Performance differentiators:

IPC vs. variable primary systems

White paper

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The Integrated Plant Control (IPC) automation system from Armstrong employs a number of differentiating approaches to provide the building owner with the best possible performance from an investment in an all-variable speed plant.

The IPC 11550, for all-variable speed chiller plants, is able to provide some of the highest efficiency levels possible through a variety of relational control and demand based control principles.

This paper compares and contrasts the control methodologies of the IPC 11550 to traditional variable primary chiller plant automation methods to help us understand how these differences lead to such a variance in overall plant performance. For those unacquainted with these overall plant performance levels, the IPC 11550 all-variable speed plant, typically consumes 30–60% less energy than a traditionally controlled variable speed chiller plant, on an annual average basis. This includes the energy used by the chillers, the cooling tower fans, the chilled water primary pumps and the cooling tower/condenser pumps.

TRADITIONAL CONTROL

Today's chiller plants are typically installed with variable speed chillers that utilize variable frequency drives on their compressors, enabling the compressor rotational speed to be slowed down as needed. During off peak load periods these chillers are able to conserve energy by slowing down the compressor for one or more of three possible "off-peak" conditions. It is important to note that the power speed relationship for a compressor is an inverse cubic relationship, so by slowing down the compressor by just 20% in speed, the power draw is reduced to 51% (0.8 × 0.8 × 0.8) of the original amount. There are three ways to unload a centrifugal chiller:

- reduce the load on the chiller
- reduce the need for condenser temperature/pressure
- allow the evaporator temperature/pressure to rise

VS CHILLER kW/ton (CENTRIFUGAL)

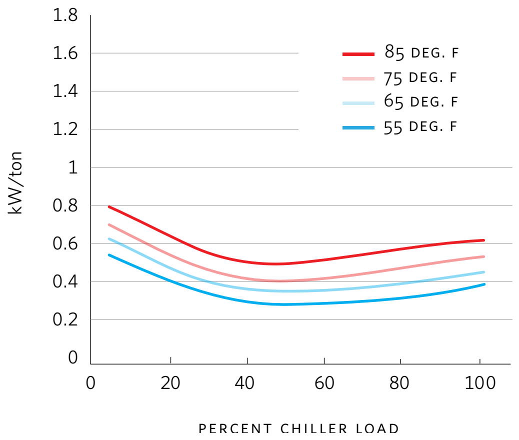


FIG. 1

CONSTANT SPEED CHILLER kW/ton (CENTRIF.)

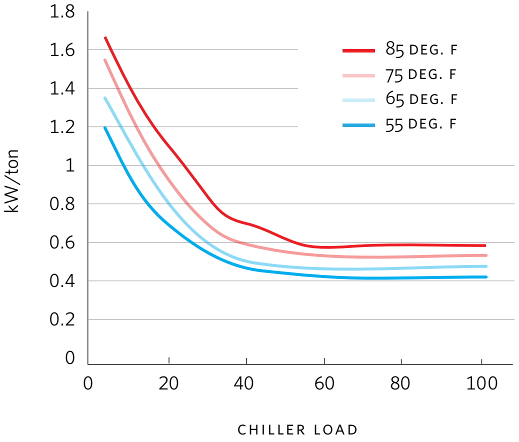


FIG. 2

The two charts above compare the efficiency (kW/ton) of a variable speed chiller (fig. 1), and a fixed speed chiller (fig. 2) for various chiller loads and entering condenser water conditions. By reducing the chiller load, the temperature differences between the two fluids in the condenser (refrigerant and cooling tower water) and the evaporator (refrigerant and the chilled water) can be reduced, to transfer this smaller amount of heat within each shell and tube assembly (condenser and evaporator). The amount of heat transfer between the two fluids is proportional to the LMTD (log mean temperature difference), this allows the chiller control to raise the evaporator pressure and lower the condenser pressure, meaning that the compressor has less "pressurizing" work to do, along with having less refrigerant flow to circulate. The energy savings are realized by slowing the compressor to provide less lift, or pressurizing of the refrigerant between the evaporator and the condenser.

If we are able to lower the leaving tower water temperature, for the same chiller load scenario, we will also be able to equally lower the condenser refrigerant temperature (and pressure). Often this is referred to as condenser relief, and reduces the "pressurizing" work that the compressor has to do, allowing it to slow down and achieve energy savings. If we are able to raise the chilled water supply temperature setpoint, then we are able to reduce the required pressure difference between the evaporator saturation pressure and the condenser pressure, again allowing a condition where the compressor can be slowed down since less "pressurizing" work is required. Often this is referred to as chilled water reset. If the variable speed chiller was the only element in the plant we could easily define the best operating scenarios for a specific load and supply of condenser water temperature. However, the chiller is just one energy consuming component in the complex arrangement of devices that comprise the chiller plant. When we examine the complex relationships between the components in the plant, we quickly realize that there is no one simple relationship that will ensure that energy savings through the three described methods will not sacrifice total plant efficiency because the efficiency of the other components (chilled water pumps, condenser pumps, and cooling tower fan) begin to degrade, in our effort to maximize the three discussed effects.

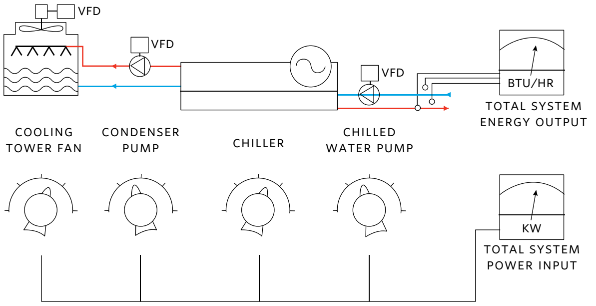


FIG. 3

Today's chiller plant topologies are typically either variable primary flow, or constant primary either with variable secondary configurations. Both are very load side focused and responsive. That means that their front end (distribution pumps) respond to the building load requirement, while the rest of the plant devices operate off of process set-points with minimal relation to the load requirement. Generally, they ignore the possibility of performance effects that could result from tuning the relationship between the evaporative cooling tower and chillers to optimize the plant performance. This is a constraint imposed on us by analogue era PID feedback control loops. Traditional designs employ three PID feedback control loops (cooling tower, refrigerant, and chilled water distribution). These seperate loops prevent the trade off of capacity between plant devices for a net plant system efficiency improvement.

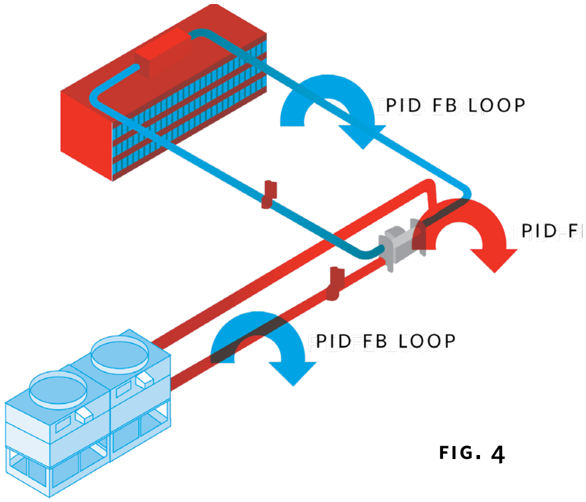


FIG. 4

IPC 11550 CONTROL TECHNOLOGIES

The IPC 11550 control algorithms are based on a number of patented control technologies, some of which are often referred to as the Hartman LOOP™ technologies, including Natural Curve Sequencing, Equal Marginal Performance Principle, and Demand Based Control. Unlike PID feedback control loops, these control technologies are digital era technologies that are implemented on micro-processor based networked environments. As opposed to maintaining control set-points in the chiller process, the IPC 11550 has pre-calculated operating relationships that optimize performance for all possible scenarios that the chiller plant could experience. This is similar to the operating map approach used in modern automotive engine management control units. By doing so, the IPC 11550, can sense a change in the load or weather situation, and can immediately adjust the plant settings and equipment arrangements to operate at the most efficient operating point for those new load scenarios. The maps are engineered for the specific combination of mechanical equipment installed (towers, chiller and pumps) and can be adjusted over time with a set of simple "tuning factors". These tuning factors allow for changes in the performance of the equipment with age, due to contributors such as degradation of heat transfer surfaces, degradation of refrigerants or changes in evaporative performance.

With this new control approach, an all-variable speed plant is now possible. The all-variable speed plant is an enhancement over the variable primary flow plant, as we also have enabled utilizing variable speed condenser pumps. Often it is suggested that having variable speed condenser pumps doesn't provide a great opportunity for savings, as pump energy is a small opportunity with the flow constraints on the condenser side of a chiller (typically >77% of design flow). This is a premature assessment that we should not race towards without first considering the possibilities that part flow on a cooling tower can still provide for the whole plant.

Consider the result of the variable flow tower on tower efficiency at off-peak operation. During part load operation at lower than design day wet-bulb temperature, we find that the tower's most efficient evaporative operating point is at part flow for the air and part flow for the water. With variable flow towers we can match the base case leaving tower water temperature with far less power (fan and pump), or we can get a leaving tower water temperature lower than the base case with some partial fan and pump speed relationship between the two operating modes above (the best evaporative efficiency speeds and the base case).

