GENERIC EMERGENCY COOLING POND ANALYSIS
Emergency Cooling Pond Analysis and the
Theoretical Basis of the GEPA
Computational Program

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I. INTRODUCTION

Emergency cooling ponds are intended to provide for the storage and dissipation of residual reactor heat during emergency shutdown conditions after the occurrence of a design basis accident (DBA), and/or for shutdown and cooldown in the event alternative water sources are not available.

Analysis of proposed pond designs is concerned with:

1. The adequacy of pond hydraulics and flow patterns to prevent short-circuiting particularly during initial reactor cooling phases.
2. The adequacy of the pond to handle multiple heat releases from both a DBA and a normal reactor shutdown and of pond surface area to provide for the dissipation of reactor heat.
3. The adequacy of the pond to provide for reasonable cooling water temperatures to the reactor cooling systems during a DBA or normal shutdown.
4. The adequacy of the pond volume and make-up water to provide ample supply to match all water losses.
5. The adequacy of the pond to perform under extreme meteorological conditions.

The basic objective of the emergency pond is to provide an adequate volume of cooling water at a reasonable temperature over a period of time to the reactor cooling systems such that the heat transfer capabilities of the reactor facilities provided for DBA cooling, will not be hindered.

Emergency cooling ponds are presently (1972) in the proposal stage and there is no field test basis for judging their adequacy. Preliminary plans indicate inconsistencies between designs of the relation between reactor size and emergency cooling pond geometries. From a design review basis, all of the characteristics of adequacy have neither yet been

identified, nor have all the design criteria been established and simulated. Numerous combinations of design and operation conditions including changing flows and heat rates, various recirculation piping arrangements, inlet-outlet schemes, addition of various cooling devices, pond geometries, and ambient meteorological conditions preclude simple analysis for all but the most elementary cases. It therefore has been necessary to develop a complex computational procedure to aid in the review of proposed designs and the development of criteria and guidelines.

Requirements of GEPA

Three overriding factors in the development of GEPA (Generic Emergency Pond Aalysis) have been:

1. To make the analysis sufficiently general that it could be applied to most conceivable cooling pond configurations, inlet-outlet configurations, and temporal regimes of flow, heat release, pond hydraulics and meteorological conditions.
2. To make data input requirements simple but consistent and complete between sites and between alternative configurations at a given site.
3. To provide flexibility for ease of modification as new theory develops particularly in relation to spray heat dissipators and inlet-outlet hydraulics.

It is specifically required that the analysis provide for:

1. Computation of ambient pond temperatures for varying meteorological conditions.
2. An analysis of the flow field at short time intervals and at numerous locations throughout the pond as the flow field develops.

3. Computation of temperature excess at short time intervals and numerous locations as the temperature field develops.
4. The inclusion of numerous inlets and outlets and all possible combinations of inlet-outlet connections, and to include non-heat source inflows and outflows.
5. Inclusion of wind shear as it drives pond circulation.
6. Inclusion of effects of inlet-outlet hydraulics incorporating various kinds of jets, weirs and other devices along with the ability to improve their formulations as knowledge increases of their role in driving the grid based computations.
7. Inclusion of spray and other heat dissipation devices as they influence the heat and flow distribution and the flexibility to improve the formulations as knowledge of their properties becomes available.

General Characteristics of GEPA

GEPA is divided into two parts based on the complexity of the analysis, the level of approximation required, and on the order in which results are needed in the numerous computations. The first part is METMIN standing for meteorological and minimum pond computations. The second part is HYETA standing for hydrodynamic and excess temperature aalysis and includes source-sink conditions for short-term computational steps. A third and basic analytic step, elementary analysis, is also presented in this documentation. The elementary and METMIN analyses are pedagogical, but represent a review procedure to screen sites for more detailed, costly, and time consuming analysis by HYETA.

METMIN carries out all the ambient meteorological computations, estimates

the pond temporal heat budget and water budget for the assumption of plug flow conditions, and provides estimates of various terms required in HYETA. METMIN is designed to run independently of HYETA and utilizes a minimum of pond geometry information including pond surface area, pond volume, and pond perimeter. The analysis assumes that all the reactor heat release is placed at one end of an ideal pond and no mixing takes place throughout the pond: that is the heat is moved through the pond with the flow in which it is introduced. METMIN provides for temporal changes in the reactor heat release and flow rate at a single source point in a format identical to that used in HYETA. METMIN also provides for the incorporation of heat loss and water loss from added heat dissipating devices.

METMIN outputs a summary table at desired times consisting of accumulated heat released to the pond, the amount of heat stored in the pond, the accumulated heat dissipated at the water surface plus that dissipated by any added devices, the accumulated waterloss including surface evaporation plus dissipation devices, windage and evaporative losses, the temperature into the ideal pond after dissipation of heat by any devices, and the outlet temperature from the pond to the reactor heat source. The temporal summary items presented in METMIN are identical to the items given by HYETA, although the results differ due to the order of approximation to physical reality. METMIN has sufficiently short computer running times and minimum input data requirements that it can be run efficiently as a separate program on a low speed remote access computer terminal.

METMIN temperature computations based on plug flow produces the lowest possible estimate of pond outlet temperatures for given heat and flow regimes. A cooling pond can perform no more efficiently than the results given in METMIN. Since plug flow is assumed, the time between start of a DBA and the beginning of recirculation of heat will be equal to the detention

time of the basin at a given flow rate. Basically, if a design is marginal based on the results of METMIN, its status will not be enhanced by analysis using HYETA.

HYETA incorporates the detailed hydrodynamic, temperature, heat budget and water budget computations at many points and for short time increments. It is based on the finite difference representation of the flow field from the two-dimensional time varying equations of fluid motion and continuity, and a finite difference representation of the temperature field from the two-dimensional time varying thermal transport equation with surface heat exchange. The time step of integration of these equations over a grid representation of the cooling pond is on the order of seconds. In HYETA an explicit integration scheme presented by Reid and Bodine (1968) is used to determine the flow field and limits the resolution of both the time and spatial grid steps to the gravity wave stability criterion.

HYETA data input requires initial designation of pond depths on a grid overlay and specification of flow and heat release source-sink information only at grid points where they apply; boundary conditions and initialization is computed internally for the non source-sink and boundary grid points. HYETA has been run at grid sizes of 20 x 20 and has the capacity to handle larger grid sizes up to the capacity of the users' computer. A 20 x 20 grid size provides the resolution of spatial scale on a 15 acre pond to about 50 x 50 ft.

HYETA incorporates the source-sink routine which at every time step assigns the flows and heat releases from the data to the proper pond inlets. Source-sink in turn calls the type of inlet and outlet subroutines to compute the changes in flow and heat as modified by sprays, jets, etc., before passing into the velocity-temperature computations. The type inlet and outlet subroutines are easily modified, replaced, or new types added as theory evolves.

Presently jets are incorporated as they influence the entrainment and exit velocities in a cell surrounding the outfall; the jet subroutine performs the empirical jet computations and passes the velocities, for the time increment, to source-sink which in turn passes them on to the main hydrodynamic and temperature excess computations.

HYETA's source-sink subroutine searches the specified outlet-inlet combinations to determine the recirculated heat passed to a given inlet of the pond. All possible combinations of outlet-inlets can be specified and depends on the piping plans from the pond outlet through the plant to the pond inlet.

HYETA provides the most detailed spatial and temporal resolution presently practical of the velocity field. It, therefore, computes the most realistic estimate of the temperature space-time distribution, whereas METMIN and any other elementary analyses are approximations. HYETA provides grid maps at specified time increments of the U and V vertically integrated fluid transport components, the pond depth, and the temperature excess for each spatial cell. HYETA provides a summary table giving at specified times the accumulated reactor heat added to the pond, the amount of heat in storage, the accumulated heat dissipated to the atmosphere from surface cooling and added devices, the accumulated water loss, and the time-temperature history of a number of points selected by the user.

HYETA requires lengthy computations requiring approximately ten minutes of computer time to simulate 72 hours of pond operation on a 20 x 20 grid with 100 foot grid spacing for a depth of 10 ft. The larger the grid spacing the shorter the running time. Also, the more complex the inlet-outlet scheme the longer the running time. The elements of HYETA are described in Section IV of this documentaion.

II. ELEMENTARY ANALYSES AND EXPECTED VALUES

Before initiating a detailed analysis of a proposed emergency cooling pond it is valuable to make elementary estimates of various parameters from basic considerations to judge the magnitude of the reactor heat release relative to the pond surface area and volume. Elementary analysis includes an estimate of the steady-state temperature excess required for heat dissipation, the corresponding estimate of the rate of evaporative water loss, an estimate of the time required to reach the steady-state temperature excess, and an estimate of temperature excess for a transient reactor heat release rate.

Estimate of Temperature Excess

The most elementary cooling pond temperature excess computation is for an assumed completely mixed recirculating pond. At steady-state the pond will reach a temperature excess where surface heat dissipation will balance the rate of reactor heat release. Since this condition will be reached slowly the reactor heat release rate should be approximated as the average value over a period of three to five days rather than at the peak value during a DBA or normal shutdown. The elementary heat balance gives the temperature excess at steady-state as:

$$\theta_{ss} = \frac{24 H_T (1 - F_{hl}/100)}{K SA} \quad (2.1)$$

where H_T = Average rate of reactor heat release, in Btu Hr⁻¹

F_{hl} = Percentage of heat loss attributable to sprays and other devices

K = Coefficient of surface heat exchange, in Btu Ft⁻² Day⁻¹ °F⁻¹

SA = Pond surface area, in Ft^2

θ_{ss} = Temperature excess, at steady state, in $^{\circ}\text{F}$

For 15 acres receiving $0.15 \times 10^9 \text{ Btu Hr}^{-1}$ of reactor heat being dissipated at a coefficient of surface heat exchange of $150 \text{ Btu Ft}^{-2} \text{ Day}^{-1} \text{ }^{\circ}\text{F}^{-1}$, with no added heat dissipation devices, the estimate of steady-state temperature excess is by equation (2.1) $\theta_{ss} = 37^{\circ}\text{F}$.

It is important to note that the temperature excess is directly proportional to the assumed constant rate of reactor heat release and inversally proportional to the pond surface area. The steady-state constant heat rate estimate of temperature excess can be interpreted as an upper limit that the transient temperature excess is approaching.

Estimate of Evaporative Water Loss

An estimate of the rate of evaporative water loss from the pond surface can be made from the temperature excess estimate as:

$$\text{TEWL} = \frac{(K-15.7) \beta \theta_{ss} \text{ SA}}{(0.26 + \beta) \rho \text{ Hvl}} \quad (2.2)$$

where β = Slope of vapor pressure-temperature relation, in $\text{mmHg}^{\circ}\text{F}^{-1}$ ($1.3 \text{ mmHg}^{\circ}\text{F}^{-1}$ at water temperatures of 100°F)

Hvl = Latent heat of vaporization, in BtuLb^{-1} (approximately 1000 BtuLb^{-1})

ρ = Specific weight of water, in LbFt^{-3} (62.4 LbFt^{-3})

TEWL = Evaporative water loss rate, in $\text{Ft}^3 \text{ Day}^{-1}$

For the above case the estimated evaporative water loss rate is $\text{TEWL} = 43,900 \text{ Ft}^3 \text{ Day}^{-1}$ or about $1.0 \text{ Acre-Ft Day}^{-1}$. The pond would be expected to loose about 0.70 ft of depth due to water surface evaporative loss over a period of ten days if no make-up water is provided.

The evaporative water loss for a completely mixed pond can be stated directly in terms of reactor heat release rate by substitution of equation (2.1) in equation (2.2) giving

$$TEWL = (1-15.7/K) \left(\frac{\beta}{0.26 + \beta} \right) \frac{24 H_r (1-PH1/100)}{\rho H_v l} \quad (2.3)$$

which indicates that basically the rate of evaporative water loss is proportional to the reactor heat release rate and independent of pond surface area at completely mixed conditions.

Temperature Excess Transient Analysis

The completely mixed pond assumption provides a basis for the estimation of transient conditions during the build-up of pond temperature excess. The transient heat balance of a completely mixed recirculating pond receiving a time varying reactor heat release of $H(t)$ is:

$$\rho c_p V_o \frac{d\theta}{dt} + K SA \theta = H(t) \quad (2.4)$$

where V_o = pond volume, in Ft^3

θ = temperature excess, in $^{\circ}\text{F}$

$\frac{d\theta}{dt}$ = rate of change of temperature excess in fully mixed pond, in $^{\circ}\text{F Day}^{-1}$

$H(t)$ = reactor heat release rate, in Btu Day^{-1}

c_p = specific heat of water, in $\text{Btu Lb}^{-1} ^{\circ}\text{F}^{-1}$ (generally taken as $1.0 \text{ Btu Lb}^{-1} ^{\circ}\text{F}^{-1}$ for fresh water)

and other terms as previously defined. The first term in equation (2.4) represents the rate at which heat is stored in the pond and the second term represents the surface heat dissipation.

If $H(t)$ is taken at a constant average value such as used in the estimate of θ_{ss} then the temperature excess as a function of time becomes:

$$\theta = \theta_{ss} [1 - \exp(-\frac{K SA t}{\rho c_p V_o})] \quad (2.5)$$

Defining the time to thermal steady-state, t_{ss} , as the time required for the temperature excess to reach 90% of its steady-state value, equation 2.5 gives:

$$t_{ss} = 2.3 \rho c_p \frac{V_o}{K SA} \quad (2.6)$$

where: t_{ss} = Time to steady state, in Days

The time to steady-state is directly proportional to pond volume and inversely proportional to pond surface area. For a pond with a surface of 15 acres and a volume of 150 Acre-Ft the time to steady state is $t_{ss} = 9.55$ days.

A slightly more realistic evaluation of the time varying temperature excess results from considering the reactor heat release rate to decay exponentially with time as:

$$H(t) = H_o e^{-a t} \quad (2.7)$$

where: a = decay rate from data, in Day^{-1}

H_o = initial heat rejection rate, in Btu Day^{-1} .

which when placed in the transient heat budget, equation (2.4), gives the time varying temperature excess as:

$$\theta(t) = \frac{H_o}{K SA - \rho c_p V_o a} [\exp(-at) - \exp(-\frac{K SA t}{\rho c_p V_o})] \quad (2.8)$$

Equation (2.8) shows that the temperature excess will increase with time then decrease in response to the decaying heat release rate. The time to maximum temperature excess (t_{max}) is found from equation (2.9) to be:

$$t_{max} = \frac{\rho c_p V_o}{K SA - \rho c_p V_o a} \ln[\frac{K SA}{\rho c_p V_o a}] \quad (2.9)$$

For the example case with $SA = 15$ acres, $V_0 = 150$ Acre-Ft, $K = 150$ Btu Ft⁻² Day⁻¹ °F⁻¹, and a reactor heat decay rate of $a = 0.69$ Day⁻¹ (the rate of the reactor heat release decreasing to one-half its value in one day) the time to maximum temperature excess is $t_{max} = 2.2$ days. For an initial heat release rate of $H_0 = 0.25 \times 10^9$ Btu Hr⁻¹, which gives a 3 day average heat release rate of 0.15×10^9 Btu Hr⁻¹ at $a = 0.69$ day⁻¹, the peak temperature excess is from equation (2.8) $\theta_{max} = 12.5$ °F, which is less than the steady-state temperature excess based on the comparable average rate of heat release computed in equation (2.1).

The time to maximum temperature, t_{max} , gives a basis for judging the assumption of a completely mixed pond as assumed in these elementary computations by comparison to the average detention time (Volume/Flow rate) of the basin. The detention time is a measure of the time required to provide complete mixing. If t_{max} is less than detention time it would be expected that the peak temperature excess is less than θ_{max} and the emergency cooling operation would take place at lower temperature excess for a longer period of time. If t_{max} is greater than the average detention time it would be expected that the fully mixed pond assumption is approached by the pond.

Results of Elementary Analysis Procedure

The experienced analyst needs no warning concerning the validity of elementary computations in preliminary stages; the results can only be indicative of what to expect from more detailed analyses. The completely mixed pond assumption is an artifact that provides elementary analytic procedures for preliminary judgement and it would be pedantic to justify them any further. It can be realistically assumed, however, that if a case is

marginal when tested by the elementary relations it will have difficulty meeting requirements that can be examined by the detailed hydrodynamic-thermal analysis provided by HYETA.

The fundamental facts of surface cooling are illustrated by the elementary analysis. Surface cooling is a long-term process taking place over many days. The pond stores the heat and temperature excess builds up over a period of time to the level where surface dissipation will balance the reactor heat release. Within the initial period of pond operation hydraulic short-circuiting may build up pond outlet temperatures at a much more rapid rate than indicated by the elementary heat budget analysis and may persist throughout the use of the pond. It is this initial period that is of foremost concern.

III. THEORETICAL BASIS OF METEOROLOGICAL AMBIENT WATER TEMPERATURE COMPUTATIONS AND MINIMUM EXCESS TEMPERATURE ANALYSIS

The time varying ambient pond temperature responding to changing meteorological conditions is evaluated in the METMIN routine. Also included in METMIN is an estimate of temperature excess due to the added heat based on plug flow conditions and utilizing a minimum of pond geometry and flow information.

METMIN is designed to run independently of HYETA and provides valuable information for the operation of the latter. If METMIN, for example, indicates severe water losses, the depths in HYETA would be similarly effected and would eventually terminate a run unless a makeup source of sufficient volume is specified. METMIN will indicate the range of temperature excess to be expected throughout the HYETA simulation. METMIN also provides estimates of the maximum ambient pond temperature and the thermal turbulent diffusivities for use in HYETA.

Definition of Ambient Temperature and Temperature Excess

Determination of temperature due to added heat sources is based on the fact that the temperature can be separated into an ambient temperature resulting from meteorological conditions and a temperature excess resulting from the advection, mixing and dissipation of an additional heat source. These definitions are based on the heat transport equation and have been derived in detail by Edinger (1971). The definitions can be illustrated from simple heat budget analysis. Let T be the temperature of the pond resulting only from heat exchange due to meteorological conditions; the temporal and spatial heat budget then is;

$$\rho c_p D \frac{dT}{dt} + K(T - T_e) = 0 \quad (3.1)$$

where D = depth of water column, Ft.

T_e = the equilibrium temperature derived from surface heat exchange principles (Edinger and Geyer, 1965), in $^{\circ}\text{F}$.

and where the total derivative $\frac{dT}{dt}$ can be interpreted as including the local temperature change with time, and the local advective and dispersive terms. The ambient temperature is defined by equation (3.1) as being the water temperature that responds to the equilibrium temperature; ambient temperature will lag equilibrium temperature and have a much smaller diurnal amplitude.

Let $T+\theta$ be the temperature of the pond resulting from the addition of heat, HA , as well as from the meteorological conditions and let θ be called the temperature excess. The total heat budget of the pond is therefore,

$$\rho c_p D \frac{d(T+\theta)}{dt} + K[(T+\theta) - T_e] = HA \quad (3.2)$$

where again the total derivative can be interpreted as incorporating the local spatial and temporal variations of temperature. Simply subtracting the ambient temperature heat budget, equation (3.1), from the heat budget with heat additions, equation (3.2), results in the temperature excess as:

$$\rho c_p D \frac{d\theta}{dt} + K\theta = HA \quad (3.3)$$

Thus temperature excess can be evaluated independently of the extensive meteorological data and computations required to determine ambient temperature, and one only needs the meteorological data for an estimate of the coefficient of surface heat exchange, K .

Computation of Ambient Temperature

The ambient temperature is defined by equation (3.1) as the temperature of the pond without the reactor heat release and resulting from the response of the pond to atmospheric heating and cooling. The ambient temperature can be computed to the detail with which the meteorological data is specified.

METMIN provides for two levels of ambient temperature computation from meteorological data, each dependent on the amount of data available to the user:

1. Partial meteorological data including the ambient pond temperature, an air temperature, a dewpoint temperature, and a wind speed for surface cooling. For the minimum data it computes the water vapor pressure-temperature relationship and the coefficient of surface heat exchange.
2. Detailed meteorological data including noontime shortwave solar radiation intensity, daily max and min air temperature and dewpoint temperature, and surface cooling wind speed. For each time period it computes the water vapor pressure-temperature relationship, the coefficient of surface heat exchange, the mean daily ambient pond temperature, and the hourly ambient pond temperature as it responds to the equilibrium temperature throughout the day.

Detailed evaluation of the ambient pond temperature begins from equation (3.1), with an evaluation of the equilibrium temperature, T_e . The equilibrium temperature, T_e , and the coefficient of surface heat exchange, K , are parameters formulated from the basic heat exchange processes of shortwave solar radiation, atmospheric long wave radiation, and reflected radiation in balance with long wave back radiation, evaporation and conduction from the water surface (Edinger and Geyer, 1965).

Using methods of Brady, et al (1969) it can be shown that the mean daily equilibrium temperature, T_{em} is:

$$T_{em} = \frac{H_{sm}}{K} + \frac{0.26 T_{am} + \beta T_{dm}}{0.26 + \beta} \quad (3.4)$$

where

T_{em} = Mean daily equilibrium temperature, in $^{\circ}F$.

H_{sm} = Mean daily short wave solar radiation, in $Btu Ft^{-2} Day^{-1}$.

T_{am} = Mean daily air temperature, in $^{\circ}F$.

T_{dm} = Mean daily dew point temperature, in $^{\circ}F$.

0.26 = Constant from Bowen Ratio, in $mmHg/^{\circ}F$.

β = Slope of vapor pressure temperature relation, in $mmHg/^{\circ}F$.

Within a daily period, the equilibrium temperature will have a maximum value that occurs at noontime and is approximately:

$$T_{emax} = \frac{H_{smax}}{K} + T_{dmax} \quad (3.5)$$

and a minimum value occurring at night given approximately as:

$$T_{emin} = T_{dmin} \quad (3.6)$$

Thus the diurnal equilibrium temperature, ETA, is presumed to have a mean value given by equation (3.4) and an amplitude given by equation (3.5) minus equation (3.6) as:

$$ETA = \frac{H_{smax}}{K} + T_{dmax} - T_{dmin} \quad (3.7)$$

where: ETA = equilibrium temperature diurnal amplitude, in $^{\circ}F$.

It is further assumed that within a diurnal period the hourly variation of equilibrium temperature is represented by the simple sinusoidal function:

$$T_e(t) = T_{em} - \frac{1}{2} ETA(\cos wt) \quad (3.8)$$

where w is the diurnal frequency of the equilibrium temperature variation per hour, and t is day-hours measured from midnight.

Evaluation of the ambient temperature in response to a sinusoidal diurnal equilibrium temperature from equation (3.1) is discussed in Edinger, et al (1968). It is shown that for steady meteorological variations over a number of days the mean daily ambient pond temperature is equal to the mean daily equilibrium temperature, equation (3.4), and the amplitude of the daily variation in ambient pond temperature, PTA, is related to the equilibrium temperature amplitude as:

$$PTA = \frac{ETA}{\sqrt{1 + (24w\rho c_p D/K)^2}}^{1/2} \quad (3.9)$$

and the time lag from noontime to the daily maximum ambient temperature is:

$$\Delta t_{max} = \frac{24}{2\pi} \tan^{-1}[w\rho c_p D/K] \quad (3.10)$$

The ambient temperature response to equilibrium temperature and its implied sinusoidal diurnal variation provides a convenient method of determining the hourly variation in ambient temperature without tabulating hour by hour meteorological data and without resort to an elaborate numerical computation based on equation (3.1).

In METMIN the detailed meteorological data inputs of H_{smax} , T_{amax} , T_{amin} , T_{dmax} , T_{dmin} and the cooling windspeed can be specified as often as

every twenty-four hours, or as infrequently as once for the whole simulation. In the former case, the mean daily equilibrium temperature is assumed to be linear between periods of differing meteorological data. The assumption that the mean daily pond ambient temperature is equal to the mean daily equilibrium temperature causes a slight underestimation of mean daily pond ambient temperature during periods of decreasing equilibrium temperature, as occurs during the fall months, and a slight overestimation of pond daily ambient temperature during periods of increasing equilibrium temperature, as occurs during the spring months.

Additional assumptions in METMIN for the evaluation of hourly ambient pond temperatures include the approximations that the mean daily air temperature required in equation (3.4) is equal to the average of the daily max and min values of air temperature, similarly for the dew point temperatures, and that the mean daily short wave solar radiation, H_{sm} , is equal to one-third the maximum noontime shortwave solar radiation rate*. It is further assumed in the evaluation of the diurnal properties of the equilibrium temperature (equations (3.4), (3.5), and (3.6)) that the coefficient of surface heat exchange is constant throughout the day at its mean daily value. This latter assumption overestimates the maximum daily value of equilibrium temperature and underestimates the minimum daily value of the equilibrium temperature, but as noted from equation (3.9), the ambient temperature amplitude is of the order of one-tenth of the equilibrium temperature amplitude. Computation of the equilibrium temperature amplitude to within 5 °F, therefore, provides an estimate of the ambient temperature amplitude to within 0.5 °F and is of the order of accuracy that might be achieved by hourly specification of the meteorological data.

*The relationship between mean daily short-wave radiation is based on a parabolic distribution of short-wave radiation from sunrise to sunset. Mean daily short-wave solar radiation is available in climatological atlases and the relationship can be used to obtain maximum noontime solar radiation required in METMIN.

Coefficient of Surface Heat Exchange

The coefficient of surface heat exchange is a parameter derived from the basic surface heat exchange processes. It is primarily a function of cooling windspeed as it influences the evaporation and heat conduction rates at the water surface. The most recent and detailed evaluation of the coefficient of surface heat exchange is reported by Brady, et al. (1969).

The most general form of the coefficient of surface heat exchange is:

$$K = 15.7 + (0.26 + \beta) f(W), \text{ in Btu Ft}^{-2} \text{ Day}^{-1} \text{ } ^\circ\text{F}^{-1} \quad (3.11)$$

where the constant term 15.7 is determined from the Boltzmann constant and other radiation parameters; the constant term 0.26 is determined from the Bowen ratio of heat transfer by conduction to evaporation; and β is the slope of the relationship between saturation vapor pressure and water temperature required in the evaporative component of surface heat exchange. The wind speed function $f(W)$ is determined from the particular formula used to evaluate evaporation, of which there are many. Empirically, the cooling wind speed is evaluated at a standard height of 18 feet above the water surface. Estimates of the cooling windspeed may require a reduction from this value to account for wind shading due to pond berms, embankments, baffles and buildings, or for wind speed estimates at other locations and/or elevations.

The particular wind speed function and method of evaluation chosen for METMIN is that proposed by Brady, et al (1969) where:

$$f(W) = 70.0 + 0.70 W^2 \quad (3.12)$$

for W in mph at the unobstructed 18 foot level, and where the vapor pressure slope is evaluated from the fitted curve to physical data of Brady, et al (1969) as:

$$\beta = 0.255 - 0.0085 T_{\beta} + 0.000204 T_{\beta}^2 \quad (3.13)$$

and where T_{β} is evaluated as:

$$T_{\beta} = (T_g + T_d)/2 \quad (3.14)$$

where T_g is the water surface temperature in $^{\circ}\text{F}$ and T_d is the dewpoint temperature in $^{\circ}\text{F}$.

Comparing equations (3.4), (3.11), (3.12), (3.13), and (3.14) it is seen that precise evaluation of the coefficient of surface heat exchange and ambient pond temperature is an iterative process. Knowing H_{sm} , T_{am} , T_{dm} , and $f(W)$ for a given day requires that T_{β} be first evaluated from equation (3.14) for an assumed value of T_g , that β be computed from equation (3.13), then K estimated from equation (3.11) for placement in equation (3.4) to give an estimate of T_m for comparison to the originally assumed T_g . The iterative process is carried out in METMIN for each set of detailed meteorological data until the desired level of accuracy is attained for the estimate of T_g and consequently the estimate of β and K . This procedure is eliminated in METMIN for partial meteorological data where the value of the ambient temperature must be specified in any event. The iterative procedure for evaluation of β and K is eliminated in HYETA by specification of the pond maximum ambient temperature and dew point temperature. This overestimates the values of β and K from those at daily ambient conditions, but compensates for any further change required due to the temperature excess during a detailed HYETA simulation.

METMIN Evaluation of Pond Temperature Excess

METMIN is designed to present the most information about a pond per-

formance from the least amount of input data. The pond temperature excess and consequently the pond heat and water budget is estimated by the plug flow heat budget derived from equation (3.3) by Edinger and Geyer (1965) as :

$$D \frac{\partial \theta}{\partial t} + Q \frac{\partial \theta}{\partial A} + \frac{K\theta}{\rho c_p} = 0 \quad (3.15)$$

where

$\frac{\partial \theta}{\partial t}$ = The spatially local change in temperature excess with time, in $^{\circ}\text{F Day}^{-1}$.

$\frac{\partial \theta}{\partial A}$ = The change in temperature excess with pond surface area, in $^{\circ}\text{F Ft}^{-2}$.

Q = The flow rate through the pond as a function of time, in $\text{Ft}^3 \text{Day}^{-1}$.

D = Pond depth, Ft.

Equation (3.15) is rewritten in a suitable finite difference form for iteration of temperature excess at equal segments of pond surface area and for each hourly time step. The derivation of the difference form used in METMIN for equation (3.15) is given in Appendix A. The pond outlet and inlet temperatures are coupled through the computation of recirculated heat and reactor heat release at each time step. It is assumed that the inlet heat is reduced by any heat dissipation devices before entering the pond. The flow and heat regimes at different times are specified from the design data.

The plug flow heat balance basically assumes that the pond is rectangular in shape with a surface area, volume, and perimeter of the prototype. It is assumed that all the heat and flow are let into one end of the ideal pond and removed at the other end for recirculation through the heat source. Plug flow assumes that any change in flow regime, Q , is instantaneously established over the pond, and that heat is simply advected

through the pond with the flow and with no mixing between adjacent pond segments.

The coefficient of surface heat exchange is assumed constant over the simulation period of temperature excess and equal to the average of the values computed for different periods of ambient meteorological conditions. This assumption is justified by the fact that dissipation of excess heat is a long term process and not greatly influenced by short term variations in the coefficient of surface heat exchange.

METMIN temperature excess computations are only as accurate as the assumption of plug flow with no mixing and are only as precise as the size of the time step between iterations and the number of segments into which the pond is divided. The heat at the inlet reaches the outlet in a time equivalent to the detention time of the pond and temperature excess decays in an exponential manner as the heat moves through the pond. Most of the heat is stored at the inlet end of the pond where temperature excess is highest.

Since hydraulic short-circuiting between the pond inlet and outlet does not exist for a plug flow pond, and since the total surface area of the pond is assumed effective for heat dissipation, the METMIN analysis will produce the lowest possible estimate of pond outlet temperatures as a function of time. Comparison of the METMIN results with those from the more detailed HYETA estimates of temperature excess gives a measure of the emergency cooling pond efficiency as it relates to hydraulic short-circuiting and recirculation.

