COOLING TOWER PERFORMANCE

C. F. Bowman, P.E.
Chuck Bowman Associates, Inc.
6500 Papermill Road, Suite 219
Knoxville, TN 37919

D. J. Benton, Ph.D.
Environmental Consulting Engineers
10938 Hardin Valley Road
Knoxville, TN 37932

Abstract

The performance of cooling towers is of great importance for the large number of nuclear plants that must rely upon cooling towers as their only means of waste heat rejection. Yet the performance of cooling towers have been problematic. Analytical tools to evaluate their performance have been developed and validated by test by the Electric Power Research Institute (EPRI), the Tennessee Valley Authority (TVA), and others. The wide-spread application of these tools to address cooling tower deficiencies can help nuclear power become more competitive. This paper discusses one of these tools, the Fast Analysis Cooling Tower Simulator (FACTS) computer code developed by TVA. The paper discusses the technical basis for FACTS and documents the various ways that the code has been validated. The paper shows how FACTS may be used to evaluate proposed modifications to improve the performance of the cooling towers such as those at TVA's Browns Ferry Nuclear Plant (BFNP) and Watts Bar Nuclear Plant (WBNP). The paper reports on a new approach to improving the performance of existing cooling towers, the Oriented Spray-Assisted Cooling Tower (OSACT), and shows how FACTS has been used to evaluate the improvement that may be expected with the OSACT design.

Purpose

The purpose of this paper is to discuss the impact that cooling tower performance has on nuclear plant efficiency and electrical output and to show how analytical tools such as FACTS may be used to address deficiencies in tooling tower performance.

Introduction

Cooling towers are relied upon to dissipate the waste heat all or part of the time at 28 of the active nuclear plant sites in the United States. Many of these plants can only operate in a closed mode where they must rely solely upon the performance of the cooling tower to cool the condenser circulating water (CCW) so that the main condenser can operate at a low back pressure (BP) and the turbine will operate efficiently. However, cooling tower performance has been notoriously problematic. The EPRI responded to these problems in cooling tower performance by conducting extensive tests [1] to validate analytical tools which may be used to evaluate cooling tower performance problems. One of these tools is the FACTS computer code which was developed by TVA [2]. The FACTS code is well documented and verified both by laboratory tests conducted by EPRI and TVA and by field acceptance tests conducted by TVA and other utilities on several types of cooling towers. However, this data has not been published in the open literature in a form that fully demonstrates the reliability and value of this important tool.

History of Cooling Tower Performance

The last comprehensive survey of utility cooling tower performance was conducted by the Tennessee Valley Authority in 1983 [3]. This survey which utilized information received from 49 questionnaires was restricted to cooling towers operating at power plant units of 500 megawatts and above. A total of 72 cooling towers including 39 mechanical draft, 32 natural draft, and 1 wet/dry were included in the survey. The extent of cooling tower thermal performance problems was indicated by results of performance testing. Acceptance tests were conducted on cooling towers which serve 81% of the installed capacity represented by the survey. Of those, 40% failed while 46% met or exceeded specifications, with counterflow towers reporting a significantly better record of success. As an indication of problems with cooling tower performance, 65% (megawatt-weighted) indicated that poor cooling tower performance resulted in decreased plant efficiency and 41% (megawatt-weighted) reported a loss in plant electrical output.

EPRI [1] evaluated the results of the TVA survey and concluded that the mean value of the performance of the cooling towers was estimated at 85%. This translates to a 2 to 2.5 ^{O}F increase in CCW temperature. EPRI reported on the results of cooling tower testing reported by the Cooling Tower Institute. These results indicated a trend toward improving the capabilities of cooling towers since the early 1970s. The lowest capabilities were reported for tests conducted in 1971 (about 65%). For the most recent year reported (1988) the measured capability was about 95% for new towers, but the results of tests performed on older towers during the same time period indicated an average capability of only 81%. EPRI defines capability as the percent of design water flow rate that can be cooled to the design cold water temperature at design conditions.

In recent years, a significant number of cooling towers have been repacked with film-fill packing. Although these film fills can result in substantial improvement in performance, fouling of these fills, if left unchecked, reverse performance gains from the tower upgrade and add substantially to cooling tower structural loading [4]. As a result, in recent years considerable emphasis has been placed on controlling CCW chemistry to avoid cooling tower fill fouling.

Impact of Cooling Tower Performance

In some instances the cooling towers have been added to the plant design to help comply with environmental limits and the cooling tower performance does not directly impact the CCW temperature. However, in the vast majority of the cases, the cooling tower is an integral part of a closed cycle heat rejection system (HRS), and the cooling tower performance directly impacts the plant performance.

The Carnot efficiency of any closed heat cycle is a function of the following:

$$\acute{\eta}_{\text{Carnot}} = (T_H - T_L) / T_H \tag{1}$$

where T_H and T_L are the absolute temperatures of the heat source and heat sink, respectively. In the case of a power plant operating on a Rankine cycle, T_L is the saturation temperature of the condenser which is determined by the condenser BP. Bowman [5] showed the relationship between the CCW temperature entering the condenser and the condenser BP and the electrical output for the TVA's BFNP when operating at 100% thermal power input.

Since the cold water temperature (CWT), leaving the cooling tower (entering the main condenser) is one of the important parameters which establish the condenser BP, the ambient wet bulb temperature (WBT) and the cooling tower performance are very important parameters because they directly affect the CWT and, therefore, the maximum possible heat cycle efficiency and electrical output. Figure 1 shows the effects that ambient WBT and the cooling tower performance have on electrical output for the TVA's WBNP [6]. Watts Bar is a 1160 megawatt electrical (MWE) pressurized water reactor (PWR) nuclear plant located in east Tennessee. The

Table 1: Impact of 5.5 In. Hga. BP Limit on MWE

	No BP Limit			BP limited to 5.5 In. Hga.		
WBT	CWT	BP 3	MWE	CWT	BP 3	MWE
40	70.3	3.08	1212.3	70.3	3.08	1212.3
50	75.5	3.55	1204.2	75.5	3.55	1204.2
60	80.9	4.14	1193.6	80.9	4.14	1193.6
70	86.8	4.88	1180.2	86.8	4.88	1180.2
75	89.8	5.32	1172.3	89.8	5.32	1172.3
80	92.9	5.81	1163.6	92.9	5.50	1111.6
85	96.1	6.35	1154.1	96.1	5.50	1010.1
90	99.3	6.97	1143.7	99.3	5.50	898.8

WBNP HRS consists of 4 CCW pumps, a triple-pressure condenser fitted with an on-line ball cleaning system, a counter-flow natural draft cooling tower, and associated piping and valves. The CCW pumps deliver a total flow of 420,000 gpm. Figure 1 shows the expected generator output in MWE and the BP in the third zone of the condenser for an array of cooling tower performance percentages and for the cooling tower performance as predicted by FACTS. However, as is the case with many nuclear plants, the WBNP condenser BP must be limited due to turbine design considerations. The WBNP condenser BP is limited to 5.5 inch Hga pressure. Figure 2 shows the impact that this limitation imposes on generator output. This limitation means that cooling tower performance is even more important at high WBT. Table I shows the relationships among the WBT, CWT, condenser BP in the third zone, and the generator output based on the FACTS model with and without BP limitations. It may be seen that at high WBT values, a reduction in the CWT of 1 °F will result in an increase in generator output of 3 MWE with no BP limitations and 32 MWE when the BP must be limited to 5.5 inches Hga.

