Cooling Tower Fan Motor Power Optimization Study

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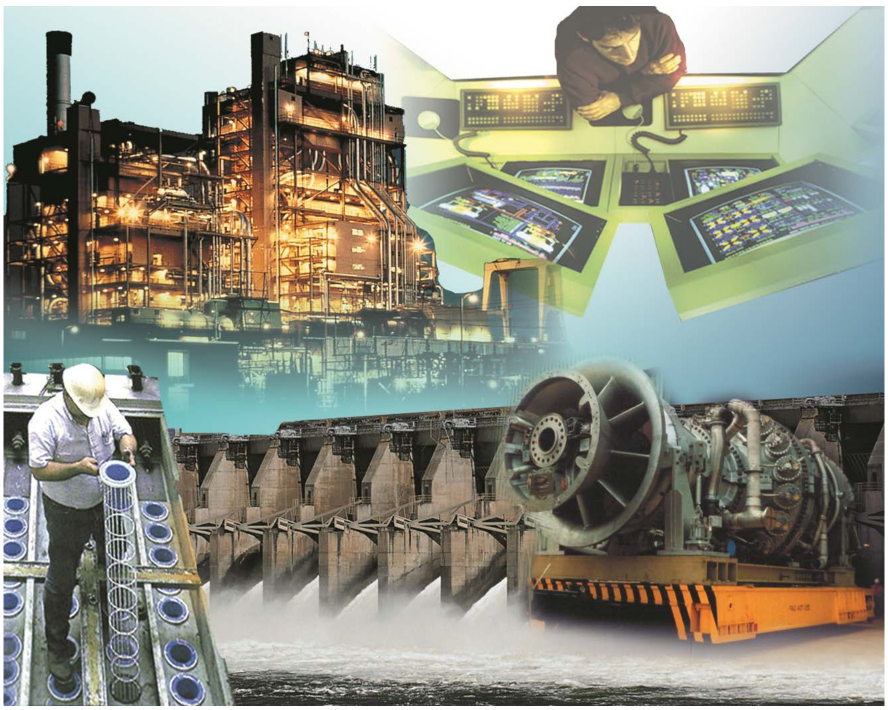

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Technical Update, November 2011

EPRI Project Manager

J. Stallings

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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CleanAir Engineering
7936 Conner Road
Powell, TN 37849-3513

Principal Investigators
D. Wheeler
M. Womack

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ABSTRACT

Cooling towers are in use at more than 200 major electric generating plants in the United States, representing approximately 800 units and a total of more than 210,000 MW. The auxiliary power consumed by cooling tower fan motors can significantly reduce the net power output of steam-cycle power plants. Cooling tower specifications are established by the economic and operational requirements of maximum unit load and the most demanding environmental conditions expected in the tower's locale. Since power plants frequently operate at less than maximum load—and the normal environmental conditions are more moderate than specified—cooling tower auxiliary power consumption could be decreased by reducing power input to fan motors. Under most conditions, the consequent increase in cooling water temperature reduces power output of the steam turbine by increasing condenser backpressure. However, if the reduction in auxiliary power is greater than the effect on turbine output, then a net positive change in unit output is the result.

For this study, a method for evaluating cooling tower control strategies was developed to estimate the effect (in terms of plant output and heat rate) of changing the operation of the plant cooling cycle, in particular, cooling tower fans. The specific operating scenarios examined were: 1) shutting off cooling tower fan(s) when possible, 2) using variable frequency drives (VFDs) on cooling tower fans to control fan speed and consequently cooling water temperature, and 3) using two-speed motors to control fan speed.

A number of beneficial outcomes were discovered, and any of the three control schemes would be advantageous under certain ambient and load conditions. The report describes specific calculations made to estimate the effects of the control strategies on three power plants at Southern Company, the host utility for this study. In addition, the report discusses general trends with respect to both ambient and load conditions as well as costs and implementation problems for each control strategy.

Keywords

Cooling Towers
Cooling Tower Fan Motor
Cooling Tower Control Strategies
Plant Cooling Cycle

EXECUTIVE SUMMARY

The auxiliary power consumed by cooling tower fan motors can represent a significant reduction in the net power output of steam-cycle power plants. The specifications for the cooling towers used in most power plants are established by the economic and operational requirements of maximum unit load and the most demanding environmental conditions expected in the locale. Since power plants are frequently operated at less than maximum load, and the normal environmental conditions are more moderate than specified, the cooling tower auxiliary power consumption could be reduced by reducing the power input to the fan motors. Under most conditions, the consequent increase in cooling water temperature results in a reduction in the power output of the steam turbine by increasing condenser backpressure. However, if the reduction in auxiliary power is greater than the effect on turbine output then a net positive change in unit output is the result.

For this study a methodology for evaluation of cooling tower control strategies was developed to estimate the effect (in terms of plant output and heat rate) of changing the operation of the plant cooling cycle, in particular the cooling tower fans. The specific operating scenarios examined were: 1) shutting off cooling tower fan(s) when possible; 2) using variable-frequency drives (VFD) on cooling tower fans to control fan speed and consequently cooling water temperature; and, 3) using two-speed motors to control fan speed.

A number of beneficial cases were found, and any of the three control schemes would be beneficial under certain ambient and load conditions. Specific calculations were made to estimate the effects of the control strategies on three Southern Company (the host utility for this study) power plants, and general trends are stated with respect to ambient and load conditions.

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1 INTRODUCTION

1.1 Scope of Work

The auxiliary power consumed by cooling tower fan motors can represent a significant reduction in the net power output of steam-cycle power plants. The specifications for the cooling towers used in most power plants are established by the economic and operational requirements of maximum unit load and the most demanding environmental conditions expected in the locale. Since power plants are frequently operated at less than maximum load, and the normal environmental conditions are more moderate than specified, the cooling tower auxiliary power consumption would be reduced by reducing the power input to the fan motors. Under most conditions, the consequent increase in cooling water temperature results in a reduction in the power output of the steam turbine (by increasing condenser backpressure). However, if the reduction in auxiliary power is greater than the effect on turbine output then a net positive change in unit output is the result.

This study develops a methodology for evaluation of three different control strategies for reducing the fan motor power based on their effect on the unit net power output and heat rate. The methodology is illustrated by examining the effectiveness at three power plants operated by Southern Company, the sponsoring utility for this study, at different conditions of ambient wet-bulb temperature and different unit loads. The load profile and wet-bulb frequency at each of these sites was examined to develop an estimate of the annual savings at each of the plants for each of the three control strategies. Finally, costs and implementation problems for each of the control strategies are discussed.

1.2 Applicability of Results

The methodology for evaluation of cooling tower control strategies, presented herein, is applicable to power plants with one or more steam turbine(s) exhausting low-pressure steam to a surface condenser, and which utilize closed-loop cooling via mechanical-draft cooling tower(s). For this study, units having either counterflow or crossflow cooling tower designs were included. Of the two subject units with counterflow towers, one was a low-temperature range, single-pressure condenser system, and the other was a high-range, two-pressure condenser system. The steam turbines ranged in size from 192 MW_e to 900MW_e.

The cooling towers examined in this study have single-speed, axial-flow, induced-draft fans. In all cases, standard 4-pole induction motors drive the fans via speed-reducing gearboxes. While the fans have variable-pitch blades, it is impractical to adjust the pitch seasonally. Therefore, the only fan control strategy currently available is to shut off power to one or more fan motor(s). However, this study also examined the effectiveness of installing either variable-frequency drive (VFD) controls or retrofitting two-speed motors and dual associated motor controls.

1.3 Air Flow Control Mechanisms

For the purposes of this study three types of cooling tower air flow control were examined:

1. De-energize Fan Motor(s) – Using the existing motors and switchgear, de-energize fan motors as needed to effect a change in the cold water temperature and condenser pressure given the prevailing conditions. Note that the water flow would be left on the idle cell(s); however, the cooling effect of the idle cells is considered negligible for this study. The auxiliary power savings would equal the normal motor power consumption rate times the number of idle cells.
2. Variable-Speed Motor Control – Assumes the installation of variable-frequency drives (VFD) to permit variable-speed cooling fan operation over the calculated speed control range for all cells of the tower. Bypass switchgear would be available for operating at 100% fan speed when warranted by conditions. However, when operating at reduced fan speed, the auxiliary power consumption of the cooling tower would be reduced proportionate to the cube of the fan speed.
3. Reduced-Speed Motor Control (Two-Speed Motors) – Assumes the installation of two-speed motors (100%/50%) and necessary switchgear to permit reduced-speed operation of one, or more, cooling tower fan motors as needed. The cooling effect of the low-speed fans would be reduced, but the auxiliary power consumption of these cells would also be reduced proportionate to the cube of the fan speed.

1.4 Technical Basis of the Study

For mechanical-draft cooling towers the cold water temperature varies with respect to the ambient (inlet) conditions, most strongly with the inlet wet-bulb temperature, but also with respect to cooling air flow, process water flow and heat load. For this study, water flow was left constant while the cold water temperature was calculated using inlet conditions ranging from 85º F_{WB} to 35º F_{WB}. Next, this calculation was repeated while varying the cooling air flow rate by means of the various control mechanisms already described. In this manner equations relating cold water temperature to inlet conditions were derived for each air flow setting. It should be noted that this was an iterative solution to match the rejected heat load (from the cooling tower) with the condenser heat duty.

The steam turbine exhaust pressure is a function of the condenser heat duty, the condenser design, the degree of fouling of the condenser tubes, the circulating water flow rate, and the cold water temperature delivered to the condenser by the cooling tower. For this study the condenser heat duty was calculated for each unit load condition examined, and the circulating water flow rate was taken to be the same as measured during the most recent cooling tower test. While the other parameters were held constant, the cooling water temperature was varied through the control range, as described above, and the turbine backpressure, turbine output and heat rate were calculated. Next, by comparing the calculated output with the baseline output (e.g. with normal cooling tower air flow), the performance impact of air flow control was determined over the range of inlet conditions.

The calculated turbine performance impacts were then compared with the fan power reductions to find which cases yielded a positive net benefit (i.e. fan power reduction greater than turbine output reduction). Those cases yielding a marginal improvement were then compared in order to select the optimum control settings under the imposed conditions. The typical unit load profile and the frequency of occurrence of particular wet-bulb temperatures in the area near the subject plant were next used to calculate the projected annual benefit of the fan controls, in terms of unit net power increase, assuming the controls were maintained at the optimum settings.

1.5 Description of Subject Units

Two of the subject units were pulverized coal fired steam-cycle units, and the third unit was a natural gas fired, combined-cycle plant. All have mechanical-draft cooling towers to provide, primarily, circulating water for steam condenser cooling. However, the design of the cooling towers and condensers differed from plant to plant, and as will be seen later, the effectiveness of the control schemes also differed. Table 1.1 provides a description of the subject generating units. More complete unit design data is found in Appendix A.

Table 1-1
Description of Generating Units Used for Study

	Plant A	Plant B	Plant C
Type	**Combined-Cycle, reheat turbine with IP&LP admission**	**Pulverized Coal 2400 psig 1000 / 1000 F**	**Pulverized Coal 3500 psig 995 / 985 F**
Nominal Capability (MW)	192 (STG, only)	500	900
Condenser Type	Single-Pressure 2-pass	Two-Pressure 2-pass	Two-Pressure 1-pass
Nominal Shell Pressure (inHgA)	3.11	2.83/4.08	3.36/4.76
Design Heat Duty (BTU/hr)	1140x10^6	2371x10^6	4150x10^6
Cooling Tower Type	10-Cell Counterflow	16-Cell Counterflow	2ea. 9-Cell Crossflow
CW Flow Design/Test (GPM)	125,000 130,000	172,000 173,929	370,000 379,245
Design Range (F)	20	28	23.7
Design Approach (F)	5.7	6	17
Design Wet-Bulb (F)	80	80	77

2 NOMENCLATURE

2.1 Definitions

condenser	-	steam surface condenser
module	-	an algorithm describing the performance parameters for a given component (cooling tower fan, cooling tower, condenser, steam turbine) under a set of input conditions
net power output	-	as used in this document net power refers to the gross steam turbine-generator output minus the power used by the cooling tower fans
two-speed fan motors	-	fan motors with two sets of windings one set for high-speed (normal) and one set of windings for low-speed (typically half the high-speed value)
VFD	-	variable-frequency drive, a motor speed control device where the control is achieved by varying the frequency of the alternating current input to the motor.

2.2 Variables

In this document, variables are defined immediately following the equation in which they are used. The following list is provided for convenience.

A	=	condenser heat transfer area
C	=	constant factor
G	=	air mass flow rate for cooling tower cell
$\frac{KaV}{L}$	=	Merkel performance characteristic for cooling tower
L	=	water mass flow rate for cooling tower cell
$\frac{L}{G}$	=	liquid to gas ratio for cooling tower cell
NTU	=	performance characteristic for condenser (number of transfer units)

P = power

Q = volumetric flow rate

R = heat transfer resistance

T = temperature

U = overall heat transfer coefficient

c_p = heat capacity

g = acceleration of gravity

h = specific enthalpy of air

$\bar{v}$ = specific volume of air

2.3 Greek Letters

Δ = change in parameter

ρ = density

μ = dynamic viscosity

ω = rotational speed

3
CALCULATION METHODOLOGY

3.1 Overview

This section describes the methodology for determining the optimum cooling tower fan motor setting for a given motor control technology. The fan motor control systems selected for analysis are

- single-speed motors, on/off control
- two-speed fan motors, full and half speed
- variable-frequency drives, fan speed continuously variable.

In order to calculate the effect of a particular fan motor control setting on the net plant output, the following modules are necessary.

- turbine exhaust pressure module- Calculates the effect of exhaust pressure on the turbine heat rate and output.
- condenser module- Calculates the turbine exhaust pressure as a function of cold water temperature.
- cooling tower module- Calculates the cold water temperature as function of air flow rate and ambient wet-bulb temperature.
- fan module-Calculates the effect of motor control setting on the air flow rate and input power requirements.

A range of fan motor power settings are input to the modules and turbine power output and cooling tower fan motor power used are calculated at each of the settings. The power used by the cooling tower fans is subtracted from the power produced by the turbine to produce the net power output for each of the fan settings. A flow diagram of the calculation routine for each motor control setting is presented in Figure 3-1. The algorithms for the individual modules are described in the succeeding sections.

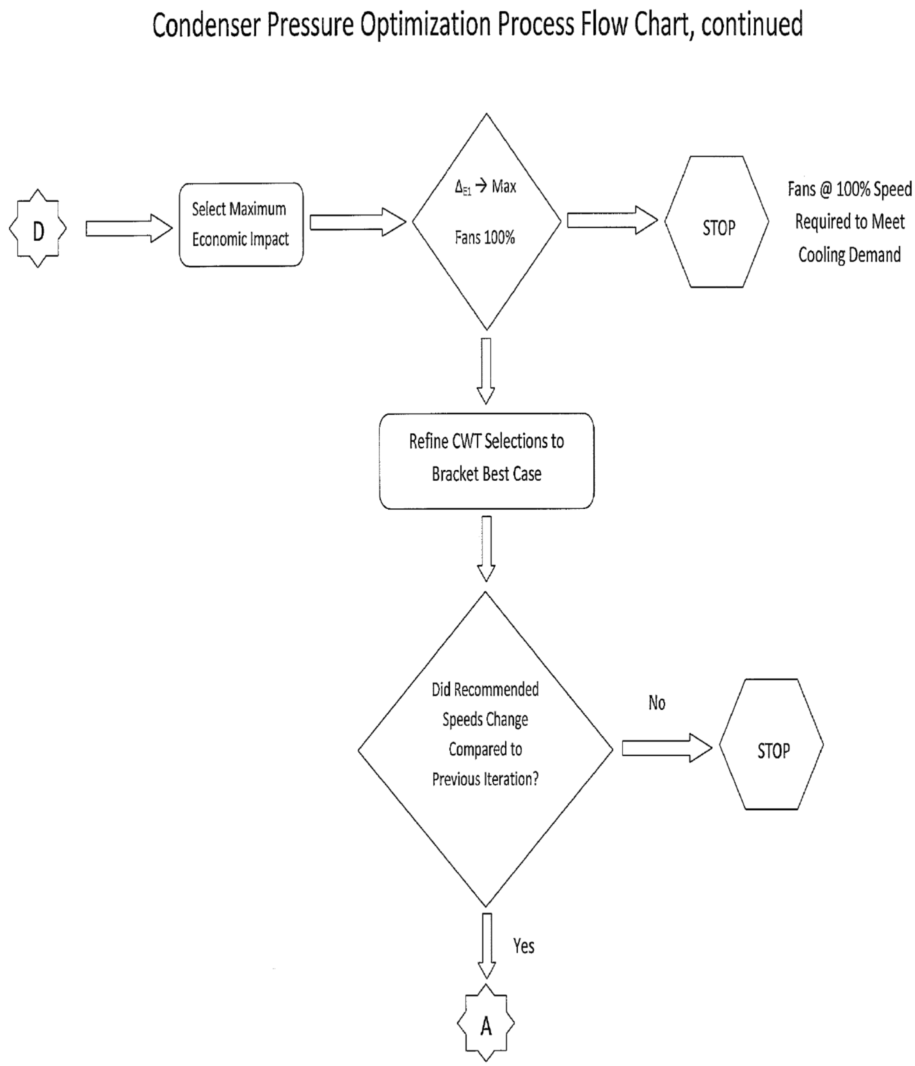


Figure 3-1 (continued on next page)
Cooling Tower Fan Motor Optimization Process Diagram

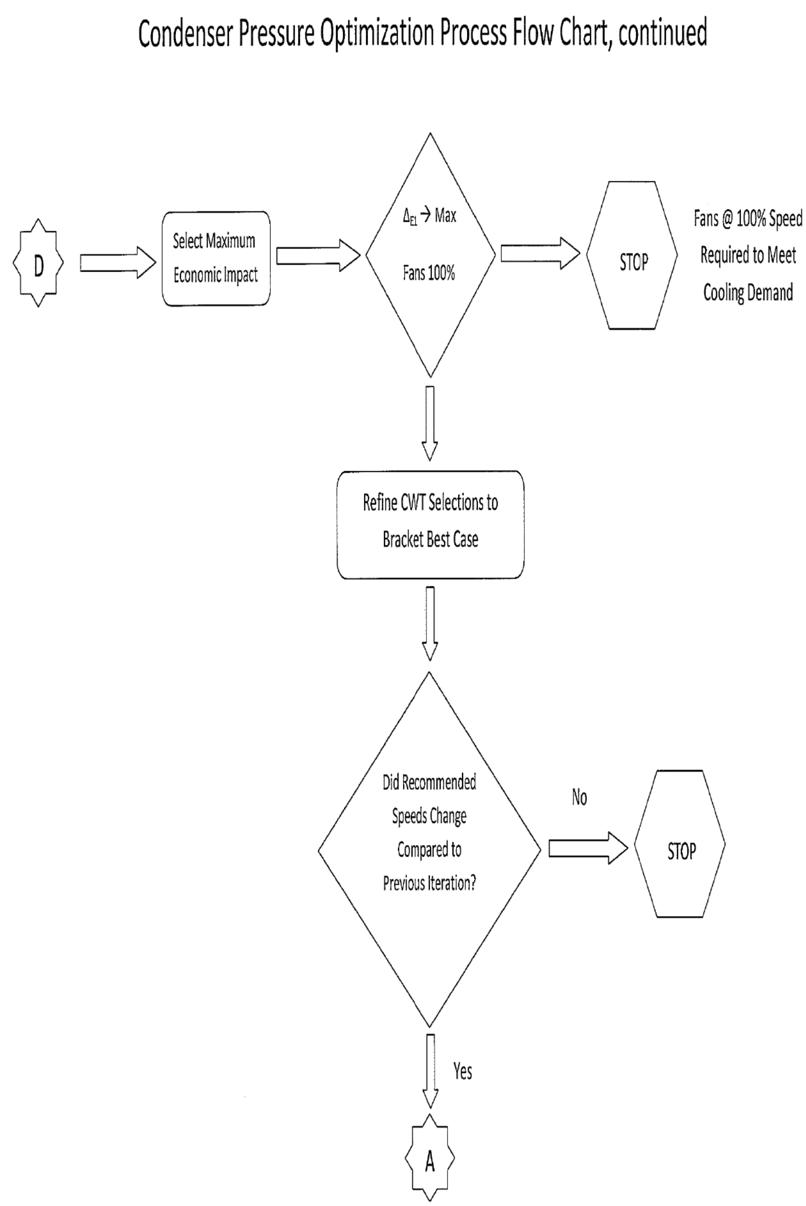


Figure 3-1 (continued on next page)
Cooling Tower Fan Motor Optimization Process Diagram

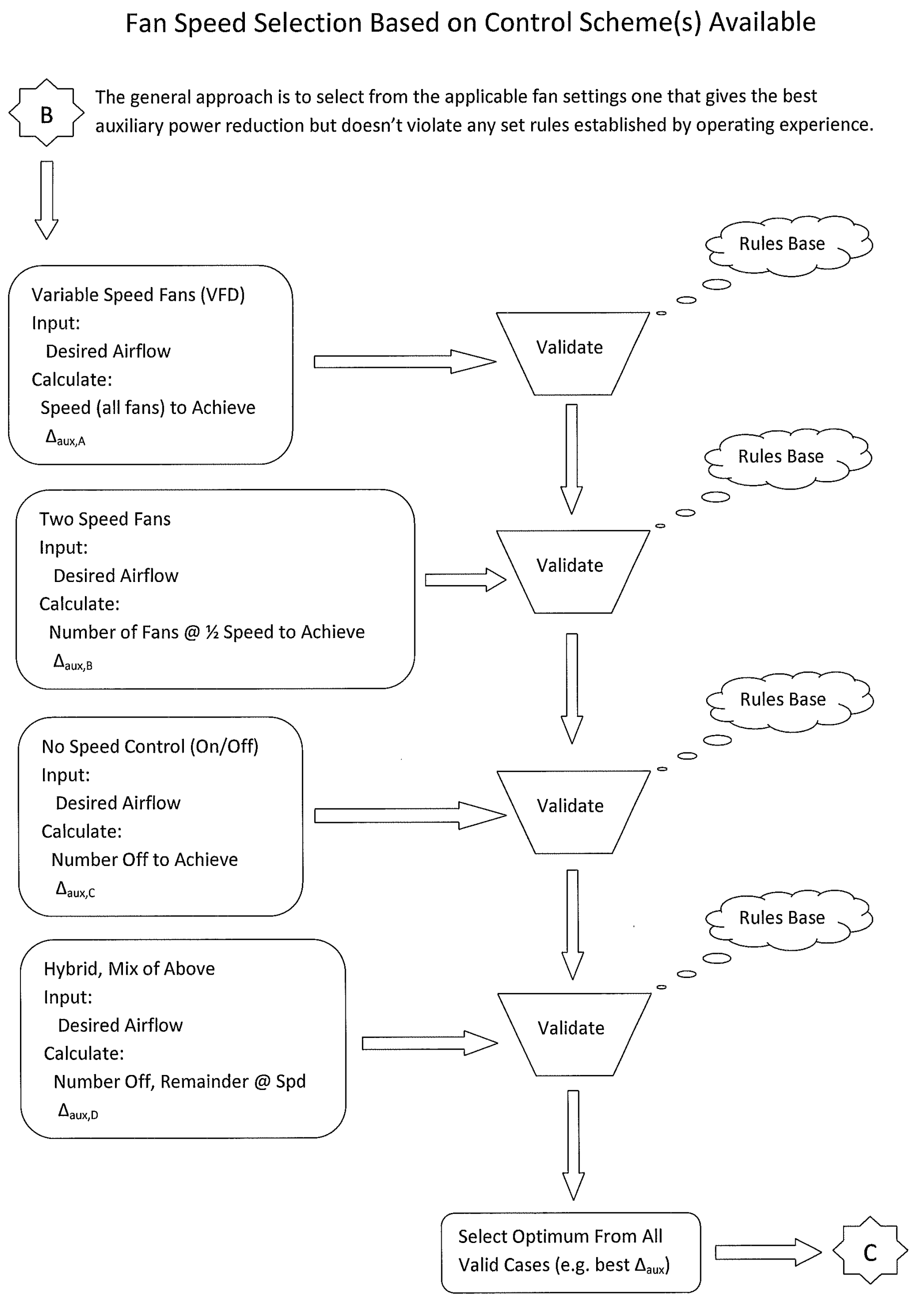


Figure 3-1
Cooling Tower Fan Motor Optimization Process Diagram

3.2 Fan Module

The cooling tower fan motor power and air flow rate used for this study are calculated directly from the fan laws. That is, air flow is directly proportional to the shaft rotational speed and power required is proportional to the cube of rotational velocity. This makes it possible to calculate the air flow rate and power requirements for the fan motor from the design values for the fan.

$$Q_p = Q_D \frac{\omega_p}{\omega_D}$$ **Equation 3-1**

$$P_p = P_D \left(\frac{\omega_p}{\omega_D} \right)^3 \left(\frac{\rho_p}{\rho_D} \right)$$ **Equation 3-2**

where

Q_p	=	predicted volumetric air flow rate
Q_D	=	design volumetric air flow rate
ω_p	=	predicted rotational velocity
ω_D	=	design rotational velocity
P_p	=	predicted fan motor power
P_D	=	reference fan motor power
ρ_p	=	predicted fan density
ρ_D	=	reference fan density.

