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THE THIRD OPTION FOR MEETING 316(B) REQUIREMENTS

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ABSTRACT

Section 316(b) of the Clean Water Act requires plants with intake flows of over 2 million gallons of water per day taken from the waters of the United States to implement the "best available" technology to reduce injury and death of fish and other aquatic life that may be impinged on or entrained in the intake. The two options commonly identified to address 316(b) are closed cycle cooling and fish screens. A third option that is often overlooked and may be less expansive is to implement changes in the plant, allowing it to operate with less condenser circulating water (CCW) flow.

Most CCW systems of power plants were originally designed to achieve an economic optimum balance between capital cost and the operating benefit of a lower main condenser (MC) pressure with the resulting increased electrical output. For those plants that are located on rivers, lakes, and oceans where CCW was abundant and free, economics often dictated high CCW flows impelled by low-head pumps and MC's designed with minimal surface areas, as larger MC's were not justified on the basis of economics. The passage of Section 316(b) of the Clean Water Act suggests a new look at the existing CCW system design for many plants with the goal of reducing the required CCW flow rate. In some instances simply reducing the CCW flow rate may be sufficient to meet 316(b) requirements. In other cases, the reduction of CCW flow may significantly reduce the capital and operating cost of adding cooling towers and/or fish screens.

This paper investigates ways to reduce the required CCW flow to existing power plants by redesigning and modifying the existing CCW system based on current technology. The result could be a new, improved, MC and other turbine cycle equipment and perhaps new CCW pumps, resulting in the same or better plant performance. The paper presents case studies in which the CCW systems for two power plants are redesigned to reduce the CCW flow

INTRODUCTION

The Environmental Protection Agency (EPA) estimates that Section 316(b) of the Clean Water Act will affect approximately 670 U.S. power plants that draw over 2 million gallons of water per day (Reference 1). These plants are required to implement the "best available" technology to reduce injury and death of fish and other aquatic life that may be killed by being impinged on the intake screens or entrained in the intake flow and exposed to the temperature and pressure changes associated with the CCW system as they pass through the plant's MC.

Two options are commonly identified to address 316(b) requirements. The first is to convert the CCW system from an open system which draws water from a lake, river, or ocean to a closed system in which cooling towers are commonly added to the plant, thus reducing the intake requirement to only that required to replace the water evaporated from the system and the blowdown that is required to control the concentration of dissolved solids in the CCW system. The second option that is commonly proposed is to replace the existing screens in the intake structure with screens designed to minimize fish impingement on to the screens.

Adding cooling towers to a power plant is often the most expensive and drastic solution. Plants are frequently located adjacent to the water source, making routing the large CCW conduits to and from the cooling towers extremely challenging if not impossible. Many plant sites are already very congested, and finding the space to locate the large cooling towers is often a major problem. Further, cooling towers consume large amounts of power that is no longer available to export off site due to increased pumping and fan power requirements. The temperature of the CCW returned to the plant from cooling towers is normally much higher than the temperature of the water taken from the original source, resulting in higher MC pressures and less efficient operation.

Replacing the existing traveling water screens in the intake structure can reduce impingement of fish at a considerable cost, sometimes requiring a completely new intake structure. However, replacing the intake screens with those of a more fish-friendly design does little to address the entrainment problem.

Imagine if one could meet the requirements of 316(b) with significantly less or no impact outside existing plant structures. The CCW systems of many power plants were originally designed to take advantage of the abundant and free CCW that was available from rivers, lakes, and oceans and the economic optimum design was a high flow, low head system with single-pressure MC's designed with minimal surface areas. Therefore, the potential may exist to reduce the required CCW flow to existing power plants by redesigning and modifying the existing CCW system to minimize intake flow based on current technology. The result could be a new and improved MC and other turbine cycle equipment and perhaps new CCW pumps and/or turbine rotors, resulting in the same or better plant performance.

