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ORIENTED SPRAY-ASSISTED COOLING TOWER

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ABSTRACT

The oriented spray-assisted cooling tower (OSACT) is a new approach to natural draft cooling tower design which increases air flow through the cooling tower while reducing water loading in the heat exchanger fill material. Rigorous computer codes which have been validated by comparison with extensive test data are used to compute the improvement in heat transfer to increase the cooling tower capability over that of conventional design. The resulting improvement in cooling system performance enhances the economic competitiveness of power plants with cooling towers by increasing the electrical output without an increase in consumption of fuel or auxiliary power.

PURPOSE

The purpose of this paper is to describe the OSACT and to provide the results of analysis showing the improved performance of natural draft cooling towers when the OSACT design is employed.

INTRODUCTION

Although the art of evaporative cooling is quite ancient, the first natural draft cooling tower was not constructed until 1916 at the Emma Pit in the Netherlands by the Dutch State Mines. Spray towers without fill packing were proposed by Green[1] in 1921 and Lewis[2] in 1930. These cooling towers employed spray nozzles that were oriented to spray vertically upward inside the tower and horizontally inward at the air inlet opening of the tower. A slightly different design was proposed by Parkinson[3] in 1968 in which a hood was extended radially outward from the bottom edge of the shell at the top of the air inlet opening to an array of spray nozzles oriented to spray horizontally inward across the opening from the hood at the top of the opening to the bottom at the tower basin. Such natural draft spray towers have been widely used in countries such as Russia where the severe climate makes freezing a serious problem, but they have not gained acceptance in the United States.

One of the virtues claimed by all of the designers of spray towers with spray nozzles in the air inlet opening and oriented to spray inward was that the sprays increase air flow. An obvious extension of this design would be to couple the design with a crossflow or counterflow tower with either a splash or thin-film fill. However, no such design has been commercially successful. The authors posit at least two reasons why this design with spray nozzles which are more or less uniformly distributed across the face of the air inlet opening has not been adopted in conjunction with conventional natural draft cooling towers with packing. Firstly, although the horizontal component of velocity of the sprayed water from the nozzles located high in the air inlet opening imparts momentum to the incoming air, these water droplets actually obstruct air flow through the lower region of the air inlet opening as they fall to the basin below. The net effect is that air flow may be increased the most at the top of the air inlet opening where it is needed the least, and the air flow is increased the least, if at all, at the bottom of the air inlet opening where it is needed the most. Secondly, the pressure required to deliver water to the top-most spray nozzles at sufficient nozzle pressure to achieve adequate spray distribution is greater than that required to distribute water over the cooling tower fill packing. Therefore, supplemental pumping is required to achieve the desired pressure. The additional capital and operating cost of this arrangement may more than offset any benefit gained. The OSACT design first described by Bowman[4] remedies these deficiencies.

COOLING TOWER PERFORMANCE ANALYSIS

It is well understood that the total heat transfer rate in a cooling tower may be expressed as,

$$dQ_t = dQ_s + dQ_e \tag{1}$$

where,
dQ_t = differential heat transfer rate
dQ_s = differential sensible heat transfer rate
dQ_e = differential latent heat transfer rate

For sensible heat transfer,

$$dQ_s = H(t_W - t_{db})\, dA_i \tag{2}$$

where
H = local heat transfer coefficient
t_W = local water temperature
t_{db} = local air dry-bulb temperature
dA_i = differential interface area

For evaporative heat transfer, the differential mass transfer rate is related to the driving potential and the mass transfer coefficient by

$$dE = K\, B\, dA_i \tag{3}$$

where
dE = differential evaporative mass transfer rate
K = mass transfer coefficient
B = mass transfer driving potential

and

$$B = x_s - x \tag{4}$$

where

x_s = mass fraction of the water in the saturated air at the water surface temperature
x = mass fraction of the water in the air in the bulk air stream

and

$$x_s = \omega_s \ / (1 + \omega \ ) \qquad (5)$$

$$x = \omega \ / (1 + \omega \ ) \qquad (6)$$

where

ω = absolute humidity.