The reference fan motor power was obtained from of the latest cooling tower performance test report for the cooling tower as provided by the host utility. The design value for the volumetric air flow rate was calculated from the design liquid-to-gas ratio using methodology described in Appendix B. The fan density is the density of air saturated with water vapor at the cooling tower cell. This value is obtained from the saturated air temperature at the air outlet which is calculated by an energy balance around the cooling tower cell by an iterative method detailed in Appendix B.

3.3 Cooling Tower Module

The calculation methodology required to calculate the cold water temperature for a specified water flow rate, range, air flow rate, and wet-bulb temperature is identical to that required to generate cooling tower performance curves. This methodology is succinctly described in reference 1. A brief description of the method is furnished in this section, and a complete formulation is furnished in Appendix B.

According the Merkel theory utilized the cold water temperature for a given range, L/G ratio, and wet-bulb temperature is given by the intersection of the demand and characteristic curves. These values utilize the mass transfer KaV/L which is defined by

$$\frac{KaV}{L} = \int_{T_{w,o}}^{T_{w,i}} \frac{dT_w}{h_w - h_a}$$

Equation 3-3

where

T_w = water temperature

$T_{w,i}$ = water temperature at air inlet of cooling tower

$T_{w,o}$ = water temperature at air outlet of cooling tower

h_a = saturated air enthalpy

h_w = saturated air enthalpy at the water temperature

A numerical integration algorithm for the determination of the integral is found in Reference 2 and summarized in Appendix B.

The characteristic curve is an equation of the form

$$\frac{KaV}{L} = C_F \left(\frac{L}{G} \right)^{-n}$$

Equation 3-4

where

C_F = fill coefficient which is a function of the fill and water distribution system in the cooling tower

n = an exponent which varies from 0.5 to 0.9 dependent on the type of fill

L = water loading for the cooling tower fill

G = air loading for the cooling tower fill.

The design (or test) conditions for the cooling allow the determination of the fill coefficient, C_F, if the value for the exponent, n, is assumed. Solving the characteristic equation for the fill coefficient,

$$C_F = \frac{KaV}{L}\left(\frac{L}{G}\right)^n \qquad \textbf{Equation 3-5}$$

A value of 0.8 for the exponent n is typical for many types film type fill. It was this value of n that was used for this study. The value of the fill coefficient, C_F, was determined for each of the three cooling towers analyzed in this study by methods fully described in Appendix B.

When the cooling tower design conditions of water and air flow rate and cooling tower range are used as input to the cooling tower module, the result should be the design performance curve for the cooling tower. These values were input to the cooling tower module. The resulting curve was compared to design performance curve for the cooling tower. The difference between the cold water temperature and the design cold water temperature was less than 0.3°F for the three cooling towers in this study.

Modeling the effect of turning fans off requires the estimation of the water temperature at the outlet of those cells whose fans are out of service. The minimal amount of cooling which will occur in these cells is difficult to estimate and is a function of the water distribution system and fill type. For this study, it was conservatively assumed that no cooling occurs. That is, that water temperature at the discharge of the cells with fan off is equal to the hot water temperature. The mixed cold water temperature is determined by

$$T_{cw,avg} = \frac{N_{c,FansOn} T_{cw,FansOn} + N_{c,FansOff} T_{cw,FansOff}}{N_c}$$

$$\frac{N_{c,FansOn} T_{cw,FansOn} + N_{c,FansOff} T_{cw,FansOn} + N_{c,FansOff} T_{hw}}{N_c} \qquad \textbf{Equation 3-6}$$

where

$T_{cw,avg}$	=	average cold water temperature
$T_{cw,FansOn}$	=	cold water temperature for cells with fans on
$T_{cw,FansOff}$	=	cold water temperature for cells with fans off
T_{hw}	=	hot water temperature at inlet of the cooling tower
N_c	=	number of cooling tower cells
$N_{c,FansOn}$	=	number of cells with fans on
$N_{c,FansOff}$	=	number of cells with fans off

Similarly, the average cold water for the cooling tower for the configuration with some cells at half speed was calculated by

$$T_{cw,avg} = \frac{N_{c,FansFull} T_{cw,FansFull} + N_{c,FansHalf} T_{cw,FansHalf}}{N_c}$$ **Equation 3-7**

where

$T_{cw,FansFull}$	=	cold water temperature for cells with fans on full speed
$T_{cw,FansHalf}$	=	cold water temperature for cells with fans at half speed
$N_{c,FansFull}$	=	number of cells with fans on
$N_{c,FansHalf}$	=	number of cells with fans off.

For each of the three plants in this study, there is no auxiliary cooling provided by the circulating water. Thus, all of the circulating water from the CW pumps at the outlet of the cooling tower goes through the condenser. For this study, the circulating water flow was set the value measured at the last cooling tower test. The circulating water temperature at the inlet of the steam surface condenser was set to the average cold water temperature for the cooling tower. The hot water temperature is equivalent to the temperature at the outlet of the steam surface condenser.

$$T_{hw} = T_{cw,SSCout} = T_{cw} + \frac{q_{cond}}{\dot{m}_{cw} c_p}$$ **Equation 3-8**

$$\dot{m}_{cw} = Q_{cw} \rho_{cw}$$ **Equation 3-9**

where

$T_{cw,SSCout}$	=	circulating water temperature at the outlet of condenser
q_{cond}	=	condenser heat duty
c_p	=	heat capacity at constant pressure of circulating water
$\dot{m}_{cw}$	=	mass flow rate of circulating water
ρ_{cw}	=	density of circulating water
Q_{cw}	=	volumetric flow rate of circulating water.

3.4 Condenser Module

The condenser module is used to predict the turbine exhaust pressure based on the cold water temperature output from the cooling tower module and the steam flow rate from the turbine module. The heat duty calculated for the condenser is also used in the cooling tower module to calculate cooling tower range.

The methods used in this study closely follow those utilized in ASME PTC 12.2 Steam Surface Condensers 1998 to predict the condenser pressure at design conditions based on test data. The condenser data required as input to the condenser module are summarized in Table 3-1.

Table 3-1
Condenser Design Parameters

		Plant A	Plant B	Plant C
Number of shells		1	2	2
Number of passes		2	2	1
Condenser surface area	Ft^2	104,441	230,000	415,202
Number of tubes-main section		12067	49600	42000
Number of tubes-air removal		400	2076	2054
Tube material		Titanium	Titanium	304SS
Diameter of tubes	in	1.0	1.0	1.0
Tube Wall Gage		22	22	22
Heat duty	BTU/hr	1140x10^6	2371x10^6	4150x10^6
Circulating water flow	gpm	108,810	172,000	337,260
Inlet water temperature	F	86	86	93
Condenser pressure(s)	inHg	3.11	2.8/4.1	3.4/4.8

The condensers at Plant B and Plant C are two-pressure condensers. This means that each of the two LP turbines is serviced by separate condensers which are connected in series on the circulating water side. The circulating water discharged from the low-pressure condenser is the inlet water to the high-pressure condenser. The heat duty for each condenser shell is calculated by multiplying the design condenser heat duty ratio of power output to the full-load power output.

$$q_{cond} = q^{*}_{cond} fc$$ **Equation 3-10**

Where:

q^*_{cond} = design condenser load

f_c = fractional unit capacity

The condensing steam pressure is calculated by

$$NTU = \frac{UA}{c_p \dot{m}_{cw}} \quad \textbf{Equation 3-11}$$

$$T_{cw,SSCout} = T_{cw,SSCin} + \frac{q_{cond}}{\dot{m}_{cw} c_p} \quad \textbf{Equation 3-12}$$

$$T_S = \frac{T_{cw,SSCout} - T_{cw,SSCin} \exp(-NTU)}{1 - \exp(-NTU)} \quad \textbf{Equation 3-13}$$

Where:

A = the heat transfer area of the condenser

U = the overall heat transfer coefficient for the condenser

$T_{cw,SSCin}$ = circulating water temperature at the inlet of condenser

$T_{cw,SSCout}$ = circulating water temperature at the outlet of condenser

T_s = saturated steam temperature on the shell of the condenser.

The pressure of saturated steam at the turbine exhaust is determined from the saturated steam temperature using standard steam tables. The overall heat transfer coefficient is determined by summing the heat transfer resistances for the

- Shell-side film, R_s
- fouling layer, R_f
- tube metal, R_m
- tube-side film, R_t.

$$U = \frac{1}{R_m + R_F + R_t + R_s} \quad \textbf{Equation 3-14}$$

Correlation equation for the component heat transfer resistances are found in Appendix C.

3.5 Turbine Module

The turbine module calculates the effect of changes in the cooling tower fan operating mode on the power output of the steam turbine cycle. This is accomplished by using the backpressure correction curves for the steam turbine. These usually plot a correction to the base heat rate as a function of turbine exhaust (condenser) pressure for multiple values of steam flow rates. The backpressure heat rate correction curve for a typical turbine is illustrated in Figure 3-2.

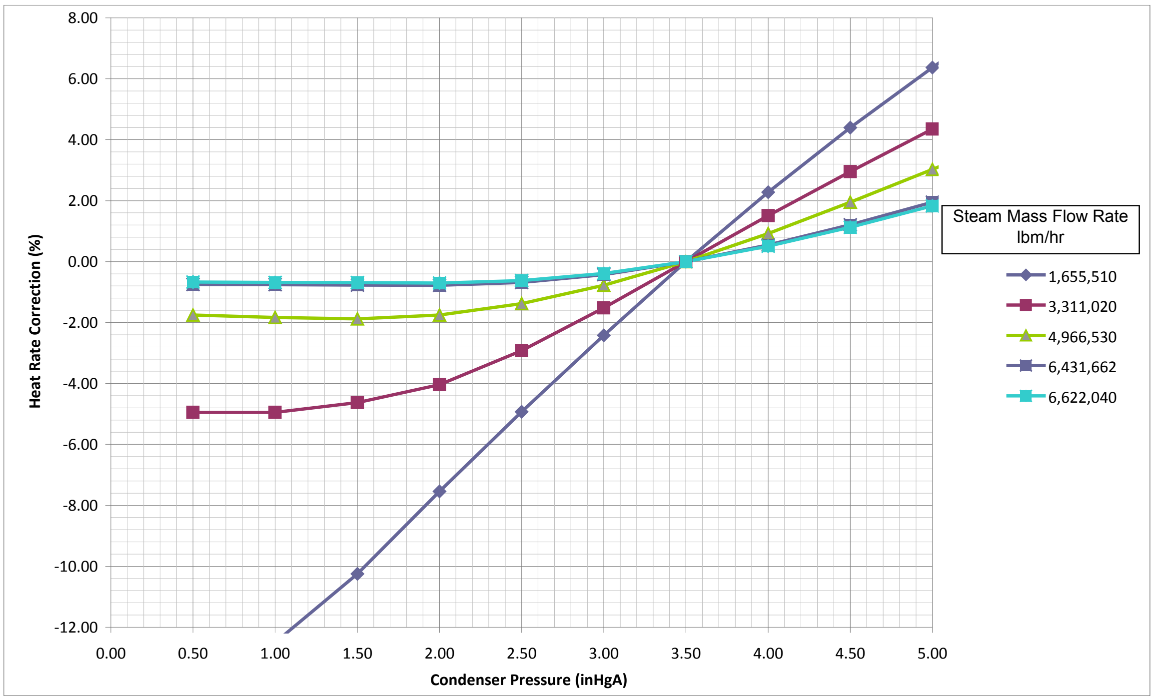


Figure 3-2
Backpressure Correction Curves

Southern Company provided tabular versions, based on the turbines manufacturers' thermal kits supplemented by correlations derived from test data, of the backpressure correction output curves for the three units under study. (Note that the heat rate correction curves were inverted in order to be used for output corrections. This approach may not be valid for all instances or parameters.) The predicted steam flow and condenser pressure for the analyzed condition were used as inputs for a two dimensional interpolation from the tabulated data. The steam flow for the analyzed condition was calculated by multiplying the steam flow at full load by the factional unit capacity.

$$\dot{m}_S = \dot{m}_S^* f_c$$ **Equation 3-15**

Where:

$\dot{m}_S$ = mass steam flow at the turbine inlet

$\dot{m}_s^*$ = mass steam flow at full load

The turbine power output was calculated by

$$P_t = P_t^* f_c \frac{-100\Delta hrc}{100 + \Delta hrc}$$ **Equation 3-16**

Where:

P_t = turbine power output at analyzed condition

P_t^* = turbine power output at full load

Δhrc = heat rate correction.

4
RESULTS

4.1 CWT Versus Wet-Bulb Temperature

For each of the fan control methods, optimum settings were found, using the methodology discussed in Section 3 of this report, given inputs of the ambient wet-bulb temperature and unit load setting. The optimum settings were the ones that yielded the highest value of net power at the given conditions. These results are tabulated in Appendix D of this report.

The fourth page from the table in Appendix D-1 is included here (next page) as an example: Plant A Condenser Performance - Half Load (i.e. One CTG at Base Load, Heat Recovery, etc.) Cooling Tower Fan Speed Control (VFD). For a given load level, each table expresses power in kilowatts as a function of ambient wet-bulb temperature and level and number of fans in operation. Losses in turbine-generated power are subtracted from savings in fan power, resulting in overall power savings for each set of conditions.

An additional product of these calculations is to determine the circulating water temperature (CWT) for each condition examined, and these data have been plotted with respect to wet-bulb temperature. Furthermore, an "optimum" CWT line may be plotted to correspond with the optimum conditions discussed in the paragraph above. Figures 4.2 through 4.9 show the results for varying air flow by means of VFD motor control. Figures 4.10 through 4.16 show the CWT obtained by changing the number of fan motors on half-speed.

Plant A Condenser Performance - Half Load (i.e. One CTG at Base Load, Heat Recovery, etc.)
Cooling Tower Fan Speed Control (VFD)

Exhaust Flow 605,150 PPH

STG Output, Nominal 95,900 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	97177	99130	100628	101538	102289	102841	103267	103596	103845	104044	104210
90% Speed	kW	96858	98835	100372	101307	102086	102671	103117	103467	103736	103945	104118
80% Speed	kW	96466	98273	99972	101026	101809	102440	102915	103290	103585	103813	103996
70% Speed	kW	95951	97642	99350	100626	101425	102108	102632	103038	103364	103624	103826
60% Speed	kW	95221	96816	98442	99939	100903	101603	102201	102662	103027	103325	103566

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
90% Speed	kW	-319	-295	-257	-231	-203	-170	-150	-130	-110	-99	-92
80% Speed	kW	-711	-857	-656	-512	-480	-401	-351	-307	-260	-231	-214
70% Speed	kW	-1226	-1488	-1278	-912	-864	-734	-635	-558	-481	-420	-384
60% Speed	kW	-1956	-2314	-2186	-1599	-1386	-1239	-1066	-935	-818	-719	-644

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.755	14.550	14.360	14.185	14.022	13.870	13.727	13.593	13.465	13.343	13.226
90% Speed	kW	355	360	365	370	374	378	382	386	389	393	397
80% Speed	kW	640	649	658	666	673	681	688	695	701	708	714
70% Speed	kW	862	874	885	896	907	917	926	935	944	953	961
60% Speed	kW	1028	1043	1056	1070	1082	1094	1105	1116	1127	1137	1147

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
90% Speed	kW	37	66	108	139	171	208	232	256	280	294	304
80% Speed	kW			1	154	194	280	337	388	441	476	500
70% Speed	kW					43	183	291	377	463	533	577
60% Speed	kW							39	181	308	418	503

Highlighted cases provide the highest net savings.

4.2 Annual Benefit of Each Control Method

In order to estimate the annualized auxiliary power savings for each method of control, the following input data was considered:

1. Unit (gross) Power Production (i.e. Load Profile) for years 2005-2010;
2. Weather conditions, specifically the ambient dry-bulb and wet-bulb temperatures, for a typical year in the area of the plant being considered;
3. Calculated net auxiliary power savings potential (optimum cases) tabulated in Appendix D.

Variables Defined:

S_n Total annualized net power savings (kW-hr) for the control schemes, as follows

Subscripts –
i fans on/off
v variable-frequency drives (VFD)
d two-speed motors (full-speed and half-speed)

P_{WB} Calculated net auxiliary power savings (kW) at given wet-bulb temperatures and optimum control setting

H_L Annual hours at the specified load condition (i.e. full-load, 75% load or minimum load)

WB_t Frequency of occurrence of wet-bulb temperature (t) during the analysis year.

For each unit load considered the total annualized power savings was estimated as:

$$S_n = \sum_{t=35}^{t=85} (P_{WB} * H_L * WB_t) \quad \textbf{Equation 4-1}$$

Finally, the calculated net power savings over the range of unit loads were summed to provide the total expected savings for a typical year.

The load distribution for the three plants is presented in Table 4.1.

Table 4-1
Load Distributions for Units

		Plant A	Plant B	Plant C
1/2 Load	hours	711	2453	2137
3/4 Load	hours	---	588	2088
Full Load	hours	5282	1747	1961
Total	hours	5993	4788	6186

Note: Load profile year 2009

Plant A is a combined-cycle plant with two gas turbines and one steam turbine. The half-load operating condition for this plant is with one gas turbine operating which reduces the heat input to the steam turbine and, therefore, its power output by half. Three-quarter load for this plant is a transitory condition which was not included in this analysis. Conditions of ramping load were also ignored for the other two units. For the load profile year, 2009, part load operation comprised 63 percent the operating hours considered for Plant B. For Plant C, part load operation comprised 68 percent of the total.

Data from the National Oceanographic and Atmospheric Administration data base was used to compile the wet-bulb frequency distributions for the plants. Weather data from Location 1, a city on the US Gulf Coast, was used for Plants A and B. Weather data from the weather station at Location 2, a town in central Georgia, was used for Plant C. The cumulative annual frequency for the plants is illustrated in Figure 4-1,

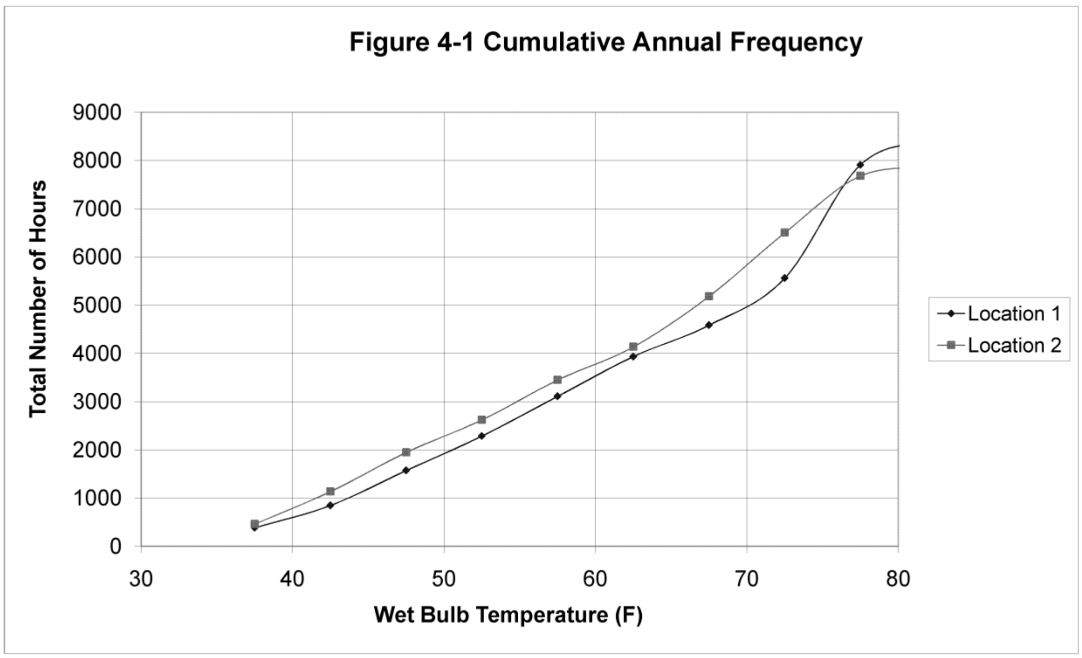


Figure 4-1
Cumulative Annual Frequency Distributions

When the wet-bulb temperature is below 35°F, the cooling towers operation is governed by the need to control icing. Therefore, these conditions were not included in the analysis. In the range where optimization is most effective (between 35 and 65°F), the distributions for all of the plants were nearly identical.

Data for the net power savings for the three units using the different control schemes is presented in Tables 4.2, 4-3, and 4.4.

Table 4-2
Plant A Net Power Savings Estimated for Various Cooling Tower Control Schemes

		Fan Control Scheme		
		Fans On/Off S_i	VFD S_v	Two-Speed Motors S_d
Half-Load (i.e. 1X1 Operation)	kW-hr	2,721	155,496	55,015
Base Load (w/o duct burners or power augmentation)	kW-hr	3,150	350,763	128,320
Total	**kW-hr**	**5,871**	**506,259**	**183,335**

Note: Load profile year – 2009

Very little increase in the net power produced was observed for the Fans On/Off scheme under any load condition. The net power savings were significantly higher for the VFD control compared to two-speed motors. Most of the increase was due to savings at full-load operation at low ambient wet-bulb temperatures. It should be noted that during other load profile years, the proportion of time at reduced load was higher than reported above. Consequently, the potential savings for VFD or two-speed motor control would increase if the average load decreases again at some point in the future.

Table 4-3
Plant B Net Savings Estimated for Various Cooling Tower Control Schemes

		Fan Control Scheme		
		Fans On/Off S_i	VFD S_v	Two-Speed Motors S_d
Minimum-Load (50% Full-Load)	kW-hr	289,038	2,400,914	1,818,693
Three Fourths Load (75% Full-Load)	kW-hr	28,136	392,688	226,609
Full-Load	kW-hr	9696	549,983	148,362
Total	**kW-hr**	**326,870**	**3,343,585**	**2,193,664**

Note: Load profile year – 2009

The analysis for Plant B indicated the majority of the net power increase for all control schemes occurs during half load operation. The Fans On/Off control scheme offers a small opportunity for savings when the unit is at half load. The VFD control scheme provided the greatest opportunity for power savings.

Table 4-4
Plant C Net Power Savings Estimated for Various Cooling Tower Control Schemes

		Fan Control Scheme		
		Fans On/Off S_i	VFD S_v	Two-Speed Motors S_d
Minimum-Load (50% Full-Load)	kW-hr	3621	453,132	97,953
Three Fourths Load (75% Full-Load)	kW-hr	999	152,677	21,090
Full-Load	kW-hr	0	0	0
Total	**kW-hr**	**4620**	**605,809**	**119,043**

Note: Load profile year – 2009

For Plant C, no opportunity for improvement in the net power produced exists with any control scheme when the unit is at full load. The Fans On/Off control offers very little opportunity for increased power production at any load. The VFD control offers a significantly greater increase in the net power than two-speed motor control. Even though Plant C had a greater number of hours of part load operation than Plant B, the opportunity for an increase in power production using the VFD control scheme is much less for Plant C. This indicates a much lower margin in the sizing of the cooling system at Plant C than at Plant B.

