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Report for the Susquehanna Project

Ultimate Heat Sink Thermal Performance

Tests Analytical Technique

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I. Introduction

The analysis of the ultimate heat sink (UHS) spray pond for the Susquehanna Steam Electric Station (SSES) has been finished. Each pond must have the thermal capacity to dissipate the thermal load associated with the LOCA or/and Emergency safe shutdown under conservative meteorological conditions and limit the cooling water temperatures to the design ranges of system components. Additionally the pond water inventory must be capable of sustaining this performance for a period of 30 days following the hypothetical LOCA or/and Emergency safe shutdown. To obtain the necessary supporting information to verify that the UHS spray pond will meet the design criteria, thermal performance tests will be performed and analyzed using the Unit 1 reactor as a source of heat.

II. Objective

The objective of this test was to verify the conservatism of computer program simulations used for the design of the spray pond as an ultimate heat sink with regard to the maximum water temperature and maximum water loss at various heat loads and meteorological conditions.

III. Discussion

The tests scheduled to be conducted on the SSES spray pond system are designed to evaluate the spray pond performance in accordance with the ASME Power Test Code PTC23 (Reference 2), and with prevailing meteorological conditions for the purpose of:

(1) Establishing the thermal performance capability of the spray pond;
(2) Establishing the drift loss as a function of wind speed;
(3) Determining the spray nozzle efficiency and spray evaporation loss;
(4) Determining the natural evaporation loss.

The detail test program and procedures are listed in Reference 1. The following two pages show a summary of the instrumentation used in this test program. The recommended accuracies are also included and are used to estimate the experimental error. Theories used to evaluate pond performance are listed in the data analysis section.

IV. SUMMARY OF INSTRUMENTATION

See Environmental Corporation's Data Collection Procedures for a summary of the systems instrumentation.

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V. Data Analysis

(1) Natural evaporation loss

Surface evaporation is monitored using three evaporation pans at the east edge of the spray pond. The arithmetic mean of the three measurements is used. Correlation between natural evaporation loss and time for a specific constant heat load will be established. Natural evaporation loss measurements will be plotted against time.

(2) Drift loss

The technique described in Reference 1 is basically designed to measure the total volume of drift over a certain period of time. Correlation between drift loss and wind speed for a specific constant heat load will be established. Drift loss measurements will be plotted against wind speed.

(3) Pond water temperature

The average pond water temperature is measured at the pond outlet i.e., the inlet to the pump suction sump structure. It is obtained from the arithmetic mean of the three measurements taken at the bottom, one-half depth, and surface of the pond. Correlation between water temperature and time for a specific constant heat load is established. Water temperature measurements will be plotted against time.

(4) Water losses

The pond total water loss term is a combination of several loss terms, as illustrated by the equation:

$$\dot{M}_T = \dot{M}_D + \dot{M}_{NE} + \dot{M}_{SE} + \dot{M}_{MIS} - \dot{M}_M \qquad (1)$$

where

$\dot{M}_T$ = total water loss

$\dot{M}_D$ = drift loss

$\dot{M}_{NE}$ = natural evaporation loss

$\dot{M}_{SE}$ = spray evaporation loss

$\dot{M}_{MIS}$ = miscellaneous loss due to seepage and sedimentation (to be neglected)

$\dot{M}_M$ = makeup water = 0

The makeup flow to the pond will be zero during the tests. The duration of the tests is too short to allow any loss due to seepage or sedimentation therefore $\dot{M}_{MIS}$ can be neglected.

The total pond water loss is measured as described in Reference 1. The correlation between total pond water loss and time for a specific constant heat load will be established. The natural evaporation is measured as described in section (1). The drift loss is measured as described in section (2). Therefore, spray evaporation loss could be determined from the above equation.

(5) Flow rate and heat load

The service water flow rage (RHRSW and ESW return to the spray pond) is measured by two instrument loops, one for each ESW loop. The heat load on the pond was calculated from the product of the mass flow rate and the temperature difference between the water leaving and returning to the pond.

(6) Spray nozzle efficiency

The spray nozzle efficiency at a specific flow is a function of spray water temperature and weather conditions. The spray nozzle efficiency is defined as:

$$\eta = \frac{T_S - T_C}{T_S - T_{WB}} \qquad (2)$$

where η = spray nozzle efficiency

T_S = spray water temperature

T_C = temperature of droplets impacting on pond surface.

T_{WB} = wet bulb temperature

Nozzle location as well as wind speed and wind direction are important in determining the effective wet bulb temperature. The ambient wet bulb temperature used to calculate η is measured at positions 50 to 100 feet upwind of the pond. However, nozzles located downward of the spray pattern are exposed to higher humidity air than the ambient wet bulb temperature would indicate.

