ISN 0287
                    FRAIN= . 1605*R *FFR /D
ISN 0288
                    FUP=(U+1.)*(FR+FP+FRAIN)+(Z-1.)*FPAIN
ISN 0289
ISN 0290
                    TI=(TX*(FR+FP)+FRAIN*TWB)/(FR+FP+FRAIM)
                    TIUP=(U*TPAR+TI+(Z-1.)*FRAIV*TWB/(FR+FP+F?AIN))/(U+1.+(Z-1.)*FPAIN
ISN 0291
                   1/(FR+FP+FRAIN))+DTG
                    DO 450 L=1.9
ISN 0292
                450 TEQULI =TEP(LT
ISN 0293
ISN 0294
                    TIN=TIUP
                    F= FUP
ISN 0295
                    ATCT=108.9
ISN 0296
ISN 0297
                    CALL JWL
                     IF (IJK.GT.0) GD TO 797
```

ISN 0298



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TOP=TOUT
ISN 0300
                     EOP=ESUM
ISN 0301
ISN 0302
                     CKTPAP=TOP-(1.+(FR+FP+Z*FRAIN-FPAP)/(U*(FR+FP+FRAIN)+FPAR))*DTG
                     DEL 2=TPAR-CKTPAR
ISN 0303
                     IF (ABS(DEL2# LE .0 .01) GO TO 460
ISN 0304
                     IF [M.GT.0] 0 TO 455
ISN 0306
ISN 0308
                     DELI=DEL2
ISN 0309
                     TPAR1=TPAR
                     TPAR = CKTPAR
ISN 0310
ISN 0311
                     M=1
                     GO TO 405
ISN 0312
                 455 TPAR 2= TPAR
ISN 0313
                     TPAR=TPAR2-DEL2*(TPAR1-TPAR2)/(DEL1-DEL2)
ISN 0314
ISN 0315
                     TPAR1 = TPAR2
ISN 0316
                     DEL 1=DEL 2
ISN 0317
                     GO TO 405
ISN 0318
                 460 EPAR=EP2+ER2+EOP
ISN 0319
                     FPUN=Z*FRAIN
ISN 0320
                     FOVER = FR + FP +Z *FR A IN- FP AR
                     FDAM=FCVER-EPAR-FSEEP
ISN 0321
                     FL 3R = FOVER - E PAR
ISN C322
ISN 0323
                     IF (FCAM.LT.0.) GO TO 795
                     TOTIN=FPIV+FRUN
ISN 0325
                     TOTOUT = EP AR +F SEEP +FD AM
ISN 0326
                     IF (IP.LT.1) GO TO 485
ISN 0327
ISN 0329
                     WP ITE (6,481)
ISN 0330
                 481 FORMAT (1HC,30HP EFFLUENT CANAL TEMPERATURES*)
                WRITE (6,482) TPIN,TP1,TP2
482 FORMAT (1HG,6HTPIN =,F6.2,6X,5HTP1 =,F6.2,6X,5HTP2 =,F6.2)
ISN 0331
ISN 0332
                 WRITE (6,483) EP2
483 FORMAT (1H0,42HTHE EVAPORATION IN P EFFLUENT CANAL, EP2 =, F12.6)
ISN 0333
ISN 0334
                 485 IF (IR.LT.1) GO TO 489
ISN 0335
                 WPITE (6,486)
486 FORMAT (1H9,30HR EFFLUENT CANAL TEMPERATUPES!)
ISN 0337
ISN 0338
ISN C339
                     WRITE (6,487) TRIN, TRI, TR2
                 487 FORMAT (1HC,6HTRIN =,F6.2,6X,5HTR1 =,F6.2,6X,5HTR2 =,F6.2)
ISN 0340
                 WFITE (6,488) ER2
488 FORMAT (1H0,42HTHE EVAPORATION IN R EFFLUENT CANAL, ER2 =,F12.6)
ISN 0341
ISN 0342
ISN 0343
                 489 WRITE 16,4901
ISN 0344
                 490 FORMAT (1HO, 22HPAR POND TEMPERATURES*)
                 WRITE (6,491) TX,TI,TIUP,TOP,TPAF,TD
491 FORMAT (1H0,4HTX =,F8.4,6X,4HTI =,F8.4,6X,6HTIUP =,F8.4,6X,5HTOP =
ISN 0345
ISN 0346
                    1, F8.4,6X,6HTP AR =, F8.4,6X,4HTD =, F8.4)
ISN 0347
                     WRITE (6,492) FRAIN, FUP
TSN 0348
                 492 FORMAT (1HO,27HPERTINENT FLOWS ARE FRAIN =,F10.6,6X,9HAND FUP =,F1
                    10.61
ISN 0349
                     WRITE {6,493 # HC