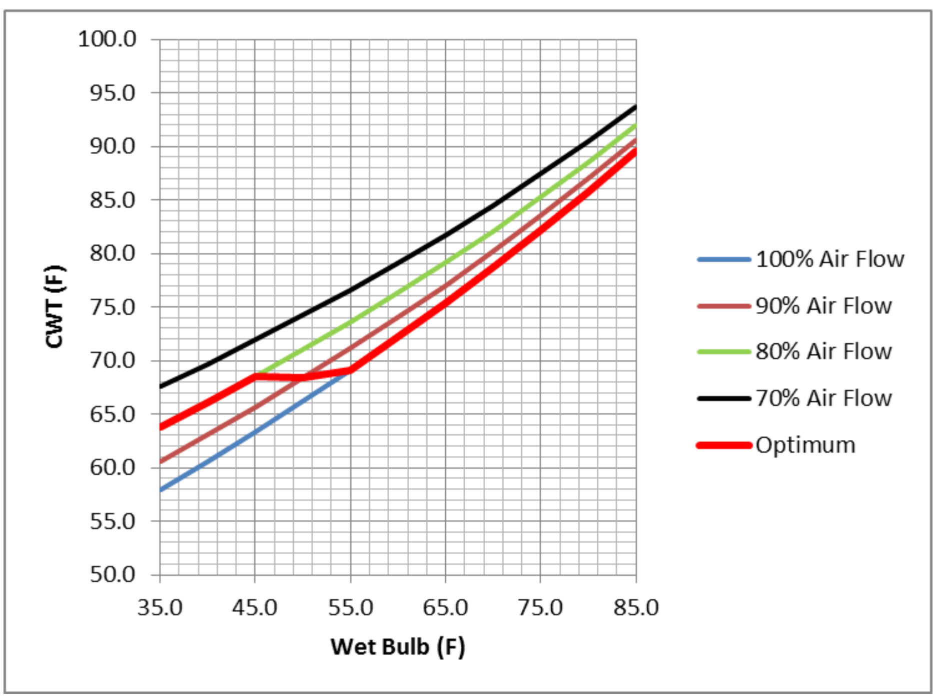


Figure 4-2
Plant A Base-Load Cooling Tower Performance (With Variable-Speed Fans)

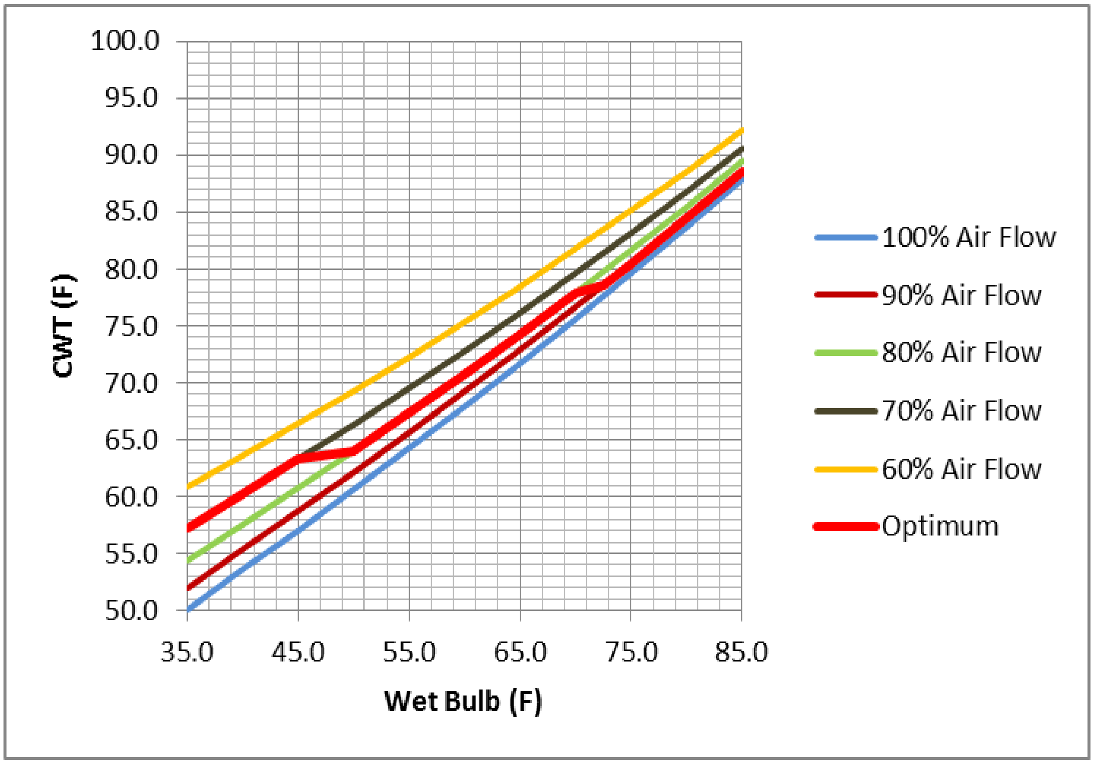


Figure 4-3
Plant A Half-Load Cooling Tower Performance (With Variable-Speed Fans)

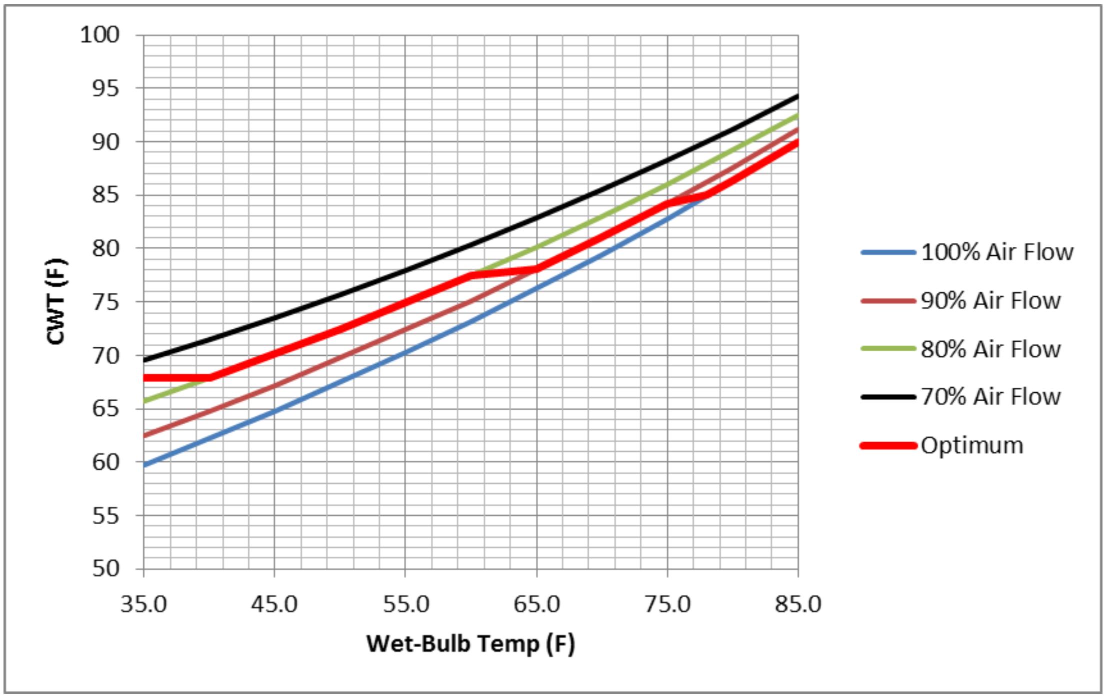


Figure 4-4
Plant B Full-Load Cooling Tower Performance (With Variable-Speed Fans)

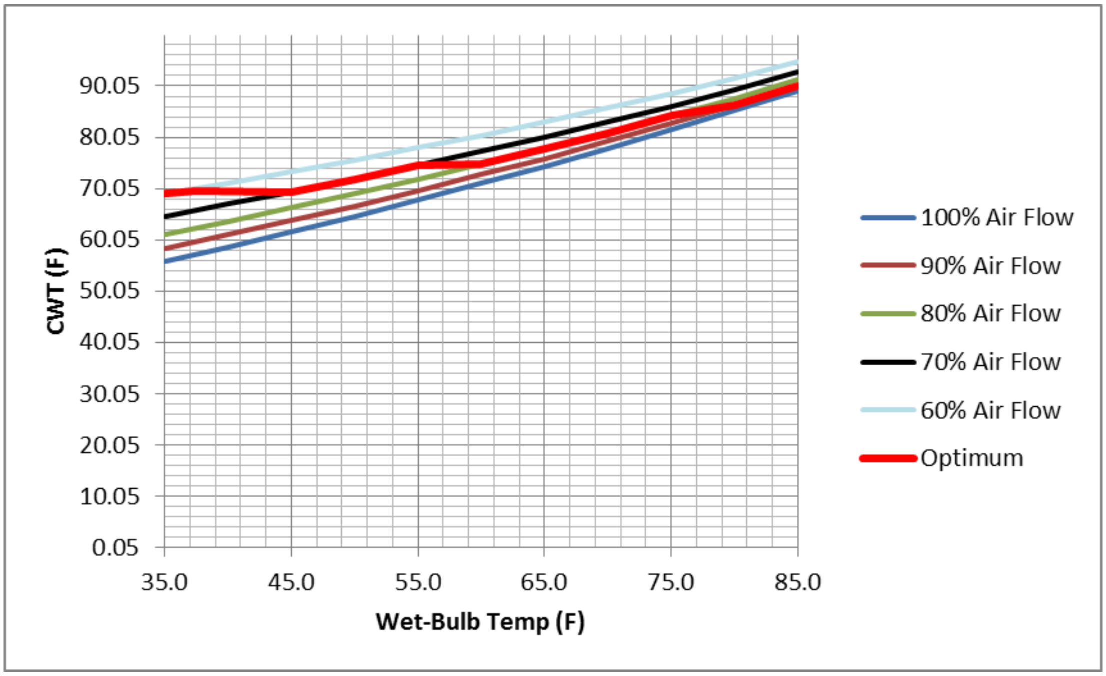


Figure 4-5
Plant B ¾-Load Cooling Tower Performance (With Variable-Speed Fans)

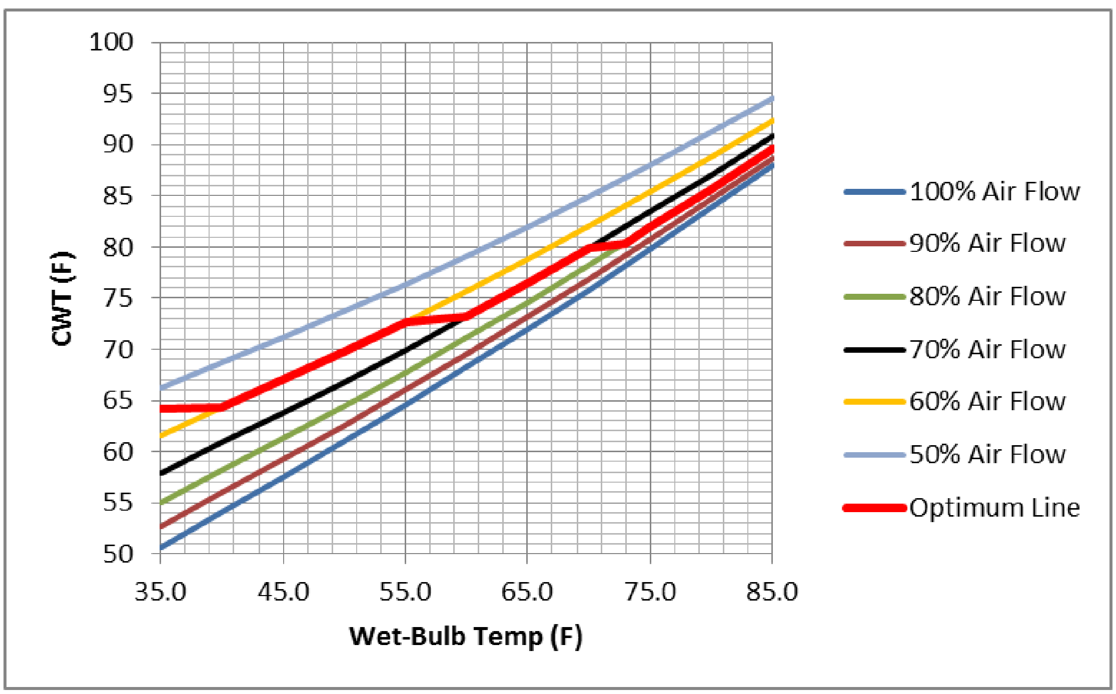


Figure 4-6
Plant B Minimum-Load Cooling Tower Performance (With Variable-Speed Fans)

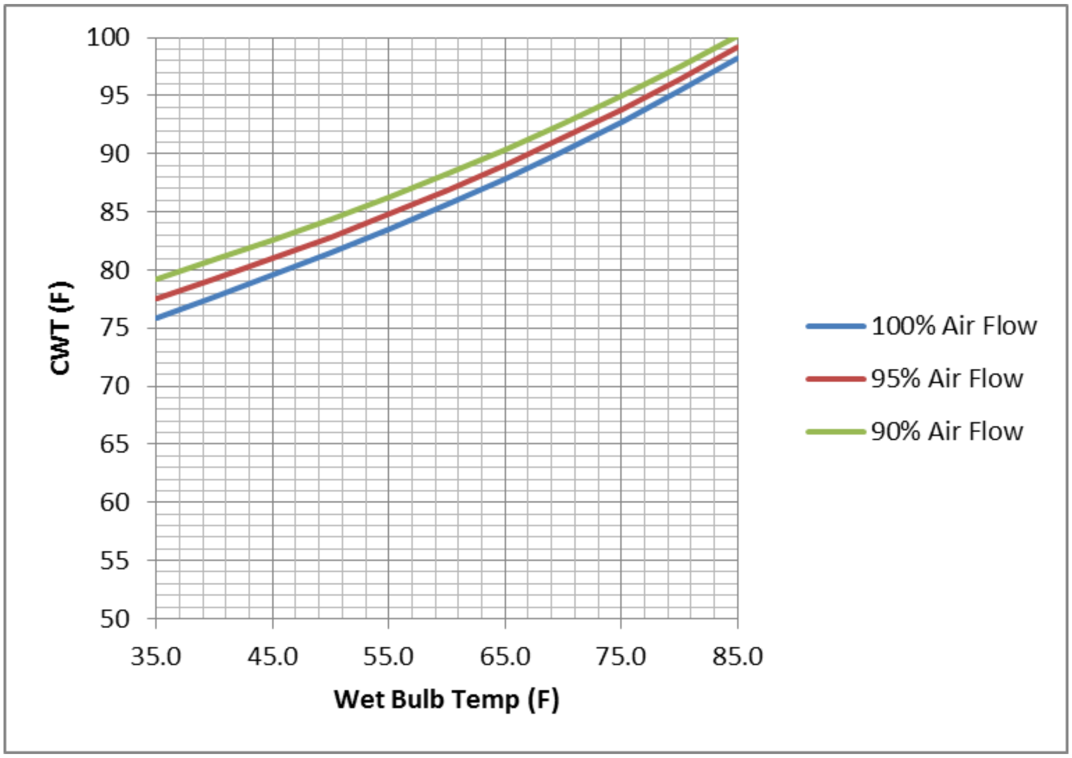


Figure 4-7
Plant C Full-Load Cooling Tower Performance (With Variable-Speed Fans)

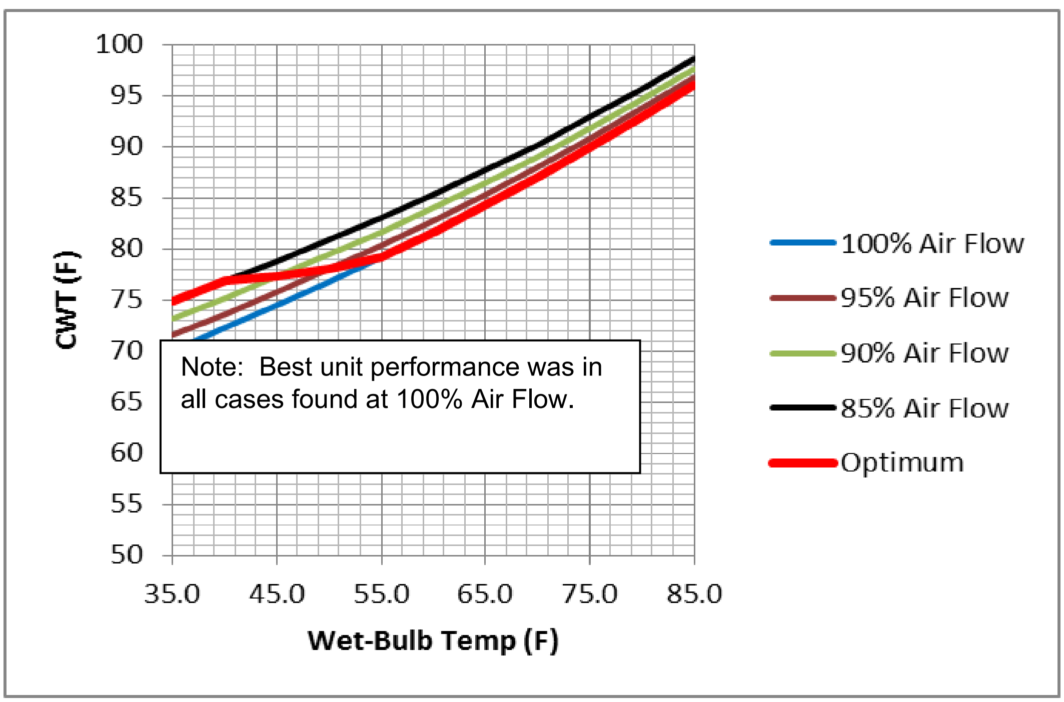


Figure 4-8
Plant C Three-Quarter-Load Cooling Tower Performance (With Variable-Speed Fans)

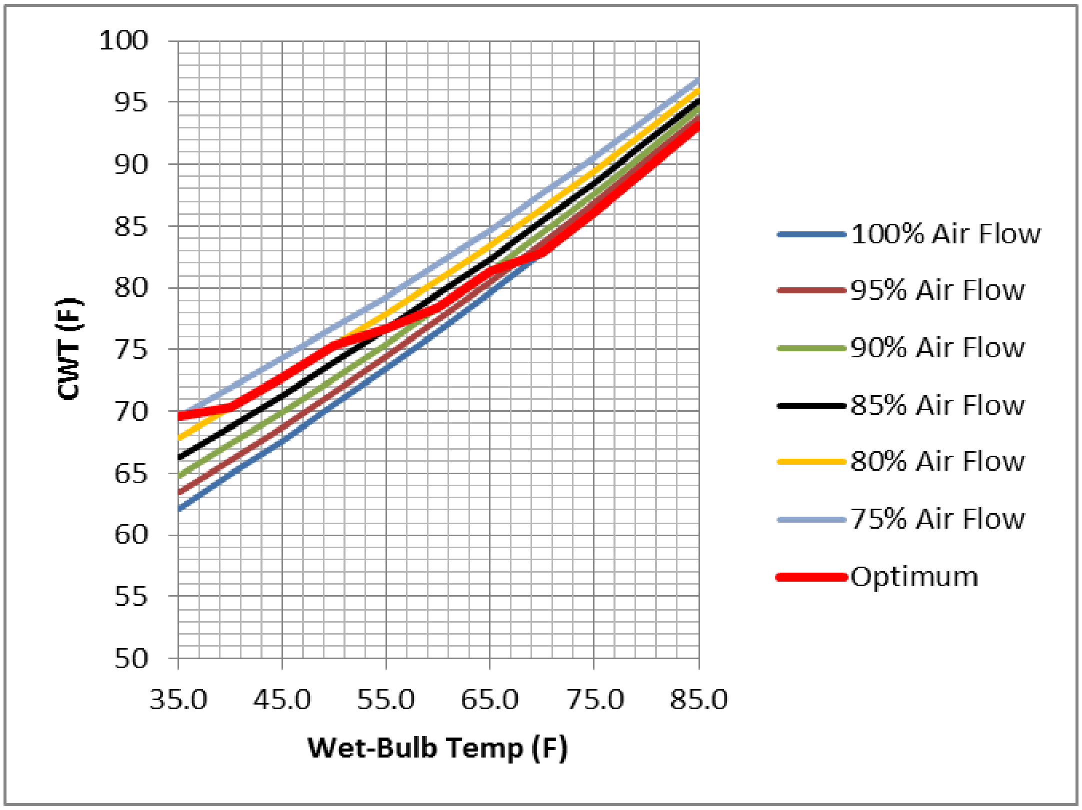


Figure 4-9
Plant C Half-Load Cooling Tower Performance (With Variable-Speed Fans)

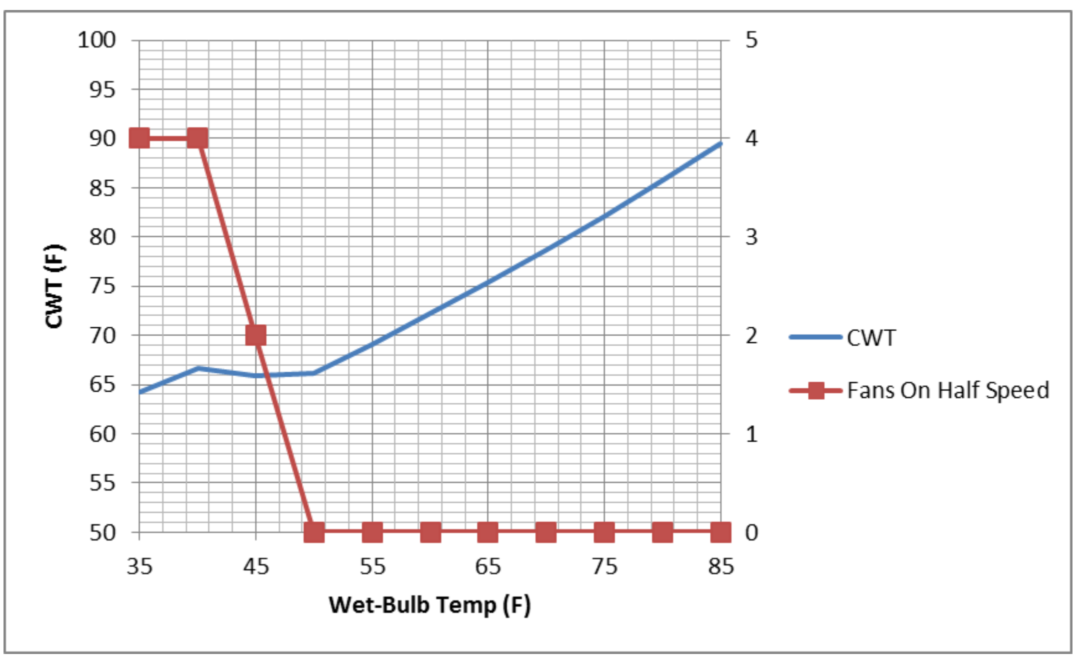


Figure 4-10
Plant A Base-Load Cooling Tower Performance (With Two-Speed Fans)

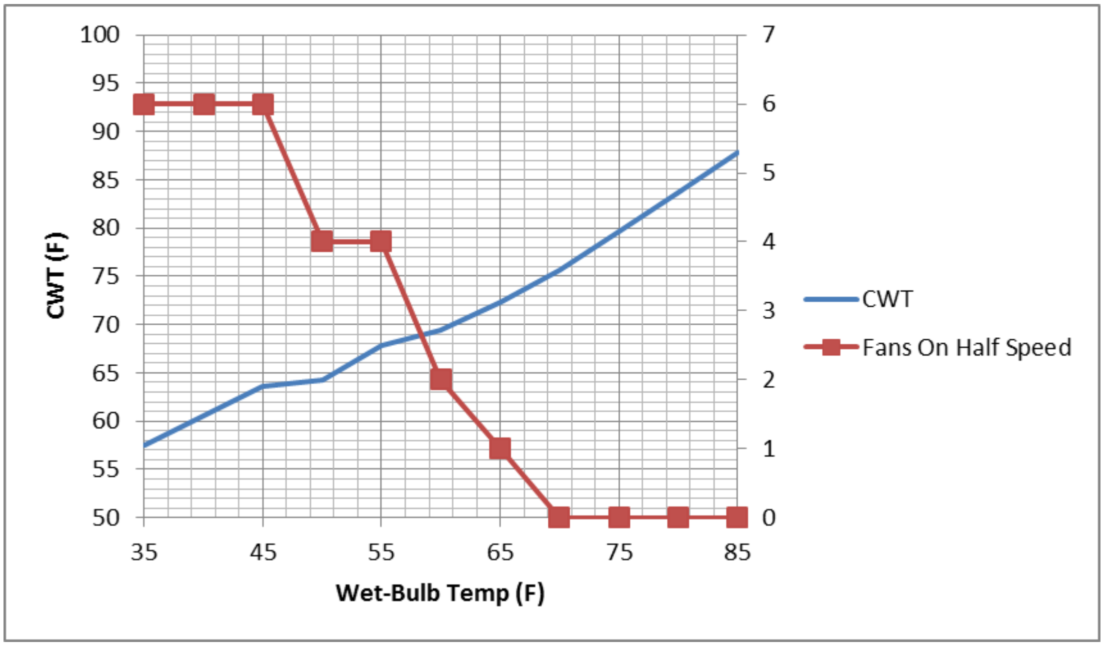


Figure 4-11
Plant A Minimum-Load Cooling Tower Performance (With Two-Speed Fans)