Figure 5 shows how we can operate the cooling tower with better evaporative efficiency, trade off pump and tower effectiveness, lower the leaving water temperature below what we could employ with fixed flow tower operation and in turn reduce the compressor work that we demand from the chiller. Yes, we save pump energy, but more importantly, we improve tower performance, and have another lever to optimize chiller performance. There are many complex thermo-hydraulic relationships like this throughout the chiller plant that would be near impossible to program into a traditional PID feedback control loop based automation system. The IPC 11550 achieves this better result, but through a different approach, the approach of pre-determined operating relationships that are simply based on the relationship of power in and cooling capacity out (tonnage).

Instead of explaining all of the thermodynamics behind the ultra-efficient all-variable speed chiller plant, this paper presents a comparison between the operation of a chiller plant with IPC 11550, and that same plant with traditional variable primary flow control through PID feedback loop control. It also then explains the sources of the differences based on heat transfer and turbo-machinery fundamentals and how they contribute to the net system efficiency of the plant.

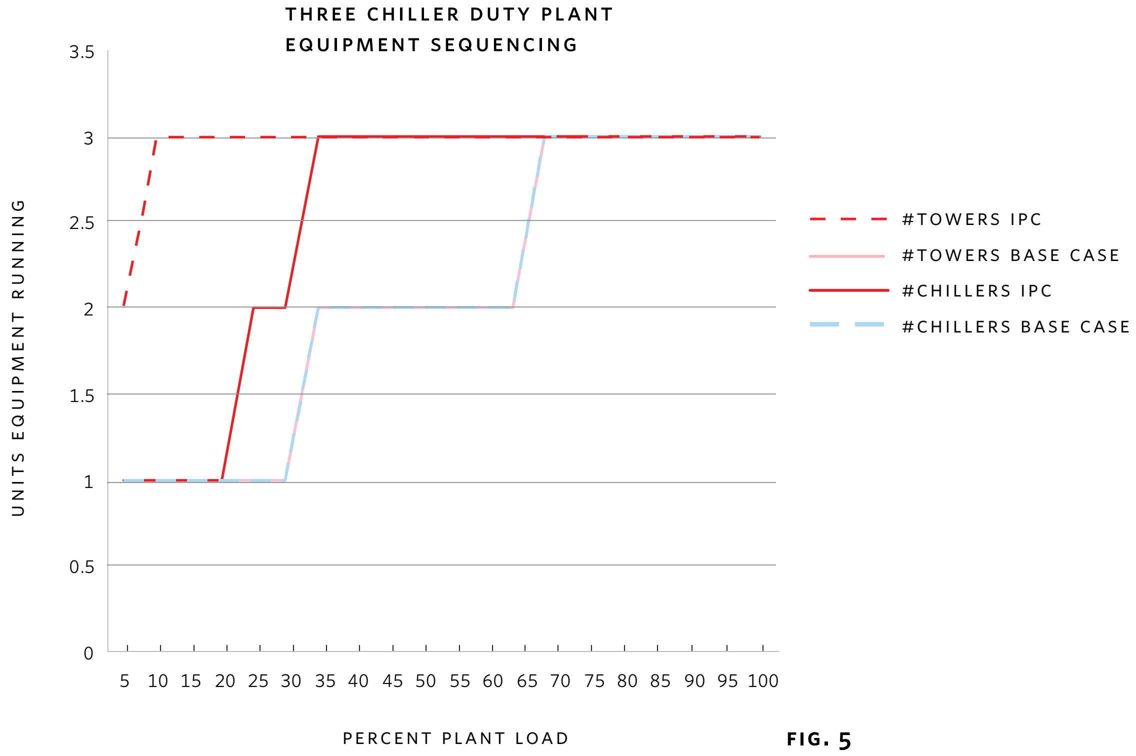


FIG. 5

TOWER DIFFERENTIATOR WITH VARIABLE FLOW

Water cooled plants release the unwanted building heat to the atmosphere through evaporative cooling towers. We will compare the regular variable primary flow plant to an all-variable flow plant, to observe the difference in power consumed by the tower and the leaving tower water temperature (LTWT), which is the primary product of the evaporative tower process. With variable flow we take advantage of two effects; improved tower efficiency and, by operating multiple towers at part flow for a smaller number of chillers, increased evaporative surface area. The chart below illustrates the differences in tower and chiller sequencing between the IPC and conventional plant control. Clearly there is more evaporative surface area by running all towers and chillers, however, for conventional plant control the concern becomes how to manage the extra pump flow requirement and fan operation so as not to consume more power than we save at the compressors. Using an all-variable plant enables us to optimize tower performance at part load and take advantage of the available evaporative surface area by slowing the fan and the water flow together, keeping those ratios nearest to their best performance (shown in Fig 6).

As shown in Fig.6, the variable flow tower is able to provide sufficient evaporative capacity with less power input and in general a lower leaving tower water temperature at part loads. This lowers the leaving tower water temperature, permits greater condenser relief (less compressor work, and less heat transfered into the tower water) and further reduces the load on the tower, placing it in an even better position for performance. With variable flow cooling towers and condensers, the delta T across both the chillers and the cooling towers is increased, which improves the efficiency of both combined.

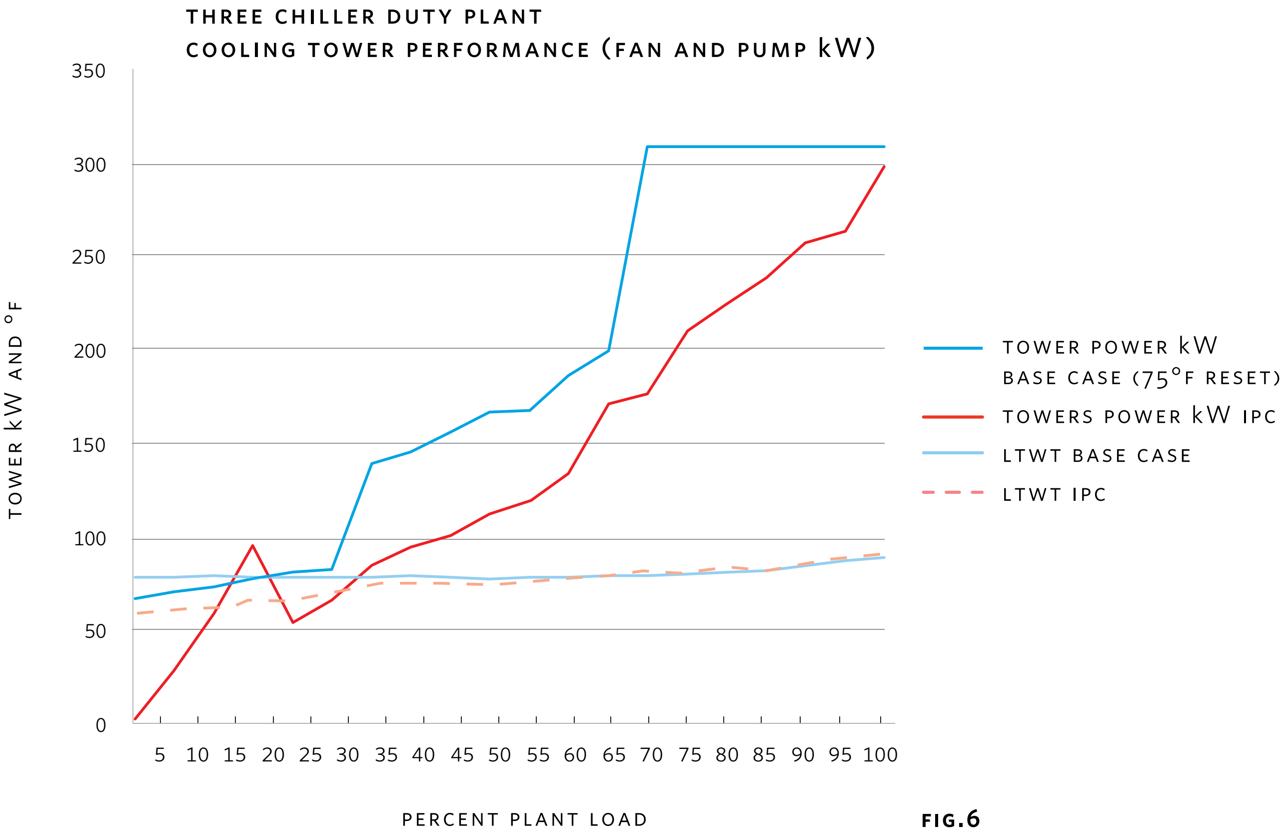


FIG.6

The plot (Fig. 7 below) indicates the reduced maximum refrigerant temperature required at part loads as influenced by Natural Curve sequencing, variable flow condenser water, and equal margin performance principle.

The lower refrigerant temperature provided by the IPC SCENARIO AT THE chiller condenser, to release heat energy to the tower, water permits the compressor to unload more than the base case variable primary flow plant (at part loads, <70% in the above). The base case is for a chiller plant with condenser water relief setpoint of 75˚F (see appendix A for the details of the three chiller VPF plant used in the base case).

