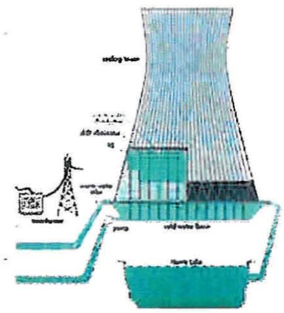
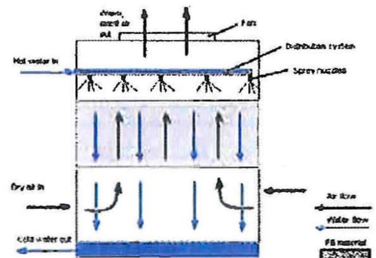
Engineering and Economic Evaluation of the Integrated Heat Rejection Cycle





Harris Location – Proposed Two Unit AP1000

Final Issue

Not Safety-Related

PREPARED BY: [signature] DATE: 03-21-2007
Pawel Kut

REVIEWED BY: [signature] for DATE: 23 MARCH 2007
Andrew D. Oehlerking

APPROVED BY: [signature] DATE: 23 MARCH 2007
Robert M. Field

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Note: This calculation was issued for client comments under S&L Evaluation number 2007-01981, Rev. 0A. The final version of that evaluation is issued here with the Progress Energy Report No. HAG-G2-GER-001, Rev. 0 with incorporation of client comments.

1.0 PURPOSE/OBJECTIVE

The purpose of this work is to perform a heat rejection system optimization study for the proposed two unit AP1000 pressurized water reactor plant to be located at the Progress Energy Harris site in North Carolina. This evaluation determines the projected performance of the integrated heat removal systems (condenser, circulating water, and cooling tower, net of associated auxiliary power requirements) for hourly intervals over one meteorological year. The goal of this evaluation is:

- Determine if there are compelling differences in net lifecycle economic benefits between various cooling tower options
- Determine whether these benefits and the ordering of options are dependent on external variables such as annual weather (average or extreme year), or time of day electricity pricing (average variation or extreme year)
- Determine whether these benefits are dependent on assumed CW flow
- Include the expected installation and maintenance costs in the evaluation.

If the predicted differences in net economic benefit are small, other considerations may be given higher consideration. These include:

- Aesthetics
- Corporate preference related to operations and maintenance issues
- First cost
- Risk associated with tower technology or vendor capability
- Associated site work for CW piping arrangement, and fit up to tower

In addition to the above evaluation, a review of cooling of tower blowdown in hot months was performed. It is not practical to size the main towers to maintain tower blowdown to temperatures below expected environmental constraints. Therefore, blowdown cooling options were reviewed and a lead candidate option was selected.

2.0 METHODOLOGY AND ACCEPTANCE CRITERIA

2.1 Modeling of the Main Condenser

The main condenser proposed for AP1000 design has been established by Westinghouse to be a triple shell, three zone, single pass, condenser with two tube bundles per shell. The proposed condenser is capable of removing 733.8 MWt of heat per shell at the nominal circulating water (CW) flow rate of 600,000 gpm at an inlet temperature of 91°F. Circulating water from cooling tower/towers is passed through the condensing tubes in each condenser shell. This circulating water is used to remove the latent heat of condensation (vaporization) from the incoming turbine exhaust. The turbine exhaust enters the condenser as steam. This steam, passing around the condenser tubes, gives up heat to the circuiting water and becomes condensate. After passing through the condenser, CW flows back to the cooling tower/towers.

2.1.1 Condenser Thermal Performance

The position paper on condenser selection and sizing [Ref. 5.1] includes condenser design backpressure only at a single circulating flow rate of 600,000 gpm at 91°F. Since the evaluation will be performed at different CW flows, temperatures, and condenser heatloads, a separate evaluation is performed herein to determine the condenser backpressure at these operating conditions. Attachment A contains a sample spreadsheet with the condenser design specifications and resultant performance curves for design operating conditions.

The methodology allows condenser backpressure to be determined for a given steam loading, condenser surface area, circulating water temperature and flow rate, condenser cleanliness, tube material, and other plant specific parameters. The methodology computes the condensing temperature based on these inputs. The condenser backpressure is then the saturation pressure at the condensing temperature. Note that this methodology assumes a full waterbox and no air pocketing within the tube bundles. The main equations used in the methodology presented below are based on the Westinghouse method [Ref. 5.2]:

$$\frac{T_o - T_i}{T_s - T_i} = \frac{T_r}{ITD} = 1 - e^{-x} = \alpha$$

$$x = \frac{J \cdot C_c \cdot C_m \cdot C_t \cdot K \cdot L}{500 \cdot \sqrt{V_{CW}}}$$

$$Q = W_c \cdot c_p \cdot (T_o - T_i)$$

where:

T_o	–	CW outlet temperature (°F)
T_i	–	CW inlet temperature (°F)
T_s	–	condensing temperature (saturation) (°F)
T_r	–	CW temperature rise (°F)
ITD	–	initial temperature difference (°F)
α	–	condenser effectiveness
x	–	effectiveness calculation exponent
J	–	tube size constant
C_c	–	tube cleanliness correction factor
C_m	–	tube material correction factor
C_t	–	CW inlet temperature correction factor
K	–	tube geometry constant
L	–	active tube length times number of passes (ft)
V_{CW}	–	CW velocity (ft/s)
W_c	–	CW flow (lb_m/hr)
c_p	–	specific heat of water (BTU/°F-lb_m)
Q	–	heat transferred by condenser (BTU/hr)

2.2 Cooling Tower Options

There are three different cooling tower options considered in this evaluation:

Option 1: Single shell natural draft hyperbolic cooling tower per one AP1000 unit.

Option 2: Two shell natural draft hyperbolic cooling towers per one AP1000 unit.

Option 3: Three round mechanical draft cooling towers per one AP1000 unit.

Each of the considered cooling tower options will be evaluated with three different CW flow rates of 500,000 gpm, 600,000 gpm, and 630,000 gpm. Cooling tower performance curves for each option are presented in Attachment B. For comparison purposes, the single shell natural draft hyperbolic cooling tower with CW flow rate of 600,000 gpm is chosen as a baseline for the evaluation.

2.3 Steam Turbine Generator Performance

The nominal gross generator output and heat rate versus the average condenser backpressure is obtained from Westinghouse [Ref. 5.9] as presented below.

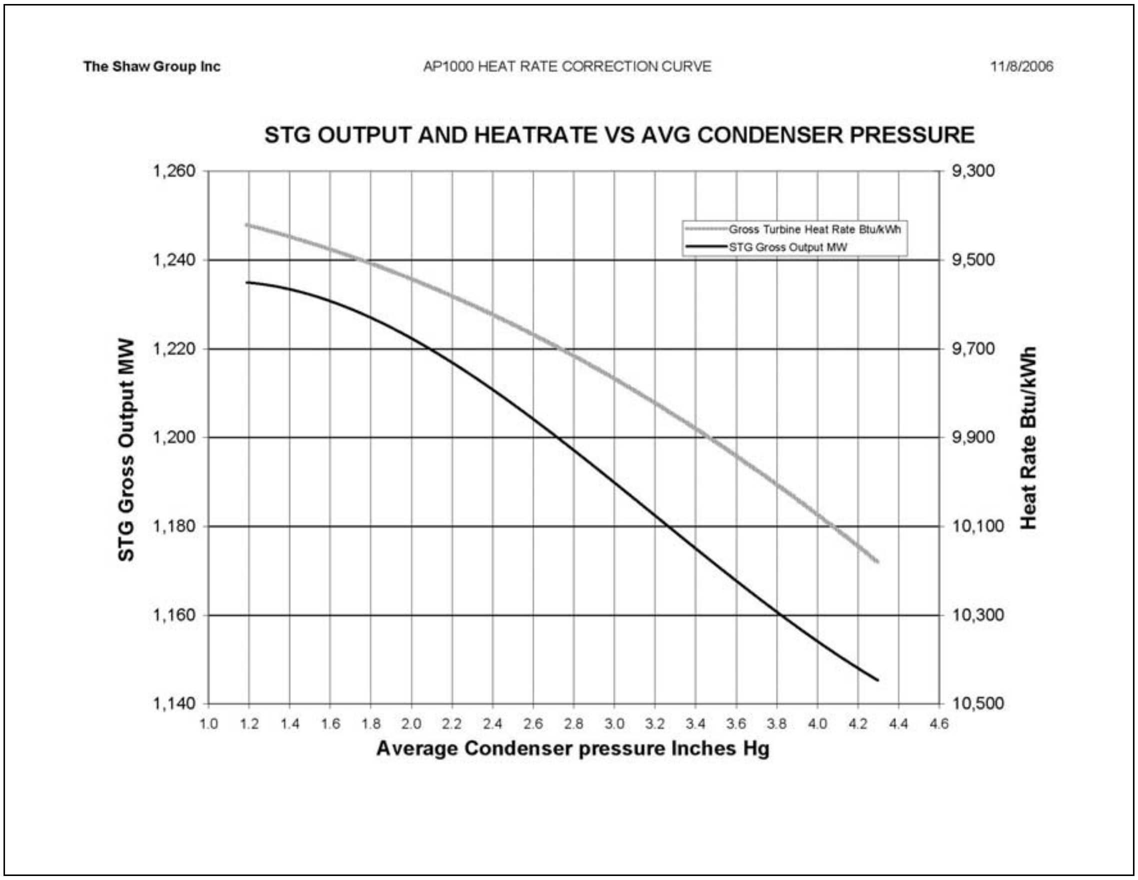

Fig. 2-1: Backpressure Correction Curve

This information is entered in to an Excel spreadsheet from which curve fit equations are created to be used in calculation of the overall gross generator output at any given condenser backpresure (Fig. 2-2, below).

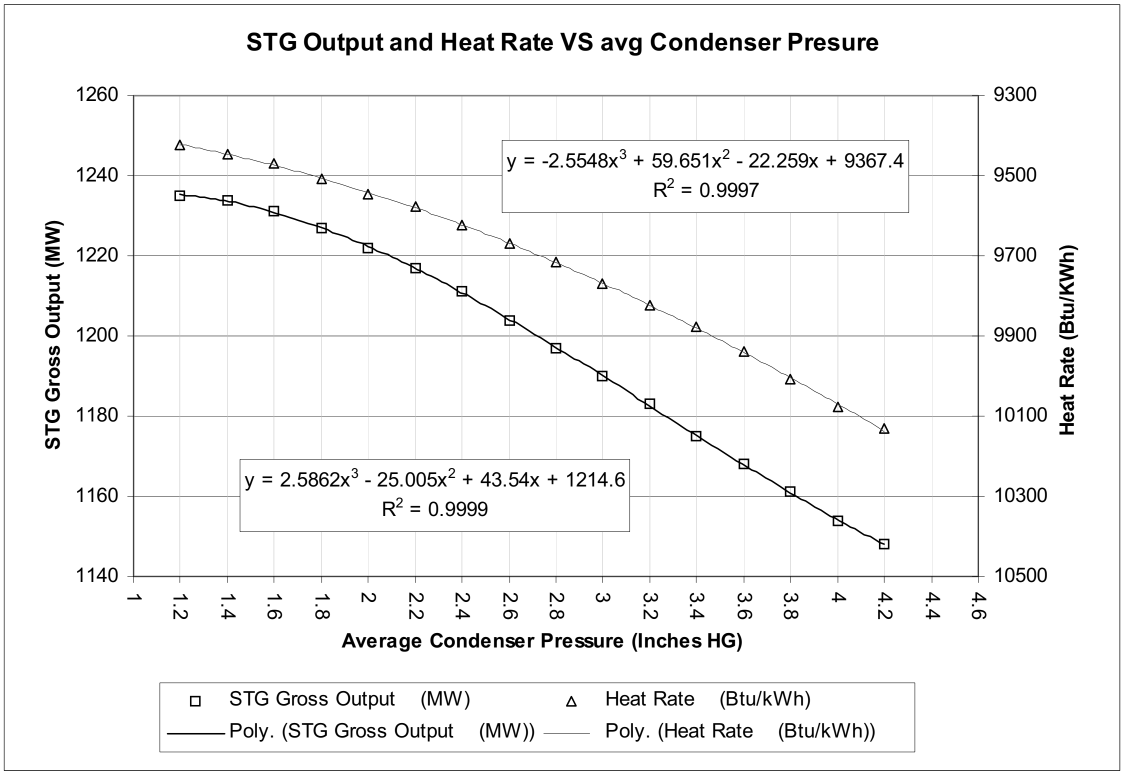

Fig. 2-2: Curvefit of Backpressure Correction Curve

2.4 Meteorological Data

Weather data for Raleigh, North Carolina from 1961 to 1990 is used to develop a hottest and an average year based on hourly wet bulb temperatures. Both weather profiles are used to evaluate all of the cooling tower options at different CW flow rates. Only wet bulb temperatures and relative humidity are used in the cooling tower evaluation since they have the greatest impact on the cooling tower performance.

2.4.1 <u>The Hottest Year Weather Data</u>

The hottest year weather data is developed from the 30 years of the meteorological data by compiling the maximum daily wet bulb temperatures and averaging them for every month out of 30 years. From the average maximum monthly temperatures the worst twelve moths are combined to generate a single (synthetic) year of hot weather. Based on this methodology the twelve hottest months and the compiled single year of hot weather are presented below.