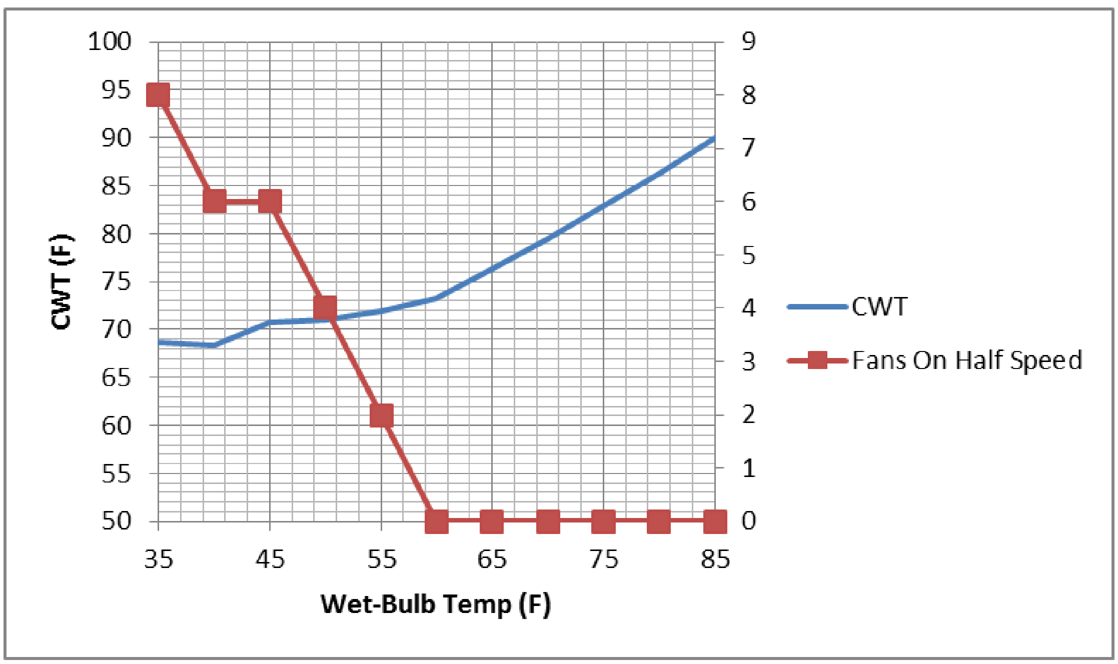


Figure 4-12
Plant B Full-Load Cooling Tower Performance (With Two-Speed Fans)

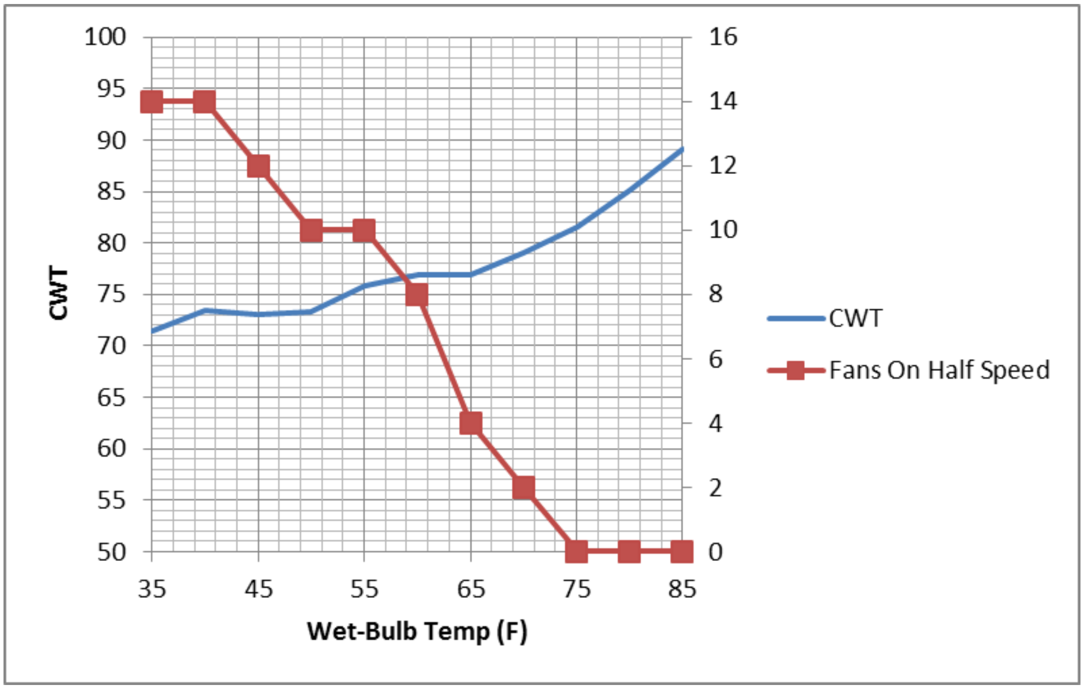


Figure 4-13
Plant B Three-Quarter-Load Cooling Tower Performance (With Two-Speed Fans)

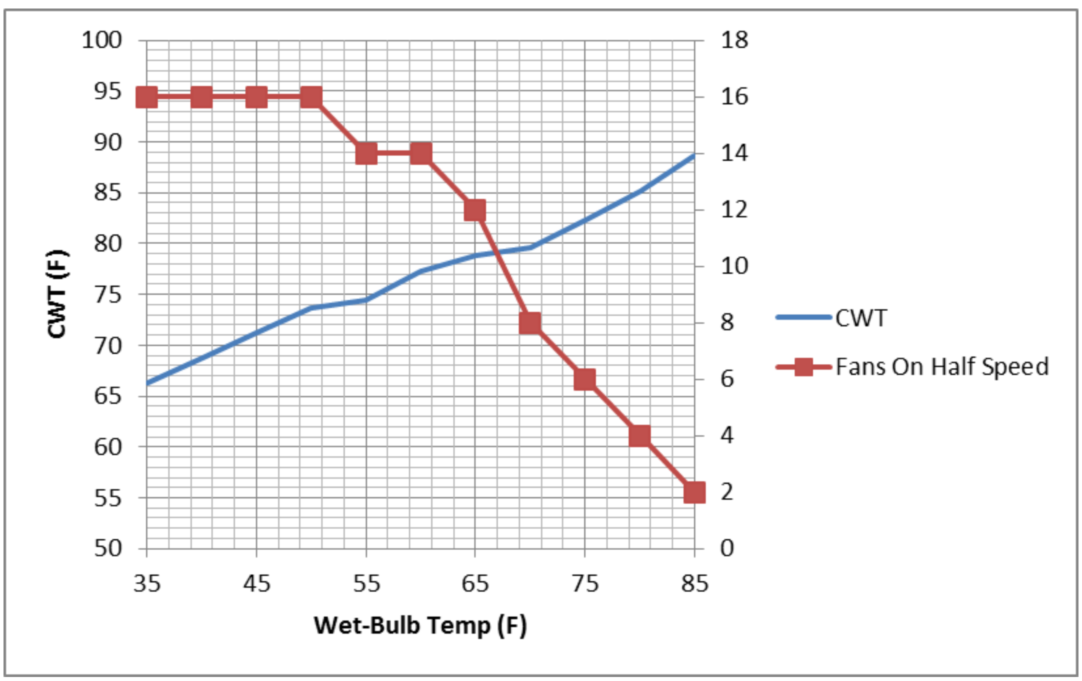


Figure 4-14
Plant B Half-Load Cooling Tower Performance (With Two-Speed Fans)

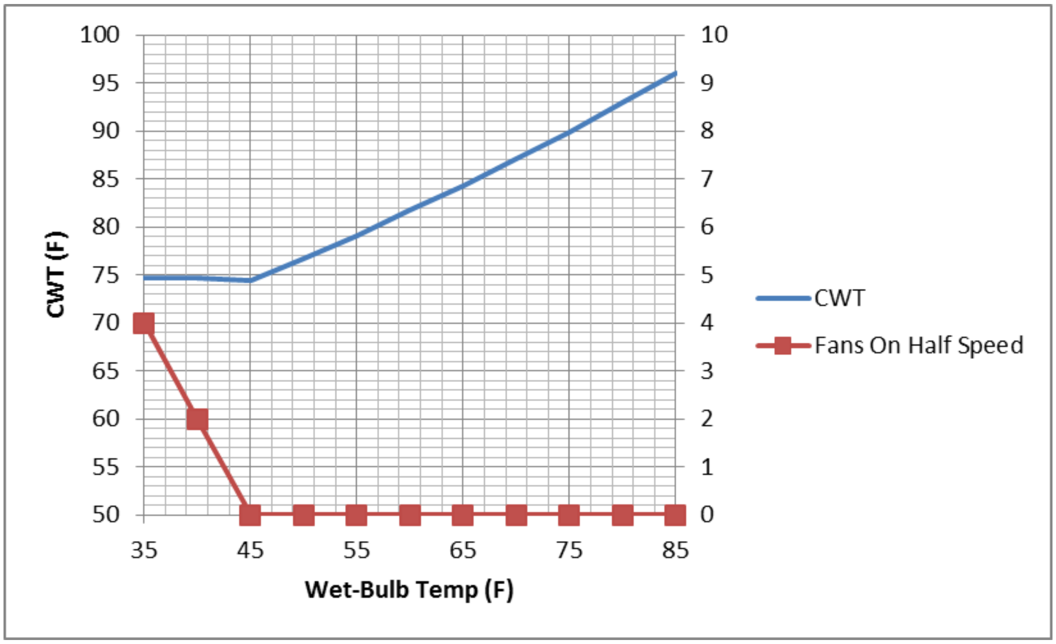


Figure 4-15
Plant C Three-Quarter-Load Cooling Tower Performance (With Two-Speed Fans)

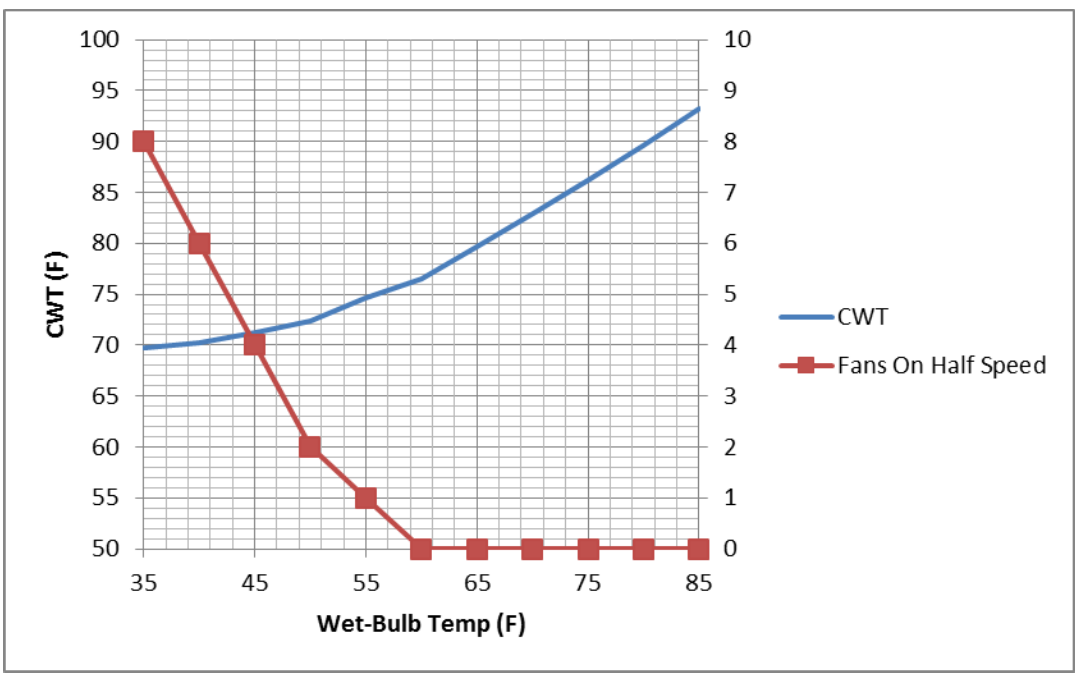


Figure 4-16
Plant C Half-Load Cooling Tower Performance (With Two-Speed Fans)

5 CONCLUSIONS

For this study a methodology for evaluation of cooling tower control strategies was developed to estimate the effect (in terms of plant output and heat rate) of changing the operation of the plant cooling cycle, in particular the cooling tower fans. The specific operating scenarios examined were: 1) shutting off cooling tower fan(s) when possible; 2) using variable-frequency drives (VFD) on cooling tower fans to control fan speed and consequently cooling water temperature; and, 3) using two-speed motors to control fan speed. Given inputs such as the heat rejection system design parameters, ambient temperature, condenser heat load, and so on, the turbine output and heat rate may be calculated. Then by comparison with the baseline performance, the net effect of the change may be determined.

The heat rejection cycles at three Southern Company power plants were modeled and examined to determine the effect on plant performance of modifying the operating conditions of cooling tower fans. Calculations were made covering the full range of ambient conditions and plant loads normally experienced, and the net effect of the different operating scenarios was estimated. Two of the subject units were pulverized coal fired steam-cycle units, and the third unit was a natural gas fired, combined-cycle plant. All have mechanical-draft cooling towers to provide, primarily, circulating water for steam condenser cooling. However, the design of the cooling towers and condensers differed from plant to plant, and as the effectiveness of the control schemes also differed.

A number of beneficial cases were found, and any of the three control schemes would be beneficial under certain ambient and load conditions. The general trends observed during this study were:

1. The most effective use of cooling tower fan control would be during cooler weather and during periods of reduced load;
2. At normal (base or maximum) unit loads, there was rarely a benefit of shutting off fans, except under conditions that would necessitate freeze protection. This corresponds with the current operating plan for the three subject plants;
3. The best return on investment for VFD control was found on the high-range counterflow cooling tower system as found at Plant B. In part this was attributable to the reduced capacity-factor that this plant experienced in the recent past;
4. The second best return on investment for VFD control was the low-range counterflow cooling tower used on a combined-cycle turbine at Plant A. This plant has experienced a high capacity factor in the recent past. If it is expected that a combined-cycle plant will operate for a significant period at reduced load, then the benefit of fan control would be greater and the return on investment shorter.

5. On a per-fan basis, the installed cost of the two-speed motor control may be similar to the cost of VFD control, and has less flexibility to follow changing conditions. The two speed fan motors also require pulling three additional wires from the motor control center to the motor. However, the simplicity of the two-speed system may be a benefit (operability and maintainability) at a plant where the experience with VFD systems is limited.
6. The experience of plant personnel with frequent cooling tower fan starts/stops was an increase in the frequency of gearbox failures necessitating major repairs. One of the additional benefits of the VFD system (and to a lesser extent the two-speed motor system) would be an inherent "soft-starting" capability. Furthermore, during short unit outages, the fans might be slowed down to minimum rather than being stopped entirely, thus reducing the number of motor starts needed.

Preliminary project planning was under way by Southern Company and EPRI at the time of this study to potentially install a limited number of VFD and/or two-speed motors as test applications. The methodology developed and described herein would be useful for estimating the effect of the proposed modifications on the thermal performance on the modified cooling tower. In addition, the future study could also provide a means to validate certain assumptions that were made during the current study by means of performance data collected over the range of fan speeds and at different ambient conditions. The future study would also provide excellent experience to ensure the operability and reliability of the modified systems.

A
DESIGN DATA FOR UNITS INCLUDED IN FAN STUDY

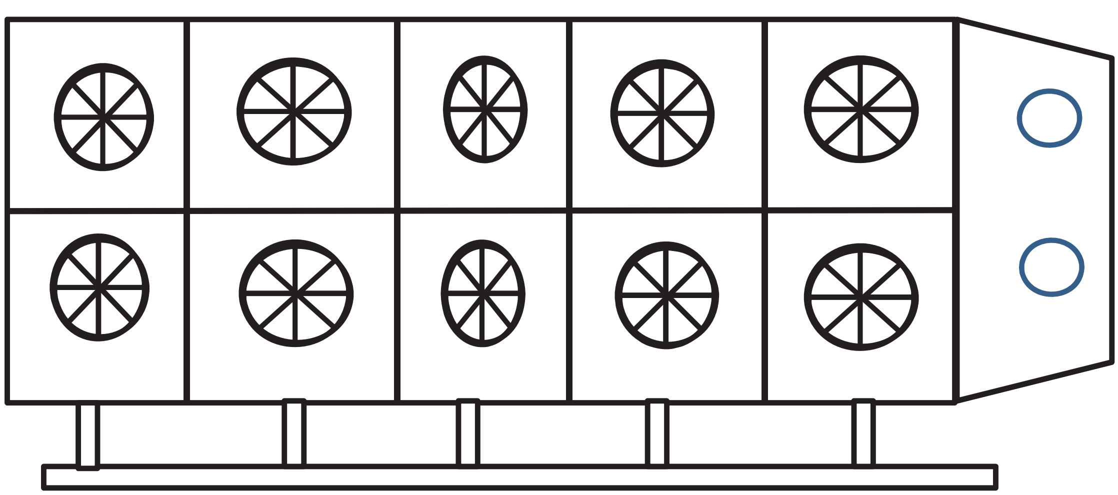
APPENDIX A DESIGN DATA FOR UNITS INCLUDED IN FAN STUDY

EPRI Cooling Tower Fan Speed Study
Plant Data Matrix

Plant Name:	Plant A	Unit No.:		
Owner:		Type:	Combined Cycle	
Location:	South	CT Type:	Ind. Draft, Counterflow	
Lat./Long.		Medium:	Fresh	fresh/salt
Elevation:		Num.Cells	10	

Plant Layout

Cooling Tower Layout



EPRI Cooling Tower Fan Speed Study
Cooling Tower Design

Plant Name:	Plant A		Unit No.:	
Type:	Combined Cycle		OEM - Tower:	Hamon
CT Type:	Ind. Draft, Counterflow		OEM - Fans:	Hudson
Medium:	Fresh	fresh/salt	OEM - Motors:	Siemens
Num.Cells	10			

Build Year:	2000		Rebuild Yr (or N/A)	
Perf. Test Year:	2010			N/A
Test Capability:	101.8	%		

CW Flow Total*	130000	gpm	Design L/G	1.24
Design Range	20	°F	Design Wet Bulb	80
Design Approach	5.7	°F	Design Airflow	52,951,220
Fill Type	Vertical/Anti-Fouling		(lb/hr - Total tower)	
Drift Elim. Type	Cellular/0.005%			

* Measured flow. Design tower flow is 125,000 GPM

Fan Diameter	32.8	ft	12500
Number Blades	8		103.044239
Motor Speed	1785	rpm	121.3071213
2nd Speed	N/A	rpm, if applicable	
Fan Speed	121	rpm	
- or Gear Ratio -			
VR Stacks ? (Y/N)	Yes, 10'		

Motor Volts	460	running

Motor Amps:		Motor KiloWatts (or pF) - if available:
Fan # A		130.3
Fan # B		129.2
Fan # C		134.8
Fan # D		132.5
Fan # E		134.1
Fan # F		132.9
Fan # G		133
Fan # H		133.2
Fan # J		135.2
Fan # K		135.9

EPRI Cooling Tower Fan Speed Study
Circulating Water Pump Design

Note: This information is optional so long as the prior cooling tower test measurement of circulating water flow is valid for all of the design cases to be examined for this study.

Plant Name:	Plant A	Unit No.:	
Available #:	2	OEM Pumps:	Ingersoll-Dresser (IDP)
In-Service #:	2	OEM Motors:	

Build Year:	2000	Rebuild Yr (or N/A):	
Perf. Test Year:	N/A		

Design Performance Data (per pump):

Flow	62,500	gpm
TDH	80	ft
HP	1411	HP
Efficiency	89.5	%

EPRI Cooling Tower Fan Speed Study
Condenser Design

Plant Name:	Plant A		Unit No.:	
OEM:	TEI			
Build Year:	2000			
Retube Year:	N/A	If Applicable		

Num. of Shells:	1
Num. Tube Passes:	2
# Shell Pressures:	1

Tubing:

Body - Material:	Titanium	Count:	12067	Tube Wall Gage:	22
Air Rem. - Material:	Titanium	Count:	400	Tube Wall Gage:	22
Other - Material:		Count:		Tube Wall Gage:	

(Perimeter/Impingment Area)

Total Surf. Area	104,441	sq. feet
Tube O.D.	1	inch

Design Values:

Cleanliness	85	%
Heat Load	1,140 x 10^6	BTU/hr
CW Flow	108,810	gpm
CW Temperature	86	^{o}F
Shell Pressure(s)	3.11	inHgA

Approximate Counts Plugged

Body:	
Air Removal:	
Other:	

EPRI Cooling Tower Fan Speed Study
Steam Turbine Design

NORMAL OPERATION: CASE 1

Ambient Temperature	65	°F
Ambient RH	60	%
Wetbulb Temperature	56.7	°F
Elevation	25	ft
CT Load	100	%
Supp Firing	off	
Power Aug	off	

Plant Name:	Plant A	Unit No.:	
OEM:	GE		
Build Year:	2000		

Design Values VWO: (Pressure/Temperature/Flow)

Main Steam	1820.9	psia	1050.2	°F	848,785	pph
CRH	448.4	psia	680.1	°F	819,258	pph
HRH	429.36	psia	1049.6	°F	934,727	pph
LP Adm	57.33	psia	498.4	°F	162,873	pph
Xover	56.46	psia	?	°F	?	pph
LP Exhaust	1.97	inHgA	100.5	°F	1,124,522	pph

Reference: Plant A Full Load Normal Operation, HB-3060.101

NORMAL OPERATION: CASE 2

Ambient Temperature	95	°F
Ambient RH	45	%
Wetbulb Temperature	77.1	°F
Elevation	25	ft
CT Load	100	%
Supp Firing	off	
Power Aug	off	

Plant Name:	Plant A	Unit No.:	
OEM:	GE		
Build Year:	2000		

Design Values VWO: (Pressure/Temperature)

Main Steam	1780	psia	1050.3	°F	828,751	pph
CRH	441.6	psia	682.5	°F	799,875	pph
HRH	423.14	psia	1050	°F	921,110	pph
LP Adm	56.25	psia	497.1	°F	156,243	pph