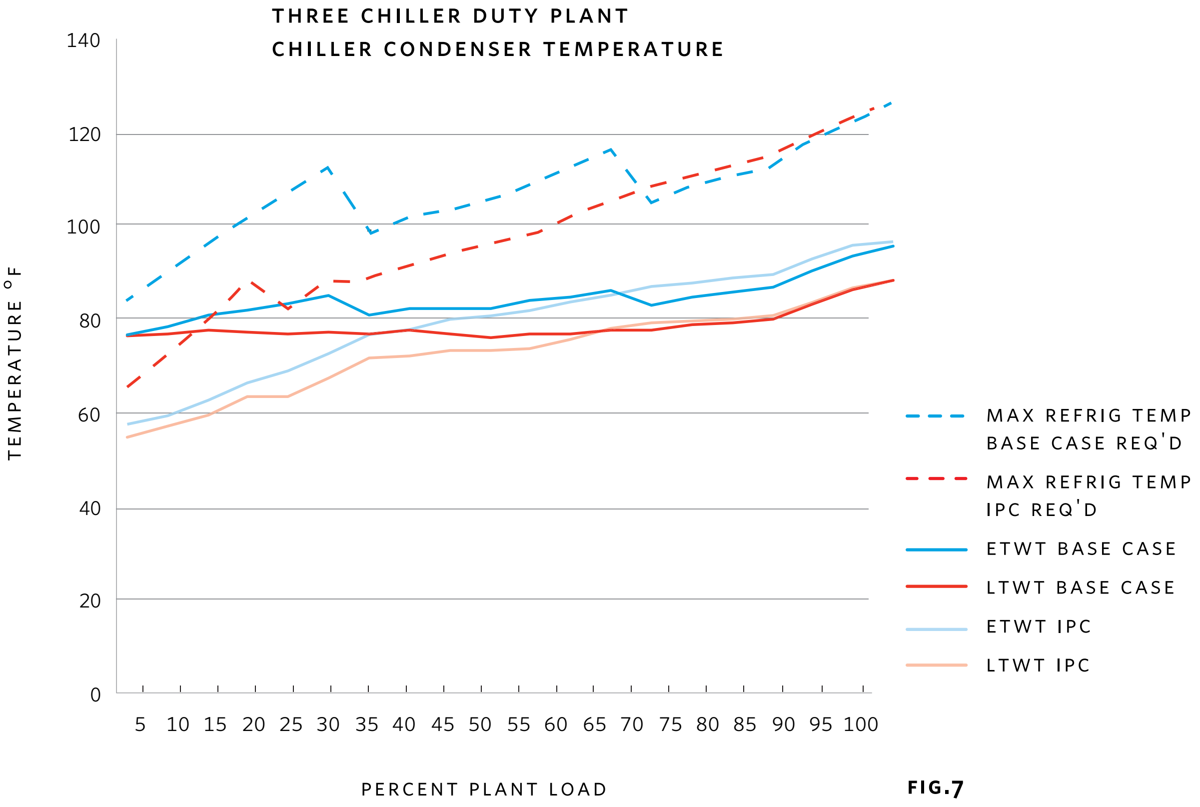


FIG.7

LEVERAGING STANDBY CAPACITY

Most larger water cooled chiller plants are designed with some degree of excess capacity or full standby pieces of equipment. The IPC all-variable speed control methods enable the plant to leverage the utilization of those stand-by assets to provide better plant efficiency levels at part load and full load scenarios. The charts that follow compare the impact of the stand-by plant to a full duty plant when operated with the IPC (Fig. 8 presents the stand-by capacity plant scenario).

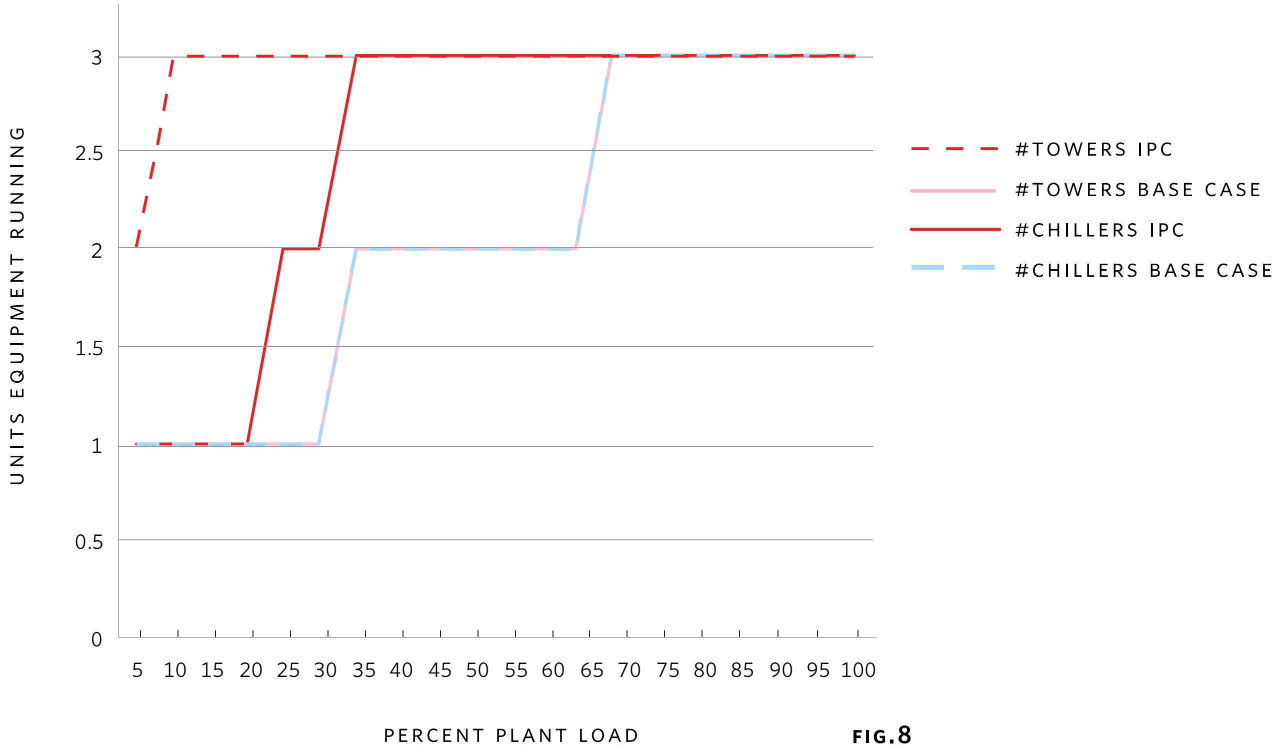

UNITS EQUIPMENT RUNNING
3
2.5
2
1.5
1
0.5
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
PERCENT PLANT LOAD
#TOWERS IPC
#TOWERS BASE CASE
#CHILLERS IPC
#CHILLERS BASE CASE

FIG.8

* * *

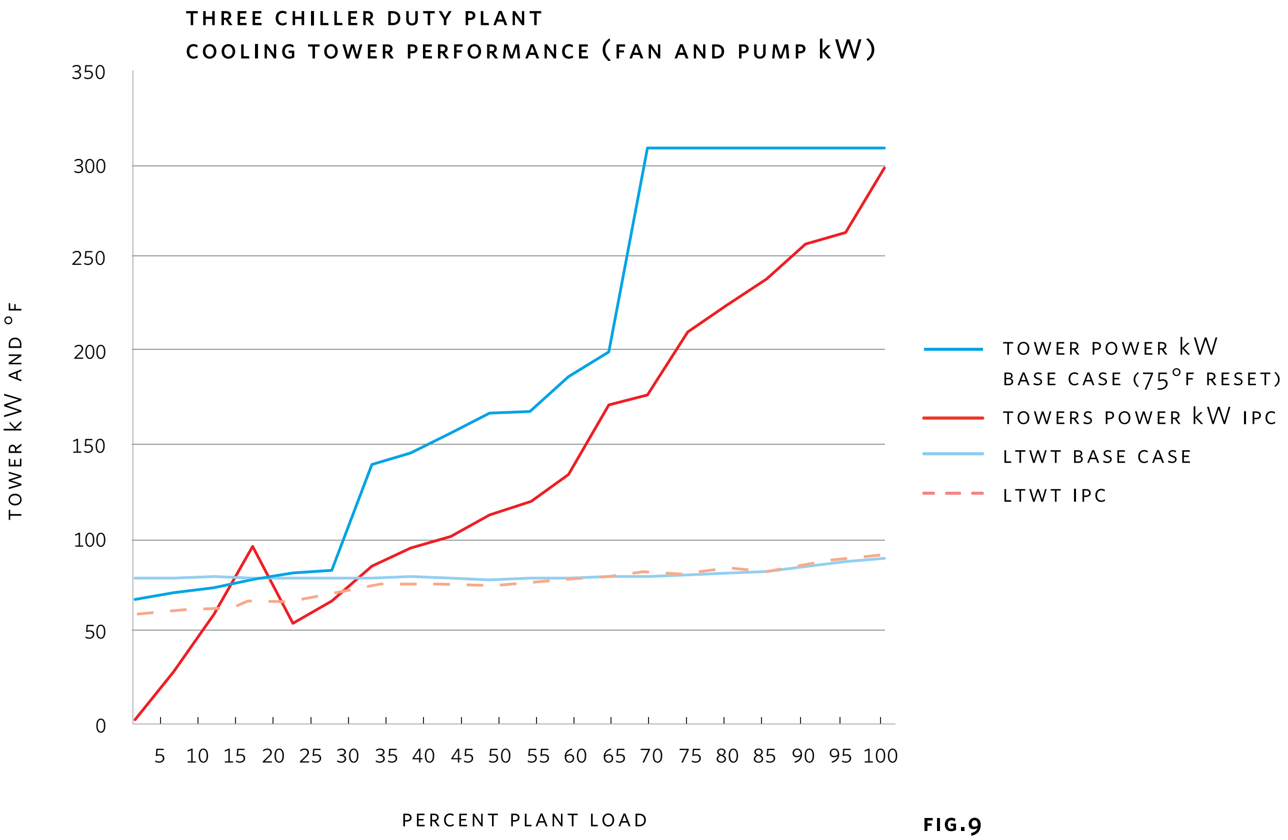

THREE CHILLER DUTY PLANT
COOLING TOWER PERFORMANCE (FAN AND PUMP kW)
TOWER kW AND °F
350
300
250
200
150
100
50
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
PERCENT PLANT LOAD
TOWER POWER kW BASE CASE (75°F RESET)
TOWERS POWER kW IPC
LTWT BASE CASE
LTWT IPC