so that

$$B = (\omega_s - \omega) / (1 + \omega\ ) \qquad (7)$$

The differential heat transfer rate is related to the differential mass transfer rate through the enthalpy of saturated water vapor, h_g, by

$$dQ_e = h_g \, dE \qquad (8)$$

where

h_g = enthalpy of saturated water vapor

Therefore, substituting into Equation 1,

$$dQ_t = H(t_w - t_{db})\, dA_i + h_g K (x_s - x)\, dA_i \qquad (9)$$

Let

$$dA_i = a \, dV \qquad (10)$$

where

a = interface area per unit of volume
V = cooling volume

Equation 9 may be written in the form

$$dQ_t = K a \, dV[\,(H/Kc_{p(a)})\, c_{p(a)}(t_w - t_{db}) + h_g(x_s - x)] \qquad (11)$$

where

$c_{p(a)}$ = specific heat of moist air

Merkel[5] simplified this relationship by suggesting that for a film of saturated air at the air/water interface, an equilibrium condition can be expressed by equating heat transferred from air to the film by convection to the heat transferred from the film to the ambient air by evaporation:

$$H\,(t_w - t_{db}) = K\, h_g(x_s - x) \qquad (12)$$

By multiplying both sides of this equation by $c_{p(a)}$ and collecting terms, the result is the Lewis number

$$Le = H/K\, c_{p(a)} = h_g(x_s - x) \ / \ c_{p(a)}\,(t_w - t_{db}) \qquad (13)$$

If one assumes a value of $Le = 1$, then Equation 11 reduces to

$$dQ_t = K a \, dV[c_{p(a)}(t_w - t_{db}) + h_g(x_s - x)] \qquad (14)$$

Noting that the heat transferred to the air is lost from the water

$$dQ_t = d(L\, c_{p(w)}\, t_w) \qquad (15)$$

where

L = water flow rate

and also noting that the differential change in enthalpy of moist air is

$$dh = c_{p(a)}\, dt + h_g \, dx \qquad (16)$$

By assuming constant, average values of $c_{p(a)}$ and h_g, then Equation 16 becomes

$$h = c_{p(a)}\, t + h_g x \qquad (17)$$

Combining equations 14, 15, and 17 yields

$$d(L\, c_{p(w)}\, t_w) = K a\, (h_s - h_a)\, dV \qquad (18)$$

where

h_s = enthalpy of saturated air at the temperature of the water
h_a = enthalpy of air

If one assumes that L and $c_{p(w)}$ are constant and $c_{p(w)} = 1$, then

$$\int dt/(h_s - h_a) = Ka \, dV/L \qquad (19)$$

This is the well known Merkel equation which has been the standard method of cooling tower performance analysis for many years. However, as shown above this approach requires several significant simplifying assumptions.

In 1956, Zivi and Brand[6] extended the analysis of Merkel to crossflow cooling towers. In 1976, Kelly[7] used the model of Zivi and Brand along with laboratory data to produce a volume of crossflow cooling tower characteristic curves to be used in graphical solutions of cooling tower performance. The graphical solutions represent the equation

$$KaY/L'' = C(L''/G'')^{-n} \qquad (20)$$

where

Y = crossflow packing height
L'' = water flow rate per unit area (water loading)
G'' = air flow rate per unit area (air loading)

and C and n are constants.

In 1977 the Cooling Tower Institute[8] published its "Blue Book" of cooling tower performance curves using the four-point Tchebycheff method for numerically evaluating the integral in Equation 19. These graphical solutions represent the equation

$$KaV/L'' = C(L''/G'')^{-n} \qquad (21)$$

Not until the advent and widespread use of the minicomputer was it possible to analyze the performance of cooling towers with rigor. Benton[8] developed the Fast Analysis Cooling Tower Simulator (FACTS) computer code for the Tennessee Valley Authority (TVA), which is one of the tools used to establish the technical basis for the claims of improved performance of natural draft cooling towers when the OSACT design is employed.