Xover	55.41	psia	?	°F	?	pph
LP Exhaust	2.76	inHgA	111	°F	1,103,629	pph

Reference: Plant A Full Load Normal Operation, HB-3060.103

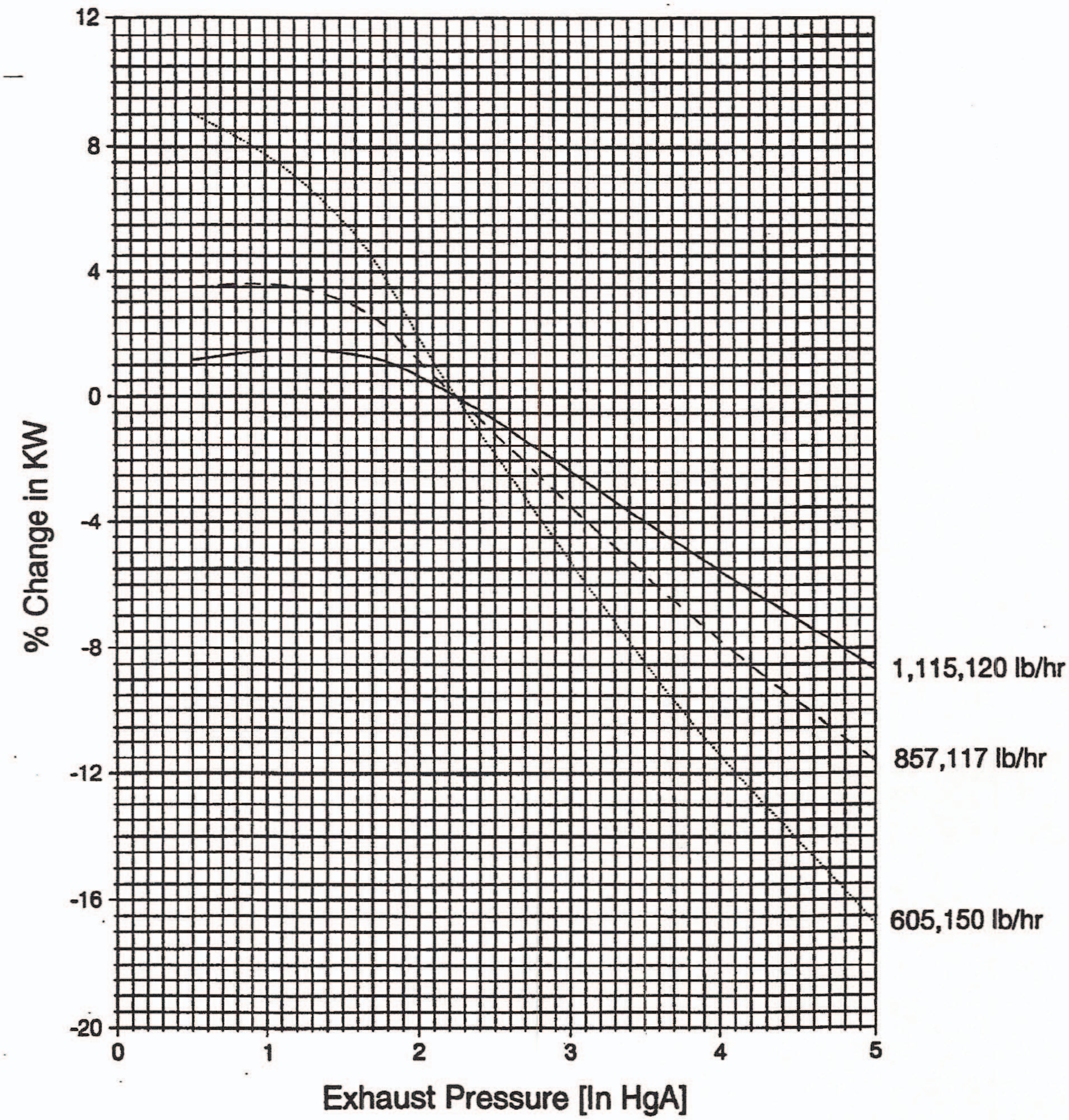
Exhaust Pressure Correction Factors

191,812 KW 2.25 IN.HGA 0 PCT MU

TC2F 33.5 IN LSB 3600 RPM
1800 PSIG 1050 F 1050 F

Plant A

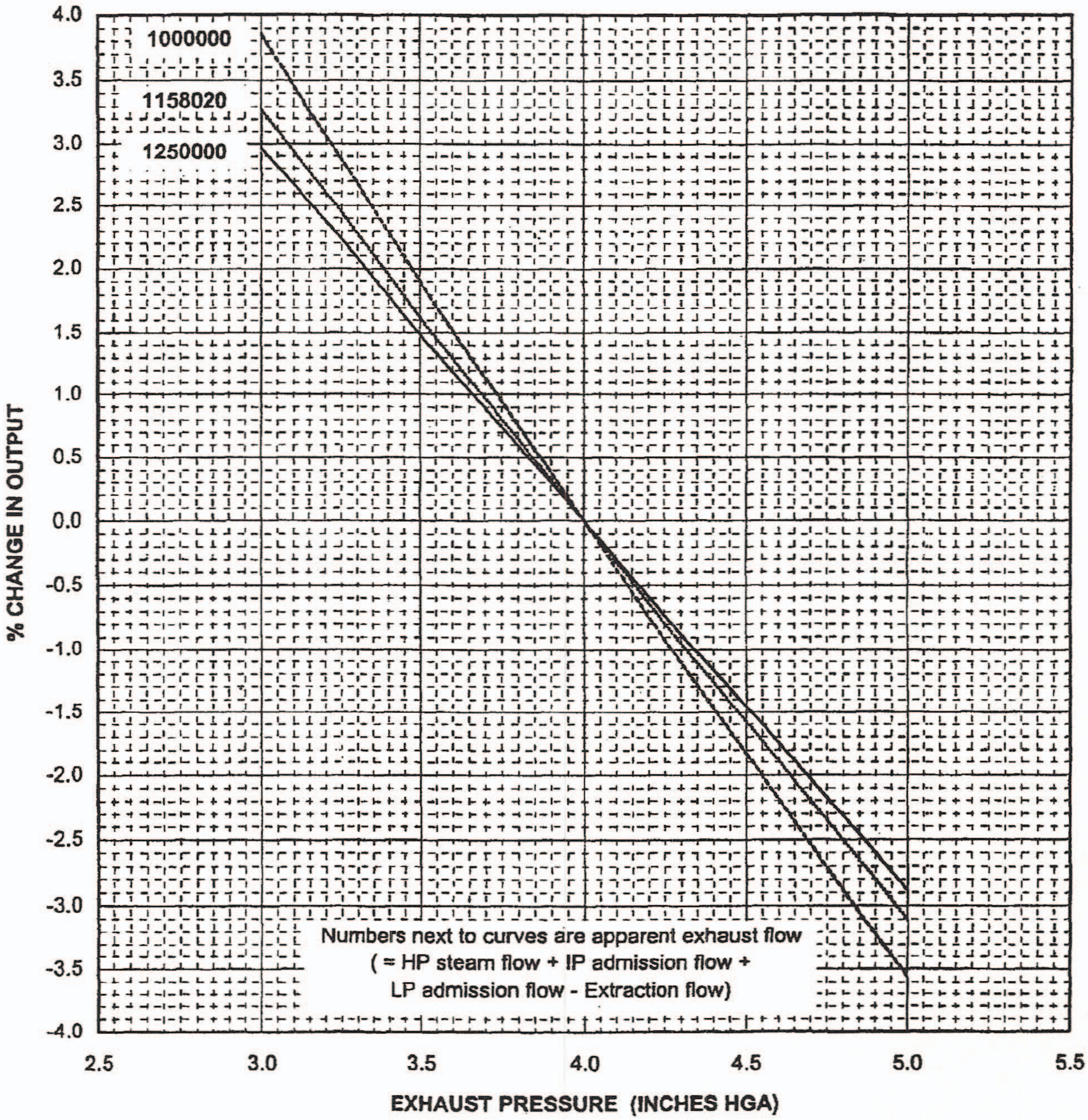
1. These corrections factors are not guaranteed.
2. Numbers by curves are exhaust flows



OUTPUT CORRECTION FOR EXHAUST PRESSURE
STEAM TURBINE 100% LOAD OPERATION

1950 PSIA / 1050 F / 1050 F
. 193,265 KW / 4.0 in HgA / 0 % MU
Expected Data - Not Guaranteed

Plant A



EPRI Cooling Tower Fan Speed Study
Effect of Ambient Conditions on Steam Production

Note 1: Only applicable for combined cycle CTG/HRSG/STG Plants

Note 2: Values reported are for duct firing out of service (i.e. heat recovery mode only).

NORMAL OPERATION: CASE 1

Ambient Temperature	65	^{o}F
Ambient RH	60	%
Wetbulb Temperature	56.7	^{o}F
Elevation	25	ft
CT Load	100	%
Supp Firing	off	
Power Aug	off	

Plant Name:	Plant A		Unit No.:	
CTG OEM:	GE	Build Year:	2000	
HRSG OEM:	Vogt	Build Year:	2000	
STG OEM:	GE	Build Year:	2000	

Design Values: (flow, each HRSG)

HP Steam Flow	424,394	pph	1055.1	^{o}F	1859.1	psia
CRH Steam Flow	409,629	pph	679.7	^{o}F	444.3	psia
IP Steam Flow	57,734	pph	?	^{o}F	444.26	psia
HRH Steam Flow	467,363	pph	1054.6	^{o}F	433.2	psia
LP Steam Flow	81,437	pph	498.4	^{o}F	58.36	psia
CTG Exhaust Flow	3,531,815	pph	1121..6	^{o}F		psia

Design Values: (temperature)

TAT or Exh. Temp	1121.6	^{o}F
Stack Temp	185.3	^{o}F

NORMAL OPERATION: CASE 2

Ambient Temperature	95	^{o}F
Ambient RH	45	%
Wetbulb Temperature	77.1	^{o}F
Elevation	25	ft
CT Load	100	%
Supp Firing	off	
Power Aug	off	

Plant Name:	Plant A		Unit No.:	
CTG OEM:	GE	Build Year:	2000	
HRSG OEM:	Vogt	Build Year:	2000	
STG OEM:	GE	Build Year:	2000	

Design Values: (flow, each HRSG)

HP Steam Flow	414,376	pph	1055.3	^oF	1817.3	psia
CRH Steam Flow	399,938	pph	682.1	^oF	437.6	psia
IP Steam Flow	55,444	pph	?	^oF	437.65	psia
HRH Steam Flow	460,555	pph	1055	^oF	427	psia
LP Steam Flow	78,122	pph	497.26	^oF	57.22	psia
CTG Exhaust Flow	3,358,721	pph	1139.3	^oF		psia
HP Steam Flow	424,934	pph				
IP Steam Flow	57,734	pph				
LP Steam Flow	81,437	pph				
CTG Exhaust Flow	3,531,815	pph				

Design Values: (temperature)

TAT or Exh. Temp	1139.3	^oF
Stack Temp	189.1	^oF

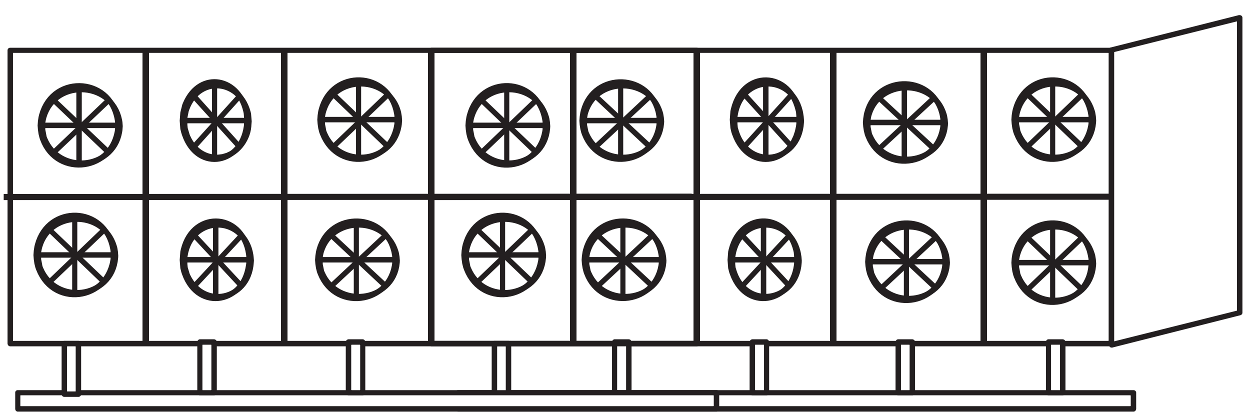
DESIGN DATA FOR PLANT B

EPRI Cooling Tower Fan Speed Study
Plant Data Matrix

Plant Name:	Plant B	Unit No.:		
Owner:		Type:	Pulverized Coal	
Location:		CT Type:	Ind. Draft, Counterflow	
Lat./Long.		Medium:	Brackish	fresh/salt
Elevation:		Num.Cells	16	

Plant Layout

Cooling Tower Layout



EPRI Cooling Tower Fan Speed Study
Cooling Tower Design

Plant Name:	Plant B		Unit No.:	
Type:	Pulverized Coal		OEM - Tower:	Evaptech
CT Type:	Ind. Draft, Counterflow		OEM - Fans:	Hudson
Medium:	Brackish	fresh/salt	OEM - Motors:	
Num.Cells	16			

Build Year:	1972		Rebuild Yr (or N/A	2009
Perf. Test Year:	2010			
Test Capability:	104.5	%		

CW Flow Total*	173,929	gpm	Design L/G	0.948
Design Range	28	°F	Design Wet Bulb	80
Design Approach	6	°F	Design Airflow	89,661,248
Fill Type	Film (Vertically Fluted)		(lb/hr - total tower)	
Drift Elim. Type	Cellular (0.0005% drift rate)			

* Measured flow. Design tower flow is 172,000 GPM

Fan Diameter	32.8	ft
Number Blades	10	
Motor Speed	1785	rpm
2nd Speed	N/A	rpm, if applicable
Fan Speed	117	rpm
- or Gear Ratio -		
VR Stacks ? (Y/N)	Yes (14 ft.)	

Motor Volts	460	running

Motor Amps:		Motor KiloWatts (or pF) - if available:
Fan # 1A		160
Fan # 2A		156.4
Fan # 3A		157.4
Fan # 4A		155.2
Fan # 5A		161.1
Fan # 6A		159.5
Fan # 7A		158.1
Fan # 8A		159.6
Fan # 1B		160.6
Fan # 2B		161.5
Fan # 3B		160
Fan # 4B		156.8
Fan # 5B		159.9
Fan # 6B		154.7
Fan # 7B		162.3
Fan # 8B		162.2

EPRI Cooling Tower Fan Speed Study
Circulating Water Pump Design

Note: This information is optional so long as the prior cooling tower test measurement of circulating water flow is valid for all of the design cases to be examined for this study.

Plant Name:	Plant B	Unit No.:	
Available #:	4	OEM Pumps:	
In-Service #:	4	OEM Motors:	

NOTE: Plant B has two sets of pumps in the circulating water loop - two (2) circulating water pumps that pump the water through the condenser and two (2) cooling tower booster pumps that pump the water to the tower. The two sets of pumps operate in series.

Build Year:	2009	Rebuild Yr (or N/A):	
Perf. Test Year:	N/A		

CIRCULATING WATER PUMP
Design Performance Data (per pump):

Flow	86000	gpm
TDH	30	ft
HP	771	HP
Efficiency	87	%

COOLING TOWER BOOSTER PUMP
Design Performance Data (per pump):

Flow	86000	gpm
TDH	60	ft
HP	1543	HP
Efficiency	87	%

EPRI Cooling Tower Fan Speed Study
Condenser Design

Plant Name:	Plant B	Unit No.:	
OEM:			
Build Year:			
Retube Year:	1990?	If Applicable	

Num. of Shells:	2
Num. Tube Passes:	1
# Shell Pressures:	2

Tubing:

Body - Material:	Titanium	Count:	49600	Tube Wall Gage:	22
Air Rem. - Material:	Titanium	Count:	2076	Tube Wall Gage:	22
Other - Material:		Count:		Tube Wall Gage:	

Total Surf. Area	230,000	sq. feet
Tube O.D.	1	inch

Design Values:

Cleanliness	85	
Heat Load	2,371 x 10^6	BTU/hr
CW Flow	172,000	gpm
CW Temperature	86	^{o}F
Shell Pressure(s)	2.83 (LP), 4.08 (HP)	inHgA

Approximate Counts Plugged

Body:	
Air Removal:	
Other:	

EPRI Cooling Tower Fan Speed Study
Steam Turbine Design

Plant Name:	Plant B	Unit No.:	
OEM:	GE		
Build Year:	1973		

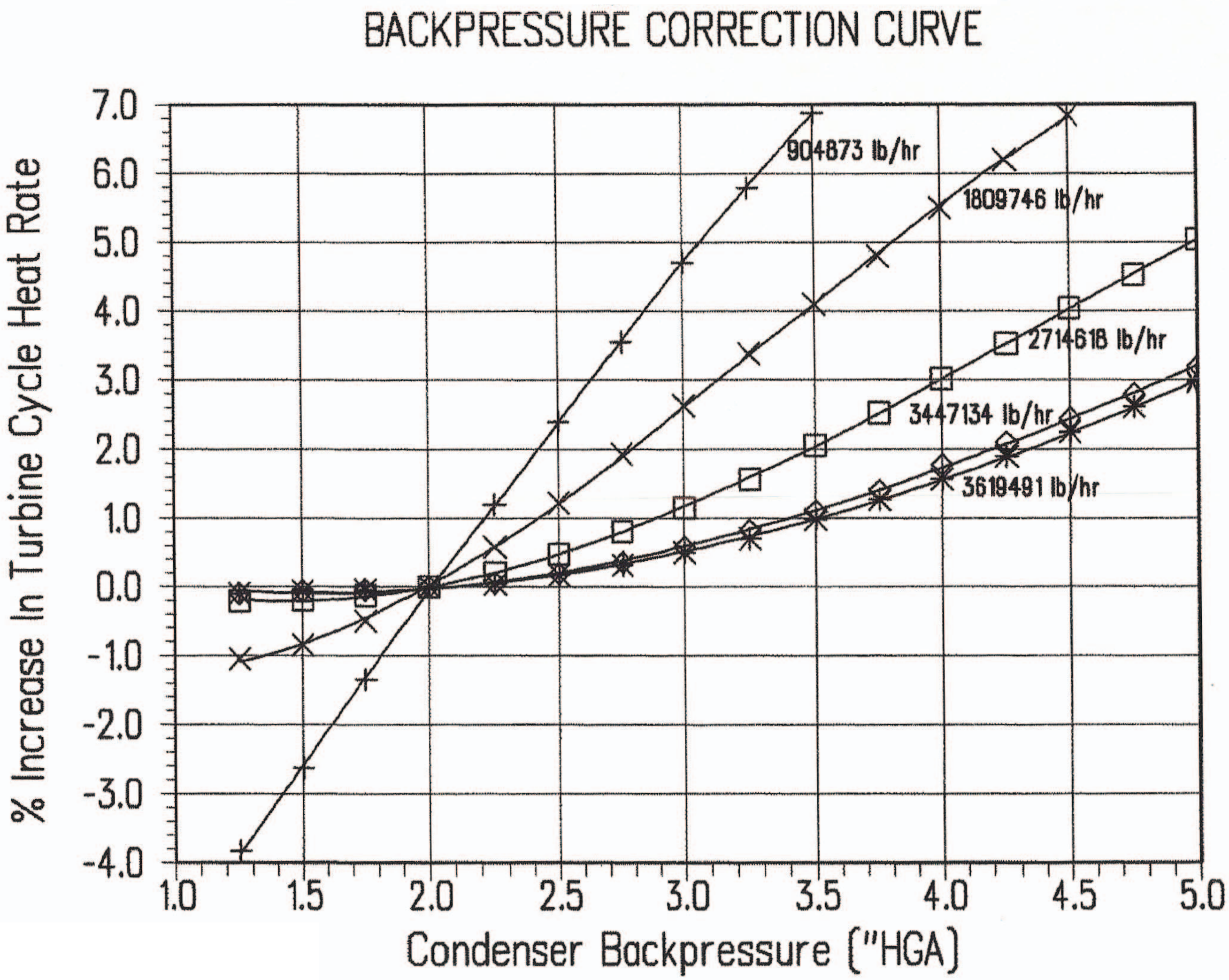
Design Values VWO: (Pressure/Temperature) — VWO with 5% overpressure

Throttle	2520	psig	1000	°F
CRH	657.2	psiA	1317.2	BTU/lb enthalpy
HRH	591.5	psiA	1000	°F
Xover	177.7	psiA	1375.7	BTU/lb enthalpy
Condenser	2	inHgA	101.1	°F

Throttle Flow	3,812,536	pph
CRH Flow	3,370,249	pph
HRH Flow	3,374,315	pph
Exhaust	2,393,958	pph

Reference: See attached Heat Balance

Plant B



BACKPRESSURE CORRECTION CURVE
% Increase In Turbine Cycle Heat Rate
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Condenser Backpressure ("HGA)
904873 lb/hr
1809746 lb/hr
2714618 lb/hr
3447134 lb/hr
3619491 lb/hr

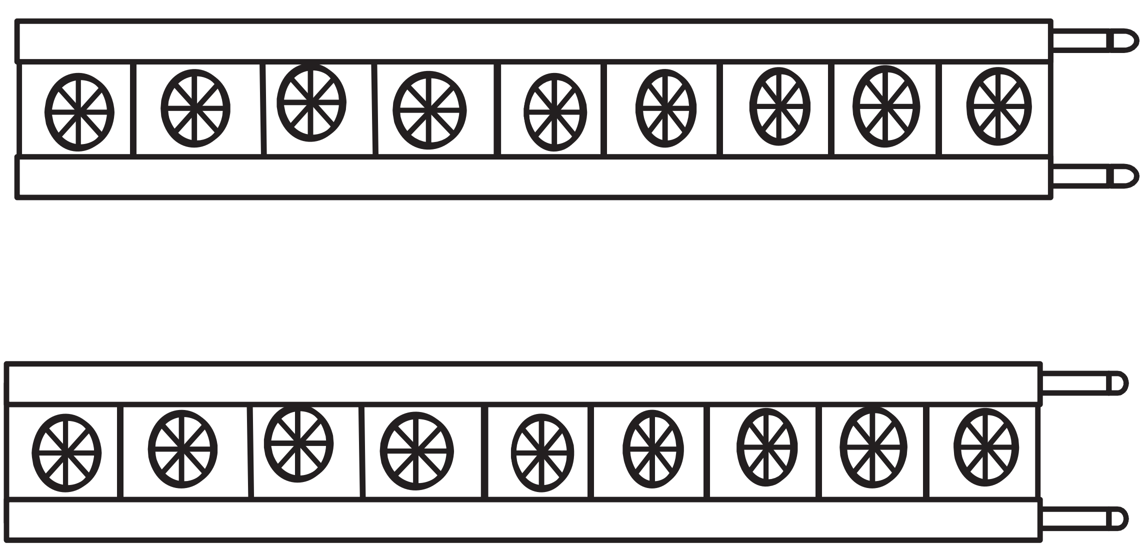
DESIGN DATA FOR PLANT C

EPRI Cooling Tower Fan Speed Study
Plant Data Matrix

Plant Name:	Plant C	Unit No.:		
Owner:		Type:	Pulverized Coal	
Location:		CT Type:	Induced Draft, Crossflow	
Lat./Long.		Medium:	Fresh	fresh/salt
Elevation:		Num.Cells	18 (2 towers, 9 cells each)	

Plant Layout

Cooling Tower Layout



EPRI Cooling Tower Fan Speed Study
Cooling Tower Design

Plant Name:	Plant C		Unit No.:	
Type:	Pulverized Coal		OEM - Tower:	Ecodyne
CT Type:	Induced Draft, Crossflow		OEM - Fans:	Various
Medium:	Fresh	fresh/salt	OEM - Motors:	Various
Num.Cells	18 (2 towers, 9 cells each)			

Build Year:	1976		Repack Yr	2007
Perf. Test Year:	2007		*Tower was repacked and an additional FRP fill support structure was added.*	
Test Capability:	105	%		

CW Flow Total*	379,245	gpm	Design L/G	1.885
Design Range	23.7	°F	Design Wet Bulb	77
Design Approach	17	°F	Design Airflow	100,458,301
Fill Type	Splash Bar		(lb/hr - total tower)	
Drift Elim. Type	Brentwood XF150			

* Measured flow. Design tower flow is 370,000 GPM

Fan Diameter		ft
Number Blades		
Motor Speed		rpm
2nd Speed		rpm, if applicable
Fan Speed		rpm
- or Gear Ratio -		
VR Stacks ? (Y/N)		

Motor Volts		running

Motor Amps:		Motor KiloWatts (or pF) - if available:
Fan # A1		143.5
Fan # A2		135.6
Fan # A3		146.5
Fan # A4		130.3
Fan # A5		132.5
Fan # A6		121.6
Fan # A7		141.5
Fan # A8		129.7
Fan # A9		129.3
Fan # B1		128.3
Fan # B2		143.6
Fan # B3		125.1
Fan # B4		146.6
Fan # B5		129.3
Fan # B6		131.7
Fan # B7		134.1

Fan # B8		121.5
Fan # B9		151.6

EPRI Cooling Tower Fan Speed Study
Condenser Design

Plant Name:	Plant C		Unit No.:		
OEM:	GE				
Build Year:	1976				
Retube Year:		If Applicable			
Num. of Shells:	2				
Num. Tube Passes:	1				
# Shell Pressures:	2				
Tubing:					
Body - Material:	304 SS	Count:	42000	Tube Wall Gage:	22
Air Rem. - Material:	304 SS	Count:	2054	Tube Wall Gage:	22
Other - Material:		Count:		Tube Wall Gage:	
Total Surf. Area	415,202				
Tube O.D.	1				
Design Values:					
Cleanliness	77				
Heat Load	4,150 x 10^6	BTU/hr			
CW Flow	337,260	gpm			
CW Temperature	93	ºF			
Shell Pressure(s)	3.363 (LP), 4.763 (HP)	inHgA			
Approximate Counts Plugged					
Body:					
Air Removal:					
Other:					

EPRI Cooling Tower Fan Speed Study
Steam Turbine Design

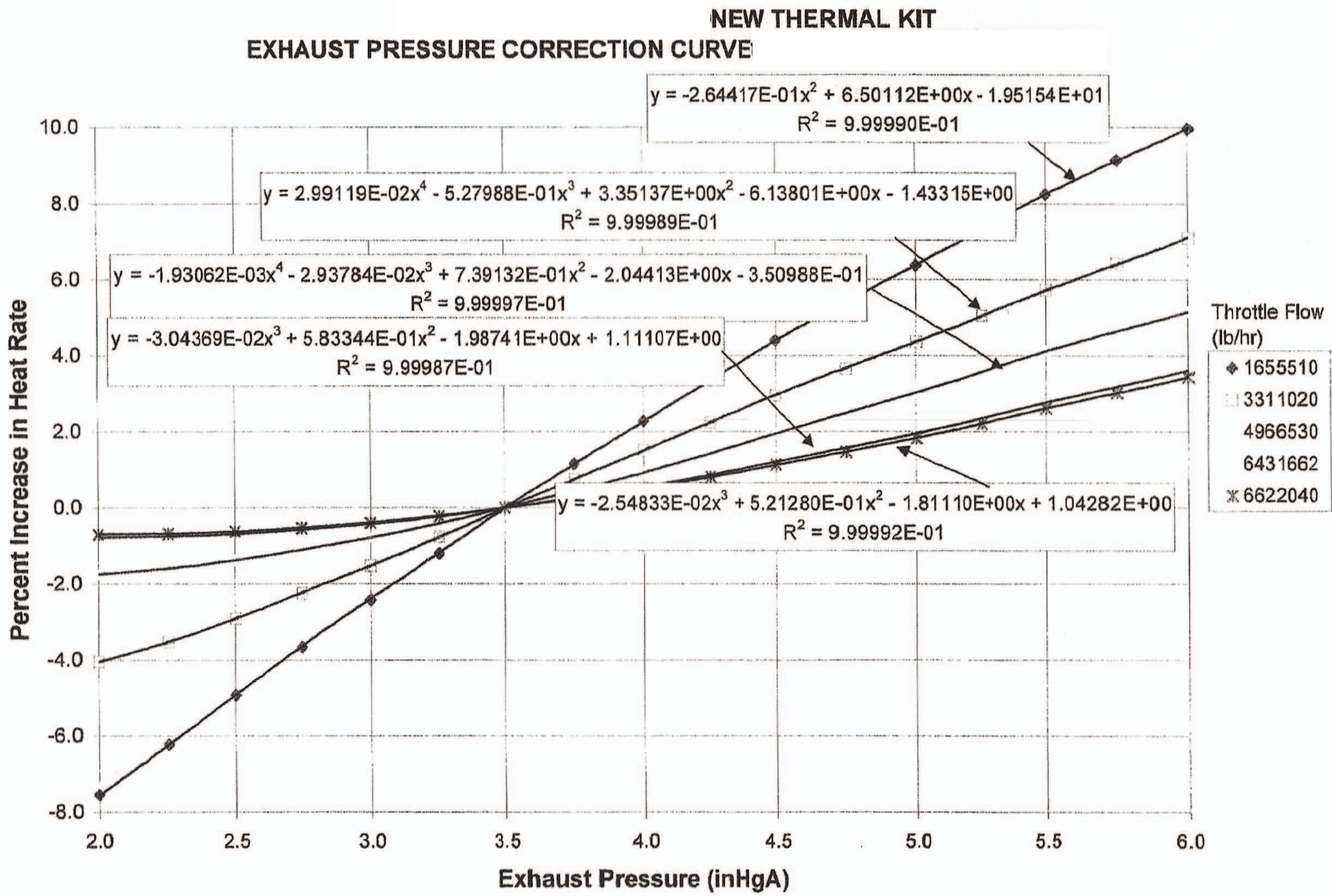
Plant Name:	Plant C	Unit No.:	
OEM:	GE		
Build Year:	1976		

