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Gentlemen:

I am submitting two papers for your review and possible publication in the Journal of the Energy Division

1. "A Performance Model for Ultimate Heat Sink Spray Ponds"

2. "Application of Models to Design of Spray Ponds for Nuclear Power Plants."

The first paper describes a computational model for performance of spray ponds in terms of temperature and water loss, and compares the model to data on several spray ponds. The second paper demonstrates how a performance model can be used in a complex methodology to assess the worst-case performance of ultimate heat sinks in nuclear power plants. While the second paper uses the performance model of the first paper, it is not dependent on a particular performance model. The two papers stand alone, but I would prefer to see them reviewed and published together.

Please inform me of your review of my papers at your earliest convenience.

Sincerely,

Original Signed By

Richard B. Codell, Ph.D.
Senior Hydraulic Engineer,
Office of Nuclear Materials Safety
and Safeguards

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A Performance Model for Ultimate Heat Sink Spray Ponds

By Richard B. Codell, Associate Member

ABSTRACT

A mathematical model for the performance of spray ponds is developed using a detailed computational approach. The model considers heat transfer and evaporation from individual droplets of sprayed water and the pond surface, and drift loss from the sprays. Modification of the temperature and humidity of the surrounding air is taken into account in calculating heat and mass transport from the sprays. Flow of air through the spray field is considered to be either driven by the ambient wind, or by natural convection. Relationships for heat and mass transfer from the drops are derived from the empirical studies of Ranz and Marshall. Numerical experiments demonstrate that the models can be simplified and still be useful for spray pond performance assessments. The models are validated with data on several industrial and nuclear power plant spray ponds, and with data from an extensively instrumented, experimental spray pond. Results of the validation studies demonstrate generally good agreement. These models are used in a complex methodology for predicting the performance of spray ponds used for nuclear power plant service, although it is not limited to this application. A subsequent paper describes the overall assessment methodology.

SUMMARY

This paper presents a mathematical model for spray pond performance. It has been tested with data from several spray ponds and was found to work well. The model is used in a methodology for nuclear power plant performance assessment, which is the subject of a subsequent paper.

KEY WORDS

Heat transfer
Spray ponds
Ultimate heat sink
Nuclear power plants

APPLICATION OF MODELS TO DESIGN OF SPRAY PONDS FOR NUCLEAR POWER PLANTS

by Richard B. Codell, Associate Member

ABSTRACT

This paper presents a complex methodology for assessing the performance of spray ponds in ultimate heat sink service at nuclear power plants. A spray pond performance model, developed in the previous paper, is used in conjunction with onsite and offsite meteorological data to predict the highest temperature and greatest 30-day water loss which can reasonably be expected to occur during the lifetime of the plant. The performance model for heat and mass transfer is used to develop an efficient phenomenological model used to scan the long-term meteorological records. Refined estimates of temperature or water loss may then be based on more complicated models if necessary. Short-term onsite data are correlated to the long-term offsite data to formulate correction factors for the difference in location. Cumulative Distribution Functions for temperature and water loss are determined from the long-term meterological records in order to predict the occurance of these quantities which are less severe than the peak. The methodology is demonstrated using data and parameters from the Palo Verde nuclear plant as an example.

SUMMARY

A complex methodology for determining the performance of ultimate heat sink spray ponds for nuclear plants is demonstrated. The most adverse temperature and water loss for the Palo Verde plant is used as an example.

KEY WORDS

Ultimate Heat Sink

Heat Transfer

Spray Ponds

Nuclear Power Plant

A Performance Model for Ultimate Heat Spray Ponds

by Richard B. Codell*
Associate Member

INTRODUCTION

The ultimate heat sink (UHS) is defined as the complex of sources of service water supply necessary to operate, shut down, and cool down a nuclear power plant safely. The UHS must be designed to dissipate the shutdown heat of one or several units and provide at least a 30 day supply of cooling water for the most adverse meteorological conditions (23). Ultimate heat sink cooling water is frequently supplied directly from the main condensor cooling water source such as a lake or river. Water may also be supplied by dedicated cooling ponds, cooling towers or spray ponds. Spray ponds are generally small impoundments in which cooling is augmented by spraying the heated water through nozzles which are oriented in the vertical direction.

In this paper, a spray pond performance model will be developed, and the good performance of the model against experimental data demonstrated. A subsequent paper will describe the way in which the spray pond performance model was used as part of a comprehensive analysis for an ultimate heat sink of a real nuclear plant (10).

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Spray Pond Performance Models

A number of spray pond performance models have appeared in the literature. They may be broadly characterized as empirical, semi-empirical and computational. Empirical models are generally relationships which have been developed from observations of the performance of spray ponds over wide ranges of meteorological and physical (e.g., nozzle spacing, pressure) conditions. Examples of this type of model are manufacturers curves (e.g., Ref. 22), the ASHRAE method (1), and Berman (2). These methods are useful for first estimates, but are extremely limited in their ability to predict performance under adverse or unusual conditions for the evaluation of spray ponds for ultimate heat sink service.

Semi-empirical methods are those characterized by models which are developed from first-principals and are mathematically more rigorous than the empirical methods. These methods are generally used to estimate the performance of a spray system composed of many spray units based on the experimentally measured performance of a single spray unit. Examples of this approach are the NTU method (18), and the SER method (5).

Computational methods are largely based on first-principals, but attempt to characterize the performance of the sprays by considering the heat and mass transfer from individual drops, relying on experimental measurements as little as possible. These models have the advantage of theoretically being able to predict spray pond performance in the absence of actual test data for a given spray system, and are likely to be more defensible than the semi-empirical models for predictions of spray performance under adverse conditions, or

conditions outside of the range of experimental data. A disadvantage of this approach is that the simulations can be computationally difficult. Examples of this method are the models of Elgawhary (12), and Myers (16, 17).

The model which will be developed in this paper is best classified as a computational method, partially based on the work of Myers (16, 17). Empirical relationships are used only for the heat and mass transfer from individual sprayed drops and the surface of the pond. In actual use for UHS analyses, the problem of long computer run times is solved by using efficient empirical performance equations based on the results of the rigorous model. This technique is described in a subsequent paper (10).

The primary purpose for developing this model was the licensing of nuclear power plants. Because of the stringent requirements for nuclear power plant licensing, the emphasis is on conservatism in the calculation although the final model has been demonstrated to be quite realistic.

Surface Heat and Mass Transfer

For typical spray ponds, a relatively small fraction of the total heat and mass transfer occurs at the pond surface. The surface heat transfer relationships are straightforward and have been well-verified for both large cooling lakes (20) and small cooling ponds (9). The rate of atmospheric heat exchange $\dot{H}$ per unit area is given by the expression:

$$\dot{H} = \dot{H}_{SN} + \dot{H}_{RJ} + \dot{H}_{AN} - \dot{H}_{BR} - \dot{H}_{E} - \dot{H}_{C} \qquad (1)$$

where $\dot{H}_{SN}$ is the net rate of solar radiation entering the pond and $\dot{H}_{RJ}$ is the net rate of artificial heat addition to the pond. The terms $\dot{H}_{AN}$, $\dot{H}_{BR}$, $\dot{H}_E$ and $\dot{H}_C$ represents the net atmosphere radiation, back radiation, evaporative, and conductive-convective heat transfer respectively, and are expressed in terms of meteorological variables and pond surface temperature by the well-known Ryan-Harleman formulas (20), which will not be reproduced here.

Spray Field Heat and Mass Transfer

In a typical spray pond, most of the heat and water loss will occur from the sprays rather than the pond surface. The spray field performance model has two parts; (a) A "microscale" submodel that considers the heat, mass, and momentum transfer of a single drop as it falls through the surrounding air, and (b) "Macroscale" submodels that consider the modification of the surrounding air resulting from the heat, mass, and momentum transfer from many drops in different parts of the spray field. The two submodels are combined into a model of performance for the entire spray field which is then combined with a submodel of the pond itself to form the spray pond performance model.

The microscale submodel considers the heat, mass, and momentum transfer from a single water drop into the surrounding air. After leaving the nozzle, the motion of the drops is assumed to be controlled by the force of gravity and drag from the surrounding air. The drag is defined in terms of the local Reynolds number $Re = 2rv\rho_A/\mu$, which is a function of drop radius r, relative velocity between the drop in the surrounding air v, air density ρ_A and air viscosity μ. Information on the motion of the drops is necessary to several parts of the overall performance modeling:

- Drift loss is determined from the trajectory by calculating the fraction of drops falling outside of the pond boundaries,

- Heat and mass transfer from the surface of the drops is a function of the local drop Reynolds number, and

- Momentum exchanged between the drop and the surrounding air affects the flow of air within the spray field.

The rate of change in a drop's temperature may be expressed in terms of the equation (12):

$$\frac{dT}{dt} = - \frac{1}{4/3\rho\ C_p \pi r^3}\ [4\pi r^2 h_d\ (C_{WA} - C_\infty)\lambda + 4\pi r^2 h_c (T - T_{A,\infty})] \qquad (2)$$

where

T = temperature of the drop, °C

C_p = heat capacity of water, cal/(gm °C)

ρ = density of water, gm/cm³

r = radius of drop, cm

h_d = mass transfer coefficient, cm/sec

C_{WA} = concentration of water in air in equilibrium at the temperature of the drop, gm water/cm³ air

C_∞ = concentration of water in air in which the drop is immersed, gm water/cm³ air

λ = heat of vaporization of water, cal/gm

h_c = heat transfer coefficient, cal/(sec cm^2 °C)

$T_{A,\infty}$ = temperature of the air in which the drop is immersed, °C.

The heat transfer coefficient h_c and mass transfer coefficient h_d have been based on the classic study of Ranz and Marshall (19):

$$h_c = \frac{k_a}{r} (1 + 0.3\ Pr^{1/3} Re^{1/2}) \tag{3}$$

$$h_d = \frac{D}{r} (1 + 0.3\ Sc^{1/3}\ Re^{1/2}) \tag{4}$$

where k_a = thermal conductivity of air

D = diffusion coefficient for water vapor in air.

The concentration of water in air is defined by the Ideal Gas Law:

$$C_{WA} = \frac{p_w M_w}{R_g T} \tag{5}$$

where p_w = vapor pressure of water at temperature T

M_w = molecular weight of water

R_g = universal gas constant

T = absolute temperature of the drop.

The parameters p, μ, Pr, Sc, D and k_a used in the above equations are thermodynamic properties of the air-water system. For the present purposes, these properties have been expressed by the following empirical relationships in terms of the absolute temperature of air, T_A, °K (3):

$$\mu = 2.7936 \times 10^{-6}\ T_A^{0.73617} \text{ gm/(cm sec)} \tag{6}$$

$$\rho = 0.353\ T_A^{-1} \text{ gm/cm}^3 \tag{7}$$

$$Pr = 0.93176\ T_A^{-0.042784} \tag{8}$$

$$Sc = 2.2705\ T_A^{-0.21398} \quad (9)$$

$$D = 5.8758 \times 10^{-6}\ T_A^{1.8615}\ \text{cm}^2/\text{sec} \quad (10)$$

$$k_a = 3.9273 \times 10^{-7}\ T_A^{0.88315}\ \text{cal/(cm sec °C)} \quad (11)$$

The vapor pressure of water is expressed in terms of the absolute water temperature T (°k)

$$\ln p_w = (71.02499 - 7381.6477/T - 9.0993037 \ln T + 0.0070831558\ T),\ \text{atmospheres} \quad (12)$$

Macroscale Models

The temperature and humidity of the air in the interior of a spray field are both elevated and will lead to diminished spray performance with respect to an isolated nozzle in unaffected air. Heated, humidified air is less dense than cooler, drier air, so convection currents will be generated, which would also be affected by the drag forces of the drops.

Separate macroscale models deal with high- and low-windspeed conditions. The high-speed model assumes that the momentum exchange in the pond resulting from drop drag and buoyancy is much less important than that caused by the wind blowing through the spray field. The low-speed model assumes that only the self-induced transfer of the air through the pond by drop drag and buoyancy is important. Both the high and low wind speed models are run at the same time in the simulation regardless of the ambient wind speed because for some cases of high-heat loadings, natural convection might be greater than wind-induced convection. The model with higher performance is then chosen as being representative of the spray field for that time interval.

In the High Windspeed Model (HWS), the spray field is represented by a rectangular volume, which is divided into N equal rectangular segments as shown in Fig. 1. Ambient air enters the first segment of the spray field at a volumetric rate determined by the windspeed, w, perpendicular to the long axis of the pond and the cross-sectional area of the spray field A_s. It is assumed that the humidity and air temperature entering a segment are determined only by humidity and air temperature which left the segment upwind.