MAIN CONDENSER DESIGN AND ANALYSIS

Symbol	Definition	Units
A	Main condenser surface area	Ft^2
CF	Cleanliness factor	
c_p	Specific heat	BTU/(LbM °F)
d	Diameter	In
F	Fanning friction factor	
H	Specific enthalpy	BTU/LbM
h	Heat transfer coefficient	BTU/(Hr Ft^2 °F)
k	Thermal conductivity	BTU/(Hr Ft °F)
LMTD	Log mean temperature difference	°F
$\dot{m}$	Mass flow rate	LbM/Hr
NTU	Number of transfer units	
Nu	Nusselt number	
P	Effectiveness	
Pr	Prandtl number	
Q	Heat transfer	BTU/Hr
r	Resistance	(Hr Ft^2 °F)/BTU
Re	Reynolds number	
t	Fahrenheit temperature	°F
TTD	Terminal temperature difference	°F
U	Overall heat transfer coefficient	BTU/(Hr Ft^2 °F)
μ	Viscosity	LbM/(Ft Sec)
ρ	Density	LbM/ Ft^3

Subscripts	Definition
CCW	Condenser circulating water
CCW_{in}	Condenser circulating water in
CCW_{out}	Condenser circulating water out
clean	Clean condition
clean-design	Clean design value
f	Condensate film
fg	Latent heat
fouled	Fouled design value
i	Inside
o	Outside
sat	Saturation
shell	Shell side convection
Shell-design	Shell side convection – design
t	Tube-side
tube	Tube side convection
tube-design	Tube side convection – design
Wall	Tube wall
wall-design	Tube wall design value

The analysis contained herein utilizes the effectiveness method for calculating MC saturation temperature and corresponding pressure where

$$P = \frac{t_{CCWout} - t_{CCWin}}{t_{sat} - t_{CCWin}}$$

$$t_{sat} = \frac{t_{CCWout} - t_{CCWin}\left(1-P\right)}{P}$$

For the MC

$$P = 1 - e^{-NTU}$$

where

$$NTU = \frac{U_{fouled}\ A}{\dot{m}_{CCW}\ c_{p-CCW}}$$

The overall heat transfer coefficient is calculated using the sum of the resistances method as recommended by Reference 2.

$$U_{clean} = \frac{1}{r_{shell} + r_{wall} + \left(\frac{d_o}{d_i}\right) r_{tube}}$$

The shell-side convection resistance is calculated using the design point method as described in Reference 3.

$$r_{shell-design} = \frac{1}{U_{clean-design}} - r_{wall-design} - \left(\frac{d_o}{d_i}\right) r_{tube-design}$$

where $U_{clean\text{-}design}$ is taken from the MC manufacturer's data sheet.

$$r_{wall-design} = \frac{d_o}{24\,k} \ln\left(\frac{d_o}{d_i}\right)$$

and

$$r_{tube-design} = \frac{1}{h_{tube-design}}$$

The tube-side convection coefficient may be calculated for off-design conditions as

$$h_{tube} = \frac{k_t}{d_i}\,Nu$$

where the Nusselt Number may be calculated using the Petukhov equation.

$$Nu = \frac{\left(F/2\right)\,\mathrm{Re}_t\;\mathrm{Pr}_t}{1.07 + 12.7\sqrt{F/2}\left(\mathrm{Pr}_t^{2/3} - 1\right)}$$

where

$$F = \left(1.58\ln\mathrm{Re} - 3.28\right)^{-2}$$

$$\mathrm{Re}_t = \left(\frac{\dot{m}_t}{A_t}\right)\left(\frac{d_i}{\mu_t}\right) \quad and \quad \mathrm{Pr}_t = \frac{\mu_t\,c_{p-t}}{k_t}$$

The shell-side convection resistance for off-design conditions is corrected using the Nusselt equation for convection heat transfer for MC's as follows (Reference 4):

$$r_{shell} = r_{shell-design}\,\frac{\left[\dfrac{k_f^3\,\rho_f^2\,H_{fg}}{\mu_f\left(t_{sat} - t_{CCWin}\right)}\right]_{shell}^{1/4}}{\left[\dfrac{k_f^3\,\rho_f^2\,H_{fg}}{\mu_f\left(t_{sat} - t_{CCWin}\right)}\right]_{shell-design}^{1/4}}$$

The design cleanliness factor is defined as

$$CF = \frac{U_{fouled}}{U_{clean}} \;\Rightarrow\; U_{fouled} = U_{clean}\;x\;CF$$

Although commonly referred to as the cleanliness factor, this value is actually a performance factor since in addition to reflecting macro-fouling that may occur on the MC tube sheet and micro-fouling on the inside diameter of the tubes, it may also reflect high air in-leakage and/or poor MC design. For the purposes of this analysis, the CF is a given design parameter, so knowing this value and the value of U_{clean}, then U_{fouled}, NTU, P, t_{sat}, and the turbine back-pressure may be determined.