                 493 FORMAT (1HO,48HTHE RATE OF CHANGE IN HEAT CONTENT OF POND, HC =,F1
ISN 0350
                    10.41
ISN 0351
                     WRITE (6,494)
                 494 FORMAT (1HO, 103HTHE EQUILIBRIUM TEMPERATURES OVER SEGMENTS OF LANG
ISN 0352
                    THAARS COOLIN RATE CURVE ARE AS FOLLOWS FOR PAR POND!)
                     WRITE (6,495) (TT(I), I=1,10)
ISN 0353
                 495 FORMAT (1H0,9HDEGREES C,4X,10F10.2)
ISN 0354
ISN C355
                     WRITE (6,496) (TEP(I), I=1,9)
ISN 0356
                 496 FORMAT (1H0,3HTEP,20X,9F10.4)
                     WRITE (6,497) EDP
ISN 0357
                 497 FORMAT (1HO,36HTHE EVAPORATION FROM PAR POND, EDP =,F12.6)
ISN 0358
                     WRITE (6,500
ISN 0359
1SN 0360
                 500 FORMAT (1HC, 45HTHE WATER BALANCE FOR PAR POND IS AS FOLLOWS!)
ISN 0361
                     WRITE (6,501)
                 501 FORMAT (1HC, 10X, 8HWATER IN)
ISN 0362
ISN 0363
                     WRITE (6,502) FRIV
                 502 FORMAT (1HO,16x,25HMAKEUP FROM RIVER, FRIV =,3x,F1).6)
ISN 0364
ISN 0365
                     WR ITE (6,503# FRUN
                 503 FORMAT (1H0 . 6x, 28HPUNOFF FROM PAINFALL, FRUN =, F10.6) WRITE (6,504) TOTIN
ISN 0366
ISN 0367
                 504 FORMAT (1HG, 22X, 8HSUBTOTAL, 14X, F10.6)
ISN Q368
ISN 0369
                     WRITE (6,505)
ISN 0370
                 505 FORMAT (1HO, 10X, 9HWATER OUT)
                     WRITE (6,506 EPAR
ISN 0371
                 506 FORMAT(1HQ.16X.19HEVAPORATION, EPAR =,9X,F19.6)
ISN 0372
ISN 0373
                     WRITE (6,507) FSEEP
```



```
ISN 0374
                507 FORMAT (1H0,16X,21HSEEPAGE LOSS, FSEEP =,7X,F10.6)
                 WRITE (6,508) FDAM
508 FORMAT (1H0,26X,23HOVERFLOW AT DAM, FDAM =,5X,F10.6)
ISN 0375
ISN 0376
                     WRITE (6,509) TOTOUT
ISN 0377
ISN 0378
                 509 FORMAT (1H0,22X,8HSUBTOTAL,14X,F10.6)
              C
ISN 0379
                     IF (FL3R.LE.O.) GO TO 800
ISN 0381
                     DO 520 L=1,9
ISN 0382
                 520 TEQ(L)=TE(L)
ISN 0383
                     TIN=TOP
ISN 0384
                     F=FL 3R
                     ATGT=4.83
ISN 0385
                     CALL JWL
IF (IJK.GT.0) GD TD 797
ISN 0386
ISN 0387
                     TRP=TOUT
ISN 0389
ISN 0390
                     EL 3P = E$UM
                 WRITE (6,530) TRP
530 FORMAT (1HO,73HTHE OVERFLOW FROM PAR DAM REACHES THE RIVER VIA LOW
ISN 0391
ISN C392
                    1EF THREE RUNS AT TRP =,F6.2)
WRITE (6,531) EL3R
ISN 0393
ISN 0394
                 531 FORMAT (1HO.57HTHE EVAPORATION IN LOWER THREE RUNS BELOW PAR DAM.
                    1EL3P = , F12.6
ISN 0395
                     008 OT 00
ISN 0396
                795 WPITE (6.7961
ISN 0397
                 796 FORMAT (1HO, 29HPAR POND LEVEL IS DECREASING.)
ISN 0398
                     GO TO 800
              C
                797 WRITE (6,798)
798 FORMAT (1H0,102HTHE INPUT CONDITIONS LEAD TO TEMPERATURES OUTSIDE
ISN 0399
ISN 0400
                    10F THE RANGE TAKEN FOR LANGHAARS COOLING RATE CURVE.)
ISN 0401
                800 GO TO 7
ISN 0402
                 810 STOP
ISN 0403
                     END
```