Heat and Water Budget Summations

The reactor heat released will be stored in the pond and dissipated to the atmosphere. The cumulative reactor heat released is equal to the

heat in storage at any instant plus the accumulated heat dissipated to the atmosphere and minus any heat advected out of the pond that does not recirculate. Advective inflows and outflows of the latter type are not accounted for in METMIN.

The accumulated reactor heat, AHR, related up to any time after a DBA is simply:

$$AHR = \int_0^t H_r(t) dt \quad (3.16)$$

and is evaluated from the specified heat regime functions.

The heat in storage in the pond at any time is:

$$HIS = \rho c_p D \int_0^{SA} \theta(A, t) dA \quad (3.17)$$

where: A = Surface area along the pond, in Ft^2

SA = Total pond surface area, in Ft^2

and is accumulated over the surface area iteration of temperature excess.

It is recomputed for the new values of temperature excess at each time step.

The heat dissipated to the atmosphere has two components; The first accounting for surface heat dissipation to the atmosphere and the second accounting for heat dissipated by any dissipation devices. The accumulated heat dissipated, AHD, is:

$$AHD = \int_0^t [K \int_0^{SA} \theta(A, t) dA + (H_r(t) + \rho c_p Q \theta(t)_{out}) (Phl/100)] dt \quad (3.18)$$

where the first term inside the time step integration is the surface heat dissipation and the second term is the heat dissipated at any device at a specified Phl or percentage heat loss due to the device. This assumes heat dissipated is a function of pond surface area. For sprays, the surface area under the sprays may be assumed not to be dissipating heat and may be subtracted.

The second term in equation (3.18) includes reactor heat plus recirculated heat above the ambient temperature conditions. Presently valid data is not available for detailed evaluation of Phl which should be a function of the ambient meteorological conditions, the flow rate to the device, the heat rate to the device, and other characteristics. When such relationships become available, the METMIN and HYETA programs are easily modified to incorporate them.

Total water loss from the pond consists of three components: evaporative water loss at the temperature excess, natural evaporative water loss at the ambient pond temperature, and water loss due to any cooling device. The natural and excess evaporative water loss are determined from the evaporative surface heat exchange component evaluated in terms of the coefficient of surface heat exchange given by Edinger and Geyer (1965) as:

$$TNEW = \frac{(K - 15.7) \beta (T_m - T_d) SA}{\rho (0.26 + \beta) Hvl} \quad (3.19)$$

and

$$TEEW = \frac{(K - 15.7) \beta}{(0.26 + \beta) Hvl} \int_0^{SA} g(A, t) dA \quad (3.20)$$

where: $TNEW$ = Natural evaporative water loss rate at ambient temperature from total pond surface area, in $Ft^3 \text{ Day}^{-1}$
 $TEEW$ = Excess evaporative water loss rate at excess temperature for total pond surface area, in $Ft^3 \text{ Day}^{-1}$
 SA = Total surface area of the pond, in Ft^2
 Hvl = Latent heat of vaporization from liquid to water vapor, in $Btu \text{ Lb}^{-1}$

It is noted that $\beta(T_m - T_d)$ is an approximation to the difference between saturation vapor pressure at the water temperature and the atmospheric water vapor pressure. The linear approximation allows evaluation of these terms without performing the iterative process of determining the

temperature-vapor pressure relation from tabulated values.

The rate of water loss, SWL, at any device is evaluated simply as:

$$SWL = Q(DW1 + EW1)/100 \quad (3.21)$$

where Q is the flow rate, DW1 is the percentage of windage and drift loss and EW1 is the evaporative water loss at the device. Like Ph1, both DW1 and EW1 must presently be inexactly specified until they can be evaluated in terms of the physics of the dissipating device.

The accumulative total water loss, ATWL, up to time t after a DBA, or shutdown, is:

$$ATWL = \int_0^t (TNEW + TEEN + SWL) dt \quad (3.22)$$

It does not include an accounting of make-up water supply but gives the value which must be supplied to maintain the pond volume.

Each of the components of the cumulative heat and water budget are independently evaluated from their basic definitions and no attempt is made to compute one value as a residual from other values. This provides an external check on the rationality and accuracy of the computations being performed, which are directly related to the number of segments of pond surface area and inversely related to the size of the iterative time step.

HYETA Parameters from METMIN

METMIN provides the value of the maximum hourly ambient pond temperature for use in HYETA when complete meteorological data is available or is specified. It also provides an estimate of the thermal turbulent diffusivity for use in HYETA.

The thermal turbulent diffusivity for use in HYETA is estimated from the Taylor dispersion formula as modified by Elder (1959) for use in open channel computations. It is a function of flow velocity, depth, and the non-dimensional friction factor. The flow velocity is estimated from the maximum flow rate through the pond during any simulation, the pond volume divided by the flow rate equals the travel time, and the pond perimeter which gives a measure of the longitudinal distance through the pond.

The value of the turbulent diffusivity is compared to the Torrence (1963) stability criterion for the advective diffusive transport equation and provides an estimate of the grid spacing, DELTAS, required in HYETA for use of the Taylor open channel dispersion formula. As explained more fully in the description of HYETA, the Taylor dispersion coefficient usually requires an unreasonably small DELTAS to satisfy the Torrence condition and an empirical estimate of a value for the thermal diffusivity in terms of a predetermined DELTAS is given.

The coefficient of surface heat exchange is recomputed in HYETA, using the specified value of the maximum pond ambient temperature, dewpoint temperature, and wind speed desired for the HYETA temperature excess evaluation.

The METMIN Program

The METMIN program listing is given in Appendix B along with a user's guide specifying data input requirements and format. METMIN data input format and program logic is designed to be similar and parallel to the more complex HYETA program. A block diagram of the major steps in METMIN is given in Fig. 3.1.

METMIN requires the pond surface area, pond volume and pond perimeter. It requires a specification of the level of meteorological data input (0.0 if partial and 1.0 if complete) and the data itself. It requires an

estimate of Phl , Dwl , and Ewl which are all assumed equal to 0.0 if no dissipation devices are used. It also requires an estimate of the non-dimensional friction factor and maximum flow rate during pond operation for dispersion estimates.

The time step of all computations is pre-set for hourly integration and NAREA (the number of area segments) is pre-set at fifty. The print out time-step variable, NPRINT, is pre-set at unity for an hourly print out of results. These parameters can be changed by replacement of their statements. The total number of steps, NSTP, for the simulation must be specified.

The temporal regimes of flow rate and heat release rate are independently specified. The number of flow regimes (the number of periods with different flows) is first determined. Each flow regime is listed with its time on after DBA or shutdown and its flow rate. With the time step, DELT, set at one hour METMIN will not recognize changes in inflow rates at less than one hour intervals.

Each heat regime is listed with its time on after DBA and values of A and B determined from the heat regime equation:

$$H(t) = A_i + B_i \log_{10}(t), \quad t = \text{hours after DBA} \quad (3.23)$$

where: A_i = Intercept of heat decay function at hour one, in Btu Hr^{-1}
 B_i = Log slope of reactor heat release rate for i-th heat regime, in $\text{Btu Hr}^{-1} (\log_{10}\text{Hr})^{-1}$

Figure 5.2 shows a typical heat release function with a constant rate up to 3.0 hours after the DBA and in which $A_1 = 162 \times 10^6 \text{ Btu Hr}^{-1}$ and $B_1 = 0$. For the second, or log slope, time regime A_2 and B_2 are computed from equation (3.23) using two points as $H = 240 \times 10^6 \text{ Btu Hr}^{-1}$ when $t = 30$ hours

and $H = 133 \times 10^6 \text{ Btu Hr}^{-1}$ when $t = 50$ hours giving $A_2 = 270 \times 10^6 \text{ Btu Hr}^{-1}$ and $B_2 = 84 \times 10^6 \text{ Btu Hr}^{-1} (\log_{10} \text{Hr})^{-1}$. This means that the reactor heat release rate can be changing with time after a specified time-on within a given regime. Each heat regime thus represents a different set of A_i and B_i values.

Because of its size and simplicity, the METMIN program can be used to rapidly judge the influence of different sets of meteorological parameters as they affect heating, cooling, and ambient pond temperature at a given site. It can also be used to determine the influence of estimates of effective surface area at a given site without resorting to the detailed topography specifications in HYETA.

Fig. 3.1. Block Diagram of METMIN.

IV. THEORETICAL BASIS FOR THE HYDRODYNAMIC EXCESS TEMPERATURE ANALYSIS

The HYETA program for cooling pond analysis is based on an explicit integration of the two spatial dimension time varying hydrodynamic and continuity equations in a fixed grid at short time intervals. The temporal and spatial velocity components generated from the hydrodynamic equations are then utilized in an explicit integration of the two spatial dimension time varying heat transport equation with surface heat exchange. The thermal regime of any water body can be predicted in no more detail than that with which the velocity field is known. Generalization to different pond configurations is achieved through grid mapping.

HYETA incorporates the elaborate source-sink bookkeeping routine which allocates the heat and flow release to any number of pond inlets, determines the recirculation of heat between any combination of pond outlets and inlets, and has a separate set of subroutines for setting advective flow and heat rates and velocities at grid locations for various types of pond inlets and outlets including sprays and jets. Generalization of emergency cooling pond analysis to many different cases is primarily achieved through the source-sink subroutine

The Hydrodynamic Flow Relations

The present state of the art of numerical waterbody dynamic modeling is at the practical level of flow field computations in the two horizontal directions (Ward, 1971). Extension to predictions of waterbody velocity fields in three spatial dimensions is yet in the theoretical stages (Pritchard, 1971). It is possible to formulate three dimensional approximations for specific phenomenological representations of simple flow problems (Gurbert and Abbott, 1972). The general three dimensional time varying

problem requires complex formulation of initial and boundary conditions, and specialized computer operational techniques even for the most specific case (Brady, 1972).

The vertically integrated equations of fluid motion allow predicting the horizontal transport vectors in two dimensions defined for the coordinate system in Fig. 4.1 as:

$$U(x,y,t) = \int_0^D u(x,y,z,t) dz \quad (4.1a)$$

$$V(x,y,t) = \int_0^D v(x,y,z,t) dz \quad (4.1b)$$

which are the vertical integral of the horizontal velocity vectors in three coordinate directions. To this order of approximation, the two dimensional equations of motion represent "pseudo-three dimensional" flow. In the emergency cooling pond modeling problem, the source-sink specification allows empirical simulation of initial pond stratification, inlet hydraulic stratification, and other three-dimensional fluid flow phenomena as discussed later in this section.

Recent application of the vertically integrated hydrodynamic relations to specific waterbody problems have been made by Reid and Bedine (1968) to storm surges in Galveston Bay; by Stover, et al (1971) for modeling specific thermal discharges in Galveston Bay; by Leendertse (1967) for modeling the tidal and wind-driven hydrodynamics of Tokyo Bay, Haringvliet Pass (the North Sea) and at a later date, Jamaica Bay at Long Island; and by Masch, et al (1969) to estuarine tidal hydraulics. Jaske and Drew (1971) have used a non-generalized and phenomenological version of the hydrodynamic relations in cooling lake analysis for a particular case study.

Leendertse (1967) presents the most detailed analysis of the theoretical

Fig. 4.1. Definition sketch of spatial and velocity coordinates.

problems involved in numerically integrating the generalized two-dimensional hydrodynamic relationships. Even at this reduced spatial dimensionality the advective inertia terms present complex numerical problems of propagating truncation errors, generating spurious waves, and generating unstable solutions after long periods of integration particularly in explicit computational schemes, (Leendertse, 1971). The advective inertia terms are usually small in comparison with frictional momentum dissipation and the gravitational water surface slope driving force, but can be important in regions of temporal variations of the velocity field such as generated by tidal boundary conditions.

A priori elimination of the advective inertia terms in the generalized analysis of emergency cooling ponds is based on a number of considerations. First, the inlet and outlet flows are changing monotonically with time as compared to a tidal oscillation and the tendency of the pond flow field is to approach a steady-state condition. Second, at steady-state the major balance is between the gravity water surface slope and the frictional forces, which is equivalent to the normal flow condition in one-dimensional hydraulic analysis. Third, the major region of rapidly changing velocities is in the vicinity of a high momentum inlet or outlet and it is impractical to reduce the computational grid spacing to simulate the details of this flow region; rather it is handled empirically in a subroutine of source-sink for different types of jets as discussed later.

Derivation of the vertically integrated momentum and continuity relations from the three-dimensional equations of fluid motion is given in Appendix C. The two-dimensional time varying hydrodynamic relations with a priori elimination of the advective inertia terms are for x-momentum:

$$\frac{\partial U}{\partial t} + gD \frac{\partial H}{\partial x} = WX - fD^{-2}(U^2 + V^2)^{1/2} U \quad (4.2a)$$

For y-momentum:

$$\frac{\partial V}{\partial t} + gD \frac{\partial H}{\partial y} = WY - fD^{-2}(U^2 + V^2)^{1/2} V \quad (4.2b)$$

and for continuity:

$$\frac{\partial H}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = RN \quad (4.2c)$$

where:

U, V = Vertically integrated horizontal transport in the x- and y-directions. ($\text{Ft}^2 \text{Sec}^{-1}$ or flow per unit width in each direction)

H = Water surface level relative to a fixed datum, in Ft.

D = Water depth, in Ft.

f = Non-dimensional friction factor

RN = Net flow addition per unit surface area, in $\text{Ft}^3 \text{Sec}^{-1} \text{Ft}^{-2}$

WX, WY = x- and y-components of wind surface stress, in $\text{Ft}^2 \text{Sec}^{-2}$

Equations (4.2a), (4.2b), and (4.2c) present three equations in the three unknowns of U, V, and H to be solved at each point in time and space. In the momentum equations the first term is the spatially local fluid acceleration, the second term is the gravity water surface slope, the third term is the surface wind stress, and the last term is frictional momentum dissipation taken as a modified velocity-squared friction law. These equations are known formally as the long-wave approximations to the equations of fluid motion and for zero friction will reproduce harmonic pond oscillations.

It is readily seen in equation (4.2a) and (4.2c) that if $V=0$ the equations reduce to the one-dimensional time varying hydraulic equations, and that for steady-state conditions ($\partial U/\partial t = 0$) further reduce to the normal

flow equation of one-dimensional analysis. Ignoring the advective inertia terms eliminates the classical steady-non-uniform hydraulic flow relations and their numerous singularity solutions known as type backwater curves. The long-wave approximations therefore apply to sub-critical flows at short time steps approaching normal depth rather than methods using a specific backwater profile; this is rationalized for ponds on the basis that during transient conditions the inflows and outflows are monotonically increasing or decreasing and local acceleration of the flow field is more important than the steady-state water surface profile. The internal fluid field will oscillate during transient conditions in response to the surface gravity wave and its reflections.

The Heat Transport Relationship

The temporal and spatial distribution of any substance, including heat, throughout a waterbody can be predicted in no more detail or accuracy than the velocity field in that waterbody. Recent applications of general transport relationships are presented in Ward (1971) and specifically for heat by Edinger (1971).

The two-dimensional transport of excess heat through a waterbody is given by:

$$D \frac{\partial \theta}{\partial t} + \frac{\partial U\theta}{\partial x} + \frac{\partial V\theta}{\partial y} - D \frac{\partial E_x}{\partial x} \frac{\partial \theta}{\partial x} - D \frac{\partial E_y}{\partial y} \frac{\partial \theta}{\partial y} + \frac{K\theta}{\rho c_p} = \frac{H\theta}{\rho c_p} \quad (4.3)$$

where:

$\theta(x,y,t)$ = Temperature excess at x , y , and t , in $^{\circ}\text{F}$

U, V = Horizontal x - and y -fluid transports from the momentum and continuity relationships, in $\text{Ft}^2 \text{Sec}^{-1}$

D = Water column depth at each x , y , and t , in Ft

E_x = x -directional turbulent dispersion coefficient, in $\text{Ft}^2 \text{Sec}^{-1}$

E_y = y-directional turbulent dispersion coefficient, in $\text{Ft}^2 \text{Sec}^{-1}$

K = Coefficient of surface heat exchange, in $\text{Btu Ft}^{-2} \text{Sec}^{-1} \text{ } ^\circ\text{F}^{-1}$

HA = Net heat input per unit surface area by other than surface heat exchange processes, $\text{Btu Ft}^{-2} \text{Sec}^{-1}$

The first term in equation (4.3) is the temporal change in heat storage in a water column with unit surface area and depth D , the next two terms are the x- and y-advective heat transports, the fourth and fifth terms are the x- and y-turbulent fluxes of heat. The summation of the first five terms are represented in the definition of temperature excess, equation (3.3), by the total derivative d/dt . The sixth term is the net rate of surface heat exchange.

Use of the coefficient of surface heat exchange to summarize the water temperature dependent heat transfer processes of back radiation, evaporation and conduction is developed by Edinger and Geyer (1965) and Brady, et al (1969). This summary of the term by term heat exchange processes at each point in space and time leads to direct step by step time integration of equation (4.3) without resort to intrastep iterations, and provides a basis for investigation of the limits on stability and convergence of the numerical temperature excess integration.

Numerical Forms Used in HYETA

The equations of motion, continuity, and heat transport in two spatial dimensions and time constitute four equations for the evaluation of U , V , H , and θ . The need for generality in specifying boundary conditions, pond shapes, and the need for examination of transient conditions dictate numerical integration of these relationships. The difference forms of the equations of motion and continuity are given in Appendix C and of heat in Appendix D.

The numerical forms of the equations in HYETA are for integration over

a time step Δt :

$$UP(I,J) = \frac{U(I,J) + \frac{g\Delta t}{2\Delta s} (D(I,J) + D(I-1,J)) (H(I-1,J) - H(I,J)) + WX(I,J) \Delta t}{(1+f\Delta t(D(I-1,J)+D(I,J)))^{-2} ((4U(I,J))^2 + (V(I,J)+V(I-1,J)+V(I,J+1)+V(I-1,J+1))^2)^{1/2}} \quad (4.4a)$$

$$VP(I,J+1) = \frac{V(I,J+1) + \frac{g\Delta t}{2\Delta s} (D(I,J+1) + D(I,J)) (H(I,J) - H(I,J+1)) + WY(I,J+1) \Delta t}{(1+f\Delta t(D(I,J)+D(I,J+1)))^{-2} ((4V(I,J+1))^2 + (U(I,J)+U(I+1,J)+U(I,J+1)+U(I+1,J+1))^2)^{1/2}} \quad (4.4b)$$

$$HP(I,J) = H(I,J) + \frac{\Delta t}{\Delta s} (UP(I,J) - UP(I+1,J) + VP(I,J) - VP(I,J+1)) + RN(I,J) \Delta t \quad (4.4c)$$

$$TP(I,J) = T(I,J) \left(1 - \frac{\Delta t (U(I+1,J) + V(I,J+1))}{\Delta s D(I,J)} - \frac{4\Delta t E}{\Delta s^2} - \frac{\Delta t K}{\rho c_p D(I,J)} \right) + \frac{\Delta t}{\Delta s D(I,J)} (U(I,J) T(I-1,J) + V(I,J) T(I,J-1)) + \frac{\Delta t E}{\Delta s^2} (T(I-1,J) + T(I+1,J) + T(I,J-1) + T(I,J+1)) + \frac{\Delta t HA(I,J)}{\rho c_p D(I,J)} \quad (4.4d)$$

where UP, VP, HP and TP are the new values at time $t + \Delta t$ in terms of previously determined values. All terms are further defined in Appendices C and D.

The explicit numerical form of the equations of fluid motion and continuity presented in Appendix C are essentially the equations published by Reid and Bodine (1968). These were chosen in preference to the integration

forms presented by Leendertse (1967) which require elaborate averaging of the flow and depth results at each time step to filter out spurious waves from tidally generated boundary conditions, and which are not a feature of flow in a small pond. Application to ponds is simplified by the assumption that a cell (or grid point) would always be dry if initially specified; thus, wave run-up on dry land is ignored. The contrary that a cell will always contain water is also implied but is physically significant for the fact that if velocities into a region are so restricted that a withdrawal rate cannot be supplied, or if the depth goes to zero, the computation should be terminated.

The explicit scheme is used by Leendertse (1967), Reid and Bodine (1968), and Stover, et al (1971). The explicit scheme was chosen because its numerical integration properties are well known theoretically, its practical application has been demonstrated by various users including those referenced, and it is relatively easy to program and to generalize for any pond configuration that can be mapped onto a rectangular grid. Its major limitation is that the ratio of spatial grid size to integration time step is limited by the gravity wave criterion for computational stability and within this criterion numerical truncation errors build up over long integration times in proportion to the temporal and spatial integration steps. The former condition produces small time steps for small specified grid spacing but small grid spacing limits truncation error, thus there is a payoff between the limitations on time step size and the pond requirements of small grid size.

Problems of recasting the advective-diffusive heat transport relation into a proper differencing form and its resulting stability and convergence properties are still being found (Torrence, 1968; Leendertse, 1971). The particular form used is compatible with the spatial predictions of the

flow field given by the equations of motion. The limits on stability and convergence are determined by examining the relationship between the time step, Δt , the spatial step, Δs , and the values of U , V , E , and K , and are discussed in the next section.

Integration in HYETA proceeds from a pond initially at rest, having $RN(I,J)$, $HA(I,J)$ and boundary velocities set by source-sink for the Δt increment and then computation of $TP(I,J)$, $HP(I,J)$, $UP(I,J)$, and $VP(I,J)$ is performed at each grid point. The new values are stored and the source-sink subroutine updates the net heat and flow additions and changes in boundary values for the next integration. The resulting values represent averages over a spatial $\Delta s \times \Delta s$ cell at the end of each time step.

Stability, Convergence, and Testing

Numerical forms of the basic partial differential equations of fluid motion and mass and heat transport must be stable to any perturbations, must continually converge to known analytic solutions, and must preserve continuity of mass, momentum and heat over the external boundaries of the solution. There is no practical a priori method of deriving differencing forms that will satisfy pre-stated conditions of a particular problem. Past experience with various differencing forms serve as a guide but each set of relations must be examined and tested for stability, convergence, and continuity properties.

The stability criterion for the explicit numerical form of the combined long-wave equations of motion and continuity is well known and has been restated by various users. It is that:

$$\frac{\Delta s}{\Delta t} \geq \sqrt{g D_{\max}} \quad (4.5)$$

where: $D_{\max}$ = Maximum pond depth expected in the simulation, in Ft.

*Other authors use $\sqrt{2g D_{\max}}$ - See Appendix E.

which has the physical interpretation that the spatial distance must be greater than the transit of the free surface gravity wave in time Δt . For a ten foot deep pond represented by a fifty foot grid spacing, the integration time steps must be less than 2.8 seconds, and a simulation period of ten days requires 300,000 iterations of the equations at each grid point. The explicit forms of the equations of motion and continuity for application to small ponds with fine spatial resolution are approaching the limits of computational economics.

The stability and convergence criterion on the advective dispersive heat transport relation can be demonstrated heuristically by examining the group of terms multiplying $T(I,J)$ in equation (4.4d) and considering the integration over Δt from $T(I,J)$ to $TP(I,J)$ as a simple first order relation in time. The multiplier terms must sum to a value greater than zero, that is be non-negative, to prevent the new values from changing algebraic sign and oscillating between positive and negative values on successive iterations. The only term that could physically change algebraic sign between iterations is the second or advective term. Also, the sum of terms should be less than unity to prevent the solution from numerically growing exponentially with time, that is becoming unstable, but not so much less than unity that long iteration times are required for the temperature to converge to a known solution. Empirically the first condition can be satisfied by requiring each term to be less than a preset value, say $1/4$, giving $(1 - 3/4)$ greater than zero. Thus it is required that Δt satisfy the lesser of:

$$\Delta t \leq \frac{D \Delta s}{8|U|} \quad (4.6a)$$

$$\Delta t \leq \frac{1}{16} \frac{(\Delta s)^2}{E} \quad (4.6b)$$

$$\Delta t \leq \frac{\rho c D}{4K} \quad (4.6c)$$

which in most cases will exceed the Δt required by the wave stability criterion of equation (4.5) and hence the latter will govern the choice of Δt for a fixed Δs . The second condition, stated by Torrence (1968), applies in regions of negative velocity components and is satisfied by assuring that the sum of the advective terms are less in absolute value than the dispersive terms. Balancing the advective and dispersive terms requires that:

$$\Delta s \leq \frac{D E}{|U|} \quad (4.6d)$$

which can be restrictive in the choice of Δs for small values of E in regions of large U and lead to prohibitively small Δs ; and by equation (4.5) small Δt , all of which are dependent on the formulation of the heat dispersion coefficient.

Formal testing of the final program version of the combined equations of motion and continuity, beside using an already tested and published form of the numerical relations, consisted of setting up numerous hydrodynamic problems that have simple solutions. The first case was for an initialized distorted water surface with no flow through the boundaries and zero friction to reproduce the natural, or seiche, oscillations of a simple rectangular basin. The second case was for an initialized level water surface with equal inflow and outflow at either end of a narrow rectangular basin and with friction to test the approach to the steady-state surface slope of the normal flow hydraulic condition. These tests gave accurate results in comparison to the algebraic solutions.

The heat budget computation was tested with the equations of motion by simulating the release of a constant amount of heat over a fixed period

of time for a case with constant inlet and outlet flow rates and, no recirculation, and determining if the heat in storage plus the accumulated heat outflow and the accumulated surface heat dissipation accounted for the accumulated heat released. The second test was to perform the same experiment but with recirculation between the inlet and outlet. In the latter case the heat in storage increased to approach the accumulated heat released, and over a period of twenty-four hours simulation at 3 second time steps (28,000 iterations) the accumulated heat dissipation began to approach the accumulated heat release as the temperature throughout the pond, and consequently the heat in storage, began to decrease. These tests indicated an accurate quantitative accounting of the heat released in relation to the overall pond heat budget.

The Friction Factor, f

The squared velocity friction law used in the equations of fluid motion depends on f , the non-dimensional friction factor. It is related to the more familiar Chezy friction coefficient by the relation:

$$f = \frac{8}{C_h^2} \quad (4.7)$$

The Chezy coefficient in turn is related the Manning coefficient by the relation:

$$C_h = \frac{1.49}{n} R^{1/6} \quad (4.8a)$$

where: R = hydraulic radius, in Ft

and f is then related to the Manning coefficient, n , as:

$$f = \frac{8n}{2.2b^{1/3}} \quad (4.8b)$$

Reid and Bodine (1968) report using values of f between 0.0009 and 0.09 which is equivalent to C_h between 60 and 19 $\text{Ft}^{1/2} \text{Sec}^{-1}$. Leendertse (1967)

uses C_h for a natural waterbody between 50 and 70 $\text{ft}^{1/2} \text{Sec}^{-1}$. Simulation on shallow ten foot deep pond cases for $f > 0.50$ ($C_h < 2.5$) and flows per unit width of $U = 2.0 \text{ ft}^2 \text{Sec}^{-1}$ perturbate the pond surface slope to the point of causing zero depth over a short distance from the inflow. Test cases with $f = 0$ have been completed resulting in undamped pond oscillations at their natural period.

The user has the same problem in estimating f for a given pond as in estimating either C_h or n in any hydraulic problem involving friction. A single value of f is externally specified as a constant over the pond throughout a simulation in HYETA.

The Turbulent Transport Coefficient

The turbulent transport terms in equation (4.3) result initially from the temporal and spatial averaging of the cross products of the instantaneous velocity and temperature fluctuations at a point. Any averaging of the velocity field is implicitly reflected in the turbulent transport terms. Turbulent transport can therefore be defined as the movement of heat throughout a waterbody not described by advective terms.

An estimate of the turbulent diffusivity from the one-dimensional open channel formulation of Elder (1959) as:

$$E(\text{ft}^2 \text{Sec}^{-1}) = 20.4 f^{1/2} \frac{U}{D} Rh \quad (4.9)$$

where Rh is the hydraulic radius, an estimate of E is made in METMIN based on a specified f , and an estimate of the mean velocity, U , through the pond and the mean pond depth. Since equation (4.9) applies to one-dimensional flow it can be interpreted to give the lowest estimate that would apply in a two dimensional situation.

The diffusivity enters the stability considerations on the temperature

equation and dictates Δs if U and E are known a priori. The value of Δs required by the Torrence (1968) condition is estimated in METMIN based on (4.6d). It is found that this value of Δs is usually unreasonably small for the representation of most ponds, thus in METMIN an estimate of E based on equation (4.9) and the condition in equation (4.6d) is made in terms of Δs . This leads to an estimate of E higher than that given by equation (4.9) and proportional to Δs . This is rationalized by the fact that as Δs is increased the velocity field tends to be averaged over a greater expanse of waterbody and the diffusivity should assume larger values to represent this averaging. Intuitively, one would expect a relationship between the numerical form of the transport equation, its spatial averaging, and consequently the diffusivity and the stability condition, but this remains to be demonstrated from phenomenological arguments. It is also necessary to demonstrate the significance of the Torrence condition through further simulation as it might influence the overall pond heat budget.

The HYETA Program

The HYETA program listing is given in Appendix E with a users guide and listing of variables. A block diagram of the major steps in the main body of the HYETA computations is given in Fig. 4.2. It has one main time loop in which boundary values and source/sink quantities are set for each time step, and computations of new water surface heights, temperature excess, and the UP and VP components are computed. This order of computation is required to allow the passing of the UP and VP components into the U and V array and updating any of the values as dictated by source/sink.

Within the main loop, the rate of surface dissipation, heat in storage, and evaporative waterloss from the water surface is computed for each cell and accumulated over the water surface. The surface dissipation and

evaporative waterloss computations are then incremented in time.

A block diagram of the Source/Sink subroutine is given in Fig. 4.3. It is called at each time step and searches sequentially through each specified source/sink to determine the flow rate and coincident reactor heat to the source. The outlets or sinks attached to each source are searched to determine the recirculated heat. The flows and heat are carried into another set of subroutines determined by the physical characteristics of the source or sink, simple advective conditions, sprays, jets, etc., which set the required velocity components in the main routine, and the heat and flows released at each point.

Fig. 4.2. Block Diagram of MAIN Portion of HYETA.

Fig. 4.3. Block Diagram of Source/Sink Subroutine of MAIN in HYETA.

Sources, Sinks, and Boundary Conditions

The inflow and outflow of water and heat for the pond enters the HYETA computations primarily through $RN(I,J)$ and $HA(I,J)$ in equations (4.4c) and (4.4d). Location of inlets and outlets dictate the I,J at which the contributions are made and the type of inlet or outlet dictates the magnitude of the contribution. One or more sources and sinks can be located in a given I,J cell, and one or more pond outlets can be connected to a given reactor heat source and inlet to the pond. The specification of sources and sinks, their specific contributions to heat and flow, and recirculation computations are carried out in the source-sink subroutine of HYETA.