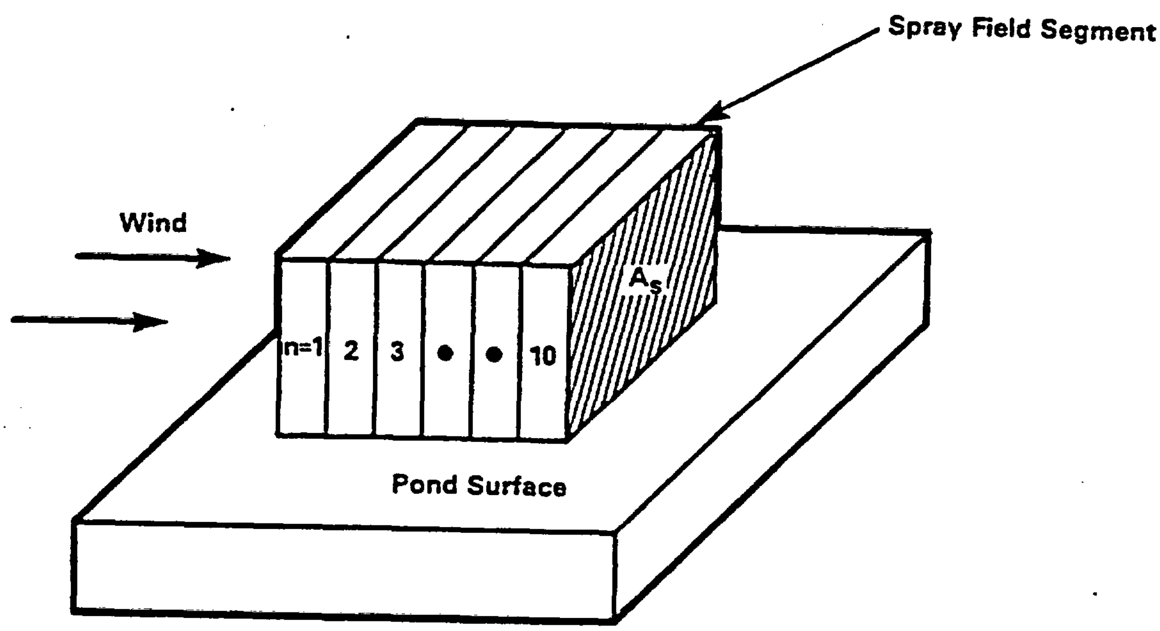

Figure 1 Segmentation of spray field for high-windspeed model

For drops of a particular average radius r_i, the heat entering the segment is proportional to the fraction of drops in that size range, the flow rate of water into the segment, and the difference between the temperature of the drop when it left the nozzle and the temperature when it reached the pond surface. The temperature of the air leaving one segment and entering the next reflects the added heat and moisture. Calculations continue with the next segment in the sequence through all pond segments. The total cooling performance of the spray field is the average drop cooling from all segments.

At low ambient windspeeds, the flow of air through the spray field is largely controlled by two mechanisms: drag from the spray droplets and buoyancy of the heated, humidified air. Because the spray-nozzle arrangements in most conventional spray fields point vertically upward, and are evenly distributed and symmetrical, it would appear that there would be little net effect of the spray droplet drag in the lateral direction. In conventional spray ponds, there would be a net downward drag caused by the falling drops, but under loads typical of UHS service, buoyancy would be the dominant force in the low-windspeed case. There are unconventional spray pond designs, however, in which the orientation of the nozzles causes significant air circulation (11).

For the low-windspeed model (LWS), the spray field is sectioned into N rectangular, annular cylinders of equal volume as shown in Fig. 2 (8, 17). Air enters the segment from all four sides and leaves the segment to enter the next segment after being heated and humidified by the sprays. Unlike the high-windspeed model, however, air also leaves through the top of the segment because of buoyancy. The net upward or downward velocity of air entering or leaving the top of each segment, v_{up}, is determined by Bernoulli's equation:

$$v_{up} = \frac{(F_b + F_d)}{\rho_A}^{1/2} \qquad (13)$$

The term F_b is the buoyant pressure on the segment:

$$F_b = A_T \, g \, \overline{\Delta\rho_A} \, \Delta z \qquad (14)$$

where

$\overline{\Delta\rho_A}$ is the average density difference between the air in the segment and the ambient air, and

Δz is one-half of the spray-field height.

The term F_d is the pressure due to drag from falling droplets:

$$F_d = \sum_i \frac{f_i \, M_{yi} \, Q}{V_i \, A_T} \quad , \qquad (15)$$

where M_{yi} is the net downward momentum imparted to the air by each of the falling drops in size range i, Q is the flowrate of water entering the entire spray field, and V_i is the volume of a drop in size range i.

A mass and enthalpy balance is then formulated by considering the heat and mass transfer starting at the center segment and stepping outward through the segments. Each segment is considered to be a compartment whose air temperature, humidity, and air-flow rate are determined by the heat and mass transfer of the segment itself and the previous and next segments. This portion of the model requires an iterative solution.

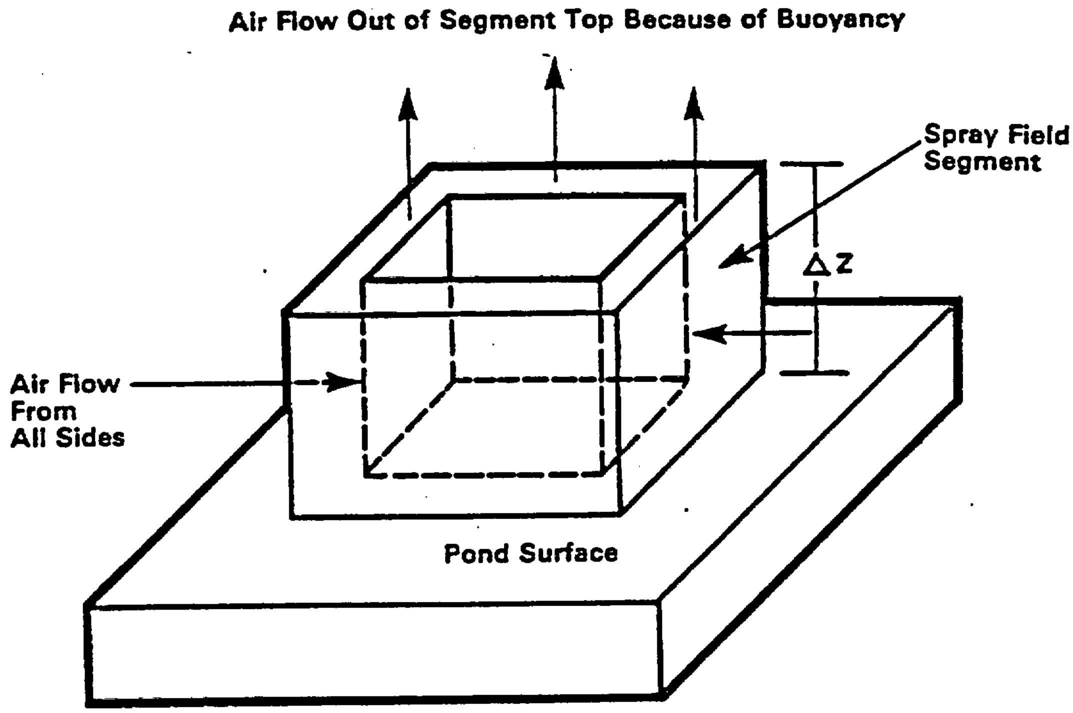

Figure 2. Segmentation of spray field for low-windspeed model

Simplifying Assumptions for Performance Models

The heat, mass, and momentum-transfer relationships for the drop depend strongly on its radius. The spray nozzles produce a wide distribution of drop radii which are characteristic of the nozzle design and operating conditions. The heat, mass, and momentum in any segment of the pond can be found by summing the contributions over the range of drop radii. If instead, a single average drop radius $\bar{r}$, could be found, which gave the same results as the summation of the results for the individual drop radius, the computational effort would be greatly reduced. Through experimentation with the HWS and LWS models, it appears that a single average drop radius could be chosen to very nearly represent the drop-diameter distribution over a wide range of operation for both the LWS and HWS models. In the case of the standard drop radius distribution for the Spraco 1751A nozzle summarized in Table 1, the average drop radius $\bar{r}$, most

Table 1 Drop-Diameter Distribution for Spraco 1751A Nozzle (3)

Radius, cm	Percent of total	Cumulative volume, %
0.0375	10	10
0.06	10	20
0.075	10	30
0.092	10	40
0.11	10	50
0.123	10	60
0.135	10	70
0.155	10	80
0.18	10	90
0.225	10	100

closely matching the results of the distributed drop radius results varied only from 0.098 cm to 0.104 cm over a wide range of conditions of wind speed, humidity and drop temperature (8).

A measure of mean drop size frequently used in spray pond models in the "Sauter" mean (6), which is the total droplet volume per unit mass divided by the total droplet surface area per unit mass. For the present discreet distribution, in 10 size ranges, the Sauter mean is calculated to be 0.085 cm. Chen and Trezek (6) estimate that the Sauter mean radius for this particular nozzle under standard conditions is between 0.079 cm based on the experimentally-measured data, to 0.096 cm based on a log-normal curve fit of the data. Use of the Sauter mean radius would result in a slightly greater cooling efficiency (less conservative) than would be predicted by the distributed-radius model.

The most accurate way to determine the effective radius is probably to perform several numerical experiments with the distributed drop radius and compare the results to the same cases where a single drop radius is used. The effective drop radius can then be chosen to match the distributed case results. In all subsequent examples of the model, the average drop radius was chosen to be 0.104 cm, since this is at the large end of the narrow range of radii determined by the numerical experiments and is conservative for the purpose of temperature calculations.

Including drag of the falling drops introduces several complications to the model. The drag term makes the equations of drop motion nonlinear, requiring a numerical integration solution. The net downward drag of the drops on the air is a destabilizing influence on the iterative solution, for the LWS model, especially at low heat loads. The net effect of eliminating drag is that the falling drops are predicted to experience more cooling and evaporation. Eliminating the drag term also increased the efficiencies predicted by the LWS model because the computed net vertical air flow is increased. In addition, it increases the stability of the iterative solution in this model because it only allows an upward flow of air in each segment. Table 2 shows the predicted spray cooling efficiencies with and without drag over a range of heat load and meteorological conditions for spray-pond test data from the Rancho Seco nuclear power plant (21). Eliminating the drag term improved the model-prototype comparison. On the basis of the good agreement with data shown by the model and the improvement in stability of the LWS model, the drag term can be eliminated from the spray performance model for typical spray-pond applications. This would not be a correct assumption for certain oriented spray configurations

Table 2 Measured Atmospheric Parameters and Spray Efficiency Predicted From Combined High-Windspeed an Low-Windspeed Model With and Without Drag Terms - Rancho Seco data (22)

Wet bulb °C	Dry Bulb °C	Sprayed Water °C	Wind Speed cm/sec	Efficiencies* measured	Efficiencies* calculated with Drag	Efficiencies* calculated without Drag
16.1	27.5	26.6	581.8	0.417	0.383	0.415
16.4	27.2	26.7	558.8	0.475	0.381	0.414
10.6	12.8	25.2	236.9	0.325	0.259	0.276
9.2	11.1	25.2	44.7	0.288	0.248	0.277
13.6	18.3	25.3	268.2	0.309	0.287	0.307
14.2	21.7	25.9	290.6	0.355	0.303	0.324
22.4	35.0	26.7	312.9	0.389	0.398	0.423
20.9	33.9	27.3	295.0	0.343	0.368	0.391
19.2	29.8	27.1	375.5	0.458	0.373	0.400
16.1	22.4	26.8	169.9	0.345	0.256	0.261
15.7	20.7	26.5	169.9	0.285	0.250	0.270
12.3	14.4	38.6	44.7	0.352	0.324	0.350
11.7	13.9	37.8	71.5	0.362	0.318	0.348
11.1	13.3	36.6	58.1	0.344	0.310	0.340
9.4	11.7	38.7	44.7	0.345	0.315	0.340
8.9	10.6	36.3	17.9	0.346	0.302	0.330

* Efficiency = (Sprayed Temp. - Cooled Temp.)/(Sprayed Temp. - Wet Bulb)

that are designed to induce lateral air flows (11). In addition, drag cannot be neglected in the drift-loss model described below since the smaller drop diameters which are most prone to drift, are strongly affected by drag.

Drift Loss Model

A fraction of the water droplets sprayed from the nozzles will be lost because they are physically carried by the wind beyond the pond borders. This "drift"

loss can be estimated by means of a mathematical model in which the trajectory of droplets are calculate under the influence of a wind field.

The model is formulated for a spray pond of conventional design, with the Spraco 1751A nozzle operating at the recommended pressure and height. The trajectories of drops leaving the spray nozzles are simulated by using a ballistics approach in a manner similar to that of the "microscale" submodel but for 21 drop radii that represent the drop-radius distribution of the Spraco 1751A nozzle, and with a numerical solution of the equations for drop motion, including the drag terms. It is conservativly assumption that all droplets are formed at the apogee of the trajectory of the largest drop.

The buoyancy of the heated, humidified air in a heavily loaded spray pond could cause an updraft on the order of tens to hundreds of centimeters per second during low-wind conditions. A single value of updraft velocity is chosen to represent an average for the 30-day period of an accident. Drift loss is sensitive to the choice of the updraft velocity. Estimates of updraft can be based on the humid air flows calculated from the LWS performance model. Typical average velocities (weighted by the top area of the spray field) are calculated to be in the range of 25 to 40 cm/sec for UHS heat loads. Drift loss is likely to be important only when there is a strong wind, and it is likely that during these conditions the convection caused by the buoyancy of the warm, humid air would be largely disrupted. Other phenomena, such as the air flow induced by momentum transfer from the sprays, and instabilities induced for the density difference are not well understood. The estimation of updraft for use in the model is therefore difficult.