Fast Analysis Cooling Tower Simulator (FACTS)

Technical Basis for FACTS

Theoretical Development of FACTS. FACTS is a computer model of the simultaneous heat, mass, and momentum transfer processes occurring throughout a cooling tower. The heat transfer within an evaporative cooling tower may be expressed in terms of the sensible and evaporative (or latent) heat transfer. For sensible heat transfer,

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

where

dQ_s = differential sensible-heat transfer rate
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

$$B = (f_S - f) / (1 - f_S) \tag{4}$$

where

f = mass fraction of water in the far field
f_S = mass fraction of the water at the interface (assumed to be saturated)

In the case of mixtures of air and water vapor,

$$f = \omega / (1 + \omega) \tag{5}$$

where

ω = absolute humidity.

By combining terms,

$$dE = K\, [(\omega_S - \omega) / (1 + \omega)]\, dA_i \tag{6}$$

where

ω_S = absolute humidity at saturation

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

$$dQ_e = h_g \, dE \tag{7}$$

where

dQ_e = differential latent heat transfer rate
h_g = enthalpy of saturated water vapor

The sum of the differential sensible- and latent-heat transfer rates is the differential total heat transfer rate, dQ_t

$$dQ_t = dQ_s + dQ_e \tag{8}$$

The differential total heat transfer rate is also related to the temperature change of the water, the constant-pressure specific heat of the water, and mass flow rate of the water by the conservation of energy principal,

$$dQ_t = -d(L \, c_{Pw} \, dt_w) \tag{9}$$

where

L = mass flow rate of water
c_{Pw} = constant-pressure specific heat of water
dt_w = differential temperature change.

The differential interface area, dA_i, within a differential volume dx, dy, dz, of the fill is expressed as,

$$dA_i = a \, dx \, dy \, dz \tag{10}$$

where

a = interface area per unit volume.

The three equations of interest are then,

$$dQ_s = Ha \, (t_W - t_{db}) \, dx \, dy \, dz \tag{11}$$

$$dE = Ka \, [(\omega_S - \omega)/(1+\omega)] \, dx \, dy \, d \tag{12}$$

$$dQ_e = h_g \; Ka \; [(\omega_S - \omega)/(1+\omega)] \, dx \, dy \, dz \tag{13}$$

The FACTS model is based on the conservation of the mass of air and the mass of water vapor as well as the conservation of the energy for the gas phase and the 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,

$$p_1 + \rho_1 V^2{}_1/2g_c + \rho_1 g y_1/g_c = p_2 + \rho_2 V^2{}_2/2g_c + \rho_2 g y_2/g_c + \text{losses} \qquad (14)$$

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

These equations are applied in their steady-state, steady-flow form. The independent variables are the horizontal distance, x, vertical distance, y, and total mass flow rate of water, L, inlet water temperature, t_h, 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, h_a, the water temperature, and pressure. The wet-bulb temperature, t_{wb}, and dry-bulb temperature, are determined using the following thermodynamic relationships for air-water vapor mixtures from computed values of ω , h_a, and p [7]:

$$h_a = \int_0^{t_{as}} c_{Pa}\, dt + \omega_S\, h_g \qquad (15)$$

where

t_{as} = adiabatic saturation temperature which is assumed to be equivalent to the wet-bulb temperature
c_{Pa} = constant-pressure specific heat of dry air

and

$$h_a = \int_0^{t_{db}} c_{Pa}\, dt + \omega\, h_g \qquad (16)$$

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

$$\iiint Ka[(\omega_S - \omega)/(1+\omega)]\, dx\, dy\, dz = \iint [\omega\rho/(1+\omega)]\, V{*}dA \qquad (17)$$

where V*dA is the dot product of the two vectors V and dA. The conservation of energy for the air within a control volume is

$$\iiint \{h_g\, Ka[(\omega_S - \omega)/(1+\omega)] + Ha(t_W - t_{db})\}\, dx\, dy\, dz = \iint [h_a \rho/(1+\omega)]\, V{*}dA \qquad (18)$$

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

$$L\, c_{pw}\, dt_w = -\int\int\int\{h_g\, Ka[(\omega_S - \omega)/(1+\omega)] + Ha(t_W - t_{db})\}dx\, dy\, dz \qquad (19)$$

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 waterflow. These average values are used with the one-dimensional integral conservation equations.

For crossflow towers, the airflow 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.

Modeling Assumptions. The assumptions made in the FACTS code are discussed in References (1) and (2). FACTS is a steady-state, steady-flow model. It is more sophisticated than a one-dimensional model, yet it contains simplifications which 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 (e.g. in the case of a natural draft cooling tower, the enthalpy of the air is constant in the chimney.)
4. The atmosphere around the a natural draft cooling tower is isentropic.
5. The water flows vertically downward.
6. Evaporation loss is neglected in the water mass balance

Model Capabilities. The specified inlet conditions of both air and water (temperatures and flows) can vary across the inlet plane. 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.

Validation of FACTS

FACTS has been the subject of extensive validation efforts by TVA[8,9], EPRI[1,10], and other utilities. 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. 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.[10] EPRI contracted with Thermatec to test several fills at their Santa Rosa, California test facility. The performance of the cement-asbestos board (CAB) fill material which was commonly used in early counterflow towers was tested at three fill heights and two fill sheet spacings. The tests were conducted at several water flow rates and air flow rates. A data reduction program, FACTR, based on FACTS was used to calculate the mass transfer characteristics from the raw data using the relationship,

$$Ka/L'' = C\,(L/G)^{n} \tag{20}$$

where

L'' = water flow rate per unit area
G = air flow rate
C = constant
n = constant

FACTS treats the rain zone of counterflow cooling towers similar to fill material. TVA conducted tests of the heat transfer in the rain zone. This study concluded that the mass transfer coefficient for the rain zone is approximately 14 to 25 % of that for CAB and 10 to 44% of that for splash bars.[9]

The validity of 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 BFNP, Sequoyah Nuclear Plant (SNP), and Paradise Steam Plant (PSP) are crossflow mechanical draft, crossflow natural draft, and counterflow natural draft, respectively. The results of these tests are shown in Figure 3. The fill characteristics used in the FACTS model for these comparisons were taken from published values[11], and no calibration of the model was used in making the predictions.