FIG.9

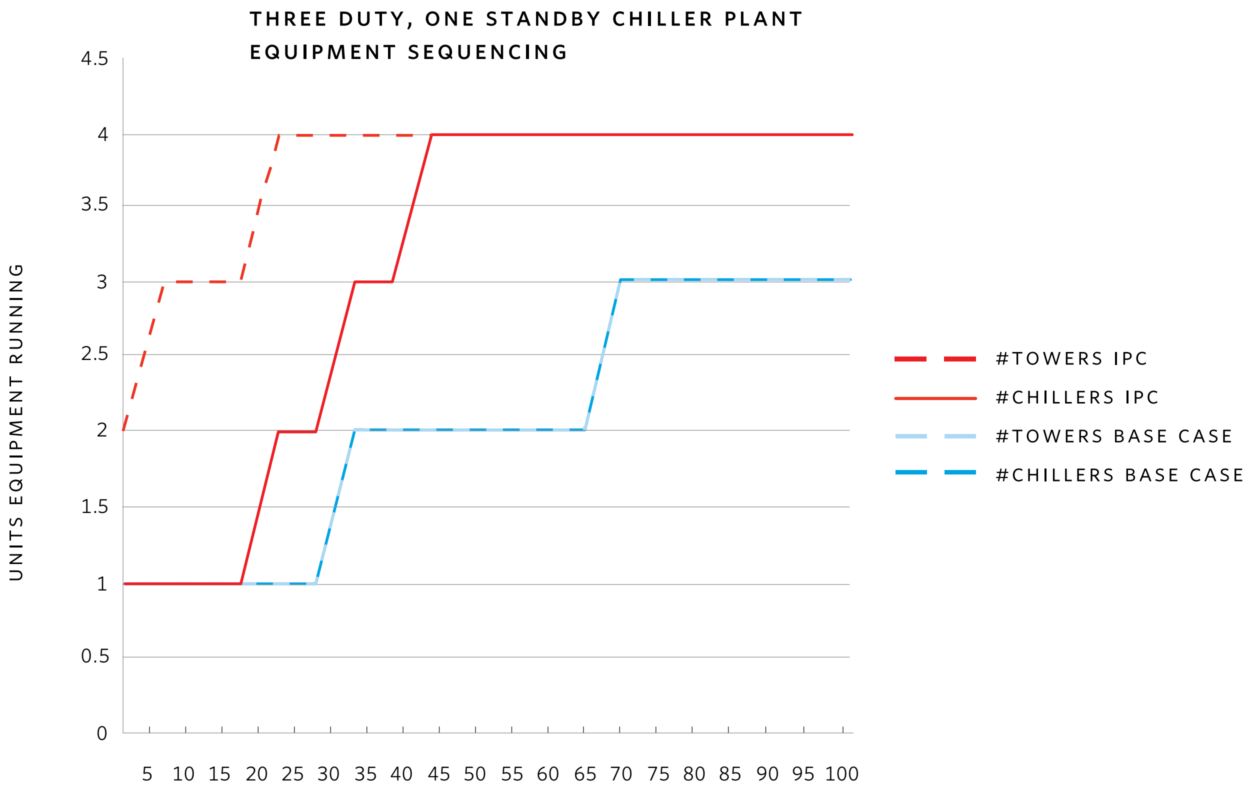

THREE DUTY, ONE STANDBY CHILLER PLANT
EQUIPMENT SEQUENCING
UNITS EQUIPMENT RUNNING
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
#TOWERS IPC
#CHILLERS IPC
#TOWERS BASE CASE
#CHILLERS BASE CASE
PERCENT PLANT LOAD

FIG.10

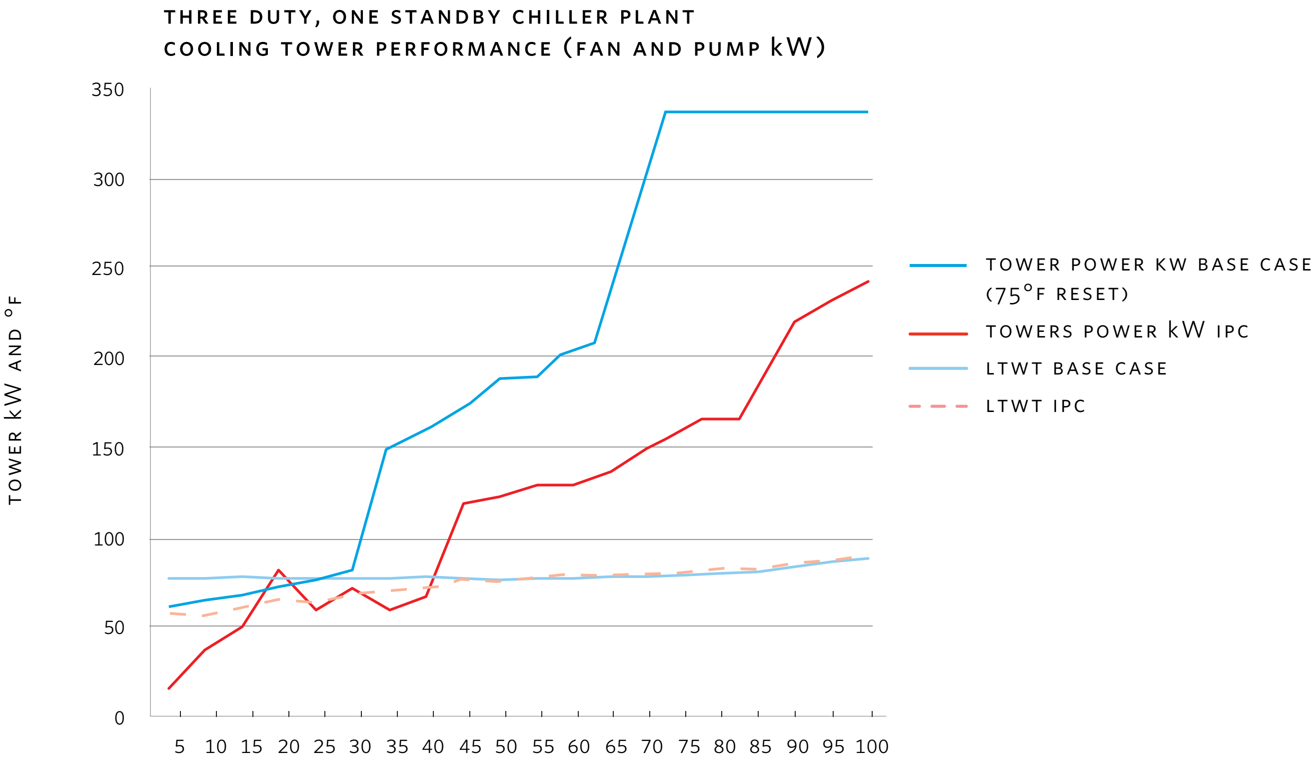

THREE DUTY, ONE STANDBY CHILLER PLANT
COOLING TOWER PERFORMANCE (FAN AND PUMP kW)
TOWER kW AND °F
350
300
250
200
150
100
50
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
TOWER POWER KW BASE CASE (75°F RESET)
TOWERS POWER kW IPC
LTWT BASE CASE
LTWT IPC
PERCENT PLANT LOAD