Fortunately, drift loss is expected to be much less important than water loss by evaporation from the sprays. Since the models presented in this paper are generally used in safety analyses, a conservatively large updraft velocity, typically 50 cm/sec, is usually chosen. This is the value used in the model-prototype comparison presented later.

The patterns for each wind speed and each drop radius in the distribution, which are predicted from the drop ballistics, are used subsequently to predict the fraction of water passing beyond the boundaries of the pond. A drop is assumed to be lost if it does not fall on the pond surface.

The drift loss model has been partially validated with field data from the Rancho Seco tests (21). While no direct measurements of drift loss were available from these tests, water loss measured from the spray pond tests run without an imposed heat load were compared to the model simulations. When corrections for evaporation from the sprays were taken into account, the measured and modeled water losses were in reasonable agreement (8). The drift loss model employed an updraft velocity of 50 cm/sec.

Pond Model

The pond model presumes that the heated effluent is instantaneously and uniformly mixed throughout the volume of the pond and that the water in the pond is uniform in temperature. Such assumptions make the model computationally simple, and will generally be adequate for small spray ponds where the heat and mass transfer rates are dominated by the sprays.

$$\frac{dT_s}{dt} = \frac{\dot{H}_{RJ} - \dot{H} - \dot{H}_{spray}}{\rho C_p V_p} \quad (16)$$

where V_p is pond volume and $\dot{H}_{spray}$ is the heat rejected by the spray.

The mass balance on the pond includes evaporative loss from the surface, evaporative loss from the sprays, drift, and blowdown or leakage:

$$\frac{dV_p}{dt} = - W_b - \frac{A\dot{H}_E}{\rho\lambda} - W_{drift} - W_{spray} \quad (17)$$

where

W_b = blowdown on leakage losses,
W_{drift} = drift loss,
W_{spray} = rate of water evaporated from all drops in the spray field.

Validation of Overall Model Performance

The spray field performance model has been compared with the data from several spray ponds with generally good results as demonstrated in Table 2 for the case of the Rancho Seco nuclear plant. Further comparisons of the model with field data on spray ponds are discussed in Refs. 8 and 9. The results of a comparison between the overall model and a realistic experimental case are now presented.

A series of four spray pond performance tests was conducted on behalf of the NRC by Battelle-Pacific Northwest Laboratories in September and October 1979 (13, 14). Three of the tests involved spraying of hot water; the remaining

test involved cooling by surface heat transfer only, without the influence of the sprays. The East Mesa spray pond, shown in Fig. 3, is located near El Centro in southern California on the site of a Department of Energy geothermal test station. The square-shaped pond is approximately 60 m on each side with sloping walls and a flat bottom, and is lined with an impermeable membrane (13). Other pond parameters are given in Table 3. About 0.235 m^3/sec of water is sprayed through 64 Spraco 1751A nozzles in the arrangement suggested by the manufacturer (22).

Table 3. Physical description of East Mesa Spray Pond

Parameter	
Nominal full-surface area	3385 m^2
Nominal full volume	4675 m^3
Nominal depth when full	1.7 m + 0.3 m mud
Altitude	11 m mean sea level
Atmospheric pressure during tests	1000-1020 mbars

The pond was extensively instrumented. Sprayed water temperature was measured at three nozzles. Water temperature was measured at several places in the pond at various depths. Pond water level was determined by three hook gauges and stilling wells. Ground temperature was measured at several depths beneath the pond liner. Extensive meteorological data were collected at several elevations from instruments located adjacent to the pond and from a reference tower located 120m from the pond. Both net and downward solar radiation were

measured. Sprayed water was collected within the pond boundaries, and its temperature measured.

The performance tests were run on the East Mesa spray pond by filling the pond with hot water and steam provided by the geothermal wells, and then spraying the pond water through the nozzles. There was no input of heat or water during the tests.

The spray pond performance model was run to simulate the performance of the prototype pond. Most of the data used in the simulation were those from the 10 meter elevation on the remote tower, since these data were most similar to actual onsite data available at nuclear plant sites. Only downward solar radiaton was used, even though net radiation was available. Measured data used in the simulations are presented in Appendix I.

An average drop radius of 0.104 cm, and an updraft of 50 cm/sec were used. The drift loss as a function of windspeed, as calculated by the drift model, is shown in Fig. 4.

Actual water loss in the pond was calculated from the measured change in pond water level with a correction for thermal expansion of water in the pond, stilling well and siphon tubes. Details of this correction are given in Ref. 9.

Comparisons between the model and prototype for the East Mesa data are shown in Figs. 5, 6 and 7 for the three hot-spraying tests. Agreement of the model with the data is generally excellent. The model shows greater temperature

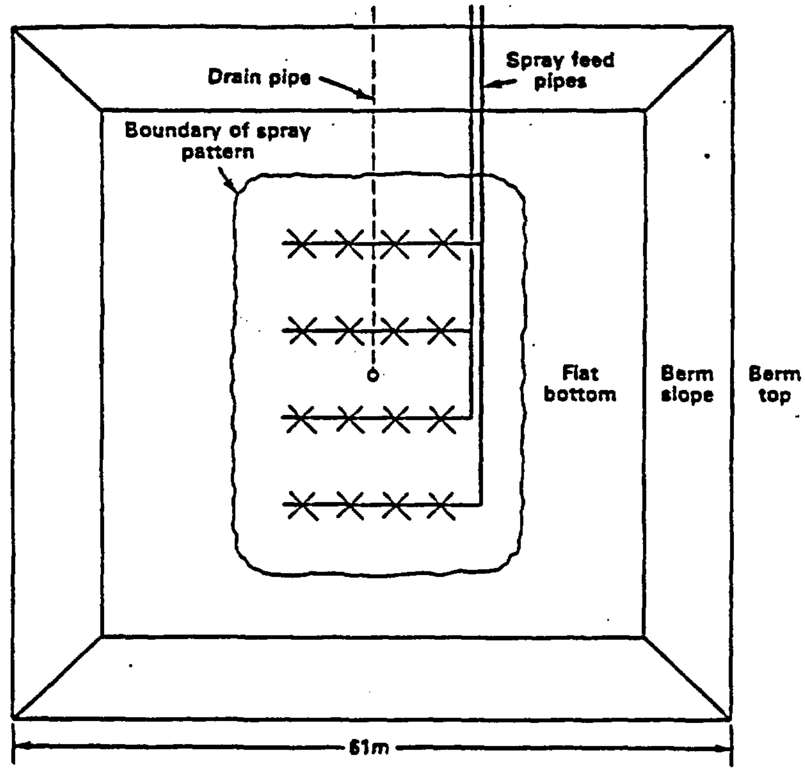

Figure 3 East Mesa Experimental spray pond - plan view

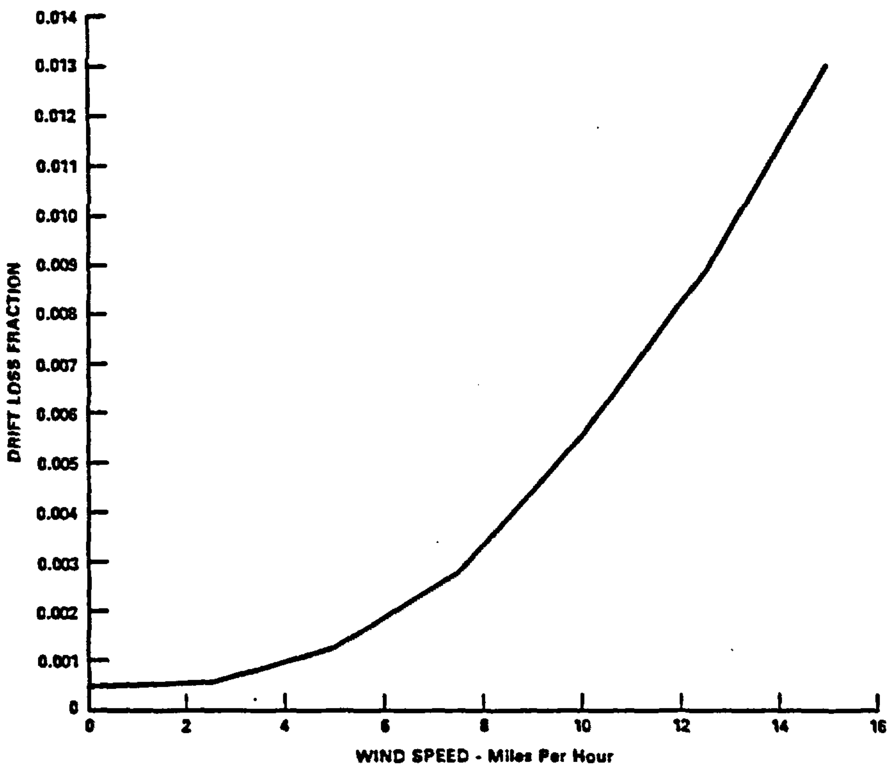

Figure 4 Drift loss function for East Mesa model

swings than was experimentally observed in some of the tests, but the reasons for this anomaly are not clear.

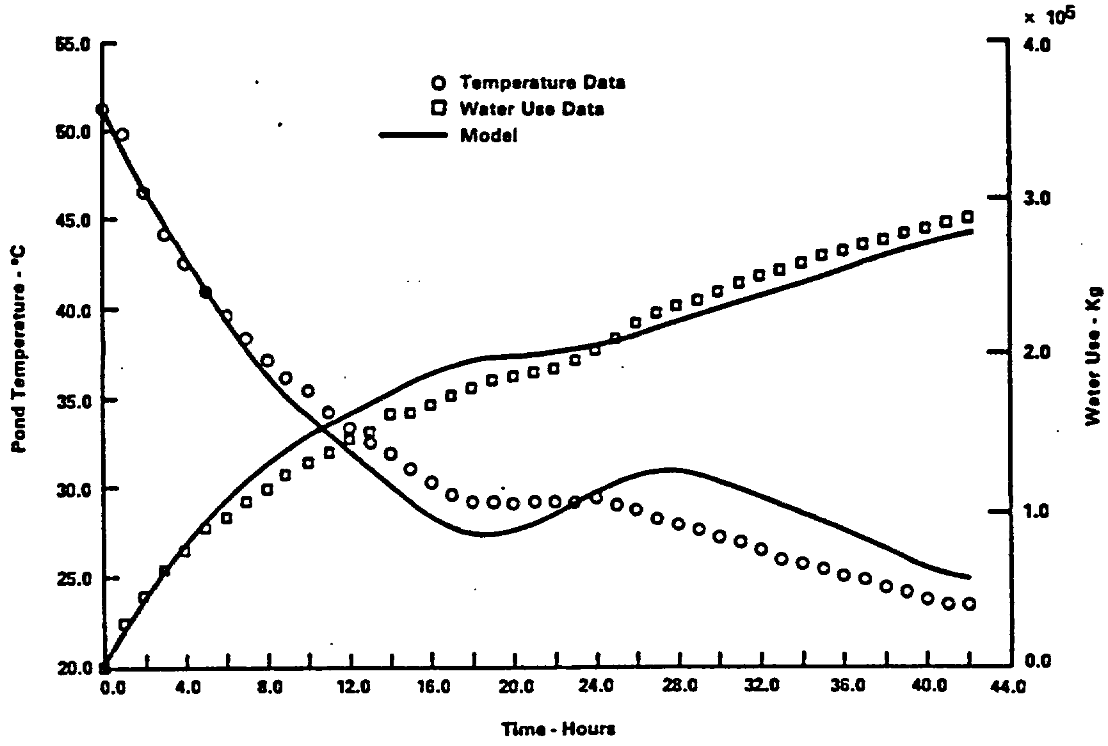

Figure 5 Pond temperature and water loss for "East Mesa Warm 1"