Single point inlets and outlets are each specified as a source or sink, its I,J location is identified and its temporal flow and heat regimes are determined. Also identified are the pond outlets connected to a particular pond inlet through the plant piping. Source-sink is called at each time step. Each specified source-sink is examined sequentially, the time regime of flow is found and the flow is determined from the data and stored in the $QH(K,1)$ array. Each source is then examined to determine the time regime of heat and the reactor heat release rate to the source is computed from the data and stored in the $QH(K,2)$ array. At this step the accumulation of reactor heat from all the sources over the Δt commences, and continues until all sources and sinks are interrogated.

A second examination of each source-sink is made to determine recirculated heat. For each source the identified sinks are called and the combined flow and mixed temperature excess for the identified sinks is computed.

The recirculated heat added to the source is computed based on the mixed temperature excess at the connected sink and the flow rate of the source, and the time period heat release $QH(K,2)$ for the source is augmented by the recirculated heat. The type subroutine for the source is then called, the $RN(I,J)$ and $HA(I,J)$

contribution determined, and any required specification of UP and VP at surrounding points are carried out.

The simple advective inlet routine places the flow and heat into the computations as contributions to $RN(I,J)$ and $HA(I,J)$, rather than as velocity and heat fluxes at the boundary to the I,J cell. The simple advective outlet routine subtracts the flow from $RN(I,J)$ and computes the excess heat removed from the product of the temperature excess at the outlet and flow, then subtracts it from $HA(I,J)$ at the outlet cell. This is an approximation that keeps the computations general, but can be overridden by placing a single I,J cell adjacent to the boundary in the grid mapping. The result will be to produce a boundary velocity equal to the flow rate divided by $D \times \Delta s$, and a temperature excess at the boundary proportional to the heat rate divided by the flow rate.

Natural inflows and outflows through the pond can be specified as source-sinks for each I,J cell where they occur. The time-onflow rate regimes are specified. Then the heat regimes for each specified inflow regime is computed by assuming the inflow heat is proportional to the product of the inflow rate and the difference between inflow temperature and pond ambient temperature. The heat regimes will be a specified negative heat source if inflow temperature is less than pond ambient temperature. The outflow excess heat is computed in the advective outlet subroutine. A separate natural inflow type subroutine can be written to carry out this computation if it is required extensively. Natural outflows are specified as sinks and the removal of excess heat is computed in the advective outlet subroutine.

Each physical type of inlet or outlet demands a separate subroutine which to date have been prepared for simple advective inlets and outlets, spray inlets, and two and three dimensional jet inlets.

Spray Sources

Sprays are utilized to dissipate reactor heat and recirculated heat before the flow is returned to the pond, and to distribute the flow over the surface area of the pond to control recirculation. Each spray nozzle could be identified as a separate source and its flow and reactor heat regime specified. In case more than one spray nozzle is within a given I,J cell on the pond grid, it is convenient to group their contribution as a single source at that point.

Spray subroutine decreases the $QH(K,I)$ rate of flow by a specified percentage windage loss (FWL) and evaporative water loss (EWL). It decreases the $QH(K,2)$ reactor heat plus recirculated heat by a specified percentage heat loss (PHL). The subroutine then adds the net flow and heat contribution to $RN(I,J)$ and $HA(I,J)$.

The percentage windage loss, evaporative water loss, and heat loss should be functions of nozzle design, meteorological conditions, flow rate, and other parameters. Information from the literature on evaporative water loss and heat loss (Seginer, 1969) may not pertain to the specific devices used and this presently appears to be proprietary information. The present spray subroutine calls for a specified percentage of windage and evaporative water loss and heat loss but can be expanded to computation of these and other parameters from specified characteristics when better information becomes available. There are eight positions in the $SS(L,K)$ data matrix for specification of spray parameters.

Under high wind velocities spray water and heat may be transferred to pond cells not containing spray devices. This situation can be simulated by reducing the heat and flow into the cells containing the sprays and establishing new sources in those cells receiving the residual.

Jet Sources

Inlets to the pond may be of sufficient velocity to act as a jet and induce entrainment and mixing in the immediate vicinity. These phenomena are smaller in scale than the area described by a $\Delta s \times \Delta s$ cell, and the hydrodynamic description of jets depends on different relations than used to describe overall pond hydrodynamics. The jet region within a cell is a balance between inertia, pressure gradient and shear stresses and is envisioned as establishing the entrainment through the sides of the cell into which the jet discharges, and moving the jet plus entrained flow out of the face of the cell normal to the jet axis. The grid should, therefore, be oriented in the direction of the jet. The computation of entrainment depends on the particular known formulation of jet properties. In the present jet subroutines the computations are provided for two-dimensional and three-dimensional jets whose dilution along the axis is proportional to a virtual source distance.

For a three-dimensional surface jet the inflow plus entrained flow along the centerline is given by:

$$\frac{Q(\xi)}{Q_o} = \frac{\xi}{\xi_{o3}} \quad (4.10)$$

where $Q(\xi)$ = Jet flow rate at distance ξ , in $\text{Ft}^3 \text{Sec}^{-1}$

Q_o = Jet flow rate, in $\text{Ft}^3 \text{Sec}^{-1}$

ξ_{o3} = Virtual source distance usually 3-5 times the jet diameter, in Ft

ξ = Distance from outfall, in Ft.

Over a Δs cell, the flow out of the cell and the flow entrained in either side are, respectively:

$$E_o = Q_o \frac{\Delta s}{\xi_{o3}} \quad (4.11)$$

and

$$E_I = \frac{1}{2} Q_o \left(\frac{\Delta s}{\xi_{o3}} - 1 \right) \quad (4.12)$$

The flow per unit width to be established at the end and sides of the cell are respectively:

$$W_o = \frac{Q_o \Delta s}{\Delta s \xi_o} \quad (4.13)$$

and

$$W_I = \frac{Q_o}{2 \Delta s} \left(\frac{\Delta s}{\xi_{o3}} - 1 \right) \quad (4.14)$$

At each time step the jet subroutine calls the QH(K,1) from source-sink, computes the cell flows from equations (4.13) and (4.14), finds the direction of the jet in relation to the zero depth boundary, and assigns the W_o and W_I with proper algebraic sign to U and V in the jet cell and surrounding cells. These values of U and V are used in the heat, continuity, and momentum computations immediately following source-sink. The jet subroutine also assigns the heat and flow to RN(I,J) and HA(I,J) for the cell into which the jet discharges.

For a two-dimensional case where the pond is shallow relative to the jet diameter the basic computations are:

$$\frac{Q(\xi)}{Q_o} = \left(\frac{\xi}{\xi_{o2}} \right)^{1/2} \quad (4.15)$$

where ξ_{o2} = the two-dimensional jet virtual source distance, in Ft.

$$\xi_o = Q_o \left(\frac{\Delta s}{\xi_{o2}} \right)^{1/2} \quad (4.16)$$

and

$$Z_I = \frac{1}{2} Q_o \left[\left(\frac{\Delta s}{s_{o2}} \right)^{1/2} - 1 \right] \quad (4.17)$$

and the established flow per unit width becomes;

$$W_o = \frac{Q_o}{\Delta s} \left(\frac{\Delta s}{s_{o2}} \right)^{1/2} \quad (4.18)$$

and

$$W_I = \frac{Q_o}{2 \Delta s} \left[\left(\frac{\Delta s}{s_{o2}} \right)^{1/2} - 1 \right] \quad (4.19)$$

and the W_o and W_I are assigned to the proper U and V as in the three-dimensional case.

It should be noted that in (4.14) and (4.19) the entrained flows would become negative if the virtual source distance equals or exceeds the DELTAS grid spacing, which physically means a jet acts as an advective inlet relative to the overall pond dynamics. The above relations therefore apply only when the virtual source distance is less than Δs .

The above procedure can be followed in preparing a type source subroutine for any of the many known jet formulations for which entrainment can be computed over the DELTAS distance from the inlet, including submerged jets, bouyant jets, and vertical jets, as required. The major function of the particular subroutine is to assign the entrainment rates to the proper velocity components. There are eight positions available in the SS(L,K) matrix for each jet type to specify characterizing parameters as explained in the HYETA users guide.

Weirs and Stratified Inlets

Weir-type devices are sometimes employed to distribute the inflow over a wide section of the pond and to achieve stratification of the inflow to prevent mixing with the stored colder water. The hydrodynamic pond computations are for shallow unstratified water bodies, but stratification of flow from an inlet could control the cells to which the flow and heat is added.

There is presently no convenient stratified flow theory that accounts for the extent of spreading in the two horizontal dimensions and the vertical transport of mass and heat from the stratified surface layer. This situation can, however, be simulated by designating cells downstream of the weir as locations of sources of flow and heat, and apportioning inputs to these cells as if from a stratified layer. Each source to these cells would be designated as an advective type inlet.

V. PROTOTYPE TEST CASE WITH WEIR INLETS

Prototype test case I is a $0.61 \times 10^6 \text{ Ft}^2$ pond with a volume of $0.7 \times 10^7 \text{ Ft}^3$ and a weir inlet separated over the length of the pond from the outlet. It is shown as mapped on a 95 ft. x 95 ft. grid in Fig. 5.1. The flow through the pond is 60.3 cfs. The heat release is specified at a constant $0.16 \times 10^9 \text{ Btu Hr}^{-1}$ for the first three hours after DBA, then increases to $0.27 \times 10^9 \text{ Btu Hr}^{-1}$, from which it decreases at a log time rate of $0.85 \times 10^8 \text{ Btu Hr}^{-1}$ as in equation (3.23).

Preliminary Estimates

The estimated steady-state temperature excess by equation (2.1) is 38.5°F .

The estimated rate of excess evaporative water loss from the water surface is by equation (2.3) $0.62 \times 10^5 \text{ Ft}^3 \text{ Day}^{-1}$. There are no added heat dissipating devices, thus the percentage volume reduction is 0.89 percent per day.

The estimated time to 90 percent of the steady-state temperature excess by equation (2.6) is 11.5 days. This should be compared to an average residence time of 1.34 days or 32 hours.

METMIN Analysis

Data input to the METMIN analysis is given in Table 5.1 for 30 days of computation. Detailed data input requirements are given in Appendix B. One flow regime is specified beginning at 0.0 hours and remaining constant at 60.3 cfs throughout the simulation. The two heat regimes are specified, the first beginning at 0.0 hours and the second beginning at 3.0 hours after DBA (see Fig. 5.2).

The dimensionless friction factor is specified at 0.005 and the maximum flow rate is specified at 60.3 cfs. These factors are used in METMIN only

to estimate the thermal diffusivity for HYETA.

Complete meteorological data is specified for three time regimes beginning at 0.0 hours, 240 hours, and 312 hours relative to the hourly ambient temperature computations. These were chosen as a period of normal ~~summer conditions followed successively ten days later by a short period~~ of high solar radiation with high nighttime humidity, and three days later by a period of cooler normal summer conditions.

Computed parameters for the METMIN temperature excess analysis are given in Table 5.2. These include the coefficient of surface heat exchange, mean daily ambient pond temperature and mean amplitude of daily temperature all averaged from the hourly ambient temperature computations. Table 5.2 also includes an estimate of the thermal diffusivity based on the Taylor dispersion formula and the basis for estimating its modification as required by the Torrence stability criterion.

The hourly results of the METMIN analysis are given in Table 5.3. The ambient temperature computations begin at an arbitrary day that is not necessarily the beginning of DBA. It shows the ambient temperature trending over ten days toward the period of extreme meteorological conditions, and decreasing from this latter period toward the second period of normal meteorological conditions. The ambient temperature reaches a peak of about 107° F during the period of extreme meteorological conditions.

The pond inlet temperature excess follows the heat release function over the first twenty-four hours until recirculation begins. The time recirculation begins in this analysis is less than the residence time found in the preliminary results because of the assumption of a finite number of plug flow segments in the pond. The pond inlet temperature excess begins to increase after 24 hours in response to recirculation and continues to rise to 25° F at 220 hours after DBA. The pond outlet temperature peaks shortly afterward to 20° F at 240

hours after DBA and then decreases.

Separate computation of the ambient temperature and the temperature excess allows superposition of their peak values and allows backcomputation to determine the worst time for DBA to occur relative to the specified ambient meteorological conditions.

The heat budget summary shows the accumulated reactor heat first going into storage and accumulated heat dissipation gradually increasing. The error in the heat balance during the first few hours after DBA is a result of the finite size of the pond segments over which the excess temperature is averaged. Heat in storage decreases after 240 hours as the accumulated heat dissipated becomes a larger fraction of the heat released.

Accumulated evaporative water loss includes the natural and excess heat contribution. It reaches 13.3 percent of the pond volume after 30 days of simulation. Make-up water supply is not included in the METMIN computation, thus the result represents the amount of make-up that must be provided, if available. The evaporative water loss from METMIN is less than that found in the preliminary estimates based on equation (2.3) because the latter is for an average heat rate at the steady-state temperature excess.

HYETA Analysis

The parameters chosen for the HYETA simulation are given in Table 5.4 as referenced to Fig. 5.1. The time step DELTAT is chosen to satisfy the hydrodynamic gravity wave stability criterion of equation (4.5).

The pond inlet weir is assumed to distribute the flow and heat into the three immediate downstream cells as a type +1.0 advective inlet. The outlet is taken as a single type -1.0 advective outlet. For this case there are three sources and one sink. Input data for the HYETA simulation is given in Table 5.5 in the format specified in the users manual. (Figure 5.3 illustrates the Hyeta data deck for this case.)

Physical constants used in the HYETA simulation are given in Table 5.6. The pond surface area and the coefficient of surface heat exchange are computed in the program. The remaining parameters are as specified in the data input. The computed map of initial depths is given in Table 5.7.

Table 5.8 gives a typical printout at specified times of U and V , the horizontal transport components, the pond depth, and the temperature excess for each cell. The results given for three hours after DBA show the water surface slope and the build up of heat along the axis of the pond. No heat has reached the pond outlet.

Table 5.9 gives the simulated time running summary of the pond heat budget and water loss. It also gives the temperature excess at selected points throughout the pond.

Fig. 5.1. Layout on Grid of Prototype Test Case I Pond.

Fig. 5.2. Heat Function for Test Case I Pond.

3.0	0.897436D8-0.28443D8	197
0.333333330.546666D8	0.0D0	196
2		195
0.33333333	0.201D2	194
1		193
0.0	0.0 0.0 0.0 0.0 0.0 0.0 0.0	192
2	101.0	191
4		190
1		189
3.0	0.897436D8-0.28443D8	188
0.333333330.546666D8	0.0D0	187
2		186
0.33333333	0.201D2	185
1		184
0.0	0.0 0.0 0.0 0.0 0.0 0.0 0.0	183
1	91.0	182
4		181
0.0	18.0	180
CARDS 12 THROUGH 179 ARE BATHYMETRY CARDS		
0.0	18.0	179
14	12	12
95.0	3.0	11
5	10	10
2	11	9
2	10	8
2	9	7
9	3	6
6	3	5
3600		4
30.0	1	3
PROTOTYPE POND NUMBER ONE		
0	0	2
000 0 0 000 0 0 0 0		1

ME-53. Continued.

[illegible]

***** MINMET ANALYSIS: PROTOTYPE PONO #1 (COMPLETE MET DATA) *****

DATA, AS INPUT:

V SA C
0.7000E 07 0.6140E 06 0.4940E 03

HTSP
120

HFRS

1

FR1J,1) FR1J,2)
0.0 60.3000

HFRS

2

HRF1J,1) HRF1J,2) HRF1J,3)
0.0 0.1645E 09 0.0
3.0000 0.2692E 09 -0.8510E 08

DWL EWL PHL
0.0 0.0 0.0

F FRMAX
0.0050 60.3000

HUT

1

NMET

3

TUMMET	XHSMX	HATX	HATMN	XHOPMX	XHOPMN	WS
0.0	5700.000	93.000	68.000	87.000	63.000	3.500
240.000	7000.000	93.000	90.000	89.000	87.000	2.500
312.000	6000.000	90.000	80.000	85.000	75.000	5.000

Table 5.1. Input Data NEWMIN Analysis Test Case I.

***** MINMET ANALYSIS: PROTOTYPE POND #1 (COMPLETE MET DATA) *****

COMPUTED PARAMETERS:

CSHL = 126.9275 BTU / FT ** 2 * DAY * DEGREE F

PTM = 98.2886 DEGREES F

PTA = 0.8575 DEGREES F

ALPHA = 1.5424 RADIANS

E = 0.0674 FT**2 / SEC

Table 5.2. Computed Parameters METMIN Analysis Test Case I.

***** HJHMET ANALYSIS: PROTOTYPE POND #1 (COMPLETE MET DATA) *****

Table 5.2. (Continued)

65

```

*****
*
* ESTIMATE OF TURBULENT THERMAL TRANSPORT DIFFUSIVITY
*
*
* WHEN DELTAS IN MAIN IS LESS THAN 63.37 FEET,
*
* THEN DIFF = 0.067 (IN FT**2/SEC).
*
*
*
* FOR LARGER DELTAS IN MAIN USE
*
* DIFF = 0.00213*DELTAS (IN FT**2/SEC)
*
*
*****

```

INDEX (K)	TIME	ACCUMULATED	EXCESS HEAT	ACCUMULATED	ACC WATER	POND TEMPERATURE		DAY	HOUR	TEMPERATURE (DEG F)
	AFTER	REACTION HEAT	STORED IN	EXCESS HEAT	LOSS	EXCESS (DEGREE F)				
	DBA	RELEASED	POND	DISSIPATED	(% POND	INLET	OUTLET			
	(HOUR)	(BTU)	(BTU)	(BTU)	VOLUME)	SUPH(1,K)	SUPH(2,K)			
		SUM(1,K)	SUM(2,K)	SUM(3,K)	SUM(5,K)					ANPTIM)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	1	93.04
2	1.0	0.165E 09	0.216E 09	0.161E 07	0.0	12.14	0.00	1	2	92.85
3	2.0	0.329E 09	0.378E 09	0.442E 07	0.0	12.14	0.00	1	3	92.68
4	3.0	0.493E 09	0.539E 09	0.843E 07	0.0	12.14	0.00	1	4	92.54
5	4.0	0.711E 09	0.769E 09	0.141E 08	0.0	16.08	0.00	1	5	92.45
6	5.0	0.921E 09	0.969E 09	0.214E 08	0.0	15.47	0.00	1	6	92.41
7	6.0	0.112E 10	0.116E 10	0.306E 08	0.1	14.97	0.00	1	7	92.44
8	7.0	0.132E 10	0.135E 10	0.400E 08	0.1	14.55	0.00	1	8	92.53
9	8.0	0.151E 10	0.153E 10	0.514E 08	0.1	14.19	0.00	1	9	92.69
10	9.0	0.170E 10	0.170E 10	0.640E 08	0.1	13.86	0.00	1	10	92.89
11	10.0	0.188E 10	0.187E 10	0.779E 08	0.1	13.58	0.00	1	11	93.15
12	11.0	0.207E 10	0.204E 10	0.930E 08	0.1	13.32	0.00	1	12	93.43
13	12.0	0.224E 10	0.220E 10	0.109E 09	0.1	13.08	0.00	1	13	93.73
14	13.0	0.242E 10	0.235E 10	0.127E 09	0.1	12.86	0.01	1	14	94.02
15	14.0	0.259E 10	0.250E 10	0.145E 09	0.2	12.66	0.01	1	15	94.30
16	15.0	0.276E 10	0.265E 10	0.165E 09	0.2	12.48	0.03	1	16	94.54
17	16.0	0.292E 10	0.280E 10	0.186E 09	0.2	12.32	0.05	1	17	94.74
18	17.0	0.309E 10	0.294E 10	0.208E 09	0.2	12.17	0.08	1	18	94.88
19	18.0	0.325E 10	0.308E 10	0.231E 09	0.2	12.05	0.13	1	19	94.97
20	19.0	0.341E 10	0.321E 10	0.255E 09	0.2	11.95	0.21	1	20	94.98
21	20.0	0.357E 10	0.334E 10	0.279E 09	0.2	11.89	0.31	1	21	94.94
22	21.0	0.372E 10	0.347E 10	0.303E 09	0.2	11.86	0.46	1	22	94.84
23	22.0	0.388E 10	0.360E 10	0.328E 09	0.3	11.68	0.65	1	23	94.69
24	23.0	0.403E 10	0.372E 10	0.360E 09	0.3	11.94	0.89	1	24	94.52
25	24.0	0.418E 10	0.384E 10	0.388E 09	0.3	12.07	1.18	2	1	94.35
26	25.0	0.433E 10	0.395E 10	0.417E 09	0.3	12.25	1.54	2	2	94.14
27	26.0	0.448E 10	0.408E 10	0.446E 09	0.3	12.50	1.95	2	3	93.97
28	27.0	0.463E 10	0.417E 10	0.479E 09	0.3	12.81	2.41	2	4	93.83
29	28.0	0.477E 10	0.428E 10	0.511E 09	0.3	13.17	2.93	2	5	93.74
30	29.0	0.492E 10	0.438E 10	0.543E 09	0.4	13.59	3.48	2	6	93.70
31	30.0	0.506E 10	0.449E 10	0.576E 09	0.4	14.06	4.07	2	7	93.73
32	31.0	0.520E 10	0.459E 10	0.611E 09	0.4	14.55	4.67	2	8	93.82
33	32.0	0.535E 10	0.468E 10	0.645E 09	0.4	15.06	5.27	2	9	93.97
34	33.0	0.548E 10	0.478E 10	0.681E 09	0.4	15.58	5.86	2	10	94.18
35	34.0	0.562E 10	0.487E 10	0.717E 09	0.4	16.09	6.43	2	11	94.43
36	35.0	0.576E 10	0.497E 10	0.754E 09	0.4	16.58	6.97	2	12	94.71
37	36.0	0.590E 10	0.506E 10	0.792E 09	0.5	17.05	7.47	2	13	95.01
38	37.0	0.603E 10	0.515E 10	0.830E 09	0.5	17.47	7.91	2	14	95.31
39	38.0	0.617E 10	0.524E 10	0.869E 09	0.5	17.84	8.31	2	15	95.58
40	39.0	0.630E 10	0.533E 10	0.909E 09	0.5	18.16	8.65	2	16	95.83
41	40.0	0.643E 10	0.542E 10	0.949E 09	0.5	18.43	8.93	2	17	96.03
42	41.0	0.657E 10	0.551E 10	0.990E 09	0.5	18.65	9.17	2	18	96.17
43	42.0	0.670E 10	0.559E 10	0.103E 10	0.6	18.82	9.35	2	19	96.25
44	43.0	0.683E 10	0.568E 10	0.107E 10	0.6	18.94	9.49	2	20	96.27
45	44.0	0.695E 10	0.577E 10	0.112E 10	0.6	19.02	9.60	2	21	96.22
46	45.0	0.708E 10	0.585E 10	0.116E 10	0.6	19.06	9.68	2	22	96.12
47	46.0	0.721E 10	0.593E 10	0.120E 10	0.6	19.08	9.74	2	23	95.98
48	47.0	0.734E 10	0.601E 10	0.125E 10	0.6	19.08	9.78	2	24	95.81
49	48.0	0.746E 10	0.609E 10	0.129E 10	0.7	19.06	9.81	3	1	95.62

Table 5.3. Results from METWIN Simulation Test Case I.

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Table 5.3. Results from METWIN Simulation Test Case I.

238.0	0.243E 11	0.983E 10	0.142E 11	4.5	25.02	20.10	10	23	106.30	
239.0	0.243E 11	0.982E 10	0.143E 11	4.5	25.00	20.10	10	24	106.12	
241	240.0	0.244E 11	0.981E 10	0.144E 11	4.5	24.98	20.09	11	1	105.74
242	241.0	0.245E 11	0.981E 10	0.144E 11	4.6	24.96	20.08	11	2	105.39
243	242.0	0.245E 11	0.980E 10	0.145E 11	4.6	24.94	20.07	11	3	105.06
244	243.0	0.246E 11	0.979E 10	0.146E 11	4.6	24.92	20.06	11	4	104.75
245	244.0	0.247E 11	0.979E 10	0.147E 11	4.6	24.90	20.05	11	5	104.49
246	245.0	0.247E 11	0.978E 10	0.147E 11	4.6	24.87	20.04	11	6	104.27
247	246.0	0.248E 11	0.977E 10	0.148E 11	4.7	24.85	20.02	11	7	104.10
248	247.0	0.248E 11	0.976E 10	0.149E 11	4.7	24.83	20.01	11	8	103.99
249	248.0	0.249E 11	0.976E 10	0.149E 11	4.7	24.81	20.00	11	9	103.93
250	249.0	0.250E 11	0.975E 10	0.150E 11	4.7	24.79	19.99	11	10	103.92
251	250.0	0.250E 11	0.974E 10	0.151E 11	4.7	24.76	19.98	11	11	103.96
252	251.0	0.251E 11	0.973E 10	0.152E 11	4.8	24.74	19.97	11	12	104.01
253	252.0	0.252E 11	0.973E 10	0.152E 11	4.8	24.72	19.95	11	13	104.09
254	253.0	0.252E 11	0.972E 10	0.153E 11	4.8	24.69	19.94	11	14	104.16
255	254.0	0.253E 11	0.971E 10	0.154E 11	4.8	24.67	19.93	11	15	104.22
256	255.0	0.254E 11	0.970E 10	0.155E 11	4.9	24.65	19.91	11	16	104.25
257	256.0	0.254E 11	0.970E 10	0.155E 11	4.9	24.62	19.90	11	17	104.24
258	257.0	0.255E 11	0.969E 10	0.156E 11	4.9	24.60	19.89	11	18	104.19
259	258.0	0.256E 11	0.968E 10	0.157E 11	4.9	24.57	19.87	11	19	104.08
260	259.0	0.256E 11	0.967E 10	0.157E 11	4.9	24.55	19.86	11	20	103.91
261	260.0	0.257E 11	0.966E 10	0.158E 11	5.0	24.53	19.85	11	21	103.70
262	261.0	0.257E 11	0.965E 10	0.159E 11	5.0	24.50	19.83	11	22	103.43
263	262.0	0.258E 11	0.965E 10	0.160E 11	5.0	24.48	19.82	11	23	103.13
264	263.0	0.259E 11	0.964E 10	0.160E 11	5.0	24.45	19.80	11	24	102.79
265	264.0	0.259E 11	0.963E 10	0.161E 11	5.0	24.43	19.79	12	1	102.44
266	265.0	0.260E 11	0.962E 10	0.162E 11	5.1	24.40	19.77	12	2	102.10
267	266.0	0.261E 11	0.961E 10	0.162E 11	5.1	24.38	19.76	12	3	101.76
268	267.0	0.261E 11	0.960E 10	0.163E 11	5.1	24.35	19.74	12	4	101.46
269	268.0	0.262E 11	0.959E 10	0.164E 11	5.1	24.33	19.73	12	5	101.19
270	269.0	0.262E 11	0.958E 10	0.165E 11	5.1	24.30	19.71	12	6	100.97
271	270.0	0.263E 11	0.957E 10	0.165E 11	5.2	24.27	19.70	12	7	100.80
272	271.0	0.264E 11	0.957E 10	0.166E 11	5.2	24.25	19.68	12	8	100.69
273	272.0	0.264E 11	0.956E 10	0.167E 11	5.2	24.22	19.66	12	9	100.64
274	273.0	0.265E 11	0.955E 10	0.167E 11	5.2	24.20	19.65	12	10	100.63
275	274.0	0.265E 11	0.954E 10	0.168E 11	5.2	24.17	19.63	12	11	100.66
276	275.0	0.266E 11	0.953E 10	0.169E 11	5.3	24.14	19.61	12	12	100.71
277	276.0	0.267E 11	0.952E 10	0.170E 11	5.3	24.12	19.60	12	13	100.79
278	277.0	0.267E 11	0.951E 10	0.170E 11	5.3	24.09	19.58	12	14	100.86
279	278.0	0.268E 11	0.950E 10	0.171E 11	5.3	24.06	19.56	12	15	100.92
280	279.0	0.269E 11	0.949E 10	0.172E 11	5.4	24.04	19.55	12	16	100.95
281	280.0	0.269E 11	0.948E 10	0.172E 11	5.4	24.01	19.53	12	17	100.94
282	281.0	0.270E 11	0.947E 10	0.173E 11	5.4	23.98	19.51	12	18	100.89
283	282.0	0.270E 11	0.946E 10	0.174E 11	5.4	23.95	19.49	12	19	100.78
284	283.0	0.271E 11	0.945E 10	0.174E 11	5.4	23.93	19.47	12	20	100.62
285	284.0	0.272E 11	0.944E 10	0.175E 11	5.5	23.90	19.46	12	21	100.40
286	285.0	0.272E 11	0.943E 10	0.176E 11	5.5	23.87	19.44	12	22	100.13
287	286.0	0.273E 11	0.942E 10	0.177E 11	5.5	23.84	19.42	12	23	99.83
288	287.0	0.273E 11	0.941E 10	0.177E 11	5.5	23.82	19.40	12	24	99.50
289	288.0	0.274E 11	0.940E 10	0.178E 11	5.5	23.79	19.38	13	1	99.15
290	289.0	0.275E 11	0.939E 10	0.179E 11	5.6	23.76	19.36	13	2	98.80
291	290.0	0.275E 11	0.938E 10	0.179E 11	5.6	23.73	19.35	13	3	98.47
292	291.0	0.276E 11	0.937E 10	0.180E 11	5.6	23.70	19.33	13	4	98.16
293	292.0	0.276E 11	0.936E 10	0.181E 11	5.6	23.67	19.31	13	5	97.89
294	293.0	0.277E 11	0.935E 10	0.181E 11	5.6	23.65	19.29	13	6	97.67
295	294.0	0.277E 11	0.934E 10	0.182E 11	5.7	23.62	19.27	13	7	97.51
296	295.0	0.278E 11	0.933E 10	0.183E 11	5.7	23.59	19.25	13	8	97.39
297	296.0	0.279E 11	0.932E 10	0.183E 11	5.7	23.56	19.23	13	9	97.34
298	297.0	0.279E 11	0.931E 10	0.184E 11	5.7	23.53	19.21	13	10	97.33
299	298.0	0.280E 11	0.930E 10	0.185E 11	5.7	23.50	19.19	13	11	97.36
300	299.0	0.280E 11	0.929E 10	0.186E 11	5.8	23.47	19.17	13	12	97.41
301	300.0	0.281E 11	0.928E 10	0.186E 11	5.8	23.44	19.15	13	13	97.49

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Table 5.3. (Continued)

Table 5.3. (Continued)