The EPA has stated that one way to minimize impingement is to reduce the velocity of the CCW at the face of the intake screen to 0.5 Ft/Sec or less. Reducing the CCW flow rate may possibly achieve this goal, and will quite obviously reduce entrainment.

Two case studies are presented: a large fossil plant and a large nuclear plant. The MC is redesigned without changing the MC shell outline or the buried CCW piping, and the CCW flow is reduced in each case until plant design limitations are approached. These limitations include the following:

- Minimum TTD
- Minimum tube velocity
- Maximum condensate temperature
- Maximum turbine back-pressure

In addition to CCW flow, consideration is given to the following:

- Changes in generator terminal output
- Changes in auxiliary power consumption
- Capital cost

FOSSIL PLANT CASE STUDY

Reference 5 describes the selection of a CCW system for a two-unit 1300 MW_e coal-fired power plant designed in 1969 to meet anticipated stream standards outside of the mixing zone of a maximum temperature of 93.0 °F, a temperature rise of 10.0 °F, and a temperature rate of change of 3.0 °F per hour. The CCW system that was designed to meet the anticipated standards called for a MC with the following design parameters:

Table I
Original Fossil Unit Main Condenser Design

Tube-side flow rate	808,000 Gal/Min
Number of shells	2
Number of tubes per shell	17,758
Tube outside diameter	1.25"
Tube length	35'
Tube wall thickness	18 BWG
Tube-side velocity	6.7 Ft/Sec
Surface area per shell	202,233 Ft^2
Tube material	90/10 Cu/Ni
CCW inlet temperature	62.0 °F
Condensing Duty	5.4 x 10^9 BTU/Hr
CCW temperature rise	13.4 °F
Minimum TTD	12.3 °F
Design cleanliness factor	85%
Average MC pressure	1.43 In.HgA
Maximum MC pressure	3.00 In.HgA

When the Clean Water Act was enacted in 1972, the stream standards promulgated under Section 316(a) required considerably more severe restrictions, but by then the plant was almost completed.

In order to reduce the amount of CCW flow to the fossil unit, the following modifications are proposed to better meet 316(b) requirements:

- Replace the existing MC tubes with 0.875" titanium tubes
- Convert the 2-shell single-pressure MC to a multi-pressure MC by routing the discharge from Shell A to the intake of Shell B through piping located under the existing MC hotwell.
- Replace the existing CCW pumps with higher head pumps.

Table 2 shows the proposed MC design to reduce the CCW flow.

Table II
Proposed Fossil Unit Main Condenser Design

Tube-side flow rate	400,000 Gal/Min
Number of shells	2
Number of tubes per shell	42,000
Tube outside diameter	0.875"
Tube length	35'
Tube wall thickness	25 BWG
Tube-side velocity	5.6 Ft/Sec
Surface area per shell	334,816 Ft^2
Tube material	Titanium
CCW inlet temperature	62.0 °F
Condensing duty	5.4×10^9 BTU/Hr
CCW temperature rise	27.0 °F
Minimum TTD	8.8 °F
Design cleanliness factor	85%
Average MC pressure – Shell A	1.40 In.HgA
Average MC pressure – Shell B	1.95 In.HgA
Maximum MC pressure	3.97 In.HgA

Figure 1 shows the monthly average net electrical output from the fossil unit for the existing MC design, the existing MC design with mechanical draft cooling towers (MDCT) added to achieve a closed cycle system, and the proposed MC design, where the net output is the generator terminal output less the pumping and fan power. The proposed MC design results in an annual average reduction in net plant output of 3.6 MW_e, whereas the addition of cooling towers to achieve a closed system results in an annual average reduction on net plant output of 33.1 MW_e, due to the power required to drive the cooling tower lift pumps and fans.