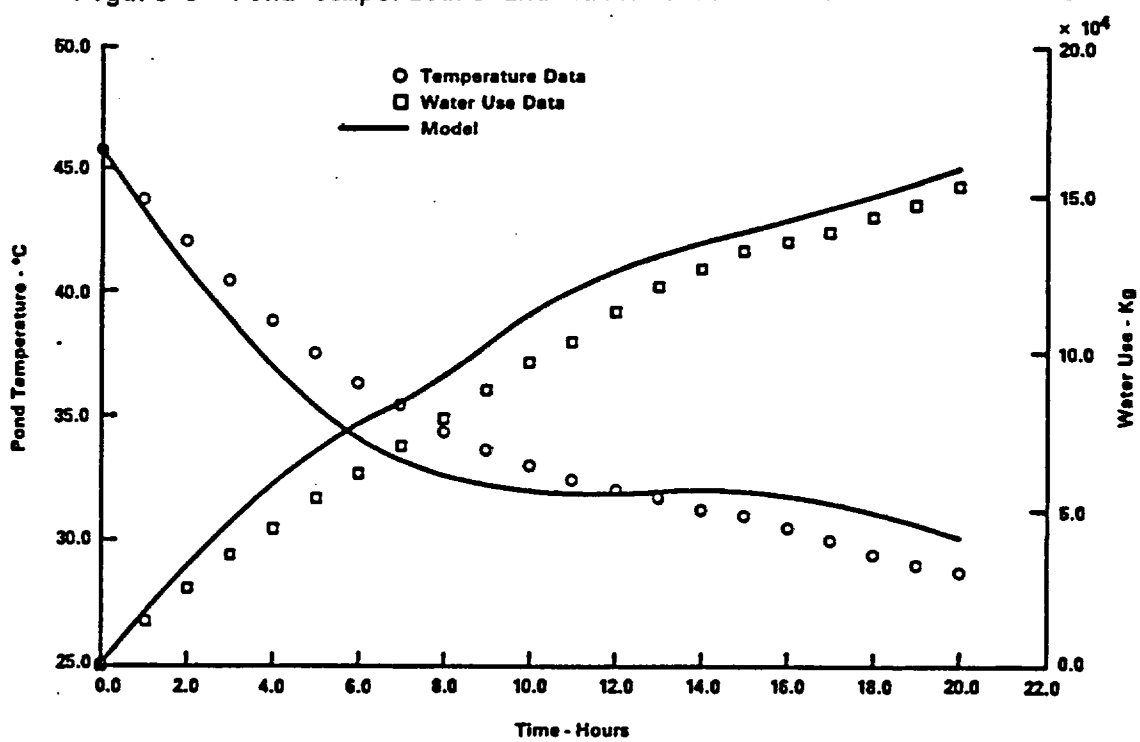

Figure 6 Pond temperature and water loss for "East Mesa Warm 2"

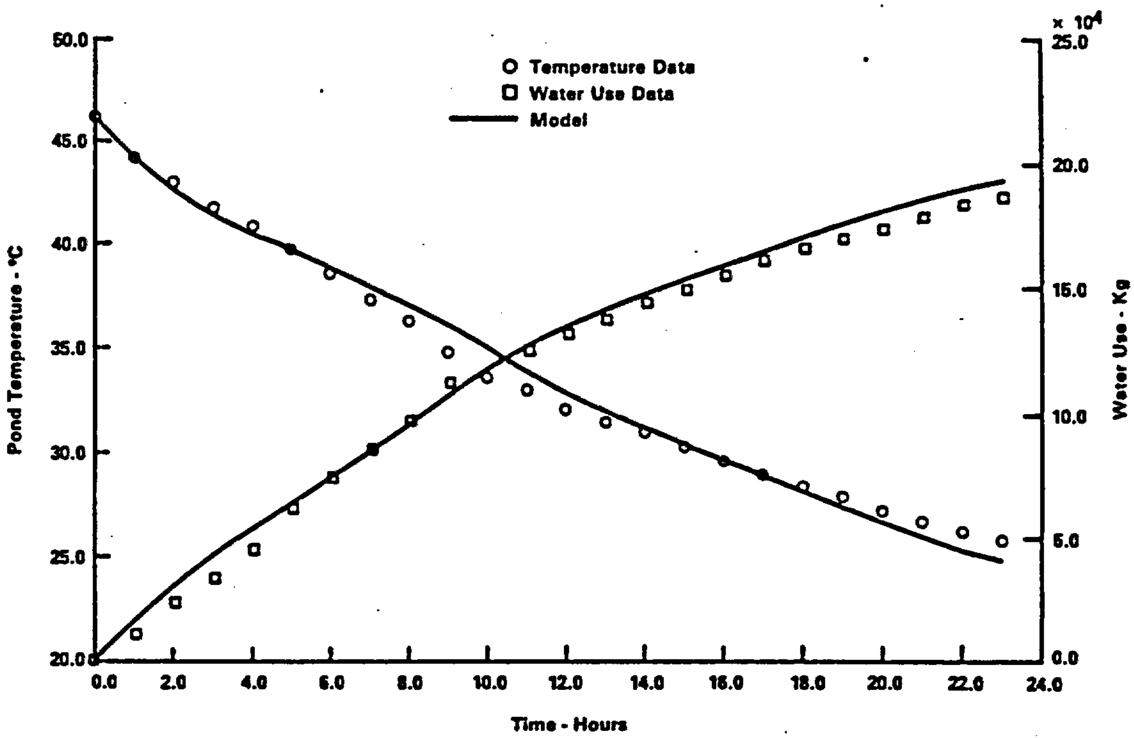

Figure 7 Pond temperature and water loss for "East Mesa Warm 3" experiment

Disagreements between the model and prototype can be caused by a number of factors. Among the most important factors is probably the simplified way in which mass and heat transfer are assumed to occur within the spray field.

In the model, it was assumed that the wind was always blowing at right angles to the major axes of the field, when in fact it may have been blowing from an oblique angle. The variation of windspeed in the vertical direction over the height of the spray field cannot be taken into account in this model, nor can the development of a boundary layer near physical obstructions in or near the pond. The model also does not take into account the complicated nature of the drop-diameter distribution, or the possibility that this distribution may

change over the spray trajectory because of drop breakup, interference, or wind effects. The model allows only two extremes: a high-windspeed and a low-windspeed condition. It does not allow a condition where there is a combination of natural and forced convection.

Other factors such as measurement errors in the meteorological data, flow measurement inaccuracies, heat transfer and leakage to the ground, pond stratification and the indirect measurement of pond water loss might also contribute to the disagreement between model and prototype performance. The relatively good agreement between the data and the model however indicates that the most important phenomena of heat and mass transfer from the ponds were properly taken into account.

Even though the drift loss model was run with conservative coefficients, drift loss during the three runs was calculated to range from only 5.5 percent to 10.5 percent of the overall water loss, and is therefore not a major factor. Loss due to drift could not be distinguished experimentally from evaporative loss in the prototype (14).

CONCLUSIONS

A computational model for the performance of spray ponds used in Ultimate Heat Sink service was developed. The spray pond model was compared to several prototypes spray ponds, and used to simulate the temperature and water loss of a well-instrumented experimental pond. Model-prototype comparisons generally confirm that the model is either accurate or conservative in predicting pond temperature and water loss. These models are in routine use for ultimate heat

sink design and evaluation by both the NRC staff and outside users. A subsequent paper will demonstrate how the performance model can be used as part of a comprehensive evaluation of spray ponds in ultimate heat sink service.

Since the model contains a number of assumptions, its use must always be justified on a case-by-case basis. The model's suitability for evaluating systems other than conventional vertical nozzle arrays must be addressed carefully. Performance tests with the prototype cooling pond or spray pond should be carried out whenever possible.

Disclaimer

The views expressed in this paper are those solely of the author, and do not necessarily represent those of the U.S. Nuclear Regulatory Commission.

Appendix I - Data used for East Mesa Simulations

(a) - "East Mesa Warm 1", 9/22/79 to 9/24/79

Time	Pond Temp. °C	Pond Height cm.	Solar Rad MW.	Wind Speed m/sec	Wet Bulb T °C	Dry Bulb T °C
1400.	51.30	13.76	2.88	.30	29.90	39.60
1500.	49.80	12.81	2.50	1.90	30.20	40.60
1600.	46.50	12.03	1.95	2.10	30.40	40.50
1700.	44.10	11.36	1.23	2.20	29.90	39.70
1800.	42.50	10.90	.48	2.30	29.10	38.70
1900.	40.90	10.41	0.00	1.80	27.00	36.00
2000.	39.60	10.17	0.00	2.10	25.90	34.00
2100.	38.30	9.81	0.00	2.30	25.20	32.20
2200.	37.10	9.53	0.00	2.20	25.40	31.10
2300.	36.20	9.23	0.00	1.50	25.30	30.60
0.	35.40	8.97	0.00	.30	24.20	29.20
100.	34.20	8.73	0.00	.70	23.30	28.30
200.	33.30	8.45	0.00	2.80	22.70	27.00
300.	32.50	8.30	0.00	.80	21.80	25.60
400.	31.90	7.94	0.00	1.80	22.00	25.90
500.	31.00	7.87	0.00	1.30	20.60	23.50
600.	30.30	7.70	0.00	2.00	21.30	24.10
700.	29.60	7.51	.15	1.20	20.40	22.80
800.	29.20	7.33	.76	.90	23.50	26.60
900.	29.20	7.18	1.48	.50	26.20	30.50
1000.	29.10	7.06	2.10	1.00	27.40	32.20
1100.	29.20	6.94	2.57	1.00	28.60	34.20
1200.	29.20	6.81	2.88	1.40	29.20	35.90
1300.	29.20	6.59	2.90	1.00	29.60	38.00
1400.	29.40	6.36	2.83	.30	30.20	39.60
1500.	29.00	6.05	2.49	1.80	30.40	40.80
1600.	28.70	5.73	1.95	2.00	30.30	41.10
1700.	28.20	5.49	1.22	2.60	30.30	40.30
1800.	27.90	5.37	.44	1.80	29.30	38.50
1900.	27.60	5.29	0.00	.70	27.10	35.70
2000.	27.20	5.15	0.00	1.20	26.30	34.40
2100.	26.90	5.00	0.00	.80	25.20	32.70
2200.	26.50	4.88	0.00	.60	24.50	31.90
2300.	25.90	4.77	0.00	.80	24.60	31.60
0.	25.70	4.65	0.00	.80	24.30	31.00
100.	25.40	4.51	0.00	.80	23.00	28.90
200.	25.00	4.42	0.00	2.60	22.40	28.20
300.	24.80	4.31	0.00	.90	20.80	25.90
400.	24.40	4.21	0.00	1.10	20.30	24.50
500.	24.10	4.11	0.00	2.50	19.80	24.40
600.	23.70	4.01	0.00	.80	20.40	24.90
700.	23.40	3.89	.13	1.20	21.00	25.90
800.	23.40	3.79	.94	.60	24.40	29.30

(b) - "East Mesa Warm 2", 9/27/79

Time	Pond Temp. °C	Pond Height cm.	Solar Rad MW.	Wind Speed m/sec	Wet Bulb T °C	Dry Bulb T °C
200.	45.80	13.82	0.00	.80	22.70	28.20
300.	43.70	13.23	0.00	.90	21.70	26.70
400.	42.00	12.78	0.00	.70	21.00	25.40
500.	40.40	12.35	0.00	.30	20.80	24.90
600.	38.80	11.99	0.00	.10	19.50	23.60
700.	37.50	11.61	.14	1.20	19.20	22.90
800.	36.30	11.28	.70	.30	21.40	24.90
900.	35.40	10.96	1.45	1.50	24.80	28.80
1000.	34.30	10.60	1.97	3.90	26.20	31.50
1100.	33.60	10.25	2.51	4.20	26.90	32.90
1200.	33.00	9.90	2.79	3.40	27.30	34.20
1300.	32.40	9.61	2.86	2.90	27.70	35.50
1400.	32.00	9.24	2.75	2.90	28.10	36.30
1500.	31.70	8.93	2.44	.90	28.90	37.30
1600.	31.20	8.69	1.60	1.60	29.30	38.00
1700.	31.00	8.49	.94	.60	29.20	37.80
1800.	30.50	8.36	.35	1.00	28.40	36.90
1900.	30.00	8.26	0.00	1.20	27.30	35.30
2000.	29.40	8.10	0.00	.90	26.60	34.60
2100.	29.00	7.97	0.00	.80	25.30	32.00
2200.	28.70	7.79	0.00	1.10	24.40	31.00

(c) - "East Mesa Warm 3", 10/1/79 to 10/2/79

Time	Pond Temp. °C	Pond Height cm.	Solar Rad MW.	Wind Speed m/sec	Wet Bulb T °C	Dry Bulb T °C
900.	46.20	13.58	1.43	1.00	23.80	28.40
1000.	44.20	13.09	2.07	.50	25.60	30.40
1100.	43.00	12.59	2.49	.60	26.20	32.10
1200.	41.70	12.17	2.75	.10	27.10	34.50
1300.	40.80	11.73	2.86	.40	27.70	36.40
1400.	39.70	11.14	2.74	1.30	28.20	37.60
1500.	38.50	10.64	2.36	2.10	29.00	38.40
1600.	37.30	10.22	1.81	2.20	29.20	38.40
1700.	36.30	9.81	1.13	2.20	28.70	38.10
1800.	34.80	9.30	.38	3.20	27.60	36.60
1900.	33.60	9.15	0.00	1.80	25.90	34.30
2000.	33.00	8.88	0.00	2.40	24.30	31.00
2100.	32.10	8.67	0.00	.90	23.90	30.10
2200.	31.50	8.50	0.00	1.10	23.40	29.80
2300.	31.00	8.30	0.00	1.20	21.90	26.60
0.	30.30	8.13	0.00	.70	22.40	27.70

(c) - "East Mesa Warm 3", 10/1 79 to 10/2/79 (continued)

Time	Pond Temp. °C	Pond Height cm.	Solar Rad MW.	Wind Speed m/sec	Wet Bulb T °C	Dry Bulb T °C
100.	29.60	7.96	0.00	.90	21.70	26.60
200.	29.00	7.76	0.00	2.20	20.70	25.60
300.	28.40	7.61	0.00	.60	19.70	23.90
400.	27.90	7.47	0.00	1.70	19.70	23.70
500.	27.20	7.34	0.00	1.80	18.90	22.70
600.	26.70	7.19	0.00	.50	17.70	21.50
700.	26.20	7.03	.03	.80	18.00	21.30
800.	25.80	6.92	.56	.60	19.60	22.90

APPENDIX II

REFERENCES

1. American Society of Heating, Refrigeration, and Air Conditioning Engineers, "Heating, Ventilating and Air Conditioning Guide," 38th Edition, 1960.