Effects due to variation in wind speed fall into two categories. In the case of high wind speeds (3 mph or greater), the wind dominates the air flow pattern in the spray region. For high wind speeds, the

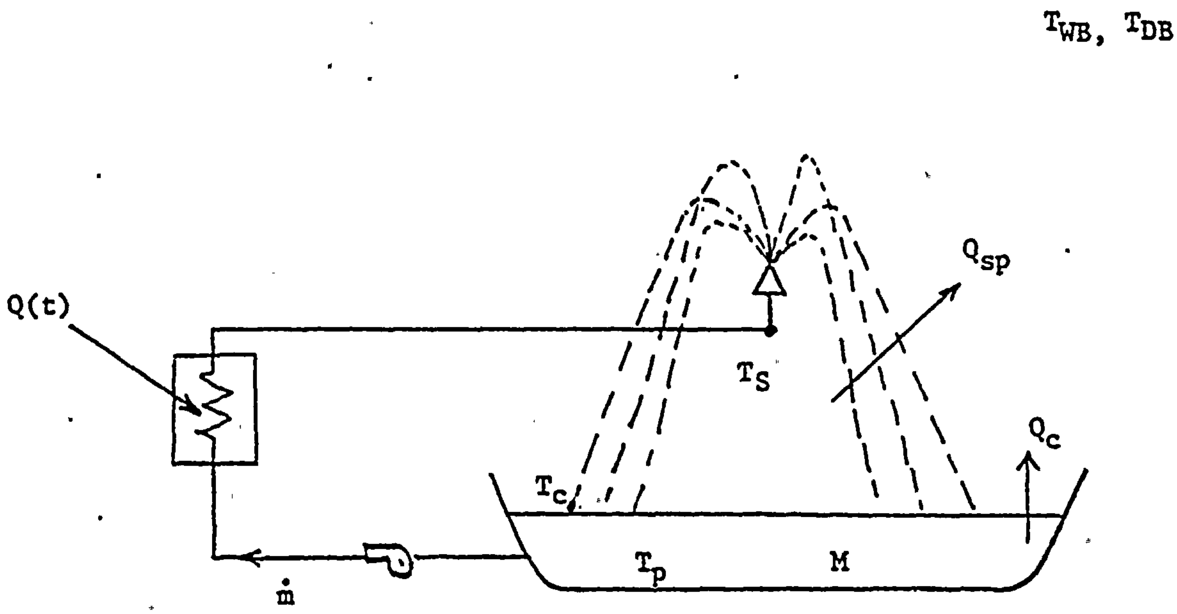
efficiency varies with the distance down the spray field in the direction of the wind. For low wind speeds (less than 6 mph), natural convection dominates the air flow pattern. Convection plumes induce air flow into the spray region from all directions, including from the down wind side of the pond. For natural convection, one expects a non-monotonic variation in the efficiency observed along a line in the direction of the wind across the pond.

For design purposes, it is desirable to know the average value of η for the entire pond. Thus a method for averaging the measurements of individual catch pans in the spray pattern is needed. Two methods for weighing individual catch pan results are used, one for the high wind case and another for low winds. The averaging patterns are selected by trying several plausible schemes and comparing the results with the value of η calculated using the mean pond temperature (Tp). The η based upon T_p is calculated for comparison because the average value of T_C must equal the mean pond temperature when the pond is operating in steady state.* Experimental data is chosen at times when pond and wet bulb temperatures are stable. The value of T_C recorded in each of the catch pans is used to compute the spray efficiency at that particular location. The average value of η for the entire pond is determined by area-averaging the η values of individual regions. The averaging of the η values would account for the effect of using upwind wet bulb temperature to calculate η. The dependence of the average η on wind and spray water temperature can then be established.

(7) Overall pond thermal performance
The transient behavior of the pond can be analyzed on the basis of a simple lumped capacity model.

*Neglecting surface evaporation

The system is described by the following diagram:



where $Q(t)$ = is the time dependent heat load

Q_{sp} = is the heat rejected from the spray (Drift and spray evaporation loss are included)

Q_c = is the surface heat transfer rate due to natural evaporation and convection

M = is the mass of water in the pond

$\dot{m}$ = is the service water mass flowrate

C_p = is the specific heat of water

T_{WB}, T_{DB} = are the wet bulb and dry bulb temperature, respectively

T_s = is the service water temperature before spray

T_c = is the service water temperature after spray

T_p = is the mean pond temperature

The energy balance is

$$\frac{d}{dt}(MC_pT_p) = Q(t) - Q_{sp} - Q_c \qquad (3)$$

Recalling from section 6, $\eta = \frac{T_S - T_C}{T_S - T_{WB}}$ (2)

The heat load is given by

$$Q(t) = \dot{m}C_p\,(T_S - T_p) \qquad (4)$$

The heat rejected from the spray,

$$Q_{sp} = \dot{m}h_f(T_S) - \dot{m}_A h_f(T_c) \qquad (5)$$

where $\dot{m}_A$ is the after spray water flow rate,

$$\dot{m}_A = \dot{m} - \dot{M}_{SE} - \dot{M}_D\,^* \qquad (6)$$

The surface heat transfer rate,

$$Q_c = hA(T_p - T_{DB}) + \dot{M}_{NE} \cdot h_f(T_p) \qquad (7)$$

where A is the pond surface area and h is the heat transfer coefficient.