680	679.0	0.455E 11	0.500E 10	0.384E 11	12.5	12.50	10.44	29	8	95.18
681	680.0	0.455E 11	0.499E 10	0.385E 11	12.5	12.48	10.42	29	9	95.25
682	681.0	0.456E 11	0.498E 10	0.385E 11	12.5	12.45	10.40	29	10	95.37
683	682.0	0.456E 11	0.497E 10	0.385E 11	12.5	12.43	10.38	29	11	95.53
684	683.0	0.456E 11	0.496E 10	0.386E 11	12.5	12.41	10.37	29	12	95.72
685	684.0	0.457E 11	0.495E 10	0.386E 11	12.6	12.39	10.35	29	13	95.93
686	685.0	0.457E 11	0.494E 10	0.387E 11	12.6	12.36	10.33	29	14	96.15
687	686.0	0.457E 11	0.493E 10	0.387E 11	12.6	12.34	10.31	29	15	96.35
688	687.0	0.457E 11	0.492E 10	0.387E 11	12.6	12.32	10.29	29	16	96.53
689	688.0	0.458E 11	0.492E 10	0.388E 11	12.6	12.29	10.27	29	17	96.67
690	689.0	0.458E 11	0.491E 10	0.388E 11	12.6	12.27	10.25	29	18	96.76
691	690.0	0.458E 11	0.490E 10	0.388E 11	12.6	12.25	10.23	29	19	96.80
692	691.0	0.458E 11	0.489E 10	0.389E 11	12.7	12.23	10.21	29	20	96.79
693	692.0	0.459E 11	0.488E 10	0.389E 11	12.7	12.20	10.20	29	21	96.72
694	693.0	0.459E 11	0.487E 10	0.389E 11	12.7	12.18	10.18	29	22	96.60
695	694.0	0.459E 11	0.486E 10	0.390E 11	12.7	12.16	10.16	29	23	96.44
696	695.0	0.460E 11	0.485E 10	0.390E 11	12.7	12.13	10.14	29	24	96.25
697	696.0	0.460E 11	0.484E 10	0.390E 11	12.7	12.11	10.12	30	1	96.04
698	697.0	0.460E 11	0.483E 10	0.391E 11	12.8	12.09	10.10	30	2	95.82
699	698.0	0.460E 11	0.482E 10	0.391E 11	12.8	12.07	10.08	30	3	95.62
700	699.0	0.461E 11	0.482E 10	0.392E 11	12.8	12.04	10.06	30	4	95.44
701	700.0	0.461E 11	0.481E 10	0.392E 11	12.8	12.02	10.05	30	5	95.30
702	701.0	0.461E 11	0.480E 10	0.392E 11	12.8	12.00	10.03	30	6	95.21
703	702.0	0.461E 11	0.479E 10	0.393E 11	12.8	11.98	10.01	30	7	95.17
704	703.0	0.462E 11	0.478E 10	0.393E 11	12.8	11.95	9.99	30	8	95.18
705	704.0	0.462E 11	0.477E 10	0.393E 11	12.9	11.93	9.97	30	9	95.25
706	705.0	0.462E 11	0.476E 10	0.394E 11	12.9	11.91	9.95	30	10	95.37
707	706.0	0.462E 11	0.475E 10	0.394E 11	12.9	11.89	9.94	30	11	95.53
708	707.0	0.463E 11	0.474E 10	0.394E 11	12.9	11.87	9.92	30	12	95.72
709	708.0	0.463E 11	0.474E 10	0.395E 11	12.9	11.84	9.90	30	13	95.93
710	709.0	0.463E 11	0.473E 10	0.395E 11	12.9	11.82	9.88	30	14	96.14
711	710.0	0.463E 11	0.472E 10	0.395E 11	12.9	11.80	9.86	30	15	96.35
712	711.0	0.464E 11	0.471E 10	0.396E 11	13.0	11.78	9.84	30	16	96.52
713	712.0	0.464E 11	0.470E 10	0.396E 11	13.0	11.75	9.83	30	17	96.67
714	713.0	0.464E 11	0.469E 10	0.396E 11	13.0	11.73	9.81	30	18	96.76
715	714.0	0.465E 11	0.468E 10	0.397E 11	13.0	11.71	9.79	30	19	96.80
716	715.0	0.465E 11	0.467E 10	0.397E 11	13.0	11.69	9.77	30	20	96.79
717	716.0	0.465E 11	0.467E 10	0.398E 11	13.0	11.67	9.75	30	21	96.72
718	717.0	0.465E 11	0.466E 10	0.398E 11	13.1	11.64	9.74	30	22	96.60
719	718.0	0.466E 11	0.465E 10	0.398E 11	13.1	11.62	9.72	30	23	96.44
720	719.0	0.466E 11	0.464E 10	0.399E 11	13.1	11.60	9.70	30	24	96.25

Table 5.3. (Continued)

THE FOLLOWING ARE THE PARAMETERS OF THE NUMERICAL SCHEME.

DELTA S = 95.00 HET
DELTA T = 3.00 SEC
NSTEPS = 3600
PRNT = 10.00 MIN
NPRNT = 1
IMAX = 14
JMAX = 12

Table 5.4. Parameters of HYDA Simulation Test Case I.

PROTOTYPE FORD NUMBER ONE			1
30.0		1	2
30.0		1	3
0	3		4
0	3		5
2	3		6
2	10		7
2	11		8
5	10		9
95.0	3.0		10
	14	12	11
0.0	18.0		12
0.0	18.0		13
0.0	18.0		14
0.0	18.0		15
0.0	18.0		16
0.0	18.0		17
0.0	18.0		18
0.0	18.0		19
0.0	18.0		20
0.0	18.0		21
0.0	18.0		22
0.0	18.0		23
0.0	18.0		24
0.0	18.0		25
0.0	18.0		26
0.0	18.0		27
0.0	18.0		28
0.0	18.0		29
0.0	18.0		30
17.0	10.0		31
17.0	10.0		32
17.0	10.0		33
17.0	10.0		34
17.0	10.0		35
0.0	18.0		36
0.0	18.0		37
0.0	18.0		38
0.0	18.0		39
0.0	18.0		40
0.0	18.0		41
0.0	18.0		42
0.0	18.0		43
0.0	18.0		44
17.0	10.0		45
17.0	10.0		46
17.0	10.0		47
17.0	10.0		48
17.0	10.0		49
17.0	10.0		50
17.0	10.0		51
0.0	18.0		52
0.0	18.0		53
0.0	18.0		54
0.0	18.0		55
0.0	18.0		56
0.0	18.0		57
0.0	18.0		58
17.0	10.0		59
17.0	10.0		60
17.0	10.0		61
17.0	10.0		62
17.0	10.0		63

Table 5.5. Input Data HYEM Simulation Test Case I.

17.0	10.0	127
17.0	10.0	128
17.0	10.0	129
17.0	10.0	130
17.0	10.0	131
17.5	10.0	132
17.0	10.0	133
17.0	10.0	134
17.0	10.0	135
0.0	10.0	136
0.0	10.0	137
0.0	10.0	138
17.0	10.0	139
17.0	10.0	140
17.0	10.0	141
17.0	10.0	142
17.0	10.0	143
17.0	10.0	144
17.0	10.0	145
17.0	10.0	146
17.0	10.0	147
17.0	10.0	148
0.0	10.0	149
0.0	10.0	150
0.0	10.0	151
0.0	10.0	152
17.0	10.0	153
17.0	10.0	154
17.0	10.0	155
17.0	10.0	156
17.0	10.0	157
17.0	10.0	158
17.0	10.0	159
17.0	10.0	160
0.0	10.0	161
0.0	10.0	162
0.0	10.0	163
0.0	10.0	164
0.0	10.0	165
0.0	10.0	166
0.0	10.0	167
0.0	10.0	168
0.0	10.0	169
0.0	10.0	170
0.0	10.0	171
0.0	10.0	172
0.0	10.0	173
0.0	10.0	174
0.0	10.0	175
0.0	10.0	176
0.0	10.0	177
0.0	10.0	178
0.0	10.0	179
0.0	10.0	180
0.0	10.0	181
0.0	10.0	182
0.0	10.0	183
0.0	10.0	184
0.0	10.0	185
0.0	10.0	186
0.0	10.0	187
0.0	10.0	188
0.0	10.0	189

Table 5.5. (Continued)

	2	4	101.0					190
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	191
	1							192
0.33333333	0.20102							193
	2							194
0.33333333	0.54666608	0.000						195
3.0	0.89748608	0.2844308						196
	1							197
	4							198
	3	2	111.0					199
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	200
	1							201
0.33333333	0.20102							202
	2							203
0.33333333	0.54666608	0.000						204
3.0	0.89748608	0.2844308						205
	1							206
	4							207
	2	6	3-1.0					208
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	209
	1							210
0.0	0.60302							211
	0							212
	0							213
0.0	0.0							214
106.57	85.0	4.2						215
0.20235	0.005							216

Table 5.5. (Continued)

FOLLOWING ARE THE VALUES OF THE CONSTANTS USED IN THIS SIMULATION.

SYMBOLIC NAME	CONSTANT	VALUE	UNITS
AREA	SURFACE AREA	0.6140 06	FT**2
CSHC	COEFFICIENT OF SURFACE HEAT EXCHANGE	0.00168	BTU/FT**2 SEC DEGREE F
DIF	DIFFUSIVITY	0.20235	FT**2/SEC
F	BED RESISTANCE COEFFICIENT	0.00500	DIMENSIONLESS
THEIA	WIND DIRECTION	0.0	RADIANS
W	WIND SPEED	0.0	KNOTS

Table 5.6. Physical Constants in HYETA Simulation Test Case I.

THE FOLLOWING ARE THE INITIAL DEFINS.

Table 5.9. Summary Time Running Heat Budget, Waterloss, and Temperature Excess at Selected Points HYDA Simulation Test Case I.

TIME, HOURS	TOTAL HEAT LOAD, BTU	TOTAL HEAT DISSIPATED, BTU	HEAT STORED, BTU	TOTAL WATER LOSS, EI#02	EXCESS TEMPERATURES, DEGREES F			
0.50	0.2750 08	0.3220 05	0.2730 08	0.4770 03	T(6, 3) = 0.00	T(9, 3) = 0.00	T(2, 9) = 2.12	T(2, 10) = 2.12
					T(2, 11) = 2.12	T(5, 10) = 0.00		
1.00	0.1090 09	0.5120 06	0.1090 09	0.9610 03	T(6, 3) = 0.00	T(9, 3) = 0.00	T(2, 9) = 6.41	T(2, 10) = 6.42
					T(2, 11) = 6.42	T(5, 10) = 0.11		
1.50	0.1910 09	0.1560 07	0.1890 09	0.1450 04	T(6, 3) = 0.00	T(9, 3) = 0.00	T(2, 9) = 8.72	T(2, 10) = 8.73
					T(2, 11) = 8.73	T(5, 10) = 0.65		
2.00	0.2730 09	0.3190 07	0.2710 09	0.1950 04	T(6, 3) = 0.00	T(9, 3) = 0.00	T(2, 9) = 10.10	T(2, 10) = 10.10
					T(2, 11) = 10.10	T(5, 10) = 1.66		
2.50	0.3550 09	0.5370 07	0.3490 09	0.2450 04	T(6, 3) = 0.00	T(9, 3) = 0.00	T(2, 9) = 10.81	T(2, 10) = 10.82
					T(2, 11) = 10.81	T(5, 10) = 3.05		
3.00	0.4360 09	0.8120 07	0.4290 09	0.2960 04	T(6, 3) = 0.00	T(9, 3) = 0.00	T(2, 9) = 11.29	T(2, 10) = 11.28
					T(2, 11) = 11.28	T(5, 10) = 4.51		

VI. PROTOTYPE TEST CASE WITH SPRAY INLETS

Prototype test case II is a $0.48 \times 10^6 \text{ Ft}^2$ pond with a volume of $0.35 \times 10^7 \text{ Ft}^3$ with spray inlets and two separate outlets. It is shown as mapped on a 60 Ft. x 60 Ft. grid in Fig. 6.1. The flow into the pond is approximately 100 cfs and changes with time. The heat released is $0.26 \times 10^9 \text{ Btu Hr}^{-1}$ on the first day after DBA or shutdown and decreases to $0.11 \times 10^9 \text{ Btu Hr}^{-1}$ in 30 days.

Preliminary Estimates

For preliminary analysis the sprays are assumed to dissipate 30 percent of the heat passing through them, have a windage loss of 2.0 percent and an arbitrarily assumed evaporative water loss of 1.3 percent of the circulating water flow.

The estimated steady-state temperature excess by equation (2.1) is 40.5° F .

The estimated rate of excess evaporative water loss from the water surface by equation (2.3) is $5.2 \times 10^5 \text{ Ft}^3 \text{ Day}^{-1}$. In addition $2.85 \times 10^5 \text{ Ft}^3 \text{ Day}^{-1}$ is lost from the spray drift and evaporation. This gives an estimate of pond volume reduction of 9.6 percent per day.

The estimated time to 90 percent of the steady-state temperature excess by equation (2.6) is 6.35 days. This should be compared to an average residence time of 0.35 days or 8.4 hours.

In these estimates the surface area (SA) has not been reduced by the amount under the sprays.

METMIN Analysis

Data input to the METMIN analysis is given in Table 6.1. The temporal simulated flow regimes times on is given in detail by the variables $\text{FR}(\text{J},1)$ and $\text{FR}(\text{J},2)$ and shows the pumping rate decreasing after the first hour and during successive days after DBA or shutdown.

The heat functions are given in the variable array HRF(J,K) and are specified as constantly decreasing rates over successive days after DBA or shutdown. These were determined from the gross specification of heat to be released in a given number of days.

The meteorological conditions are for a specification of minimum data, and include the pond temperature, air and dew point temperatures, and a cooling wind speed. No ambient temperature computations are performed for the minimum data specification.

Table 6.2 gives a listing of the constants used in the METMIN temperature excess analysis. It also includes an estimate of the thermal diffusivity for use in HYETA and modification required to satisfy the Torrence stability criterion.

Table 6.3 gives the simulated time results of the METMIN analysis. The ambient pond temperature is a constant as specified for partial meteorological data. The outlet temperature excess indicates that recirculation begins at five hours after DBA or shutdown, which is to the preliminary estimate of pond residence time. The inlet temperature excess builds up to a maximum of 35.5 °F after 70 hours and the outlet temperature excess reaches a maximum of 24.4 °F after 95 hours.

The heat budget summations show that the accumulated heat dissipated is a large fraction of the accumulated heat released shortly after DBA and is a result of the spray dissipators. The accumulated evaporative water loss from the sprays, the excess heat in the pond, and natural evaporation at ambient conditions is 90 percent of the pond volume after 30 days of simulation.

HYETA Analysis

The parameters chosen for the Hyeta simulation are given in Table 6.4 and are referenced to the Fig. 6.1 gridded map. The time step of integration

is chosen to satisfy the hydraulic gravity wave stability condition of equation 4.5.

Fig. 6.1 shows that there are two sets of inlet sprays and two different pond outlets. The flow through the reactor and heat release is specified for each outlet and set of inlet sprays. Each cell containing spray modules is designated as an advective inlet source receiving a flow and heat rate proportional to the number of nozzles. For this case there are 24 sources and 2 sinks. Input data for the HYETA simulation is given in Table 6.5. Detailed data input requirements and units of measurement are given in the users guide and program listing in Appendix E.

Constants used in the simulation are given in Table 6.6. The pond surface area and coefficient of surface heat exchange are computed in the program. The remaining parameters are as specified in the data input. The computed map of initial depths is given in Table 6.7.

The resulting U and V horizontal transport components, the pond depth, and the temperature excess at each cell are given in Table 6.8 after 120 minutes of simulation. The depths are referenced to the center of a cell, the corresponding U component is through the left-hand side of the cell, and the corresponding V component is through the lower side of the cell. A positive U component is directed to the right of the table and a positive V component is directed toward the top of the table.

The results in Table 6.8 show the build-up of depth and temperature excess in the vicinity of the nozzles. Temperature excess is beginning to build-up in the vicinity of the pond outlets indicating the onset of recirculation at less than three hours.

The time running summary of the overall pond heat budget, water budget, and temperature excess at selected points is given in Table 6.9. The total heat load is the accumulated reactor heat released up to the indicated time.

The total heat dissipated includes the contribution from the water surface and the sprays. The total water loss includes the contribution from the sprays, the excess temperature evaporation, and the natural evaporation at specified ambient conditions.

■ pond
outlet
 inlet
springs

Fig. 6.1. Layout on Grid of Prototype Test Case II Pond.

***** MINNET ANALYSIS: PROTOTYPE POND #2 (PARTIAL PEI DATA) *****

DATA, AS INPUT:

Y SA G
0.3000E 07 0.4800E 06 0.4000E 04

NTSP
120

NFRS
10

FR(J,1)	FR(J,2)
0.0	123.6000
1.0000	98.9200
24.0000	38.8300
48.0000	34.4700
72.0000	32.8000
96.0000	31.6600
120.0000	30.7900
144.0000	30.3700
168.0000	29.0300
336.0000	27.1800

NHAFS
9

HRF(J,1)	HRF(J,2)	HRF(J,3)
0.0	0.2779E 09	0.0
24.0000	0.2862E 09	0.0
48.0000	0.2141E 09	0.0
72.0000	0.1867E 09	0.0
96.0000	0.1676E 09	0.0
120.0000	0.1571E 09	0.0
144.0000	0.1498E 09	0.0
168.0000	0.1272E 09	0.0
336.0000	0.1088E 09	0.0

DWL	EML	PHL
2.0000	1.3000	30.0000

F	FRMAX
0.0000	123.6000

MUT
0

PT	AT	DJPT	MWS
95.0000	95.0000	95.0000	3.0000

Table 6.1. Input Data METWIN Analysis Test Case II.

****MINNET ANALYSIS: PROTOTYPE POND #2 (PARTIAL MEY. DATA) ****

COMPUTED PARAMETERS:

CSH = 133.8900 BTU / FT**2 * DAY * DEGREE F

PTM = 45.0000 DEGREES F

PTA = 0.0 DEGREES F

ALPHA = 0.0 RADIANS

E = 1.4425 FT**2 / SEC

Table 6.2. Computed Parameters MINNET Analysis Test Case II.

```

*****
*
* ESTIMATE OF TURBULENT THERMAL TRANSPORT DIFFUSIVITY
*
* WHEN DELTAS IN MAIN IS LESS THAN 40.65 FEET,
*
* THEN DIFF = 1.443 (IN FT**2/SEC).
*
*
* FOR LARGER DELTAS IN MAIN USE
*
* DIFF = 0.07063*DELTAS (IN FT**2/SEC)
*
*****

```

***** CALCULATIONS FOR DBA *****

***** AMBIENT CALCULATIONS *****

TIME (K)	TIME AFTER (HOURS)	ACCUMULATED REACTOR HEAT RELEASED (BTU)	EXCESS HEAT STORED IN POND (BTU)	ACCUMULATED EXCESS HEAT DISSIPATED (BTU)	ACC. WATER LOSS 1% POND VOLUME)	POND TEMPERATURE EXCESS (DEGREE F)	DAY	TEMPERATURE (DEG F)
		SUMM(10,K)	SUMM(14,K)	SUMM(13,K)	SUMM(15,K)	SUMM(11,K) SUMM(12,K)	I	J
1	0.0	0.0	0.0	0.0	0.0	0.0 0.0	1	1
2	1.0	0.298E 09	0.222E 09	0.921E 08	0.9	7.51 0.00	1	2
3	2.0	0.596E 09	0.420E 09	0.187E 09	0.8	9.39 0.02	1	3
4	3.0	0.894E 09	0.629E 09	0.284E 09	1.1	9.40 0.07	1	4
5	4.0	0.119E 10	0.825E 09	0.385E 09	1.4	9.43 0.19	1	5
6	5.0	0.149E 10	0.101E 10	0.490E 09	1.8	9.51 0.43	1	6
7	6.0	0.179E 10	0.120E 10	0.599E 09	2.1	9.68 0.83	1	7
8	7.0	0.209E 10	0.137E 10	0.715E 09	2.5	9.97 1.44	1	8
9	8.0	0.238E 10	0.153E 10	0.839E 09	2.8	10.39 2.22	1	9
10	9.0	0.268E 10	0.168E 10	0.969E 09	3.1	10.94 3.13	1	10
11	10.0	0.298E 10	0.111E 10	0.111E 10	3.5	11.58 4.11	1	11
12	11.0	0.328E 10	0.196E 10	0.126E 10	3.8	12.26 5.08	1	12
13	12.0	0.357E 10	0.209E 10	0.141E 10	4.2	12.94 5.97	1	13
14	13.0	0.387E 10	0.221E 10	0.157E 10	4.5	13.56 6.76	1	14
15	14.0	0.417E 10	0.235E 10	0.174E 10	4.9	14.12 7.44	1	15
16	15.0	0.447E 10	0.249E 10	0.191E 10	5.2	14.60 8.04	1	16
17	16.0	0.477E 10	0.258E 10	0.204E 10	5.6	15.02 8.68	1	17
18	17.0	0.506E 10	0.267E 10	0.227E 10	5.9	15.39 9.08	1	18
19	18.0	0.536E 10	0.277E 10	0.246E 10	6.2	15.74 9.56	1	19
20	19.0	0.566E 10	0.287E 10	0.265E 10	6.6	16.08 10.04	1	20
21	20.0	0.596E 10	0.296E 10	0.285E 10	6.9	16.41 10.53	1	21
22	21.0	0.626E 10	0.305E 10	0.305E 10	7.3	16.75 11.01	1	22
23	22.0	0.655E 10	0.314E 10	0.325E 10	7.6	17.09 11.48	1	23
24	23.0	0.685E 10	0.322E 10	0.346E 10	8.0	17.42 11.94	1	24
25	24.0	0.715E 10	0.330E 10	0.367E 10	8.3	17.74 12.38	2	1
26	25.0	0.744E 10	0.346E 10	0.383E 10	8.5	31.64 12.46	2	2
27	26.0	0.772E 10	0.353E 10	0.400E 10	8.6	31.69 12.53	2	3
28	27.0	0.801E 10	0.370E 10	0.416E 10	8.8	31.74 12.59	2	4
29	28.0	0.829E 10	0.382E 10	0.433E 10	8.9	31.78 12.65	2	5
30	29.0	0.858E 10	0.394E 10	0.449E 10	9.1	31.82 12.71	2	6
31	30.0	0.887E 10	0.406E 10	0.466E 10	9.2	31.86 12.75	2	7
32	31.0	0.915E 10	0.417E 10	0.483E 10	9.4	31.90 12.80	2	8
33	32.0	0.944E 10	0.429E 10	0.500E 10	9.5	31.93 12.84	2	9
34	33.0	0.973E 10	0.440E 10	0.518E 10	9.7	31.96 12.88	2	10
35	34.0	0.100E 11	0.451E 10	0.535E 10	9.8	31.98 12.92	2	11
36	35.0	0.103E 11	0.462E 10	0.553E 10	10.0	32.01 12.96	2	12
37	36.0	0.106E 11	0.473E 10	0.571E 10	10.1	32.04 13.02	2	13
38	37.0	0.109E 11	0.484E 10	0.589E 10	10.3	32.08 13.09	2	14
39	38.0	0.112E 11	0.494E 10	0.607E 10	10.4	32.13 13.20	2	15
40	39.0	0.115E 11	0.505E 10	0.625E 10	10.6	32.21 13.34	2	16
41	40.0	0.117E 11	0.515E 10	0.643E 10	10.7	32.31 13.54	2	17
42	41.0	0.120E 11	0.525E 10	0.662E 10	10.9	32.45 13.80	2	18
43	42.0	0.123E 11	0.534E 10	0.681E 10	11.0	32.63 14.13	2	19
44	43.0	0.126E 11	0.544E 10	0.700E 10	11.2	32.86 14.54	2	20
45	44.0	0.129E 11	0.553E 10	0.719E 10	11.3	33.15 15.02	2	21
46	45.0	0.132E 11	0.561E 10	0.739E 10	11.5	33.48 15.57	2	22
47	46.0	0.134E 11	0.570E 10	0.758E 10	11.7	33.87 16.18	2	23
48	47.0	0.137E 11	0.579E 10	0.779E 10	11.8	34.29 16.84	2	24
49	48.0	0.140E 11	0.588E 10	0.799E 10	12.0	34.75 17.52	3	1

Table 6.3. Results from NETMIR Simulation Test Case II.

680	679.0	0.9401	11	0.403E	10	0.898E	11	85.1	22.78	14.72	29	8	95.00
681	680.0	0.942E	11	0.403E	10	0.897E	11	85.2	22.78	14.72	29	9	95.00
682	681.0	0.943E	11	0.403E	10	0.896E	11	85.3	22.78	14.72	29	10	95.00
683	682.0	0.944E	11	0.403E	10	0.895E	11	85.4	22.78	14.72	29	11	95.00
684	683.0	0.945E	11	0.403E	10	0.894E	11	85.5	22.78	14.72	29	12	95.00
685	684.0	0.946E	11	0.403E	10	0.893E	11	85.6	22.78	14.72	29	13	95.00
686	685.0	0.947E	11	0.403E	10	0.892E	11	85.7	22.78	14.72	29	14	95.00
687	686.0	0.948E	11	0.403E	10	0.891E	11	85.8	22.78	14.72	29	15	95.00
688	687.0	0.949E	11	0.403E	10	0.890E	11	85.9	22.78	14.72	29	16	95.00
689	688.0	0.950E	11	0.403E	10	0.890E	11	86.0	22.78	14.72	29	17	95.00
690	689.0	0.951E	11	0.403E	10	0.890E	11	86.2	22.78	14.72	29	18	95.00
691	690.0	0.952E	11	0.403E	10	0.890E	11	86.3	22.78	14.72	29	19	95.00
692	691.0	0.953E	11	0.403E	10	0.890E	11	86.4	22.78	14.72	29	20	95.00
693	692.0	0.955E	11	0.403E	10	0.890E	11	86.5	22.78	14.72	29	21	95.00
694	693.0	0.956E	11	0.403E	10	0.891E	11	86.6	22.78	14.72	29	22	95.00
695	694.0	0.957E	11	0.403E	10	0.891E	11	86.7	22.78	14.72	29	23	95.00
696	695.0	0.958E	11	0.403E	10	0.891E	11	86.8	22.78	14.72	29	24	95.00
697	696.0	0.959E	11	0.403E	10	0.891E	11	86.9	22.78	14.72	30	1	95.00
698	697.0	0.960E	11	0.403E	10	0.891E	11	87.0	22.78	14.72	30	2	95.00
699	698.0	0.961E	11	0.403E	10	0.891E	11	87.1	22.78	14.72	30	3	95.00
700	699.0	0.962E	11	0.403E	10	0.891E	11	87.2	22.78	14.72	30	4	95.00
701	700.0	0.963E	11	0.403E	10	0.891E	11	87.3	22.78	14.72	30	5	95.00
702	701.0	0.964E	11	0.403E	10	0.892E	11	87.5	22.78	14.72	30	6	95.00
703	702.0	0.965E	11	0.403E	10	0.892E	11	87.6	22.78	14.72	30	7	95.00
704	703.0	0.967E	11	0.403E	10	0.892E	11	87.7	22.78	14.72	30	8	95.00
705	704.0	0.968E	11	0.403E	10	0.892E	11	87.8	22.78	14.72	30	9	95.00
706	705.0	0.969E	11	0.403E	10	0.892E	11	87.9	22.78	14.72	30	10	95.00
707	706.0	0.970E	11	0.403E	10	0.892E	11	88.0	22.78	14.72	30	11	95.00
708	707.0	0.971E	11	0.403E	10	0.892E	11	88.1	22.78	14.72	30	12	95.00
709	708.0	0.972E	11	0.403E	10	0.892E	11	88.2	22.78	14.72	30	13	95.00
710	709.0	0.973E	11	0.403E	10	0.892E	11	88.3	22.78	14.72	30	14	95.00
711	710.0	0.974E	11	0.403E	10	0.892E	11	88.4	22.78	14.72	30	15	95.00
712	711.0	0.975E	11	0.403E	10	0.892E	11	88.5	22.78	14.72	30	16	95.00
713	712.0	0.976E	11	0.403E	10	0.892E	11	88.6	22.78	14.72	30	17	95.00
714	713.0	0.977E	11	0.403E	10	0.893E	11	88.8	22.78	14.72	30	18	95.00
715	714.0	0.978E	11	0.403E	10	0.893E	11	88.9	22.78	14.72	30	19	95.00
716	715.0	0.980E	11	0.403E	10	0.893E	11	89.0	22.78	14.72	30	20	95.00
717	716.0	0.981E	11	0.403E	10	0.893E	11	89.1	22.78	14.72	30	21	95.00
718	717.0	0.982E	11	0.403E	10	0.893E	11	89.2	22.78	14.72	30	22	95.00
719	718.0	0.983E	11	0.403E	10	0.893E	11	89.3	22.78	14.72	30	23	95.00
720	719.0	0.984E	11	0.403E	10	0.893E	11	89.4	22.78	14.72	30	24	95.00

Table 6.3. (Continued)

FOLLOWING ARE THE PARAMETERS OF THE NUMERICAL SCHEME.

DELTA = 60.00 FEET
DELTAI = 1.00 SEC
NSTEPS = 7200
PRNT = 30.00 MIN
NPRNT = 1
IMAX = 20
JMAX = 12

Table 6.4. Parameters of HYEDA Simulation Test Case II.

PROTOTYPE POND NUMBER TWO

30.0

7200

8

11

4

8

5

8

16

10

13

6

14

7

60.0

1.0

20

12

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

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0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

11.0

7.0

11.0

7.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

0.0

16.0

11.0

7.0

11.0

3.0

1

2

3

4

5

6

7

8

9

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Table 6.5. Input Data HEDM Simulation Test Case II.