2. Berman, L. D., Evaporative Cooling of Circulating Water, New York, Pergamon Press, 1961.

3. Bird, R. B., Stewart, W. E., Lightfoot, E. N., Transport Phenomena, John Wiley and Sons, Inc., New York, N.Y., 1960.

4. Brady, D. K., Graves, W. L., and Geyer, J. C., Surface Heat Exchange at Power Plant Cooling Lakes, Report No. 5, Edison Electric Institute, EEI Publication 69-401, New York, N.Y., 1969.

5. Chen, K. H. and Trezek, G. J., "Spray Energy Release Approach to Analyzing Spray System Performance," Proceedings of American Power Conference, 1976, Vol. 38, pp. 1435-1448, Illinois Institute of Technology, Chicago IL.

6. Chen, K. H., and Trezek, G. J. "The Effects of Heat Transfer, Local Wet Bulb Temperature, and Droplet Size Distribution Function on the Thermal Performance of Sprays," Journal of Heat Transfer, ASME, Vol. 99, August 1977, pp. 381-385.

7. Codell, R. and Nuttle, W. K., "Analysis of Ultimate Heat Sink Cooling Ponds," USNRC Report NUREG-0693, November 1980.

8. Codell, R., "Analysis of Ultimate Heat Sink Spray Ponds," USNRC Report NUREG-0733, August 1981.

9. Codell, R. B., "Comparison Between Field Data and Ultimate Heat Sink Cooling and Spray Pond Models," U.S. Nuclear Regulatory Commission NUREG-0858, Sept. 1982.

10. Codell, R. B., "Applicaton of Models to Design of Spray Ponds for Nuclear Power Plants," (this issue)

11. Ecolaire Co., "Topical Report-Oriented Spray Cooling System," Ecolaire Condenser, Lehigh Valley, Pa., January 1977.

12. Elgawhary, A. M., "Spray Pond Mathematical Model for Cooling Fresh Water and Brine," Ph.D. Thesis, Oklahoma State University, Stillwater, 1971.

13. Hadlock, R. K. and Abbey, O. B., "Thermal Performance Measurements on Ultimate Heat Sinks--Cooling Ponds," USNRC Report NUREG/CR-0008, PNL-2463, February 1978.

14. Hadlock, R. K. and Abbey, O. B., "Thermal Performance and Water Utilization Measurements on Ultimate Heat Sinks--Cooling Ponds and Spray Ponds," USNRC Report NUREG/CR-1886, PNL-3689, May 1981.

15. Jirka, G. H., Abraham, G., and Harleman, D. R. F., "An Assessment of Techniques for Hydrothermal Prediction," Technical Report No. 203, R. M. Parsons Laboratory for Waste Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge MA, July 1975.

16. Myers, D., Personal Communication, 1976

17. Pennsylvania Power and Light, "Preliminary Safety Analysis Report, Susquehanna Steam Electric Station, Units 1 and 2," Amendment 12, PPL, Allentown, Pa.

18. Porter, K. W., Yang, V. and Yanik, A. "Thermal Performance of Spray -Cooling Systems," Proceedings of the American Power Conference, Volume 38, 1976, pp. 1458-1472.

19. Ranz, W. D. and Marshall, W. R., "Evaporation From Drops," Chemical Engineering Progress 48, 1952, pp. 141-173.

20. Ryan, P. J. and Harleman, D. R. F., "An Analytical and Experimental Study of Transient Cooling Ponds Behavior," Report No. 161, R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, January 1973.

21. Schrock, V. E. and Trezek, G. J., "Rancho Seco Nuclear Service Spray Ponds - Performance Evaluation," Report No. WHM-4, University of California (Berkeley) for Sacramento Municipal Utilities District, July 1973.

22. SPRACO, "Spray Ponds-The Answer to Thermal Pollution Problems," Spray Engineering Company, Burlington, Mass., undated.

23. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.27, "Ultimate Heat Sink for Nuclear Power Plants."

APPENDIX III - NOTATION

The following symbols are used in this paper:

Nomenclature

A = pond surface area

A_s = cross-sectional area of the spray field

A_T = Top area of segment in LWS model

C_p = heat capacity of water

C_{WA} = concentration of water in air in equilibrium at the temperature of the drop

C_∞ = concentration of water in air in which the drop is immersed

D = diffusion coefficient for water vapor in air

F_b = buoyancy pressure

F_d = drag pressure

f_i = fraction of drops in radius range r_i

g = acceleration of gravity

h_c = heat transfer coefficient for drop

h_d = mass transfer coefficient for drop

$\dot{H}$ = rate of atmospheric heat transfer

$\dot{H}_{AN}$ = net rate of longwave atmospheric radiation entering the pond, measured directly

$\dot{H}_{BR}$ = net rate of back radiation leaving the pond surface

$\dot{H}_C$ = net rate of heat flow from the pond caused by conduction and convection

$\dot{H}_E$ = heat loss from the pond surface caused by evaporation

$\dot{H}_{RJ}$ = net rate of heat addition by the plant .

$\dot{H}_{SN}$ = net rate of shortwave solar radiation entering the pond

$\dot{H}_{spray}$ = heat rejected by sprays

k_a = thermal conductivity of air

Nomenclature (Continued)

M_{yi} = downward momentum transferred to air from drops

P_W = vapor pressure of water

Pr = Prantl number

Q = flow rate of water to spray field

r = radius of drop

r_i = radius of drop in size range i

Re = Reynolds number

R_g = universal gas constant

Sc = Schmidt number

t = time

T = temperature of water

T_A = air temperature

$T_{A,\infty}$ = temperature of air in which the drop is immersed within spray field

T_s = pond temperature

v = absolute velocity of drop relative to air, cm/sec

V_i = volume of a drop in size range i

V_p = pond volume

W_b = flow rate of the blowdown or leakage stream

W_{drift} = water loss attributable to drift

W_{spray} = rate of water evaporated from all drops in the spray field

Δz = spray field half-height

λ = heat of vaporization of water

μ = viscosity of air

ρ = density of water

ρ_A = density of air

$\overline{\Delta\rho_A}$ = density difference between air in segments and ambient air

Application of Models to Design of Spray Ponds for Nuclear Power Plants

by Richard Codell*
Associate Member

Introduction

The ultimate heat sink (UHS) is defined as the complex of sources of service water supply necessary to operate, shut down, and cool down a nuclear power plant safely (5). Spray ponds are frequently used as a source of cool water for the UHS. A previous paper described the development of a spray pond performance model, and compared it to data collected in the field (3). The present paper describes the way in which the spray performance model is used in a typical UHS analysis for a nuclear plant. While the methodology has been developed for stringent safety evaluations on nuclear power plants, it could also be used in studies of normal cooling ponds, spray ponds, and cooling towers to make meaningful predictions of their future performance.

Design Basis Analysis of a Spray Pond

The spray pond performance model described in Ref. 3 is one part of a systematic method which is currently being used by the U.S. Nuclear Regulatory Commission (NRC) and others to evaluate spray pond performance. The objective of the analysis is to predict the performance of the ultimate heat sink under the

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most adverse conditions which can reasonably be expected to occur during the lifetime of the plant. To accomplish this goal using readily available data, the following steps are performed:

- Screen a long-term offsite meteorological record to determine the most adverse conditions for heat exchange and water loss which has occurred at the site;

- Using the period of most adverse meteorological conditions, determine the maximum water temperature and water loss under emergency plant heat load;

- Correlate long-term offsite data to short term onsite data in order to determine the adequacy of the data base, and possible correction factors for temperature and water loss; and

- Determine the recurrence interval for "worst case" and less severe meteorological conditions in order to quantify the probability of the design basis temperature and water loss (optional step)

Five computer programs are used for the spray-cooling-pond analysis (2). The complicated sequence in which these programs are used to determine design-basis temperature and water loss is shown in Fig. 1, and is described below.

Simplified Spray Performance Regression Models - Program SPRCO

Models of spray performance were developed in Ref. 3, and were shown to perform well in realistic field tests. The computer programs for these models are

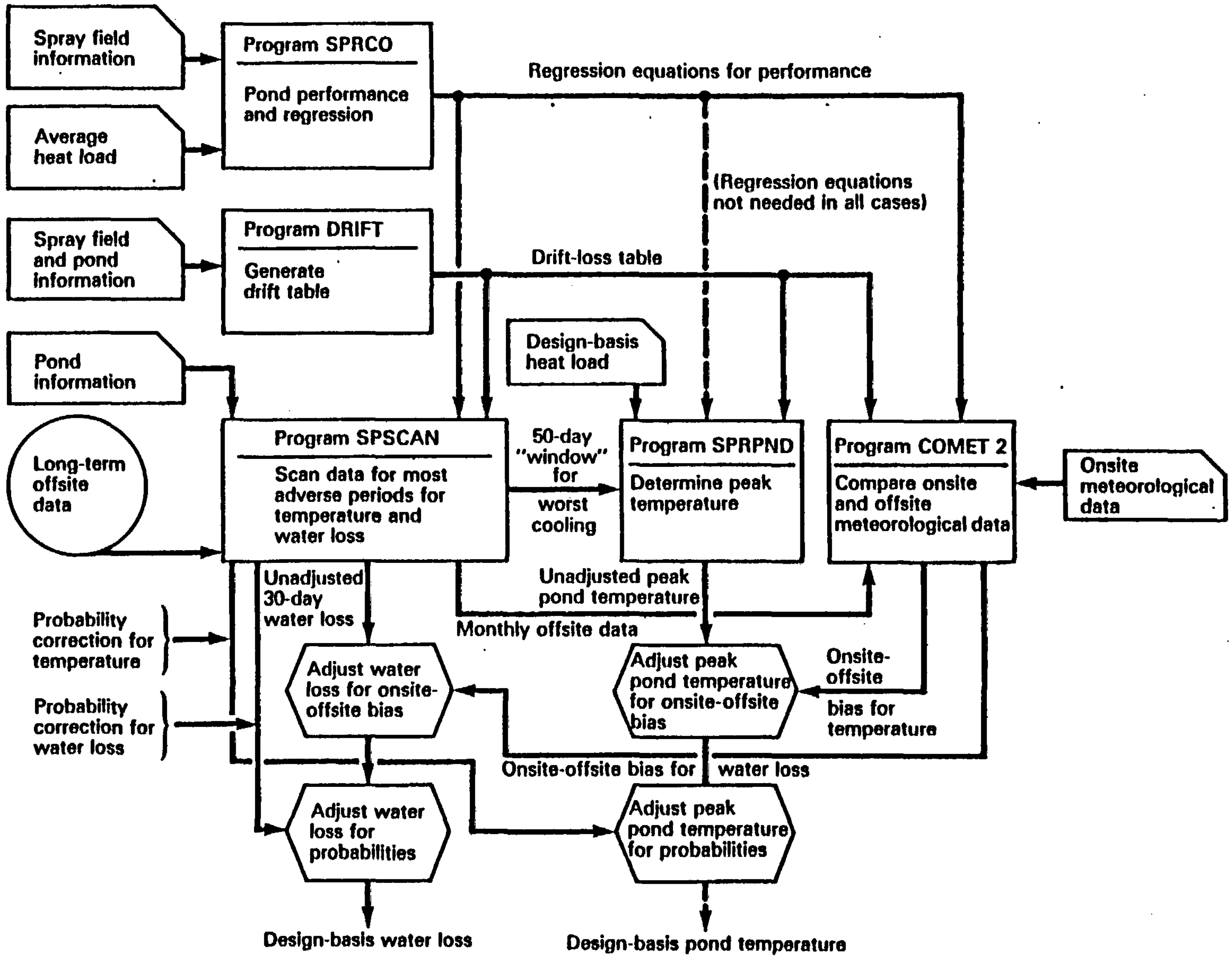

Figure 1. Flowchart for design-basis water loss and temperature determination

very time consuming, however. Using the rigorous performance models for a long (tens of years) simulation would be prohibitively costly and inefficient. An approximate model for spray performance based on results of the rigorous models is used in all subsequent analyses instead.

The High Wind Speed (HWS) and Low Wind Speed (LWS) spray-performance models described in Ref. 3 are exercised over wide ranges of the independent meteorological variables for the pond under consideration. The results are then formulated into regression equations relating performance to the meteorological variables which can then be used to predict the performance of the sprays.

Program SPRCO generates sets of values of the independent variables (wind speed, wet bulb and dry bulb temperatures, and sprayed water temperature) chosen as uniformly-distributed random variables in given ranges, runs the HWS and LWS models for the given spray pond design to generate cooling efficiency and water loss for each set of conditions and performs the multiple-linear-regressions. Correlations of the regression equations with the HWS and LWS models are generally excellent, as will be demonstrated in the example which is presented later.