			٠.		A	1000
		PΚ	ŞF		8*4	000 CB C
		TC	SF		P*4	000090
		TT	SF	C	P *4	0.00010
		DTG	۶F		P×4	000 CB0
		EK L	S F		R #4	000 000
		EL3	SF		F*4	000000
		EOP	SF		R *4	000CD8
RESE		FFC	SF		P*4	000 CE8
MANN		GAS	SF		P*4	000CF8
		JHL	SF	ΧF	I *4	იღიდი
		TC 4	SF		P *4	000000
2557		TIN	S	С	P *4	0.00000
وجد والمتحرب وا		TK3	\$F		P*4	000 010
是这五人	93	TL4	SF		R*4	000020
	~	TRP	SF		R*4	000030
	1	AT OT	5	C	R *4	000000
RMHH		EL3R	SF		R*4	000058
산산인전		FKL1	SF		P*4	000064
		FRIV	SF		P *4	000074
1 31 31 31		TIUP	SF		R*4	000080
W 3. M		TOUT	F	С	P *4	000004
****		TOTAL	C F		044	00000

NAME	7	AG	TYPE	ADD.	NAME	T AG	TYPE	ADD.	NAME	TA	G	TYPE	ADD.	NAME	TΑ	G	TYPE	ADD.
В			R *4	000000	D	SF	R*4	000028	F :	S	C	P. *4	000008	H	SF		R *4	000000
1	SF		I *4	000030	J	SF	[* 4	000034	L	SF		[*4	000038	4	S		1 *4	000030
R	SF		₽*4	000040	U	SF	R*4	000044	W	SF		₽ ★4.	000048	2	SF		0 * 4	333646
8Q	5	C	P *4	00005C	8.5	\$F	F * 4	QOQDE4	EC :	SF		R*4	300 C50	EM	SF		P *4	930E08
۴C	SF		R*4	000054	FK	SF	P *4	000058	FL	SF		2*4	000050	FP	SF		D#4	333653
FR	SF		R*4	000064	5 A	SF	R*4	000068	GB :	SF.	C	R *4	DACCCC	яC	SE		₹*4	300161
HS	SF		R *4	000070	HT	SF	P*4	OOCE 2C	IC	SF		1 * 4	203074	IK	SE		[*4	000078
IL	SF		I *4	000070	ΙP	SF	I*4	000 C80	IR .	SE		I *4	000084	PC	SF		R *4	330188
PΚ	\$ F		8*4	000 CBC	Pl.	SF	₽*4	<b>0000090</b>	P₽	SF		R*4	000094	PR	\$ F		P#4	333098
TC	SF		P*4	000696	TD	SF	R*4	0000CA0	TE.	SF		P *4	000E54	TI	SF		R#4	000CA4
TT	SF	C	P *4	000010	TX	SF	R*4	900CA8	T1	SF		P*4	DODCAC	VP.	SF		R *4	333E78
DTG	SF		P*4	000 CB0	EC2	SF	P * 4	000CB4	EC 3	SF		R *4	000088	EC4	SF		R#4	DBCCC
EK L	SF		R #4	000000	EK 2	SF	0 * 4	000004	EK3	SF		P.* 4	200008	EL 2	SF		R *6.	333666
EL3	SF		F*4	000000	EL4	SF	P*4	000 CD4	EMD	S	-	2 *4	000038	EMS	SF		R*4	222EA)
EOP	SF		R #4	000CD8	EP 2	SF	R * 4	phococ	ER2	SF	_	P*4	000 CE0	FFA	ŚF		R *4	3300E4
FFC	SF		P*4	000 CE8	FFF	SF	P * 4	OCCCC	FFR	SF		P * 4	000CF0	FUP	SE		R*4	323CF4
GAS	ŞF		P*4	000CF8	GB S	SF	R*4	000 CFC	HTS	SF		R *4	303EC4	114		C	I * 4	333348
JWL	ŞF	ΧF	I *4	იღიდი	TC 1	SF	F*4	cococo	TC2	SF		P*4	000004	T C3	5 F .	_	R *4	333D38
TC 4	SF		P *4	000000	TEP	SF	P*4	OTHOREC		S	-	2 *4	000080	TES			P * 4	222=13
TIN	S	C	P *4	0.00000	TKL	SF	R* 4	000010	TK1	SF		P * 4	300D14	T ( 2	SF		R #4	220218
TK3	\$F		P*4	0.00 01.0	Til	SF	P * 4	000020	TL2	SF		R*4	000024	TL3	SF		R*4	333D23
TL4	SF		R*4	000020	TOP	SF	P*4	000 030	TPI	SF		R *4	300D34	TP 2	SF		R # 4	000038
TRP	SF		R*4	000030	TR1	SF	P*4	000 040	TP2	SF		8*4	000044	TW3	SF		R#4	000048
AT OT	5	C	R *4	000000	DEL 1	SF	2*4	000040	DEL2			P*4	200051	EKL3	SF		R *4	000054
EL3R	SF		R*4	000058	EPAR	SE	R*4	000D5C	ESUM	F	3	P *4	000044	FDAM	SF		P*4	222052
FKL 1	SF		P * 4	000D64	FKL2		P#4	000068	FL3R	SE		P *4	300D6C	FPAR			Q *4	200272
FRIV			P *4	000074	FRUN		P*4	000078	PAIR			P.* 4	300 D7C		SE	С	₽ #4	222282
TIUP	SF		R * 4	000080	TKL1		R*4	200 084	TKL2			R *4	000088	TKL3	SE	•	2*4	22203C
TOUT	F	C.	R *4	000004	TPAR		P # 4	000090	TPIN			P#4	000094	TRIV			2 *4	220298
TRIV	SF	-	R*4	000 D9 C	FOVER		R*4	COODAO	FRAIN			2*4	000DA4	FSEEP			D*4	)))DA3
TOTIN			P * 4	COCDAC	TPAR1		₽*4	200 082	TPAR2	_		R *4	000DB4	CKTPAR			2*4	000038
IBCCM#	F	ΧF	P *4	000000	TOTOUT		R <b>×</b> 4	010080	T. AIRE			) · · · ¬		CAIFMA	2 1		• • •	00000
25 5 6.14	•	(K.)	7	A CANADA	. 51001	•	73. "T	£/00 <b>£</b>					1					t