Table 6.5. (Continued)

11.0	7.0	190
0.0	16.0	191
0.0	16.0	192
11.0	7.0	193
11.0	3.0	194
11.0	3.0	195
11.0	3.0	196
11.0	3.0	197
11.0	3.0	198
11.0	3.0	199
11.0	3.0	200
11.0	3.0	201
11.0	3.0	202
11.0	3.0	203
11.0	3.0	204
11.0	3.0	205
11.0	7.0	206
11.0	7.0	N 207
0.0	16.0	208
0.0	16.0	209
0.0	16.0	210
0.0	16.0	211
0.0	16.0	212
11.0	7.0	213
11.0	7.0	214
11.0	7.0	215
11.0	7.0	216
11.0	7.0	217
11.0	7.0	218
11.0	7.0	N 219
11.0	7.0	220
11.0	7.0	221
11.0	7.0	222
11.0	7.0	223
11.0	7.0	224
11.0	7.0	225
0.0	16.0	226
0.0	16.0	227
0.0	16.0	228
0.0	16.0	229
0.0	16.0	230
0.0	16.0	231
0.0	16.0	232
0.0	16.0	233
0.0	16.0	234
0.0	16.0	235
0.0	16.0	236
0.0	16.0	237
0.0	16.0	238
0.0	16.0	239
0.0	16.0	240
0.0	16.0	241
0.0	16.0	242
0.0	16.0	243
0.0	16.0	244
0.0	16.0	245
0.0	16.0	246
0.0	16.0	247
0.0	16.0	248
0.0	16.0	249
0.0	16.0	250
0.0	16.0	251
0.0	16.0	252

Table 6.5. (continued)

	1	3	72.0					253
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	254
	2							255
0.0	0.47222201							256
1.0	0.38888801							257
	1							258
0.0	0.95673607	0.000						259
	1							260
	25							261
	2	3	82.0					262
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	263
	2							264
0.0	0.47222201							265
1.0	0.38888801							266
	1							267
0.0	0.95673607	0.000						268
	1							269
	25							270
	3	3	92.0					271
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	272
	2							273
0.0	0.47222201							274
1.0	0.38888801							275
	1							276
0.0	0.95673607	0.000						277
	1							278
	25							279
	4	4	72.0					280
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	281
	2							282
0.0	0.47222201							283
1.0	0.38888801							284
	1							285
0.0	0.95673607	0.000						286
	1							287
	25							288
	5	4	82.0					289
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	290
	2							291
0.0	0.47222201							292
1.0	0.38888801							293
	1							294
0.0	0.95673607	0.000						295
	1							296
	25							297
	6	4	92.0					298
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	299
	2							300
0.0	0.47222201							301
1.0	0.38888801							302
	1							303
0.0	0.95673607	0.000						304
	1							305
	25							306
	7	5	72.0					307
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	308
	2							309
0.0	0.47222201							310
1.0	0.38888801							311
	1							312
0.0	0.95673607	0.000						313
	1							314
	25							315

		8	5	82.0				316
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	317
	2							318
0.0	0.47222201							319
1.0	0.38888801							320
	1							321
0.0	0.95673607	0.000						322
	1							323
	25							324
	9	5	92.0					325
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	326
	2							327
0.0	0.47222201							328
1.0	0.38888801							329
	1							330
0.0	0.95673607	0.000						331
	1							332
	45							333
	10	6	72.0					334
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	335
	2							336
0.0	0.47222201							337
1.0	0.38888801							338
	1							339
0.0	0.95673607	0.000						340
	1							341
	25							342
	11	9	82.0					343
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	344
	2							345
0.0	0.47222201							346
1.0	0.38888801							347
	1							348
0.0	0.95673607	0.000						349
	1							350
	25							351
	12	6	92.0					352
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	353
	2							354
0.0	0.47222201							355
1.0	0.38888801							356
	1							357
0.0	0.95673607	0.000						358
	1							359
	25							360
	13	13	42.0					361
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	362
	2							363
0.0	0.55555501							364
1.0	0.42592501							365
	1							366
0.0	0.13009008	0.000						367
	1							368
	26							369
	14	13	52.0					370
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	371
	2							372
0.0	0.55555501							373
1.0	0.42592501							374
	1							375
0.0	0.13009008	0.000						376
	1							377
	26							378
								379

Table 6.5. (Continued)

Table 6.5. (Continued)

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	15	13	62.0					380
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	381
	2							382
0.0	0.55555501							383
1.0	0.42592501							384
	1							385
0.0	0.13009008	0.000						386
	1							387
	26							388
1.3	16	13	72.0					389
	2.0	30.0	0.0	0.0	0.0	0.0	0.0	390
	2							391
0.0	0.55555501							392
1.0	0.42592501							393
	1							394
0.0	0.13009008	0.000						395
	1							396
	26							397
1.3	17	13	82.0					398
	2.0	30.0	0.0	0.0	0.0	0.0	0.0	399
	2							400
0.0	0.55555501							401
1.0	0.42592501							402
	1							403
0.0	0.13009008	0.000						404
	1							405
	26							406
1.3	18	13	92.0					407
	2.0	30.0	0.0	0.0	0.0	0.0	0.0	408
	2							409
0.0	0.55555501							410
1.0	0.42592501							411
	1							412
0.0	0.13009008	0.000						413
	1							414
	26							415
1.3	19	14	42.0					416
	2.0	30.0	0.0	0.0	0.0	0.0	0.0	417
	2							418
0.0	0.55555501							419
1.0	0.42592501							420
	1							421
0.0	0.13009008	0.000						422
	1							423
	26							424
1.3	20	14	52.0					425
	2.0	30.0	0.0	0.0	0.0	0.0	0.0	426
	2							427
0.0	0.55555501							428
1.0	0.42592501							429
	1							430
0.0	0.13009008	0.000						431
	1							432
	26							433
1.3	21	14	62.0					434
	2.0	30.0	0.0	0.0	0.0	0.0	0.0	435
	2							436
0.0	0.55555501							437
1.0	0.42592501							438
	1							439
0.0	0.13009008	0.000						440
	1							441
	26							442

	22	14	72.0					443
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	444
	2							445
0.0	0.55555501							446
1.0	0.42592501							447
	1							448
0.0	0.13009008	0.000						449
	1							450
	26							451
	23	14	82.0					452
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	453
	2							454
0.0	0.55555501							455
1.0	0.42592501							456
	1							457
0.0	0.13009008	0.000						458
	1							459
	26							460
	24	14	92.0					461
1.3	2.0	30.0	0.0	0.0	0.0	0.0	0.0	462
	2							463
0.0	0.55555501							464
1.0	0.42592501							465
	1							466
0.0	0.13009008	0.000						467
	1							468
	26							469
	25	8	11-1.0					470
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	471
	2							472
0.0	0.54444402							473
1.0	0.44444402							474
	0							475
	0							476
	26	16	10-1.0					477
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	478
	2							479
0.0	0.64444402							480
1.0	0.48888802							481
	0							482
	0							483
0.0	0.0							484
95.0	95.0	3.00						485
1.648	0.005							486

Table 6.5. (Continued)

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SYMBOLIC NAME	CONSTANT	VALUE	UNITS
AREA	SURFACE AREA	0.4860 06	FT**2
CSHE	COEFFICIENT OF SURFACE		
	HEAT EXCHANGE	0.00155	BTU/FT**2 SEC DEGREE F
DIF	DIFFUSIVITY	1.64800	FT**2/SEC
F	BED RESISTANCE COEFFICIENT	0.00900	DIMENSIONLESS
THEJA	WIND DIRECTION	0.0	RADIANS
W	WIND SPEED	0.0	KNOTS

[illegible]

THE FOLLOWING ARE THE INITIAL DEFINS.

Table 6.8. Typical Printout of U, V, D, and Temperature Excess at Specified Time Step HYDRA Simulation Test Case II.

AT NSTEPS = 7200 (TIME = 120.000 MINUTES), THE VALUES OF U (FT**2 / SEC) ARE																			
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	-0.02	-0.05	0.15	0.05	0.11	0.17	-0.12	-0.12	-0.11	-0.13	0.11	0.08	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	-0.01	-0.01	0.17	0.15	0.19	0.17	-0.03	-0.15	-0.21	-0.11	0.11	0.16	0.19	0.32	0.0	0.0	0.0	0.0
0.0	0.0	0.00	-0.01	0.09	0.13	0.17	0.13	-0.00	-0.11	-0.16	-0.07	0.07	0.16	0.22	0.25	-0.17	-0.17	-0.14	0.0
0.0	0.0	0.01	-0.01	0.05	0.10	0.14	0.09	-0.00	-0.12	-0.12	-0.03	0.05	0.11	0.16	0.13	-0.10	-0.17	-0.08	0.0
0.0	0.0	0.01	0.02	0.03	0.06	0.10	0.06	-0.02	-0.14	-0.12	-0.02	0.04	0.06	0.09	0.08	-0.00	-0.06	-0.02	0.0
0.0	0.0	-0.04	0.00	0.03	0.08	0.03	0.01	-0.04	-0.12	-0.13	-0.06	0.03	0.04	0.06	0.06	0.02	0.02	-0.01	0.0
0.0	0.0	0.0	0.01	0.00	0.09	-0.01	0.02	-0.00	-0.10	-0.14	-0.11	-0.03	0.01	0.05	0.07	0.06	0.07	0.00	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.14	-0.17	-0.13	-0.06	0.02	0.04	0.06	0.08	0.05	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.06	-0.01	0.04	-0.02	-0.02	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.07	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AT NSTEPS = 7200 (TIME = 120.000 MINUTES), THE VALUES OF V (FT**2 / SEC) ARE																			
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.01	0.01	-0.05	0.06	0.04	0.09	0.34	0.15	0.07	0.02	-0.04	0.04	0.05	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.04	0.06	0.06	0.13	0.15	0.17	0.23	0.20	0.16	0.12	0.08	0.12	0.12	0.12	0.62	0.0	0.0	0.0	0.0
0.0	0.03	0.04	0.04	0.09	0.12	0.15	0.19	0.19	0.20	0.15	0.11	0.13	0.18	0.25	0.38	0.16	0.02	-0.07	0.0
0.0	-0.01	0.01	-0.01	0.01	0.05	0.09	0.12	0.14	0.16	0.16	0.16	0.16	0.21	0.27	0.32	0.23	0.12	0.01	0.0
0.0	-0.03	-0.02	-0.00	-0.00	-0.02	0.05	0.11	0.12	0.10	0.12	0.15	0.16	0.18	0.22	0.25	0.22	0.15	0.06	0.0
0.0	0.0	0.07	0.08	0.10	0.02	0.07	0.07	0.04	0.02	0.03	0.08	0.13	0.16	0.17	0.16	0.12	0.07	0.05	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.06	-0.01	0.02	0.05	0.07	0.06	0.07	0.08	0.03	-0.02	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.06	0.01	-0.04	-0.07	0.01	0.04	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.10	-0.17	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AT NSTEPS = 7200 (TIME = 120.000 MINUTES), THE VALUES OF DEPTH (FT) ARE																			
*****	4.01	4.01	4.01	4.02	4.02	4.01	3.99	4.00	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.00	*****	*****	*****
*****	4.01	8.01	8.01	8.01	8.01	8.01	8.00	8.01	8.01	8.01	8.01	8.02	8.02	8.01	8.01	4.00	*****	*****	*****
*****	4.02	8.01	8.01	8.02	8.02	8.02	8.02	8.01	8.02	8.02	8.02	8.02	8.02	8.01	8.01	4.01	4.00	4.00	*****
*****	4.02	8.01	8.01	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.01	8.01	8.01	8.01	4.01	*****
*****	4.02	8.01	8.01	8.01	8.02	8.02	8.02	8.01	8.01	8.01	8.01	8.02	8.02	8.02	8.01	8.01	8.01	4.02	*****
*****	4.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.02	8.01	8.01	8.01	8.01	4.01	*****
*****	4.01	4.03	4.01	4.00	4.01	8.01	8.01	8.00	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	4.00	*****
*****	4.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	4.01	4.01	*****	*****
*****	4.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	4.00	4.00	*****	*****
*****	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	4.01	*****
AT NSTEPS = 7200 (TIME = 120.000 MINUTES), THE VALUES OF TEMPERATURE EXCESS (DEGREES F) ARE																			
*****	1.00	1.18	1.34	1.43	1.39	1.22	0.94	0.21	0.36	0.53	0.83	1.13	1.24	*****	*****	*****	*****	*****	*****
*****	1.33	1.67	1.91	1.98	1.86	1.47	1.03	0.53	0.48	0.69	1.15	1.78	2.01	1.98	1.66	*****	*****	*****	*****
*****	1.80	2.64	2.97	3.02	2.75	1.84	1.15	0.68	0.60	0.91	1.67	3.08	3.30	2.41	1.58	0.40	0.19	0.11	*****
*****	1.99	2.92	3.26	3.28	2.94	1.91	1.15	0.72	0.67	1.05	1.97	3.59	3.76	2.61	1.58	0.66	0.28	0.14	*****
*****	1.84	2.66	2.95	2.95	2.61	1.64	0.99	0.65	0.67	1.11	2.09	3.76	3.98	2.64	1.57	0.77	0.35	0.18	*****
*****	1.43	1.60	1.72	1.70	1.50	1.09	0.72	0.53	0.62	1.09	2.09	3.76	3.85	2.55	1.52	0.79	0.38	0.20	*****
*****	1.11	1.14	1.12	0.99	0.77	0.54	0.42	0.55	1.02	1.96	3.56	3.63	2.34	1.39	0.77	0.40	0.22	*****	*****
*****	0.88	1.24	1.66	1.76	1.42	1.08	*****	0.33	0.49	0.91	1.67	3.04	3.07	1.95	1.22	0.73	0.43	*****	*****
*****	1.16	1.17	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****

1 t	TOTAL HEAT LOAD, BTU	TOTAL HEAT DISSIPATED, BTU	HEAT STORED, BTU	TOTAL WATER LOSS, FT**3	EXCESS TEMPERATURES, DEGREES F			
0.50	0.1350 09	0.4110 08	0.9140 08	0.7330 04	T(8,11) =	0.06	T(4, 8) =	1.42
					T(5, 8) =	1.43	T(16,10) =	0.25
					T(13, 6) =	1.66	T(14, 7) =	1.67
1.00	0.2710 09	0.8500 08	0.1770 09	0.1470 05	T(8,11) =	0.32	T(4, 8) =	2.19
					T(5, 8) =	2.21	T(16,10) =	0.78
					T(13, 6) =	2.53	T(14, 7) =	2.59
1.50	0.4060 09	0.1280 09	0.2580 09	0.2050 05	T(8,11) =	0.62	T(4, 8) =	2.79
					T(5, 8) =	2.81	T(16,10) =	1.23
					T(13, 6) =	3.23	T(14, 7) =	3.33
2.00	0.5420 09	0.1750 09	0.3370 09	0.2630 05	T(8,11) =	0.94	T(4, 8) =	3.26
					T(5, 8) =	3.28	T(16,10) =	1.66
					T(13, 6) =	3.76	T(14, 7) =	3.90

Table 6.9. Summary Time Running Heat Budget, Water Loss, and Temperature Excess at Selected Points HERTS Simulation Test Case II.

APPENDIX A
DERIVATION OF METMIN PLUG FLOW HEAT BUDGET EQUATIONS

1. Basic heat budget is:

$$D \frac{\partial \theta}{\partial t} + Q \frac{\partial \theta}{\partial A} + \frac{K}{\rho c_p} \theta = 0 \quad (A.1)$$

where:

ρ = Specific weight, in LB Ft^{-3} , c_p = specific heat, in $\text{Btu Lb}^{-1} \text{ } ^\circ\text{F}^{-1}$

D = depth, in Ft.

A = surface area, in Ft^2 .

Q = flow rate through pond (any change with time felt instantaneously), in $\text{Ft}^3 \text{ Sec}^{-1}$

K = coefficient of surface heat exchange, in $\text{Btu Ft}^{-2} \text{ Sec}^{-1} \text{ } ^\circ\text{F}^{-1}$.

$\theta(A,t)$ = temperature excess at area "A" away from pond inlet and at time "t", in $^\circ\text{F}$

2. Form of finite differences: choose forward in time and space for unconditionally stable iterative (implicit) solution. Divide pond into equal area segments, " ΔA ", between inlet and outlet

Difference form of (A.1) is:

$$\frac{D}{\Delta t} (TP(A+\Delta A) - T(A+\Delta A)) + \frac{Q}{\Delta A} (TP(A+\Delta A) - TP(A)) + \frac{K}{\rho c_p} [TP(A+\Delta A)] = 0 \quad (A.2)$$

where:

TP = T-prime or temperature excess at new time step

T = temperature excess at present time step

D = pond depth

Solve for TP(A+ΔA):

$$TP(A+\Delta A) \left[\frac{D}{\Delta t} + \frac{Q}{\Delta A} + \frac{K}{\rho c_p} \right] = TP(A) \left[\frac{Q}{\Delta A} \right] + \frac{D}{\Delta t} T(A+\Delta A)$$

multiply through by Δt/D giving:

$$TP(A+\Delta A) \left[1 + \frac{Q\Delta t}{\Delta A} + \frac{K\Delta t}{\rho c_p D} \right] = TP(A) \left[\frac{Q\Delta t}{D\Delta A} \right] + T(A+\Delta A)$$

Solve for TP(A+ΔA)

$$TP(A+\Delta A) = [TP(A) \frac{Q\Delta t}{D\Delta A} + T(A+\Delta A)] / \left[1 + \frac{Q\Delta t}{\Delta A} + \frac{K\Delta t}{\rho c_p D} \right] \quad (A.3)$$

Note: If we use $(TP(A) + TP(A+\Delta A))/2$ in surface dissipation, we have the restriction that $Q/D\Delta A \geq K/2\rho c_p D$ for stable solution. This is eliminated by taking dissipation at TP(A+ΔA) which slightly over-estimates this term.

2. Computational procedure

Begin computations with $T(A+\Delta A) = 0$ at $t = 0$.

Recirculation Condition: Index A = 1 at inlet, A = NAREA + 1 at outlet. Thus

$$TP(1) = [T(NAREA + 1) + \frac{H(t)}{\rho c_p Q} (1 - Fhl/100.0)]$$

Gives new TP(1) to iterate over area TP(A,1) to TP(NAREA+1) at each time step. Fhl = percent heat loss attributable to sprays.

TP(NAREA+1) at pond outlet known at end of each definition DELT computation to begin new definition DELT.

APPENDIX B

METMIN USER GUIDE AND PROGRAM LISTING

The METMIN routine computes ambient temperatures and the coefficient of surface heat exchange from meteorological conditions, as well as estimating temperature excesses from a simple plug flow-heat budget computation. Two general steps in METMIN are:

1. Estimating time increment for plug flow-heat budget computations, and
2. Establishing input parameters

Estimating Time Steps for Plug Flow Heat Budget

DELT = time step (hours in plug flow computation)

NAREA = number of segments of total area for plug flow computations
(integer)

NTSP = number of time steps desired in simulation (integer).

Note that total simulation time will be NTSP*DELT hours.

(The program is already set for DELT = 1.0 hour. Thus

NTSP = hours of simulation for this arrangement.)

NPRNT = number of DELT's between print steps (integer).

NPRNT*DELT is the point time interval (hours).

Values of DELT = 1.0, NAREA = 50, NPRNT = 1 will generally be adequate for small ponds - such values have been preset in the program. Different values of these parameters can be easily utilized by changing the individual statements within the program.

Data Input Requirements

V = pond volume (ft^3)

SA = pond surface area (ft^2)

C = pond perimeter (ft)

NFRS = number of temporal flow regimes (integer). For each regime, I, one must specify:

FR(I,1) = time flow regime turned on (hours)
(in ascending order)

FR(I,2) = regime's constant flow rate (cfs)

NHRFS = number of temporal heat regime (integer). For each regime, J, one must specify:

HRF(J,1) = time heat regime turned on (hours)
(in ascending order)

HRF(J,2) = constant heat release rate (Btu hr^{-1})

HRF(J,3) = slope of log-time heat release rate (Btu hr^{-1})

DWL = spray percentage wind loss

EWL = spray percentage evaporative water loss

PHL = percentage heat loss

F = dimensionless friction factor for use in thermal diffusivity estimate.

FRMAX = maximum inflow rate during simulation (cfs) for use in thermal diffusivity estimate

MDT = specification of type of meteorological calculation (integer).

For "partial met data" specify 0, for "complete met data" specify 1). If MDT = 0, one must specify:

PT = constant ambient pond temperature ($^{\circ}\text{F}$)

AT = constant air temperature ($^{\circ}\text{F}$)

DDPT = constant dew point temperature ($^{\circ}\text{F}$)

WWS = constant cooling wind speed (mph)

For MDT = 1 specify:

NMET = number of changes (regimes) in meteorological data
(integer). For each regime K, specify:

TOMET(K) = time on (hours) for this regime (in ascending
order)

XHSMX(K) = noontime short wave radiation ($\text{Btu ft}^{-2} \text{ Day}^{-1}$)

HATMX(K) = daily maximum air temperature ($^{\circ}\text{F}$)

HATMN(K) = daily minimum air temperature ($^{\circ}\text{F}$)

XHDPX(K) = daily maximum dew point temperature ($^{\circ}\text{F}$)

XHDPMN(K) = daily minimum dew point temperature ($^{\circ}\text{F}$)

WS(K) = cooling wind speed (mph).

Assembling Data Deck

With the exception of the first card (which contains a job title) all input cards should be considered as divided into eight sections each of ten columns. Within each column all data must be right justified. (Refer to Fig. B.1).

CARD #1 (columns 2-80) JOB TITLE (any alphanumeric)

<u>CARD #</u>	<u>Columns 1-10</u>	<u>Columns 11-20</u>	<u>Columns 21-30</u>	<u>Card Format</u>
2	V	SA	C	(E)
3	NTSP			(I)
4	NFRS(=I)			(I)
5 thru (I+4)	FR(I,1)	FR(I,2)		(E)
(I+5)	NHRFS(=J)			(I)
(I+6) thru (I+5+J)	HRF(J,1)	HRF(J,2)	HRF(J,3)	(E)
(I+J+6)	DWL	EWL	PHL	(F)

<u>CARD #</u>	<u>Columns 1-10</u>	<u>Columns 11-20</u>	<u>Columns 21-30</u>	<u>Card Format</u>
(I+J+7)	F	PRMAX		(F)
(I+J+8)	MDT			(I)

If MDT = 0:

CARD (I+J+9): (F format)

Columns 1-10: PT
 Columns 11-20: AT
 Columns 21-30: DDPT
 Columns 31-40: WWS

If MDT = 1:

CARD (I+J+9): (I format)

Columns 1-10: NMET (-K)

CARDS (I+J+10) thru (I+J+K+9): (F format)

Columns 1-10: TONMET(K)
 Columns 11-20: XHHSMX(K)
 Columns 21-30: HATMX(K)
 Columns 31-40: HATMN(K)
 Columns 41-50: XHDPMX(K)
 Columns 51-60: XHDPMN(K)
 Columns 61-70: WS(K)

Fig. B.1. METMIN Data Deck Assembly.

```

C      ***** PROGRAM LISTING *****
C      *
C      *
C-----*
C      *          METHIN
C      *
C      *
C      *****
C      *****
C-----*
C      *
C      *****
C      *****
C      *
C-----*
C      *          ALPHABETICAL LISTING OF CONSTANTS AND
C      *          VARIABLES USED IN PROGRAM METHIN
C      *
C      *
C-----*
C      *          AD=AVERAGE POND DEPTH (FEET)
C      *
C-----*
C      *          ALPHA= TIME FROM NOON TO MAX HOURLY AMBIENT POND
C      *                   TEMPERATURE AVERAGED OVER ALL PERIODS IN
C      *                   COMPLETE MET DATA CALCULATION
C      *
C-----*
C      *          AMPI= HOURLY AMBIENT POND TEMPERATURE (DEG F)
C      *
C-----*
C      *          APTDPI= AVERAGE OF POND TEMPERATURE AND DEW POINT TEMP
C      *                   (FOR PARTIAL MET DATA)
C      *
C-----*
C      *          AT= AIR TEMPERATURE, FOR PARTIAL MET DATA (DEG F)
C      *
C-----*
C      *          AV= AVERAGE FLOW VELOCITY IN POND AT MAXIMUM FLOW
C      *                   RATE (FT/SEC)
C      *
C-----*
C      *          BETA= SLOPE OF SATURATION VAPOR-PRESSURE VS WATER
C      *                   TEMPERATURE CURVE (MM-H2O/DEG F) AVERAGED OVER ALL
C      *                   PERIODS IN COMPLETE MET DATA CALCULATION
C      *
C-----*
C      *          C= POND PERIMETER (FEET)
C      *
C-----*
C      *          CP= SPECIFIC HEAT OF WATER (BTU/LB DEGREE F)
C      *
C-----*
C      *          CS1= COMPUTED CONSTANT FOR USE IN CALCULATION
C      *
C-----*
C      *          CS2= COMPUTED CONSTANT FOR USE IN CALCULATION
C      *
C-----*
C      *          CS3= COMPUTED CONSTANT FOR USE IN CALCULATION
C      *
C-----*
C      *          CS4= COMPUTED CONSTANT FOR USE IN CALCULATION
C      *
C-----*
C      *          CS5= COMPUTED CONSTANT FOR USE IN CALCULATION
C      *
C-----*
C      *          CSHE= COEFFICIENT OF SURFACE HEAT EXCHANGE
C      *                  (BTU/FI**2 DAY DEG F) AVERAGED OVER ALL PERIODS
C      *                  IN COMPLETE MET DATA CALCULATION
C      *
C-----*
C      *          DECA=SEGMENT AREA IN POND (FT**2)
C      *
C-----*
C      *          DELT= TIME STEP IN INTEGRATION (HOURS)
C      *
C-----*
C      *          DPDT= DEW POINT TEMPERATURE (DEG F) FOR PARTIAL MET DATA

```

```

C      *
C      *      OPT= DEW POINT TEMPERATURE (DEG F) AVERAGED OVER ALL
C      *      PERIODS IN COMPLETE MET DATA
C      *
C      *      OWL=SPRAY PERCENTAGE WIND LOSS
C      *
C      *      E= THERMAL DIFFUSIVITY ESTIMATE FOR MAIN (FT**2/SEC)
C      *
C      *      ETA= EQUILIBRIUM TEMPERATURE AMPLITUDE (DEG F)
C      *
C      *      EWL= SPRAY PERCENTAGE EVAPORATIVE WATER LOSS
C      *
C      *      F= DIMENSIONLESS FRICTION FACTOR
C      *
C      *      FFW= SURFACE EVAPORATION WIND SPEED FUNCTION (FOR
C      *      PARTIAL MET DATA)
C      *
C      *      FRMAX= MAXIMUM INFLOW RATE DURING SIMULATION (CFS)
C      *
C      *      FWS(I)= SURFACE EVAPORATION WIND SPEED FUNCTION FOR
C      *      I-TH PERIOD (IN COMPLETE MET DATA)
C      *
C      *      GAMMA= SPECIFIC WEIGHT OF WATER (LBS/FT**3)
C      *
C      *      HATMIN(I)= DAILY MINIMUM AIR TEMPERATURE (DEG F) FOR
C      *      I-TH PERIOD (IN COMPLETE MET DATA)
C      *
C      *      HATMX(I)= DAILY MAXIMUM AIR TEMPERATURE (DEG F) FOR
C      *      I-TH PERIOD (IN COMPLETE MET DATA)
C      *
C      *      HDPTM= DAILY MIN DEW POINT TEMPERATURE (DEG F) AVERAGED
C      *      OVER ALL PERIODS IN COMPLETE MET DATA CALCULATION
C      *
C      *      HDPTMX= DAILY MAX DEW POINT TEMPERATURE (DEG F) AVERAGED
C      *      OVER ALL PERIODS IN COMPLETE MET DATA CALCULATION
C      *
C      *      HHSMX= NCNTRIME SHORT WAVE RADIATION (BTU/FT**2 DAY)
C      *
C      *      HLW= LATENT HEAT OF VAPORIZATION (BTU/LB)
C      *
C      *      HM= HEAT RELEASE RATE AT ANY TIME THR (BTU/HR)
C      *
C      *      MDT= METEOROLOGICAL DATA TYPE, INTEGER (0= PARTIAL,
C      *      1= COMPLETE)
C      *
C      *      NAREA= NUMBER OF AREA SEGMENTS
C      *
C      *      NFRS= NUMBER OF TEMPORAL FLOW REGIMES
C      *
C      *      FR(I,1)= TIME FLOW REGIME ON (HOURS)
C      *
C      *      FR(I,2)= CONSTANT FLOW RATE (CFS)
C      *
C      *      NHRFS= NUMBER OF TEMPORAL HEAT REGIMES
C      *
C      *      HRF(I,1)= TIME HEAT REGIME ON (HOURS)
C      *
C      *      HRF(I,2)= CONSTANT HEAT RELEASE RATE (BTU/HR)
C      *
C      *      HRF(I,3)= SLOPE OF LOG-TIME HEAT RELEASE RATE
C      *      (BTU / HR)
C      *