Drift Loss Model - Program DRIFT

The computer program DRIFT, described in Ref. 3, computes the drift loss from a spray pond. The program requires the input of the spray-field geometry and drop diameter distribution and outputs the drift-loss fraction for various windspeeds between zero and 50 miles per hour. The spray-field geometry is

described by specifying the distances downwind from one or several groups of sprays to the edge of the pond surface and the fraction of the total flow of the spray field represented by each group. The wind is assumed to be blowing in the direction that minimizes the distance between the sprays and the edge of the pond.

Data Screening - Program SPSCAN

The ultimate heat sink should be evaluated for the most adverse conditions of heat loss and water loss likely to be encountered at the site. Long-term meteorological records, frequently on the order of 30-40 years, are available from the US Weather Service, but rarely very close to the sites. These long-term data are screened with program SPSCAN. Correction factors to account for differences between onsite and offsite data are formulated later.

The screening model requires two types of data: (a) weather data such as wet-and dry-bulb temperatures, dewpoint, windspeed, and atmospheric pressure, which may be obtained from the US Weather Service tapes, and (b) rates of net solar radiation which are not generally given on the tape. Solar radiation is synthesized from time of year, latitude, and cloud-cover (6).

Data from the tapes are screened using the regression equations for spray efficiency and evaporation and the wind speed-drift loss table. The screening model, program SPSCAN, calculates a continuous spray pond temperature and a 30-day running-average evaporative and drift water loss, assuming a steady 30-day average heat load and a full pond inventory. This procedure identifies the time periods of the long-term record most likely to give either the highest

pond temperature or greatest 30-day water loss. Hourly meteorological data are stored for a 50-day "window" around the time determined to give maximum pond temperature for a steady heat load. This window of data will be subsequently employed in program SPRPND using the time-varying heat load to the pond, in order to determine the peak pond temperature. Maximum water loss can be determined from the screening program directly, since water loss is most affected by the cumulative heat load, and is not as highly sensitive to the variability in heat load as is the peak pond temperature.

The cumulative frequency distributions (CDF) of all hourly pond temperatures and 30-day evaporation rates calculated from the meteorological record using the average heat load is also generated by this program. These CDF's are used later in the analysis to estimate the probabilities associated with the peak values of pond temperature and water loss.

Determination of Maximum Pond Temperature - Program SPRPND

Program SPRPND calculates the maximum temperature in the UHS pond under the influence of the time varying plant accidental heat load. The simulation of the pond is performed within the 50 day meterology window provided by program SPSCAN, with the starting time for the accidental heat load chosen to give the maximum instantaneous pond temperature. This is usually accomplished by making multiple runs, incrementing the starting time in each case by several hours, and choosing the highest resulting temperature. Either the regression equations for spray performance or the full HWS/LWS performance models may be used in this program. The latter option may have slightly higher accuracy, but the

computations are much more time consuming. The regression equations generally give adequate results.

Onsite-Offsite Correlation - Program COMET2

The meteorological data for UHS performance must generally be obtained from offsite weather stations (such as airports) for which long-term records are available. The site meteorology may be significantly different from that of the offsite station, however. It is necessary to determine if serious, long term discrepancies exist between the data bases for two sites.

The bias that would be introduced by using the offsite data in the temperature calculations can be estimated by comparing the monthly average pond temperatures or water loss calculated by using the onsite data with the pond temperature or water loss using the offsite data. These biases can be used as correction factors for the water losses and peak temperatures calculated using the long-term offsite data. Experimentation with the models using both hourly and 30 day average meteorological data has shown that the proposed correction factors using pond temperature and evaporation rates calculated with the 30-day average meteorology reliably account for the differences between the onsite and offsite data sets. The biases in pond temperature and evaporation can also be related to differences in each meteorological parameter separately allowing a comparison between onsite and offsite data sets, even if one or more meteorological parameters are missing.

Example

A complete study of a UHS spray pond illustrates the procedure for evaluating the design-basis performance at nuclear power plants. Details of pond design and meteorology are taken from the analysis performed for the Operating License review of the Palo Verde Nuclear Power Station (1), but do not necessarily reflect the final design for this plant.

The Palo Verde spray ponds use of conventional SPRACO design, with 4 header pipes per pond and 20 four-nozzle clusters per header. A plan view of the spray ponds is shown in Fig. 2. The design-basis heat load is shown in Fig. 3. This heat load is based on the rate of heat rejection from the plant due to residual reactor heat and auxilliary equipment, but does not take into account the thermal inertia of systems. It is therefore a worst-case heat load and should give conservatively high temperature predictions. Other parameters characterizing the pond are given in Table 1. The spray nozzles are Spraco 1751A, operating at standard pressure and arranged in accordance with the manufacturer's recommendations.

The data for the sample problem are provided by the 33-year US Weather Service tape record (1948-1980) from Tuscon, Arizona. Onsite meteorological data were available at the plant site from August 1973 to August 1978.

The design-basis evaluation consists of running the five computer programs previously described, sequentially as shown in Fig. 1. The step-by-step analysis of this spray pond is demonstrated below.

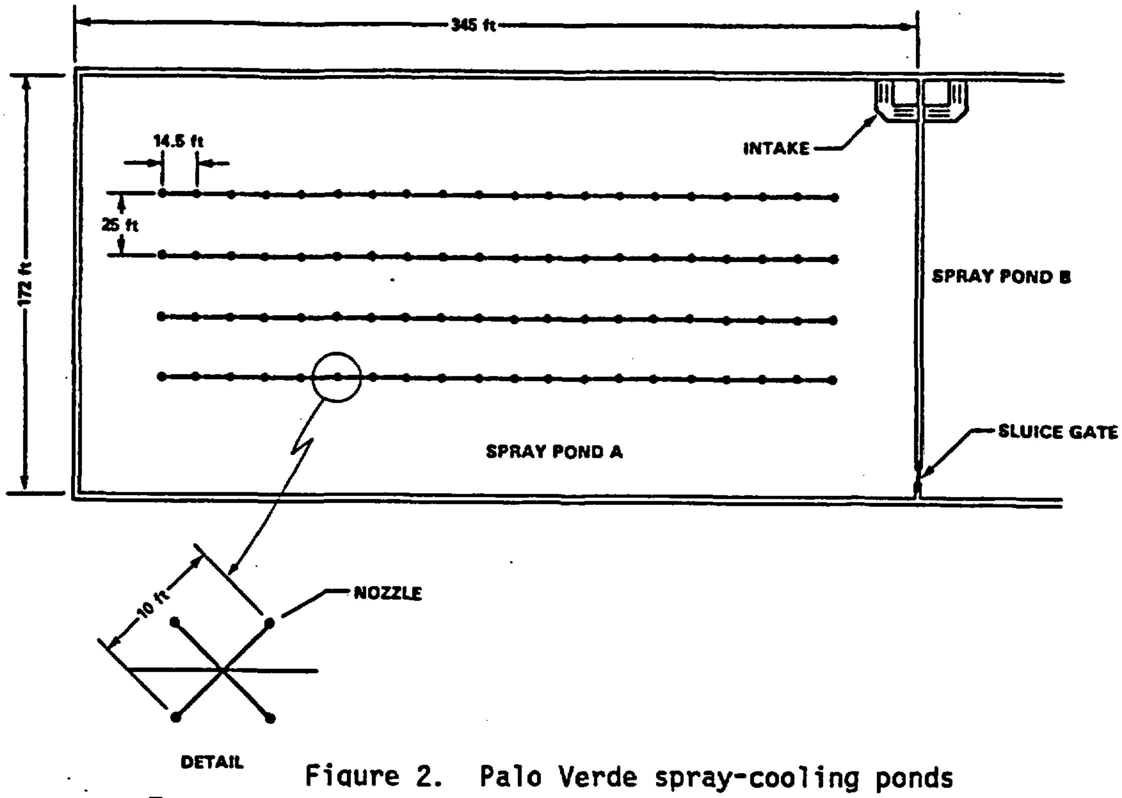

Figure 2. Palo Verde spray-cooling ponds

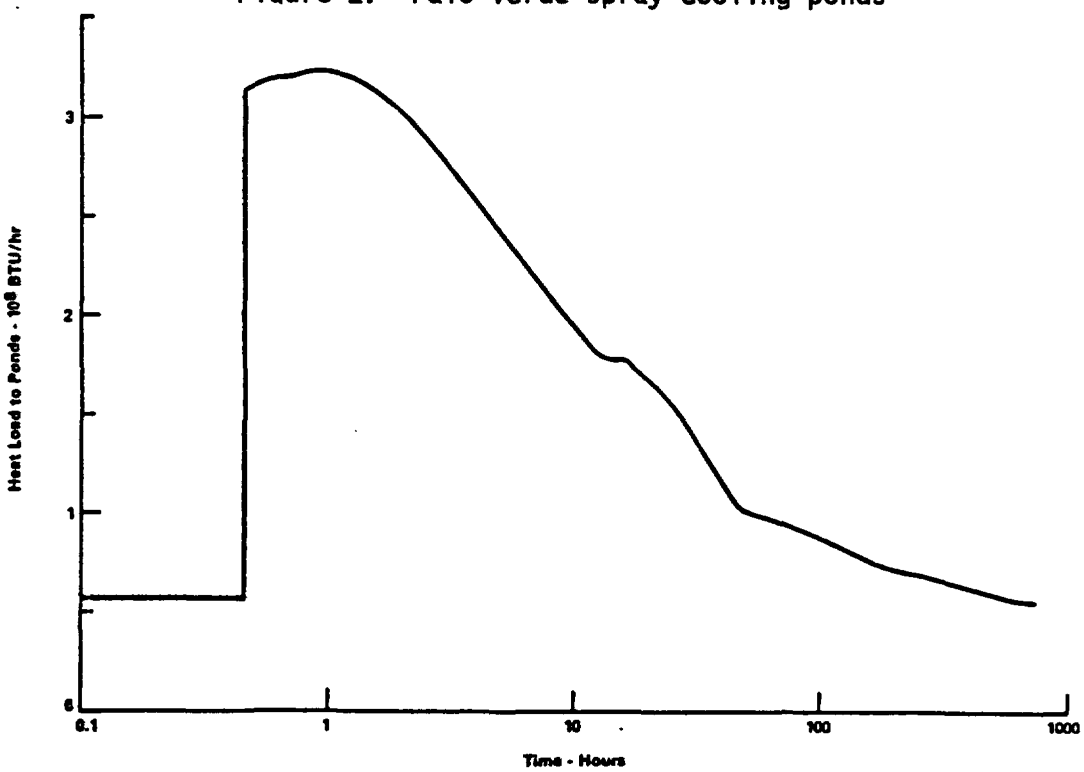

Figure 3. Design-basis heat load for example

Table 1. Parameters of Palo Verde Spray-Pond Example (Values for each pond)

Variable	Quantity
Usable initial pond volume	$2.02 \times 10^4 m^3$ ($7.13 \times 10^5 ft^3$)
Pond surface area	$5513 m^2$ ($59,340 ft^2$)
Flowrate through sprays	$1.07 m^3/sec$ ($37.8 ft^3/sec$)
Number of nozzles	320
Nozzle pressure	$43 kg/m^2$ (7 psig)
Width of spray field	26.5m (87 ft)
Length of spray field	84.7m (287 ft)
Height of nozzles above initial pond surface	1.5m (5 ft)
Height above nozzles attained by spray	2.1m (7ft)

1. Determine Characteristics of Spray Field

The characteristics of the spray field were determined from photographs of sprays operating at the design pressure, and from promotional literature (4), which indicated that the spray from the nozzle will reach a height of about 2.1m (7 ft) above the nozzles at a pressure of 43 Kg/m^2 (7 psig). The heaviest accumulation of water will occur at a radius of about 4m (13 ft). If friction between the drop and the air is neglected, simple ballistics indicates that the initial drop velocity should be about 6.9m/sec (22.5 ft/sec) and the initial angle of the drop trajectory with the horizon should be about 71°.

The arrangement of sprays is shown in Fig. 2. The length and width and height of the spray field are about 84.7m (287 ft), 26.5m (87 ft), an 3.6 m (12 ft), respectively, taking the width of the spray "umbrella" into account.

The average drop radius is taken as 0.104 cm, since this value gave good model-prototype agreement in other situations using the same nozzle and operating conditions (2, 3).