FIG.11

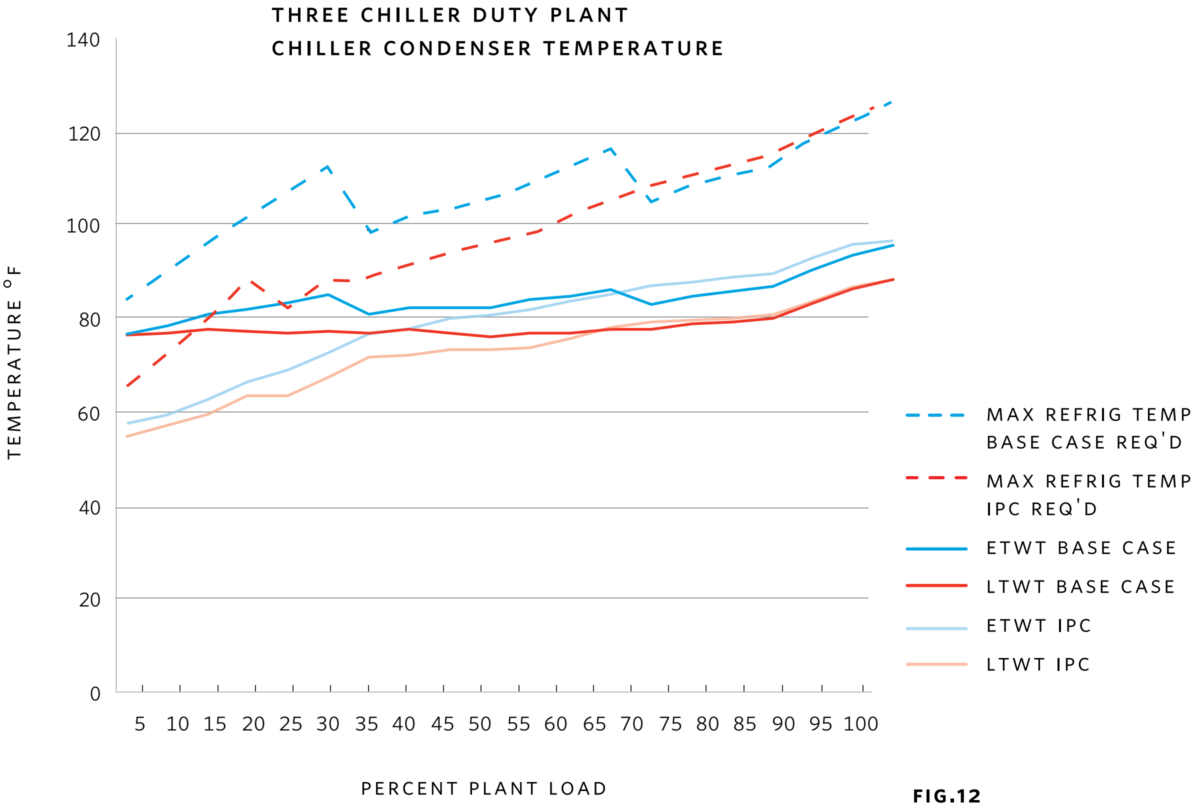

THREE CHILLER DUTY PLANT
CHILLER CONDENSER TEMPERATURE
TEMPERATURE °F
140
120
100
80
60
40
20
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
PERCENT PLANT LOAD
MAX REFRIG TEMP BASE CASE REQ'D
MAX REFRIG TEMP IPC REQ'D
ETWT BASE CASE
LTWT BASE CASE
ETWT IPC
LTWT IPC

FIG.12

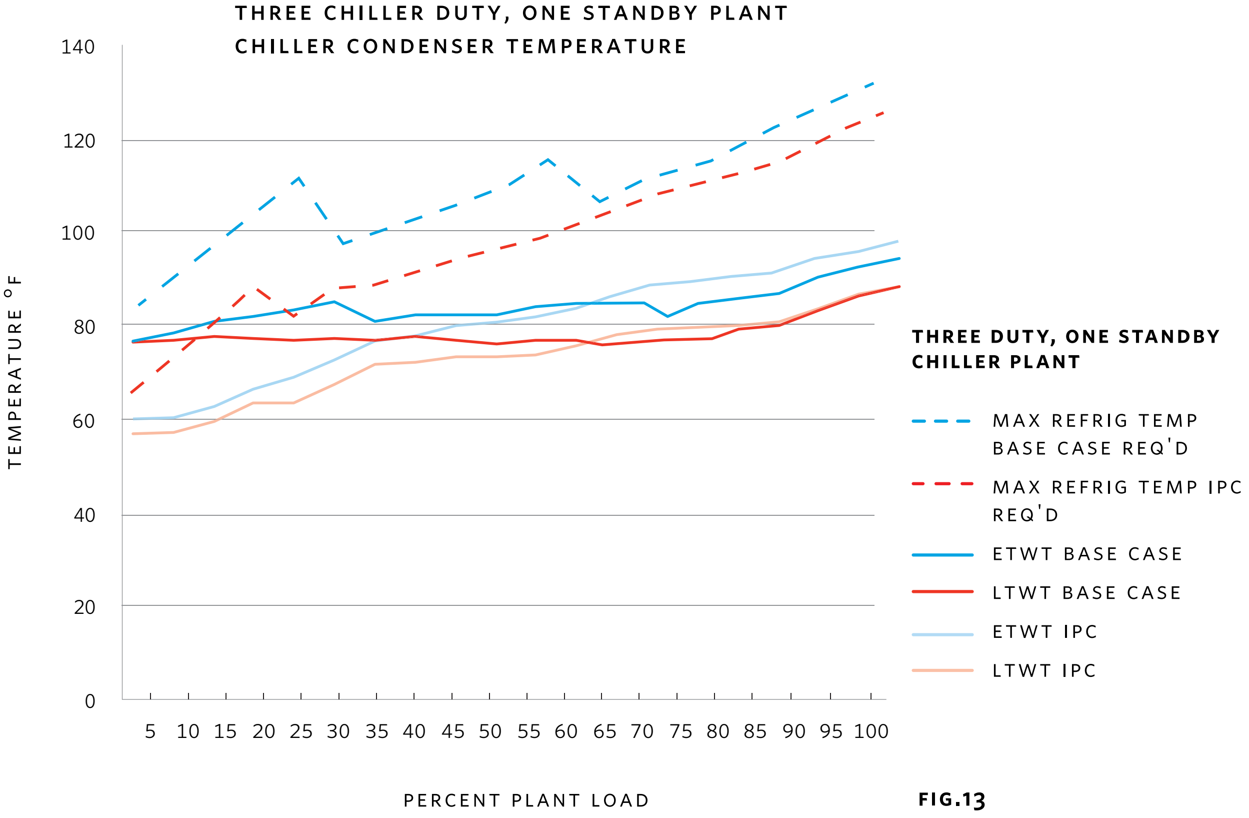

THREE CHILLER DUTY, ONE STANDBY PLANT
CHILLER CONDENSER TEMPERATURE
TEMPERATURE °F
140
120
100
80
60
40
20
0
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
PERCENT PLANT LOAD
THREE DUTY, ONE STANDBY CHILLER PLANT
MAX REFRIG TEMP BASE CASE REQ'D
MAX REFRIG TEMP IPC REQ'D
ETWT BASE CASE
LTWT BASE CASE
ETWT IPC
LTWT IPC

FIG.13

THREE CHILLER DUTY PLANT

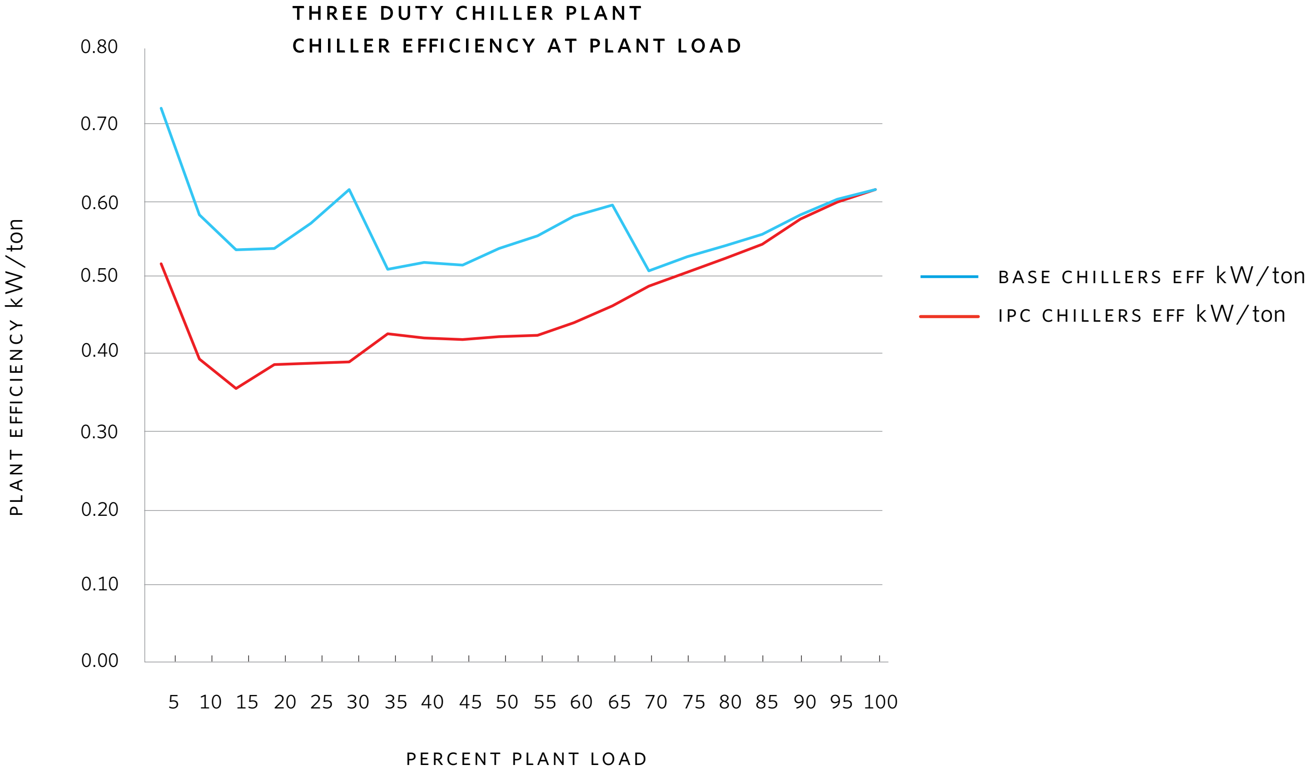
PLANT LOAD PROFILE SUMMARY				
% LOAD	% TIME OPERATING AT LOAD POINT	kW/ton IPC	ECWT (°F)	WET BULB °F
5%	4%	0.75	55.5	50.0
10%	7%	0.59	57.5	51.5
15%	9%	0.56	60	53.0
20%	9%	0.62	63.4	55.0
25%	9%	0.48	63.3	57.0
30%	9%	0.52	66.6	60.0
35%	9%	0.53	70.7	63.0
40%	9%	0.53	71	64.5
45%	9%	0.55	72	66.0
50%	7%	0.54	72.1	66.5
55%	5%	0.55	72.2	67.0
60%	5%	0.57	74.1	69.0
65%	5%	0.61	76	71.0
70%	3%	0.63	77.2	72.0
75%	2%	0.65	77.6	73.0
80%	1%	0.67	78.1	73.5
85%	1%	0.69	78.6	74.0
90%	1%	0.73	81.6	77.0
95%	0%	0.77	83.6	80.0
100%	0%	0.8	85	80.8