Table 2-1: Synthetic Compilation of 'Hottest' Weather Year

Month	Year	Maximum Daily Wet Bulb Temperatures Averaged Over a Single Month (°F)
January	1974	52.35
February	1990	52.21
March	1973	55.14
April	1977	60.55
May	1980	67.98
June	1981	74.12
July	1981	76.7
August	1978	77.01
September	1980	72.68
October	1984	65.03
November	1985	59.44
December	1971	51.74

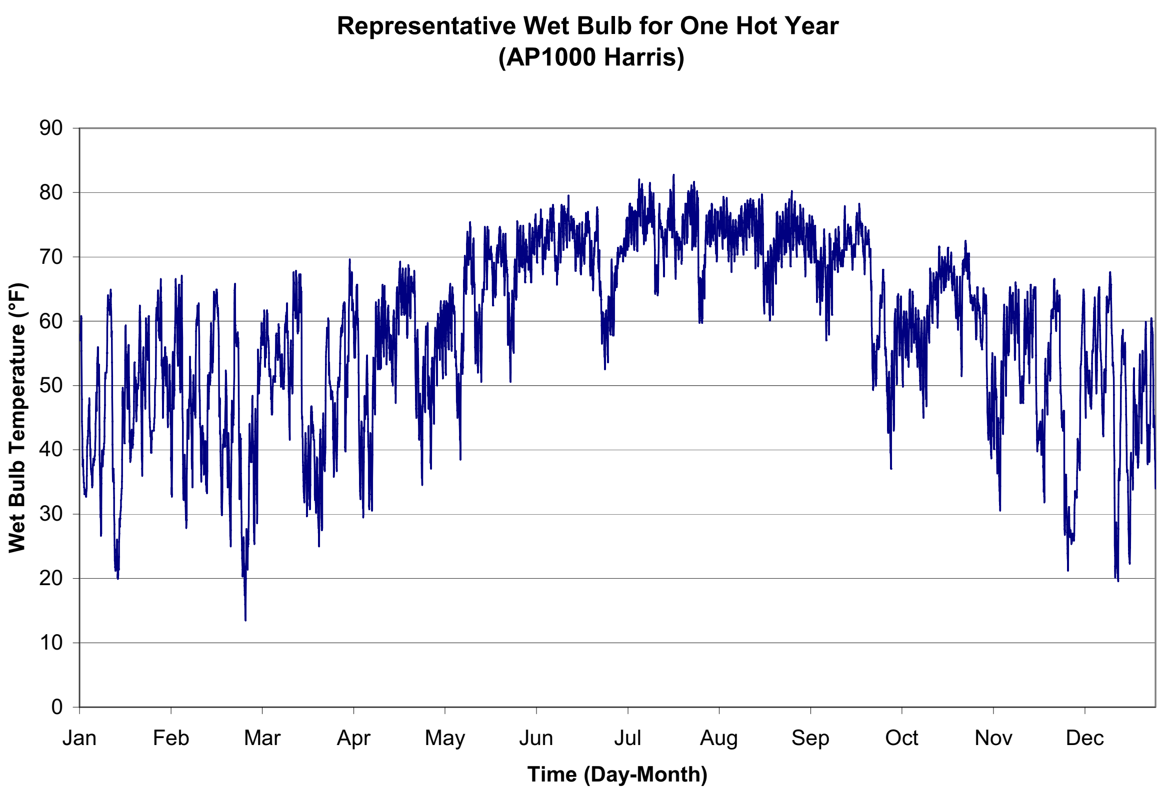

Fig. 2-3: 'Hottest' Year Wet Bulb Temperatures using Synthetic Weather Data Compilation

2.4.2 The Average Year Weather Data

The average year weather data is developed from the 30 years of the meteorological data by averaging the hourly wet bulb temperatures and relative humidities to generate a single year of average weather. Based on this methodology the compiled single year of average weather is presented below.

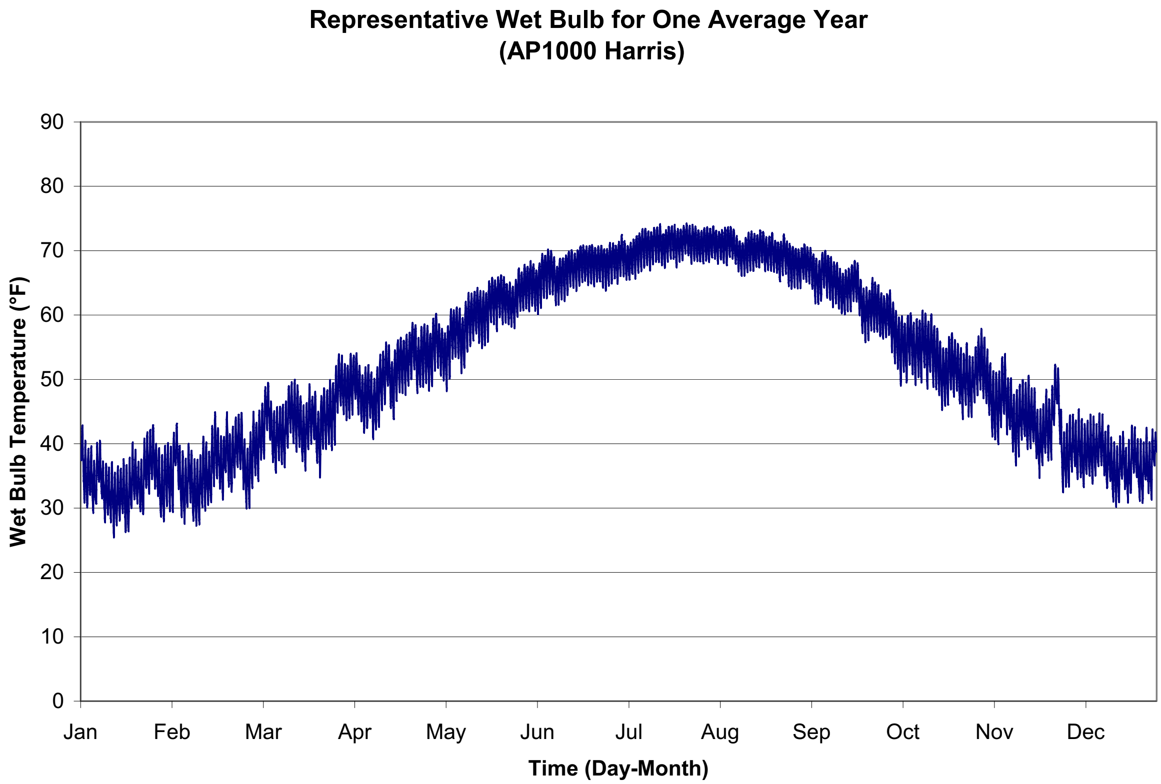

Fig. 2-4: 'Average' Year Wet Bulb Temperatures

Finally, for comparison purposes the single hot year wet bulb temperature is compared to the average year wet bulb temperature in Fig. 2-5 below.

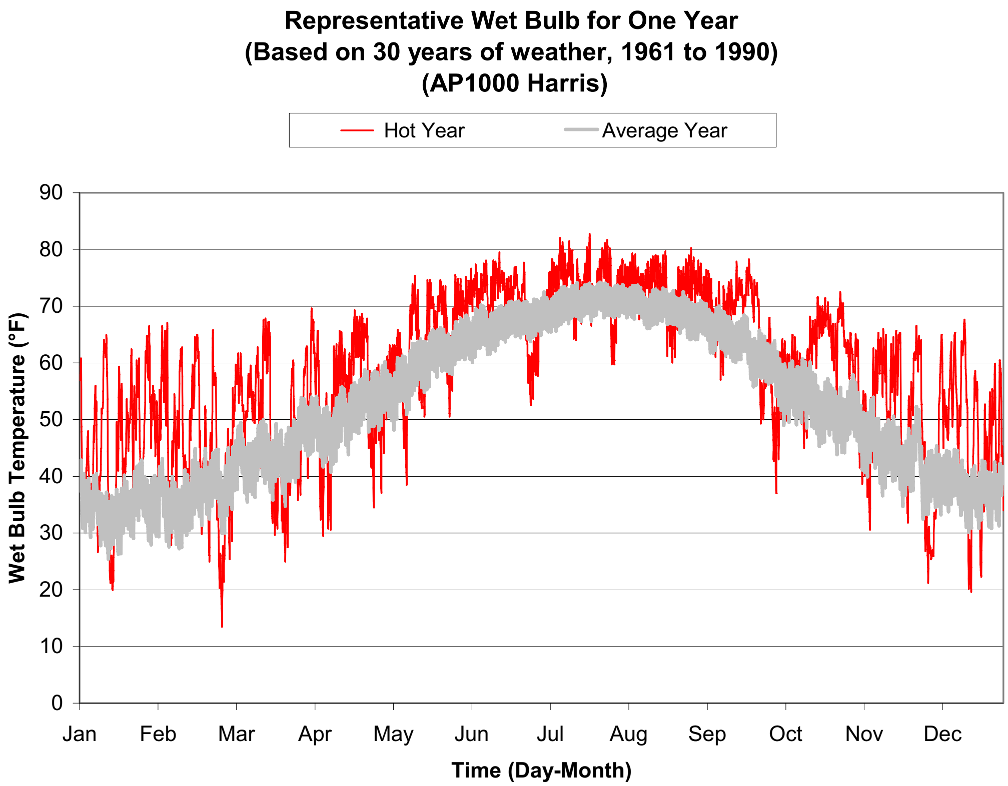

Fig. 2-5: Comparison of 'Hot' and 'Average' Year Wet Bulb Data

2.5 Circulating Water Pumping Power

The cooling tower selection is partly dependent on the overall energy consumption by the CW pumps which could vary depending on the cooling tower option, CW pipe routing, and CW flow rate. The CW pump energy consumption is dependent on the CW flow rate, elevation difference between the cooling tower basin and distribution header, and the frictional pressure drop in the CW system. The following equation from Crane [Ref. 5.8] represents the total energy used by the CW pumps:

$$P_{CW} = \frac{Q \cdot (H_{static} + H_{piping} + H_{condenser} \cdot (Q/600{,}000)^2 \cdot \rho}{247{,}000 \cdot e_p \cdot e_m} \cdot \frac{745.7}{1000{,}000} \ (MWe)$$

where:

Q	- total CW flow rate (gpm)
H_{static}	- elevation difference between the cooling tower basin and distribution header (ft)
H_{piping}	- CW piping frictional head loss (ft) – see Assumption 3.3
$H_{condenser}$	- condenser frictional head loss (ft)

$H_{condenser}$ - condenser frictional head loss (ft)
e_p - CW pump efficiency (fraction) – see Assumption 3.4
e_m - CW pump motor efficiency (fraction) – see Assumption 3.4

2.6 Mechanical Draft Cooling Tower Fan Power

The mechanical draft cooling tower option has an additional energy usage in form of 12 fans per tower for 3 towers for the total of 36 fans. Each fan motor output is taken as 250 hp [Ref. 5.6] for the total of 9000 hp (6.71 MWe) for thee towers. This 6.71 MWe is then subtracted from the gross plant generation for the mechanical cooling tower option.

Note that for northern climates, tower fans are often operated at reduced speed or in a feathered condition for cooler months. It has been determined that for southern climates, year round operation of fans at full speed is often cost effective. The Harris site may have winter time wet bulb temperatures which make two-speed fan operation economical. This has not been factored into the evaluation, but would show some additional benefit for mechanical draft towers relative to natural draft towers.

2.7 Hourly Electricity Pricing

To account for the significant differences in the spot power market, hourly selling prices for electricity are used in the model. The hourly selling prices for electricity for central North Carolina from the years 2002 to 2006 were reviewed and two representative years were selected. Year 2005 was selected to represent a relatively high priced energy market and 2004 was selected to represent more typical hourly selling prices. By utilizing the selected hourly selling prices, the differential net production between the considered options is translated into an annual difference in revenues.

2.8 Cooling Tower Maintenance Cost

In addition to the differences in the initial cost of construction for each of the cooling tower options, there are some differences in the expected maintenance cost that need to be included in the overall economic evaluation. The following four items specify typical expected cost variables associated with maintenance of the cooling towers.

2.8.1 Cooling Tower Fill Inspection and Replacement

The typical cooling tower fill provided with a new cooling tower should last ~10 years without significant maintenance cost. After about 15 to 20 years total fill replacement is typically needed. Due to the anticipated short duration of nuclear plant outages (~ one month every 18 months), fill replacement is usually done in stages of 10 to 25% per outage. The overall fill replacement cost is similar between the three cooling tower options considered in this evaluation and is therefore not included in the comparative economic evaluation.

2.8.2 Distribution Piping/Nozzle Inspection and Replacement

The distribution piping/nozzle inspection is usually performed on an annual or semiannual basis. The distribution nozzles are visually inspected and cleaned or replaced as required. The overall distribution piping/nozzle maintenance cost is similar between the three cooling tower options considered in this evaluation and is therefore not included in the economic evaluation.

2.8.3 Mechanical Components Inspection and Maintenance

Mechanical draft cooling towers (Option 3) include a variety of mechanical components (such as motors, fans, speed reducers, etc.) that require periodic inspection and maintenance. According to the cooling tower manufacturer, the approximate cost of inspection and maintenance is ~$5,000 per cell per year. Since the each cooling tower consists of 12 cells and there are three mechanical draft cooling towers per AP1000 unit, the total yearly cost is approximately $180,000 (36 x $5,000) per AP1000 unit in current dollars.

2.8.4 Mechanical Components Replacement

In addition to the inspection and maintenance cost as outlined in Section 2.8.3, the mechanical components will degrade over time and will need to be replaced. According to the cooling tower manufacturer most of the mechanical components will need to be replaced after ~10 to ~30 years of operation. The approximate cost of replacing major mechanical components (such as motors, fans, speed reducers, etc) is $65,000 to ~$70,000 per cell. With the total of 36 cells the total single time replacement cost is ~$2,340,000 to ~$2,520,000 in current dollars. With the expected nuclear plant life 60 years and the average life of the cooling tower mechanical components of ~20 years it is expected that each of the major cooling tower mechanical components will need to be replaced twice over the 60 year life of the nuclear plant. Therefore, after conservatively taking the higher replacement value the total replacement cost would be approximately $5,040,000 in current dollars. However, since the equipment degradation is not uniform and it is predicted that the original mechanical components should last at least 10 years with out replacement the ~$5,040,000 will be equally distributed over the remaining 50 years of the plant life for ~ $100,800 (in current dollars) per year from year 10 to 60.