\*\*\*\*\* COMMON INFORMATION \*\*\*\*\*

### NAME OF COMMON BLOCK \* \* SIZE OF BLOCK 0000 84 HEXADECIMAL BYTES

VAR. NAME	TYPE	REL. ADDR.	VAR. NAME	TYPE	PEL . ADDP .	VAR. NAME	TYPE	PEL. ADDP.	VAR. NAME	TYPE	REL. ADDR.
TIN	R * 4	000000	TOUT	R * 4	030004	F	P *4	500008	TCTA	2 * 4	000000
TT	R*4	000010	EMQ	R*4	000038	ВQ	R*4	00005C	TEQ	P#4	00008)
ESUM	R*4	0000A4	IJK	[+4	9000 A8	GB	R *4	0000040	TAIR	R#4	0000BJ

```
PAGE 012
LABEL
        ADDR
                             L AB EL
                                      ADDR
                                                           LABEL
                                                                    ADDP
                                                                                         LABEL
                                                                                                 ADDR
                                                                                                001015
                                                             190
                                                                  001876
                                                                                           210
       0011C6
                               185
                                    00166C
  2 20
       001CEA
                               250
                                    001E58
                                                             260
                                                                  001 EDC
                                                                                           270
                                                                                                DDIFAB
                                                                                                002204
  300
       002068
                               310
                                    0020EC
                                                             320
                                                                  002188
                                                                                           350
  400
       002484
                               403
                                     0024C2
                                                             405
                                                                  002510
                                                                                           408
                                                                                                00255C
                                    00269C
                                                             430
                                                                   002750
                                                                                           450
                                                                                                0028DA
  410
       00261C
                               · 420
                                    002 A3 E
                                                             485
                                                                  002824
                                                                                           489
                                                                                                0028 90
  455
       0029F4
                               460
      002DF8
                                    002E86
                                                             797
                                                                  002ED2
                                                                                           800
                                                                                                002EE8
  520
                                95
      002EEE
  810
```

\*OPTIONS IN EFFECT\* NAME=

NAME = MAIN, OPT=00, LINECHT=58

\*OPTIONS IN EFFECT\*

SOURCE, EBCDIC, NOLIST, NODECK, LDAD, MAP, NOEDIT, ID, NO XREF

\*STATISTICS\*

SOURCE STATEMENTS \*

402 , PROGRAM SIZE =

12060

\*STATISTICS\* NO DIAGNOSTICS GENERATED

\*\*\*\*\* END OF COMPILATION \*\*\*\*\*

LEVEL 18 ( SEPT 69 )

OS/360 FORTRAN H

DATE /1.250/08.18.27

COMPILER OPTIONS - NAME= MAIN, OPT=DO, LINECNT=58, SOURCE, EBCDIC, NOLIST, NODECK, LOAD, MAP, NOEDIT, ID, NOXREF ISN 0002 SUBROUTINE JWL ISN 0003 DIMENSION TT(10), EMQ(9), BQ(9), TEQ(9) ISN 0004 COMMON TIN, T UT, F, ATOT, TT, EMQ, BQ, TEQ, ESUM, IJK, GB, TAIR ISN 0005 HFG=581. ISN 0006 T=TIN ISN 0007 IJK=0 ISN 0008 I = 1ISN 0009 SUM=0. ISN 0010 ESUM=0. ISN 0011 HOLD=0. ISN 0012 EHCLD=0. ISN 0013 1020 TDIF = TT(1) -T ISN 0014 IF(TDIF.LT.0.) GO TO 1050 ISN 0016 [+]=[ ISN 0017 GO TO 1020 1050 J=[-1 ISN COL8 ISN C019 IF (J.LE.0) 00 TO 1099 ISN 0021 IF ((TT(I)-TEQ(J)).LE.O.) GD TO 1080 ISN 0023  $X = \{TT(I) - TEQ(J)\} / \{T - TEQ(J)\}$ ISN 0024 AINC=-ALOG(X)\*F\*500./EMQ(J) ISN 0025 EINC=((EMQ(J)\*TEQ(J)+BQ(J)+GB\*(TAIP-TEQ(J)))\*AINC+500.\*F\*(EMQ(J)-G 1B)\*(T-TEQ(J))\*(1.-X)/EMQ(J))/500./HFG