In 1989 EPRI published the results of the Cooling Tower Performance Prediction and Improvement (CTPPI) project[1] in which heat and mass transfer coefficients and pressure drop data were obtained for eight crossflow and eight counterflow commercial fills in an engineering-scale facility that was 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. Three correlations were used:

(1) $Ka/L'' = C(L^+/G^+)^{n_1}$

(2) $Ka/L'' = C(L^+)^{n_2} (G^+)^{n_3}$

(3) $Ka/L'' = C(L^+)^{n_2} (G^+)^{n_3} (T^+)^{n_4}$

where

$L^+ = L / L_O$

$G^+ = G / G_O$

and L_O and G_O are reference values, making L^+ and G^+ dimensionless. For counterflow fills, an additional parameter, air travel distance, ATD, was included in all correlation forms with the exponent, n_5 , because the performance of counterflow fills is dependent upon the fill depth. The comparison between measured and computed CWT for 4 of the most common fills tested for each of the 3 correlations is shown on Figures 4 - 9. The FACTS code predicted the CWT to within 0.69 ^{O}F of the measured value on average. FACTS performed best with Correlation 1 in the crossflow towers, but the results improved somewhat with Correlation 2 in the counterflow towers.

Evaluation of Cooling Towers with FACTS

FACTS has been used not only to predict the performance of existing cooling tower designs but also to evaluate proposed modifications of existing cooling towers to improve their performance. EPRI[1] reported on two instances in which FACTS has been used to evaluate proposed cooling tower modifications and then those predictions were compared with actual test data after the modification was implemented.

In the first instance, a ring of plastic film-type packing was added above existing sheets of CAB in a counterflow cooling tower. The original CAB was arranged in the typical "stadium" shape in which there were 7 tiers at the periphery which stepped down to 4 tiers at the center. This arrangement is frequently used to achieve approximately uniform air flow through the fill. The plastic film-type packing was placed in a "doughnut ring" on top of the PVC near the outer periphery and on top of the 6th tier such that the new packing was flush with the 7th tier. When the FACTS model was run for this arrangement, the fill characteristic for the appropriate fill material was specified at each node. FACTS predicted that the additional fill material would reduce the CWT from 87.9 ^{O}F to 85.2 ^{O}F at a WBT of 60 ^{O}F. EPRI reported that field test results for this situation have verified this prediction in improved performance.

In a second instance reported by EPRI[1], a film-type fill was inserted as diagonal fill wedges into a crossflow mechanical draft cooling tower. This design, shown in Figure 10,[12] effectively converts a portion of a crossflow tower into a counterflow. This design was implemented at one of the TVA's BFNP cooling towers and was tested along side of an identical cooling tower without the modification in 1980. The FACTS code later analyzed both cooling towers without reference to the results of the field tests. The results of this analysis is shown in Figure 3 as BFN (HYBRID). It may be seen that the uncertainty in the model results are essentially the same for the modified (HYBRID) tower as for the unmodified tower even though the fill was nonuniform.

TVA utilized FACTS in a recent study to evaluate the WBNP Unit 1 cooling tower.[6] As shown in Figure 2, FACTS predicts that this tower will prove to be short of predicted performance with an actual performance of about 90% of design. The actual deficiency varying as a function of wet bulb temperature. The effect of this deficiency is to move the "Knee" of the curve shown in Figure 2 to a lower wet bulb temperature such that reductions in electrical output due to BP limitations will occur more frequently than expected. In addition, there will be a loss of 4-5 MWE throughout the year when the unit is not limited by BP due to the warmer CCW. TVA investigated several alternative modifications to the heat rejection system at WBNP using the FACTS code. Some of the alternatives considered included repacking the existing cooling tower with a film-type fill, adding 2 feet of film-type fill on top of the existing CAB fill over approximately 80% of the plan area of the cooling tower, add a supplemental mechanical draft cooling tower, and converting the existing cooling tower into an OSACT. Each of these alternatives were shown to have advantages and disadvantages. FACTS predicted an improvement in performance of 32% by repacking the existing cooling towers, but at a very high capital cost. Both alternatives which involved the new film-type fill required an expensive chemical treatment of the CCW to prevent plugging of the fill due to the accumulation of bacterial slime and silt. Adding supplemental mechanical draft cooling tower is not only very expensive, but also requires CCW treatment and increases the auxiliary power requirement. Converting the cooling tower ot an OSACT is relatively inexpensive and does not require chemical treatment of the CCW, but it is a new technology.

Oriented Spray-Assisted Cooling Tower

The authors have developed a version of FACTS which models the patented OSACT[13]. The OSACT is a new, revolutionary approach to cooling tower design which may be applied either to new or existing cooling towers. The OSACT design, shown in Figure 11, diverts a portion of the total amount of 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.

To quantify the improvement in performance with the OSACT, a version of FACTS was created which computes the performance of the 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. An input file is required which defines the air temperature and velocity as it exits from the sprays. These values are calculated using a thermal model developed by TVA to analyze oriented spray cooling ponds for ultimate heat sink applications.[14] This model has been thoroughly validated against both experimental data and full scale field test data.[15, 16] The actual improvement in performance with the OSACT design varies depending upon the cooling tower design. For the WBNP cooling tower design, approximately 13% of the CCW flow would be diverted to spray trees, and the L/G ratio would be reduced by approximately 20%. The resulting improvement in CWT as shown in Figure 12 is approximately 1 °F.

Conclusion

For those nuclear plants where the cooling tower is an integral part of a closed cycle heat rejection system, the performance of the cooling tower places a thermodynamic limit on the thermal efficiency of the plant, since it defines the heat sink temperature. However, the thermal performance of this important component can be problematic. EPRI has aggressively addressed this issue by conducting tests of fill materials which have been useful to validate analytical tools such as FACTS which have proven useful in evaluating cooling tower performance and proposed modifications to cooling towers to improve performance. The FACTS model has been validated not only with engineering-scale test facilities but also by comparison with acceptance tests which have been performed on a number of cooling towers. A modified version of FACTS has been used to predict the performance of the OSACT which may be back-fitted to improve the performance of existing cooling towers without requiring fill replacement or expensive chemical treatment of the CCW. These tools should be utilized to improve the thermal performance of these plants to help keep nuclear energy a viable, competitive energy option.

References

(1) *Cooling Tower Performance Prediction and Improvement,* Palo Alto, Calif.: Electric Power Research Institute, 1989. GS-6370. [report]

(2) Benton, D, J., *A Numerical Simulation of Heat Transfer in Evaporative Cooling Towers,* Norris, Tenn.: Tennessee Valley Authority, September 1983. WR28-1-900-100. [report]

(3) Boroughs, R. D., and J. E. Terrell, *A Survey of Utility Cooling Towers*, Chattanooga, Tenn.: Tennessee Valley Authority, April 1983. TVA/OP/EDT-83/13. [report]

(4) Mortensen, K. P. and S. N. Conley, "Film Fill Fouling in Counterflow Cooling Towers: Mechanism and Design", CTI Journal, Vol. 15, No. 2, Summer 1994, Cooling Tower Institute, Houston, Texas.