2.9 Economic Evaluation Method

The relative economics of the three tower options are examined as follows:

- Cash In – Annual cash in is based on the net production for the three options determined hourly as net generation difference (gross output, adjusted for corresponding condenser backpressure, minus CW and tower fan power) times the corresponding hourly selling price ($/MW-hr). (House load outside of CW and tower fans is assumed to be common to all three options). Inflation is not considered and the annual revenues over the sixty year plant life are set to a net present value using an assumed discount rate (see Assumption 3.7).
- Installed Cost – The installed cost for tower options is an overnight cost in 2006 dollars which does not include allowance for funds used during construction (AFUDC). The capital cost is the estimated installation cost for the three tower options, including support systems unique to each option. Costs which are common to all three towers, such as CW pumps and motors, and makeup and blowdown systems were not estimated or included. Installed cost is based on vendor input for basic tower supply and erection, while support costs for civil and electrical works are based on recent S&L cost studies for similar installations.

  Design and overhead costs for owners, engineer, and construction management are taken as a fixed percentage of the cost for the option.
- Maintenance Cost – Maintenance cost differences are described in Section 2.8. These assume no inflation and are brought back to a net present value using the same discount rate as used for revenues. Note that the cost of fill replacement is considered to be uniform across all options.

2.10 Environmental Constraints on Blowdown

Blowdown from the towers, whether of natural or mechanical draft design, is required to maintain tower water chemistry within design limits. It is expected that blowdown will be regulated by environmental permit and that a maximum blowdown temperature will be established. Often these limits are based on a 24-hour average.

For this evaluation it is assumed that the blowdown will be limited to a maximum temperature of 91^{o}F. (Whether this is an hourly or 24-hour average does not impact the evaluation).

3.0 ASSUMPTIONS

3.1 Pump Heat - The total temperature increase due to the pump heat addition is estimated to be very small and is the therefore ignored for simplicity of the evaluation.

3.2 Makeup and Blowdown Streams Energy Contribution - Makeup to the CW is provided from the Harris Reservoir. Since the makeup is only a small fraction of the CW, the energy added by the makeup will not be considered when establishing the required CT outlet temperature.

3.3 CW Piping Friction Pressure Drop - CW piping frictional head loss is assumed 20 ft for all cases. This assumption is reasonable since most of the pressure drop will be through the condenser and in the static elevation differences, which are accurately modeled.

This is an important consideration in layout and sizing for CW piping in the detailed design stage. However, for this evaluation, differences between tower options associated with this effect are considered to be small

3.4 CW Pump and Motor Efficiency - CW pump and motor efficiency is assumed 85% and 95% respectively for all cases. The assumed efficiency values are typical for this type of application. Pump efficiencies are not expected to vary significantly for the different tower options.

Again, this is an important design consideration in the detailed design phase. It may be possible that mechanical draft towers afford a better opportunity to use more efficient and easily serviced horizontal CW pumps. These considerations are not, however, expected to change the overall ranking of options.

3.5 Mechanical Tower Fan Power – Auxiliary power for mechanical draft fan towers is assumed at 250 hp per fan. Fans are assumed to run at 100% capacity when the plant is online.

3.6 Economic Analysis – Economic analysis is based on a unit capacity factor of 1. Accounting for forced and planned outages is not expected to change the economic ranking of options.

3.7 Discount Rate – A discount rate of 10% per annum is used to bring future electricity revenues and maintenance costs into present value calculations.

4.0 DESIGN INPUTS

4.1 Natural Draft Tower – Single Shell - Single shell natural draft hyperbolic cooling tower data is assumed as follows [Ref.'s 5.5 & 5.6]:

Design Range = 25.2°F

Design Wet Bulb Temperature = 77°F

Design Relative Humidity = 43%

Design CW Flow = 600,000 gpm

Design Approach = 16.1°F

Preliminary Budgetary Price = $60,000,000

Performance curves were also provided as illustrated in Appendix B.

4.2 Natural Draft Tower – Two Shells - Two shell natural draft hyperbolic cooling tower data is assumed as follows [Ref.'s 5.5 & 5.6]:

Design Range = 25.2°F

Design Wet Bulb Temperature = 77°F

Design Relative Humidity = 43%

Design CW Flow = 600,000 gpm

Design Approach = 11.2°F

Preliminary Budgetary Price = $80,000,000

Performance curves were also provided as illustrated in Appendix B.

4.3 Mechanical Draft Tower – 36 Cells - Three round mechanical draft cooling tower data is assumed as follows [Ref.'s 5.5 & 5.6]:

Design Range = 25.2°F

Design Wet Bulb Temperature = 77°F

Design Relative Humidity = 43%

Design CW Flow = 600,000 gpm

Design Approach = 8.8°F

Fan Power = 250 hp per cell (total of 12 cells per tower)

Preliminary Budgetary Price = $40,000,000

Performance curves were also provided as illustrated in Appendix B.

4.4 Weather Data - Weather information used for this study is based weather for Raleigh, North Carolina from 1961 to 1990 [Ref. 5.3].

4.5 Condenser Data - Condenser information such as surface area, number of tubes, tube material, outside diameter and material gauge are taken from condenser optimization study [Ref. 5.1].

4.6 Time of Day Electricity Pricing - Time of the day energy pricing used for this study is based on (confidential) information provided by Progress Energy for 2002 to 2006 [Ref. 5.4].

5.0 REFERENCES

5.1 Position Paper, "Circulating Water System & Condenser Optimization for AP1000 standard Plant", DCP/NUS0302, 10/31/2006.

5.2 "General Information on Surface Condensers," Westinghouse Electric Co, 1310-70-E.

5.3 Weather Data for Raleigh, North Carolina from 1961 to 1990.

5.4 Time of the day energy pricing provided by Progress Energy for 2002 to 2006.

5.5 Cooling Tower Performance Curves, SPX Cooling Technologies.

a. Natural Draft (1 Tower) Model # 8600 264-6.6-404, Performance Curve at Waterflow = 500,000 gpm, 600,000 gpm, and 630,000 gpm, 01-02-2007.

b. Natural Draft (2 Towers) Model # 8540 222-6.6-355, Performance Curve at Waterflow = 500,000 gpm, 600,000 gpm, and 630,000 gpm, 01-02-2007.

c. Round Mechanical Draft (3 Towers) Model # B86060-6.6-12, Performance Curve at Waterflow = 500,000 gpm, 600,000 gpm, and 630,000 gpm, 12-21-2006.

5.6 Cooling Tower Options and Budgetary Pricing, SPX Cooling Technologies 01-19-2007.

5.7 (a) Environmental Permit NC0039586, Issued on 04-12-2002.

(b) e:mail from Paul Snead (Progress Energy), to Brandon Clark, S&L, :RE. RFI concerning NPDES Blowdown Limitations for Cooling Tower Study," December 18, 2006.

5.8 Crane Technical Paper 410, "Flow of Fluids Through Valves, Fittings, and Pipe", Twenty Fifth printing –1991.

5.9 Westinghouse Data on Backpressure Correction for Unit Performance.

6.0 EVALUATIONS

6.1 Analyzed Cases

Each of the cooling tower options was evaluated at three different CW flowrates (500,000 gpm, 600,000 gpm, and 630,000 gpm) using two different weather profiles (the representative 'hot' year and the 'average' year). In addition, two different energy rates were applied to the net production differences between the base case and each option. (Note that 'net' power refers to gross production less the CW pump and tower fan power consumed for each option. Auxiliary power serving the power block is common to all options and not considered here). For the base case, a single natural draft hyperbolic tower with 600,000 gpm CW flow is used. The following table presents the cases considered in this evaluation:

Table 6-1: Description of Case Analysis

Case No.	CW Flow (gpm)	Cooling Tower Type	Weather Data
1a	600,000	Single Tower – Natural Draft	Hot/Average Year
1b	600,000	Two Towers – Natural Draft	Hot/Average Year
1c	600,000	Three Towers – Mechanical Draft	Hot/Average Year
2a	500,000	Single Tower – Natural Draft	Hot Year
2b	500,000	Two Towers – Natural Draft	Hot Year
2c	500,000	Three Towers – Mechanical Draft	Hot Year
3a	630,000	Single Tower – Natural Draft	Hot Year
3b	630,000	Two Towers – Natural Draft	Hot Year
3c	630,000	Three Towers – Mechanical Draft	Hot Year

6.2 Economic Evaluation

In considering the comparison of the various cooling tower options, three main costs/ benefits should be considered:

(a) Production - This evaluation calculated the detailed net present value for production benefits for an average and the hot single year of plant operation for each cooling tower option.

(b) Initial Cost - Additionally, the initial 'overnight' cooling tower cost was based on vendor input and expected cost differences associated with procurement, support systems, and general contractor items to integrate the towers into the site.

(c) Maintenance - Finally, inspection and maintenance (replacement parts) cost differences were considered over the anticipated 60 years of the plant life.

The simplified economic analyses are prepared with an assumed discount rate of 10% without accounting for inflation in energy prices and maintenance cost differences.

6.3 Environmental Constraints on Blowdown

Blowdown from the towers, whether of natural or mechanical draft design, is required to maintain tower water chemistry within design limits. Blowdown will be regulated by environmental permit. A maximum blowdown temperature is not currently identified, but may be established as a part of the final permitting process. The current regulations for new generation do not refer to a maximum blowdown temperature, but do refer to the mixing zone temperature [Ref. 5.7]. The measurement of mixing zone temperatures and averaging periods may not be currently defined.

With expected extreme wet bulb temperatures in the range of 78 to 81°F, and expected approach temperatures for aged towers to be in the range of 15 to 20°F, it may not be prudent to expect that blowdown temperatures and associated mixing zone temperature will environmental regulations. Note that a mid-west two-unit nuclear plant with perched lake cooling has had periodic issues with high mixing zone temperatures associated with hot blowdown. A forced downpower to address periodically high blowdown temperatures may not be economical. Therefore, the options below are considered.

6.3.1 Option 1 – Blowdown Tower

A dedicated (small) cooling tower for blowdown could be included in the design. However, in addition to operating and maintenance expense, such a tower would have the same difficulty in achieving the close approach temperature needed to meet the environmental limit (as would the main tower). With the complexity and cost of a separate tower, to be used only a small fraction of operating hours, this option is not practical or cost effective.

6.3.2 Option 2 – Cooling Blowdown using Makeup

For this option, blowdown is cooled, as necessary, by makeup using a plate and frame heat exchanger. An illustration of such a unit is shown below in Fig. 6-1.

Figure 6-1: Large Plate and Frame Heat Exchanger (Courtesy Alpha Laval)

Large units such as these are equipped with titanium or stainless steel plates for fresh water duty. These units are capable of very close approach temperatures (approaches in the range of 3.5 to 5°F are economically achievable). A single unit is capable of flow in excess of 15,000 gpm, and could likely accomplish the total blowdown cooling duty for two units. The design cycle for blowdown cooling is illustrated below (Fig. 6-2).

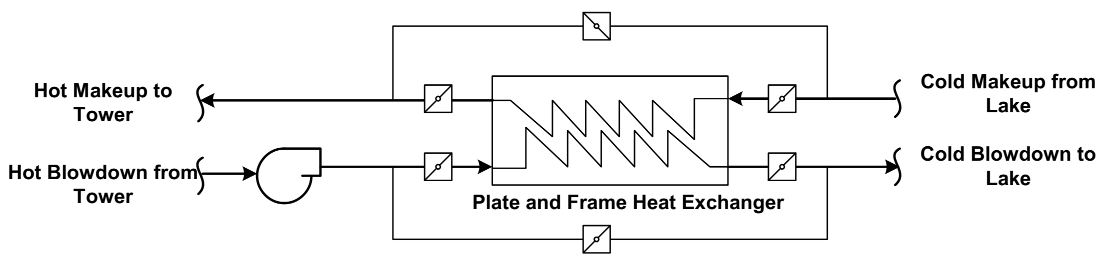

Figure. 6-2: Cooling Cycle for Blowdown using Makeup

Since blowdown and makeup are operated simultaneously, the design will essentially always have a cooling medium. Further, the design is passive without requirements for power actuated valves or devices. Blowdown is either gravity fed or pump driven, depending on plant layout. The plate and frame heat exchanger will not impact this aspect of the blowdown system design.

Since heating of the makeup adds to the tower heat load and costs some plant efficiency, a bypass is included in the design such that cooling will only be effected when required by permit. It is likely that this flow balancing through and around the heat exchanger could be performed as a seasonal activity (without the need for automated valves and associated instrumentation). This would assist in heat rate improvement without the associated capital, operating, and maintenance costs of automated equipment.

Since the heat exchanger is passive and has high anticipated reliability, and it is expected that it will only occasionally require cleaning, there is no required redundancy for this equipment. The unit can simply be bypassed during the short time frame associated with disassembly for cleaning.

6.3.3 Summary

In summary, a makeup / blowdown system designed to cool blowdown (as necessary) using makeup in a plate and frame heat exchanger may be a cost effective option to reliably maintain blowdown and mixing zone temperatures within environmental limits. This approach would eliminate constraints on main tower performance and avoid unit downpowers for this issue. Since a cost effective option to address the environmental permitting issue associated with blowdown heat load is available, and common to all options, the need for and cost of this supplemental cooling option is not studied further here.

Note: To prevent any undesirable impact of the hot makeup water on the service water system (makeup system is planned to be common for service water and circulating water) the plate and frame heat exchanger should be installed only on the circulating water leg of the makeup system.

7.0 SUMMARY AND CONCLUSIONS

7.1 Results of Analyzed Cases

Following is the summary of results of all analyzed cases for a single hot weather year including and average gross generator output and the yearly generation differences. Additionally, Cases 1a*/1b*/1c* are run with an average year weather to account for generation differences.