Design Values VWO: (Pressure/Temperature)

Throttle	3675	psig	1000	ºF
CRH	799.5	psiA	1270.3	BTU/lb enthalpy
HRH	719.6	psiA	1000	ºF
Xover	182.6	psiA	1356.7	BTU/lb enthalpy
Condenser	3.5	inHgA	120.6	ºF

Throttle Flow	6,617,285	pph
CRH Flow	assume = HRH	pph
HRH Flow	5,865,592	pph
Exhaust	3,954,505	pph

Plant C



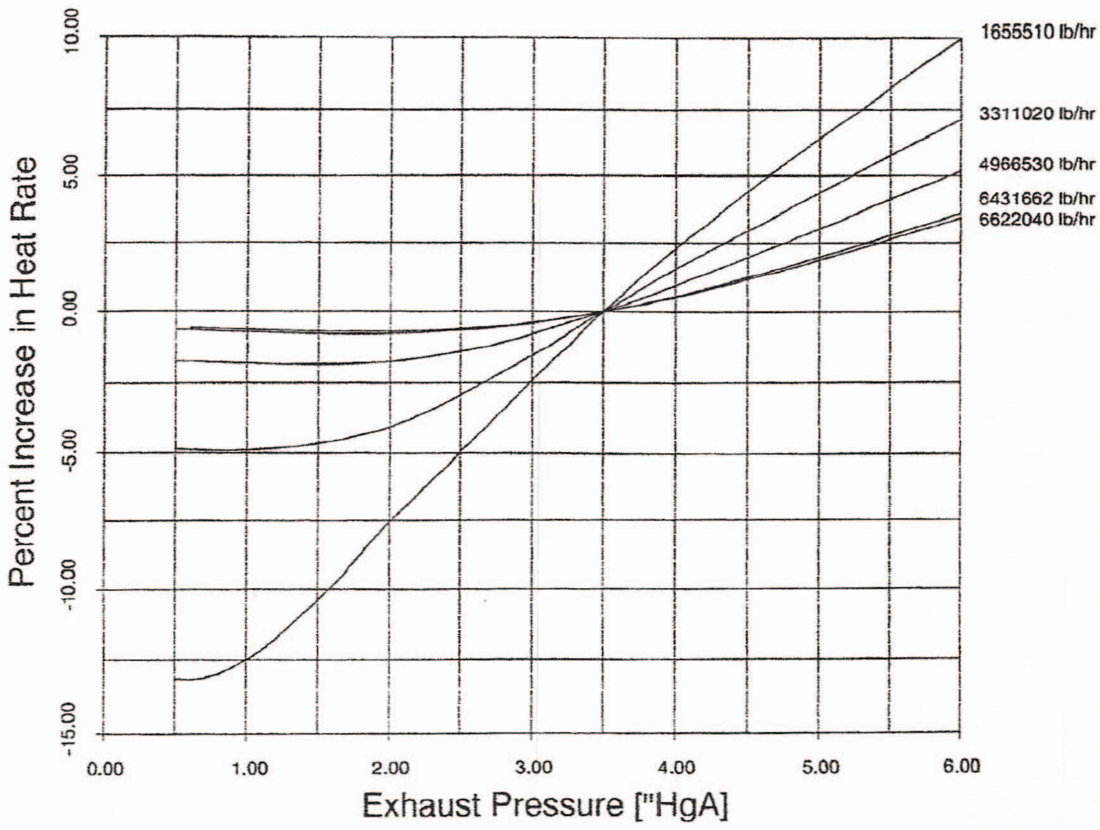
NEW THERMAL KIT
EXHAUST PRESSURE CORRECTION CURVE
y = -2.64417E-01x^2 + 6.50112E+00x - 1.95154E+01
R^2 = 9.99990E-01
y = 2.99119E-02x^4 - 5.27988E-01x^3 + 3.35137E+00x^2 - 6.13801E+00x - 1.43315E+00
R^2 = 9.99989E-01
y = -1.93062E-03x^4 - 2.93784E-02x^3 + 7.39132E-01x^2 - 2.04413E+00x - 3.50988E-01
R^2 = 9.99997E-01
y = -3.04369E-02x^3 + 5.83344E-01x^2 - 1.98741E+00x + 1.11107E+00
R^2 = 9.99987E-01
y = -2.54833E-02x^3 + 5.21280E-01x^2 - 1.81110E+00x + 1.04282E+00
R^2 = 9.99992E-01
Percent Increase in Heat Rate
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Exhaust Pressure (inHgA)
Throttle Flow (lb/hr)
1655510
3311020
4966530
6431662
6622040

Exhaust Pressure Correction Factors

927918. KW 3.50 IN HG ABS .0 PCT MU
TC4F 33.5 IN LSB 3600 RPM
3500. PSIG 995./ 985. T

Method of using curves

1. Flows near curves are throttle flows at 3500.0 PSIG and 995.0 deg F.
2. These correction factors assume constant control valve opening.
3. Apply corrections to heat rates and kW loads at 3.50 "HgA and 0.0% MU.
4. The percent change in kW load for various exhaust pressures is equal to (minus Pct increase in Heat Rate) 100/(100 + Pct increase in Heat Rate).
5. These corrections factors are not guaranteed.
6. Correction factors give change in Net Heat Rate.



B
COOLING TOWER CALCULATIONS

Calculations in this section require software to calculate the specific humidity, specific volume and enthalpy of saturated air. Such software is commercially available. Equations for these properties can be found in the ASHRAE Handbook of Fundamentals which also contains tabulated values for these parameters as a function of temperature.

B.1 Design Calculations

B.1.1 Determination of Cooling Tower Air Flow at Design Conditions

The cold water temperature discharged from a cooling tower is directly related to the mass air flow rate through the cooling tower cell. Based on the fan laws, the volumetric air flow rate is independent of the inlet air density and proportional to the fan rotational velocity. The volumetric of air is related to mass air flow rate by

$$Q_D = G_D \bar{v}_D$$

$$G_D = \frac{L_D}{\left(\frac{L}{G}\right)_D}$$

$$L_D = G_{cw} \rho_{cw}$$

Where:

Q_D	=	volumetric flow of air at design conditions
Q_{cw}	=	volumetric flow rate of circulating water
$\bar{v}_D$	=	specific volume of air at the cooling tower exhaust at design conditions
ρ_{cw}	=	density of circulating water
L	=	mass water flow rate for cooling tower cell
G	=	mass air for cooling tower cell.

The design liquid-to-gas ratio is part of the design conditions for the cooling tower.

In order to calculate the specific volume of saturated air, it is necessary to determine the temperature and specific humidity at the cooling tower outlet. This can be determined from the outlet air enthalpy.

From mass and energy balance for the cooling tower,

$$h_{a,o} = h_{a,i} + \frac{L}{G} \text{Range} = h_{a,i} + \frac{L}{G}(T_{hw} - T_{cw})$$

Where:

$h_{a,o}$ = enthalpy of saturated at air at the cooling tower outlet

$h_{a,i}$ = enthalpy of saturated at air at the cooling tower inlet

T_{hw} = hot water temperature

T_{cw} = cold water temperature.

At design conditions, the hot water, cold water temperature, and the L/G ratio are known.

The inlet air enthalpy is calculated from the design wet-bulb temperature and design barometric pressure using the psychrometric software. This allows the saturated enthalpy at the outlet to be determined. The corresponding saturated air temperature can be determined using a trial and error calculation which allows the specific humidity and specific volume to be calculated.

B.1.2 Algorithm for Calculation of Mass Transfer Coefficient

The numerical evaluation of the integral of the Merkel equation by a four point Tchebechev integration as specified in CTI ATC-105.

The Merkel integral is

$$\frac{KaV}{L} = \int_{T_{w,o}}^{T_{w,i}} \frac{dT_w}{h_w - h_a}$$

Where:

T_a = water temperature

$T_{w,i}$ = water temperature at air inlet of cooling tower

$T_{w,o}$ = water temperature at air outlet of cooling tower

h_a = saturated air enthalpy

h_w = saturated air enthalpy at the water temperature

The numerical form of this integral is

$$\frac{KaV}{L} \approx \frac{(T_{hw} - T_{cw})}{4} \sum_{j=1,4} \frac{1}{h_{w,j} - h_{a,j}}$$

Where:

$h_{w,j}$ = the enthalpy of saturated air at the water temperature at increment j

$h_{a,j}$ = the enthalpy of saturated air at the bulk water temperature at increment j

The formulae for calculating the incremental values of water temperature and air enthalpy are summarized in Table B-1.

Table B-1
Equations For Calculating Incremental Values for Merkel Integration

Increment	Water Temperature, $T_{w,j}$	Air Enthalpy, $h_{a,j}$
1	$T_{w,1} = T_{cw} + 0.1(T_{hw} - T_{cw})$	$h_{a,1} = h_{a,i} + 0.1\frac{L}{G}c_{pw}\left(T_{hw} - T_{cw}\right)$
2	$T_{w,2} = T_{cw} + 0.4(T_{hw} - T_{cw})$	$h_{a,2} = h_{a,i} + 0.4\frac{L}{G}c_{pw}\left(T_{hw} - T_{cw}\right)$
3	$T_{w,3} = T_{cw} + 0.6(T_{hw} - T_{cw})$	$h_{a,3} = h_{a,i} + 0.6\frac{L}{G}c_{pw}\left(T_{hw} - T_{cw}\right)$
4	$T_{w,4} = T_{cw} + 0.9(T_{hw} - T_{cw})$	$h_{a,4} = h_{a,i} + 0.9\frac{L}{G}c_{pw}\left(T_{hw} - T_{cw}\right)$

The saturated air enthalpy, $h_{w,j}$, is determined at the water temperature, $T_{w,j}$, using the psychrometric software.

B.1.3 Calculation of Characteristic Fill Characteristic Constant

At the design point, the hot and cold water temperature, wet-bulb temperature, and the L/G ratio are known. This makes it possible to evaluate the Merkel integral as described in the previous section. Once this done, it is possible to evaluate calculate the value of the fill characteristic constant, C_F, by

$$C_F = \left(\frac{KaV}{L}\right)_D \left(\frac{L}{G}\right)_D^{0.8}$$

Once the curve is determined it possible to calculate the value of the mass transfer coefficient at any known value of L/G by

$$\frac{KaV}{L} = C_F \left(\frac{L}{G}\right)^{-0.8}$$

The simultaneous solution of the characteristic equation for the cooling tower and the Merkel integral were used to calculate the expected cold water temperature at every combination of air flow, water loading, and wet-bulb temperature analyzed in this study.

B.2 Algorithm for Calculating Cold Water Temperature at Projected Conditions

The required values for input to the cooling tower module calculating the cold water temperature from a cooling tower cell are summarized in Table B-2.

Table B-2
Required values for input to the cooling tower module calculating the cold water temperature from a cooling tower cell

Parameter	Source
Water Flow Rate – Volumetric	Cooling tower water flow divide by the number of cells for the cooling tower
Heat Duty	Variable input from condenser module
Air Flow Rate	Calculated as fraction of the design air flow rate
Wet-Bulb Temperature	Variable input

The process of calculating the cold water temperature at the projected conditions is a nested series of iterative loops. Iterative loops must be used to calculate the L/G ratio, the cold water temperature for each cell, and finally the hot water temperature for the cooling tower. The iteration overall iteration process is illustrated in Figure B-1.

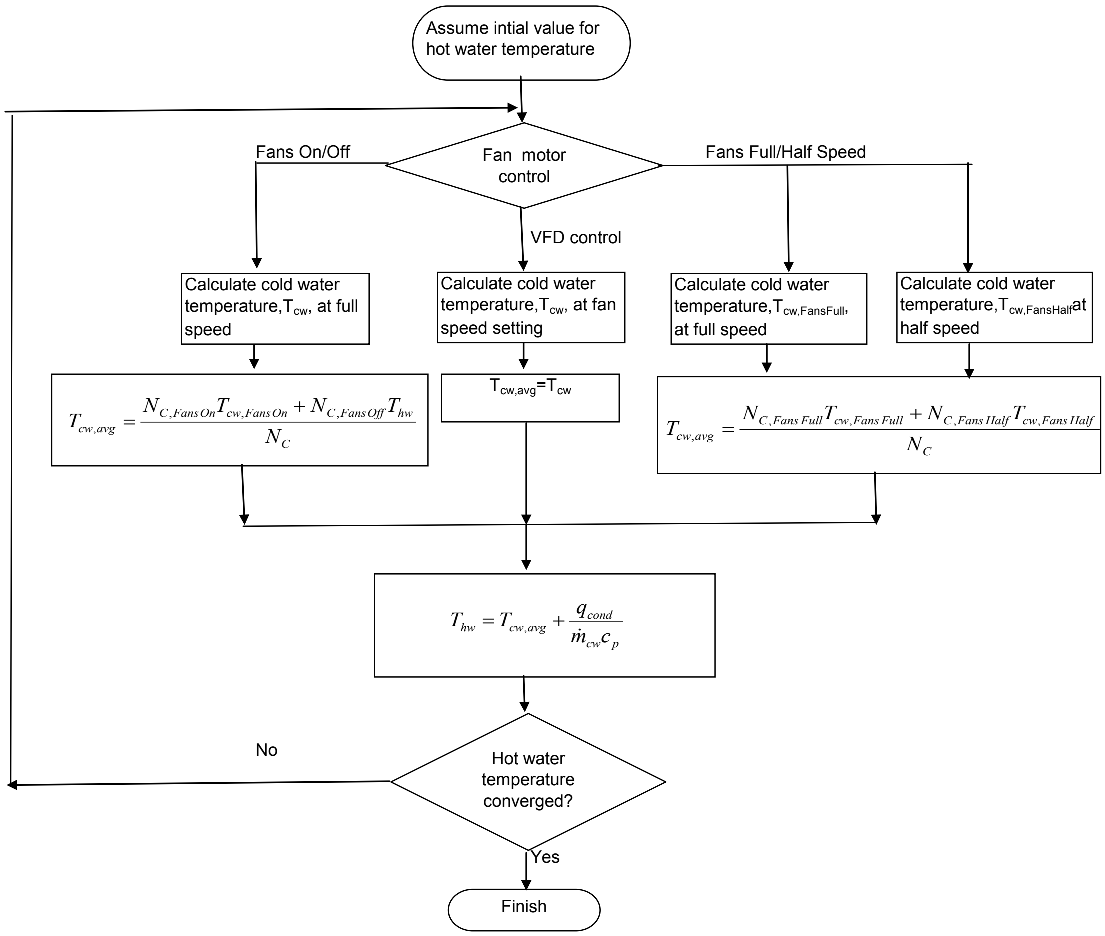


Figure B-1
Iterative Calculation Process For Water Temperatures at Projected Conditions

The first step of each iteration is the calculation of the L/G ratio.

B.2.1 Calculation of L/G Ratio

The liquid mass flow rate for a cell is calculated by

$$L = \frac{Q_{cw} \rho_{cw}}{N_{cell}}$$

Where:

Q_{cw} = volumetric flow rate of circulating water

N_{cell} = number of cooling tower cells

ρ_{cw} = density of circulating water

The volumetric air flow rate is calculated by

$$Q_p = Q_D \frac{\omega_p}{\omega_D}$$

Where:

Q_p	=	predicted volumetric air flow rate
Q_D	=	design volumetric air flow rate
ω_p	=	predicted rotational velocity
ω_D	=	design rotational velocity

The method for calculating the design volumetric air flow rate for each cooling tower is specified in section B1.1. The ratio of rotational velocities, $\frac{\omega_p}{\omega_D}$, is given by speed setting of the fan e.g. 0.5 for two-speed motors at low-speed, 0.8 for VFD controlled motors at 80 per cent speed. The mass flow rate of dry air is determined by

$$G = \frac{Q_P}{\bar{v}}$$

Where:

$\bar{v}$	=	specific volume at the cell air outlet

The enthalpy of saturated air at the outlet is calculated by

$$h_{a,o} = h_{a,i} + \frac{L}{G}(T_{hw} - T_{cw})$$

Where:

$h_{a,o}$	=	enthalpy of saturated at air at the cooling tower outlet
$h_{a,i}$	=	enthalpy of saturated at air at the cooling tower inlet
T_{hw}	=	hot water temperature
T_{cw}	=	cold water temperature.

The inlet enthalpy for the cooling tower cell is determined from the wet-bulb temperature for the prediction. The starting point for the iteration specified below is the cold water temperature for the cell, T_{cw}.

With the assumption of the necessary values, the outlet enthalpy and value for G can be determined by iterative techniques as indicated by the flow chart in Figure B-2.

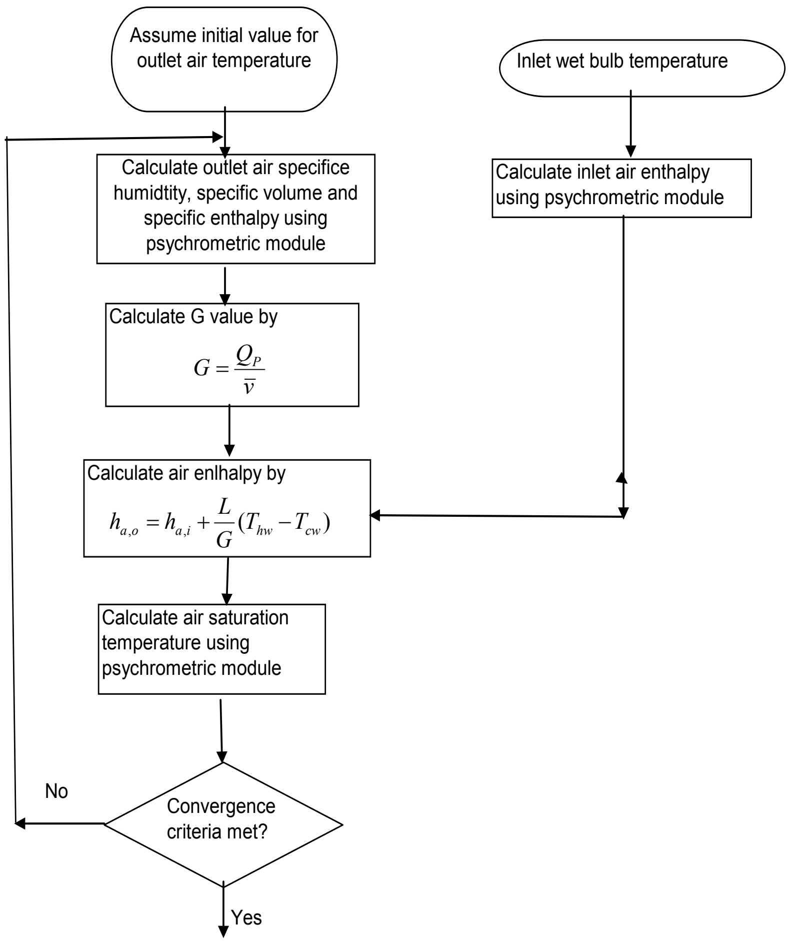


Figure B-2
Iterative Loop for Determination of L/G Ratio

B.2.2 Determination of Cold Water Temperature

The cold water temperature for the cell is the only point where the characteristic equation

$$\left[\frac{KaV}{L}\right]_C = C_F\left(\frac{L}{G}\right)^{-0.8}$$

and the Merkel integral

$$\left[\frac{KaV}{L}\right]_I = \int_{T_{Tcw}}^{T_{hw}} \frac{dT_w}{h_w - h_a}$$

yield the same value of the mass transfer coefficient, $\frac{KaV}{L}$.

The L/G ratio having been determined by the procedure documented in the Section B.1, the mass transfer coefficient, $\frac{KaV}{L}$, is calculated from the characteristic equation. The value of the mass transfer coefficient is also calculated from the Merkel integral is also calculated using the algorithm specified in section B1.2. If the difference in the two values does not meet the convergence criteria, a new value of cold water temperature is assumed, the L/G ratio recalculated, and the mass transfer coefficient recalculated by the characteristic equation and the Merkel integral recalculated.

$$\Delta k = \left| \left[\frac{KaV}{L} \right]_C - \left[\frac{KaV}{L} \right]_I \right|$$

This process, illustrated in Figure B-3, is repeated until the convergence criteria is satisfied.

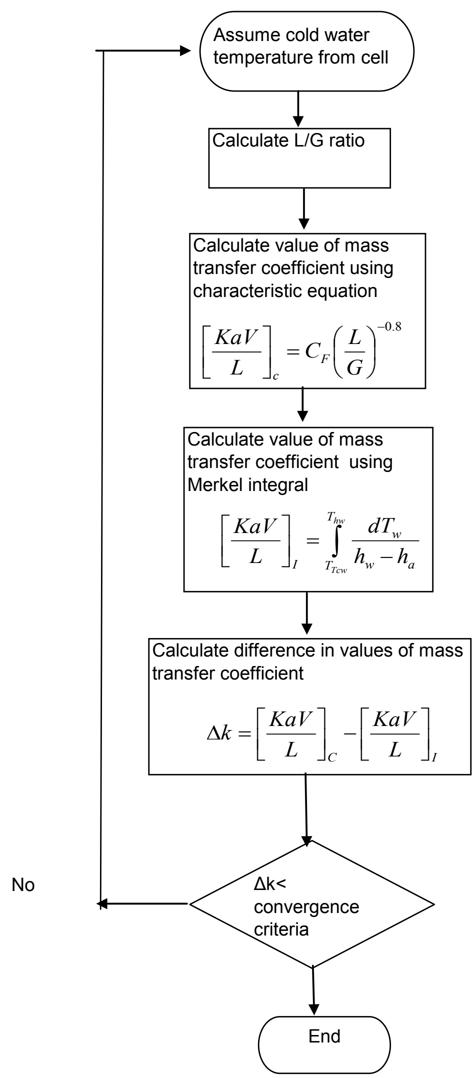


Figure B-3
Iterative Loop for Determination of L/G Ratio

B.2.3 Determination of Hot Water Temperature

The mixed cold water temperature having been determined, it is possible to calculate a new value for the hot water temperature.

$$T_{hw} = T_{cw,avg} + \frac{q_{cond}}{\dot{m}_{cw} c_p}$$

$$\dot{m}_{cw} = Q_{cw} \rho_{cw}$$

Where:

$T_{cw,avg}$	=	average cold water temperature for the cooling tower
q_{cond}	=	condenser heat duty
c_p	=	heat capacity at constant pressure of circulating water
$\dot{m}_{cw}$	=	mass flow rate of circulating water
ρ_{cw}	=	density of circulating water
Q_{cw}	=	volumetric flow rate of circulating water.

The new hot water temperature is compared to that initially assumed. If the absolute value of the difference between the new and old calculated hot water temperatures is greater than the convergence criteria (a convergence criteria of 0.1°F was used for this study) then the calculated hot water temperature is the starting point for a new iteration beginning with a calculation of the L/G ratio(s).