(5) Bowman, C.F., "Heat Balance Models Improve Thermal Performance Monitoring", EPRI-P^2EP Nuclear Plant Performance Improvement Seminar, May 1993, Electric Power Research Institute, Palo Alto, California.

(6) Benton, D.J., *Results of Analysis of the Watts Bar Nuclear Plant Heat Rejection System,* Norris, Tenn.: Tennessee Valley Authority, April 1992. WR28-2-85-136. [report]

(7) Van Wylen, G.J. and R. E. Sonntag, Fundamentals of Classical Thermodynamics 2nd Ed., Wiley, New York, 1973.

(8) Benton, D. J., and W. R. Waldrop, *Computer Simulation of Transport Phenomena in Evaporative Cooling Towers,* Norris, Tenn.: Tennessee Valley Authority, March 1985. WR28-1-900-141. [report]

(9) Brackett, C. A. and J. R. Missimer, *Results of Model Tests of Heat Transfer in the Rain Zone of a Counterflow Natural Draft Cooling Tower,* Norris, Tenn.: Tennessee Valley Authority, March 1985. WR28-1-900-141. [report]

(10) Rehberg, R. L., *Thermal Performance of Cement-Asbestos Cooling Tower Fill in an Experimental Test Facility*, Norris, Tenn.: Tennessee Valley Authority, February, 1985. WR28-1-900-152. [report]

(11) Majumdar, A. K., and A. K. Singhal, *VERA2D-A Computer Program for Two-Dimensional Analysis of Flow, Heat and Mass Transfer in Evaporative Cooling Towers,* Volume II-User's Manual, 1981, Electric Power Research Institute, Palo Alto, California.

(12) Phelps, P. M., *Sloped Film Fill Assembly Cooling Tower,* U. S. Patent No. 3,917,764, Nov. 4, 1975, The United States Patent and Trademark Office, Washington, D. C.

(13) Bowman, C. F., *Oriented Spray-Assisted Cooling Tower*, U. S. Patent No. 5,407,606, Apr. 18, 1995, The United States Patent and Trademark Office, Washington, D. C.

(14) Berger, M. H. and Taylor, R. E., "An Atmospheric Spray Cooling Model," In *Environmental Effects of Atmospheric Heat/Moisture Release: Cool Towers, Cool ponds and Area Sources; Proceedings of the 2nd AIAA/ASME Thermophysics and Heat Transfer Conference, Palo Alto, CA, May 24-26, 1978,* 59-64. New York: American Society of Mechanical Engineers, 1978.

(15) Bowman, C. F., Smith, D. M., and Davidson, J. S., "Application of the TVA Spray Pond Model to Steady-State and Transient Heat Dissipation Problems," Proceedings of the American Power Conference, Volume 43, 1981.

(16) Bowman, C. F., "Analysis of the Spray Pond Ultimate Heat Sink for the Advanced Boiling Water Reactor", Proceedings of the American Power Conference, Volume 56, 1994.