```

C	*	NDAY= DAY NUMBER	*
C	*		*
C	*	NMET= NUMBER OF CHANGES IN METEOROLOGICAL DATA	*
C	*		*
C	*	NPKNT= NUMBER OF DELT BETWEEN RESULTS PRINTED OUT	*
C	*		*
C	*	NTSP= NUMBER OF TIME STEPS FOR SIMULATION	*
C	*		*
C	*	P(I)= POND TEMPERATURE USED IN COMPUTATIONS (DEG F)	*
C	*		*
C	*	PHL= PERCENTAGE HEAT LOSS (FOR USE IN PARTIAL MET DATA)	*
C	*		*
C	*	PL= PHASE LAG FOR USE IN COMPUTATIONS	*
C	*		*
C	*	PT= POND TEMPERATURE (DEGREE F)	*
C	*		*
C	*	PTA= POND TEMPERATURE AMPLITUDE (DEG F) AVERAGED	*
C	*	OVER ALL PERIODS IN COMPLETE MET DATA CALCULATION	*
C	*		*
C	*	PTM= DAILY MEAN POND TEMPERATURE (DEG F) AVERAGED	*
C	*	OVER ALL PERIODS IN COMPLETE MET DATA CALCULATION	*
C	*		*
C	*	PTMX= MAXIMUM POND TEMPERATURE (DEGREE F)	*
C	*		*
C	*	QM= FLOW RATE FOR USE IN COMPUTATIONS	*
C	*		*
C	*	SA= TOTAL AREA (FT**2)	*
C	*		*
C	*	SUMM(I,J)= SUMMARY RESULTS MATRIX (LISTED IN PROGRAM)	*
C	*		*
C	*	THR= TIME CLOCK (HOURS) FOR SIMULATION	*
C	*		*
C	*	TM(M)= TEMPERATURE EXCESS AT POND SEGMENTS,	*
C	*	PRESENT VALUES, (DEGREE F)	*
C	*		*
C	*	TONMET(I)= TIME ON (HOURS) FOR I-TH PERIOD CHANGE IN	*
C	*	MET CONDITIONS (IN COMPLETE MET DATA)	*
C	*		*
C	*	TPM(M)= TEMPERATURE EXCESS AT POND SEGMENTS,	*
C	*	NEW TIME (DEGREE F)	*
C	*		*
C	*	TX= DIFFERENCE IN TEMPERATURE EXCESS BETWEEN	*
C	*	ADJACENT POND SEGMENTS	*
C	*		*
C	*	V= POND VOLUME (FT**3)	*
C	*		*
C	*	WS(I)= COOLING WIND SPEED (MPH) FOR I-TH PERIOD (IN	*
C	*	COMPLETE MET DATA)	*
C	*		*
C	*	WWS= COOLING WIND SPEED (MPH) FOR PARTIAL MET DATA	*
C	*		*
C	*	XALPHA(I)= TIME FROM NOON TO MAX HOURLY AMBIENT POND	*
C	*	TEMPERATURE FOR I-TH PERIOD (IN COMPLETE	*
C	*	MET DATA)	*
C	*		*
C	*	XDETA(I)= SLOPE OF SATURATION VAPOR-PRESSURE VS WATER	*
C	*	TEMPERATURE CURVE (MM-HG/DEG F) FOR I-TH	*
C	*	PERIOD (IN COMPLETE MET DATA)	*
C	*		*
C	*	XCSHE(I)= COEFFICIENT OF SURFACE HEAT EXCHANGE	*
C	*	(BTU/FT**2 DAY DEG F) FOR I-TH PERIOD	*
C	*	(IN COMPLETE MET DATA)	*
C	*		*

```
*
C *      XDPT(I)= AVERAGE OF MIN & MAX DEW POINT TEMPERATURES
C *          FOR I-TH PERIOD (DEG F) (IN COMPLETE MET DATA)
C *
C *      XHDPMN(I)= DAILY MIN DEW POINT TEMPERATURE (DEG F) FOR
C *          I-TH PERIOD (IN COMPLETE MET DATA)
C *
C *      XHDPMX(I)= DAILY MAX DEW POINT TEMPERATURE (DEG F) FOR
C *          I-TH PERIOD (IN COMPLETE MET DATA)
C *
C *      XHHSMX(I)= NOONTIME SHORT WAVE RADIATION FOR I-TH
C *          PERIOD (IN COMPLETE MET DATA)
C *
C *      XPTA(I)= POND TEMPERATURE AMPLITUDE (DEG F) FOR I-TH
C *          PERIOD (IN COMPLETE MET CALCULATION)
C *
C *      XPTM(I)= DAILY MEAN POND TEMPERATURE FOR I-TH PERIOD
C *          (IN COMPLETE MET DATA)
C *
C *
C *
C *****
C *****
C
C
C
C
REAL*8 TITLE(9)
DIMENSION TONMET(50), XHHSMX(50), HATMX(50), HAIMN(50),
1 XHDPMT(50), XHDPMN(50), WS(50), XDPT(50), FWS(50),
2 XBETA(50), XCSE(50), XPTM(50), AMPT(3600), P(6), XPTA(50),
3 XALPHA(50)
DIMENSION TM(100), TPM(100), FR(20,2), HRF(20,3), SUNN(0,3600)
C
C
C *****
C *****
C
C      INITIALIZE AND READ IN DATA
C
C *****
C *****
C
DATA GAMMA, CP /62.4, 1.0/
DATA HLV /1000.0/
DELTA= 1.0
NAREA= 50
NPRNT= 1
C
10 FORMAT(8I10)
20 FORMAT(8F10.4)
30 FORMAT(8E10.4)
35 FORMAT(10A8)
C
READ(5,35) (TITLE(I), I= 1,9)
READ(5,30) V, SA, C
READ(5,10) NTSP
READ(5,10) NFRS
DO 40 I= 1, NFRS
READ(5,30) (FR(I,J), J=1,2)
40 CONTINUE
READ(5,10) NHRFS
DO 50 I = 1, NHRFS
--- READ(5,30) (HRF(I,J), J= 1,3)
```

```

50 CONTINUE
  READ(5,20) DWL, EWL, PHL
  READ(5,20) F, FRMAX

```

```

C -----
C
C *****
C *
C *      COMPLETE AVERAGE DEPTH (FEET)
C *
C *****

```

```

C
C      AD = V / SA

```

```

C *****
C *
C *      COMPUTE VAPOR-PRESSURE SLOPE, COEFFICIENT OF SURFACE
C *      HEAT EXCHANGE, AND, IF COMPLETE METEOROLOGICAL DATA
C *      REQUESTED, THEN ALSO MEAN DAILY AMBIENT WATER
C *      TEMPERATURE, MAXIMUM HOURLY AMBIENT WATER TEMPERATURE
C *      AND ITS TIME FROM NOON.
C *
C *****

```

```

C
C      READ(5,10) MDI
C      IF(MDI.EQ.1) GO TO 70
C      READ(5,20) PT, AT, DQPT, WWS
C      DPT= DDPT
C      APTDPT= 0.5 * (PT + DLPT)
C      BETA = 0.255 - 0.0085 * APTDPT + 0.000204 * APTDPT * APTDPT
C      FFW= 70.0 + 0.70 * WWS * WWS
C      CSHE= 15.7 + FFW * (BETA + 0.26)
C      PTM = PT
C      PTA= 0.0
C      ALPHA= 0.0
C      GO TO 180
C      70 READ(5,10) NMET
C      80 FORMAT(7F10.3)

```

```

C
C      DO 90 I= 1, NMET
C      READ(5,80) YDNMET(I), XHSMX(I), HATMX(I), HATMN(I),
C      1 XHOPMX(I), XHOPMN(I), WS(I)
C      90 CONTINUE

```

```

C
C      DO 120 K= 1, NMET
C      XDPT(K)= 0.5 * (XHOPMX(K) + XHOPMN(K))
C      FWS(K)= 70.0 + 0.70 * WS(K) * WS(K)
C      P(1)= 0.50 * (HATMX(K) + HATMN(K))

```

```

C
C      DO 100 J= 2,5
C      APTDPT = (P(J-1) + XDPT(K)) / 2.0
C      XBETA(K)= 0.255 - 0.0085*APTDPT + 0.000204*APTDPT*APTDPT
C      XCSHE(K)= 15.7 + FWS(K)*(XBETA(K) + 0.26)
C      P(J)= XHSMX(K) / (3.0*XCSHE(K)) + (0.26*P(1) + XBLTA(K)*XDPT(K))
C      1 / (XBETA(K) + 0.26)

```

```

C
C      PJ= P(J)
C      IF(ABS(P(J)-P(J-1)).LE.0.50) GO TO 110

```

```

C      100 CONTINUE

```

```

C      110 XPTM(K)= PJ

```

```

C
C      120 CONTINUE

```

```

C
DO 130 K= 1, NMET
  ETA= 0.5 * (XHDPMX(K)-XHDPMN(K)+XHHSMX(K)/XCSHE(K))
  PL= 6.283186 * AD * GAMMA * CP / XCSHE(K)
  XPTA(K)= ETA / SQRT(1.0 + PL*PL)
  XALPHA(K)= ATAN(PL)
130 CONTINUE
C
  A1= 0.0
  A2= 0.0
  A3= 0.0
  A4= 0.0
  A5= 0.0
  A6= 0.0
  A7= 0.0
  A8= 0.0
  A9= 0.0
C
DO 140 K= 1, NMET
  A1= A1 + XDPT(K)
  A2= A2 + XBETA(K)
  A3= A3 + XCSHE(K)
  A4= A4 + XPTA(K)
  A5= A5 + XHDPMX(K)
  A6= A6 + XHDPMN(K)
  A7= A7 + XHSMX(K)
  A8= A8 + XPTA(K)
  A9= A9 + XALPHA(K)
140 CONTINUE
C
C
  FACTOR= 1.0 / FLOAT(NMET)
C
  DPT= A1 * FACTOR
  BETA= A2 * FACTOR
  CSHE= A3 * FACTOR
  PTA= A4 * FACTOR
  HDPTMN= A5 * FACTOR
  HDPTMX= A6 * FACTOR
  HSMX= A7 * FACTOR
  PTA= A8 * FACTOR
  ALPHA= A9 * FACTOR
C
C
C
C
--- IF(NMET.EQ.1) GO TO 165
  NMETM1= NMET - 1
  DO 160 J= 1, NMETM1
C
  DT= TONMET(J+1) - TONMET(J)
  NN= 1 + IFIX(DT)
C
  DO 150 N= 1, NN
    KK= N + IFIX(1.0/DT)
C
    AMPT(KK)= XPTM(J) + (XPTM(J+1)-XPTM(J))*FLOAT(N) /
    1 (TONMET(J+1) - TONMET(J) -XPTA(J)*COS(6.28*FLOAT(KK-1)/24.0
    2 -XALPHA(J))
C
150 CONTINUE
160 CONTINUE
165 CONTINUE

```

```

C      LI= IFIX(NTSP*DELTA(NMET)) + 1
C      L2= NTSP * IFIX(DELTA)
C
C      DO 170 L= L1, L2
C        AMPT(L)= XPTM(NMET) -XPTA(NMET)*COS(6.28*FLUAT(L-1)/24.0
C        1 -XALPHA(NMET))
C      170 CONTINUE
C
C
C      *****
C      *
C      *----- PRINT OUT DATA JUST READ IN AS WELL AS
C      *      COMPUTED VARIABLES, PARAMETERS, ETC.
C      *
C      *****
C
C      180 WRITE(6,750)
C      WRITE(6,35) (TITLE(I),I=1,9)
C      WRITE(6,190)
C      190 FORMAT('0', 'DATA, AS INPUT:')
C      WRITE(6,200)
C      200 FORMAT('0', '      V              SA              C')
C      WRITE(6,210) V, SA, C
C      210 FORMAT(' ', 3(E10.4,5X))
C      WRITE(6,220)
C      220 FORMAT('0', '      NTSP')
C      WRITE(6,310) NTSP
C      230 FORMAT('0', '      NFRS')
C      WRITE(6,310) NFRS
C      WRITE(6,240)
C      240 FORMAT('0', '      FR(J,1)      FR(J,2)')
C      DO 250 I= 1, NFRS
C      WRITE(6,320) (FR(I,J), J= 1,2)
C      250 CONTINUE
C      WRITE(6,260)
C      260 FORMAT('0', '      NHRFS')
C      WRITE(6,310) NHRFS
C      WRITE(6,270)
C      270 FORMAT('0', '      HRF(J,1)      HRF(J,2)      HRF(J,3)')
C      DO 280 I= 1, NHRFS
C      WRITE(6,330) (HRF(I,J), J= 1,3)
C      280 CONTINUE
C      WRITE(6,290)
C      290 FORMAT('0', '      DWL      EWL      PHL')
C      WRITE(6,320) DWL, EWL, PHL
C      WRITE(6,300)
C      300 FORMAT('0', '      F      FRMAX')
C      WRITE(6,320) F, FRMAX
C      310 FORMAT(' ', 6I10)
C      320 FORMAT(' ', 6F10.4)
C      330 FORMAT(' ', F10.4, 5X, E10.4, 5X, E15.4)
C      WRITE(6,340)
C      340 FORMAT('0', '      MDT')
C      WRITE(6,310) MDT
C      IF(MDT.EQ.1) GO TO 360
C      WRITE(6,350)
C      350 FORMAT('0', '      PT      AT      DOPT      WWS')
C      WRITE(6,320) PT, AT, DOPT, WWS
C      GO TO 400
C      360 WRITE(6,370)
C      370 FORMAT('0', '      NMET')

```



```

WRITE(6,310) NMET
WRITE(6,380)
380 FORMAT('0', ' TONMET XHSMX HATMX HATMN XHOPMX
1 XHOPMN WS ')
DO 390 I= 1, NMET
WRITE(6,80) TONMET(I), XHSMX(I), HATMX(I), HATMN(I),
1XHOPMX(I), XHOPMN(I), WS(I)
390 CONTINUE

```

```

C
C
400 AV= C * FRMAX / (2.0 * V)
C

```

```

WRITE(6,750)
WRITE(6,35) (TITLE(1),1=1,9)
WRITE(6,410)
410 FORMAT('0', 'COMPUTED PARAMETERS:')
WRITE(6,420) CSHE
420 FORMAT('0', 'CSHE = ', F10.4, ' BTU / FT** 2 * DAY * DEGREE F')
WRITE(6,430) PTM
430 FORMAT('0', 'PTM = ', F10.4, ' DEGREES F')
WRITE(6,440) PTA
440 FORMAT('0', 'PTA = ', F10.4, ' DEGREES F')
WRITE(6,450) ALPHA
450 FORMAT('0', 'ALPHA = ', F10.4, ' RADIANS')

```

```

C
C
C *****
C *
C * ESTIMATE DIF FROM AVERAGE FLOW VELOCITY *
C * USING TAYLOR FORMULA *
C *
C *****
C
E= 14.3 * SQRT(2.0) * 2.0 * AV * SQRT(SA*F) * AD /
1 (SQRT(SA) * 2.0 * AD)

```

```

C
WRITE(6,460) E
460 FORMAT('0', 'E = ', F10.4, ' FT**2 / SEC')

```

```

C
C *****
C *
C * COMPUTED CONSTANTS USED IN CALCULATIONS *
C *
C *****
C

```

```

DELA= SA/FLOAT(NAREA)
NPT= NAREA + 1
CS1= 2.0*DELT*3600.0/(DELA*AD)
CS2= CSHE * DELT / (24.0 * GAMMA * CP * AD)
CS3= CSHE * DELA * DELT / 48.0
CS4= GAMMA * CP * DELA * AD / 2.0
CS5= (CSHE-15.7)*BETA*DELA*DELT / (48.0*HLV*GAMMA*(10.26+BETA))

```

```

C
C *****
C *
C * SUMMARY RESULTS MATRIX *
C *
C * SUMM(1,N)= TEMPERATURE OF INLET *
C * SUMM(2,N)= TEMPERATURE OF OUFLET *
C * SUMM(3,N)= ACCUMULATED SURFACE HEAT DISSIPATION *
C * SUMM(4,N)= HEAT IN STORAGE *
C * SUMM(5,N)= ACCUMULATED WATER LOSS *

```

```

C      * SUMM16,N1= ACCUMULATED REACTOR HEAT
C      *
C      *****
C
SUMM11,1)= 0.0
SUMM12,1)= 0.0
SUMM13,1)= 0.0
SUMM14,1)= 0.0
SUMM15,1)= 0.0
SUMM16,1)= 0.0
C
C      DO 470 M= 1, NP1
C
      TM(M)= 0.0
      TPM(M)= 0.0
470 CONTINUE
C
C      *****
C      *
C      *      BEGIN TIME AND AREA SEGMENT ITERATIONS ON POND
C      *      TEMPERATURE EXCESS, ACCUMULATING HEAT DISSIPATED
C      *      AND WATERLOSS.
C      *
C      *****
C
C      DO 550 N= 2, NYSP
C
      THR= FLOAT(N-1)*DELT
C
      DO 480 M= 1, NP1
      TPM(M)= 0.0
480 CONTINUE
C
      SUMM13,N)= SUMM13,N-1)
      SUMM15,N)= SUMM15,N-1)
      SUMM16,N)= SUMM16,N-1)
      DO 490 K= 1, NFRS
      IF (THR.GT.FRI(K,1)) GO TO 490
      QM= FRI(K-1,2)
      GO TO 500
490 CONTINUE
      QM= FR(NFRS,2)
500 CONTINUE
C
      DO 510 K= 1, NHRFS
      IF (THR.GT.HRF(K,1)) GO TO 510
      HM= HRF(K-1,2) + HRF(K-1,3)*ALOG10(THR)
      GO TO 520
510 CONTINUE
      HM= HRF(NHRFS,2) + HRF(NHRFS,3)*ALOG10(THR)
520 CONTINUE
      IF (HM.LE.0.0) HM= 0.0
C
C
      SUMM14,N)= 0.0
      TPM1)= (TM(NP1) + HM/(GAMMA*CP*QM*3600.0))*(1.0-PHL/100.0)
C
      DO 530 M= 2, NP1
      TPM(M)= (TPM(M-1)*QM*CS1/2.0 + TM(M))/(1.0 + CS1*QM/2.0 + CS2)
530 CONTINUE

```

```

C
C
      TM(1) = TPM(1)
      DO 540 M = 2, NP1
      TM(M) = TPM(M)
      TX = TPM(M-1) + TPM(M)
      SUMM(1,N) = TPM(1)
      SUMM(2,N) = TPM(NP1)
      SUMM(3,N) = SUMM(3,N) + CS3*TX
      SUMM(4,N) = SUMM(4,N) + CS4*TX
      SUMM(5,N) = SUMM(5,N) + CS5*TX + CS5*2.0*(PJM-DPT)
540 CONTINUE
C
C
      SUMM(3,N) = SUMM(3,N) + (GAMMA*CP*QM*3600.*DEL(T*TPM(NP1) +
      IHM*DELT))*(PHL/100.0)
      SUMM(5,N) = SUMM(5,N) + QM*3600.*DELT*(CWL+CWL)/100.0
      SUMM(6,N) = SUMM(6,N) + HM*DELT
C
C
550 CONTINUE
C
C
      *****
      *
      *          PRINT OUT ESTIMATE OF TURBULENT THERMAL
      *          TRANSPORT DIFFUSIVITY
      *
      *****
C
      DELNEW = 2.0 * E / AV
      WRITE(6,750)
      WRITE(6,35) (TITLE(I), I=1,9)
      WRITE(6,560)
      WRITE(6,560)
      WRITE(6,570)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,590)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,600) DELNEW
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,610) E
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,620)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,630) AV
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,580)
      WRITE(6,570)
C
560 FORMAT(//////////)
C

```

```
570 FORMAT(' *****
1*****')
```

```
580 FORMAT(' *
1 - - - - - *')
```

```
590 FORMAT('+', ' ESTIMATE OF TURBULENT THERMAL TRANSPORT DIFF
1USIVITY ')
```

```
600 FORMAT('+', ' WHEN DELTAS IN MAIN IS LESS THAN ', F8.2,
1' FEET,')
```

```
610 FORMAT('+', ' THEN DIFF = ', F8.3, ' (IN FT**2/SEC).')
```

```
620 FORMAT('+', ' FOR LARGER DELTAS IN MAIN USE')
```

```
630 FORMAT('+', ' DIFF = ', F8.5, '*DELTAS (IN FT**2/SEC)')
```

```
*****
```

```
* PRINT OUT TABLE OF VALUES FOR TIME (HOURS),
* ACCUMULATED REACTOR HEAT RELEASED (BTU),
* EXCESS HEAT STORED IN POND (BTU),
* ACCUMULATED EXCESS HEAT DISSIPATED (BTU),
* ACCUMULATED TOTAL WATER LOSS (% POND VOLUME),
* POND INLET TEMPERATURE (DEGREE F),
* POND OUTLET TEMPERATURE (DEGREE F)
```

```
*****
```

```
WRITE(6,750)
WRITE(6,35) TITLE(1), I=1,5)
WRITE(6,640)
```

```
640 FORMAT(1H0)
```

```
WRITE(6,650)
```

```
650 FORMAT('***** CALCULATIONS FOR DBA *****
1***** *AMBIENT CALCULATIONS*')
```

```
WRITE(6,640)
```

```
WRITE(6,660)
```

```
660 FORMAT(' TIME ACCUMULATED EXCESS HEAT ACCUMULATED
1ACC WATER POND TEMPERATURE')
```

```
WRITE(6,670)
```

```
670 FORMAT(' INDEX AFTER REACTOR HEAT STORED IN EXCESS HEAT
1 LOSS EXCESS (DEGREE F)')
```

```
WRITE(6,680)
```

```
680 FORMAT(' (K) DBA RELEASED POND DISSIPATED
1 (% POND DAY HOUR TEMPERATURE')
```

```
WRITE(6,690)
```

```

690 FORMAT('      (HOUR)      (BTU)      (BTU)      (BTU)
      1 VOLUME) INLET  OUTLET      (DeG F)'')

```

```

C
WRITE(6,700)

```

```

700 FORMAT('-----
      1-----')

```

```

C
WRITE(6,710)
710 FORMAT('      SUMM(6,K)      SUMM(4,K)      SUMM(3,K)
      1 SUMM(5,K) SUMM(1,K) SUMM(2,K)      1 J      AMP(1(K))')

```

```

C
WRITE(6,700)

```

```

C
IF(MDT.NE.0) GO TO 725
DO 720 I= 1, NTSP
AMP(I)= PT
NDAY= NTSP / 24
720 CONTINUE
725 CONTINUE

```

```

C
J= 0
DO 730 K= 1, NTSP, NPRNT
THOUR= DELT*FLOAT(K-1)
SUMM(5,K)= SUMM(5,K) + 100. / V
I= (K-1)/24 + 1
J= J + 1
IF(J.GT.24) J=1
M= (I-1)*24 + J
WRITE(6,740) K, THOUR, SUMM(6,K), SUMM(4,K), SUMM(3,K),
1 SUMM(5,K), SUMM(1,K), SUMM(2,K), I, J, AMP(M)
730 CONTINUE

```

```

C
740 FORMAT(15, F8.1, E13.3, E15.3, E15.3, F9.1, F11.2, 11.2,
      1 '8X, T3, T6, F10.2)

```

```

C
C
C
C
WRITE(6,750)

```

```

750 FORMAT('HI')

```

```

C
STOP
END

```

APPENDIX C

DERIVATION OF EQUATIONS OF MOTION TO EXPLICIT DIFFERENCES

Integration of the basic three-dimensional Navier-Stokes equations of fluid motion is presented in detail by Pritchard (1971). A brief outline is given here.

Begin with the N-S momentum balance as:

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = - \frac{1}{\rho} \frac{\partial P}{\partial x_i} + g_i + \frac{g F_i}{\rho} \quad (C.1)$$

and continuity:

$$\frac{\partial U_i}{\partial x_i} = m \quad (C.2)$$

for $i, j = 1, 2, 3$ and where:

U_1 is the x_1 (longitudinal) velocity component, in Ft Sec^{-1}

U_2 is the x_2 (lateral) velocity component, in Ft Sec^{-1}

U_3 is the x_3 (vertical) velocity component, in Ft Sec^{-1}

$g_3 = g$, $g_1 = g_2 = 0$ is the gravitational acceleration, in Ft Sec^{-2}

P is the fluid pressure, in Lb Ft^{-2}

F_i is the sum of the frictional dissipation and external forces per unit fluid volume in the i -th direction, in Lb Ft^{-3}

m is the net fluid additions per unit volume, in $\text{Ft}^3 \text{ Sec}^{-1} \text{ Ft}^{-3}$

Equations (C.1) and (C.2) give four equations for the four unknowns of U_1 , U_2 , U_3 , and P . Order of magnitude arguments reduce the vertical equation of motion to the hydrostatic equation, thus giving in expanded form:

x_1 momentum:

$$\frac{\partial u_1}{\partial t} + \frac{\partial u_1 u_1}{\partial x_1} + \frac{\partial u_2 u_1}{\partial x_2} + \frac{\partial u_3 u_1}{\partial x_3} = -\frac{1}{\rho} \frac{\partial P}{\partial x_1} + \frac{g F_1}{\rho} \quad (C.3a)$$

 x_2 momentum:

$$\frac{\partial u_2}{\partial t} + \frac{\partial u_1 u_2}{\partial x_1} + \frac{\partial u_2 u_2}{\partial x_2} + \frac{\partial u_3 u_2}{\partial x_3} = -\frac{1}{\rho} \frac{\partial P}{\partial x_2} + \frac{g F_2}{\rho} \quad (C.3b)$$

 x_3 momentum:

$$\frac{\partial P}{\partial x_3} = -\rho g \quad (C.3c)$$

continuity:

$$\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = 0 \quad (C.3d)$$

Integrating each term of each equation above from the free water surface at $x_1 = \eta(x_2, x_3)$ to the bottom at $x_1 = h(x_2, x_3)$, and applying kinematic boundary conditions at the surface and bottom gives in the same order as above:

$$\frac{\partial}{\partial t} \int_{\eta}^h u_1 dx_3 + \frac{\partial}{\partial x_1} \left\{ u_1 \int_{\eta}^h u_1 dx_3 \right\} + \frac{\partial}{\partial x_2} \left\{ u_2 \int_{\eta}^h u_1 dx_3 \right\} = -\frac{1}{\rho} \frac{\partial}{\partial x_1} \int_{\eta}^h P dx_3 + \int_{\eta}^h \frac{F_1}{\rho} dx_3 \quad (C.4a)$$

$$\frac{\partial}{\partial t} \int_{\eta}^h u_2 dx_3 + \frac{\partial}{\partial x_1} \left\{ u_1 \int_{\eta}^h u_2 dx_3 \right\} + \frac{\partial}{\partial x_2} \left\{ u_2 \int_{\eta}^h u_2 dx_3 \right\} = -\frac{1}{\rho} \frac{\partial}{\partial x_2} \int_{\eta}^h P dx_3 + \int_{\eta}^h \frac{F_2}{\rho} dx_3 \quad (C.4b)$$

$$-\frac{\partial}{\partial t} (h - \eta) + \frac{\partial}{\partial x_1} \int_{\eta}^h u_1 dx_3 + \frac{\partial}{\partial x_2} \int_{\eta}^h u_2 dx_3 = \int_{\eta}^h m dx_3 \quad (C.4c)$$

$$P = -g \int_{\eta}^h \rho dx_3 \quad (C.4d)$$

Defining the x_1 transport of flow per unit width as:

$$U = \int_{\eta}^h U_1 dx_3 \quad (C.5)$$

the x_2 transport of flow per unit width as:

$$V = \int_{\eta}^h U_2 dx_3 \quad (C.6)$$

and approximating where necessary the U_1 and U_2 components of velocity as:

$$U_1 = \frac{U}{D} \quad \text{and} \quad U_2 = \frac{V}{D} \quad (C.7)$$

where the depth is $D = h - \eta$, and assuming that density is constant over the depth D , reduces the above equations to:

$$\frac{\partial U}{\partial t} + \frac{1}{D} U \frac{\partial U}{\partial x} + \frac{1}{D} V \frac{\partial U}{\partial y} = -gD \frac{\partial \eta}{\partial x} + \int_{\eta}^h F_1 dx_3 \quad (C.8a)$$

$$\frac{\partial V}{\partial t} + \frac{1}{D} U \frac{\partial V}{\partial x} + \frac{1}{D} V \frac{\partial V}{\partial y} = -gD \frac{\partial \eta}{\partial y} + \int_{\eta}^h F_2 dx_3 \quad (C.8b)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = RN \quad (C.8c)$$

where η is the water surface level relative to a fixed datum, RN is net flow addition per unit surface area, and the temporal change in the bottom coordinate is zero. Vertical integration thus eliminates the vertical velocity component from initial consideration and gives the pressure as a simple function of surface slope. It

should be noted that Pritchard (1971) suggests that solution of the three-dimensional problem to include U_3 and variable density coupled through an equation of state to constituent mass balances should begin with a trial solution for two-dimensional transport followed by relaxation to the U_3 and density fields.

Friction is evaluated by a velocity-squared law and surface wind stress is incorporated in the external body force integral to give:

$$\int_{\eta}^h F_1 dx_3 = WX - r \frac{(U^2 + V^2)^{1/2} U}{D^2} \quad (C.9)$$

where r is a non-dimensional friction coefficient that can be related to the more familiar friction laws of Chezy or Manning.

The non-linear advective inertia terms lead to complex numerical integration problems. Their contribution relative to friction can be estimated.

Require that:

$$\frac{1}{D} U \frac{\partial U}{\partial x} \ll r \frac{U^2}{D^2} \quad (C.10)$$

Let $\Delta U = \alpha U$ where α is a coefficient which, when multiplied by U , will indicate the change in the mean transport over a length of pond for $\Delta x = L$, then it is required that

$$\frac{\alpha U^2}{DL} \ll r \frac{U^2}{D^2} \quad (C.11)$$

or must have:

$$\alpha \ll r \frac{L}{D} \quad (C.12)$$

The change over $L = \Delta s$ in velocity then must be:

$$\alpha = \frac{U(x+\Delta s) - U(x)}{U(x+\Delta s)} \ll f \frac{\Delta s}{D} \quad (C.13)$$

The allowable spatial change in the transport rate increases with friction and Δs but decreases with depth, and is on the order of

$$\alpha \ll \frac{(0.01)(100)}{10} = 0.10$$

or 10 percent for a typical pond case.

Derivation of Differencing Relations

The vertically integrated equation of motion and continuity from Reid and Bodine is written as:

$$\frac{\partial U}{\partial t} + gD \frac{\partial H}{\partial x} = WX - f (\sqrt{U^2 + V^2}) UD^{-2} \quad (C.14)$$

$$\frac{\partial V}{\partial t} + gD \frac{\partial H}{\partial y} = WY - f (\sqrt{U^2 + V^2}) VD^{-2} \quad (C.15)$$

$$\frac{\partial H}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = RN \quad (C.16)$$

where:

x and y = horizontal cartesian coordinates, in Ft.

t = time, sec.

U and V = vertically integrated x and y components, respectively,

of transport $\text{Ft}^3 \text{Sec}^{-1}$ per ft of width

g = gravitational acceleration, in Ft Sec^{-2}

H = water level relative to selected datum, in Ft.

D = depth of water (a factor of x, y, t), in Ft.

f = nondimensional coefficient of bed resistance

RN = net flow addition per unit surface area, in $\text{Ft}^3 \text{Sec}^{-1}$ per Ft^2 surface area

WX, WY = x and y components of wind stress divided by the density of water (latter assumed constant), $\text{Ft}^2 \text{Sec}^{-2}$

Consider the following grid:

Key

$\square$ U, WX

$\circ$ V, WY

Δ D, H, Z, T

As per Reid and Bodins, all variables located at the center of blocks are calculated at even half steps of t ; all other variables are computed at odd half steps of t . Furthermore, variables used in the solution of equations (C.14) - (C.16) are as shown below:

Grid nomenclature used in HYETA simulation
Figure C.2.