**ESUM** 

R\*4

0000A4

IJK

```
ISN 0026
                    HOLD=SHM
ISN 0027
                    EHCLD=ESUM
ISN 0028
                    SUM = SUM+ A I NC
ISN 9029
                    ESUM = ESUM + EINC
ISN 0030
                    IF (SUM.GE.ATOT) GO TO 1080
ISN C032
                    T=TY(1)
                    I = [ + ]
ISN 0033
ISN 0034
                    GO TO 1050
ISN 0035
               1080 AINC=ATOT-HOLD
                    Y=EMQ(J)*AINC/F/500.
ISN 0036
ISN 0037
                    TOUT=TEQ(J)+(T-TEQ(J))/EXP(Y)
ISN C038
                    X=1./EXP(Y)
                    EINC = (IEMQ(J)*TEQ(J)+BQ(J)+BQ(J)+GB*(TAIR-TEQ(J))]*AINC+500**F*(EMQ(J)-G
ISN 0039
                   1B)*(T-TEQ(J))*(1.-x)/EMQ(J))/500./HFG
ISN 0040
                    ESUM=EHOLD+EINC
ISN 0041
                    GD TO 1096
ISN 0042
               1090 IJK=IJK+1
ISN 0043
               1096 CONTINUE
                    PETURN
ISN 0044
ISN 0045
                    END
                                                                     SIZE OF PROGRAM 2004 FO HEXADECIMAL BYTES PAGE 002
                                                          JWL /
NAME
        TAG
               TYPE
                    ADD.
                                  NAME
                                           TAG
                                                  TYPE
                                                       ADD.
                                                                     NAME
                                                                             TAG
                                                                                    TYPE ADD.
                                                                                                       NAME
                                                                                                                TAG
                                                                                                                      TYPE
                                                                                                                           ADD.
    F
       F
               P *4
                    000008
                                       I SF
                                                  1*4
                                                       000094
                                                                         J SF
                                                                                    I *4
                                                                                         200099
                                                                                                           T SF
                                                                                                                      ₽ *4
                                                                                                                           300090
    X SEA
               P*4
                     0000A0
                                       Y SFA
                                                  R*4
                                                       0000A4
                                                                        вұ
                                                                           F
                                                                                    2 * 4
                                                                                         000050
                                                                                                          GB F
                                                                                                                   C
                                                                                                                      R*4
                                                                                                                            DACCCC
   TT F
            C
               R *4
                    000010
                                     EMO
                                         F
                                                  P#4
                                                       000038
                                                                       HEG SE
                                                                                    R *4
                                                                                         303048
                                                                                                         IJK SF
                                                                                                                      T *4
                                                                                                                           333348
                                                                                                                   C
                                                                                                         TIN F
  JWL
               1 *4
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                                     SUM SF
                                                  R * 4
                                                       000080
                                                                       TEO F
                                                                                    R*4
                                                                                         000080
                                                                                                                   C
                                                                                                                      R*4
                                                                                                                            22222
                                         F
 AINC SE
               P *4
                    000084
                                    ATOT
                                              C
                                                 P*4
                                                       000000
                                                                      EINC SE
                                                                                    R *4
                                                                                         000088
                                                                                                        ESUM SF
                                                                                                                   C
                                                                                                                      R#4
                                                                                                                           DODDDA4
 HOLD SF
               R *4
                    0000BC
                                    TAIR
                                         F
                                              C
                                                 R*4
                                                       000080
                                                                      TDIF S
                                                                                    F * 4
                                                                                         200000
                                                                                                        TOUT S
                                                                                                                      ₽ *4
                                                                                                                           000004
EHOLD SF
               R*4
                    000004
                                     FX P
                                             ΧF
                                                  R*4
                                                       000000
                                                                      ALDG
                                                                                   R *4
                                                                                         000000
                                       **** COMMON INFORMATION
   NAME OF COMMON BLOCK *
                                       SIZE OF BLOCK
                                                         0000B4 HEXADECIMAL BYTES
                                                                  VAR. NAME TYPE
                                                                                                  VAR. NAME
                                                                                                             TYPE
                                                                                                                    REL. ADDR.
 VAR. NAME
             TYPE
                   REL. ADDR.
                                 VAR. NAME
                                             TYPE
                                                    REL. ADDR.
                                                                                    REL . ADDR .
      TIN
              P #4
                    000000
                                      TOUT
                                              2 * 4
                                                     000004
                                                                              R * 4
                                                                                     000008
                                                                                                      AT OT
                                                                                                               2*4
                                                                                                                     000000
              R*4
                    000010
                                       EMQ
                                              R*4
                                                    000038
                                                                              R #4
                                                                                     000050
                                                                                                       TEQ
                                                                                                               8 * 4
                                                                                                                     000080
       ŢŢ
                                                                        ВQ
                                              I * 4
                                                     0000A8
                                                                        GB
                                                                               R*4
                                                                                                               9 * 4
                                                                                                                     200080
```

DOCCO

TAIR

- 96 -

LABEL ADDR

LABEL ADDR

LABEL ADDR

LABEL ADDR

PAGE 003

1020 00014C 1096 0004CA 1050 00017C

1080 000358

1090 0004BA

\*OPTIONS IN EFFECT\*

NAME= MAIN.DPT=00.LINECNT=58

\*OPTIONS IN EFFECT\*

SOURCE, EBCDIC, NOLIST, NODECK, LOAD, MAP, NOEDIT, ID, NOXREF

\*STATISTICS\*

SOURCE STATEMENTS =

44 , PROGRAM SIZE =

1264

\*STATISTICS\* NO DIAGNOSTICS GENERATED

\*\*\*\*\* END OF COMPILATION \*\*\*\*\*

\*STATISTICS\* NO DIAGNOSTICS THIS STEP

OS/360 LOADER

OPTIONS USED - PRINT, MAP, LET, CALL, RES, SIZE=184320, EP=MAIN

NAME TYPE	ADDR	NAME TYPE	ADDR	NAME TYPE	ADDR	NAME TYPE	ADDR	NAME TYPE	ADDR
MAIN SD	83808	JWL SD	86728	IHCSLOG * SD	86 C18	ALOGIO * LR	86C18	ALGG * LR	86C34
IHC SEXP * SD	96 DD8	EXP # LR	86 DD8	IHCECOMH* SD	86F88	IBCOM# * LR	86F88	FOIOCS# * LR	87044
INTSWTCH* LR	87F66	IHCCOMH2 SD	87F80	SEQDASD * LR	88098	IHCERRM * SD	88380	ERRMON + LR	68380
IHCERRE * LR	88398	IHCURPT * SD	88920	IHCEFNTH* SD	88C20	ARITH# * LR	88C20	ADJSWTCH* LR	88 F8 C
IHCEFIOS* SD	89138	FIOCS# * LR	89138	FIOCSBEP* LR	8913E	IHCFCVTH* SD	8A 270	ADCON# * LR	8A270
FCVAOUTP* LR	8A31A	FC VLOUTP . LR	8A3AA	FCVZOUTP* LR	BA4FA	FCVIOUTP* LR	8A886	FCVEDUTP* LR	8AD88
FCVCOUTP* LR	8 AFA2	INT6SWCH* LR	8 B 2 8 3	IHCUATBL * SD	88 3E 0	IHCETRCH* SD	8BA18	IHCTRCH * LR	88A18
FDDTDA # 1D	88 A 20	SBLANKCOM CM	BBCAB				•		