Table 7-1: Net Annual Production Revenue of Tower Options

Case No.	Weather Profile	CT Type	CW Flow	Average Gross Output	Average Fan Power	Average CW Pump Power	Average Gross Output Less Fan&CW	Yearly Generation Revenue Difference from Base (2005 Energy Pricing)	Yearly Generation Revenue Difference from Base (2004 Energy Pricing)
			(gpm)	(MWe)	(MWe)	(MWe)	(MWe)	($)	($)
Case 1a	Hot Year	ND-1shell	600,000	1219.11	0	17.10	1202.01	Base	Base
Case 1b	Hot Year	ND-2shells	600,000	1225.98	0	16.42	1209.56	$ 3,112,119	$ 2,296,636
Case 1c	Hot Year	MD-3 shells	600,000	1222.97	6.71	13.77	1202.49	$ 538,627	$ 378,405
Case 1a*	Average Year	ND-1shell	600,000	1224.42	0	17.11	1207.30	Base	Base
Case 1b*	Average Year	ND-2shells	600,000	1229.59	0	16.43	1213.15	$ 2,485,941	$ 1,839,726
Case 1c*	Average Year	MD-3 shells	600,000	1226.83	6.71	13.77	1206.34	$ (47,679)	$ (54,050)
Case 2a	Hot Year	ND-1shell	500,000	1217.38	0	12.72	1204.66	$ 966,065	$ 714,937
Case 2b	Hot Year	ND-2shells	500,000	1223.57	0	12.15	1211.41	$ 3,734,088	$ 2,749,561
Case 2c	Hot Year	MD-3 shells	500,000	1221.04	6.71	9.94	1204.39	$ 1,145,909	$ 823,673
Case 3a	Hot Year	ND-1shell	630,000	1219.65	0	18.60	1201.05	$ (349,436)	$ (257,533)
Case 3b	Hot Year	ND-2shells	630,000	1226.04	0	17.89	1208.15	$ 2,584,366	$ 1,906,274
Case 3c	Hot Year	MD-3 shells	630,000	1222.98	6.71	15.10	1201.17	$ 53,378	$ 22,259

The results indicate that the performance of the two-shell natural draft tower generates the most electricity revenue for all cases. This option however has the highest initial cost, which needs to be accounted for in the tower selection. In Section 7.3, the generation differences are compared against the initial tower cost and maintenance cost differences over the assumed 60 years of the plant life (for a base flow of 600,000 gpm).

Note that the highest net generation for all tower options is for the low flow, 500,000 gpm case. This case also has the lowest initial capital cost since CW pumps, CW pump motors, CW piping, CW valves, and civil structures associated with these components are smaller and lower cost for this target flow rate. Note that annual revenues are relatively insensitive to the assumed CW flow within the range of 500,000 to 630,000 gpm.

7.2 Cooling Tower Performance

Cooling tower design typically includes a single design point, which in this case is:

Design Range = 25.2°F
Design Wet Bulb Temperature = 77°F
Design Relative Humidity = 43%
Design CW Flow = 600,000 gpm

This single design point does not indicate the performance the tower during typical operation which spans a range of conditions. The following figures present cooling tower approach temperatures for the different tower options with a hot year average. A nominal relative humidity of 74.6% is used for the curves. Fig. 7-1 illustrates expected performance for the three options at a CW flow rate of 600,000 gpm.

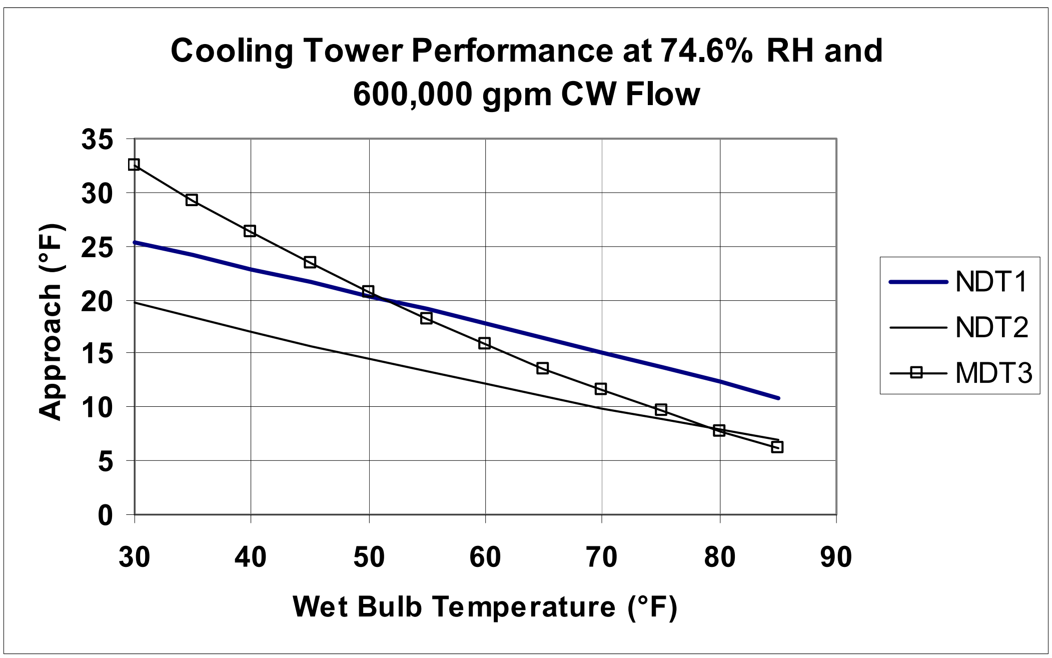

Fig. 7-1: Tower Performance for Three Tower Options vs. Wet Bulb Temp.

In addition, Fig. 7-2 presents performance for three different CW flow rates for the average annual wet bulb.

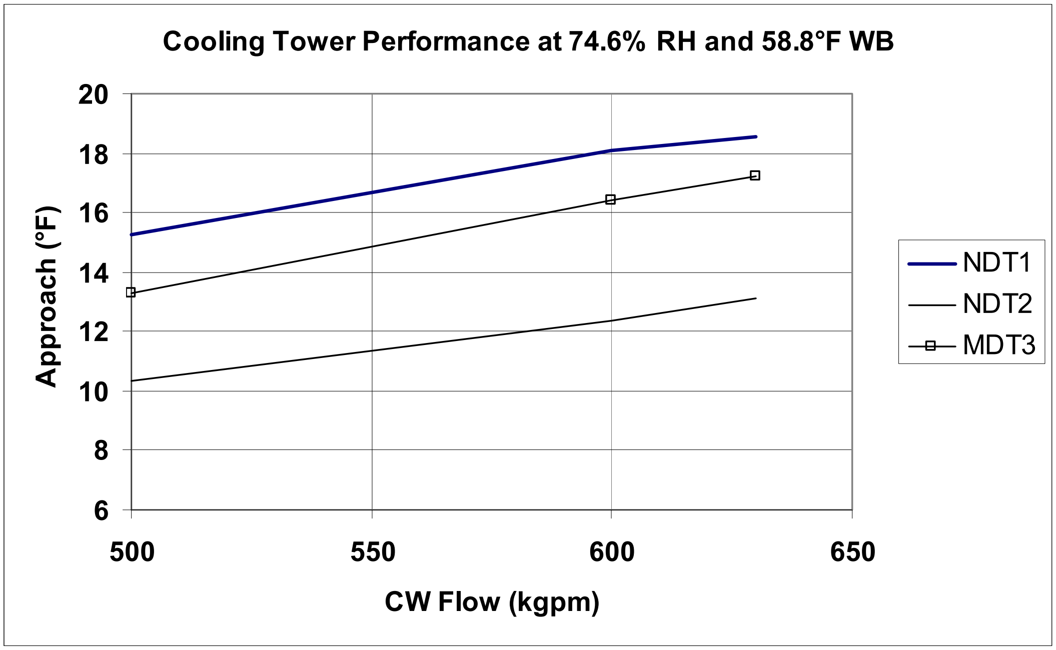

Fig. 7-2: Tower Performance for Three Tower Options vs. CW Flow

7.3 Economic Comparison

The cooling tower performance evaluation demonstrated that the two-shell natural draft cooling tower design resulted in the largest yearly gross generation revenue for all cases considered. However this is also the cooling tower option with the highest initial cost. The simplified economic evaluation shown below incorporates the initial tower cost and maintenance differences along with the generation revenue differences for the expected 60-year life of the plant for the cases with an assumed 600,000 gpm of CW flow.

Table 7-2: Life Cycle Cost-Benefit for Tower Options (Hot Year, 600,000 gpm)

	Hot Year				
Type of Cooling Tower	Single Tower - Natural Draft	Two Towers - Natural Draft	Round Mech. Draft	Two Towers - Natural Draft	Round Mech. Draft
CW flowrate (gpm)	600000	600000	600000	600000	600000
Energy Rate	High	High	High	Average	Average
Initial Tower Cost ($ 10^3)	$ (60,000)	$ (80,000)	$ (40,000)	$ (80,000)	$ (40,000)
Piping Connection Cost Differences ($ 10^3)	$ (1,301)	$ (1,486)	$ (1,858)	$ (1,486)	$ (1,858)
Electrical Connection Cost Differences ($ 10^3)	$ (200)	$ (300)	$ (10,915)	$ (300)	$ (10,915)
Tower Basin Cost Differences ($ 10^3)	$ -	$ -	$ (4,311)	$ -	$ (4,311)
Auger Cast Pilings Differences ($ 10^3)	$ (2,000)	$ (2,500)	$ (750)	$ (2,500)	$ (750)
Other Differences ($$10^3$)	$ (7,748)	$ (8,807)	$ (9,385)	$ (8,807)	$ (9,385)
CT Initial Cost ($ 10^3)*	**$ (71,249)**	**$ (93,093)**	**$ (67,219)**	**$ (93,093)**	**$ (67,219)**
Contractor+Eng.+Manag,+Owner+Cont. ($ 10^3)	(42,393)	(55,390)	(39,996)	(55,390)	(39,996)
Construction Cost ($ 10^3)*	**(113,642)**	**(148,483)**	**(107,215)**	**(148,483)**	**(107,215)**
Yearly Production Difference ($ 10^3)	$ -	3112.1	538.6	2296.6	378.4
Yearly Maintenance Difference ($ 10^3)	$ -	$ -	$ (180.0)	$ -	$ (180.0)
Yearly Replacement Parts Cost Difference - After Year 10 ($ 10^3)	$ -	$ -	$ (100.8)	$ -	$ (100.8)
Rate of Return (%)	10%	10%	10%	10%	10%
	.				
Present Value of Maint. Cost Difference ($ 10^3)	$ -	$ -	$ (1,794.1)	$ -	$ (1,794.1)
Present Value of Repl. Parts Cost Difference ($ 10^3)	$ -	$ -	$ (385.3)	$ -	$ (385.3)
Total Present Value of CT Cost Including Maintenance Differences ($ 10^3)	**(113,642)**	**(148,483)**	**(109,394)**	**(148,483)**	**(109,394)**
Present Value of Production Difference ($ 10^3)	$0	$31,019	$5,368	$22,891	$3,772
Total Present Value of CT Cost Including Production Difference Benefits ($ 10^3)	**($113,642)**	**($117,465)**	**($104,026)**	**($125,593)**	**($105,623)**

* The presentd cost exludes common items such as CW pumps, makeup and blowdown systems, tower fill replacement, etc.

Table 7-2 (single hot year weather) indicates that the generation benefits partially offset the high initial cost of the two-shell natural draft tower.

For the high (2005 year) energy rate the mechanical draft tower indicates the lowest overall cost (net present value) with the single-shell natural draft tower in second place (-$9,616,000) and the two-shell natural draft tower with the highest cost (-$13,439,000) per one AP1000 unit.

For the average (2004 year) energy rate, the mechanical draft tower indicates the lowest overall cost (net present value) with the single-shell natural draft tower in second place (-$8,019,000) and the two-shell natural draft tower with the highest cost (-$19,970,000) per one AP1000 unit.

Table 7-3 below repeats the above analysis for the average weather year.

Table 7-3: Life Cycle Cost-Benefit for Tower Options (Average Weather, 600,000 gpm)

	Average Year				
Type of Cooling Tower	Single Tower - Natural Draft	Two Towers - Natural Draft	Round Mech. Draft	Two Towers - Natural Draft	Round Mech. Draft
CW flowrate (gpm)	600000	600000	600000	600000	600000
Energy Rate	High	High	High	Average	Average
Initial Tower Cost ($ 10^3)	$ (60,000)	$ (80,000)	$ (40,000)	$ (80,000)	$ (40,000)
Piping Connection Cost Differences ($ 10^3)	$ (1,301)	$ (1,486)	$ (1,858)	$ (1,486)	$ (1,858)
Electrical Connection Cost Differences ($ 10^3)	$ (200)	$ (300)	$ (10,915)	$ (300)	$ (10,915)
Tower Basin Cost Differences ($ 10^3)	$ -	$ -	$ (4,311)	$ -	$ (4,311)
Auger Cast Pilings Differences ($ 10^3)	$ (2,000)	$ (2,500)	$ (750)	$ (2,500)	$ (750)
Other Differences ($$10^3$)	$ (7,748)	$ (8,807)	$ (9,385)	$ (8,807)	$ (9,385)
CT Initial Cost ($ 10^3)*	**$ (71,249)**	**$ (93,093)**	**$ (67,219)**	**$ (93,093)**	**$ (67,219)**
Contractor+Eng.+Manag,+Owner+Cont. ($ 10^3)	(42,393)	(55,390)	(39,996)	(55,390)	(39,996)
Construction Cost ($ 10^3)*	**(113,642)**	**(148,483)**	**(107,215)**	**(148,483)**	**(107,215)**
Yearly Production Difference ($ 10^3)	$ -	$ 2,486	$ (47.7)	$ 1,839.7	$ (54.1)
Yearly Maintenance Difference ($ 10^3)	$ -	$ -	$ (180.0)	$ -	$ (180.0)
Yearly Replacement Parts Cost Difference - After Year 10 ($ 10^3)	$ -	$ -	$ (100.8)	$ -	$ (100.8)
Rate of Return (%)	10%	10%	10%	10%	10%
	.				
Present Value of Maint. Cost Difference ($ 10^3)	$ -	$ -	$ (1,794.1)	$ -	$ (1,794.1)
Present Value of Repl. Parts Cost Difference ($ 10^3)	$ -	$ -	$ (385.3)	$ -	$ (385.3)
Total Present Value of CT Cost Including Maintenance Differences ($ 10^3)	**(113,642)**	**(148,483)**	**(109,394)**	**(148,483)**	**(109,394)**
Present Value of Production Difference ($ 10^3)	$0	$24,778	($475)	$18,337	($539)
Total Present Value of CT Cost Including Production Difference Benefits ($ 10^3)	**($113,642)**	**($123,705)**	**($109,870)**	**($130,147)**	**($109,934)**

* The presentd cost exludes common items such as CW pumps, makeup and blowdown systems, tower fill replacement, etc.