ORIENTED SPRAY-ASSISTED COOLING TOWER

Description of the OSACT

The OSACT is a new, approach to cooling tower design which may be applied either to new or existing cooling towers. The OSACT design, shown in Figure 1, diverts a portion of the total amount of condenser circulating water (CCW) from the cooling tower, through a header pipe, and to a series of spray trees consisting of vertical riser pipes, spray arms, and spray nozzles which are evenly spaced external to the cooling tower so as to produce a uniform spray pattern oriented toward the central axis of the cooling tower, which is the desired direction of air flow. The sprayed water then lands on an apron extending from the header pipe to the cooling tower basin. The apron is sloped gently toward the cooling tower basin such that the sprayed water drains into the cooling tower basin. The water spray droplets apply a drag force to the air, increasing the air velocity and air flow into the cooling tower over that achieved with conventional cooling tower design. By spraying the water to be cooled in a region external to the cooling tower in a manner such that the spray falls just short of the cooling tower basin, the spray does not interfere with the operation of the cooling tower, proper, and the maximum increase in air velocity is achieved just above the cooling tower basin where it is the most effective. By diverting a portion of the water to be cooled to the spray trees external to the cooling tower, the water loading in the cooling tower heat exchanger section is reduced and the resistance to air flow through the cooling tower caused by the water falling through the heat exchanger section of the cooling tower is reduced. Therefore, the effectiveness of evaporative cooling is improved.

Technical Basis for the OSACT

Technical basis for FACTS. FACTS is a steady-state, steady-flow numerical computer model of cooling tower thermal performance. It is more sophisticated than the one-dimensional Merkel model, yet it contains simplifications that prevent it from being classified as a true two-dimensional code. The following are the other major assumptions made:

1. The flow of air is two-dimensional in the fill region of a crossflow tower and one-dimensional in the fill region of a counterflow tower.
2. Wet-bulb temperature is equivalent to the adiabatic saturation temperature.
3. The cooling tower is externally adiabatic.
4. The atmosphere around the natural draft cooling tower is isentropic.
5. The water flows vertically downward inside the tower.
6. Evaporation loss is neglected in the water mass balance.

The FACTS model is based on the conservation of the mass of air and water vapor as well as the conservation of energy for the gas phase and energy for the water phase. These conservation equations in conjunction with the Bernoulli equation constitute the set of equations which are solved by FACTS to simulate cooling tower performance. The form of the Bernoulli equation used is,

$$p_1+\rho_1 v^2_1/2g_c+\rho_1 g y_1/g_c = p_2+\rho_2 v^2_2/2g_c+\rho_2 g y_2/g_c+\text{losses} \qquad (22)$$

where the subscripts 1 and 2 represent two locations along a streamline and

p = pressure
ρ = density
v = total velocity
g_c = Newton's constant
g = acceleration of gravity

It is convenient to express Equations 2, 3 and 8 in terms of the absolute humidity, ω, and to let

$$dV = dx\,dy\,dz \qquad (23)$$

so that the three equations of interest are then,

$$dQ_s = Ha\,(t_w - t_{db})\,dx\,dy\,dz \qquad (24)$$

$$dE = Ka\,[(\omega_s - \omega)/(1+\omega)]\,dx\,dy\,d \qquad (25)$$

$$dQ_e = h_g\ Ka\ [(\omega_s - \omega)/(1+\omega)]\,dx\,dy\,dz \qquad (26)$$

These equations are applied in their steady-state, steady-flow form. The independent variables are the horizontal distance (x), vertical distance (y), total mass flow rate of water, inlet hot water temperature, and the ambient wet- and dry-bulb temperatures. The dependent variables in the conservation equations are air velocity, absolute humidity, the enthalpy of the air-water vapor mixture, the water temperature, and pressure. The wet-bulb temperature and dry-bulb temperature are determined using the following thermodynamic relationships for air-water vapor mixtures from computed values of t, h_a, and p.