TCTAL LENGTH 8554 ENTRY ADDRESS 83808 A KANAMATAN KANAMAKAN KANAMAKANA KANAMAKAN KANAMAKAN KANAMAKAN KANAMAKAN KANAMAKAN KANAMAKAN KAN

M	•	Ł	T

IR	ΙÞ	IL	IΚ	10		
1	1	c.	0	Ć.		
PR	PP	PL	PΚ	PC		
2102.	1811.	o.	0.	0.		
FP	FP	FP AP		FSEEP	FFF	
0.167500	0.166800	0.202900	9.0	00850	0.6300	
FL	FK	FC				
C.O	0.0	0.0				
TR IV	Ti	D TG				
18.85	21.05	1.94				
TAIR	T WB	PAIR	W	HS	P	D
22.22	17.21	12.300	7.3	43.90	4.10	31.9000
U	Z	н	FFR	FFA	FFC	
2.30	2.71	20.40	0.25	1.00	1.00	

OUT PUT

LANGHAARS COOLING RATE CURVE FOR OPEN CONDITIONS!

DEGREES C	95.00	85.00	75.00	65.00	55,00	45.00	35.33	25.00	15.00	5. nn
нт	1947.61	1356.02	921.79	608.64	385.90	228.97	118.44	39.74	-17.94	-52.31
EM		59.1586	43-4235	31.3148	22.2743	15.6926	11,0525	7.8700	5.7689	4.437
В		-3672.46	-2334.98	-1426.83	-839.19	-477.20	-268.39	-157.01	-134.48	-84.50
TE		62.8202	54.7831	46.9658	39 +6462	33.2066	28.2555	25.5281	25.7204	28.9383
LANGHAARS COO	LING RATE C	UPVE FOR S	NAMP CONDI	TIONS!						
DEGPEES C	95.00	85.00	75.00	65.00	55.00	45.00	35.00	25.00	15.03	5. 30
HTS	1144.21	799.72	546.19	362.64	231.36	138.12	71.70	23.68	-12.20	-40.38
EMS		34.4489	25.3535	18.3542	13.1285	9.3241	6.6419	4.8023	3.5878	2.8179
вѕ		-2128.43	-1355.32	-830.38	-499.71	-281.46	-160.77	-96.38	-66.02	-54, 47
TES		61.7852	53 • 457 1	45.2419	37. 3772	30.1868	24.2048	20.0696	18.4906	19.3296





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P EFFLUENT CANAL TEMPERATURES!
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TPIN = 22.34 TP2 = 36.16TP1 = 63.53

THE EVAPORATION IN P EFFLUENT CANAL, EP2 = 0.637147

R EFFLUENT CANAL TEMPERATURES!

TRIN = 20.89 TR1 = 68.50

TR2 = 40.04

THE EVAPORATION IN R EFFLUENT CANAL, ER2 = 0.007299

PAR POND TEMPERATURES!

TX = 38.1045

TI = 37.7780

TIUP = 29.6114

TOP = 25.6264

TPAR = 23.3989

TD = 25.7477

PERTINENT FLOWS ARE FRAIN = 0.005307 AND FUP = 1.129776 THE RATE OF CHANGE IN HEAT CONTENT OF POND, HC =

THE EQUILIBRIUM TEMPERATURES OVER SEGMENTS OF LANGHARS COOLING PATE CURVE ARE AS FOLLOWS FOR PAR POND.

DEGREES C

95.00

85.00

75.00

65.00 62.6844 54.5980 46.7091 39.2853 32.6944

55.00

35.00

25.00 27.5282 24.5068 24.3271

15.00

27.1268

TEP

THE EVAPORATION FROM PAR POND, ECP = 0.016264

THE WATER BALANCE FOR PAR POND IS AS FOLLOWS!

WATER IN

MAKEUP FROM RIVER. FRIV =

0.131400

RUNDER FROM RAINFALL, FRUN = 0.014382

SUBTOTAL

0.145781

WATER OUT

EVAPORATION, EPAR =

0.030709

SEEPAGE LOSS, FSEEP =

0.002800

OVERFLOW AT CAM. FCAM =

0.112272

SUB TO TAL

0.145781

THE CVERFLOW FROM PAR CAM REACHES THE RIVER VIA LOWER THREE RUNS AT TRP = 25.58

THE EVAPORATION IN LOWER THREE RUNS BELOW PAR DAM, ELBR = 0.000589

# LIMN Printout 2

INPUT						
IR	IP	IL	ΙK	ıc		
Ģ	1	0	0	0		
PR	PP	PL	PK	PC		
0.	1811.	o.	0.	^.		
FR	FP	FPAR		FSEEP	FFF	
0.0	0.166800	0.150000	0.0	002800	1.0000	
FL	FK	· FC				
0.0	0.0	9.9				
TRIV	Т1	DTG				
18. 65	21.05	1.94				
TAIR	TWB	PAIR	W	нѕ	R	D
22.22	17.21	12.300	7.3	43.90	4.19	31.0000
U	Z	н	FFR	FFA	FFC	
2.30	2.71	20.40	<b>≎.2</b> 5	1.00	1.00	

DUTPUT

LANGHAARS COOLING RATE CURVE FOR OPEN CONDITIONS!