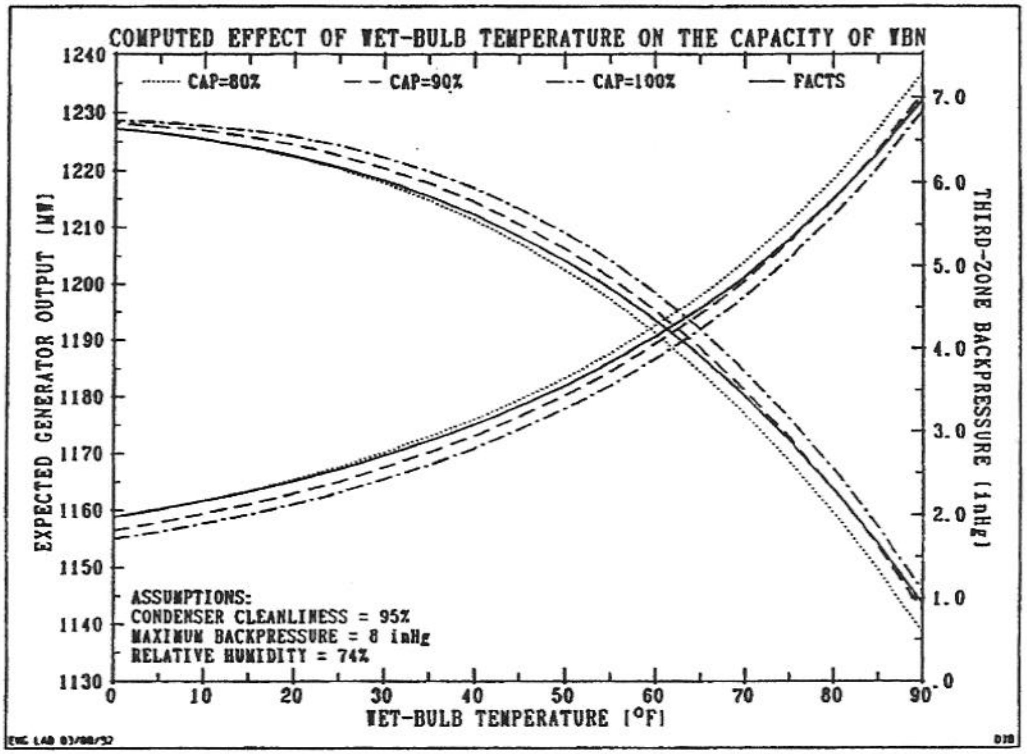

Figure 1

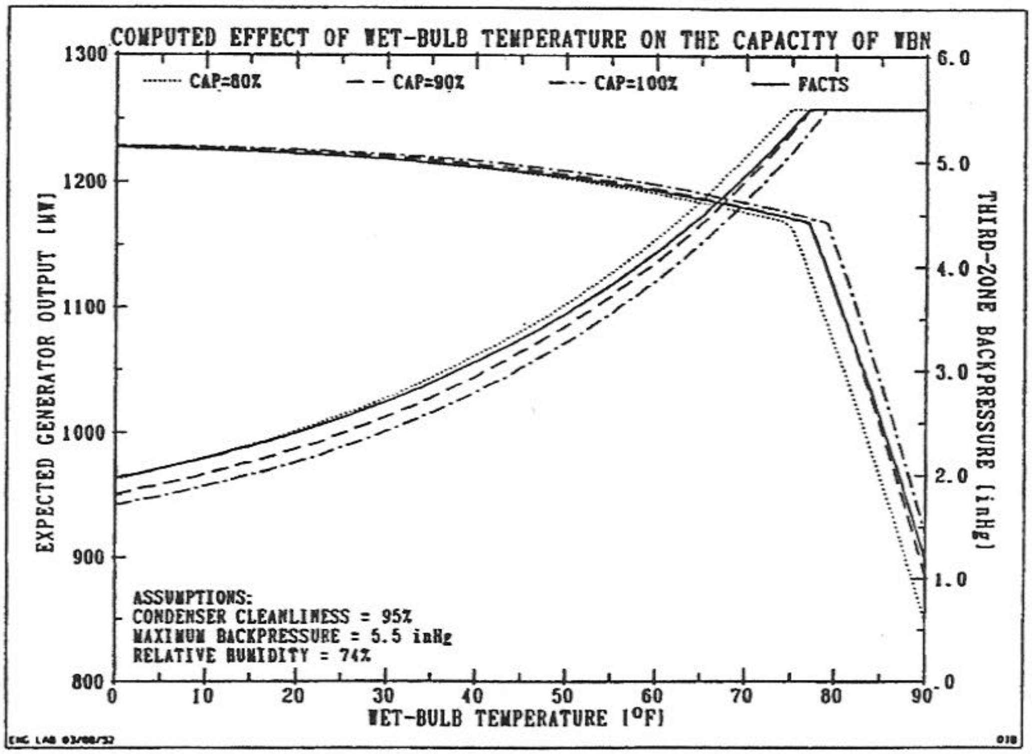

Figure 2

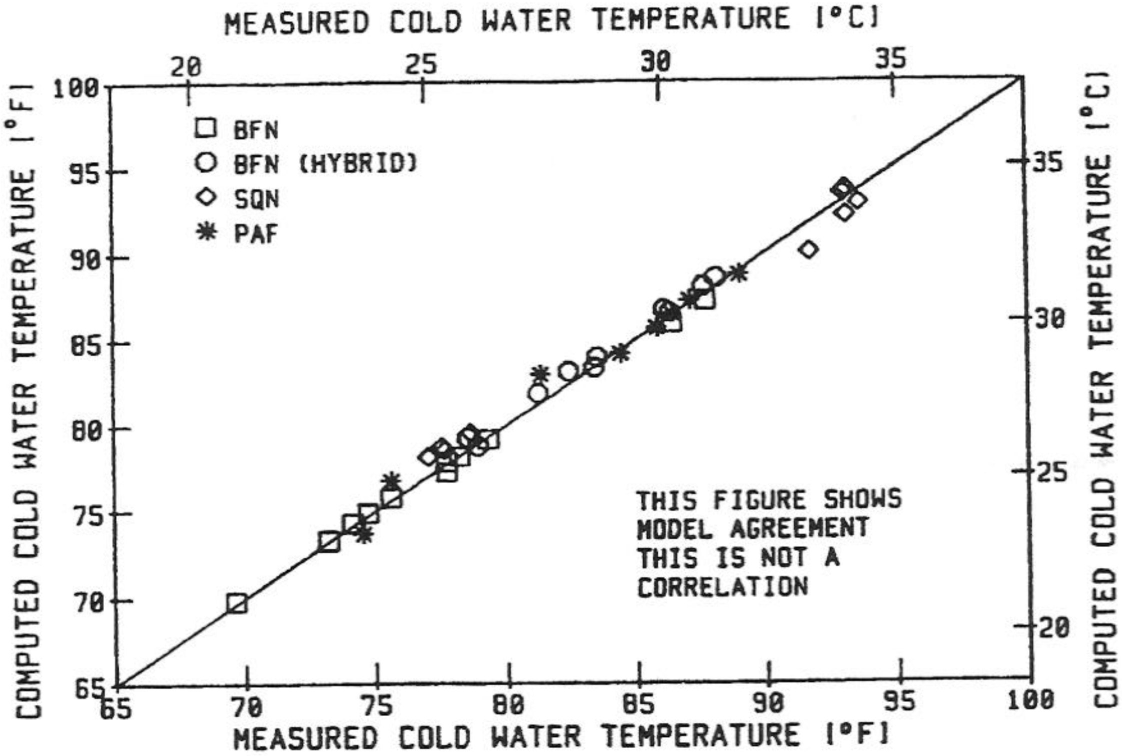

Figure 3