2. Formulate Regression Equations for Spray-Field Performance

Program SPRCO is used to generate the coefficients of regression equations which are in turn used to represent the spray performance models in subsequent programs. The form of the regression equations is given in Table 2. The resulting coefficients for the regression equations of spray efficiency and water loss are given in Table 3. It should be noted that the correlation

Table 2 - Regression Equations for
Heat Exchange and Evaporation from Palo Verde Sprays

$$\eta_{HWS} = a_{11} + a_{12}T_A + a_{13}T_W + a_{14}T_{HOT} + a_{15}w + a_{16}\sqrt{w}$$

$$Q_{HWS} = a_{21} + a_{22}T_A + a_{23}T_W + a_{24}T_{HOT} + a_{25}w + a_{26}\sqrt{w}$$

$$\eta_{LWS} = a_{31} + a_{32}T_A + a_{33}T_A^2 + a_{34}T_A^3 + a_{35}T_W + a_{36}T_{HOT} + a_{37}T^2_{HOT}$$

$$Q_{LWS} = a_{41} + a_{42}T_A + a_{43}T_A^2 + a_{44}T_A^3 + a_{45}T_W + a_{46}T_{HOT} + a_{47}T^2_{HOT}$$

where

η	=	efficiency of approach to wet bulb temperature
Q	=	fraction of sprayed water which evaporates
T_A	=	ambient dry bulb temperature, °F
T_W	=	ambient wet bulb temperature, °F
T_{HOT}	=	temperature of water leaving spray nozzles, °F
w	=	ambient wind speed, miles per hour
HWS	=	high wind speed model
LWS	=	low wind speed model

Table 3. a_{ij} coefficients in regression equations

i=	1	2	3	4
j= 1	-.52081961E+00	-.41030098E-01	-.17923454E+01	-.54647539E-01
2	.60270774E-03	.15795074E-03	.39611059E-01	.18650336E-02
3	.34186544E-02	-.34569057E-03	-.44561821E-03	-.18419824E-04
4	.21298950E-02	.43551187E-03	.15441632E-05	.59208560E-07
5	-.32461489E-01	-.13308257E-02	.30593336E-02	-.24699791E-03
6	.26306659E+00	.10979900E-01	.12103781E-01	-.35976508E-04
7	-	-	-.34350872E-04	.23860101E-05

coefficient r^2 between the regression equations and the computed spray performances was about 99%, indicating a very good fit.

3. Formulate Drift Loss Table

A table of wind speed versus drift loss is generated by program DRIFT, using the pond geometry data presented in Table 1 and Fig. 2. The drop size distribution used corresponds to that for the SPRACO 1751 nozzle in 21 ranges. A single value for updraft must be chosen for the DRIFT program. A value of 50 cm/second was used. Average updraft based only on the mass flux in the Low Wind Speed model were determined to range from about 25 to 40 cm/sec. Drift loss, however, is a phenomenon which is likely to be important only during windy conditions; which would disrupt and diminish the natural convection responsible for updrafts. Therefore the 50 cm/second value of updraft is probably conservative. Table 4 gives the tabular drift fraction as a function of wind speed. The drift loss fraction for a 25 cm/sec updraft is shown for comparison. Thirty-day water losses calculated with the 50 cm/second case were approximately 12 percent greater than for the 25 cm/second use in the present example.

4. Scan Meteorological Record

The periods of most-adverse meteorology with respect to cooling performance and water loss were determined by program SPSCAN from the Phoenix tape meteorological record using program SPSCAN and the regression equations from program SPRCO and the drift-windspeed table from program DRIFT. The 30-day average heat load is determined from the heat load presented in Fig. 3.

Table 4. Drift loss as a function of wind speed and updraft

Wind Speed MPH	Drift Loss Fraction*	Drift Loss Fraction**
0	0	0.0005
2.5	0	0.005
5	0.000196	0.00086
7.5	0.000712	0.00171
10	0.00171	0.00329
12.5	0.00311	0.00539
15	0.0050	0.00871
17.5	0.0084	0.0120
20	0.0114	0.0151
22.5	0.0144	0.0205
25	0.0192	0.0251
30	0.0311	0.0383
35	0.0493	0.0602
40	0.0807	0.0985
45	0.126	0.149
50	0.194	0.216

*Updraft 25 cm/sec
**Updraft 50 cm/sec

The 50-day window of hourly values of the meteorlogical parameters determined by this program is subsequently used by program SPRPND to determine peak pond temperature. Peak 30-day evaporation is determined directly from the output of SPSCAN to be about 41200m^3(1.45 x 10^6 ft^3). Note that this water consumption is greater than the usable volume of the ponds.

Additional output information from SPSCAN is used to prepare correction factors for comparison of the onsite-offsite data bases, and to determine the frequency statistics for pond temperature and evaporation.

5. Determine the Uncorrected Design-Basis temperature

Once the period of most-adverse meteorology for cooling has been determined by program SPSCAN, program SPRPND is run to simulate the pond temperature under the actual design-basis heat loads. Program SPRPND was set up to vary the delay time for the start of the heat load from 0 to 750 hours in 5-hour increments within the 50-day window determined by program SPSCAN. The peak pond temperature as a function of delay time is shown in Fig. 4. The maximum temperature was determined to be 34.25°C (93.65°F) for a delay time of 435 hours from the start of the 50 day window. The pond temperature as a function of time after commencement of the accidental heat load for this case is given in Fig. 5 . The peak temperature occurs at about 40 hours after commencement of the heat load.

The above analysis was performed with the regression models for spray cooling efficiency determined by program SPRCO. Sensitivity runs using the rigorous spray performance model indicate that the predicted peak temperature would be only about 0.2°C lower, even though the rigorous model would take two orders of magnitude more computer time. The use of the regression model for spray performance is therefore well-justified.

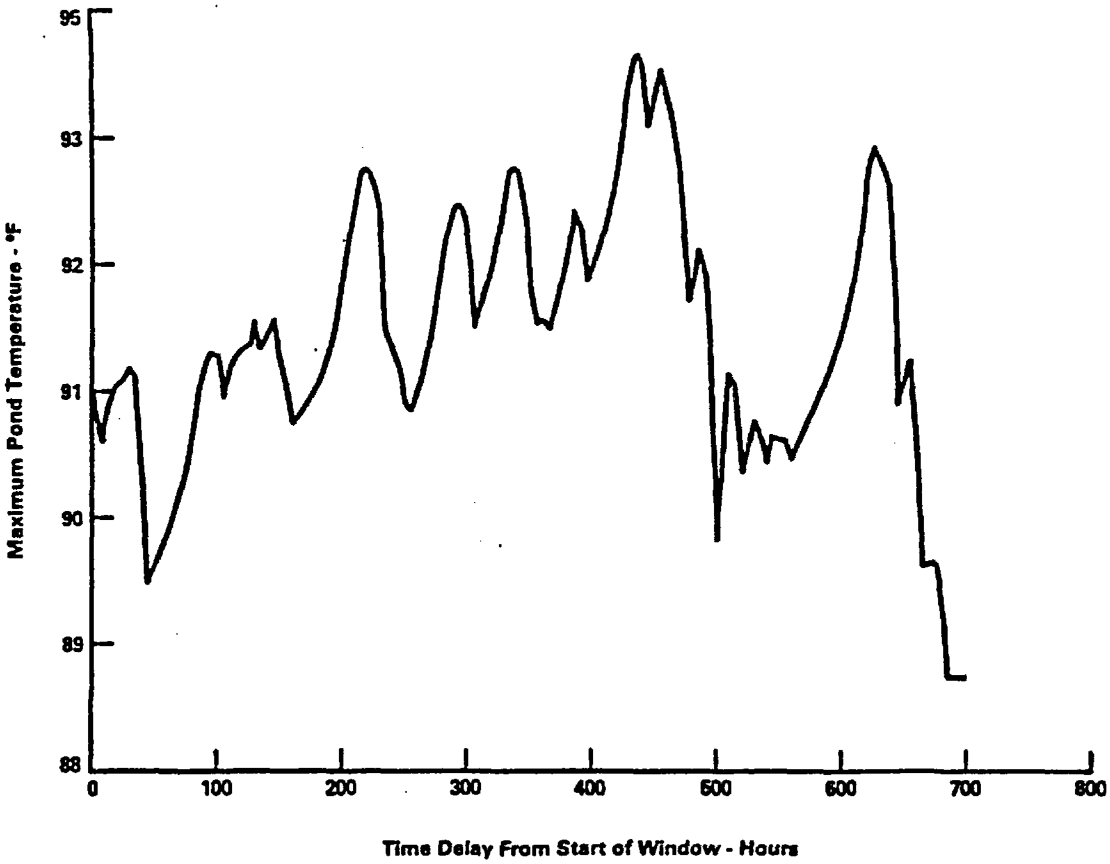

Figure 4 Maximum pond temperature as Function of Delay Time

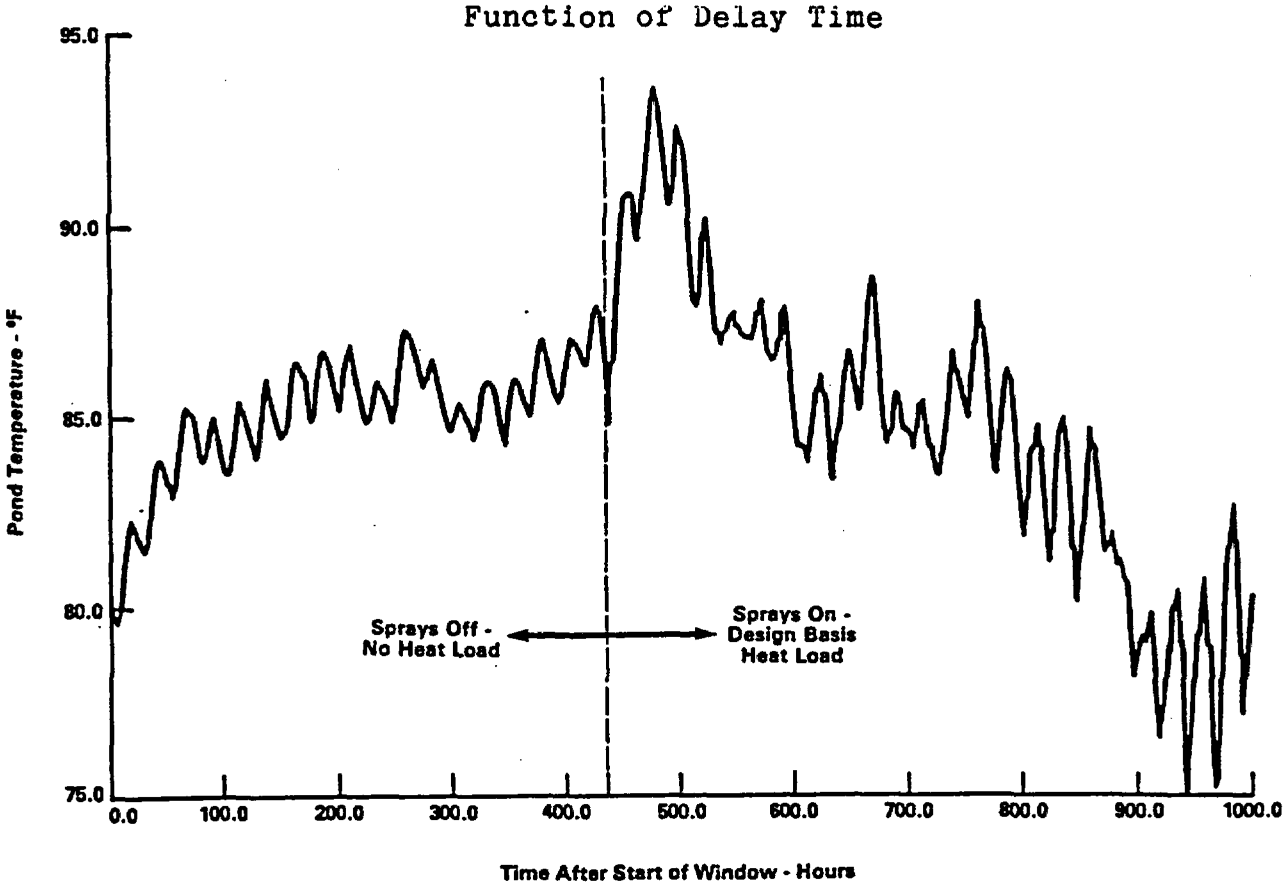

Figure 5 - Uncorrected pond temperature for TSKIP = 435 hours

6. Correct Results for Differences Between Onsite and Offsite Meteorological Data

Program COMET2 was used to estimate the differences in the meteorological data bases of the site and the point at which the long-term meteorological data were taken. Monthly average values of wet-bulb temperature, dry-bulb temperature, windspeed, barometric pressure, dewpoint temperature, and solar radiation were obtained from program SPSCAN for a 15-month period corresponding to the period of onsite May-October data availability at the Palo Verde site. The output from COMET2 is shown plotted in Figures 6 and 7 for temperature and water loss respectively. It is clear from the results that there are differences between the two data sets and that the Phoenix data are conservative. The average bias for the Palo Verde site data indicates that the spray-pond temperature should be about 0.4°C (0.74°F) lower than predicted from program SPRPND. The evaporation should also be less by about 1690m^3 (59,700 ft^3). The corrected maximum temperature and water loss should therefore be 33.8°C (92.9°F), and 41350m^3 (1.40 x 10^6 ft^3). The corrected 30 day maximum water loss is slightly less than the available water stored in the ponds.