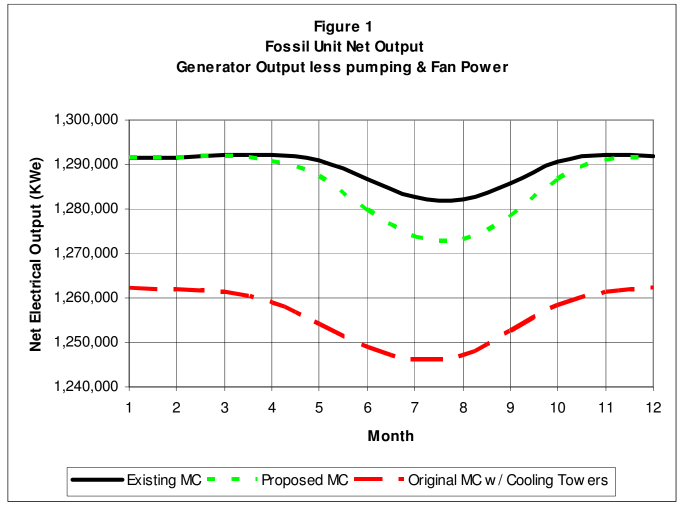

Figure 1
Fossil Unit Net Output
Generator Output less pumping & Fan Power

Table III shows the required pumping and fan power for each alternative.

Table III
Fossil Unit
Pumping and Fan Power Requirements per Unit (KW_e)

Alternative	Existing MC	Existing MC w/MDCT	Proposed MC
CCW Pump	4,751	4,751	5,079
Cooling tower lift pump	0	17,313	0
Cooling tower fans	0	12,528	0
Total	4,751	34,592	5,079

The estimated direct capital cost to add the cooling towers, cooling tower lift pumps and motors, and the associated structures, piping, electrical service, and site preparation for two units is in excess of 300 million dollars, whereas the estimated direct capital cost to modify the MC and replace the existing CCW pumps with higher head pumps is approximately 20 million dollars for two units. In addition to the advantages in net plant output and capital cost, the proposed CCW system change would result in avoiding the cooling tower and lift pump maintenance costs and would provide the plant with an upgraded MC and new CCW pumps.

Since the original intake structure was designed for an intake velocity of 1.0 Ft/Sec, reducing the CCW flow to less than 50% would result in an intake velocity of less than 0.5 Ft/Sec, thus meeting the EPA requirements for impingement mitigation. Additionally, reducing the CCW flow by more than 50% significantly reduces entrainment. Reducing the CCW flow by over 50% while almost doubling the CCW temperature rise through the plant makes compliance with Section 316(a) of the Clean Water Act less difficult in that the higher discharge temperatures promotes heat rejection inside the licensed mixing zone down stream of the plant.

The author readily concedes that the fossil plant case study presented herein is somewhat of a "straw man" in that the temperature rise through the MC is less than is normally the case, and therefore the CCW flow rate is higher. However, many older MC's were designed with high CCW flow and low temperature rise. Regardless, one may see by inspection that even if the CCW flow were half the value in this case study, resulting in approximately half the number of cooling towers and lift pumps, there would still remain a significant advantage for the proposed redesign of the CCW system in capital, operating, and maintenance costs.

NUCLEAR PLANT CASE STUDY

The two-unit 1200 MW_e nuclear plant was nearing completion just as the Clean Water Act became law in 1972, well after the MC was designed and erected. Two cross-flow natural draft cooling towers were added along the plant discharge channel after the plant was well under construction, because they were required to meet the thermal stream standards under Section 316(a). The CCW system can operate in either open or helper mode in which the discharge from the plant is pumped over the cooling towers where the CCW is cooled prior to being discharged back into the river. Although the plant can meet the existing 316(a) requirements by operating the CCW system in either open mode or helper mode provision was made in the design and implementation for closed mode operation in anticipation of that being required in the future. These provisions included the following:

- Space for a third natural draft cooling tower
- A tee in the piping to the existing cooling towers
- A channel from the cooling tower discharge channel to the plant intake channel
- Gate structures permitting the CCW to flow either back to the river or to the plant intake.
- A new safety-related service water pumping station located away from the CCW intake structure

Table IV shows the original and current design of the MC for the nuclear plant case study. The MC was re-tubed with titanium tubes as part of the nuclear industry's program to remove copper from the secondary systems. The design cleanliness factor is 95%, because the MC is served by an on-line ball cleaning system. As one may see from Table IV, the MC was re-tubed with smaller diameter, thinner, tubes, increasing the surface area and reducing the CCW flow, tube velocity, TTD, and pressure slightly.

The object of the redesign of the nuclear plant CCW system proposed herein is to reduce the required CCW flow such that impingement and entrainment are minimized and no additional cooling towers would be required if closed cycle operation is mandated by 316(b) considerations.