DEGREES C	95.00	85.00	75.00	65. CQ	55+00	45•C0	35.00	25.00	15.37	2 • 70
нт	1947.61	1356.02	921.79	608.64	385.90	228.97	118.44	39.74	-17.94	-62.31
EM		59.1586	43. 4235	31.3148	22.2743	15.6925	11.0525	7.8700	5.7589	4.4370
В		-3672.46	-2334.98	-1426.83	-839.19	-477.20	-268.39	-157.01	-104.48	-84.50
TE		62.8202	54 • 783 1	46.9658	39.6462	33.2066	28.2555	25.5281	25.7204	28, 9383
LANGHAARS CO	DLING RATE C	URVE FOR S	WAMP CONDI	TIONS!						
DEGREES C	95.00	85.90	75.90	65.00	55.00	45.00	35.00	25.00	15.00	5.00
HTS	1144.21	799.72	546.19	362.64	231.36	138.12	71.70	23.68	-12.20	-41.38
EMS		34.4489	25,3535	18.3542	13.1285	9.3241	6.6419	4.8023	3.5878	2.8179
BS		-2128.43	-1355.32	-830.38	-490.71	-281.45	-160.77	-96 - 38	-66-02	-54.47



TES 61.7852 53.4571 45.2419 37.3772 30.1868 24.2048 20.0696 18.4305 19.3296

P EFFLUENT CANAL TEMPERATURES!

TP1 = 63.51TPIN = 22.32 TP2 = 36.16

THE EVAPORATION IN P EFFLUENT CANAL, EP2 = 0.007143

PAR POND TEMPERATURES

TI = 35.5748TX = 36.1591

TIUP = 28.3989

TDP = 24.7670

TPAR = 22.7075

TD = 24.3550

PERTINENT FLOWS ARE FRAIN = 0.005307

AND FUP = 0.577027

THE RATE OF CHANGE IN HEAT CONTENT OF POND, HC = 5.6719

THE EQUILIBRIUM TEMPERATURES OVER SEGMENTS OF LANGHAARS COOLING PATE CURVE ARE AS FOLLOWS FOR PAR POND!

DEGREES C TEP

95.00 62.7243 54.6525 46.7847 39.3915

32.8452 27.7423

24.8074 24.7372 27.6600

THE EVAPORATION FROM PAR POND, EOP = 0.011929

THE WATER BALANCE FOR PAR POND IS AS FOLLOWS!

WATER IN

MAKEUP FROM RIVER, FRIV =

0.016800

RUNOFF FROM PAINFALL, FRUN = 0.014382

SUBTOTAL

0.031182

WATER OUT

EVAPORATION, EPAR =

0.019073

SEEPAGE LOSS, FSEEP =

0.002800

OVERFLOW AT DAM, FDAM =

0.009309

SUBTOTAL

0.031182

THE OVERFLOW FROM PAP CAM REACHES THE RIVER VIA LOWER THREE RUNS AT TRP = 25.71 THE EVAPORATION IN LOWER THREE RUNS BELOW PAR DAM, ELSR = 0.000564

# LIMN Printout 3

IR	ΙP	IL	ΙK	IC		
0	O	1	1	1		
PR	PP	PL	PK	PC		
0.	0.	2062.	1494.	2256.		
FR	FP	FPAR		FSEEP	FFF	
0.0	0.0	0.0	0.0		0.0	
FL	FK	FC				
0.173000	0.185000	0.181000	)			
TR IV	Ŧ1	ÐTG				
24.20	0.0	0.0				
TAIR	TWB	PAIR	W	НS	R	Đ
27.30	24.30	21.200	6.0	39.00	0.0	1.0000
U	Z	н	FFR	f FA	FFC	
0.0	0.0	9.0	0.0	0.0	0.0	

OUT PUT

LANGHAARS COOLING RATE CURVE FOR OPEN CONDITIONS!

DEGREES C	95.00	85.00	75.00	65.00	55.00	45.00	35.33	25.00	15.00	5.00
нт	1768.52	1220.94	818.89	528.82	322.36	176.78	74.11	0.87	-52.93	-94.42
EM		54.7582	40.2055	29.0067	20.6456	14.5585	10.2671	7.3237	5.3804	4.1487
8		-3433.50	-2196.53	-1356.62	-813.14	-478.36	-285.24	-182.22	-133.64	-115,16
TE		63.4152	55.6025	48,1136	41.2749	35.5363	31.5896	30.2064	32.0867	37.1598

LANGHAARS COOLING RATE CURVE FOR SWAMP CONDITIONS!