The heat duty for each condenser shell is calculated by multiplying the design condenser heat duty by the ratio of power output to the full-load power output.

$$q_{cond} = q^{*}_{cond} fc$$

where

q^{*}_{cond}	=	design condenser load
f_c	=	fractional unit capacity

C
CONDENSER MODULE

The condensing steam pressure is calculated by

$$NTU = \frac{UA}{c_p \dot{m}_{cw}}$$

$$T_{cw,SSCout} = T_{cw,SSCin} + \frac{q_{cond}}{\dot{m}_{cw} c_p}$$

$$T_S = \frac{T_{cw,SSCout} - T_{cw,SSCin} \exp(-NTU)}{1 - \exp(-NTU)}$$

Where:

A	=	the heat transfer area of the condenser
U	=	the overall heat transfer coefficient for the condenser
$T_{cw,SSCin}$	=	circulating water temperature at the inlet of condenser
$T_{cw,SSCout}$	=	circulating water temperature at the outlet of condenser
T_s	=	saturated steam temperature on the shell of the condenser

The pressure of saturated steam at the turbine exhaust is determined from the saturated steam temperature using standard steam tables. The overall heat transfer coefficient is determined by summing the heat transfer resistances for the

- Shell-side film, R_s
- fouling layer, R_f
- tube metal, R_m
- tube-side film, R_t.

$$U = \frac{1}{R_m + R_F + R_t + R_s}$$

The tube metal resistance, R_m is calculated by

$$R_m = \frac{d_o}{2} k_m \ln\left(\frac{d_o}{d_i}\right)$$

Where:

k_m = the conductivity of the condenser tube metal

d_o = the outside diameter of the condenser tubes

d_i = inside diameter of the condenser tubes

The fouling resistance is calculated by

$$R_f = \frac{1 - c_c^*}{U^*}$$

Where:

c_c^* = design cleanliness factor for condenser

The tube-side fouling resistance is calculated by

$$R_t = \frac{d_o}{d_i h_t} = \frac{d_o}{d_i}\left[0.158 \frac{k}{d_i} \mathrm{Re}^{0.835}\, \mathrm{Pr}^{0.462}\right]^{-1}$$

Where:

h_t = tube-side heat transfer coefficient

k = thermal conductivity of water

Re = tube-side Reynolds number

Pr = Prandtl number

The Prandtl number for water is calculated by

$$\mathrm{Pr} = \frac{c_p \mu}{k}$$

Where:

c_p = the heat capacity of water

μ = viscosity of water

The Reynolds number is calculated by

$$\mathrm{Re} = \frac{\rho V}{\mu}$$

Where:

V	=	tube-side water velocity
ρ	=	density of water

All properties are evaluated at the average tube-side temperature.

The shell-side resistance, R_s , is evaluated by

$$R_s = \frac{1}{h_s} = \left[C_s \frac{k^3 \rho^2 g l_t}{\mu \frac{\dot{m}_s}{n_t}} \right]^{-1}$$

Where:

h_s	=	shell-side heat transfer coefficient
g	=	acceleration of gravity
l_t	=	effective tube length
n_t	=	number of condenser tubes
$\dot{m}_s$	=	mass flow rate of steam
C_s	=	constant for shell-side heat transfer, dependent on condenser design

The fluid properties are evaluated at the at the shell-side film temperature.

The constant for shell-side heat transfer, C_s, is calculated from the design conditions of the condenser by

$$C_s = \left[R_s^* \frac{k^3 \rho^2 g l_t}{\mu \frac{\dot{m}_s^*}{n_t}} \right]^{-1}$$

D
OPTIMIZATION TABLES

APPENDIX D – 1 PLANT A OPTIMIZATION RESULTS

Plant A Condenser Performance - Base Load CTG, Heat Recovery, Only
Cooling Tower Fans On/Off

Exhaust Flow 1,115,120 PPH

STG Output, Nominal 191,812 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 10 Fans	kW	186298	188283	189892	191213	192265	193251	193929	194269	194455	194587	194677
9 Running - 1 Off	kW	185151	186906	188846	190228	191410	192376	193288	193911	194237	194422	194546
8 Running - 2 Off	kW	183421	185455	187091	188906	190182	191291	192187	193025	193711	194087	194310
7 Running - 3 Off	kW	181275	183281	185199	186711	188366	189662	190730	191607	192356	193063	193649

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 10 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
9 Running - 1 Off	kW	-1148	-1378	-1046	-985	-855	-876	-641	-358	-218	-166	-130
8 Running - 2 Off	kW	-2877	-2828	-2801	-2307	-2083	-1961	-1742	-1244	-744	-500	-367
7 Running - 3 Off	kW	-5023	-5003	-4693	-4502	-3900	-3589	-3199	-2662	-2099	-1524	-1028

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.120	14.923	14.743	14.578	14.427	14.286	14.156	14.035	13.921	13.813	13.712
Base Case - 10 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
9 Running - 1 Off	kW	131	133	135	136	138	139	140	141	143	144	145
8 Running - 2 Off	kW	263	266	269	272	275	278	280	283	285	287	289
7 Running - 3 Off	kW	394	399	404	408	413	417	421	424	428	431	434

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
9 Running - 1 Off	kW											14
8 Running - 2 Off	kW											
7 Running - 3 Off	kW											

Highlighted cases provide the highest net savings.

Plant A Condenser Performance - Half Load (i.e. One CTG at Base Load, Heat Recovery, etc.)
Cooling Tower Fans On/Off

Exhaust Flow 605,150 PPH

STG Output, Nominal 95,900 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 10 Fans	kW	97177	99130	100628	101538	102289	102841	103267	103596	103845	104044	104210
9 Running - 1 Off	kW	96573	98467	100194	101194	101994	102608	103070	103432	103711	103927	104103
8 Running - 2 Off	kW	95831	97630	99445	100744	101576	102271	102789	103192	103510	103756	103950
7 Running - 3 Off	kW	94832	96598	98359	99992	101006	101758	102373	102838	103204	103497	103726

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 10 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
9 Running - 1 Off	kW	-604	-662	-434	-344	-294	-234	-196	-164	-134	-117	-107
8 Running - 2 Off	kW	-1346	-1499	-1183	-794	-713	-571	-478	-404	-335	-288	-260
7 Running - 3 Off	kW	-2345	-2532	-2270	-1546	-1283	-1084	-894	-759	-641	-547	-484

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.755	14.550	14.360	14.185	14.022	13.870	13.727	13.593	13.465	13.343	13.226
Base Case - 10 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
9 Running - 1 Off	kW	131	133	135	136	138	140	141	142	144	145	146
8 Running - 2 Off	kW	262	266	270	273	276	279	282	285	287	290	293
7 Running - 3 Off	kW	393	399	404	409	414	419	423	427	431	435	439

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
9 Running - 1 Off	kW									10	28	40
8 Running - 2 Off	kW										2	33
7 Running - 3 Off	kW											

Highlighted cases provide the highest net savings.

Plant A Condenser Performance - Base Load CTG, Heat Recovery, Only
Cooling Tower Fan Speed Control (VFD)

Exhaust Flow 1,115,120 PPH

STG Output, Nominal 191,812 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	186298	188283	189892	191213	192265	193251	193929	194269	194455	194587	194677
90% Speed	kW	185792	187565	189346	190656	191738	192676	193541	194038	194308	194465	194583
80% Speed	kW	185115	186748	188552	189895	191058	191982	192828	193584	194020	194273	194426
70% Speed	kW	184074	185804	187281	188917	190058	191081	191900	192640	193341	193832	194119

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
90% Speed	kW	-507	-719	-546	-557	-527	-575	-388	-231	-147	-123	-93
80% Speed	kW	-1183	-1536	-1340	-1318	-1207	-1270	-1101	-685	-435	-314	-251
70% Speed	kW	-2224	-2479	-2611	-2297	-2207	-2170	-2029	-1629	-1114	-755	-557

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.120	14.923	14.743	14.578	14.427	14.286	14.156	14.035	13.921	13.813	13.712
90% Speed	kW	356	360	365	369	373	376	380	383	386	389	392
80% Speed	kW	641	649	657	664	671	678	684	690	696	701	706
70% Speed	kW	862	874	884	894	904	913	921	929	937	944	951

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
90% Speed	kW								152	240	267	299
80% Speed	kW								6	261	387	456
70% Speed	kW										189	394

Highlighted cases provide the highest net savings.

Plant A Condenser Performance - Half Load (i.e. One CTG at Base Load, Heat Recovery, etc.)
Cooling Tower Fan Speed Control (VFD)

Exhaust Flow 605,150 PPH

STG Output, Nominal 95,900 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	97177	99130	100628	101538	102289	102841	103267	103596	103845	104044	104210
90% Speed	kW	96858	98835	100372	101307	102086	102671	103117	103467	103736	103945	104118
80% Speed	kW	96466	98273	99972	101026	101809	102440	102915	103290	103585	103813	103996
70% Speed	kW	95951	97642	99350	100626	101425	102108	102632	103038	103364	103624	103826
60% Speed	kW	95221	96816	98442	99939	100903	101603	102201	102662	103027	103325	103566

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
90% Speed	kW	-319	-295	-257	-231	-203	-170	-150	-130	-110	-99	-92
80% Speed	kW	-711	-857	-656	-512	-480	-401	-351	-307	-260	-231	-214
70% Speed	kW	-1226	-1488	-1278	-912	-864	-734	-635	-558	-481	-420	-384
60% Speed	kW	-1956	-2314	-2186	-1599	-1386	-1239	-1066	-935	-818	-719	-644

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.755	14.550	14.360	14.185	14.022	13.870	13.727	13.593	13.465	13.343	13.226
90% Speed	kW	355	360	365	370	374	378	382	386	389	393	397
80% Speed	kW	640	649	658	666	673	681	688	695	701	708	714
70% Speed	kW	862	874	885	896	907	917	926	935	944	953	961
60% Speed	kW	1028	1043	1056	1070	1082	1094	1105	1116	1127	1137	1147

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
90% Speed	kW	37	66	108	139	171	208	232	256	280	294	304
80% Speed	kW			1	154	194	280	337	388	441	476	500
70% Speed	kW					43	183	291	377	463	533	577
60% Speed	kW							39	181	308	418	503

Highlighted cases provide the highest net savings.

Plant A Condenser Performance - Base Load CTG, Heat Recovery, Only
Two-Speed Cooling Tower Fan Motors

Exhaust Flow 1,115,120 PPH

STG Output, Nominal	191,812 kW											
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	186298	188283	189892	191213	192265	193251	193929	194269	194455	194587	194677
2 Fans @ Half Speed	kW								193998	194289	194457	194581
4 Fans @ Half Speed	kW								193433	193943	194230	194406
6 Fans @ Half Speed	kW								192412	193148	193723	194065
8 Fans @ Half Speed	kW								191195	191871	192503	193120
10 Fans @ Half Speed	kW								189519	190256	190932	191501

STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
2 Fans @ Half Speed	kW								-271	-166	-130	-95
4 Fans @ Half Speed	kW								-836	-512	-357	-270
6 Fans @ Half Speed	kW								-1857	-1307	-864	-612
8 Fans @ Half Speed	kW								-3074	-2584	-2084	-1556
10 Fans @ Half Speed	kW								-4750	-4199	-3655	-3176

Fan Power Reduction:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.755	14.550	14.360	14.185	14.022	13.870	13.727	13.593	13.465	13.343	13.226
2 Fans @ Half Speed	kW	230	233	236	239	242	244	247	249	251	254	256
4 Fans @ Half Speed	kW	459	466	472	477	483	488	493	498	503	508	512
6 Fans @ Half Speed	kW	689	698	707	716	725	732	740	747	754	761	768
8 Fans @ Half Speed	kW	918	931	943	955	966	977	987	997	1006	1015	1024
10 Fans @ Half Speed	kW	1148	1164	1179	1194	1208	1221	1233	1246	1257	1269	1280

Highlighted cases yield a marginal improvement in net power output

Net Savings												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
2 Fans @ Half Speed	kW									86	124	161
4 Fans @ Half Speed	kW										151	242
6 Fans @ Half Speed	kW											156

Highlighted cases provide the highest net savings.

Plant A Condenser Performance - Half Load (i.e. One CTG at Base Load, Heat Recovery, etc.)
Two-Speed Cooling Tower Fan Motors

Exhaust Flow 605,150 PPH

STG Output, Nominal 95,900 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	97177	99130	100628	101538	102289	102841	103267	103596	103845	104044	104210
1 Fan @ Half Speed	kW				101415	102183	102757	103191	103533	103794	104003	104176
2 Fans @ Half Speed	kW				101263	102053	102649	103095	103457	103728	103946	104123
4 Fans @ Half Speed	kW				100935	101728	102383	102869	103261	103565	103804	103993
6 Fans @ Half Speed	kW				100495	101312	102030	102575	102988	103332	103605	103819
8 Fans @ Half Speed	kW				99771	100806	101525	102141	102611	103003	103304	103553
10 Fans @ Half Speed	kW				98665	99984	100859	101488	102045	102491	102849	103147

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
1 Fan @ Half Speed	kW				-123	-106	-85	-76	-63	-51	-41	-34
2 Fans @ Half Speed	kW				-275	-236	-193	-171	-139	-118	-98	-87
4 Fans @ Half Speed	kW				-603	-561	-458	-398	-335	-280	-239	-217
6 Fans @ Half Speed	kW				-1043	-976	-812	-692	-608	-513	-438	-391
8 Fans @ Half Speed	kW				-1767	-1482	-1316	-1125	-985	-842	-740	-657
10 Fans @ Half Speed	kW				-2872	-2305	-1983	-1778	-1551	-1354	-1195	-1062

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.755	14.550	14.360	14.185	14.022	13.870	13.727	13.593	13.465	13.343	13.226
1 Fan @ Half Speed	kW	115	116	118	119	121	122	123	125	126	127	128
2 Fans @ Half Speed	kW	230	233	236	239	242	244	247	249	251	254	256
4 Fans @ Half Speed	kW	459	466	472	477	483	488	493	498	503	508	512
6 Fans @ Half Speed	kW	689	698	707	716	725	732	740	747	754	761	768
8 Fans @ Half Speed	kW	918	931	943	955	966	977	987	997	1006	1015	1024
10 Fans @ Half Speed	kW	1148	1164	1179	1194	1208	1221	1233	1246	1257	1269	1280

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
1 Fan @ Half Speed	kW					15	37	47	62	75	86	94
2 Fans @ Half Speed	kW					6	52	76	110	134	156	169
4 Fans @ Half Speed	kW						30	96	163	223	268	295
6 Fans @ Half Speed	kW							48	139	241	323	377
8 Fans @ Half Speed	kW								11	164	275	367
10 Fans @ Half Speed	kW										74	218

Highlighted cases provide the highest net savings.

APPENDIX D – 2 PLANT B OPTIMIZATION RESULTS

Plant B Condenser Performance - Full Load

Steam Flow 3,447,134 PPH

STG Output, Nominal 500,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 16 Fans	kW	492852	494746	496397	497571	498394	499034	499517	499846	500060	500183	500287
15 Running - 1 Off	kW	491701	493712	495484	496844	497873	498569	499152	499573	499866	500060	500174
14 Running - 2 Off	kW	490234	492444	494254	495904	497081	497993	498623	499159	499549	499827	500023
13 Running - 3 Off	kW	---	490830	492827	494487	496012	497096	497949	498538	499042	499431	499710

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 16 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
15 Running - 1 Off	kW	-1151	-1034	-913	-727	-522	-465	-365	-273	-194	-123	-114
14 Running - 2 Off	kW	-2618	-2302	-2143	-1667	-1313	-1041	-894	-687	-511	-356	-264
13 Running - 3 Off	kW	---	-3916	-3570	-3084	-2382	-1938	-1568	-1308	-1019	-752	-577

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.219	15.021	14.841	14.676	14.524	14.384	14.254	14.133	14.020	13.913	13.812
Base Case - 16 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
15 Running - 1 Off	kW	155	157	159	161	162	164	166	167	168	170	171
14 Running - 2 Off	kW	310	314	318	322	325	328	331	334	337	339	342
13 Running - 3 Off	kW	465	471	477	482	487	492	497	501	505	509	513

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
15 Running - 1 Off	kW										47	57
14 Running - 2 Off	kW											77
13 Running - 3 Off	kW											

Plant B Condenser Performance - 75% Load

Steam Flow 2,585,350 PPH

STG Output, Nominal 375,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 16 Fans	kW	370626	372275	373523	374463	375132	375606	375888	376070	376198	376248	376282
15 Running - 1 Off	kW	369823	371647	372999	374062	374842	375373	375729	375973	376115	376212	376257
14 Running - 2 Off	kW	368879	370856	372372	373536	374415	375061	375535	375806	376010	376136	376217
13 Running - 3 Off	kW	367754	369814	371534	372828	373853	374630	375174	375589	375832	376014	376130
12 Running - 4 Off	kW	366332	368506	370413	371933	373067	373991	374695	375185	375575	375800	375982
11 Running - 5 Off	kW	364464	366885	368868	370633	372020	373068	373930	374592	375077	375452	375698

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 16 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
15 Running - 1 Off	kW	-803	-628	-524	-400	-290	-234	-159	-96	-83	-36	-25
14 Running - 2 Off	kW	-1747	-1419	-1151	-927	-716	-546	-353	-264	-188	-111	-65
13 Running - 3 Off	kW	-2872	-2461	-1989	-1634	-1279	-977	-714	-481	-366	-233	-151
12 Running - 4 Off	kW	-4294	-3769	-3110	-2530	-2065	-1615	-1193	-885	-623	-448	-299
11 Running - 5 Off	kW	-6162	-5391	-4655	-3829	-3112	-2538	-1958	-1478	-1121	-795	-583

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.993	14.791	14.607	14.437	14.280	14.134	13.998	13.870	13.750	13.636	13.527
Base Case - 16 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
15 Running - 1 Off	kW	155	157	159	161	163	164	166	167	169	170	172
14 Running - 2 Off	kW	310	314	318	322	325	329	332	335	338	341	343
13 Running - 3 Off	kW	465	471	477	483	488	493	498	502	507	511	515
12 Running - 4 Off	kW	620	628	636	643	651	657	664	670	676	681	687
11 Running - 5 Off	kW	775	785	795	804	813	822	830	837	845	852	858

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
15 Running - 1 Off	kW							7	71	86	135	147
14 Running - 2 Off	kW								71	150	229	278
13 Running - 3 Off	kW								22	141	278	364
12 Running - 4 Off	kW									53	233	387
11 Running - 5 Off	kW										56	275

Plant B Condenser Performance - 50% Load

Steam Flow 1,723,567 PPH

STG Output, Nominal 250,000 kW

STG Output, Nominal												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 16 Fans	kW	248860	250386	251544	252395	253019	253422	253723	253899	254010	254052	254086
15 Running - 1 Off	kW	248432	250010	251239	252184	252840	253288	253645	253831	253985	254035	254069
14 Running - 2 Off	kW	247914	249564	250878	251903	252607	253131	253502	253752	253914	254011	254050
13 Running - 3 Off	kW	247285	249015	250432	251515	252328	252932	253324	253652	253823	253971	254027
12 Running - 4 Off	kW	246528	248350	249847	251036	251972	252617	253110	253455	253714	253866	253989
11 Running - 5 Off	kW	245591	247491	249096	250419	251435	252227	252796	253204	253520	253736	253876
10 Running - 6 Off	kW	244383	246385	248117	249551	250716	251638	252325	252850	253215	253507	253717

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 16 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
15 Running - 1 Off	kW	-428	-376	-305	-211	-179	-134	-78	-68	-25	-17	-16
14 Running - 2 Off	kW	-945	-822	-665	-493	-413	-291	-221	-148	-96	-41	-36
13 Running - 3 Off	kW	-1575	-1371	-1112	-880	-691	-491	-399	-247	-187	-81	-59
12 Running - 4 Off	kW	-2332	-2037	-1697	-1360	-1048	-805	-613	-444	-296	-186	-97
11 Running - 5 Off	kW	-3268	-2895	-2448	-1976	-1584	-1195	-927	-696	-490	-316	-210
10 Running - 6 Off	kW	-4477	-4001	-3427	-2845	-2303	-1784	-1398	-1050	-796	-545	-369

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.766	14.560	14.369	14.193	14.029	13.876	13.732	13.596	13.466	13.343	13.224
Base Case - 16 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
15 Running - 1 Off	kW	155	157	159	161	163	165	166	168	170	171	173
14 Running - 2 Off	kW	309	314	318	322	326	329	333	336	339	342	346
13 Running - 3 Off	kW	464	471	477	483	489	494	499	504	509	514	518
12 Running - 4 Off	kW	619	628	636	644	651	659	666	672	679	685	691
11 Running - 5 Off	kW	774	785	795	805	814	823	832	840	848	856	864
10 Running - 6 Off	kW	928	942	954	966	977	988	998	1008	1018	1027	1037

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
15 Running - 1 Off	kW						31	88	100	144	154	156
14 Running - 2 Off	kW						38	111	188	244	302	310
13 Running - 3 Off	kW						3	100	257	322	433	459
12 Running - 4 Off	kW							53	228	382	499	594
11 Running - 5 Off	kW								144	359	540	654
10 Running - 6 Off	kW									222	483	668

Plant B Condenser Performance - Full Load, VFD Fan Control

Steam Flow 3,447,134 PPH

STG Output, Nominal	500,000 kW											
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	492852	494746	496397	497571	498394	499034	499517	499846	500060	500183	500287
90% Speed	kW	492213	494096	495799	497035	497986	498640	499194	499592	499872	500059	500169
80% Speed	kW	491370	493268	494888	496312	497344	498128	498697	499187	499546	499806	499995
70% Speed	kW	490151	492103	493730	495174	496388	497298	498013	498525	498970	499333	499602

STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
90% Speed	kW	-639	-650	-598	-536	-409	-394	-323	-254	-188	-124	-118
80% Speed	kW	-1482	-1478	-1509	-1259	-1050	-905	-820	-658	-515	-377	-292
70% Speed	kW	-2701	-2643	-2667	-2397	-2006	-1736	-1504	-1321	-1090	-850	-685

Fan Power Reduction:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.219	15.021	14.841	14.676	14.524	14.384	14.254	14.133	14.020	13.913	13.812
90% Speed	kW	636	645	652	660	667	673	679	685	691	696	701
80% Speed	kW	1185	1201	1215	1229	1242	1254	1265	1276	1287	1296	1306
70% Speed	kW	1613	1634	1654	1673	1690	1706	1722	1737	1751	1764	1777

Highlighted cases yield a marginal improvement in net power output

Net Savings												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
90% Speed	kW			55	124	258	279	357	431	502	572	583
80% Speed	kW					192	349	445	618	772	919	1014
70% Speed	kW							218	416	661	914	1092

Plant B Condenser Performance - 75% Load, VFD Fan Control

Steam Flow 2,585,350 PPH

STG Output, Nominal 375,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	370626	372275	373523	374463	375132	375606	375888	376070	376198	376248	376282
90% Speed	kW	370144	371864	373132	374140	374886	375394	375734	375972	376111	376209	376254
80% Speed	kW	369494	371266	372617	373680	374489	375082	375529	375788	375990	376112	376205
70% Speed	kW	368640	370461	371915	373014	373919	374614	375118	375516	375753	375952	376066
60% Speed	kW	367448	369215	370795	372056	373018	373826	374458	374956	375313	375603	375782

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
90% Speed	kW	-482	-411	-391	-323	-246	-212	-154	-97	-87	-38	-28
80% Speed	kW	-1132	-1009	-906	-783	-642	-525	-359	-282	-208	-135	-77
70% Speed	kW	-1986	-1814	-1608	-1448	-1213	-992	-770	-553	-445	-296	-216
60% Speed	kW	-3178	-3060	-2728	-2407	-2114	-1780	-1430	-1114	-885	-645	-499

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.993	14.791	14.607	14.437	14.280	14.134	13.998	13.870	13.750	13.636	13.527
90% Speed	kW	672	681	689	698	705	712	719	726	732	739	744
80% Speed	kW	1209	1226	1241	1256	1270	1283	1295	1307	1319	1330	1341
70% Speed	kW	1628	1651	1671	1691	1710	1727	1744	1760	1776	1790	1805
60% Speed	kW	1943	1970	1994	2018	2040	2061	2081	2100	2119	2137	2154

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
90% Speed	kW	190	269	299	375	459	500	566	629	645	700	716
80% Speed	kW	78	217	335	473	628	758	936	1025	1111	1195	1263
70% Speed	kW			63	243	496	735	974	1207	1331	1495	1589
60% Speed	kW						281	652	987	1234	1492	1654

Plant B Condenser Performance - 50% Load, VFD Fan Control

Steam Flow 1,723,567 PPH

STG Output, Nominal 250,000 kW

		85	80	75	70	65	60	55	50	45	40	35
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	248860	250386	251544	252395	253019	253422	253723	253899	254010	254052	254086
90% Speed	kW	248573	250104	251292	252207	252850	253288	253639	253825	253981	254032	254066
80% Speed	kW	248194	249737	250971	251939	252609	253117	253474	253731	253889	254000	254041
70% Speed	kW	247661	249230	250522	251525	252291	252860	253251	253570	253766	253908	254002
60% Speed	kW	246912	248514	249847	250928	251801	252424	252931	253266	253553	253741	253870
50% Speed	kW	245810	247427	248823	249994	250948	251728	252312	252771	253120	253381	253615