Table IV
Nuclear Unit Main Condenser Design

	Original MC	Current MC
Tube-side flow rate	530,000 Gal/Min	524,000 Gal/Min
Number of shells	3	3
Number of tubes per shell	19,620	27,897
Tube outside diameter	0.875"	0.75"
Tube length	50'	50'
Tube wall thickness	18 BWG	22 BWG
Tube-side velocity	5.7 Ft/Sec	5.2 Ft/Sec
Surface area per shell	224,000 Ft^2	273,000 Ft^2
Tube material	90/10 Cu/Ni	Titanium
CCW inlet temperature	62.0 ^oF	61.0 ^oF
Condensing Duty	7.72 x 10^9 BTU/Hr	7.83 x 10^9 BTU/Hr
CCW temperature rise	29.0 ^oF	28.9 ^oF
Minimum TTD	11.6 ^oF	6.0 ^oF
Design cleanliness factor	95%	95%
Average MC pressure	2.03 In.HgA	1.88 In.HgA
Maximum MC pressure	3.86 In.HgA	3.58 In.HgA

In order to reduce the amount of CCW flow to the nuclear unit, the following modifications are proposed:

- Convert the 3-shell single pressure MC into a multi-pressure MC by routing the discharge of shell A to the (previous) discharge of Shell B and the (previous) intake of Shell B to the intake of Shell C
- Replace the existing CCW pumps with higher head pumps.

Consideration must be given to the following constraints:

- Minimum TTD – The minimum TTD should not be less that 5.0 ^oF
- Minimum tube velocity – should not be below 5.0 Ft/Sec
- Maximum condensate temperature – should not exceed 140 ^oF
- Maximum turbine back-pressure – should not exceed 5.5 In.Hga

When operating with the MC shells in series in open mode with a maximum CCW intake temperature of 85 ^oF, flows less than 350,000 Gal/Min must be excluded based on the above criteria. A CCW flow of 350,000 Gal/Min constitutes an intake flow reduction to 66% of the original intake flow which may be sufficient to meet 316(b) requirements for at least a portion of the year. When operating with the MC shells in series in closed mode with a maximum CCW intake temperature of 94 ^oF, based on the highest ambient wet-bulb temperature of 80 ^oF, flows less than approximately 430,000 Gal/Min must be excluded.

For purposes of this study, the cold water temperature coming from the cooling towers is assumed to be the same whether the existing CCW flow is distributed over three cooling towers (the third being added) or the redesigned CCW flow is sent to the two existing towers. Although there is a small difference in the temperature rise across the MC and thus that of the hot water temperature going to the cooling towers between the two alternatives, the cold water temperature coming from a natural draft cooling tower is not sensitive to the hot water temperature entering the tower, permitting the assumption that the cold water temperature would be the same for the two alternatives.

Table V shows the proposed revised CCW system design for the nuclear plant assuming open and closed modes of operation.

Table V
Proposed Nuclear Unit Main Condenser Designs with Open and Closed Modes of Operation

	Proposed Mult-Pressure MC Design Open Mode	Proposed Multi-Pressure MC Design Closed Mode
Tube-side flow rate	350,000 Gal/Min	430,000 Gal/Min
Number of shells	3	3
Number of tubes per shell	27,897	27,897
Tube outside diameter	0.75”	0.75”
Tube length	50'	50'
Tube wall thickness	22 BWG	22 BWG
Tube-side velocity	10.4 Ft/Sec	12.8 Ft/Sec
Surface area per shell	273,000 Ft^2	273,000 Ft^2
Tube material	Titanium	Titanium
Condensing Duty	7.83 x 10^9 BTU/Hr	7.83 x 10^9 BTU/Hr
CCW temperature rise	44.8 °F	36.5 °F
Minimum TTD	6.1 °F	6.2 °F
Design cleanliness factor	95%	95%
Maximum MC pressure	5.35 In.HgA	5.45 In.HgA

The proposed design would require new CCW pumps and motors rated at 115 and 180 feet of head for open and closed cycle operation, respectively. The CCW piping between the CCW pumps and the MC would need to be evaluated for the higher operating pressure.