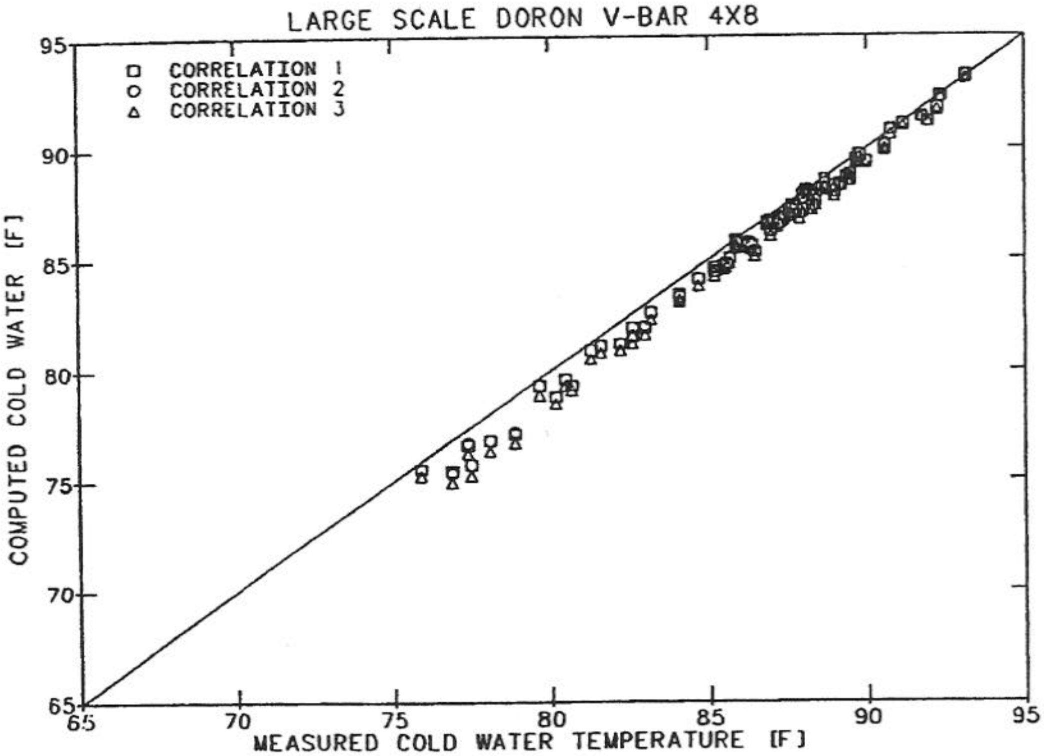

Figure 4

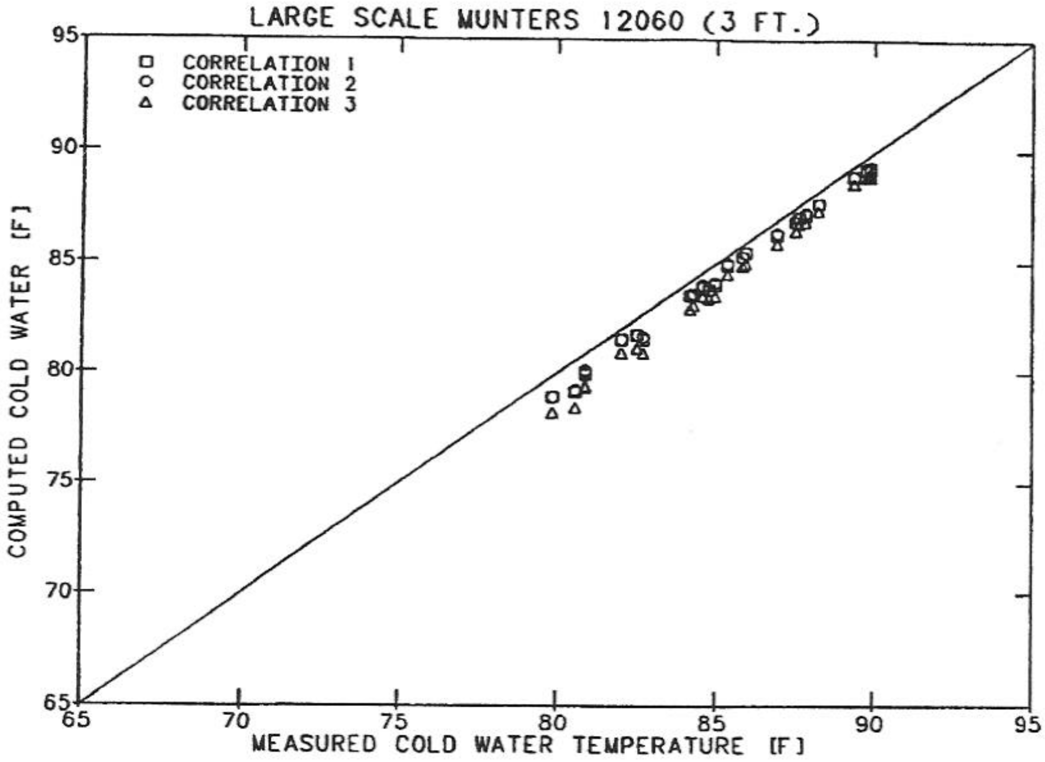

Figure 5

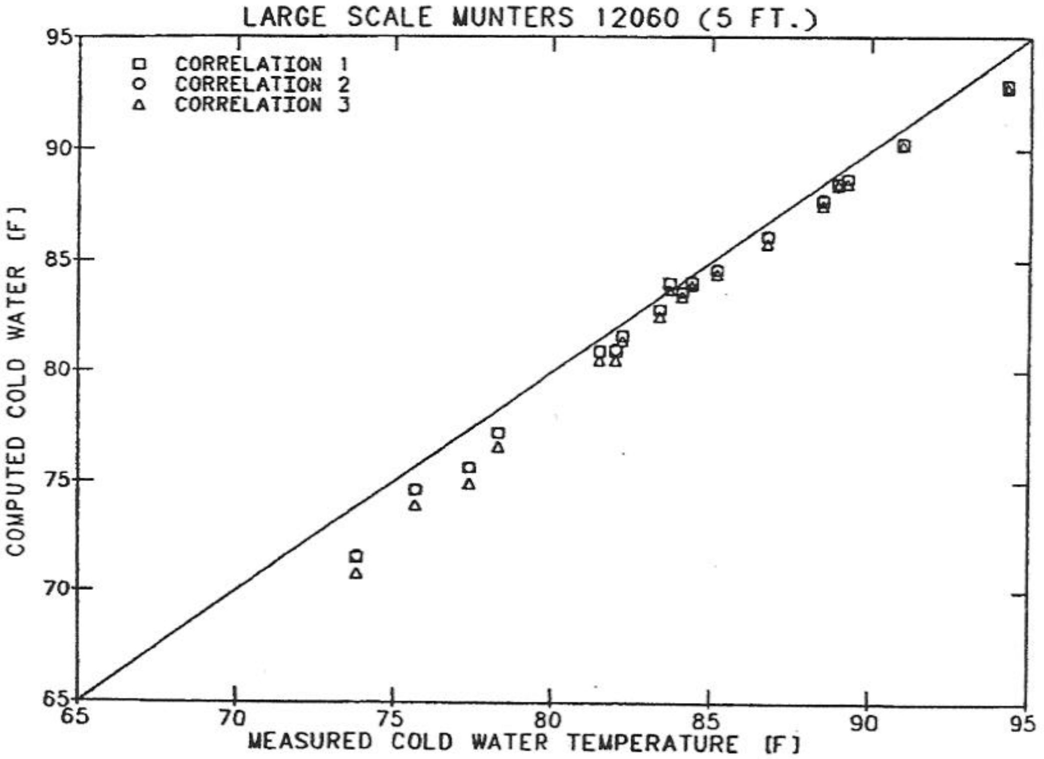

Figure 6