AVERAGE ANNUAL PLANT EFFICIENCY: 0.56 kw/ton

THREE DUTY, ONE STANDBY CHILLER PLANT

PLANT LOAD PROFILE SUMMARY				
% LOAD	% TIME OPERATING AT LOAD POINT	kW/ton IPC	ECWT (°F)	WET BULB °F
5%	4%	0.73	57	50.0
10%	7%	0.56	56.9	51.5
15%	9%	0.52	59.4	53.0
20%	7%	0.57	63.2	55.0
25%	9%	0.49	62.9	57.0
30%	9%	0.51	66.2	60.0
35%	9%	0.48	68.3	63.0
40%	9%	0.49	69.8	64.5
45%	9%	0.58	73.5	66.0
50%	7%	0.53	73.8	66.5
55%	5%	0.53	73.8	67.0
60%	5%	0.54	75.8	69.0
65%	5%	0.53	77.1	71.0
70%	3%	0.55	77.4	72.0
75%	2%	0.56	77.8	73.0
80%	1%	0.57	78.1	73.5
85%	1%	0.58	78.7	74.0
90%	1%	0.63	81.6	77.0
95%	0%	0.66	83.5	80.0
100%	0%	0.69	84.7	80.8

AVERAGE ANNUAL PLANT EFFICIENCY: 0.54 kw/ton


THREE DUTY CHILLER PLANT
CHILLER EFFICIENCY AT PLANT LOAD

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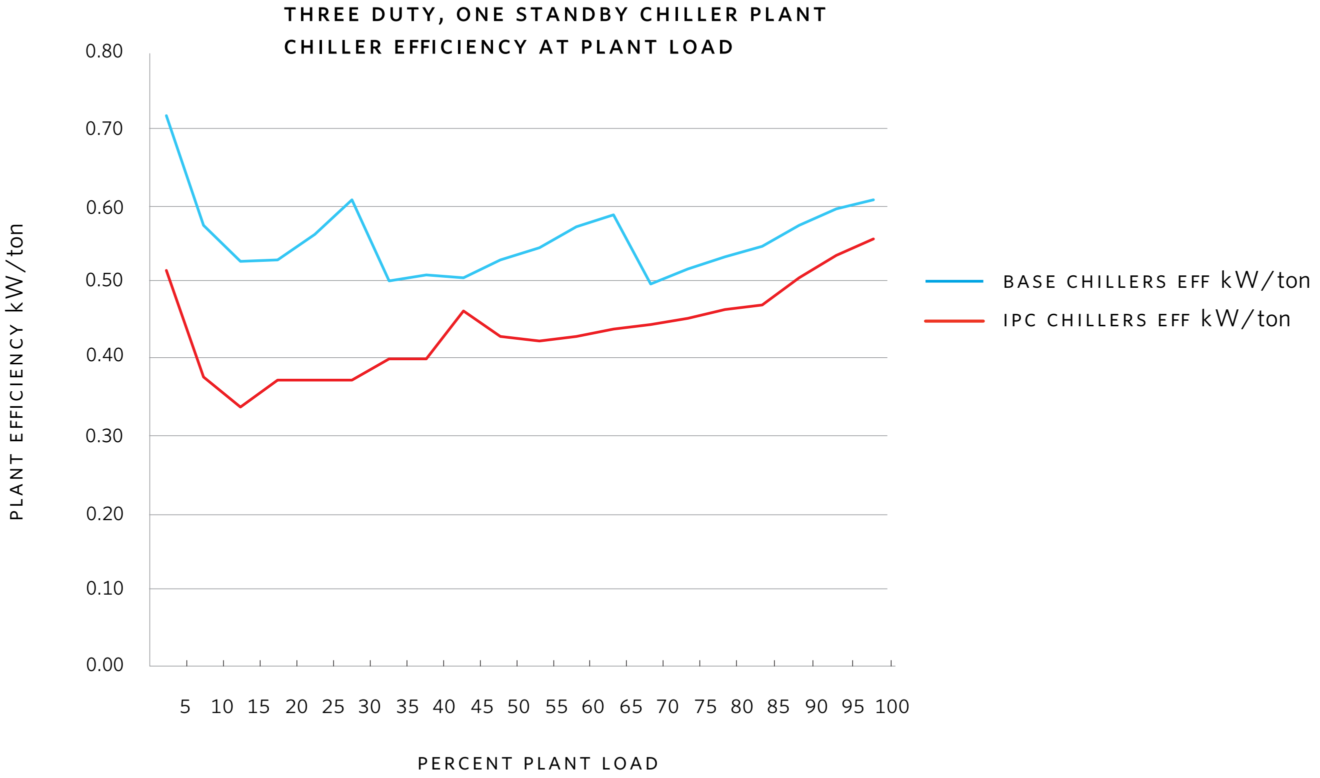
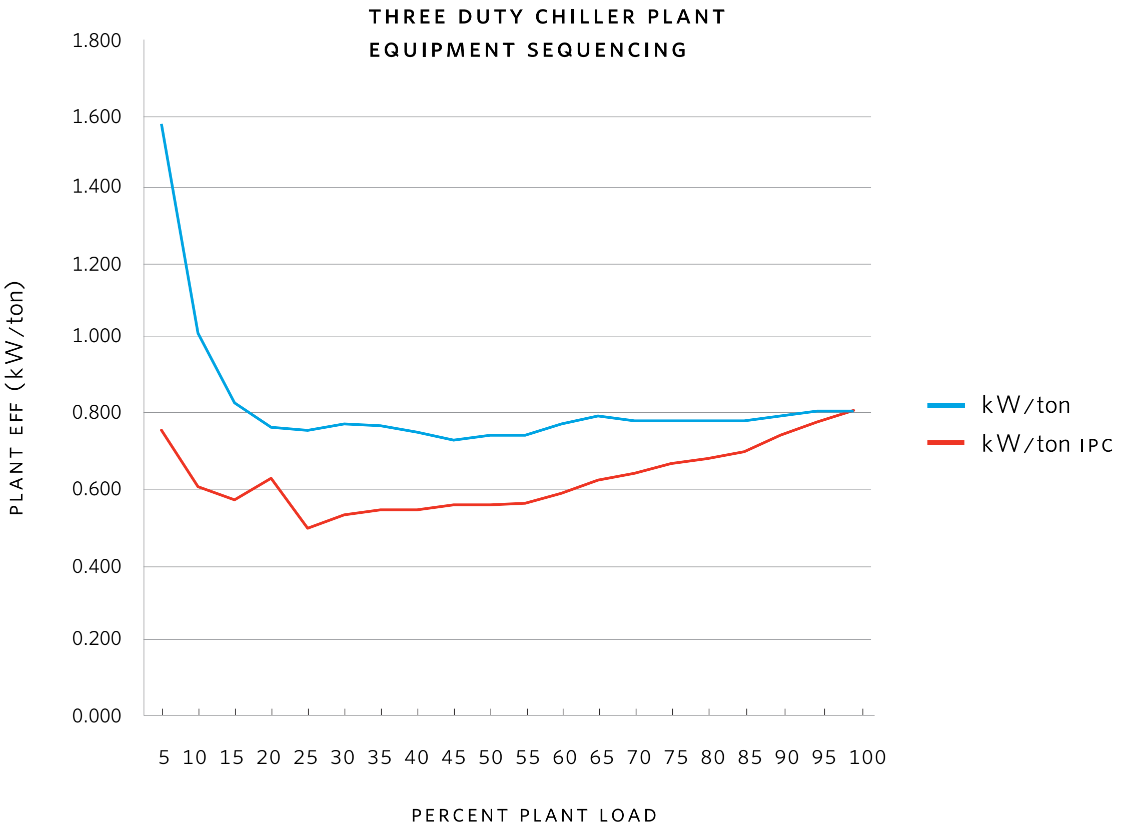
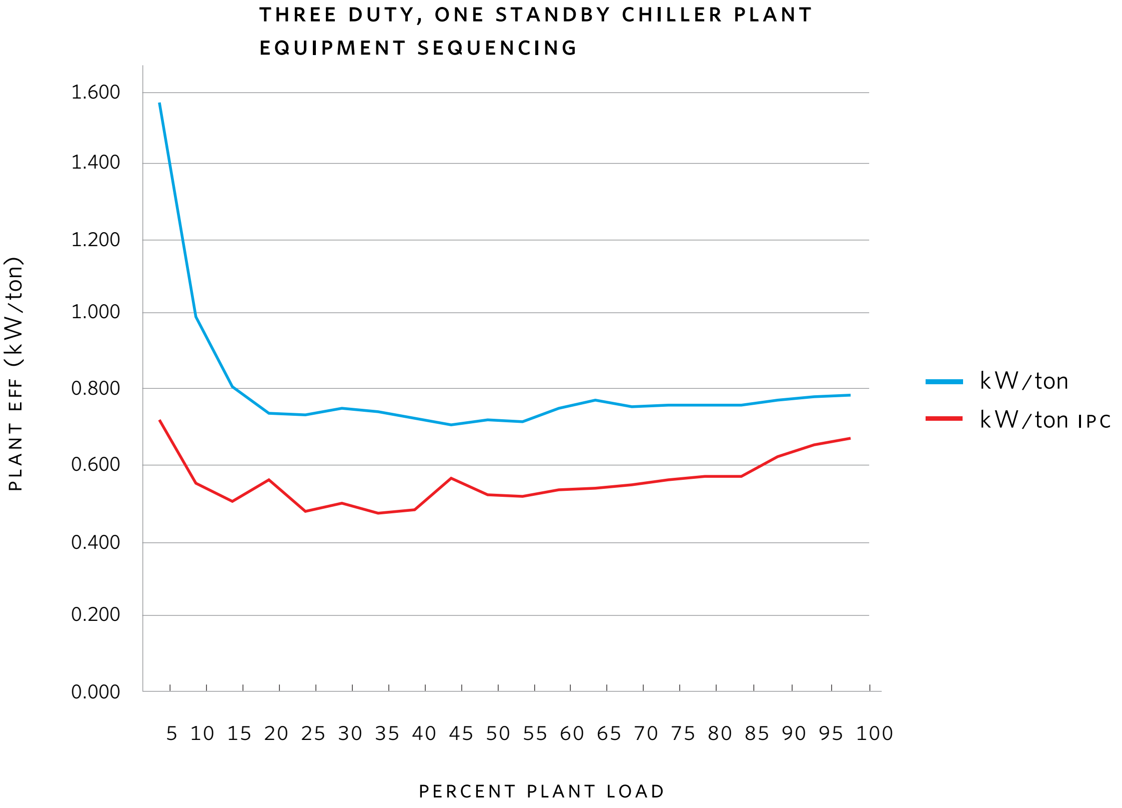
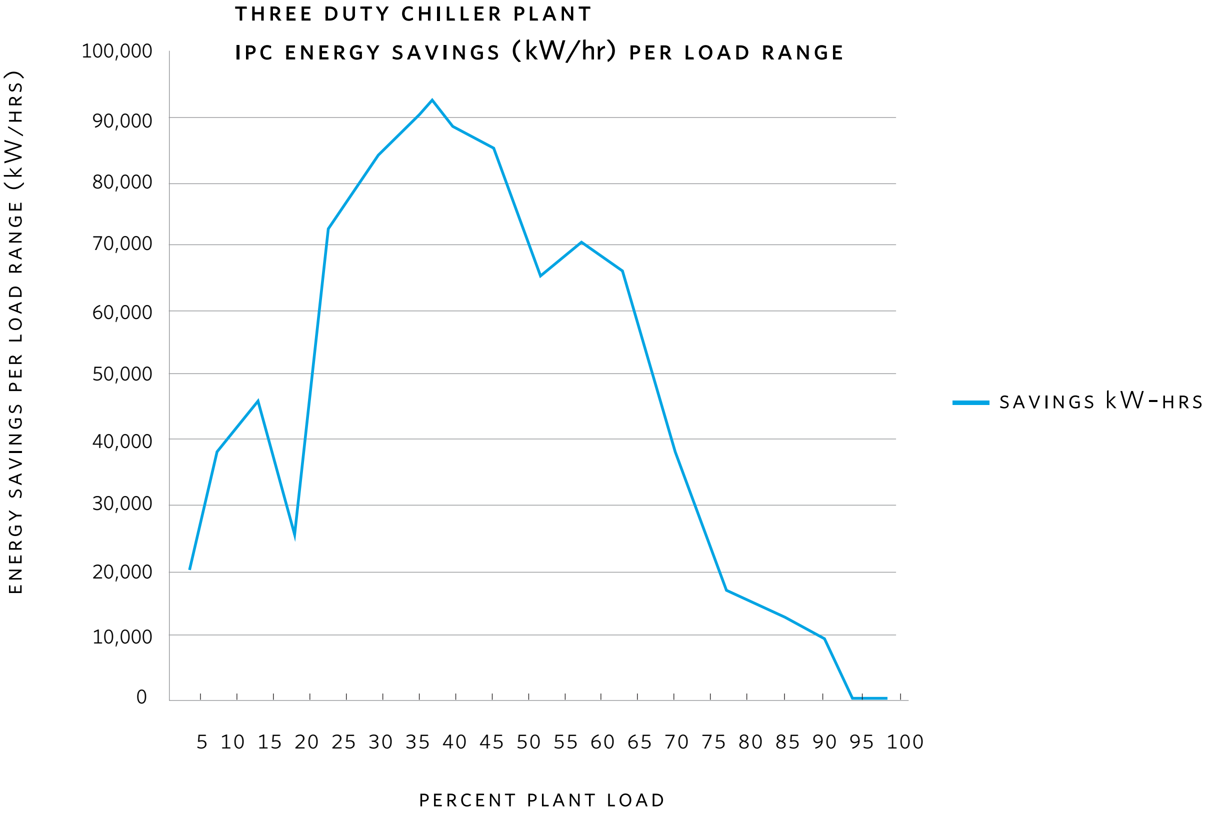