Figure 2 shows the monthly average net electrical output from the nuclear unit for the existing and proposed MC design for both open and closed mode of operation, where the net output is the generator terminal output less the pumping power. The proposed CCW system design results in an annual average reduction in net plant output of 10.5 MW_e/unit if closed mode of operation is not required to meet 316(b). If closed mode of operation is required, the proposed design would result in an annual average reduction in net plant output of only 6.4 MW_e./unit

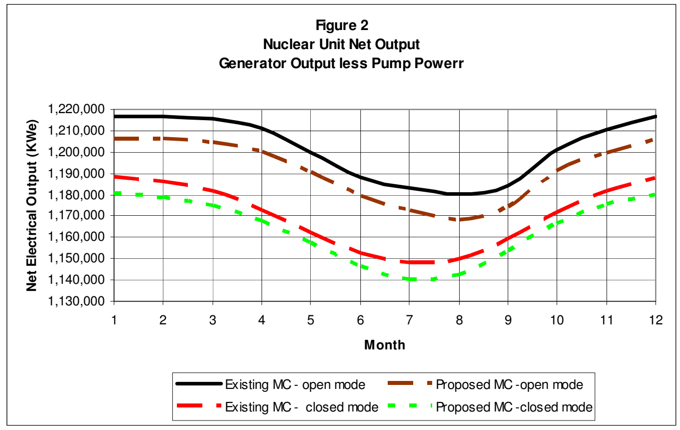

Table VI shows the required pumping and fan power for each alternative.

Table VI
Nuclear Unit
Pumping Power Requirements Per Unit (KW_e)

Alternative	Existing CCW Open	Existing CCW Closed	Proposed CCW Open	Proposed CCW Closed
CCW Pump	3,993	3,993	10,000	19,032
CT lift pump	0	9,570	0	7,853
Total	3,993	13,563	10,000	26,885

The estimated direct capital cost to add the third cooling tower and associated piping is in excess of 60 million dollars, not including the foundation. The existing two natural draft cooling towers rest on 60” and 72” diameter caissons some of which are 120’ deep due to the difficult subsurface conditions. On the other hand, the estimated direct capital cost to replace the existing CCW pumps and motors and place the existing three MC shells in series is only approximately 15 and 24 million dollars for open and closed mode operation, respectively.

What will be required for the nuclear plant to meet 316(b) requirements is beyond the scope of this investigation. Certainly, the plant is likely to be required to mitigate the impingement and entrainment that is presently occurring in some manner. One likely outcome would be to require closed cycle operation of the CCW system if no modifications are made to the MC, likely necessitating the addition of a third cooling tower. Whether or not reducing the CCW flow by one-third would be sufficient to meet 316(b) requirements is a subject for further study. Certainly if closed mode of operation is required, consideration should be given to modifying the CCW system as described herein, although the present worth cost of the loss in net plant output by doing so must also be considered.

Consideration should be given to installing variable speed CCW pumps to permit adjusting the CCW flow as required to permit either open or closed mode of operation.

CONCLUSIONS

Although the final solution will be based on the circumstances of each plant, two methods are commonly proposed for meeting the requirements of Section 316(b) of the Clean Water Act to reduce impingement and entrainment. These are (1) adding cooling towers to convert the CCW system to a closed system and (2) installing fish screens. These two solutions might be the most expensive and/or least effective means of meeting the requirements. Since the MC's in many existing power plants were designed and installed in an age when CCW was abundant and no thought was given to minimizing the effects of impingement and entrainment, a third alternative should be considered - that of significantly reducing the required CCW flow through redesign and modifications to the CCW system. The surface area of many MC's can be increased through re-tubing without changing the MC's shell, permitting the same or a lower turbine back-pressure to be maintained with less CCW flow. If the MC has more than one shell, they can be placed in series without having to relocate the buried CCW piping, creating a multi-pressure MC which utilizes the same CCW flow more than once to further reduce the CCW flow. This approach may permit compliance with 316(b) without requiring any modifications outside of existing plant structures and would result in acquiring new plant equipment such as new MC tubes and new CCW pumps and motors. Nor would there be a significant increase in the house load associated with cooling tower pumps and fan motors and an increase in maintenance costs associated with these new components.

Even if it is determined that cooling towers are required, reducing the CCW flow can greatly reduce the cost of compliance with 316(b), since the cost of a cooling tower is a strong function of the CCW flow, and cooling tower lift pump and fan power would be reduced.

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