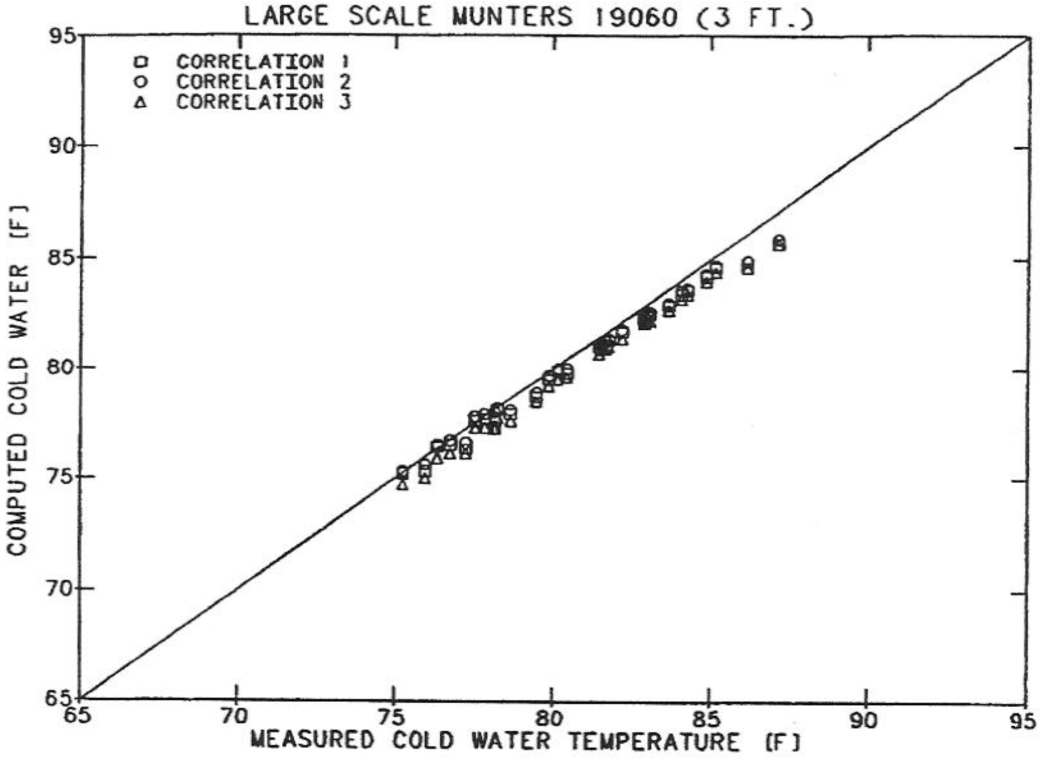

Figure 7

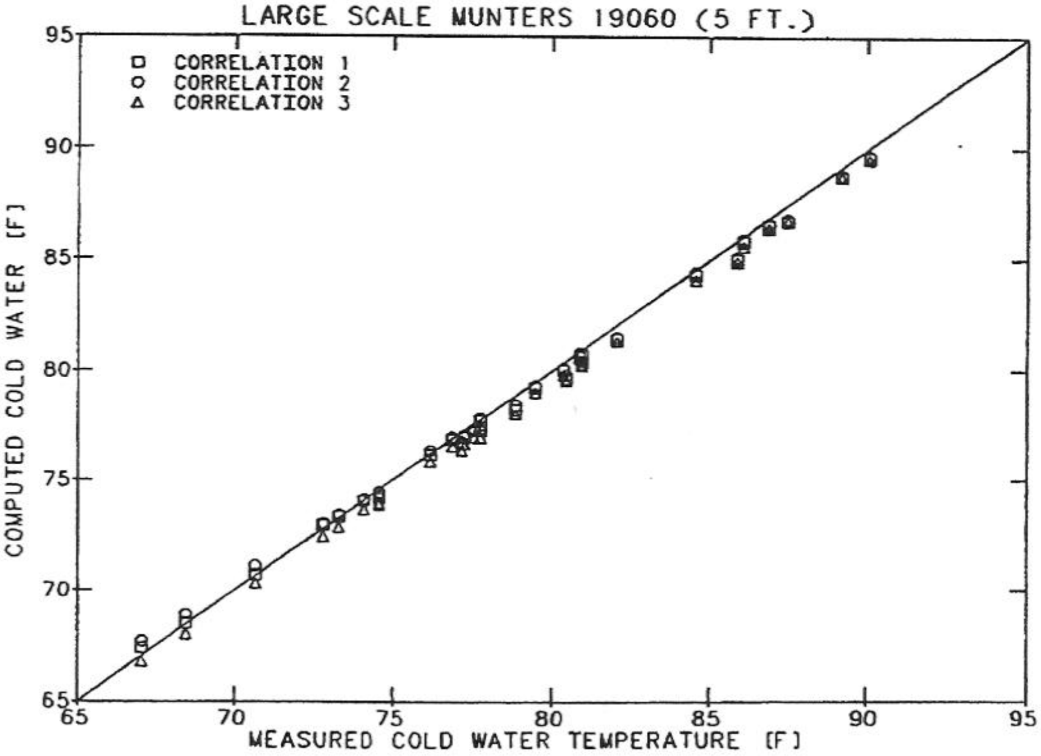

Figure 8

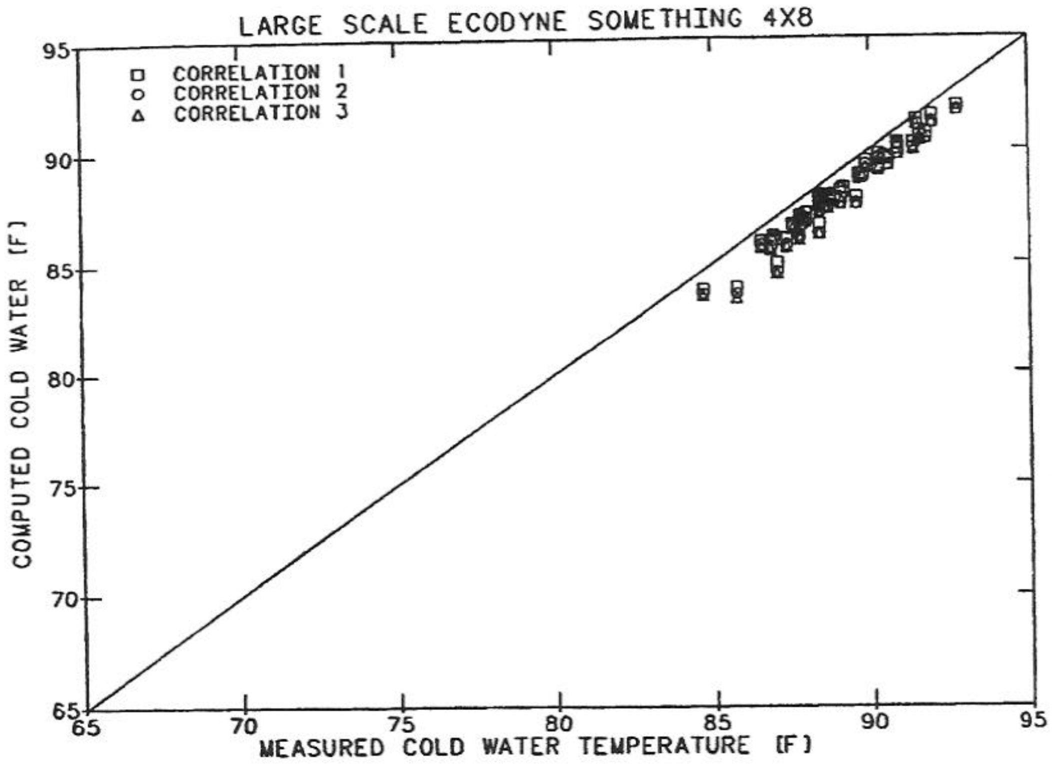

Figure 9