THREE DUTY, ONE STANDBY CHILLER PLANT
CHILLER EFFICIENCY AT PLANT LOAD



THREE DUTY CHILLER PLANT
EQUIPMENT SEQUENCING



THREE DUTY, ONE STANDBY CHILLER PLANT
EQUIPMENT SEQUENCING



THREE DUTY CHILLER PLANT
IPC ENERGY SAVINGS (kW/hr) PER LOAD RANGE

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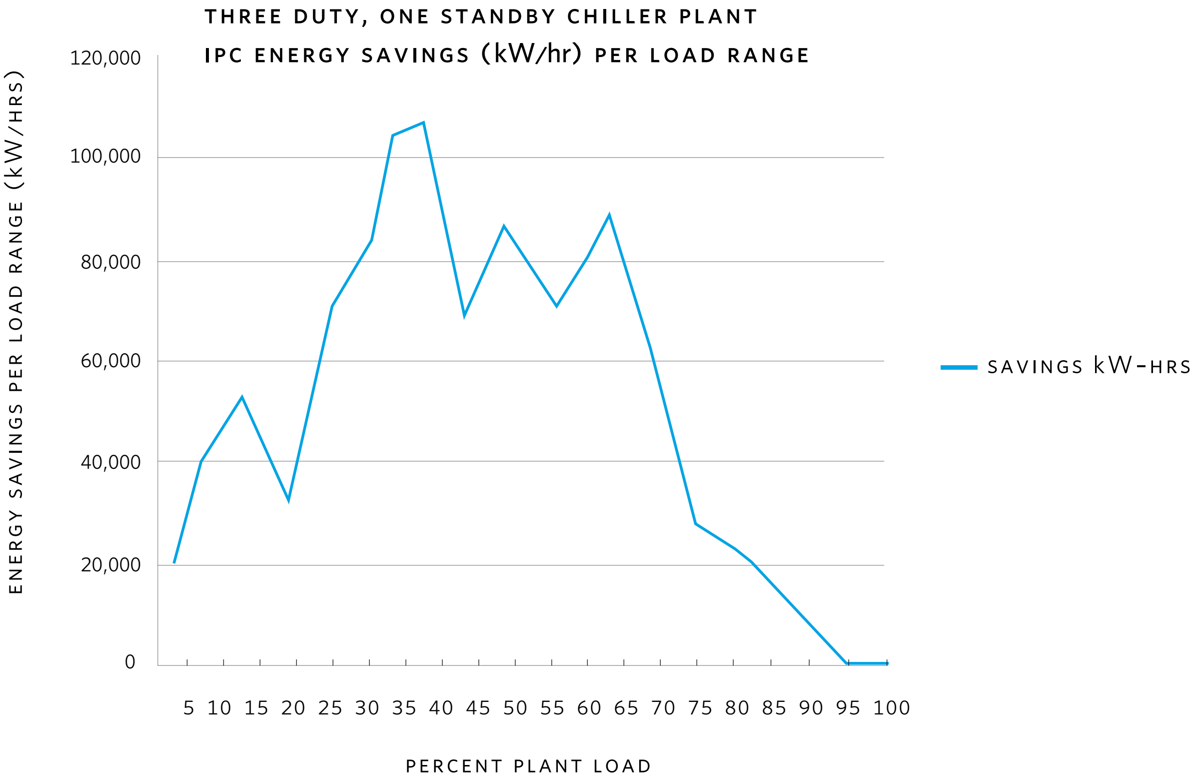


THREE DUTY, ONE STANDBY CHILLER PLANT
IPC ENERGY SAVINGS (kW/hr) PER LOAD RANGE

	3 DUTY CHILLER	3 DUTY / 1 STANDBY
Estimated Plant Annual Average kW/ton (fans, pumps, chillers) BASE CASE	0.80 kW/ton	0.80 kW/ton
Estimated Base case annual electrical consumption $ (calculated)	$328,769	$328,769
Estimated IPC 11550 controlled chilled water plant annual electrical consuption $	$229,185	$215,420
Energy Savings $ per year	$99,584	$113,349
Percent Energy Savings (per year – IPS vs. VPF)	30%	34%
Plant Annual Average kW/ton (fans, pumps, chiller – IPC)	0.56 kW/ton	0.54 kW/ton

Performance Differentiators of IPC all-variable speed plant solutions:

1 Advantage of lower condenser pressure requirement from natural curve sequencing, from a LMTD advantage (lower load per chiller) at the condenser.