P-scripted symbols denote values at a time step Δt later. Note that because of the half step scheme, the difference $UP-U$ is centered in time at the level of H , and the difference $HP-H$ is centered in time at the level of UP or VP . Further, the frictional terms of equations (C.14) and (C.15) are given by $f(\sqrt{U^2 + V^2})UP D^{-2}$ and $f(\sqrt{U^2 + V^2})VP D^{-2}$, respectively (i.e., note use of primes) where the estimation of $\sqrt{U^2 + V^2}$ and D are centered spatially at the position for UP or VP . Since U, V are not available at common locations, this requires a suitable spatial averaging in order to obtain centered values of $\sqrt{U^2 + V^2}$ and D . The resulting recursive equations for U , V , and H , using centered differences for the spatial derivatives, are derived as follows:

Equation C.14 (for the I, J block):

$$\begin{aligned} \frac{UP(I,J) - U(I,J)}{\Delta t} + g \left(\frac{D(I,J) + D(I-1,J)}{2} \right) \left(\frac{H(I,J) - H(I-1,J)}{\Delta s} \right) = X(I,J) \\ - f UP(I,J) \left(\frac{D(I-1,J) + D(I,J)}{2} \right)^{-2} \sqrt{U^2 + V^2} \end{aligned} \quad (C.17)$$

However, $\sqrt{U^2 + V^2}$ must be centered spatially at $U(I,J)$. In a similar manner a centered D is obtained. That is (referring to Fig. C.1):

$$(U^2 + V^2)^{1/2} = [(U(I,J))^2 + \frac{(V(I,J) + V(I-1,J) + V(I,J+1) + V(I-1,J+1))^2}{4}]^{1/2}$$

or

$$(U^2 + V^2)^{1/2} = \frac{1}{4} [(4U(I,J))^2 + (V(I,J) + V(I-1,J) + V(I,J+1) + V(I-1,J+1))^2]^{1/2} \quad (C.18)$$

and solving equation (C.17) for $UP(I,J)$ using equation (C.18):

$$\begin{aligned}
 UP(I,J) & \left\{ 1 + f\Delta t \left(\frac{1}{D(I-1,J)+D(I,J)} \right)^2 \left[(4U(I,J))^2 + (V(I,J)+V(I-1,J)) \right. \right. \\
 & \quad \left. \left. + V(I,J+1)+V(I-1,J+1)) \right]^2 \right\}^{1/2} \\
 & = U(I,J) + \frac{g\Delta t}{2\Delta s} (D(I,J)+D(I-1,J)) (H(I-1,J)-H(I,J)) + WX(I,J)\Delta t
 \end{aligned}
 \tag{C.19}$$

Call

$$\begin{aligned}
 G_1(I-1,J) & = \left\{ 1 + f\Delta t \left(\frac{1}{D(I-1,J)+D(I,J)} \right)^2 \left[(4U(I,J))^2 + (V(I,J)+V(I-1,J)) \right. \right. \\
 & \quad \left. \left. + V(I,J+1)+V(I-1,J+1)) \right]^2 \right\}^{1/2}
 \end{aligned}$$

so that equation (C.19) becomes:

$$UP(I,J) = \frac{1}{G_1(I-1,J)} \left\{ U(I,J) + \frac{g\Delta t}{2\Delta s} (D(I,J)+D(I-1,J)) (H(I-1,J)-H(I,J)) + WX(I,J)\Delta t \right\}
 \tag{C.20a}$$

Now let $I = I+1$:

$$\begin{aligned}
 UP(I+1,J) & = \frac{1}{G_1(I,J)} \left\{ U(I+1,J) + \frac{g\Delta t}{2\Delta s} (D(I+1,J) + D(I,J)) (H(I,J)-H(I+1,J)) \right. \\
 & \quad \left. + X(I+1,J)\Delta t \right\}
 \end{aligned}
 \tag{C.20b}$$

Equation C.21 (for the I,J block) is derived in a manner identical to equation (C.20):

$$VP(I, J+1) = \frac{1}{G_2(I, J)} \left\{ V(I, J+1) + \frac{g \Delta t}{2 \Delta s} (D(I, J+1) + D(I, J)) (H(I, J) - H(I, J+1)) \right. \\ \left. + WX(I, J+1) \Delta t \right\} \quad (C.21)$$

where

$$G_2(I, J) = \left\{ 1 + f \Delta t \left(\frac{1}{D(I, J) + D(I, J+1)} \right)^2 \left[(4V(I, J+1))^2 + (U(I, J) + U(I+1, J) \right. \right. \\ \left. \left. + U(I, J+1) + U(I+1, J+1))^2 \right]^{1/2} \right\}$$

Equation C.16 (for the I;J Block):

$$\frac{HP(I, J) - H(I, J)}{\Delta t} + \frac{UP(I+1, J) - UP(I, J)}{\Delta s} + \frac{VP(I, J+1) - VP(I, J)}{\Delta s} = RN(I, J) \quad (C.22)$$

so that

$$HP(I, J) = H(I, J) + \frac{\Delta t}{\Delta s} [UP(I, J) - UP(I+1, J) + VP(I, J) - VP(I, J+1)] + RN(I, J) \Delta t \quad (C.23)$$

Notes:

- (1) Primes are used for U and V in equations (C.22) and (C.23) as UP and VP, respectively, since we first use initial conditions for H and boundary conditions for U and V to find new U's and V's. After this is done, we use these new values for U and V to determine new values for H.
- (2) In equation (C.22) the term

$$\frac{\partial H}{\partial x} = \frac{H(I, J) - H(I-1, J)}{\Delta x} \quad (C.24)$$

is a priori centered spatially at $U(I, J)$

- (3) In equation (C.17) we center Q spatially at $U(I,J)$ by taking an average of four values of V located symmetrically about $U(I,J)$. This is done in equation (C.18) and shown in Fig. C.1
- (4) Once having obtained H 's, we can find D 's via their definition

$$D(I,J) = H(I,J) - Z(I,J) \quad (C.25)$$

APPENDIX D
DERIVATION OF SPATIAL-TEMPORAL DIFFERENCE FORM
OF TEMPERATURE EXCESS EQUATION

The vertically homogeneous time-varying two-dimensional heat balance for excess temperature is given in equation (4.3) as:

$$\rho c_p D \left\{ \frac{\partial \theta}{\partial t} + \frac{1}{D} \frac{\partial U \theta}{\partial x} + \frac{1}{D} \frac{\partial V \theta}{\partial y} - \frac{\partial (E_x \frac{\partial \theta}{\partial x})}{\partial x} - \frac{\partial (E_y \frac{\partial \theta}{\partial y})}{\partial y} \right\} + K \theta = HA \quad (D.1)$$

where:

- θ = Temperature excess at x,y and t, in $^{\circ}F$.
- U, V = Vertically integrated horizontal transport vectors, in $Ft^2 \text{ Sec}^{-1}$
- ρ, c_p = Specific weight and heat of water, in $Lb \text{ Ft}^{-3}$, and $Btu \text{ Lb}^{-1} \text{ } ^{\circ}F^{-1}$ respectively
- D = Water column depth, in Ft
- E_x, E_y = Longitudinal dispersion coefficient in x- and y-directions, in $Ft^2 \text{ Sec}^{-1}$
- K = Coefficient of surface heat exchange, in $Btu \text{ Ft}^{-2} \text{ Sec}^{-1} \text{ } ^{\circ}F^{-1}$
- HA = Net heat addition per unit surface area, in $Btu \text{ Ft}^{-2} \text{ Sec}^{-1}$
(from source-sink)

For differencing let $TP(I,J)$ be the temperature excess at new time, and $T(I,J)$ be the temperature excess at present time. Temperatures are centered in the I,J cell, transport vectors are half-spaced through the sides of the cell. The forward difference explicit representation of (D.1) becomes for $E_x = E_y = E$:

$$\begin{aligned}
TP(I,J) = T(I,J) & \left[1 - \frac{\Delta t}{\Delta s} \frac{D(I,J)}{D(I,J)} (U(I+1,J) + V(I,J+1)) - \frac{h\Delta t E}{\Delta s^2} - \frac{\Delta t K}{\rho c_p} \frac{D(I,J)}{D(I,J)} \right] \\
& + \frac{\Delta t}{\Delta s} \frac{D(I,J)}{D(I,J)} (U(I,J) T(I-1,J) + V(I,J) T(I,J-1)) \\
& + \frac{\Delta t E}{\Delta s^2} (T(I-1,J) + T(I+1,J) + T(I,J-1) + T(I,J+1)) + \frac{HA(I,J)\Delta t}{\rho c_p} \frac{D(I,J)}{D(I,J)}
\end{aligned}
\tag{D.2}$$

Convergence and stability criteria for numerical integration are determined by examining:

$$0 \leq \left[1 - \frac{\Delta t}{\Delta s} \frac{D(I,J)}{D(I,J)} (U(I+1,J) + V(I,J+1)) - \frac{h\Delta t E}{\Delta s^2} - \frac{\Delta t K}{\rho c_p} \frac{D(I,J)}{D(I,J)} \right] \leq 1
\tag{D.3}$$

APPENDIX E

HYETA USER GUIDE AND PROGRAM LISTING

There are two basic steps in preparing a cooling pond design for simulation using the HYETA model: (1) mapping the pond onto a finite-difference grid, and (2) coding the simulation information for computer input.

Mapping the Pond

The initial task is to choose a grid spacing (Δs) which provides adequate resolution while allowing a reasonable time increment (Δt). These parameters are related by the following equations:

$$\Delta t \leq \frac{\Delta s}{\sqrt{2g D_{\max}}}$$

$$\leq \frac{D \Delta s}{8 |U_{\max}|}$$

$$\leq \frac{(\Delta s)^2}{16E}$$

$$\leq \frac{\rho c_p D}{4K}$$

and also the Torrence condition given in equation (4.6d).

where:

g = gravitational acceleration, in Ft Sec^{-2}

ρ = density of water, in Lb Ft^{-3}

c_p = specific heat of water, in $\text{Btu Lb}^{-1} \text{ } ^\circ\text{F}^{-1} \approx 1.0$ for fresh water

$D_{\max}$ = maximum depth expected, in Ft

D = average depth, in Ft

U = maximum flow per unit width expected, in $\text{Ft}^2 \text{Sec}^{-1}$

E = diffusivity, in $\text{Ft}^2 \text{Sec}^{-1}$

K = coefficient of surface heat exchange, in $\text{Btu Ft}^{-2} \text{Sec}^{-1} \text{ } ^\circ\text{F}^{-1}$

The first equation will most often provide the upper limit of Δt ; it is best to use 60-80 percent of this value.

For the example shown in Section 5, Fig. 5.1, a Δs of 95 feet was chosen. The corresponding maximum Δt is 4.47 seconds; the simulation value was taken as 67 percent of this value, or 3 seconds.

Coding

The pond design and simulation information is organized for computer input as follows:

Card 1

Columns 2-72: TITLE, job title, any alphanumeric

Card 2

Columns 1-10: PRNT, print interval (minutes) F-format

Columns 11-20: NPRINT: print options, I-format

If NPRINT = 1, flows per unit width, depths, and temperature excesses are printed every PRNT minutes (simulation time);

If NPRINT = 0, they are omitted. In either case, summary statistics are recorded every PRNT minutes.

Card 3

Columns 1-10: NSTEP, number of Δt increments program is to compute, I-format

NSTEP times Δt is the real time the program is to simulate.

Cards 4 to 9

Columns 1-10: IRCRD(L,1) I-format

Columns 11-20: IRCRD(L,2) I-format

I and J are the coordinates of cells for which temperature excess histories are to be kept. There are six such cells.

Card 10

Columns 1-10: DELTAS, Δs (feet) F-format

Columns 11-20: DELTAT, Δt (seconds) F-format

Card 11

Columns 1-10: IMAX, number of cells in the x-direction, I-format

Columns 11-20: JMAX, number of cells in the y-direction, I-format

Cards 12 to (12 + IMAX x JMAX)

Columns 1-10: H, average distance from datum to free - surface level, F-format

Columns 11-20: Z, average distance from datum to pond bottom, F-format

For "dry" cells, H should be 0 and Z should have a value at least a foot greater than the free-surface level.

Values of H and Z for each cell are input beginning with the bottom left-hand cell, and working from right to left, bottom to top.

Card (12 + IMAX x JMAX)

Columns 1-10: NSS, number of sources and sinks, I-format

In the example there are three sources and one sink.

NSS is input as four.

For each source or sink:

Card $KK + 1$ (where $KK = 12 + IMAX \times JMAX$)

Columns 1-10: identification number, $ISS(K,1)$, ranging from 1 to NSS , I-format

Columns 11-20: $ISS(K,2)$ I-format

Columns 21-30: $ISS(K,3)$ I-format

$ISS(K,2)$ and $ISS(K,3)$ are the coordinates of the cell in which the source or sink is located.

Columns 31-40: $SS(K,1)$ source/sink type, F-format

Type values are specified using Table E.1.

Card $KK + 2$

Columns 1-10:

Columns 11-20:

Columns 21-30:

Columns 31-40:

Columns 41-50:

Columns 51-60:

Columns 61-70:

Columns 71-80:

Characterizing parameters, $SS(K,2)$ through $SS(K,9)$, Values are specified using Table E.1.

Card $KK + 3$

Columns 1-10: NQR , number of flow regimes, I-format

Card $(KK + 4)$ to $(3 + NQR + KK)$

Columns 1-10: time on (hours) for this flow regime, F-format

Columns 11-20: flow (cfs), D-format (right-justified)

There can be as many as ten regimes; there must be at least one.

Card $(4 + NQR + KK)$

Columns 1-10: NHR , number of heat regimes, I-format

Cards (5 + NQR + KK) to (4 + NQR + KK + NHR)

Columns 1-10: time on (hours) for each heat regime, F-format

Columns 11-20: intercept at hour one, in Btu Hr^{-1} , D-format
(right justified)

Columns 21-30: slope, in $\text{Btu Hr}^{-1} (\log_{10} \text{Hr})^{-1}$, D-format
(right justified)

Heat regimes are specified using the following formula:

$$H_i = A_i + B_i \log t$$

where

A_i = intercept at hour one, in Btu Hr^{-1} of i -th regime

B_i = slope, in $\text{Btu Hr}^{-1} (\log_{10} \text{Hr})^{-1}$, of i -th regime

For each sink, specify a zero for NHR and omit its heat regime descriptions.

For each source, the first heat regime can begin no sooner than its corresponding flow. For a constant heat source, specify the slope (B_i) as zero.

There can be ten heat regimes for each source.

Card (5 + NQR + KK + NHR)

Columns 1-10: Number of sinks hydraulically connected to this source, ISS(K,6), I-format
(8 or less)

Card (6 + NQR + KK + NHR)

Columns 1-10:

Columns 11-20:

Columns 21-30:

Columns 31-40:

Columns 41-50:

Columns 51-60:

Columns 61-70:

Columns 71-80:

Identification numbers of each connected sink, I-format. If a sink is being specified, number of connected sinks is set to zero.

Last three cards:Card 1 (third from last card)

Columns 1-10: W, wind shear speed, in knots, F-format

Columns 11-20: THETA, wind shear direction, in radians measured counterclockwise from positive x-axis, F-format

Card 2 (next to last card)

Columns 1-10: PTMAX, pond temperature, in °F, F-format

Columns 11-20: DPT, dew point temperature in °F, F-format

Columns 21-30: CWS, cooling wind speed, in Mi Hr^{-1} , F-format

Card 3 (last card)

Columns 1-10: DIP, diffusivity, $\text{Ft}^2 \text{Sec}^{-1}$, F-format

The diffusivity is obtained from the METMIN analysis

Columns 11-20: F, dimensionless bed resistance coefficient
F-format

NOTES:

All data cards may be numbered in the last five columns, as shown in Fig. 5.3.

There may be as many as 40 sources and sinks. This number may be increased by changing the first index in the arrays SS, ISS (COMMON/AREAL/), and QH (SRCSNK).

To increase the grid capacity from 20×20 to 60×60 , remove those cards labelled 20×20 in columns 73-80 and replace them with the cards labelled 60×60 (shown on 139). In this case, only every other (for grids up to 40×40) or every third (for grids up to 60×60) grid variable is printed and no output of initial depths appears.

Fig. E.1. HYETA Data Deck Assembly.

TABLE E.1.

HYETA PARAMETER SPECIFICATIONS

Name	Type	Parameters							
	Designation (+ = inlet - = outlet)	1	2	3	4	5	6	7	8
Simple advective inlet to pond	+ 1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Simple advective outlet from pond	- 1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spray inlet	+ 2.0	EWL	PDL	PHL	0.0	0.0	0.0	0.0	0.0
Round surface jet inlet	+ 3.0	Virtual source distance	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Two-dimensional vertically mixed jet inlet	+ 4.0	Virtual source distance	0.0	0.0	0.0	0.0	0.0	0.0	0.0


```

C      SS(K,9+2*ISS(K,6)+3*L), L = 1, ISS(K,5): TIME ON THE,
C      HEAT FUNCTION INTERCEPT (BTU/HR), AND LOG SLOPE
C      (BTU/HR) FOR SOURCE/SINK K
C      SSHL: SUM OF SPRAY DEVICE HEAT DISSIPATION (BTU)
C      SSWLC: SUM OF SPRAY DEVICE WATER LOSSES (FT**3)
C      T(50,50): TEMPERATURE EXCESS (DEGREES F)
C      U(50,50): FLOW PER UNIT WIDTH, X - DIRECTION (FT**2/HR)
C      V(50,50): FLOW PER UNIT WIDTH, Y - DIRECTION (FT**2/HR)
C      Z(50,50): DISTANCE FROM DATUM TO POND BOTTOM (FT)
C
C
C      MAIN
C
C      APTDPT: AVERAGE POND AND DEW POINT TEMPERATURE (DEGREES F)
C      AREA: POND SURFACE AREA (FT**2)
C      BETA: SLOPE OF THE SATURATED VAPOR PRESSURE CURVE (MMHG/DEGREE F)
C      CSHE: COEFFICIENT OF SURFACE HEAT EXCHANGE (BTU/FT**2 SEC DEGREE F)
C      CWS: COOLING WIND SPEED (MI/HR)
C      DIF: DIFFUSIVITY (FT**2/SEC)
C      DPT: DEW POINT TEMPERATURE (DEGREES F)
C      EWLN: EVAPORATIVE WATER LOSS, NATURAL (FT**3)
C      EWLE: EVAPORATIVE WATER LOSS, EXCESS (FT**3)
C      F: DIMENSIONLESS REC COEFFICIENT
C      FCWS: EVAPORATIVE WIND SPEED FUNCTION (BTU/FT**2 LAY MFG)
C      GRAV: GRAVITATIONAL CONSTANT (FT/SEC**2)
C      HL: HEAT OF VAPORIZATION (BTU/LB)
C      IMAX: NUMBER OF CELLS IN X - DIRECTION
C      JMAX: NUMBER OF CELLS IN Y - DIRECTION
C      LFCO: LOCATION OF FINAL CONNECTED OUTLET IN ISS(K,L) ARRAY ( =
C      6 + ISS(K,6))
C      NEC: NUMBER OF EMPTY CELLS
C      NHR: NUMBER OF HEAT REGIMES ( = ISS(K,5))
C      NQR: NUMBER OF FLOW REGIMES ( = ISS(K,4))
C      N: COMPUTATION COUNTER, N MAX = NSTEPS, COMPUTATION CLOCK
C      AN: INTERVAL AT WHICH GRIDS ARE PRINTED AND RECORDS ALPH, IN
C      TERMS OF THE COMPUTATION CLOCK (N)
C      NSTEPS: NUMBER OF TIME INCREMENTS PROGRAM IS TO COMPUTE
C      PRNT: INTERVAL AT WHICH GRIDS ARE PRINTED AND RECORDS K, P, (MIN)
C      PTFAX: POND TEMPERATURE (DEGREES F)
C      REENL(50,50): RATE OF EXCESS EVAPORATIVE WATER LOSS (FT/SEC)
C      RN(50,50): NET SOURCE/SINK TERM, CONTINUITY EQUATION (FT/SEC)
C      RNEWL: RATE OF NATURAL EVAPORATIVE WATER LOSS (FT/SEC)
C      SHE: SURFACE HEAT EXCHANGE (BTU)
C      THETA: WIND SHEAR DIRECTION MEASURED COUNTERCLOCKWISE FROM
C      POSITIVE X - AXIS (RADIAN)
C      TP(50,50): ARRAY FOR PLACING RESULTS OF T CALCULATION
C      UP(50,50): ARRAY FOR PLACING RESULTS OF U CALCULATION
C      VDK: VAN DORN COEFFICIENT (FT**2/SEC**2 KNOTS)
C      VP(50,50): ARRAY FOR PLACING RESULTS OF V CALCULATION
C      W: WIND SHEAR SPEED (KNOTS)
C      X: WIND SHEAR, X - DIRECTION (FT**2/SEC**2)
C      Y: WIND SHEAR, Y - DIRECTION (FT**2/SEC**2)
C
C
C      SRCSNK
C
C      HRS: REACTOR HEAT RELEASED PER TIME STEP (BTU)
C      LFCU: LOCATION OF FINAL CONNECTED OUTLET IN ISS(K,L) ARRAY ( =
C      6 + ISS(K,6))
C      NHR: NUMBER OF HEAT REGIMES ( = ISS(K,5))
C      NQR: NUMBER OF FLOW REGIMES ( = ISS(K,4))
C      QH(100,2): ARRAY FOR STORING FLOWS ASSOCIATED WITH EACH
C      SOURCE/SINK K (QH(K,1) CFS) AND HEATS BEFORE RECIRCULATION

```

```

C      (QHK,2) BTU/SEC)
C      QS:  SUM OF FLOWS OF CONNECTED SINKS (CES)
C      QTS:  SUM OF TEMPERATURE TIMES FLOW OF CONNECTED SINKS
C      IFT**3 DEGREES F/SEC)
C      SSSL:  SPRAY DEVICE HEAT LOSSES PER TIME STEP (BTU)
C      SSWL:  SPRAY WATER LOSSES PER TIME STEP (FT**3)
C      TOUT:  CALORIMETRIC SINK TEMPERATURE (DEGREES F)
C      THR:  COMPUTATION CLOCK TIME (HR)

```

```

C      IMPLICIT REAL*8 (A-H,O-Z)

```

```

C      COMMON /AREA1/ SS(40,85), H(20,20), Z(20,20), DEPTH(20,20),      20 X 20
C      2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECD(160,121), 20 X 20
C      3 SHRS, SSSL, DELTAT, DELTAS, GAMMA, CP, SSWL, ANG, AWL, EHS,
C      4 ISS(40,15), IRCRD(16,2), NSS, NPRNT, IMAXM1, JMAXM1, NPRU1

```

```

C      DIMENSION UP(20,20), VP(20,20), TP(20,20), RN(20,20), REWL(20,20) 20 X 20
C      REAL SNGL
C      REAL*8 TITLE(9)

```

```

C      CP = 0.99800
C      GAMMA = 62.24700
C      GRAV = 32.200
C      HL = 970.300

```

```

C      1 FORMAT(7I10,I5)
C      2 FORMAT(F10.4,I10)
C      3 FORMAT(9A8)
C      4 FORMAT(5F10.3, 2I10)
C      6 FORMAT(7F10.4,F5.2)
C      7 FORMAT(F10.4,2D10.2)
C      8 FORMAT(3I10,F10.4)

```

```

C      READ NUMERICAL PARAMETERS
C      READ(5,3) (TITLE(I), I=1,9)
C      READ(5,2) PRNT, NPRNT
C      READ(5,1) NSTEPS

```

```

C      READ LOCATIONS FOR TEMPERATURE EXCESS HISTORIES
C      DO 17 L = 1, 6
C      READ(5,1) IRCRD(L,1), IRCRD(L,2)

```

```

17 CONTINUE

```

```

C      READ BATHYMETRY
C      READ(5,4) DELTAS, DELTAT
C      READ(5,1) IMAX, JMAX
C      NEC = 0

```

```

C      DO 125 J=1, JMAX
C      DO 125 I=1, IMAX
C      READ(5,4) H(I,J), Z(I,J)
C      U(I,J) = 0.0
C      VP(I,J) = 0.0
C      VT(I,J) = 0.0
C      VP(I,J) = 0.0
C      T(I,J) = 0.0
C      TP(I,J) = 0.0
C      R(I,J) = 0.0
C      REWL(I,J) = 0.0
C      HA(I,J) = 0.0
C      DEPTH(I,J) = H(I,J) - Z(I,J)
C      IF(DEPTH(I,J).GT.0.0) GO TO 125
C      DEPTH(I,J) = -100.0
C      NEC = NEC + 1

```

125 CONTINUE

C

C

READ SOURCE/SINK CHARACTERISTICS

READ(5,1) NSS

DO 130 K = 1, NSS

READ(5,8) ISS(K,1), ISS(K,2), ISS(K,3), SS(K,1)

READ(5,6) (SS(K,L), L=2,9)

READ(5,1) ISS(K,4)

NQR = ISS(K,4)

DO 131 L = 1, NQR

READ(5,7) SS(K,8+2*L), SS(K,9+2*L)

131

CONTINUE

READ(5,1) (SS(K,5)

IF(ISS(K,5).EQ.0) GO TO 134

NHR = ISS(K,5)

DO 132 L = 1, NHR

READ(5,7) SS(K,7+2*ISS(K,4)+3*L),

2 SS(K,9+2*ISS(K,4)+3*L),

3 SS(K,9+2*ISS(K,4)+3*L)

132

CONTINUE

134

READ(5,1) ISS(K,6)

IF(ISS(K,6).EQ.0) GO TO 130

LFCO = 7 + ISS(K,6)

READ(5,1) (ISS(K,L), L=7,LFCO)

130 CONTINUE

C

C

READ METEOROLOGY, DIFFUSIVITY, AND FRICTION

READ(5,4) W, THETA

READ(5,4) PTMAX, DPT, CWS

READ(5,4) DIF, F

C

C

COMPUTE WIND SHEAR TERMS AND METEOROLOGICAL VARIABLES

VDK = 0.0

IF(W.LE.14.0) GO TO 195

VDK = $2.5E-6 + (1.0 - 14.0 / W) * (1.0 - 14.0 / W)$

195

VDK = VDK + $1.1E-6$

X = VDK * W * W * COS(THETA)

Y = VDK * W * W * SIN(THETA)

APTDP1 = 0.5 * (PTMAX + DPT)

BETA = $0.255 - 0.0025 * APTDP1 + 0.000204 * APTDP1 * APTDP1$ FCWS = $70.0 + 0.7 * CWS + CWS$ CSHE = $115.7 + (BETA + 0.26) * FCWS / 86400.0$

BC = BETA * (CSHE - 0.00018171296)

BGH = $(0.26 + BETA) * GAMMA * HL$

RNEWL = BC * (PTMAX - DPT) / BGH

C

C

C

COMPUTE CONVENIENT CONSTANTS

C

NOTE: THESE VARIABLES ARE DEFINED BELOW ONLY

IMAXM1 = IMAX - 1

JMAXM1 = JMAX - 1

C

FDT = F * DELTAT

DTDS = DELTAT / DELTAS

GDT2DS = GRAV * DTDS / 2.0

XDT = X * DELTAT

YDT = Y * DELTAT

DT4DS = DIDS / 4.0

DTDS2 = DTDS / DELTAS

TF2 = DTDS2 * UIF

T4F2 = 4.0 * TF2

CG = CP * GAMMA

DTCCG = DELTAT * CSHE / CG

```

      DS2 = DELTAS * DELTAS
      CGS2DT = CSHE * US2 * DELTAT
      CGDS2 = CG * DS2
      CGC = CSHE / CG
      DTCC = DELTAT / CG
      AREA = DS2 * DFLOAT(JMAX * IMAX - NEC)
      EWLN = AREA * DELTAT * NNEWL
      DS2DT = US2 * DELTAT

C
      NN = IFIX(SNGL(60.0 * PRNT / DELTAT + 0.5))
      NPROT = 1

C
C
C      INITIALIZE PERMANENT SUMMARY STATISTICS
      SHRS = 0.0
      AHD = 0.0
      ANL = 0.0

C
C      PRINT INITIAL INFORMATION
      WRITE(6,50) ('TITLE'), I=1,9)
50  FORMAT('1', '///// 9AB)
      WRITE(6,70)
70  FORMAT('1', 'THE FOLLOWING ARE THE PARAMETERS OF THE NUMERICAL SCH-
      CEME.')
      WRITE(6,75) DELTAS
75  FORMAT('1', 'DELTAS = ', F9.2, ' FEET')
      WRITE(6,80) DELTAT
80  FORMAT('1', 'DELTAT = ', F9.2, ' SEC')
      WRITE(6,85) NSTEPS
85  FORMAT('1', 'NSTEPS = ', I6)
      WRITE(6,90) PRNT
90  FORMAT('1', 'PRNT = ', F11.2, ' MIN')
      WRITE(6,115) NPRNT
115 FORMAT('1', 'NPRNT = ', I7)
      WRITE(6,95) IMAX
95  FORMAT('1', 'IMAX = ', I8)
      WRITE(6,100) JMAX
100 FORMAT('1', 'JMAX = ', I8)
      IF(IMAX.GT.20) GO TO 112
      WRITE(6,105)
105 FORMAT('1', 'THE FOLLOWING ARE THE INITIAL DEPTHS.')
      WRITE(6,110)
110 FORMAT('0')
      CALL GRIDDEPTH,IMAX,JMAX)
112 WRITE(6,5)
5  FORMAT('1', 'THE FOLLOWING ARE THE VALUES OF THE CONSTANTS USED IN
      C THIS SIMULATION.')
      WRITE(6,10)
10  FORMAT('1', 'SYMBOLIC NAME', 5X, 'CONSTANT', 23X, 'VALUE', 10X, 'U-
      CNITS')
      WRITE(6,15)
15  FORMAT('1', '_____', 5X, '_____', 23X, '_____', 10X, '_____'
      C_____')
      WRITE(6,20) AREA
20  FORMAT('0', 'AREA', 14X, 'SURFACE AREA', 19X, E10.3, 5X, 'FT**2')
      WRITE(6,25)
25  FORMAT('1', 'CSHE', 14X, 'COEFFICIENT OF SURFACE')
      WRITE(6,30) CSHE
30  FORMAT('1', 23X, 'HEAT EXCHANGE', 13X, F10.5, 5X, 'BTU/FT**2 SEC D
      CEGREE F')
      WRITE(6,35) DIF
35  FORMAT('1', 'DIF', 15X, 'DIFFUSIVITY', 20X, F10.5, 5X, 'FT**2/SEC'
      2)

```

```

WRITE(6,45) F
45 FORMAT(' ', ' ', 17X, 'BED RESISTANCE COEFFICIENT', 5X, F10.5, 5X,
'DIMENSIONLESS')
WRITE(6,60) THETA
60 FORMAT(' ', 'THETA', 13X, 'WIND DIRECTION', 17X, F10.5, 5X, 'RADIANS')
WRITE(6,65) W
65 FORMAT(' ', 'W', 17X, 'WIND SPEED', 21X, F10.5, 5X, 'KNOTS')

```

```

C
C   INTEGRATE EQUATIONS OVER DESIRED NUMBER OF TIME INCREMENTS
DO 200 N = 1, NSTEPS

```

```

C
C   SET BOUNDARY SOURCE/SINK VALUES
CALL SRCNKIN

```

```

C
C   DISPLAY RESULTS, IF DESIRED
IF((IN/NN) * NN.EQ.N) CALL DISPLAY(N,IMAX,JMAX)

```

```

C
C   INITIALIZE TIME STEP SUMMARY STATISTICS
EHS = 0.0
EHL = 0.0
SHE = 0.0

```

```

C
C   COMPUTE NEW HEIGHTS AND TEMPERATURES

```

```

DO 350 J = 2, JMAX1

```

```

DO 350 I = 2, IMAX1

```

```

IF(DEPTH(I,J).LE.0.0) GO TO 350

```

```

RN(I,J) = R(I,J) - RNEWL - REEKL(I,J)

```

```

H(I,J) = H(I,J) + DTDS * (U(I,J) + V(I,J)

```

```

- U(I+1,J) - V(I,J+1)) + DELTA * RN(I,J)