The interrelationship among the dependent and independent variables is evident from the formulation of the conservation equations that follow. The conservation of mass for the water vapor within a control volume is expressed as

$$\int\int\int Ka[(\omega_s-\omega)/(1+\omega)]dx\,dy\,dz = \int\int [\omega\rho/(1+\omega)]\boldsymbol{V}\cdot dA \qquad (27)$$

where $\boldsymbol{V}\cdot dA$ is the dot product of the two vectors $\boldsymbol{V}$ and dA. For conservation of energy for the air within a control volume

$$\int\int\int\{h_g Ka[(\omega_s-\omega)/(1+\omega)]+Ha(t_w-t_{db})\}\,dx\,dy\,dz = \int\int[h_a\rho/(1+\omega)]\boldsymbol{V}\cdot dA \qquad (28)$$

Finally, the conservation of energy for the water within a control volume is

$$Lc_{pw}dt_w = -\int\int\int\{h_g Ka[(\omega_s-\omega)/(1+\omega)]+Ha(t_W-t_{db})\}\,dx\,dy\,dz \quad (29)$$

Simulation of the mass, momentum, and heat transfer processes in the cooling tower requires that the tower be discretized, or divided into computational cells. Each cell is treated as a control volume, and the governing equations are applied to each. At each cell the computed dependent variables from the adjacent upstream cells are utilized. These variables are defined at nodes located at the mid-points of the cell boundaries. The use of boundary nodes assures conservation of mass and energy from cell to cell. Applying the Bernoulli equation and conservation equations to each cell results in a set of nonlinear simultaneous equations relating the dependent variables. These implicit nonlinear simultaneous equations are solved using the Gauss-Seidel method.

For counterflow towers, the air is assumed to flow between collinear hyperboloid pathlines. The fraction of air mass flow between each pathline is computed and reflects flow resistance in both the fill and the rain zones. The pressure drop and transfer characteristics of the fill are integrated in the radial direction to obtain average values. These are weighted by the velocity head, air flow, and water flow. These average values are used with the one-dimensional integral conservation equations.

For crossflow towers, the air flow distribution is evaluated using the Bernoulli equation (with head loss) and the conservation of mass for air. These equations are applied to each computational cell.

The specified inlet conditions of both air and water (temperatures and flows) can vary across the inlet plane. FACTS requires as input a sensible heat transfer coefficient, H, and a mass transfer coefficient, K, which are a function of the fill characteristics as input. FACTS can model towers containing hybrid fills or fills that have voids or obstructions. FACTS allows for the input of separate correlations for spray and rain regions in counterflow towers.

FACTS has been the subject of extensive validation efforts by TVA[10,11], Electric Power Research Institute (EPRI)[12,13], and other utilities. EPRI undertook an aggressive program in the mid-1980's to study the thermal performance of cooling tower fill materials and to compare numerical models for accuracy in predicting cooling tower performance. In 1989 EPRI published the results of the Cooling Tower Performance Prediction and Improvement Project.[12] Heat and mass transfer coefficients and pressure drop data were obtained for eight crossflow and eight counterflow commercial fills in an engineering-scale facility built at the Parish Station of Houston Lighting and Power Company. A test matrix of roughly 50 test points for crossflow and 65 points for counterflow was run with each fill to provide input for the regression analysis of the test data. The FACTS code predicted the CWT to within 0.4 °C of the measured value on average.[14]

The validity of the FACTS model has been tested by comparing model results with field data collected on cooling towers at 3 TVA power plants. These towers are fundamentally different in design. The cooling towers at Browns Ferry Nuclear Plant, Sequoyah Nuclear Plant, and Paradise Steam Plant are crossflow mechanical draft, crossflow natural draft, and counterflow natural draft, respectively. FACTS predicted the results of these tests to within an average absolute error of 0.3 °C, and no calibration of the model was used in making the predictions.[10]

Technical basis for oriented spray cooling system. The thermal performance of the oriented spray cooling system (OSCS) which encircles the OSACT is based on models developed by TVA from 1975 to 1983 to analyze oriented spray cooling ponds for nuclear plant ultimate heat sink applications. The derivation of the TVA thermal model has been published.[15] The following assumptions are made:

1. Drops are spherical with constant diameter and uniform internal temperature distribution throughout their flight.
2. Collision between drops is neglected.
3. Nozzles, initial drop velocities, and drop size distribution are axisymmetric.
4. Air velocity and thermodynamic air properties are uniform across the entire spray region.
5. The initial drop velocity is such that the calculated height and diameter of the spray pattern for a vertical nozzle agree with measured values.
6. Drop size distribution is known.
7. Conditions are uniform across the inlet and exit area of the control volume.
8. Air enters at known ambient psychometric conditions.
9. The relative humidity within the control volume and at the exit of the control volume is 100 percent.
10. Ambient wind is neglected.
11. Bulk drag forces are known functions of velocity.

The drag force on a droplet is integrated over the trajectory to determine the drag impulse on that droplet during flight. The droplet size distribution for a nozzle is used to determine the rate of generation of droplets in each class per unit mass flow rate. The resulting rates and the drag impulse per droplet are used in a summation over all droplet classes to determine the bulk drag force of the spray upon the air. The prediction of air flow and bulk drag force are coupled through iteration. Once the air flow has been determined, the exit wet bulb temperature may be calculated for a given heat load by assuming saturation conditions. The local wet-bulb temperature in the spray region is then set equal to the exit wet-bulb temperature. The model calculates the instantaneous velocities and rates of heat and mass transfer under degraded wet-bulb conditions for a representative selection of individual drops of water for a single nozzle. Numerical integration is used to find the temperature of these drops when they reach the surface below. From these individual drop temperatures, the average cold water temperature for the entire flow from that nozzle is calculated. The performance of a single nozzle is considered to be the same as that of all nozzles in the pond that operate at the same elevation and pressure.

Verification of the TVA OSCS model has occurred over a number of years by comparing the results predicted by the model with tests conducted at several facilities. Berger and Taylor[15] compared the model with the results of tests conducted at the Rancho Seco Nuclear Plant for the classical vertical sprays. Bowman Et Al.,[16] compared the results of the TVA OSCS model with tests conducted by the Ecolaire Condenser Company on the OSCS located at the Ingersoll-Rand Corporation's Phillipsburg, New Jersey, plant. This facility is shown in Figure 2. However, extensive test data from a full-scale OSCS were not available until 1979 when Conn[17] published the results of tests conducted on the OSCS at the Washington Public Power Supply System Nuclear Project No. 2 shown in Figures 3 and 4. Bowman[18] compared the TVA OSCS model with the results of these tests. For the same wet-bulb temperature and cooling range, the TVA OSCS model predicts an approach to wet-bulb temperature that is an average of 0.8 °C higher than the measured values, which indicates that the TVA model is conservative.

Integration of OSCS and FACTS. To quantify the improvement in cooling tower performance with the oriented spray assist (OSA), a version of FACTS was created which computes the performance of a cooling tower with and without the spray trees in operation. As previously noted, one of the capabilities of FACTS is that the specified inlet conditions of both the air and water temperatures and flows may be varied across the inlet plane. In the OSA version of FACTS, an input file is required which defines the air temperature and velocity as it exits from the sprays and enters the cooling tower. These values are generated by running the TVA OSCS model with an array of wet-bulb and hot water temperatures. The CCW flow which is sprayed through the spray trees is subtracted from the water going over the cooling tower fill material.

PERFORMANCE IMPROVEMENT WITH OSACT

The advantages of the OSACT design over conventional natural draft cooling tower design are as follows:

1. Water from the spray nozzles on spray trees which are evenly spaced around the base of the cooling tower and which spray in the direction of the central axis of the cooling tower imparts momentum to the air flow by applying a drag force to the air and thus increases air flow into the cooling tower.
2. Air flow into the cooling tower is increased in the lower regions of the air inlet opening where it is most beneficial.
3. Diverting a portion of the CCW to the spray trees reduces the water loading on the cooling tower fill material.
4. Diverting a portion of the CCW to the spray trees reduces the resistance to air flow in the cooling tower.