Table 7-3 (single average year weather) indicates that the generation benefits partially offset the high initial cost of the two-shell natural draft tower.

For the high (2005 year) energy rate the mechanical draft tower indicates the lowest overall cost with the single-shell natural draft tower in second place (-$3,772,000) and the two-shell natural draft tower with the highest cost (-$13,835,000) per one AP1000 unit.

For the average (2004 year) energy rate the mechanical draft tower indicates the lowest overall cost with the single-shell natural draft tower in second place (-$3,708,000) and the two-shell natural draft tower with the highest cost (-$20,213,000) per on AP1000 unit.

7.4 Cooling Tower Makeup and Blowdown

As described in Section 6.3, a makeup / blowdown system designed to cool blowdown as necessary using makeup in a plate and frame heat exchanger is considered to be a cost effective option to reliably maintain blowdown temperatures within environmental limits. This approach would eliminate constraints on main tower performance and avoid unit downpowers for this issue. Since a cost effective option to address the environmental permitting issue associated with blowdown heat load is available, and common to all options, the need for and cost of this supplemental cooling option is not studied further here.

Note: To prevent any undesirable impact of the hot makeup water on the service water system (makeup system is planned to be common for service and circulating water) the plate and frame heat exchanger should be installed only on the circulating water leg of the makeup system.

7.5 Summary

7.5.1 Monthly Production

The various tower options will result in differences in production. The breakdown in net monthly production relative to the baseline option of the single natural draft tower is summarized in Table 7-4 below:

Table 7-4: Projected Monthly Production Differences for Tower Options

	'Average' Weather Year			'Hot' Weather Year		
Month	**Baseline[1] (MW-hr Net)[4]**	**2 x NDT[2] (ΔMW-hr)**	**3xMDT[3] (ΔMW-hr)**	**Baseline[1] (MW-hr Net)**	**2xNDT[2] (ΔMW-hr)[4]**	**3xMDT[3] (ΔMW-hr)**
January	860,519	643	-3,168	857,630	2,422	-2,919
February	778,038	858	-2,843	774,994	2,511	-1,973
March	859,847	2,133	-2,743	857,116	3,313	-2,062
April	829,096	3,655	-1,424	825,919	4,720	-193
May	851,565	5,749	47	847,594	6,717	1,329
June	817,785	7,379	2,155	812,575	8,409	3,975
July	841,053	8,466	3,304	836,810	9,069	4,594
August	841,915	8,277	2,854	837,879	8,875	3,646
September	820,530	6,612	938	815,660	7,604	2,004
October	855,825	4,130	-1,616	850,943	5,779	-301
November	831,710	2,275	-2,667	827,730	3,999	-1,626
December	861,340	1,046	-3,245	857,983	2,766	-2,247

1) Baseline is for production using a single natural draft tower per AP1000 unit, 411-ft base x 600-ft height.
2) 2 x NDT – two natural draft towers per AP1000 unit, 362-ft base x 540-ft height.
3) 3 x MDT – three circular mechanical draft towers per AP1000 unit, twelve cells each, one 250 hp fan per cell.
4) Monthly production, in net MW-hr accounts for auxiliary power loads and main power transformer losses of 60 MWe (excluding CW pumps and tower fans), and CW pump and tower fan power per Table 7-1.

7.5.2 Economic Evaluation

Analysis presented here indicates a net present benefit for the mechanical draft tower option over a range of conditions encompassing:

(a) energy pricing

(b) imposed weather

(c) CW flow rates

Analysis results are summarized in the table below:

Table 7-5: Life Cycle Cost-Benefit Summary for Tower Options

Cooling Tower Type	Weather Data	Overall Net Cost Difference (Net Present Value) From The Lowest Cost Option ($ per AP1000 unit)	
		2005 Energy Rate	2004 Energy Rate
Three Towers – Mechanical Draft	Hot Year	Lowest Cost	Lowest Cost
Single Tower – Natural Draft	Hot Year	-$9,616,000	-$8,019,000
Two Towers – Natural Draft	Hot Year	-$13,439,000	-$19,970,000
Three Towers – Mechanical Draft	Average Year	Lowest Cost	Lowest Cost
Single Tower – Natural Draft	Average Year	-$3,772,000	-$3,708,000
Two Towers – Natural Draft	Average Year	-$13,835,000	-$20,213,000

While mechanical draft towers were demonstrated to show a high net present economic benefit, a siting study, including local meteorology (i.e., wind rows), for such towers was not included here. It may not prove to be practical to site the towers without the potential for periodic bouts of high recirculation flows and lost tower performance. Crossflow circular mechanical draft towers at one operating nuclear unit have exhibited periodic CW temperatures in excess of 100°F, well above the targeted value for Harris of 91°F. If mechanical draft towers are selected for this site, this selection must be with supported assurance that the siting of the towers will not result in the potential for excessive recirculation.

The single large natural draft option was a clear second, showing a high economic benefit relative to the two tower natural draft tower.

7.5.3 Optimal CW Flow

The optimal CW flow is at the lower end of the assumed range, or 500,000 gpm. This target flow also has the lowest initial capital cost since CW pumps, CW pump motors, CW piping, CW valves, auxiliary electrical power infrastructure, and civil structures associated with these components are smaller and lower cost for this flow.

7.5.4 Comparison to Historical Projects

Fig. 7-3 below provides an indication of the sizing of the Progress Harris AP1000 condenser and CW flow relative to historical nuclear projects. Overall, the condenser surface is larger than previous projects while the CW flow rate is on the low end of flows which were determined to be economical for those projects. It is likely that that these two items are related.

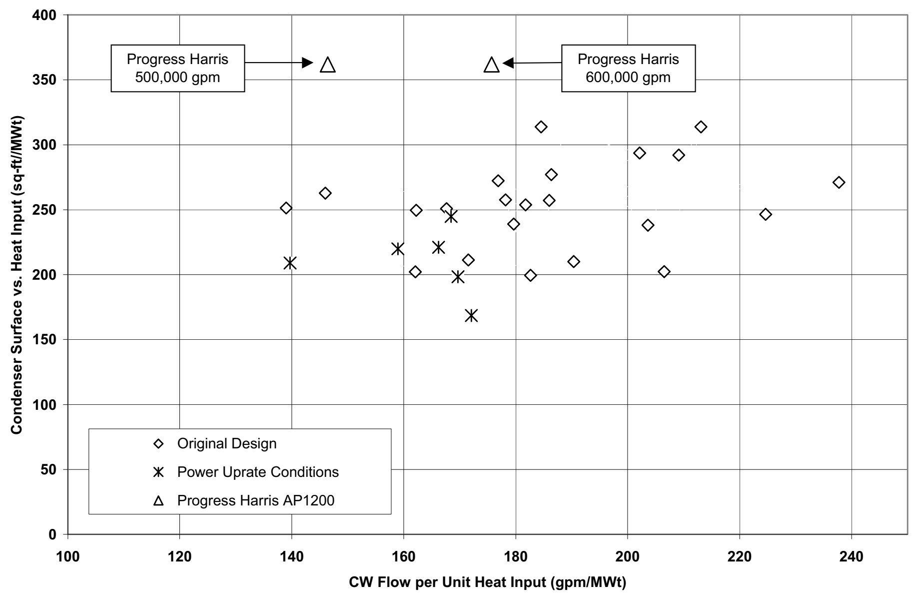

Fig. 7-3: Comparison of Heat Rejection Capability

7.5.3 Disclaimers and Cautions

In using this study for future work and design decisions, the following cautions are offered:

(1)	Constraints on Tower Siting – It is understood that limited real estate at the Harris site presents constraints on tower siting. Selection of the mechanical draft tower option should be predicated on an understanding of prevailing wind conditions during limiting weather periods and adequate spacing of the towers to avoid excessive recirculation flows during these periods.
(2)	Economic Evaluation - Economic analysis is based on a simple approach to discounting future electricity revenues and maintenance and refurbishment cost differences. This analysis does not consider AFUDC, construction schedules, overall project budgets, corporate capital requirements, inflation, and many other items found in a more sophisticated analysis.
(3)	Installed Tower Cost Differences - Estimates for installed tower costs are not based on site specific layouts and piping runs. Tower cost data was only obtained from one vendor.

(4)	Tower Performance Degradation - Degradation of tower performance in not accounted for in the project production figures. Based on discussions with leading industry cooling tower experts, modern low fouling film fill is expected to retain performance over many years.
(5)	Extreme Pricing on Hot Summer Days - Net production benefit may not reflect extreme pricing (beyond that for the year 2005) on hot summer days. The economic analysis is not as sensitive for electricity pricing for high demand winter periods since the backpressure penalty on production is not as severe for the associated winter weather.
(6)	Design CW Flow - The design point for the condenser and towers is 600,000 gpm (nominal flow). The indicated optimal flow is at the low end of the range (i.e., 500,000 gpm). However, the study did not examine increased condenser surface area or larger tower area (at higher capital cost).