```

```

DEPTH(I,J) = H(I,J) - Z(I,J)

```

```

IF(DEPTH(I+1,J).LE.0.0) T(I+1,J) = T(I,J)

```

```

IF(DEPTH(I-1,J).LE.0.0) T(I-1,J) = T(I,J)

```

```

IF(DEPTH(I,J+1).LE.0.0) T(I,J+1) = T(I,J)

```

```

IF(DEPTH(I,J-1).LE.0.0) T(I,J-1) = T(I,J)

```

```

TP(I,J) = T(I,J) * (1.0 - DTDS * (U(I+1,J)

```

```

+ V(I,J+1)) / DEPTH(I,J) - TF2 - DICG

```

```

/ DEPTH(I,J)) + DTDS * (U(I,J) * T(I-1,J) + V(I,J)

```

```

* T(I,J-1)) / DEPTH(I,J) + TF2 * (T(I-1,J)

```

```

+ T(I+1,J) + T(I,J-1) + T(I,J+1)) + DICG * HA(I,J)

```

```

/ DEPTH(I,J)

```

```

350 CONTINUE

```

```

C
C   RETURN COMPUTED TEMPERATURES TO COMPUTING ARRAY AND
C   INCREMENT SUMMARY STATISTICS

```

```

DO 375 J = 2, JMAX1

```

```

DO 375 I = 2, IMAX1

```

```

IF(DEPTH(I,J).LE.0.0) GO TO 375

```

```

IF(ABS(TP(I,J)).LT.1.00-50) TP(I,J) = 0.000

```

```

T(I,J) = TP(I,J)

```

```

EHS = EHS + CGDS2 * DEPTH(I,J) * T(I,J)

```

```

SHE = SHE + CGS2DT * T(I,J)

```

```

REEKL(I,J) = RC * T(I,J) / BGN

```

```

EHL = EHL + DS2DT * REEKL(I,J)

```

```

375 CONTINUE

```

```

C
C   COMPUTE NEW FLOWS PER UNIT WIDTH

```

```

DO 300 J = 2, JMAX1

```

```

DO 300 I = 2, IMAX1

```

```

IF(DEPTH(I,J).LE.0.0) GO TO 300

```

```

IF(DEPTH(I+1,J).LE.0.0) GO TO 333

```

```

ADSC = V(I,J) + V(I+1,J) + V(I,J+1) + V(I+1,J+1)

```

```

AOSQ = ADSC * ADSC

```



```

      ADSQ = DEPTH(I,J) + DEPTH(I+1,J)
      ADSQ = ADSQ * ADSQ
      G = 1.0 + FDT * USQRT(16.0 * U(I+1,J) * U(I+1,J)
      + ADSQ) / ADSQ
      UP(I+1,J) = IU(I+1,J) + GDT2DS * (DEPTH(I+1,J)
      + DEPTH(I,J)) * (H(I,J) - H(I+1,J)) + XDT) / G
      IF(DEPTH(I,J+1).LE.0.0) GO TO 300
      ADSQ = U(I,J) + U(I+1,J) + U(I,J+1) + U(I+1,J+1)
      ADSQ = ADSQ * ADSQ
      ADSQ = DEPTH(I,J) + DEPTH(I,J+1)
      ADSQ = ADSQ * ADSQ
      G = 1.0 + FDT * USQRT(16.0 * V(I,J+1) * V(I,J+1)
      + ADSQ) / ADSQ
      VP(I,J+1) = (V(I,J+1) + GDT2DS * (DEPTH(I,J+1)
      + DEPTH(I,J)) * (H(I,J) - H(I,J+1)) + YDT) / G
300      CONTINUE
C
C      RETURN COMPUTED VALUES TO COMPUTING ARRAYS
      DO 325 J = 2, JMAX1
      DO 325 I = 2, IMAX1
      IF(DEPTH(I,J).LE.0.0) GO TO 325
      IF(DEPTH(I+1,J).LE.0.0) GO TO 321
      U(I+1,J)=UP(I+1,J)
      IF(DEPTH(I,J+1).LE.0.0) GO TO 325
      V(I,J+1)=VP(I,J+1)
321      CONTINUE
325      CONTINUE
C
C      INCREMENT PERMANENT SUMMARY STATISTICS
      ARD = ARD + SR2 + SSHLC
      AML = AML + EWLN + EWLE + SSWLC
C
200 CONTINUE
C
C      PRINT SUMMARY STATISTICS
      NPRDT = NPRDT - 1
      WRITE(6,400)
400  FORMAT('1', 'TIME', 1, 5X, 'TOTAL', 8X, 'TOTAL', 9X, 'HLAT', 9X,
      2 'TOTAL', 8X, 'EXCESS TEMPERATURES, DEGREES F')
      WRITE(6,405)
405  FORMAT('1', 63X, '_____')
      WRITE(6,410)
410  FORMAT('1', 'HOURS', 5X, 'HEAT', 9X, 'HEAT', 10X, 'STORED', 1, 6X,
      2 'WATER')
      WRITE(6,415)
415  FORMAT('1', 1, '____')
      WRITE(6,420)
420  FORMAT('1', 10X, 'LOAD', 1, 8X, 'DISSIPATED', 1, 3X, 'BTU', 10X,
      2 'LUSS,')
      WRITE(6,425)
425  FORMAT('1', 37X, '____')
      WRITE(6,430)
430  FORMAT('1', 10X, 'BTU', 10X, 'BTU', 24X, 'FI*3')
      WRITE(6,435)
435  FORMAT('1', 10X, '____', 10X, '____', 24X, '____')
      DO 890 M = 1, NPROT
      WRITE(6,440) (RECORD(M,L), L=1,5), (IRCRD(L,1), IRCRD(L,2),
      2 RECORD(M,L+5), L=1,2)
      WRITE(6,445) (IRCRD(L,1), IRCRD(L,2), RECORD(M,L+5), L=3,4)
      WRITE(6,445) (IRCRD(L,1), IRCRD(L,2), RECORD(M,L+5), L=5,6)
890 CONTINUE
440  FORMAT('0', F7.2, 3X, E10.3, 3X, E10.3, 4X, E10.3, 3X, E10.3, 3X,
      2 'T1', 12, ' ', 12, ' ') = ' ', F7.2, 3X, 'T1', 12, ' ', 12,
      3 ' ') = ' ', F7.2)

```

```

445 FORMAT(' ', 63X, 'T(', 12, ' ', 12, ' ) = ', F7.2, 3X, 'T(', 12,
2 ' ', 12, ' ) = ', F7.2)

```

```

C
-----
STOP
END
SUBROUTINE SRC(SNKIN)
C
C SUBROUTINE SRC(SNK) COMPUTES FLOWS AND HEAT LOADS FOR EACH SOURCE OF
C SINK AND ASSIGNS THESE VALUES TO THE PROPER TYPE SUBROUTINE.
C
C ---
IMPLICIT REAL*8 (A-H,U-Z)
COMMON /AREA1/ SS(40,PS), H(20,20), Z(20,20), DEPTH(20,20), 20 X 20
2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECUP(60,12), 20 X 20
3 SHRS, SSWLC, DELTAT, DELTAS, GAMMA, CP, SSWLC, AML, AWL, EMS,
4 ISS(40,15), IRCRD(6,2), NSS, NPRNT, IMAXM1, JMAXM1, NPRGT
DIMENSION QH(40,2)
C
C INITIALIZE CONTINUITY AND TEMPERATURE SOURCE/SINK TERMS
DO 100 J = 2, JMAXM1
DO 100 I = 2, IMAXM1
R(I,J) = 0.0
HA(I,J) = 0.0
100 CONTINUE
THR = DELTAT * G(FLOAT(N)) / 3600.0
C
C INITIALIZE TIME STEP SUMMARY STATISTICS
HRS = 0.0
SSHL = 0.0
SSWE = 0.0
C
C --- COMPUTE FLOWS AND UNRECIRCULATED HEATS FOR EACH SOURCE/SINK
DO 10 K = 1, NSS
-----
QH(K,1) = 0.0
QH(K,2) = 0.0
-----
IF(THR.LE.SS(K,10)) GO TO 10
NQR = ISS(K,4)
DO 30 L = 1, NQR
IF(THR.GE.SS(K,8+2*L)) GO TO 30
QH(K,1) = SS(K,7+2*L)
GO TO 40
30 CONTINUE
QH(K,1) = SS(K,9+2*ISS(K,4))
40 IF(SS(K,1).LT.0.0) GO TO 10
IF(THR.LE.SS(K,10+2*ISS(K,4))) GO TO 10
NHR = ISS(K,5)
DO 50 L = 1, NHR
IF(THR.GE.SS(K,7+2*ISS(K,4)+3*L)) GO TO 50
QH(K,2) = ISS(K,5+2*ISS(K,4)+3*L) + SS(K,6+2*ISS(K,4)
+3*L) * DLOG10(THR) / 3600.0
GO TO 60
50 CONTINUE
QH(K,2) = (SS(K,8+2*ISS(K,4)+3*ISS(K,5)) + SS(K,9+2*ISS(K,4)
+3*ISS(K,5)) * DLOG10(THR)) / 3600.0
2 IF(QH(K,2).LT.0.0) QH(K,2) = 0.0
HRS = HRS + QH(K,2) * DELTAT
60
10 CONTINUE
C
C COMPUTE RECIRCULATED HEATS
DO 15 K = 1, NSS
IF(SS(K,1).LT.0.0) GO TO 15
IF(THR.LE.SS(K,10+2*ISS(K,4))) GO TO 15
IF(ISS(K,6).EQ.0) GO TO 15
QTS = 0.0

```

```

      QS = 0.0
      TOUT = 0.0
      LFLO = 6 + ISS(K,6)
      DO 70 M = 7, LFLO
        IF (QH(ISS(K,M),1).EQ.0.0) GO TO 70
        QTS = QTS + QH(ISS(K,M),1)
        * T(ISS(ISS(K,M),2),ISS(ISS(K,M),3))
        QS = QS + QH(ISS(K,M),1)
        TOUT = QTS / QS
      70 CONTINUE
      QH(K,2) = QH(K,2) + GAMMA + CP * QH(K,1) * TOUT
15 CONTINUE

```

```

C CALL THE PROPER BOUNDARY SUBROUTINE

```

```

DO 20 K = 1, NSS

```

```

  IF (THR.LE.SS(K,10)) GO TO 20

```

```

  IF (SS(K,1).EQ.1.0) CALL ADVECI(K,QH(K,1),QH(K,2))

```

```

  IF (SS(K,1).EQ.-1.0) CALL ADVECI(K,QH(K,1))

```

```

  IF (SS(K,1).EQ.2.0) CALL SPRAY(K,QH(K,1),QH(K,2),SSHLC,SSWLC)

```

```

  IF (SS(K,1).EQ.3.0) CALL JET3D(K,QH(K,1),QH(K,2))

```

```

  IF (SS(K,1).EQ.4.0) CALL JET2D(K,QH(K,1),QH(K,2))

```

```

20 CONTINUE

```

```

C INCREMENT SUMMARY STATISTICS

```

```

SHRS = SHRS + HRS

```

```

SSHLC = SSHLC

```

```

SSWLC = SSWLC

```

```

RETURN

```

```

END

```

```

SUBROUTINE ADVECI(K,Q,HT)

```

```

IMPLICIT REAL*8 (A-H,O-Z)

```

```

COMMON /AREAL/ SS(40,85), H(20,20), Z(20,20), DEPTH(20,20), 20 X 20

```

```

2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECURD(60,12), 20 X 20

```

```

3 SHRS, SSHLC, DELTA1, DELTA5, GAMMA, CP, SSWLC, AH0, AHL, FHS,

```

```

4 ISS(40,15), ICRD(6,2), NSS, NPRM1, IMAXM1, JMAXM1, NPRM1

```

```

DS2 = DELTA5 * DELTA5

```

```

R(ISS(K,2),ISS(K,3)) = R(ISS(K,2),ISS(K,3)) + Q / DS2

```

```

HA(ISS(K,2),ISS(K,3)) = HA(ISS(K,2),ISS(K,3)) + HT / DS2

```

```

RETURN

```

```

END

```

```

SUBROUTINE ADVECI(K,Q)

```

```

IMPLICIT REAL*8 (A-H,O-Z)

```

```

COMMON /AREAL/ SS(40,85), H(20,20), Z(20,20), DEPTH(20,20), 20 X 20

```

```

2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECURD(60,12), 20 X 20

```

```

3 SHRS, SSHLC, DELTA1, DELTA5, GAMMA, CP, SSWLC, AH0, AHL, FHS,

```

```

4 ISS(40,15), ICRD(6,2), NSS, NPRM1, IMAXM1, JMAXM1, NPRM1

```

```

R(ISS(K,2),ISS(K,3)) = R(ISS(K,2),ISS(K,3)) - Q / (DELTA5

```

```

2 * DELTA5)

```

```

HA(ISS(K,2),ISS(K,3)) = HA(ISS(K,2),ISS(K,3)) - GAMMA * CP * Q

```

```

2 * T(ISS(K,2),ISS(K,3)) / (DELTA5 * DELTA5)

```

```

RETURN

```

```

END

```

```

SUBROUTINE SPRAY(K,Q,HT,SSHLC,SSWLC)

```

```

IMPLICIT REAL*8 (A-H,O-Z)

```

```

COMMON /AREAL/ SS(40,85), H(20,20), Z(20,20), DEPTH(20,20), 20 X 20

```

```

2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECURD(60,12), 20 X 20

```

```

3 SHRS, SSHLC, DELTA1, DELTA5, GAMMA, CP, SSWLC, AH0, AHL, FHS,

```

```

4 ISS(40,15), ICRD(6,2), NSS, NPRM1, IMAXM1, JMAXM1, NPRM1

```

```

DS2 = DELTA5 * DELTA5

```

```

R(ISS(K,2),ISS(K,3)) = R(ISS(K,2),ISS(K,3)) + (1.0 - (SS(K,2)

```

```

2 + SS(K,3)) / 100.0) * Q / DS2

```

```

HA(ISS(K,2),ISS(K,3)) = HA(ISS(K,2),ISS(K,3)) + (1.0 - SS(K,4)

```

```

2 / 100.0) * HT / DS2

```

```

      SSWL = SSWL + (SS(K,4)/100.0) * HT * DELTAT
      SSWL = SSWL + ((SS(K,2) + SS(K,3)) / 100.0) * DELTAT * Q
      RETURN
      END
      SUBROUTINE JET3D(K,Q,HT)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /AREA1/ SS(40,85), H(20,20), Z(20,20), DEPTH(20,20),      20 X 20
      2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECORD(60,12), 20 X 20
      3 SHRS, SSWLC, DELTAT, DELTAS, GAMMA, CP, SSWLC, AHD, AWL, EHS,
      4 ISS(40,15), IRCRD(6,2), NSS, NPRNT, IMAXM1, JMAXM1, NPRNT
      DS2 = DELTAS * DELTAS
      W0 = Q / SS(K,2)
      W1 = Q * (DELTAS / SS(K,2) + 1.0) / (2.0 * DELTAS)
      I = ISS(K,2)
      J = ISS(K,3)
      IF(DEPTH(I-1,J).GT.0.0) GO TO 10
      U(I+1,J) = W0
      V(I,J+1) = - W1
      V(I,J) = W1
      GO TO 40
      10 IF(DEPTH(I,J+1).GT.0.0) GO TO 20
      V(I,J) = - W0
      U(I,J) = W1
      U(I+1,J) = - W1
      GO TO 40
      20 IF(DEPTH(I+1,J).GT.0.0) GO TO 30
      U(I,J) = - W0
      V(I,J) = W1
      V(I,J+1) = - W1
      GO TO 40
      30 IF(DEPTH(I,J-1).GT.0.0) GO TO 40
      V(I,J+1) = W0
      U(I,J) = W1
      U(I+1,J) = - W1
      40 R(I,J) = R(I,J) + Q / DS2
      HA(I,J) = HA(I,J) + HT / DS2
      RETURN
      END
      SUBROUTINE JET2L(K,Q,HT)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /AREA1/ SS(40,85), H(20,20), Z(20,20), DEPTH(20,20),      20 X 20
      2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECORD(60,12), 20 X 20
      3 SHRS, SSWLC, DELTAT, DELTAS, GAMMA, CP, SSWLC, AHD, AWL, EHS,
      4 ISS(40,15), IRCRD(6,2), NSS, NPRNT, IMAXM1, JMAXM1, NPRNT
      DS2 = DELTAS * DELTAS
      W0 = Q / DSQRT(DELTAS * SS(K,2))
      W1 = Q * (DSQRT(DELTAS / SS(K,2)) + 1.0) / (2.0 * DELTAS)
      I = ISS(K,2)
      J = ISS(K,3)
      IF(DEPTH(I-1,J).GT.0.0) GO TO 10
      U(I+1,J) = W0
      V(I,J+1) = - W1
      V(I,J) = W1
      GO TO 40
      10 IF(DEPTH(I,J+1).GT.0.0) GO TO 20
      V(I,J) = - W0
      U(I,J) = W1
      U(I+1,J) = - W1
      GO TO 40
      20 IF(DEPTH(I+1,J).GT.0.0) GO TO 30
      U(I,J) = - W0
      V(I,J) = W1
      V(I,J+1) = - W1

```

```

      GO TO 40
30 IF(DEPTH(I,J-1).GT.0.0) GO TO 40
   V(I,J+1) = WC
   U(I,J) = WI
   U(I+1,J) = - WI
40 R(I,J) = R(I,J) + G / DSZ
   HA(I,J) = HA(I,J) + HT / USZ
   RETURN
END
SUBROUTINE DSPLAY(N,NA,NB)
C
C SUBROUTINE DSPLAY DISPLAYS THE FLOWS PER UNIT WIDTH, DEPTHS,
C AND TEMPERATURE EXCESSES, IF AND WHEN DESIRED. IN ADDITION, IT
C RECORDS THE VALUES OF THOSE VARIABLES WHICH ARE LATER PRINTED
C IN THE SUMMARY STATISTICS.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /AREA1/ SS(40,85), F(20,20), Z(20,20), DEPTH(20,20), 20 X 20
      2 U(20,20), V(20,20), T(20,20), R(20,20), HA(20,20), RECORD(60,12), 20 X 20
      3 SHRS, SSHLC, DELTAT, DELTAS, GAMMA, CP, SSWLC, AMU, AWL, EHS,
      4 ISS(40,15), IRCRD(6,2), NSS, NPRNT, IMAXM1, JMAXM1, NPRNT
      DIMENSION UC(20,20), VC(20,20), DEPTH0(20,20), TC(20,20), 20 X 20
      2 TX(20,20) 20 X 20
      TMIN = DELTAT * CFLCAT(N) / 60.0
      IF(NPRNT.EQ.0) GO TO 70
      DO 60 J = 1, NB
        DO 60 I = 1, NA
          IF(DEPTH(I,J).GT.0.0) GO TO 65
          TX(I,J) = -100.0
          GO TO 60
65 TX(I,J) = T(I,J)
60 CONTINUE
      IF(NA.GT.20) GO TO 90
      DO 90 J = 1, NB
        DO 90 I = 1, NA
          UC(I,J) = U(I,J)
          VC(I,J) = V(I,J)
          DEPTH0(I,J) = DEPTH(I,J)
          TC(I,J) = TX(I,J)
90 CONTINUE
      GO TO 130
80 IF(NA.GT.40) GO TO 100
      NA = NA / 2
      DO 110 J = 1, NB
        DO 110 I = 1, NA
          UC(I,J) = U(2*I,J)
          VC(I,J) = V(2*I,J)
          DEPTH0(I,J) = DEPTH(2*I,J)
          TC(I,J) = TX(2*I,J)
110 CONTINUE
      GO TO 130
100 NA = NA / 3
      DO 120 J = 1, NB
        DO 120 I = 1, NA
          UC(I,J) = U(3*I,J)
          VC(I,J) = V(3*I,J)
          DEPTH0(I,J) = DEPTH(3*I,J)
          TC(I,J) = TX(3*I,J)
120 CONTINUE
130 WRITE(6,10) N, TMIN
      10 FORMAT('1', 'AT NSTEPS = ', I6, ' (TIME = ', F10.3, ' MINUTES), TH
      2E VALUES OF U (FT**2 / SEC) ARE')
      CALL GRID(UC,NA,NB)

```

```

      WRITE(6,20) N, TMIN
20  FORMAT('0', 'AT NSTEPS = ', 16, ' TIME = ', F10.3, ' MINUTES), TH
    2E VALUES OF V (FT**2 / SEC) ARE')
      CALL GRID(VD,NA,NB)
      WRITE(6,30) N, TMIN
30  FORMAT('0', 'AT NSTEPS = ', 16, ' TIME = ', F10.3, ' MINUTES), TH
    2E VALUES OF DEPTH (FT) ARE')
      CALL GRID(DEPTH,NA,NB)
      WRITE(6,40) N, TMIN
40  FORMAT('0', 'AT NSTEPS = ', 16, ' TIME = ', F10.3, ' MINUTES), TH
    2E VALUES OF TEMPERATURE EXCESS (DEGREES F) ARE')
      CALL GRID(TO,NA,NB)
70  THR = TMIN / 60.0
      RECORD(NPROT,1) = THR
      RECORD(NPROT,2) = SHRS
      RECORD(NPROT,3) = AHD
      RECORD(NPROT,4) = EHS
      RECORD(NPROT,5) = AWL
      DO 50 L = 1,6
        RECORD(NPROT,L+5) = T(IGRID(L,1),ICRCL(L,2))
50  CONTINUE
      NPRGT = NPRGT + 1
      RETURN
      END
      SUBROUTINE GRID(A,NC,ND)
C
C      SUBROUTINE GRID PRINTS A GRID OF LENGTH NA AND WIDTH NB.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION A(20,20)
      DO 100 K=1, ND
        J=ND - K + 1
        WRITE(6,10) (A(I,J), I=1, NC)
100 CONTINUE
10  FORMAT(' ', 20F6.2)
      RETURN
      END

```

APPENDIX F

GLOSSARY OF SYMBOLS IN DOCUMENTATION

- A = Pond surface area, in Ft^2 .
- A_i = Constant in reactor heat release rate log-time relation, in Btu Hr^{-1} for i -th time regime.
- AHD = Accumulated reactor heat dissipated, in Btu.
- AHR = Accumulated reactor heat released, in Btu.
- ATWL = Accumulated total waterloss, in Ft^3 .
- B_i = Log slope in reactor heat release rate, log-time relation, in $\text{Btu Hr}^{-1} (\log_{10} \text{Hr})^{-1}$ for i -th time regime.
- B = Slope of water vapor pressure-temperature relation, in $\text{mmHg } ^\circ\text{F}^{-1}$.
- C_h = Chezy friction coefficient.
- c_p = Specific heat of water, in $\text{Btu Lb}^{-1} ^\circ\text{F}^{-1}$. (equals 1.0 for fresh water)
- DELTA S = Grid size in HYETA, in Ft.
- D = Pond depth, in Ft.
- D_{max} = Maximum pond depth in HYETA simulation, in Ft.
- Dwl = Percentage of flow to nozzles lost by water drift.
- E = Thermal dispersion coefficient, in $\text{Ft}^2 \text{Sec}^{-1}$.
- E_x = x-directional turbulent dispersion coefficient, in $\text{Ft}^2 \text{Sec}^{-1}$.
- E_y = y-directed turbulent dispersion coefficient, in $\text{Ft}^2 \text{Sec}^{-1}$.
- E_o = Entrained plus jet flow at a distance Δs from jet, in $\text{Ft}^3 \text{Sec}^{-1}$.
- E_I = Entrained flow into Δs block containing jet, in $\text{Ft}^3 \text{Sec}^{-1}$.
- ETA = Daily equilibrium temperature amplitude, in $^\circ\text{F}$.
- Evl = Percentage of flow into nozzles lost by evaporation.
- F_i = External forces per unit fluid volume, in Ft Sec^{-2} .
- FR(J,1) = Time on in METMIN flow regime specification, hours after DBA.
- FR(J,2) = Flow rate specification in METMIN, in $\text{Ft}^3 \text{Sec}^{-1}$.
- f = Non-dimensional friction factor.
- $f(w)$ = Wind speed function in coefficient of surface heat exchange evaluation.
- g = Gravitational acceleration, in Ft Sec^{-2} .

- H = Water surface height above datum, in Ft.
- $H(I,J)$ = Water surface height above datum in numerical scheme at time t , in Ft.
- $HP(I,J)$ = Water surface height above datum in numerical scheme at time $t+\Delta t$, in Ft.
-
- HA = Net heat addition per unit surface area by other than surface heat exchange processes, in $\text{BTU Ft}^{-2} \text{Sec}^{-1}$.
-
- $HRF(J,K)$ = Heat time regimes in METMIN.
- H_{am} = Mean daily solar radiation, in $\text{BTU Ft}^{-2} \text{Day}^{-1}$.
- H_{amax} = Daily maximum solar radiation, in $\text{BTU Ft}^{-2} \text{Day}^{-1}$.
- HIS = Heat in storage, in BTU.
- H_r = Average rate of reactor heat release, in BTU Hr^{-1} .
- $H(t)$ = Reactor heat release rate as a function of time in elementary analysis, in BTU Day^{-1} .
- Hvl = Latent heat of vaporization, in Btu lb^{-1} .
- K = Coefficient of surface heat exchange, in $\text{BTU Ft}^{-2} \text{Day}^{-1} \text{ } ^\circ\text{F}^{-1}$.
- n = Manning roughness coefficient in $\text{Ft}^{1/6}$.
- $NAREA$ = Number of area steps in METMIN.
- Phl = Percentage of heat loss attributable to sprays and other devices.
- PTA = Ambient pond temperature diurnal amplitude, in $^\circ\text{F}$.
- Q_o = Jet flow rate, in $\text{Ft}^3 \text{Sec}^{-1}$.
- Q = Pond flow rate, in $\text{Ft}^3 \text{Sec}^{-1}$.
- $QH(K,1)$ = Flow rate at each source of time step in source/sink subroutine, in $\text{Ft}^3 \text{Sec}^{-1}$.
- $QH(K,2)$ = Heat rate at each source at time step in source/sink subroutine, in BTU Sec^{-1} .
- $Q(\xi)$ = Jet flow plus entrained velocity at a distance ξ from virtual source point, in $\text{Ft}^3 \text{Sec}^{-1}$.
- R = Hydraulic radius, in Ft.
- RN = Net flow addition per unit surface area in continuity, in $\text{Ft}^3 \text{Sec}^{-1} \text{Ft}^{-2}$.

- ρ = Specific weight of water, in Lb Ft^{-3} .
- SA = Total surface area of pond in Ft^2 .
- SWL = Spray water loss rate, in $\text{Ft}^3 \text{ Sec}^{-1}$.
- $T(I,J)$ = Temperature excess in numerical scheme at time t , in $^{\circ}\text{F}$.
- $TP(I,J)$ = Temperature excess in numerical scheme at time $t+\Delta t$, in $^{\circ}\text{F}$.
- T = Pond ambient temperature, in $^{\circ}\text{F}$.
- T_{am} = Mean daily air temperature, in $^{\circ}\text{F}$.
- T_Q = Average of pond surface temperature and dew point temperature, in $^{\circ}\text{F}$.
- T_d = Dew point temperature, in $^{\circ}\text{F}$.
- T_{dm} = Mean daily dew point temperature, in $^{\circ}\text{F}$.
- T_{dmax} = Daily maximum dew point temperature, in $^{\circ}\text{F}$.
- T_{dmin} = Daily minimum dew point temperature, in $^{\circ}\text{F}$.
- T_e = Equilibrium temperature, in $^{\circ}\text{F}$.
- $T_e(t)$ = Hourly equilibrium temperature, in $^{\circ}\text{F}$.
- T_{em} = Mean daily equilibrium temperature, in $^{\circ}\text{F}$.
- T_{emax} = Daily maximum equilibrium temperature, in $^{\circ}\text{F}$.
- T_{emin} = Daily minimum equilibrium temperature, in $^{\circ}\text{F}$.
- T_s = Pond surface temperature, in $^{\circ}\text{F}$.
- $TEEW$ = Excess evaporative waterloss rate at excess temperature for the total pond surface area, in $\text{Ft}^3 \text{ Day}^{-1}$.
- $TEWL$ = Evaporative waterloss rate from total pond surface area, in $\text{Ft}^3 \text{ Day}^{-1}$.
- $TNEW$ = Natural evaporative waterloss rate at ambient temperature from total pond surface area, in $\text{Ft}^3 \text{ Day}^{-1}$.
- t_{max} = Time after DBA to maximum temperature excess for exponentially decaying heat load, in Days.
- t_{ss} = Time to steady-state in elementary analysis, in Days.
- θ = Pond temperature excess, in $^{\circ}\text{F}$.
- θ_{ss} = Steady-state temperature excess for completely mixed pond in elementary analysis, in $^{\circ}\text{F}$.

U_1, U_2, U_3 = Velocity components at a point, in Ft Sec^{-1} .

U = X-directed horizontal transport vector, in $\text{Ft}^2 \text{Sec}^{-1}$.

$U(I,J)$ = U-transport in numerical scheme at time t , in $\text{Ft}^2 \text{Sec}^{-1}$.

$UP(I,J)$ = U-transport in numerical scheme at time $t+\Delta t$, in $\text{Ft}^2 \text{Sec}^{-1}$.

V = Y-directed horizontal transport vector, in $\text{Ft}^2 \text{Sec}^{-1}$.

$V(I,J)$ = V-transport in numerical scheme at time t , in $\text{Ft}^2 \text{Sec}^{-1}$.

$VP(I,J)$ = V-transport component in numerical scheme at time $t+\Delta t$, in $\text{Ft}^2 \text{Sec}^{-1}$.

V_0 = Pond volume, in Ft^3 .

W_1 = Entrained flow per unit width into jet block, in $\text{Ft}^2 \text{Sec}^{-1}$.

W_0 = Jet flow per unit width exiting from a block, in $\text{Ft}^2 \text{Sec}^{-1}$.

WX = x-component of surface wind stress, in $\text{Ft}^2 \text{Sec}^{-2}$.

WY = y-component surface wind stress, in $\text{Ft}^2 \text{Sec}^{-2}$.

ω = Diurnal frequency of equilibrium temperature variation, in $2\pi/24$ radians Hr^{-1} .

x_1, x_2, x_3 = Indexed x, y, z coordinate vectors, in Ft.

ξ = Jet distance from virtual source point, in Ft.

ξ_{02} = Virtual source distance for two dimensional vertically mixed jet, in Ft.

ξ_{03} = Virtual source distance for three-dimensional jet, in Ft.

Δs = DELTAS grid spacing, in Ft.

Δt = DELTAT time step in integration, in Sec.

t_{max} = Time delay from noon to daily maximum ambient pond temperature, in Hr.

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