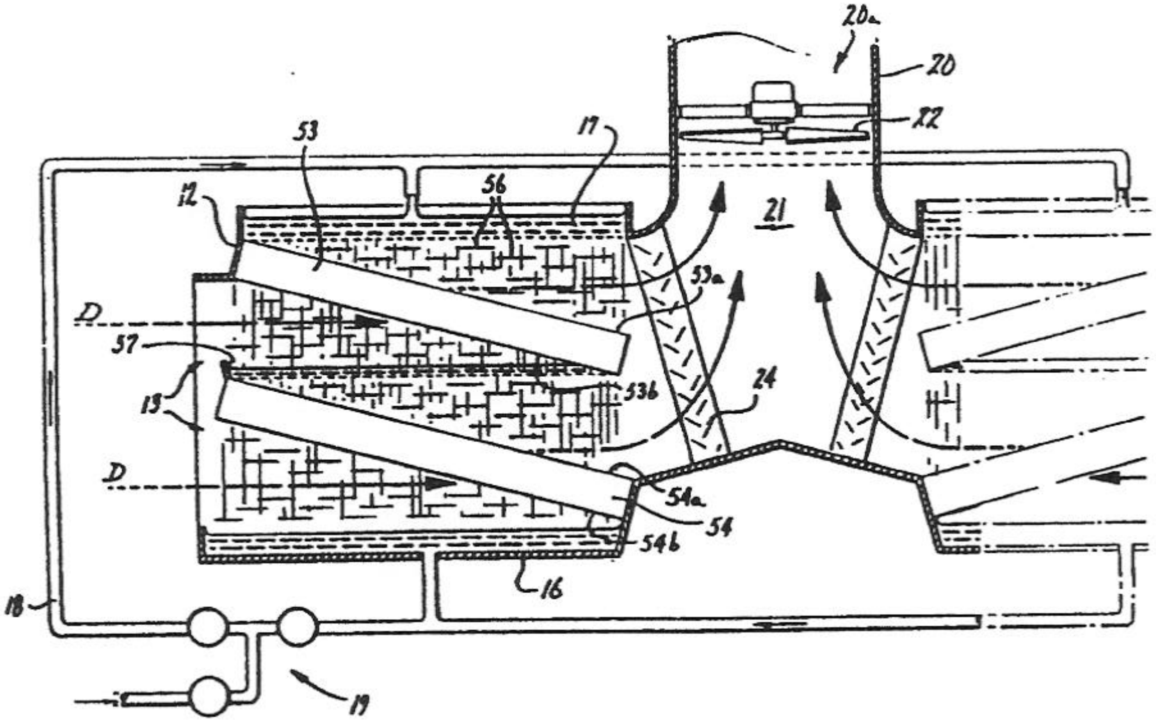

Figure 10

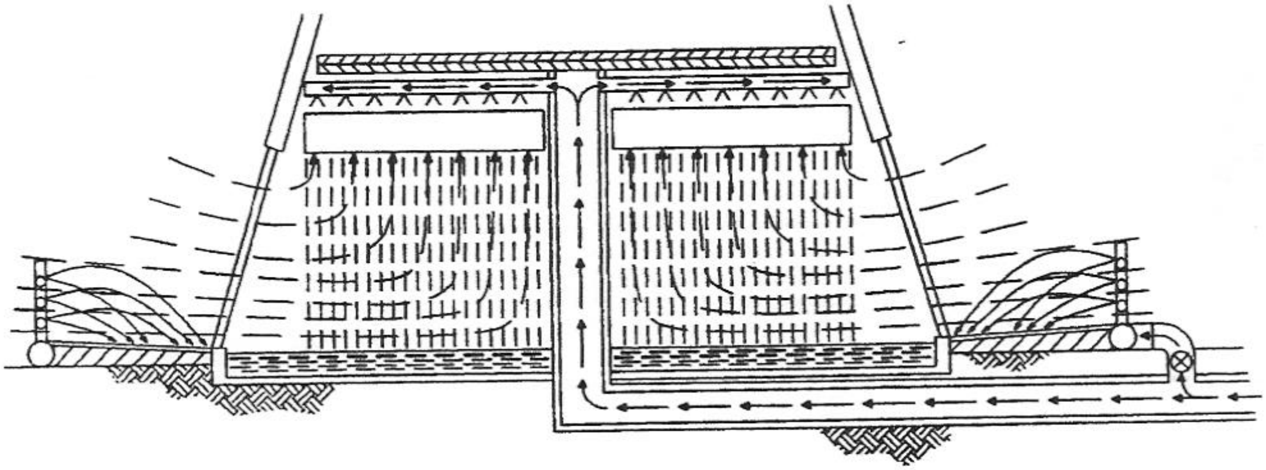

Figure 11

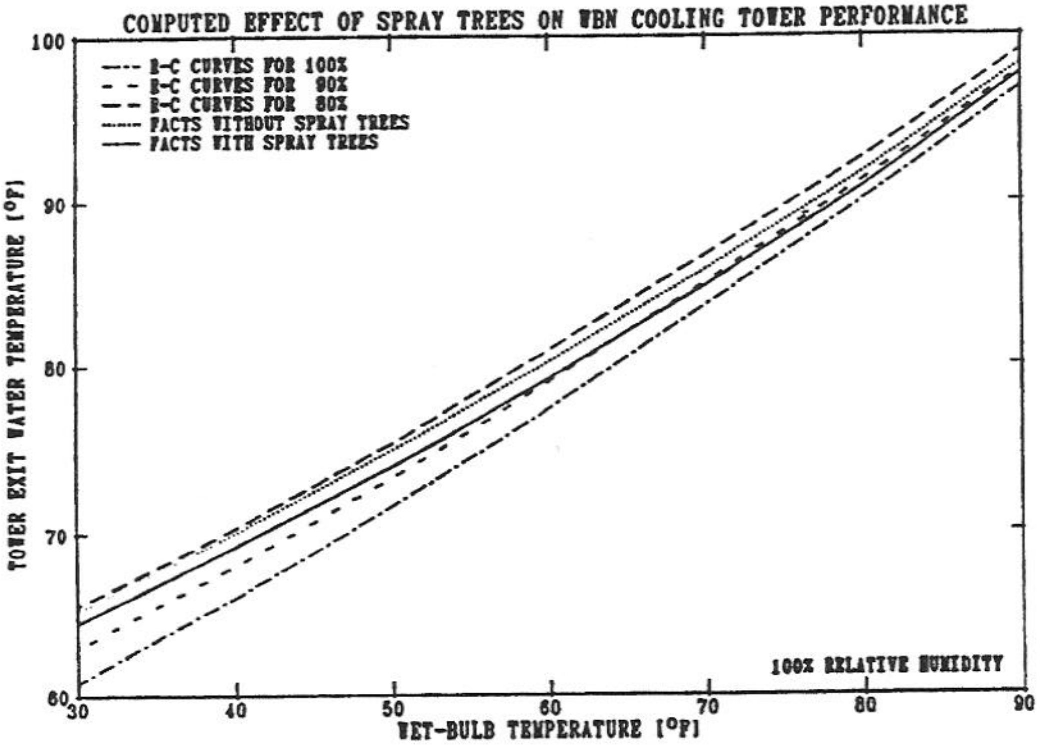

Figure 12