The actual improvement in performance with the OSACT design varies depending upon the cooling tower design. The amount of CCW that can be diverted to the spray trees is a function of the cooling tower basin diameter, since the spacing of the spray trees is fixed to achieve maximum air entrainment in the spray, and a function of the pressure available at the spray nozzles. The nozzle pressure is determined by the pressure required at the cooling tower interface to distribute the CCW over the cooling tower fill material minus the pressure drop in the header piping and spray trees.

The advantages of the OSACT design over conventional cooling tower design are clearly evident in the following example. The authors conducted a study for improving the performance of the Watts Bar Nuclear Plant (WBNP) cooling tower design with the OSACT design using the OSA version of FACTS. The WBNP cooling towers are counterflow, hyperbolic natural draft towers which are 154 meters high with a basin diameter of 123 meters. The normal CCW flow is 26,494 liters/sec. (420,000 gpm), and with the OSACT design, 13% of the CCW flow would be diverted to the spray trees. A comparison between the critical performance parameters with a hot water temperature of 53.33 °C (128 °F) and an ambient wet-bulb temperature of 26.67 °C (80 °F) is shown in Table 1.

<u>Table 1</u>

	w/o OSA	w/ OSA
Dry air flow, kg/sec	19,651	22,070
Average water loading, kg/sec-sq m	2.536	2.211
Total pressure drop, atmospheres	0.00111	0.00115
Liquid/gas ratio, dimensionless	1.35	1.05
Spray cold water temperature, °C		35.56
Basin cold water temperature, °C		32.33
Tower cold water temperature, °C	33.22	32.72

The distribution of horizontal air velocity as it enters the cooling tower with and without the OSA is shown in Figure 5, and the distribution of vertical air velocity as it enters the fill region with and without the OSA is shown in Figure 6. Not only is the air flow increased as indicated in Table 1, but the increase in air flow is predominantly in the lower part of the air inlet which increases the air flow in the center of the tower. Even though the air flow is increased by 12% with the OSA, the total pressure drop is increased by only 3% due to the lower water loading. The L/G ratio is reduced by approximately 20% with the OSA.

From Table 1 it may be seen that the cold water temperature coming from the sprays is greater than that from the fill section of the cooling tower. However, the weighted average cold water temperature with OSA is 0.5 °C less than the conventional design. Figure 7 shows this relation between the cold water temperature with and without OSA as a function of wet-bulb temperature. The improvement in cold water temperature is about the same for all wet bulb temperatures.

Bowman and Benton[14] have shown that the reduction in cold water temperature of 0.5 °C which may be achieved by converting the cooling tower to an OSACT would increase the installed plant capacity at WBNP by 3 megawatts without increasing either fuel consumption or required auxiliary power. In addition, the plant's output would be increased by 32 megawatts during extremely high wet-bulb temperatures, because the plant output is limited by main condenser back pressure limitations.

CONCLUSION

The OSACT is a new approach to natural draft cooling tower design in which a portion of the CCW is diverted to a series of spray trees which encircle the base of the cooling tower. The resulting water spray towards the central axis of the cooling tower increases the air flow into the lower portion of the air inlet opening. The net result is a reduction of the liquid/gas (L/G) ratio and a reduction of the cooling tower cold water temperature. The technical basis for these claims of improved thermal performance with the OSACT design is an analysis performed by the authors using the OSCS model and a modified version of the FACTS code, both of which were developed by TVA. FACTS is not constrained by simplifying assumptions employed when performing cooling tower analysis based on the Merkel equation, but rather FACTS is a rigorous analytical code. Although no full-scale tests have been performed to confirm the advantages of the OSACT, both FACTS and the TVA OSCS model have been validated as to the predicted cold water temperature by comparison with extensive test data. Therefore, the claims for improved performance with the OSACT design are well supported by a reliable technical basis.

The OSACT design is not only applicable to future natural draft cooling tower designs, but it may also be backfitted to existing cooling towers to increase the plant's electrical generating capacity without increasing either fuel consumption or the required auxiliary power requirements.