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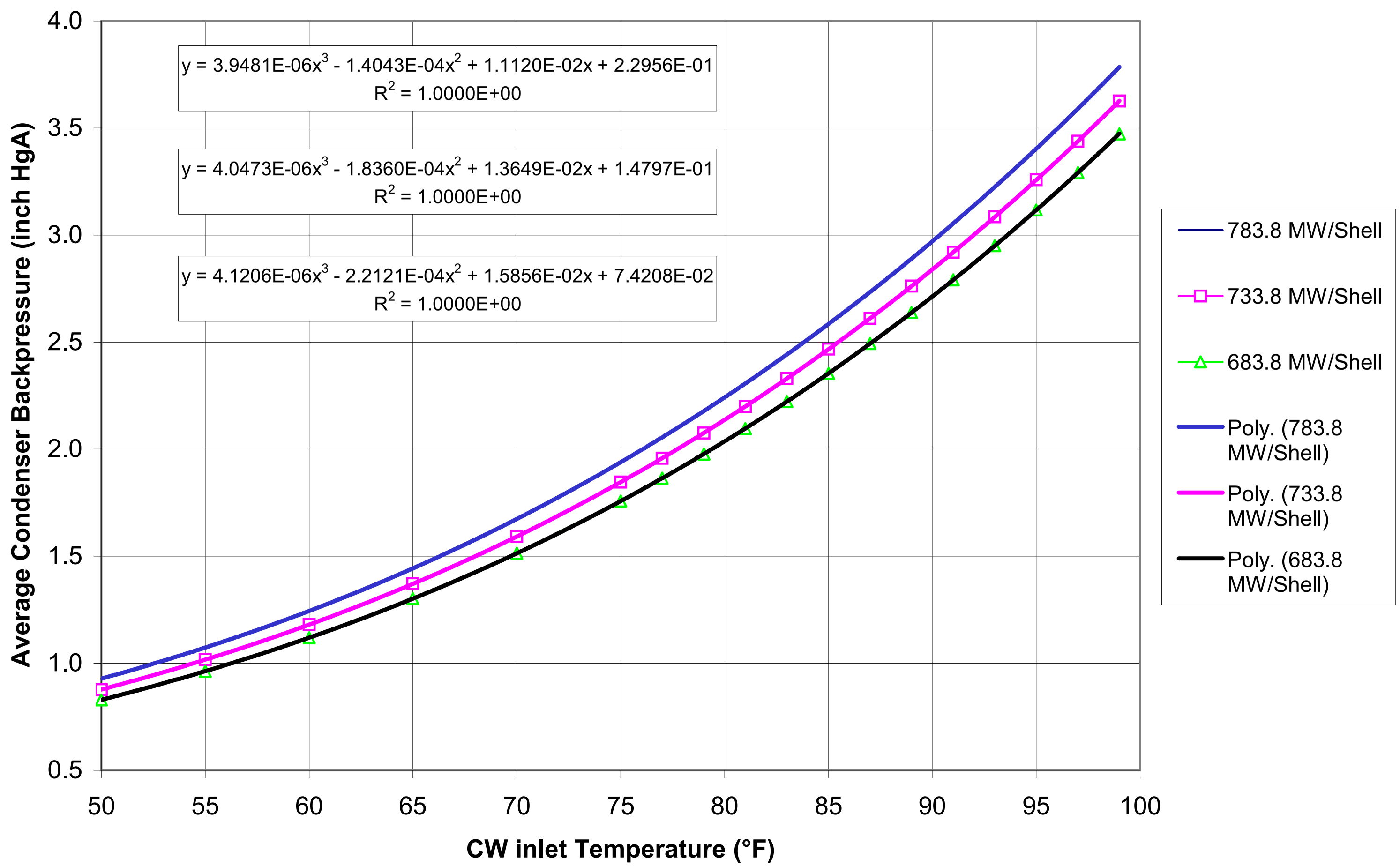
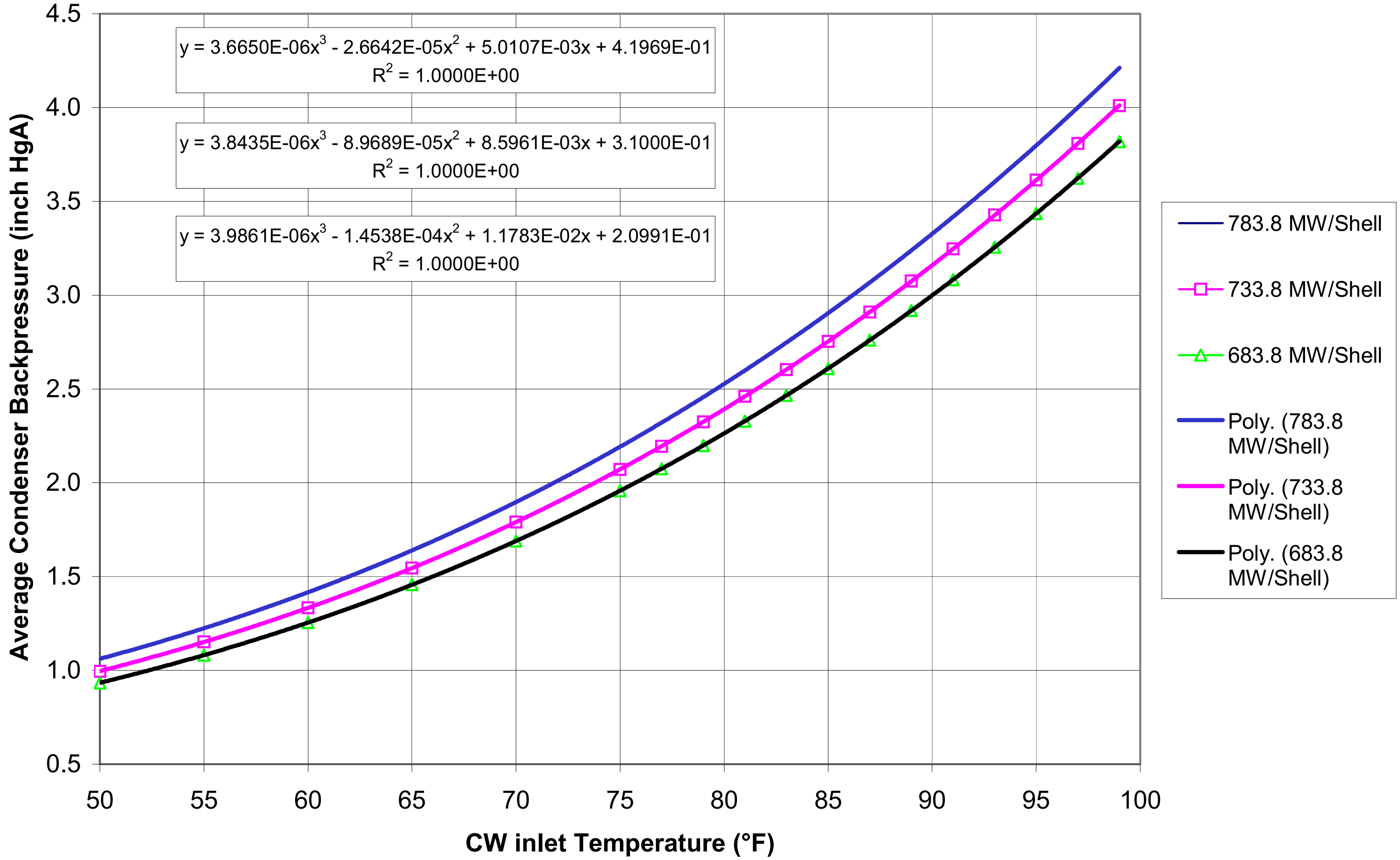
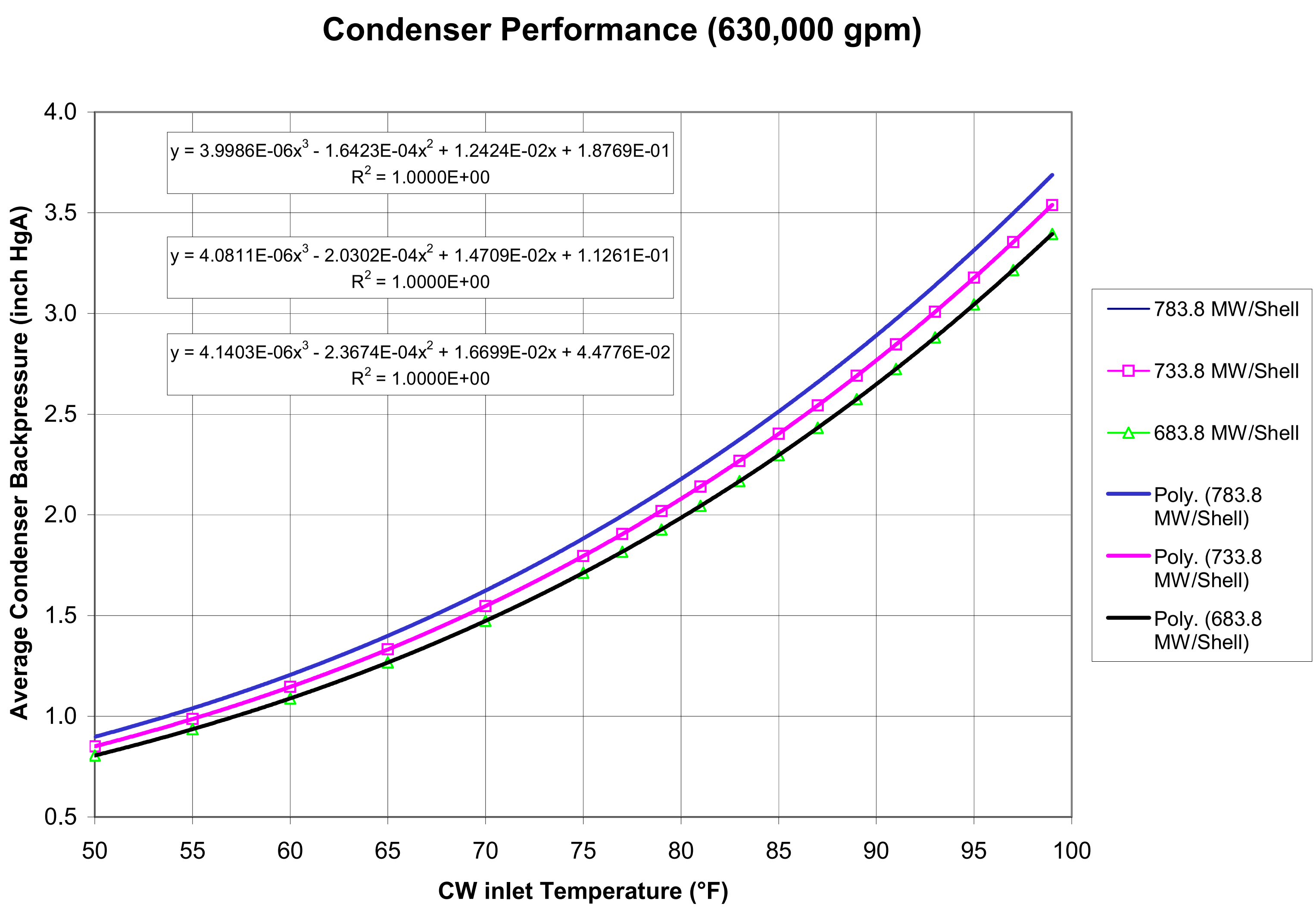
ATTACHMENT A

Condenser Performance (600,000 gpm)



Condenser Performance (500,000 gpm)





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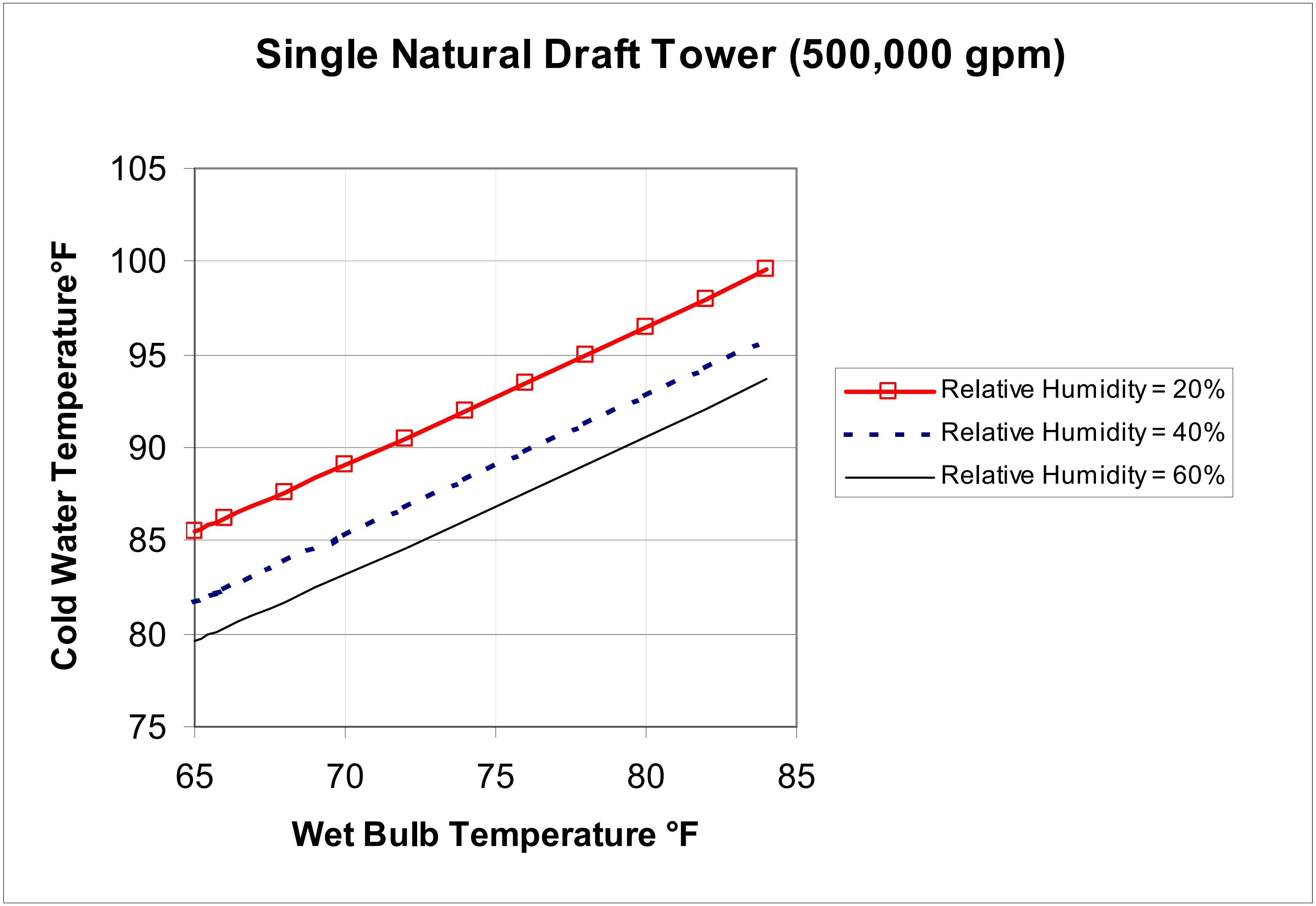
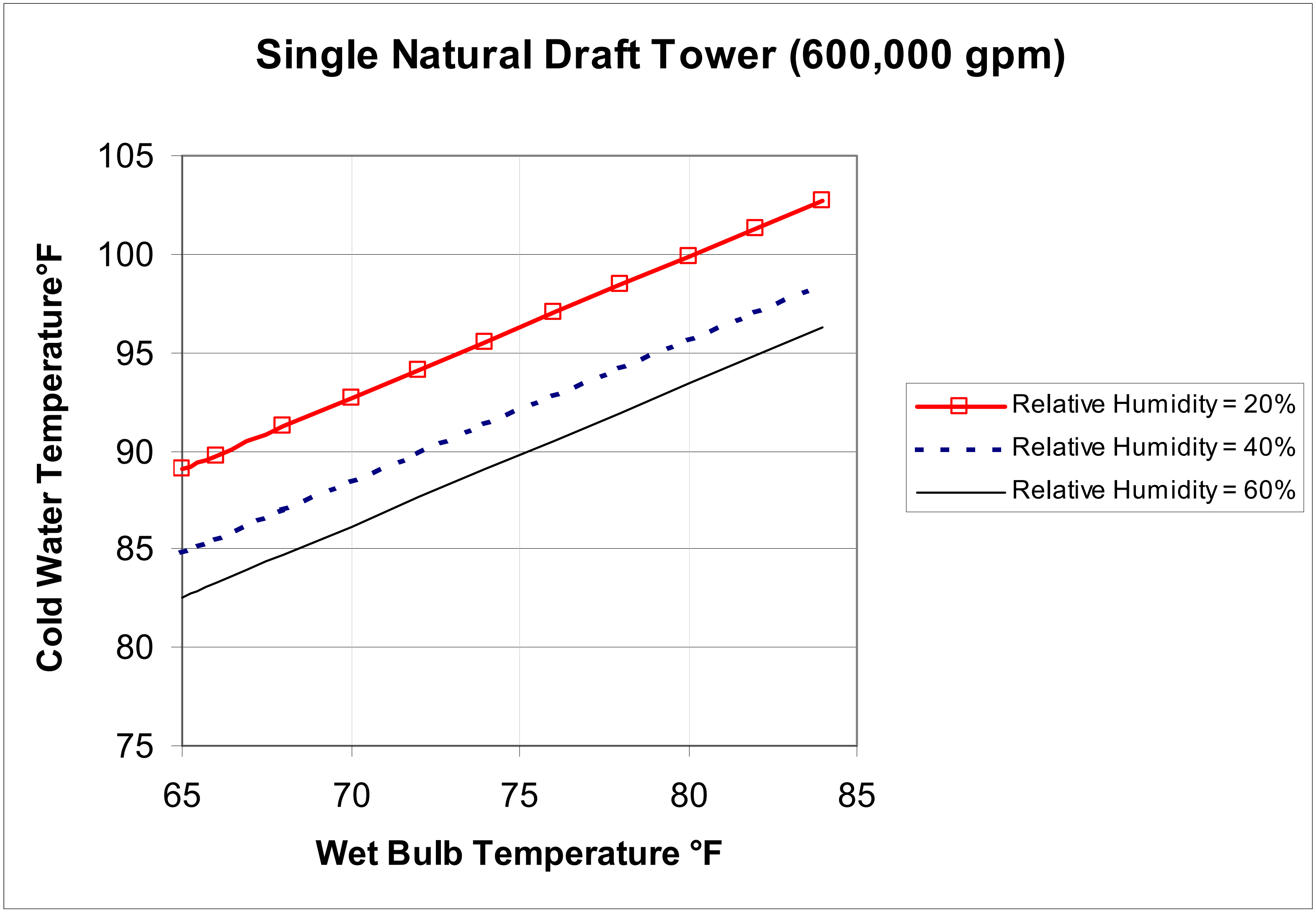
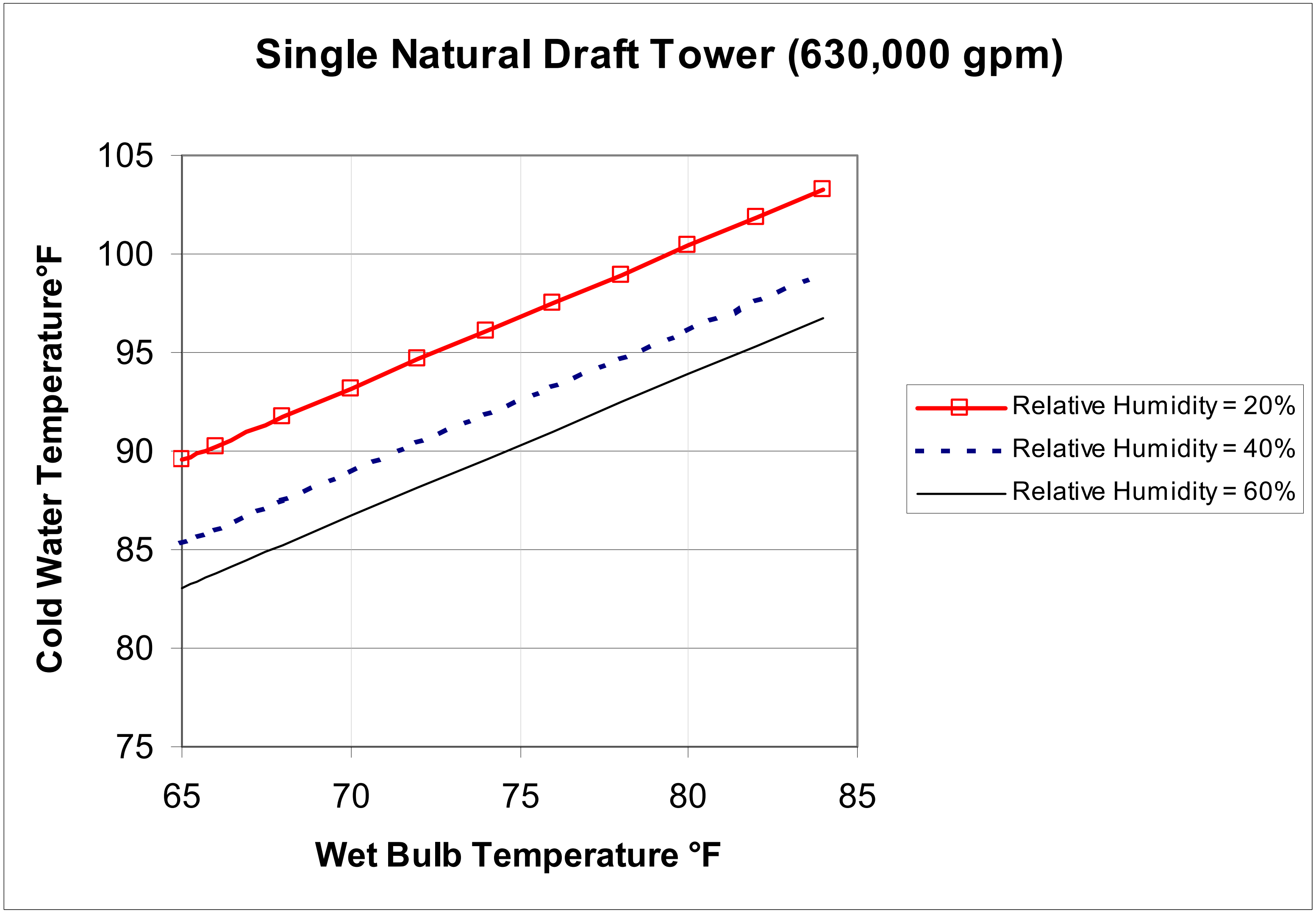
ATTACHMRNT B