Recalling from section 4, the system mass balance is

$$\frac{dM}{dt} = -\dot{M}_D - \dot{M}_{NE} - \dot{M}_{SE} \qquad (8)$$

*See page 5 for definition of mass flow terms.

The essential steps to evaluate the spray pond performance are:

1. Compute T_S using (4), $T_S = T_P + \frac{Q(t)}{\dot{M}C_P}$

2. Compute $\dot{m}_A$ using (6)

3. Compute Q_{SP} using (5)

4. Compute T_P by combining (3) and (7)

5. Compute η using (2)

6. Compute water loss using (8)

VI. Computer Models

Computer simulation programs are presently being used to analyze the thermal performance of the SSES spray pond system according to requirements specified in Reference 3.

The average three-hourly atmospheric conditions and heat load recorded during the test are used as input to our simulation programs to generate natural evaporation, drift, spray evaporation loss and spray efficiency. These results are then used as input to our system performance program to generate pond water temperature and pond water loss for a specific constant heat load. These calculated values are then compared to test results. Consequently, the conservativeness of the computer programs can be shown.

VII. Error Estimation

(1) Pond water loss

Contact point gauges with an accuracy of ± 0.001 ft are used. Frequency of readings is 4 hours. In 24 hours, the approximate change in water level is 5 inches. Therefore, error = $\frac{5 \times 0.001}{12 \times 6} \times 100$

$= \underline{1.44\%}$

(2) Pond water temperature

Temperature sensors with an accuracy of ± 0.1 °F are used. Frequency of readings is 5 minutes.

$$\text{Error} = \frac{\text{accuracy}}{\text{temperature change in 5 minutes}} \times 100\%$$

(3) Natural evaporation loss

Evaporation pans with accuracy of ± 0.001 ft are used. The volumetric error would be (± 0.001x pan surface area) ft^3. Frequency of readings is 60 minutes.

$$\text{Error} = \frac{\text{volumetric error}}{\text{water loss in 60 minutes}} \times 100\%$$

(4) Flow rate

Service water flow meter with an accuracy of ± 1.5% is used.

(5) Service water temperature (Frequency of readings is 10 minutes)

Temperature sensors with an accuracy of ± 0.1 °F are used.

$$\text{Error} = \frac{\text{accuracy}}{\text{temperature change in 10 minutes}} \times 100\%$$

(6) Heat load

$$Q = \dot{m}\,\Delta T$$

$$\varepsilon_Q = \varepsilon_{\dot{m}} + \varepsilon_{\Delta T}$$

where ε is the percent error

Q is the heat load

$\dot{m}$ is the service water mass flow rate

ΔT is the service water temperature difference

$\varepsilon_{\dot{m}} = \pm 1.5\%$ from section (4), $\varepsilon_{\Delta T}$ is estimated in section (5) of error estimation

(7) Spray nozzle efficiency

$$\eta = \frac{T_S - T_C}{T_S - T_{WB}}$$

$$\varepsilon_\eta^2 = \left(\frac{\partial \eta}{\partial T_S}\right)^2 \varepsilon_{TS}^2 + \left(\frac{\partial \eta}{\partial T_C}\right)^2 \varepsilon_{TC}^2 + \left(\frac{\partial \eta}{\partial T_{WB}}\right)^2 \varepsilon_{T_{WB}}^2$$

where ε is the percent error

η is the spray nozzle efficiency

T_S is the service water temperature before spray

T_C is the service water temperature after spray

T_{WB} is the ambient wet bulb temperature

$$\frac{\partial \eta}{\partial T_S} = \frac{T_C - T_{WB}}{(T_S - T_{WB})^2}$$

$$\frac{\partial \eta}{\partial T_C} = \frac{-1}{(T_S - T_{WB})}$$

$$\frac{\partial \eta}{\partial T_{WB}} = \frac{T_S - T_C}{(T_S - T_{WB})^2}$$

VIII. References

1. Susquehanna Steam Electric Station Units 1 and 2, "Ultimate Heat Sink Thermal Performance Tests Report", July 1981.

2. ASME Power Test Code 23-1958, "Atmospheric Water Cooling Equipment".

3. Regulatory Guide 1.27, Rev. 2.