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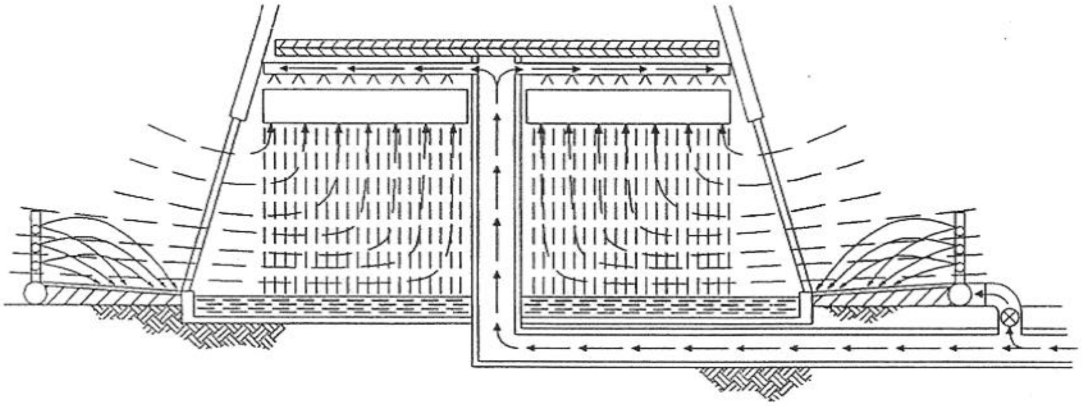