Single Natural Draft Tower (600,000 gpm)
Cold Water Temperature°F
105
100
95
90
85
80
75
65
70
75
80
85
Wet Bulb Temperature °F
Relative Humidity = 20%
Relative Humidity = 40%
Relative Humidity = 60%


Single Natural Draft Tower (630,000 gpm)
Cold Water Temperature°F
105
100
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70
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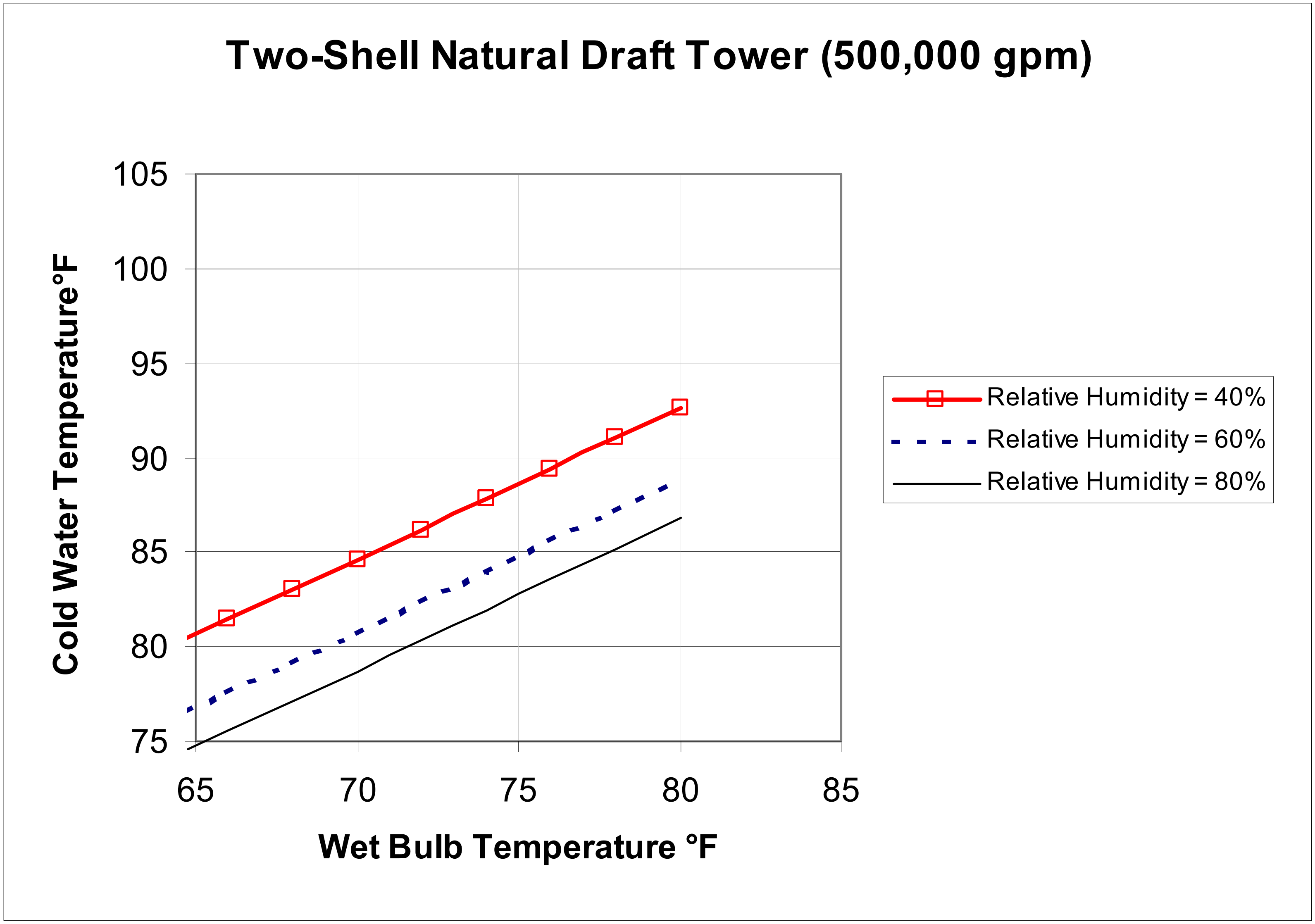
80
85
Wet Bulb Temperature °F
Relative Humidity = 20%
Relative Humidity = 40%
Relative Humidity = 60%


Two-Shell Natural Draft Tower (500,000 gpm)
Cold Water Temperature°F
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100
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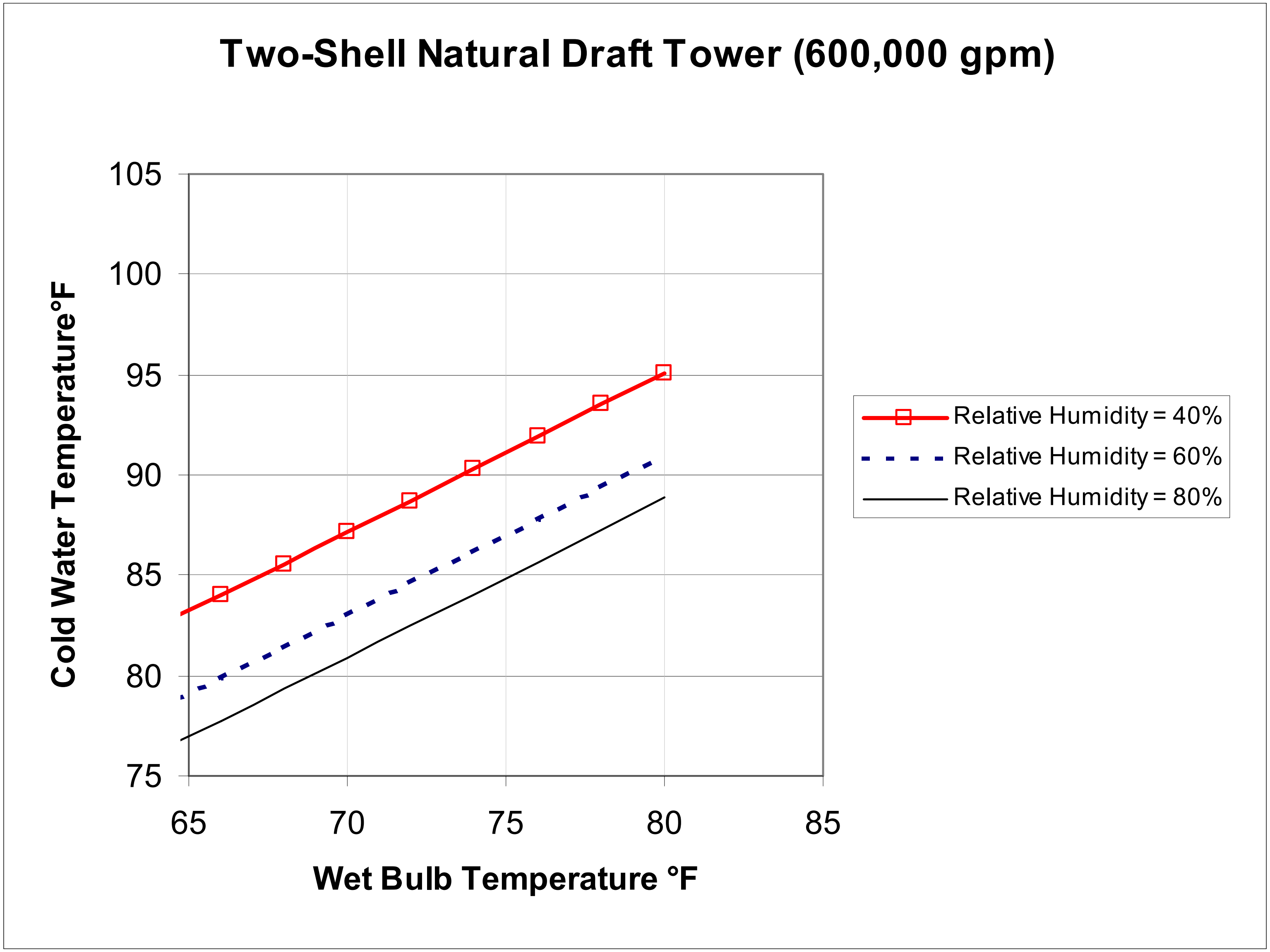
85
Wet Bulb Temperature °F
Relative Humidity = 40%
Relative Humidity = 60%
Relative Humidity = 80%