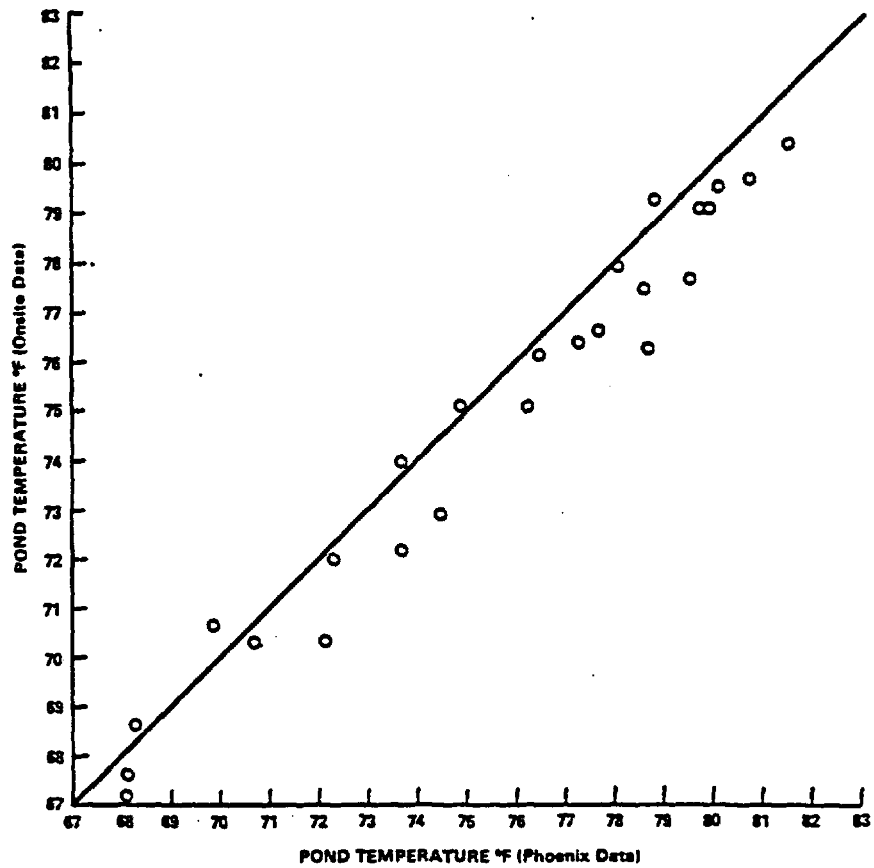

Figure 6 Onsite-offsite comparison for pond temperature

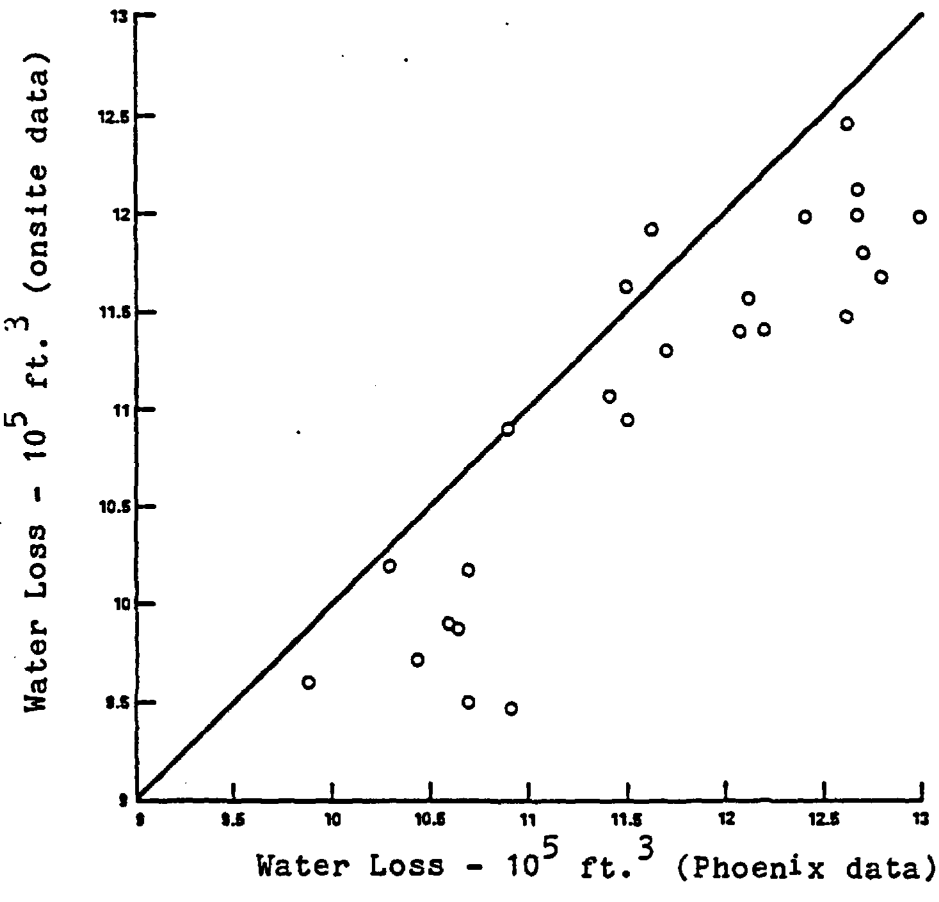

Figure 7 Onsite - offsite comparison of pond water loss

7. Adjust Results for Probability of Adverse Conditions

Peak water temperature and peak 30-day evaporation are calculated deterministically using the most adverse meteorological data available in order to maximize these quantities from the available data. The probability of the accident coinciding exactly with the period of most adverse meteorology, of course, would be very small. It is useful to quantify the probabilities of the peak pond temperature and 30 day evaporation, as well as the probabilities of conditions less severe than the peak. These less severe temperatures and water losses could be used in combined-event risk analyses. It has not been the practice at NRC to perform such combined-event analyses for Ultimate Heat Sinks, however.

An approximation of the probabilities of the peak pond temperature and peak 30-day water loss can be made using the output of program SPSCAN during step 4 above. The pond temperature and 30-day running average water loss are continuously calculated for a steady heat load and a full pond inventory between May and October of each year. The temperature and water loss results are catagorized for each hour of the May-October period of the tape record. Cumulative distribution functions, (CDF) shown in Fig. 8, are then calculated in program SPSCAN which sorts the temperatures or evaporations from highest to lowest, and sums their respective probabilities.

Since the actual heat load would be time-varying rather than constant, the CDF for pond temperature should be viewed as a "correction" factor for the peak temperature. For example, the corrected peak pond temperature determinstically calculated from program SPRPND and COMET2 was 34.25°C (93.7°F) which corresponds to the single worst hour in 33 years, or the 99.99965 percentile meteorology.

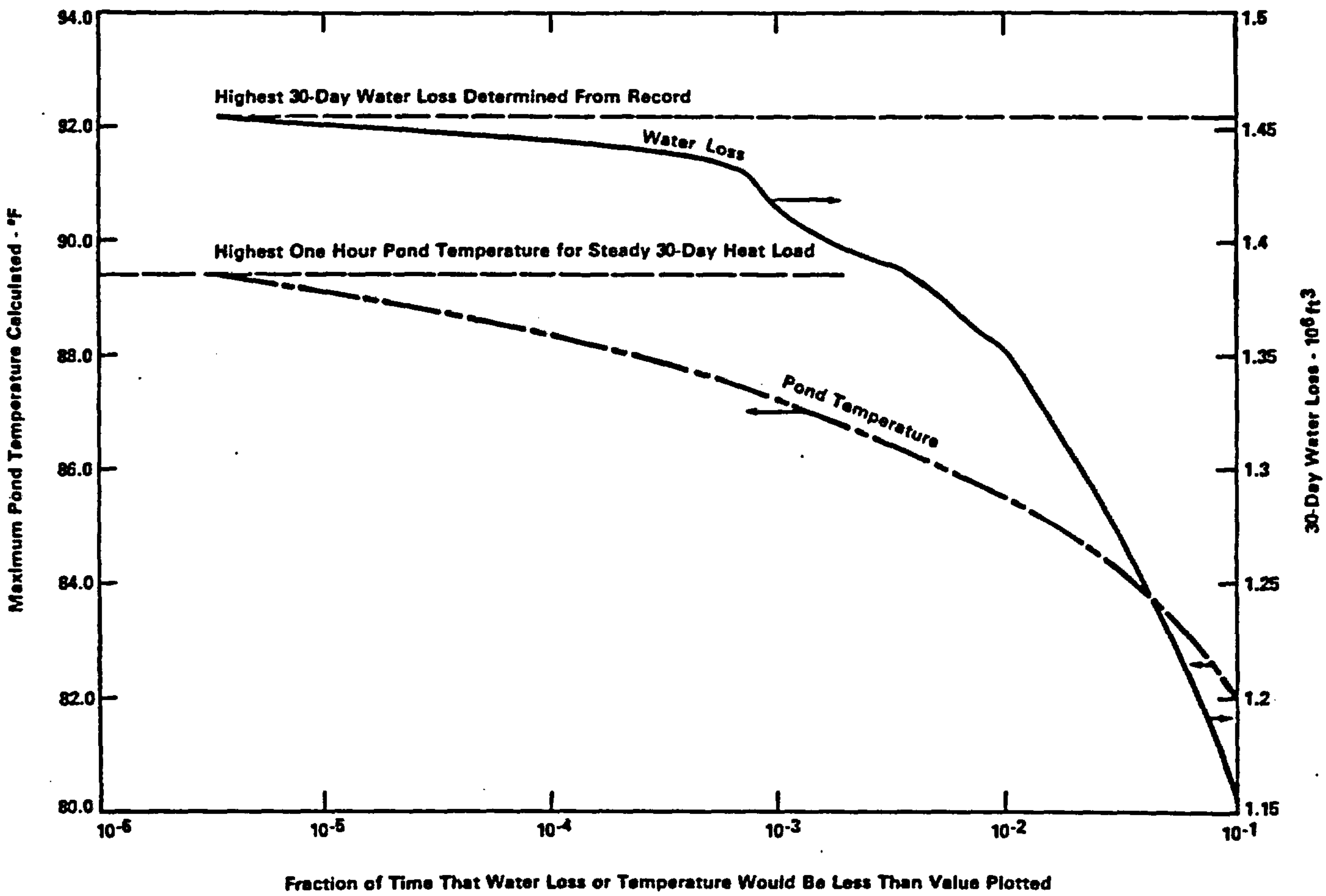

Figure 8 Correction for peak pond temperature and water loss using meteorological data more probable than worst case

If the 90 percentile meteorology was specified, Fig. 8 would indicate a correction factor of 2°C (3.7°F) to be subtracted from the deterministic peak, giving a temperature of 32.1°C (89.9°F). The 30-day water loss for the 90 percentile meteorology can be read directly from Fig. 8 to be about 32,850m^3 (1.16 x 10^6 ft^3), which is about 20% lower than the deterministic peak 30-day water loss taken from the SPSCAN run.

Since the CDF curves in this case have been generated from only the May-October data, they are not representative of the whole-year data base, but would be representative at the higher percentiles since temperature and water loss would be greatest in these months. The CDF curves generally should not be used to predict temperatures on water losses at lower than the 90th percentile.

Conclusions

A set of computer programs has been developed for the design and evaluation of ultimate heat sink cooling ponds and spray ponds for nuclear power plants. The performance of the ponds in terms of water temperature and water loss is calculated on the basis of physically sound principals of atmospheric heat mass and momentum transfer. Agreement of the model with experimental data is generally excellent.

The design basis performance of the spray pond is calculated from long-term offsite meteorological records corrected for differences observed between the onsite and offsite data. The recurrence interval for severe meteorological conditions is calculated, and could be used to factor the UHS performance into combined-event risk studies. The procedures presented in this

paper represent a useful framework in which to reliably assess the adequacy of spray ponds for nuclear power plants. The methodology should also have broad appeal for the evaluation of the performance of cooling ponds, spray ponds, and cooling towers in general, and is not dependent on the computer programs used in this paper.

Disclaimer

The opinions stated in this paper are solely those of the author and do not necessarily represent the official policy of the USNRC.

Appendix I - References

1. Arizona Public Service Company, "Final Safety Analysis Report, Palo Verde Nuclear Generating Station", Section 9.2.

2. Codell, R. B., "Analyses of Ultimate Heat Sink Spray Ponds," U.S. Nuclear Regulatory Commission, NUREG-0733, August 1981.

3. Codell, R. B., "A Performance Model for Ultimate Heat Sink Spray Ponds." (This issue.)

4. SPRACO, "Spray Ponds--The Answer to Thermal Pollution Problems," Spray Engineering Company, Burlington, MA, undated.

5. U.S. Nuclear Regulatory Commission, "Regulatory Guide 1.27, "Ultimate Heat Sink for Nuclear Power Plants," Rev. 1, 1976.

6. Wunderlich, W. O., "Heat and Mass Transfer between a Water Surface and the Atmosphere," Report No. 14, TVA Engineering Laboratory, Norris, TN, 1972.

Appendix II - Notation

The following symbols are used in this paper:

CDF = Cumulative Distribution Function

a_{ij} = Coefficients in regression equations for spray performance

T_A = dry bulb temperature

T_{HOT} = temperature of water leaving nozzles

T_W = wet bulb temperature

w = ambient wind speed

Q_{HWS} = fraction of sprayed water which evaporates in High Wind Speed model

Q_{LWS} = fraction of sprayed water which evaporates in Low Wind Speed model

η_{HWS} = efficiency of High Wind Speed model

η_{LWS} = efficiency of Low Wind Speed model