Figure 1

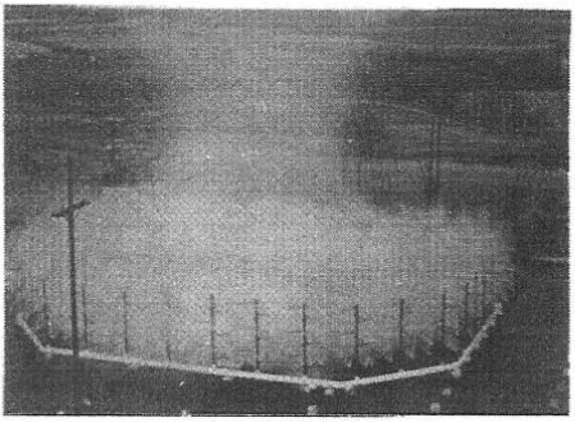

Figure 2

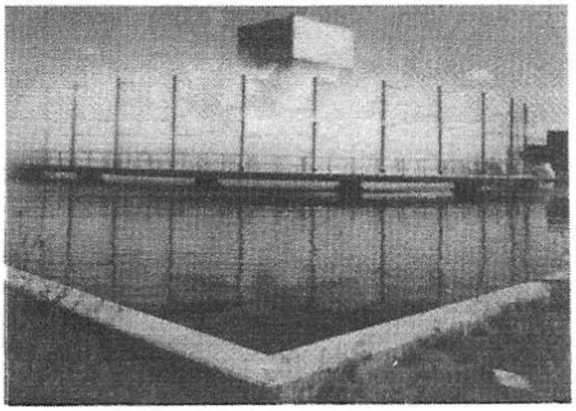

Figure 3

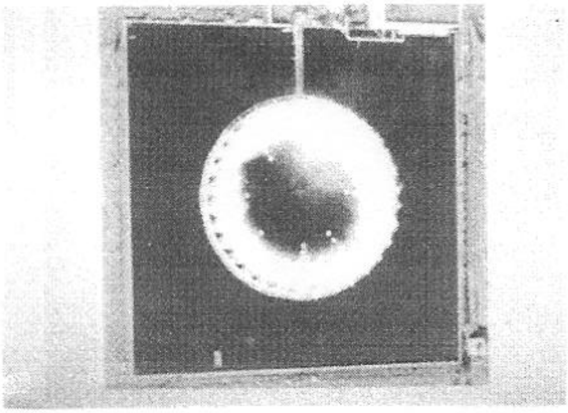

Figure 4

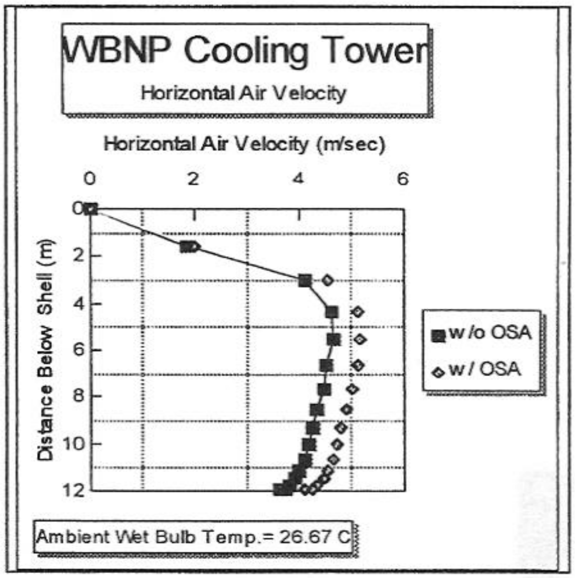

Figure 5

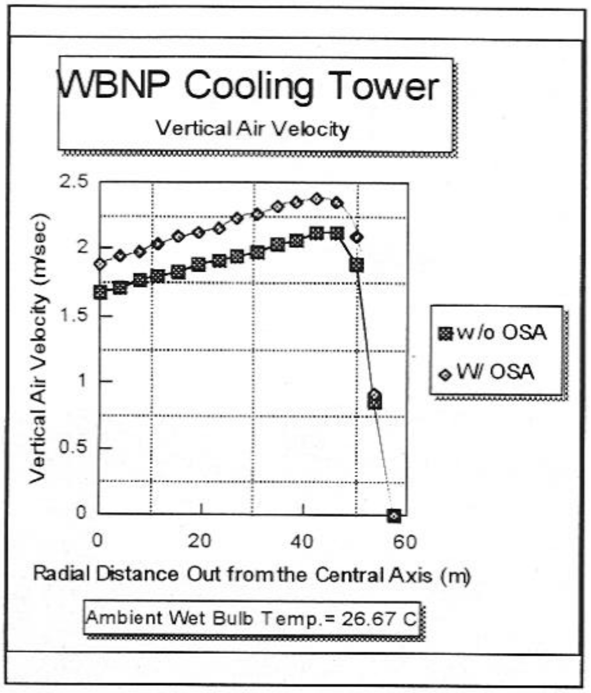

Figure 6

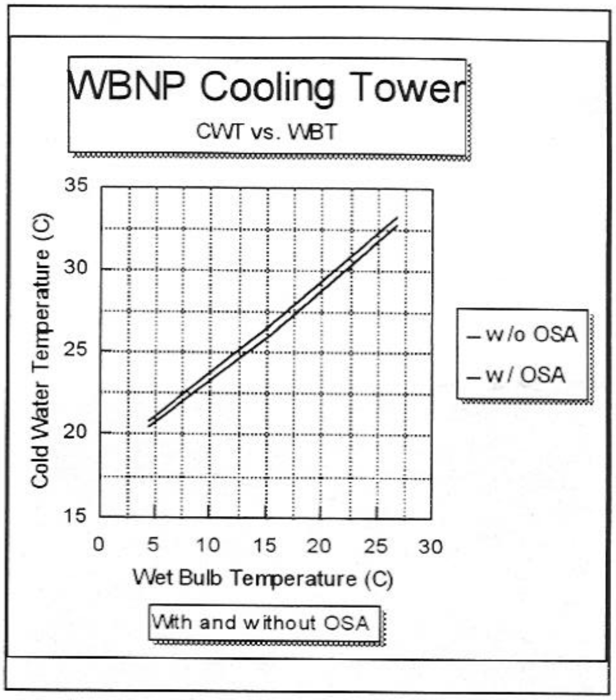

Figure 7