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
90% Speed	kW	-286	-283	-252	-188	-169	-134	-84	-74	-29	-20	-20
80% Speed	kW	-666	-649	-573	-456	-410	-305	-249	-169	-121	-52	-45
70% Speed	kW	-1198	-1156	-1022	-870	-728	-562	-472	-330	-244	-144	-84
60% Speed	kW	-1947	-1872	-1696	-1467	-1218	-998	-792	-634	-457	-311	-215
50% Speed	kW	-3049	-2959	-2721	-2401	-2072	-1694	-1411	-1129	-890	-670	-471

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.766	14.560	14.369	14.193	14.029	13.876	13.732	13.596	13.466	13.343	13.224
90% Speed	kW	671	680	689	698	706	714	721	729	736	742	749
80% Speed	kW	1208	1225	1241	1257	1272	1286	1299	1312	1325	1337	1349
70% Speed	kW	1626	1650	1671	1692	1712	1731	1749	1767	1783	1800	1816
60% Speed	kW	1941	1968	1994	2019	2043	2065	2087	2108	2128	2148	2167
50% Speed	kW	2166	2197	2226	2254	2280	2305	2329	2353	2375	2397	2419

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
90% Speed	kW	384	398	438	510	537	580	638	654	707	722	729
80% Speed	kW	542	576	669	801	861	980	1050	1143	1203	1285	1304
70% Speed	kW	428	493	649	822	983	1168	1277	1437	1539	1656	1732
60% Speed	kW		96	298	552	825	1067	1295	1474	1671	1837	1952
50% Speed	kW					208	611	918	1224	1485	1727	1948

Plant B Condenser Performance - Full Load, Two-Speed Fans

Steam Flow 3,447,134 PPH

STG Output, Nominal 500,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW							499514	499841	500057	500182	500289
2 Fans @ Half Speed	kW							499267	499647	499919	500089	500203
4 Fans @ Half Speed	kW							498938	499397	499719	499958	500101
6 Fans @ Half Speed	kW							498548	499059	499455	499743	499957
8 Fans @ Half Speed	kW							498107	498630	499091	499444	499710
9 Fans @ Half Speed	kW							497847	498395	498854	499255	499553

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
2 Fans @ Half Speed	kW							-247	-194	-138	-93	-87
4 Fans @ Half Speed	kW							-577	-444	-338	-224	-188
6 Fans @ Half Speed	kW							-967	-782	-602	-439	-332
8 Fans @ Half Speed	kW							-1407	-1211	-966	-738	-579
9 Fans @ Half Speed	kW							-1667	-1446	-1203	-927	-736

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.219	15.021	14.841	14.676	14.524	14.384	14.254	14.133	14.020	13.913	13.812
2 Fans @ Half Speed	kW							290	292	295	297	299
4 Fans @ Half Speed	kW							579	584	589	594	598
6 Fans @ Half Speed	kW							869	877	884	890	897
8 Fans @ Half Speed	kW							1159	1169	1178	1187	1196
9 Fans @ Half Speed	kW							1304	1315	1325	1336	1345

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
2 Fans @ Half Speed	kW							42	98	156	204	212
4 Fans @ Half Speed	kW							3	141	251	370	410
6 Fans @ Half Speed	kW								94	281	452	565
8 Fans @ Half Speed	kW									212	449	617
9 Fans @ Half Speed	kW									123	408	609

Plant B Condenser Performance - 75% Load, Two-Speed Fans

Steam Flow 2,585,350 PPH

STG Output, Nominal	375,000 kW											
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW			373604	374506	375123	375521	375746	375876	375948	375964	375955
1 Fan @ Half Speed	kW			373450	374387	375032	375460	375708	375851	375935	375962	375959
2 Fans @ Half Speed	kW			373290	374256	374931	375387	375664	375823	375918	375959	375962
4 Fans @ Half Speed	kW			372940	373956	374698	375216	375551	375750	375867	375940	375963
6 Fans @ Half Speed	kW			372543	373606	374411	374987	375393	375644	375799	375893	375950
8 Fans @ Half Speed	kW			372089	373184	374059	374703	375170	375496	375695	375821	375905
10 Fans @ Half Speed	kW			371530	372706	373623	374346	374880	375271	375540	375712	375822
12 Fans @ Half Speed	kW					373099	373882	374496	374959	375296	375539	375696
14 Fans @ Half Speed	kW					372496	373302	373987	374521	374933	375254	375480
16 Fans @ Half Speed	kW					371743	372624	373340	373946	374430	374813	375117
STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
1 Fan @ Half Speed	kW			-154	-119	-92	-61	-38	-26	-13	-1	4
2 Fans @ Half Speed	kW			-314	-251	-192	-135	-83	-53	-30	-5	7
4 Fans @ Half Speed	kW			-664	-550	-425	-306	-195	-126	-81	-24	7
6 Fans @ Half Speed	kW			-1061	-900	-712	-534	-353	-232	-150	-70	-6
8 Fans @ Half Speed	kW			-1515	-1322	-1065	-818	-577	-381	-253	-143	-50
10 Fans @ Half Speed	kW			-2074	-1800	-1500	-1175	-866	-605	-408	-252	-133
12 Fans @ Half Speed	kW					-2024	-1639	-1250	-918	-652	-425	-260
14 Fans @ Half Speed	kW					-2628	-2219	-1759	-1355	-1015	-710	-475
16 Fans @ Half Speed	kW					-3380	-2898	-2406	-1930	-1518	-1151	-839

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.993	14.791	14.607	14.437	14.280	14.134	13.998	13.870	13.750	13.636	13.527
1 Fan @ Half Speed	kW			139	141	142	144	145	147	148	149	150
2 Fans @ Half Speed	kW			278	282	285	288	290	293	296	298	300
4 Fans @ Half Speed	kW			557	563	569	575	581	586	591	596	601
6 Fans @ Half Speed	kW			835	845	854	863	871	879	887	894	901
8 Fans @ Half Speed	kW			1113	1126	1138	1150	1161	1172	1182	1192	1202
10 Fans @ Half Speed	kW			1391	1408	1423	1438	1452	1465	1478	1490	1502
12 Fans @ Half Speed	kW					1708	1725	1742	1758	1774	1788	1803
14 Fans @ Half Speed	kW					1992	2013	2032	2051	2069	2086	2103
16 Fans @ Half Speed	kW					2277	2300	2323	2344	2365	2385	2404

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
1 Fan @ Half Speed	kW				22	50	83	107	121	135	148	154
2 Fans @ Half Speed	kW				31	93	153	208	240	266	293	307
4 Fans @ Half Speed	kW				13	144	270	385	460	510	572	608
6 Fans @ Half Speed	kW					142	329	518	647	737	824	896
8 Fans @ Half Speed	kW					74	332	585	792	929	1050	1152
10 Fans @ Half Speed	kW						262	586	860	1070	1239	1369
12 Fans @ Half Speed	kW						86	492	840	1122	1363	1543
14 Fans @ Half Speed	kW							273	696	1054	1376	1628
16 Fans @ Half Speed	kW								414	846	1233	1565

Plant B Condenser Performance - 50% Load, Two-Speed Fans

Steam Flow 1,723,567 PPH

STG Output, Nominal 250,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	248873	250376	251502	252287	252808	253159	253391	253529	253593	253609	253613
2 Fans @ Half Speed	kW	248612	250152	251309	252145	252700	253078					
4 Fans @ Half Speed	kW		249928	251093	251979	252574	252985					
6 Fans @ Half Speed	kW		249604	250843	251777	252421	252866					
8 Fans @ Half Speed	kW		249276	250556	251542	252242	252723					
10 Fans @ Half Speed	kW			250230	251251	252015	252545					
12 Fans @ Half Speed	kW			249849	250904	251731	252323					
14 Fans @ Half Speed	kW			249407	250511	251377	252036	252506	252855			
16 Fans @ Half Speed	kW			248913	250072	250938	251662	252201	252597	252899	253126	253296

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0					
2 Fans @ Half Speed	kW	-261	-224	-192	-142	-108	-80					
4 Fans @ Half Speed	kW		-448	-408	-308	-234	-174					
6 Fans @ Half Speed	kW		-772	-658	-510	-387	-293					
8 Fans @ Half Speed	kW		-1100	-946	-745	-566	-436					
10 Fans @ Half Speed	kW			-1271	-1036	-793	-614					
12 Fans @ Half Speed	kW			-1653	-1382	-1077	-835					
14 Fans @ Half Speed	kW			-2094	-1776	-1431	-1123	-884	-674			
16 Fans @ Half Speed	kW			-2589	-2215	-1871	-1497	-1190	-932	-693	-483	-317

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	14.766	14.560	14.369	14.193	14.029	13.876	13.732	13.596	13.466	13.343	13.224
2 Fans @ Half Speed	kW	271	275	278	282	285	288					
4 Fans @ Half Speed	kW		549	557	563	570	576					
6 Fans @ Half Speed	kW		824	835	845	855	864					
8 Fans @ Half Speed	kW		1098	1113	1127	1140	1153					
10 Fans @ Half Speed	kW			1391	1409	1425	1441					
12 Fans @ Half Speed	kW			1670	1690	1710	1729					
14 Fans @ Half Speed	kW			1948	1972	1995	2017	2038	2059			
16 Fans @ Half Speed	kW			2226	2254	2280	2305	2329	2353	2375	2397	2419

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
2 Fans @ Half Speed	kW	10	50	86	140	177	208					
4 Fans @ Half Speed	kW		101	148	256	336	402					
6 Fans @ Half Speed	kW		52	177	335	468	571					
8 Fans @ Half Speed	kW			167	381	574	717					
10 Fans @ Half Speed	kW			120	372	632	827					
12 Fans @ Half Speed	kW			17	308	633	893					
14 Fans @ Half Speed	kW				196	564	894	1154	1384			
16 Fans @ Half Speed	kW				39	409	808	1140	1421	1682	1914	2102

APPENDIX D – 3 PLANT C OPTIMIZATION RESULTS

Plant C Condenser Performance - Full Load

Steam Flow 6,431,662 PPH

STG Output, Nominal	900,000 kW											
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 18 Fans	kW	890462	893881	896739	899077	900925	902389	903556	904475	905184	905706	906088
17 Running - 1 Off	kW	888018	891667	894728	897291	899390	901054	902389	903463	904320	904993	905506
STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 18 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
17 Running - 1 Off	kW	-2444	-2214	-2011	-1787	-1535	-1334	-1167	-1012	-863	-713	-582
Fan Power Reduction:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.736	15.545	15.372	15.215	15.072	14.941	14.821	14.710	14.607	14.511	14.422
Base Case - 18 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
17 Running - 1 Off	kW	133	135	137	138	139	141	142	143	144	145	146
No cases yield a marginal improvement in net power output												
Net Savings												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
17 Running - 1 Off	kW											

Plant C Condenser Performance - 75% Load, Fans Off

Steam Flow 4,824,000 PPH

STG Output, Nominal 675,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 18 Fans	kW	677060	679989	682352	684216	685661	686748	687526	688081	688465	688702	688835
17 Running - 1 Off	kW	675552	678647	681181	683212	684817	686059	686986	687659	688145	688485	688698
16 Running - 2 Off	kW	673760	677033	679747	681965	683743	685152	686249	687069	687675	688120	688439

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 18 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
17 Running - 1 Off	kW	-1508	-1342	-1171	-1004	-845	-688	-540	-422	-321	-217	-137
16 Running - 2 Off	kW	-3300	-2956	-2605	-2251	-1919	-1595	-1277	-1013	-790	-582	-395

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.381	15.185	15.008	14.846	14.698	14.561	14.435	14.318	14.208	14.106	14.009
Base Case - 18 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
17 Running - 1 Off	kW	133	135	137	138	140	141	142	143	144	145	146
16 Running - 2 Off	kW	267	270	273	276	279	282	284	286	289	291	293

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
17 Running - 1 Off	kW											9
16 Running - 2 Off	kW											

Plant C Condenser Performance - 50% Load, Fans Off

Steam Flow 3,216,000 PPH

STG Output, Nominal	450,000 kW											
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 18 Fans	kW	464633	467448	469566	471114	472188	473015	473643	474146	474521	474792	474981
17 Running - 1 Off	kW	463717	466651	468930	470617	471804	472688	473370	473910	474329	474641	474866
16 Running - 2 Off	kW	462634	465697	468151	469981	471325	472282	473034	473611	474082	474441	474708

STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - 18 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
17 Running - 1 Off	kW	-915	-797	-636	-497	-384	-326	-274	-237	-192	-151	-114
16 Running - 2 Off	kW	-1999	-1751	-1414	-1133	-864	-733	-610	-535	-439	-351	-272

Fan Power Reduction:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.026	14.825	14.641	14.472	14.316	14.171	14.036	13.909	13.790	13.677	13.570
Base Case - 18 Fans	kW	0	0	0	0	0	0	0	0	0	0	0
17 Running - 1 Off	kW	133	135	137	138	140	141	143	144	145	146	147
16 Running - 2 Off	kW	266	270	273	277	280	282	285	288	290	293	295

Highlighted cases yield a marginal improvement in net power output

Net Savings												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
17 Running - 1 Off	kW											33
16 Running - 2 Off	kW											22

Plant C Condenser Performance - Full Load, VFD Fan Control

Steam Flow 6,431,662 PPH

STG Output, Nominal	900,000	kW									
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	890462	893881	896739	899077	900925	902389	903556	904475	905184	905706	906088
95% Speed	kW	889251	892732	895656	898086	900050	901609	902856	903862	904654	905269	905726
90% Speed	kW	887854	891404	894396	896915	898998	900669	902014	903101	903982	904683	905234

STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
95% Speed	kW	-1211	-1149	-1083	-992	-875	-780	-700	-614	-530	-436	-363
90% Speed	kW	-2608	-2477	-2343	-2162	-1927	-1720	-1542	-1375	-1201	-1023	-854

Fan Power Reduction:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.736	15.545	15.372	15.215	15.072	14.941	14.821	14.710	14.607	14.511	14.422
95% Speed	kW	301	305	309	312	315	317	320	322	325	327	329
90% Speed	kW	616	624	631	637	643	649	654	659	664	668	672

Highlighted cases yield a marginal improvement in net power output

Net Savings												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
95% Speed	kW											
90% Speed	kW											

Plant C Condenser Performance - 75% Load, VFD Fan Control

Steam Flow 4,824,000 PPH

STG Output, Nominal 675,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	677060	679989	682352	684216	685661	686748	687526	688081	688465	688702	688835
95% Speed	kW	676267	679252	681685	683626	685152	686326	687188	687813	688260	688564	688748
90% Speed	kW	675350	678394	680900	682926	684538	685801	686763	687467	687985	688357	688609
85% Speed	kW	674297	677404	679986	682102	683805	685162	686225	687026	687624	688067	688390
80% Speed	kW	673067	676240	678902	681111	682916	684373	685537	686453	687143	687668	688064

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
95% Speed	kW	-793	-737	-667	-590	-509	-421	-338	-268	-205	-137	-87
90% Speed	kW	-1711	-1596	-1452	-1290	-1123	-947	-763	-614	-480	-345	-226
85% Speed	kW	-2763	-2586	-2366	-2114	-1856	-1585	-1301	-1055	-842	-635	-445
80% Speed	kW	-3994	-3750	-3450	-3105	-2746	-2374	-1988	-1629	-1322	-1033	-771

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.381	15.185	15.008	14.846	14.698	14.561	14.435	14.318	14.208	14.106	14.009
95% Speed	kW	301	305	309	312	315	318	321	323	326	328	331
90% Speed	kW	615	623	631	637	644	650	656	661	666	671	676
85% Speed	kW	896	908	919	929	938	947	955	963	970	978	984
80% Speed	kW	1146	1161	1175	1188	1200	1211	1222	1232	1241	1250	1259

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
95% Speed	kW								55	121	191	244
90% Speed	kW								47	186	326	450
85% Speed	kW									129	343	539
80% Speed	kW										217	488

Plant C Condenser Performance - 50% Load, VFD Fan Control

Steam Flow 3,216,000 PPH

STG Output, Nominal 450,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	464633	467448	469566	471114	472188	473015	473643	474146	474521	474792	474981
95% Speed	kW	464101	466968	469170	470802	471937	472796	473455	473982	474387	474685	474900
90% Speed	kW	463504	466422	468715	470421	471643	472540	473239	473788	474225	474554	474796
85% Speed	kW	462822	465795	468182	469970	471291	472236	472981	473554	474026	474389	474662
80% Speed	kW	462032	465064	467538	469429	470865	471881	472667	473286	473781	474181	474489
75% Speed	kW	461111	464203	466755	468773	470309	471444	472281	472954	473480	473916	474264

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
95% Speed	kW	-531	-481	-396	-312	-252	-219	-189	-164	-134	-106	-81
90% Speed	kW	-1128	-1027	-851	-693	-546	-475	-404	-358	-296	-238	-184
85% Speed	kW	-1810	-1653	-1383	-1144	-897	-779	-662	-592	-495	-403	-318
80% Speed	kW	-2601	-2384	-2028	-1685	-1324	-1133	-976	-860	-740	-611	-492
75% Speed	kW	-3521	-3245	-2811	-2341	-1880	-1571	-1363	-1192	-1041	-876	-717

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.026	14.825	14.641	14.472	14.316	14.171	14.036	13.909	13.790	13.677	13.570
95% Speed	kW	301	305	309	312	316	319	322	325	328	330	333
90% Speed	kW	615	623	631	638	645	652	658	664	670	675	681
85% Speed	kW	895	908	919	930	940	950	959	967	976	984	992
80% Speed	kW	1145	1161	1175	1189	1202	1214	1226	1237	1248	1258	1268
75% Speed	kW	1366	1384	1401	1418	1433	1448	1462	1475	1488	1500	1512

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
95% Speed	kW					64	100	133	161	193	224	252
90% Speed	kW					99	177	254	306	373	437	496
85% Speed	kW					43	171	296	375	481	580	673
80% Speed	kW						81	250	377	507	647	776
75% Speed	kW							99	283	447	625	795

Plant C Condenser Performance - Full Load, Two-Speed Fans

Steam Flow 6,431,662 PPH

STG Output, Nominal 900,000 kW

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW							903228	904183	904932	905513	905945
1 Fan @ Half Speed	kW							902773	903773	904588	905215	905714
2 Fans @ Half Speed	kW							902229	903319	904177	904868	905424
4 Fans @ Half Speed	kW							901006	902223	903214	904009	904677
6 Fans @ Half Speed	kW							899498	900895	901974	902898	903675
8 Fans @ Half Speed	kW							897650	899202	900414	901464	902375
9 Fans @ Half Speed	kW							896561	898166	899484	900613	901575

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
1 Fan @ Half Speed	kW							-455	-410	-344	-298	-231
2 Fans @ Half Speed	kW							-999	-864	-755	-644	-521
4 Fans @ Half Speed	kW							-2222	-1961	-1718	-1504	-1268
6 Fans @ Half Speed	kW							-3730	-3288	-2958	-2614	-2269
8 Fans @ Half Speed	kW							-5578	-4981	-4518	-4049	-3569
9 Fans @ Half Speed	kW							-6667	-6018	-5448	-4899	-4370

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.736	15.545	15.372	15.215	15.072	14.941	14.821	14.710	14.607	14.511	14.422
1 Fan @ Half Speed	kW	117	118	120	121	122	123	124	125	126	127	127
2 Fans @ Half Speed	kW	234	236	239	242	244	246	248	250	252	253	255
4 Fans @ Half Speed	kW	467	473	478	483	488	492	496	500	503	506	510
6 Fans @ Half Speed	kW	701	709	717	725	731	738	744	749	755	760	764
8 Fans @ Half Speed	kW	934	946	956	966	975	984	992	999	1006	1013	1019
9 Fans @ Half Speed	kW	1051	1064	1076	1087	1097	1107	1116	1124	1132	1140	1147

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
1 Fan @ Half Speed	kW											
2 Fans @ Half Speed	kW											
4 Fans @ Half Speed	kW											
6 Fans @ Half Speed	kW											
8 Fans @ Half Speed	kW											
9 Fans @ Half Speed	kW											

Plant C Condenser Performance - 75% Load, Two-Speed Fans

Steam Flow 4,824,000 PPH

STG Output, Nominal	675,000 kW											
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW							687364	687952	688368	688642	688803
1 Fan @ Half Speed	kW							687152	687768	688233	688547	688744
2 Fans @ Half Speed	kW							686880	687566	688079	688428	688664
4 Fans @ Half Speed	kW							686273	687069	687666	688118	688431
6 Fans @ Half Speed	kW							685503	686405	687112	687665	688083
8 Fans @ Half Speed	kW							684483	685524	686389	687039	687561
9 Fans @ Half Speed	kW							683896	685010	685927	686656	687223

STG Output Change:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
1 Fan @ Half Speed	kW							-213	-184	-135	-95	-59
2 Fans @ Half Speed	kW							-484	-386	-289	-214	-138
4 Fans @ Half Speed	kW							-1092	-883	-702	-524	-372
6 Fans @ Half Speed	kW							-1862	-1546	-1256	-978	-720
8 Fans @ Half Speed	kW							-2881	-2427	-1979	-1603	-1242
9 Fans @ Half Speed	kW							-3469	-2941	-2441	-1986	-1580

Fan Power Reduction:												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.381	15.185	15.008	14.846	14.698	14.561	14.435	14.318	14.208	14.106	14.009
1 Fan @ Half Speed	kW	117	118	120	121	122	123	124	125	126	127	128
2 Fans @ Half Speed	kW	233	236	239	242	244	246	249	251	253	254	256
4 Fans @ Half Speed	kW	467	473	478	483	488	493	497	501	505	509	512
6 Fans @ Half Speed	kW	700	709	717	725	732	739	746	752	758	763	768
8 Fans @ Half Speed	kW	933	945	956	967	977	986	994	1002	1010	1018	1025
9 Fans @ Half Speed	kW	1050	1063	1076	1088	1099	1109	1119	1128	1136	1145	1153

Highlighted cases yield a marginal improvement in net power output

Net Savings												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
1 Fan @ Half Speed	kW										32	69
2 Fans @ Half Speed	kW										40	118
4 Fans @ Half Speed	kW											141
6 Fans @ Half Speed	kW											49
8 Fans @ Half Speed	kW											
9 Fans @ Half Speed	kW											

Plant C Condenser Performance - 50% Load, Two-Speed Fans

Steam Flow 3,216,000 PPH

STG Output, Nominal 450,000 kW

STG Output, Nominal												
Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW							473542	474057	474449	474738	474944
1 Fan @ Half Speed	kW							473424	473956	474368	474667	474893
2 Fans @ Half Speed	kW							473288	473840	474275	474587	474833
4 Fans @ Half Speed	kW							472999	473577	474043	474410	474686
6 Fans @ Half Speed	kW							472648	473277	473769	474188	474495
8 Fans @ Half Speed	kW							472223	472915	473428	473889	474259
9 Fans @ Half Speed	kW							471983	472658	473241	473710	474111

STG Output Change:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Base Case - Full Speed	kW	0	0	0	0	0	0	0	0	0	0	0
1 Fan @ Half Speed	kW							-117	-101	-81	-71	-51
2 Fans @ Half Speed	kW							-254	-218	-174	-151	-111
4 Fans @ Half Speed	kW							-543	-481	-406	-328	-258
6 Fans @ Half Speed	kW							-893	-780	-680	-550	-449
8 Fans @ Half Speed	kW							-1318	-1143	-1021	-849	-686
9 Fans @ Half Speed	kW							-1558	-1400	-1208	-1028	-833

Fan Power Reduction:

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
Air Outlet Specific Volume	ft3/lbm	15.026	14.825	14.641	14.472	14.316	14.171	14.036	13.909	13.790	13.677	13.570
1 Fan @ Half Speed	kW	117	118	120	121	122	124	125	126	127	128	129
2 Fans @ Half Speed	kW	233	236	239	242	245	247	249	252	254	256	258
4 Fans @ Half Speed	kW	466	472	478	484	489	494	499	503	508	512	516
6 Fans @ Half Speed	kW	699	709	717	726	734	741	748	755	762	768	774
8 Fans @ Half Speed	kW	932	945	957	968	978	988	998	1007	1016	1024	1032
9 Fans @ Half Speed	kW	1049	1063	1076	1089	1101	1112	1123	1133	1143	1152	1161

Highlighted cases yield a marginal improvement in net power output

Net Savings

Wet Bulb Temperature	F	85	80	75	70	65	60	55	50	45	40	35
1 Fan @ Half Speed	kW							7	25	46	57	78
2 Fans @ Half Speed	kW								34	80	105	147
4 Fans @ Half Speed	kW									102	184	258
6 Fans @ Half Speed	kW									82	218	325
8 Fans @ Half Speed	kW										175	347
9 Fans @ Half Speed	kW										125	328

E
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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 o PO Box 10412, Palo Alto, California 94303-0813 o USA
800.313.3774 o 650.855.2121 o askepri@epri.com o www.epri.com