DEGREES C	95.00	85.00	75.00	65.00	55.00	45.00	35.00	25.00	15.00	5.00
HTS	1120.56	776.07	522.54	338.99	207.71	114.47	48.)5	0.03	-35.85	-64+03
EMS		34 • 4489	25.3535	18.3542	13.1285	9.3241	6.6419	4.8023	3.5878	2.8179
BS		-2152.09	-1378.98	-854.03	-514.36	-305.11	-184.42	-120.03	-89.67	-78.12
TES		62-4718	54.3900	46.5304	39.1787	32.7233	27.7657	24.9945	24.9927	27.7226

THE C EFFLUENT CW TEMPERATURES ARE AS FOLLOWS!

TC1 = 71.49 TC2 = 44.03 TC3 = 31.06 TC4 = 35.93

THE MIXED TEMPERATURE OF THE TWO DETLET STREAMS AT THE RIVER FOR FOUR MILE CREEK, FROM C REACTOR, IS TC = 34.58

THE EVAPORATION IN FOUR MILE CREEK, FROM C REACTOR, IS EC = 0.009505

THE K EFFLUENT CW TEMPERATURES ARE AS FOLLOWS!

TK1 = 54.84 TK2 = 48.50 TK3 = 29.40

THE L EFFLUENT ON TEMPERATURES ARE AS FOLLOWS!

TL1 = 69.42 TL2 = 52.86 TL3 = 33.56 TL4 = 38.27

THE TEMPERATURES IN STEEL CREEK NEAP THE RIVER ARE AS FOLLOWS.

TKL1 = 31.56 TKL2 = 34.43 TKL3 = 33.89 TKL = 32.40

THE TEMPERATURE OF STEEL CREEK OUTLET AT THE RIVER, FROM K AND L REACTORS, IS TKL = 32.40

THE EVAPORATION IN PEN BRANCH AND STEEL CREEKS, FROM K AND L REACTORS, IS EKL = 0.013187

# LIMN Printout 4

INPUT						
IR O	IP O	IL 1	1 K 1	. IC 1		
PR 0•	PP 0.	PL 2100 •	PK 2100.	PC 2250•		
FR O.C	0.0	6.0		FSEEP	FFF C.O	
FL 0.180000	FK 0.180000	0.180				
TRIV 27.80	T1 0.0	DTG 0.0				
TAIR 30.90	TWB 25.60	PAIP 21.780	₩ 3.8	HS 60.00	R 0•0	D 1.9900
0.0	0 • 0	0.0	FFR D.O	FFA C.C	FFC C•9	
JUTPUT						

### LANGHAARS COOLING RATE CURVE FOR OPEN CONDITIONS!

DEGREES C	95.00	85.30	75.00	65.00	55.00	45.00	35.00	25.00	15.00	5.00
нт	1521.51	1048.40	700.80	449.79	270.90	144.50	55.13	-8.87	-56.10	-92.70 <sup>'</sup>
EM		47.3114	34.7598	25.1008	17.8893	12.6392	8.9379	6.3992	4.7231	3.6607
В		-2973.08	-1976 -18	-1181.77	-713.01	-424.26	-257.70	-168.84	-126.94	-111.51
TE		64.1087	56.5649	49.4711	43.2110	38.3141	35.5453	35.7616	39.5805	46.7140



#### LANGHAARS COOLING RATE CURVE FOR SWAMP CONDITIONS!

DEGREES C	95.00	85.00	75.00	65.00	55.00	45.00	35.00	25.00	15.00	5.00
нтѕ	1113.13	768.65	515.11	331.57	200.28	107.04	40.62	-7.40	-43.28	-71.46
EMS		34.4489	25.3535	18.3542	13.1285	9.3241	6.6419	4.8023	3.5878	2.8179
BS		-2159.51	-1386.40	-861.46	-521.78	-312.54	-191.84	-127 -46	-97.09	-85.55
TES		62.6873	54.6828	46.9351	39.7443	33.5197	28.8837	26.5407	27.3623	30.3577

THE C EFFLUENT ON TEMPERATURES ARE AS FOLLOWS!

TC1 = 75.22

TC2 = 48.30

TC3 = 29.77

TC4 = 38.53

THE MIXED TEMPERATURE OF THE TWO OUTLET STREAMS AT THE RIVER FOR FOUR MILE CREEK, FROM C REACTOR, IS TO = 36.11

THE EVAPORATION IN FOUR MILE CREEK, FROM C REACTOR, 1S EC # 0.010464

THE K EFFLUENT CW TEMPERATURES ARE AS FOLLOWS!

TK1 = 72.06

TK2 = 60.42

TK3 = 29.12

THE L EFFLUENT CW TEMPERATURES ARE AS FOLLOWS!

TL1 = 72.06

TL2 = 56.91

TL3 = 35.62

TL4 = 40.72

THE TEMPERATURES IN STEEL CREEK NEAR THE RIVER ARE AS FOLLOWS!

TKL1 = 32.59

TKL2 = 36.13

TKL3 = 35.58

TKL = 33.50

THE TEMPERATURE OF STEEL CREEK OUTLET AT THE RIVER, FROM K AND L REACTORS, IS TKL = 33.50

THE EVAPORATION IN PEN BRANCH AND STEEL CREEKS, FROM K AND L REACTORS, IS EKL = 0.017415





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TL/jh