Two-Shell Natural Draft Tower (600,000 gpm)
Cold Water Temperature°F
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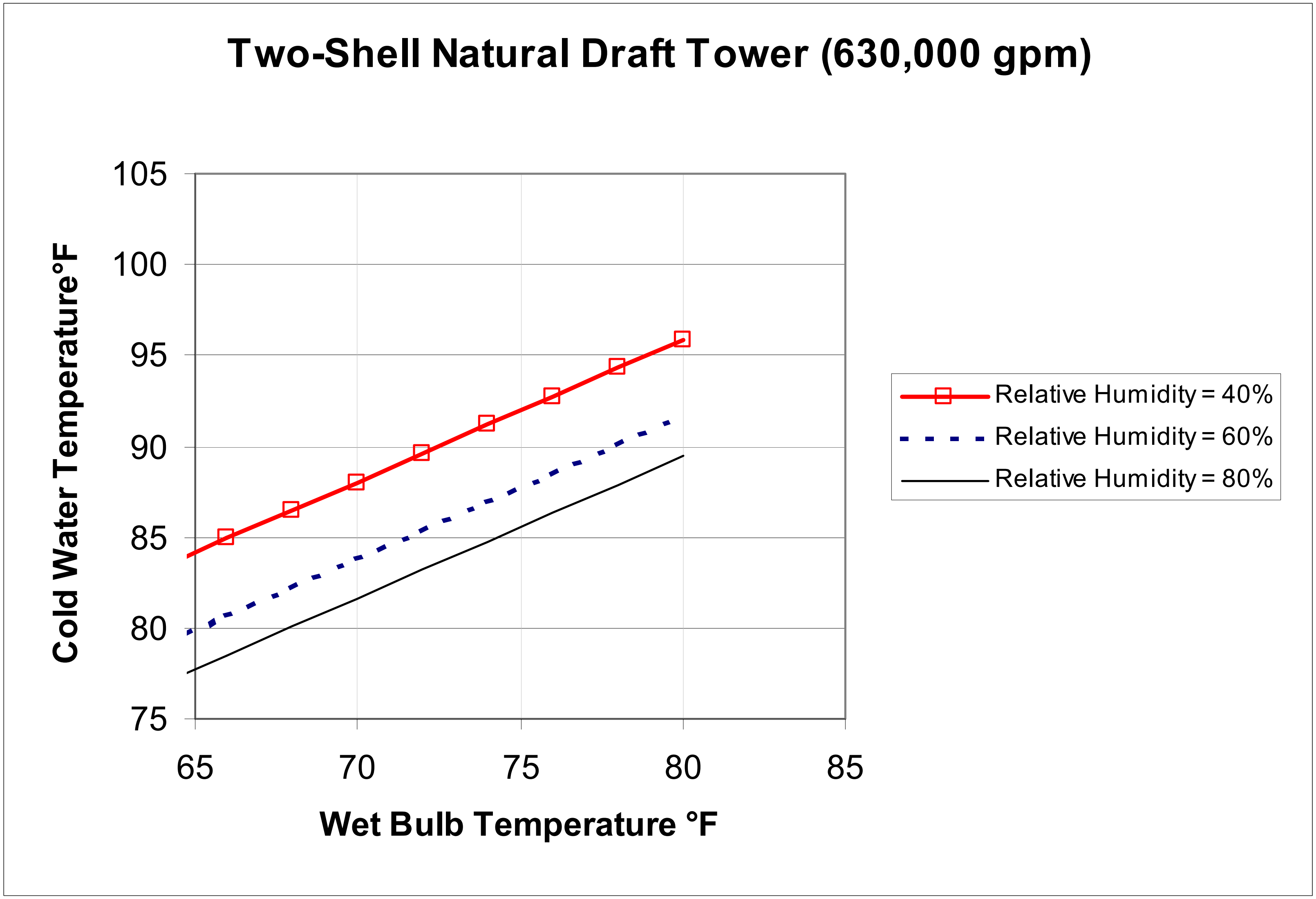
Wet Bulb Temperature °F
Relative Humidity = 40%
Relative Humidity = 60%
Relative Humidity = 80%


Two-Shell Natural Draft Tower (630,000 gpm)
Cold Water Temperature°F
105
100
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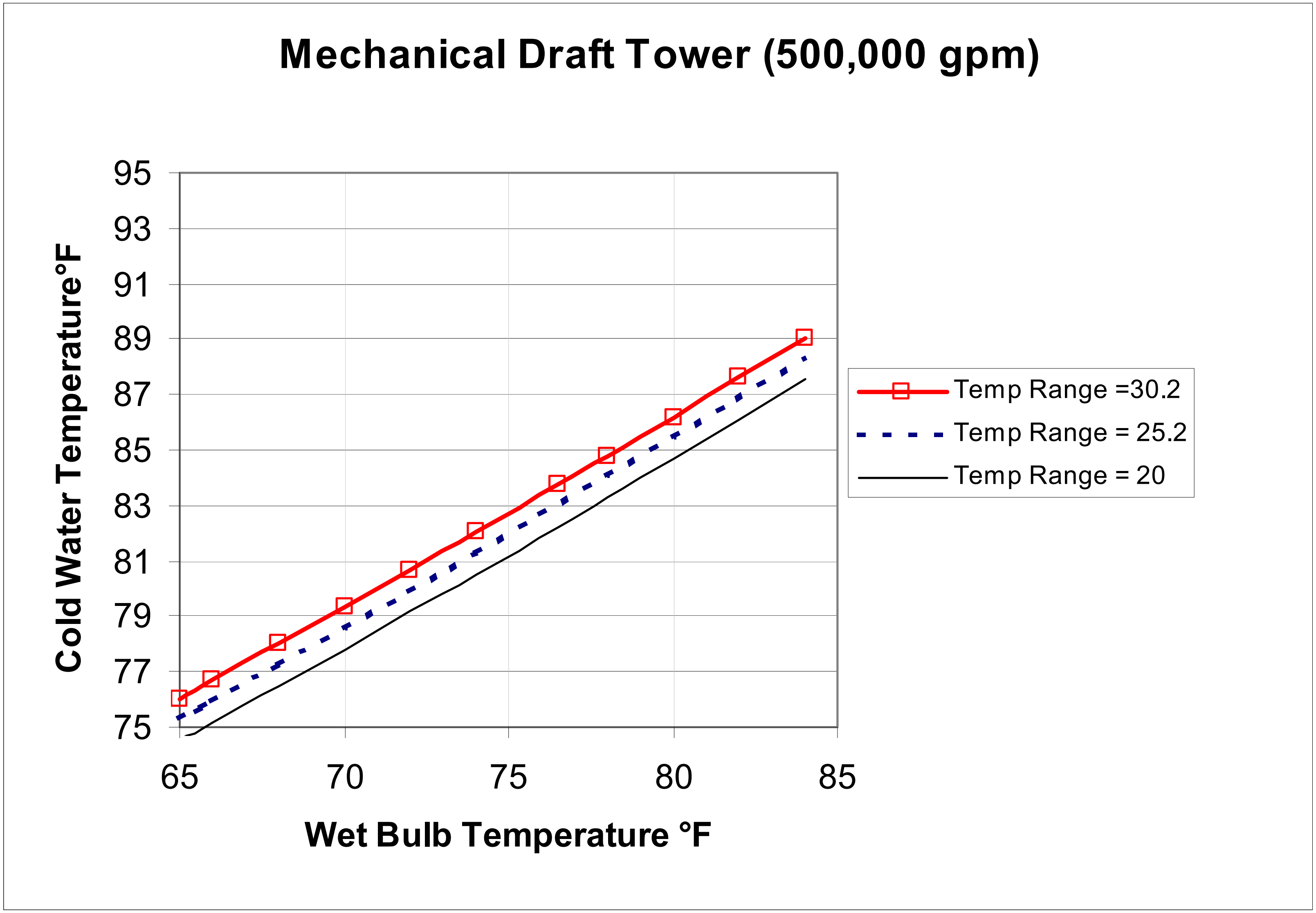
80
85
Wet Bulb Temperature °F
Relative Humidity = 40%
Relative Humidity = 60%
Relative Humidity = 80%


Mechanical Draft Tower (500,000 gpm)
Cold Water Temperature°F
95
93
91
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83
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75
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70
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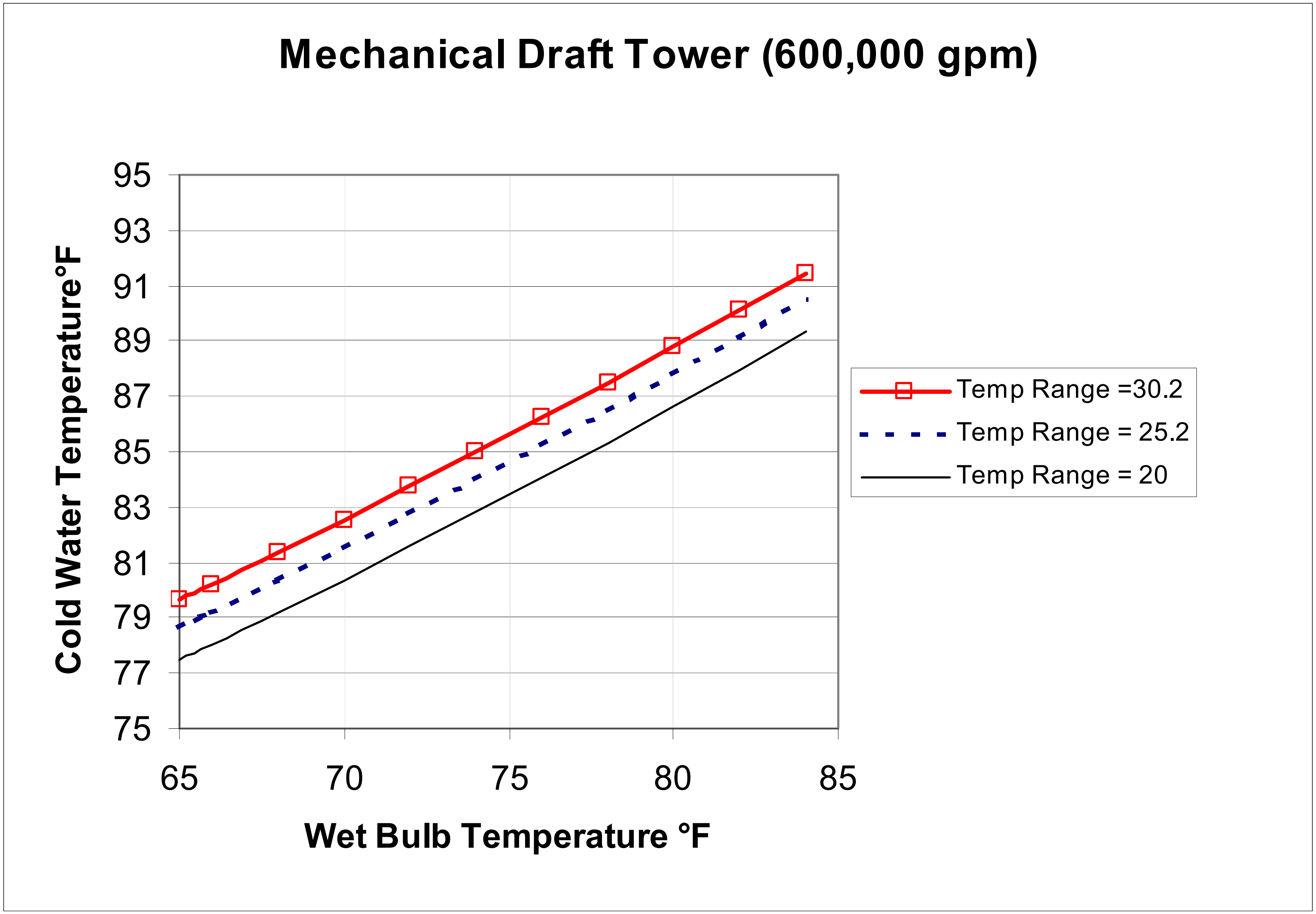
80
85
Wet Bulb Temperature °F
Temp Range =30.2
Temp Range = 25.2
Temp Range = 20


Mechanical Draft Tower (600,000 gpm)
Cold Water Temperature°F
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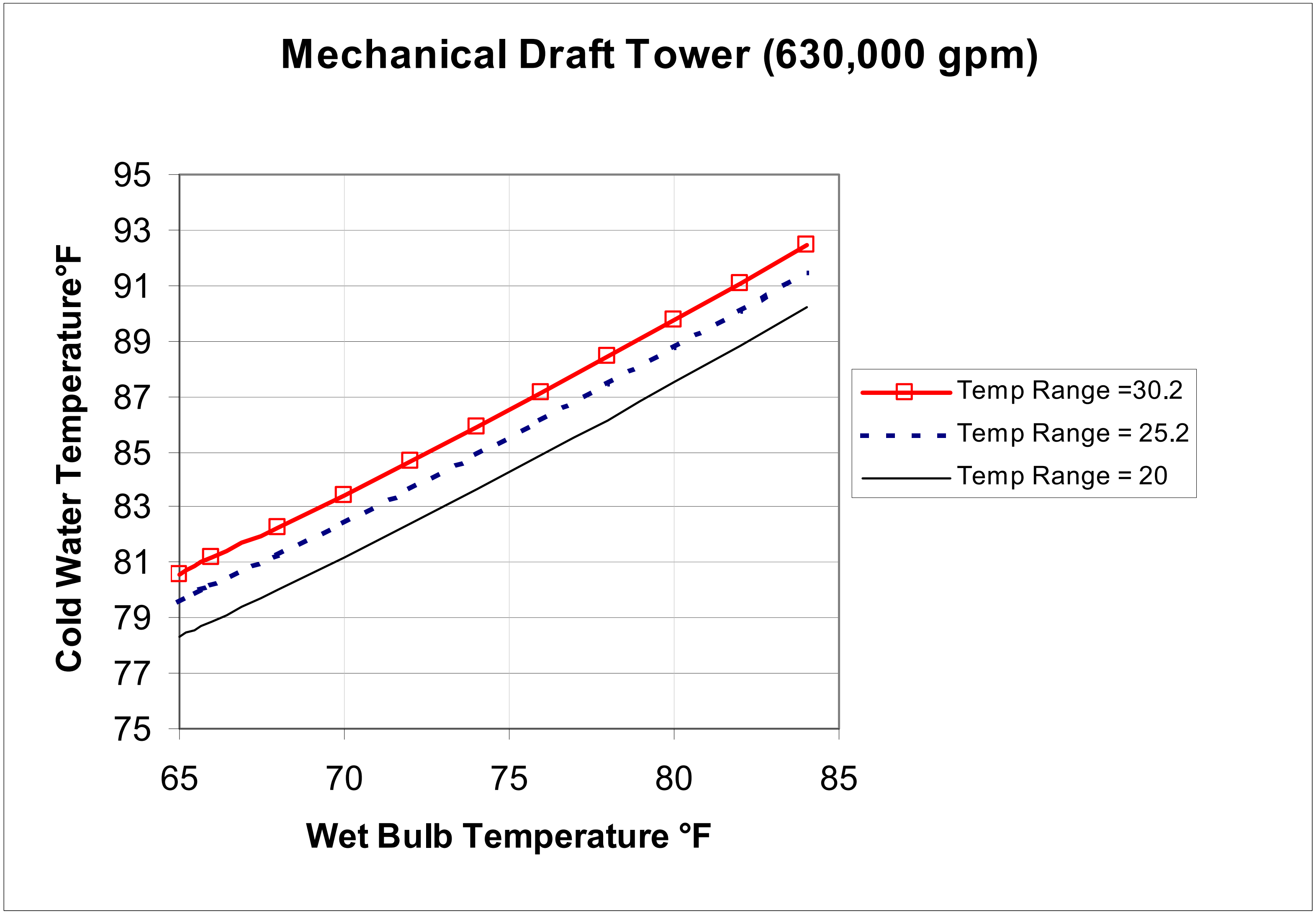
Wet Bulb Temperature °F
Temp Range =30.2
Temp Range = 25.2
Temp Range = 20



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