2 Variable flow tower arrangement permits higher tower performance and thus system efficiency through balancing of air and water flow ratios.

3 When standby equipment is available, the IPC can further improve the above effects to make the plant more efficient by employing idle assets, even at full load operation (typical for mission critical configurations such as data centers, or hospitals).

APPENDIX A

Base case plant
Three duty chillers no standby

Chilled water plant energy analysis IPC 11550

PROJECT NAME:

CONTACT:

DATE PREPARED:

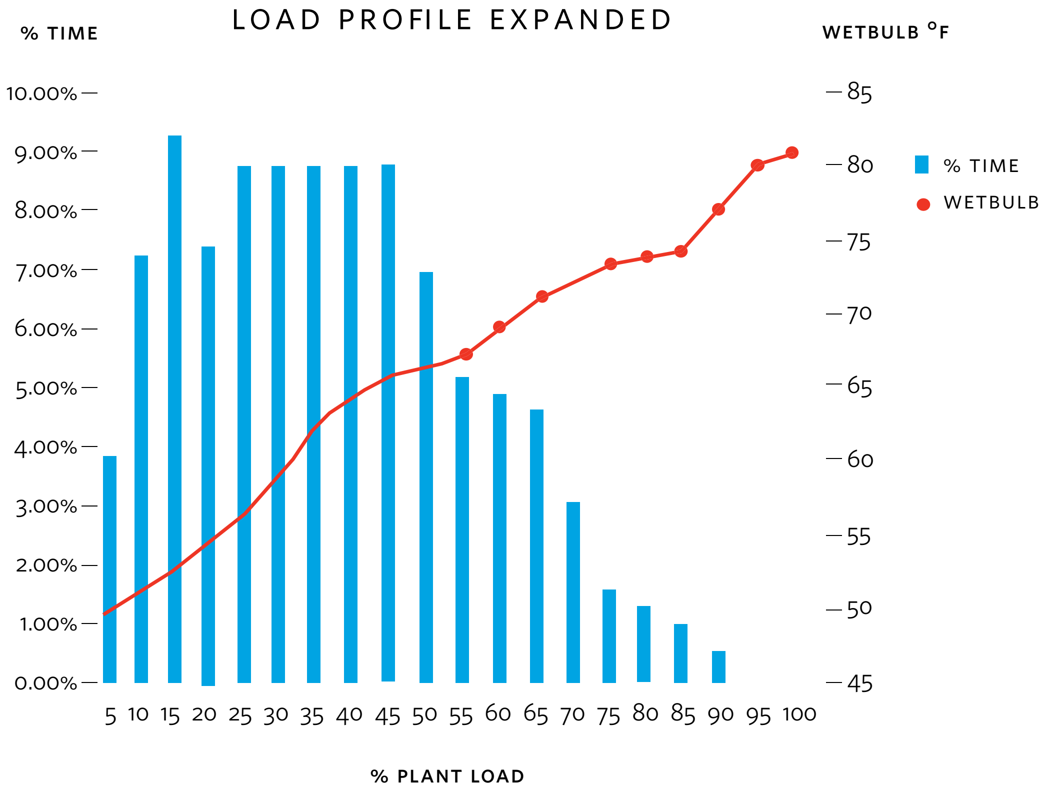
CITY OF CONSTRUCTION: Newark - 24 hour operation

STATE/PROVINCE: COUNTRY:

SALES PERSON:

Chilled water plant energy savings analysis: Hours/day (12 or 24) **24**
Months/year **7**
Days/week **7**

PLANT CONFIGURATION DATA	
Plant / building load	2600
Installed tonnage (load plus standby)	2600
Chiller duty tons (each)	866.7
Duty chiller rating tons (each)	866.7
Design system delta T (across chiller plant)	12 °F
Number of duty chillers (total)	3
Cooling tower design delta T	10 degress°F
Cooling towers design day flow	7328 GPM
Cooling tower flow turndown capacity (% of full flow)	0.33 %
Chiller type (make, model)	High performance variable speed centrifugal oil lubricated chiller
Chiller turn down limit by vs	0.3 %
Chiller minimum flow rating (% of full flow)	0.38 %
Cooling tower fan design point hp	198.6 hp
Cooling tower pump design point head rating	70 ft
Chilled water pump design point head rating (VPF, or VP-VS)	140 ft
Tower minimum fan speed	0.25 %
Power cost ($ per kW-hr)	0.0917
Base case configuration	Variable speed secondary flow system with variable speed fans on cooling towers, capacity based sequencing on two variable speed chillers, cw temp rest.
Estimated plant annual average kW/ton (fans, pumps, chillers) BASE CASE	0.80 kW/ton
Estimated base case annual electrical consumption $ (calculated)	**$328,769**



% LOAD	ECWT	TONNAGE LOAD	% TIME ESTIMATED	kw/ton BASE CASE
5	74.66	130	4%	1.582
10	75.01	260	7%	1.007
15	75.87	390	9%	0.816
20	75.23	520	7%	0.747
25	75.11	650	9%	0.740
30	75.24	780	9%	0.760
35	75.16	910	9%	0.752
40	75.63	1040	9%	0.733
45	75.03	1170	9%	0.713
50	74.38	1300	7%	0.726
55	75.19	1430	5%	0.726
60	75.04	1560	5%	0.759
65	75.87	1690	5%	0.780
70	75.59	1820	3%	0.765
75	76.66	1950	2%	0.767
80	77.29	2080	1%	0.766
85	77.92	2210	1%	0.767
90	80.66	2340	1%	0.781
95	83.36	2470	0%	0.793
100	84.98	2600	0%	0.794
			100%	**0.802**

APPENDIX B

Ultra-efficient chiller plant configuration
Three duty chillers with IPC 11550

IPC ULTRA EFFICIENT PLANT DATA	Final system configuration	Variable primary flow
	Cooling towers design day flow (IPC plant)	7328 gpm
	Cooling tower flow turndown capacity (% of full flow) %	33%
	Chiller type, centrifugal water cooled (make, model)	High performance variable speed centrifugal oil lubricated chiller: IPLV COP = 8.2
	Chiller turn down limit by VS (% of DD building load/qty duty chillers)	30%
	Chiller minimum flow rating (% of full flow)	38%
	Cooling tower pump design point head rating	70 ft
	IPC 11550 system confiugrations	All variable speed plant, three duty chiller, headered arrangement of CHW pumps and CW pumps.

3 DUTY CHILLER

Base case configuration	Variable primary flow plant, three chillers, zero standby, tower reset to 75F, variable speed chillers
Estimated plant annual average kW/ton (fans, pumps, chillers) BASE CASE	0.80 kW/ton
Estimated base case annual electrical consumption $ (calculated)	$328,769
Estimated IPC 11550 controlled chilled water plant annual electrical consuption $	$229,185
Energy savings $ per year	$99,584
Percent energy savings (per year)	**30%**
Plant annual average kW/ton (fans, pumps, chiller)	**0.56 kW/ton**

PLANT LOAD PROFILE SUMMARY				
% LOAD	% TIME OPERATING AT LOAD POINT	kW/ton IPC	ECWT (°F)	WET BULB F
5%	4%	0.75**	55.5	50.0
10%	7%	0.59	57.5	51.5
15%	9%	0.56	60	53.0
20%	7%	0.62	63.4	55.0
25%	9%	0.48	63.3	57.0
30%	9%	0.52	66.6	60.0
35%	9%	0.53	70.7	63.0
40%	9%	0.53	71	64.5
45%	9%	0.55	72	66.0
50%	7%	0.54	72.1	66.5
55%	5%	0.55	72.2	67.0
60%	5%	0.57	74.1	69.0
65%	5%	0.61	76	71.0
70%	3%	0.63	77.2	72.0
75%	2%	0.65	77.6	73.0
80%	1%	0.67	78.1	73.5
85%	1%	0.69	78.6	74.0
90%	1%	0.73	81.6	77.0
95%	0%	0.77	83.6	80.0
100%	0%	0.8	85	80.8
Average annual plant efficiency			**0.56**	**kW/ton**

NOTES:

3 DUTY / 1 STANDBY CHILLER

Estimated plant annual average kW/ton (fans, pumps, chillers) BASE CASE	0.80 kW/ton
Estimated base case annual electrical consumption $ (calculated)	$328,768
Estimated IPC 11550 controlled chilled water plant annual electrical consuption $	$215,419
Energy savings $ per year	$113,348
Percent energy savings (per year)	**34%**
Plant annual average kW/ton (fans, pumps, chiller)	**0.54 kW/ton**

PLANT LOAD PROFILE SUMMARY

% LOAD	% TIME OPERATING AT LOAD POINT	kW/ton IPC	ECWT (˚F)	WET BULB F
5%	4%	0.73**	57	50.0
10%	7%	0.56	56.9	51.5
15%	9%	0.52	59.4	53.0
20%	7%	0.57	63.2	55.0
25%	9%	0.49	62.9	57.0
30%	9%	0.51	66.2	60.0
35%	9%	0.48	68.3	63.0
40%	9%	0.49	69.8	64.5
45%	9%	0.58	73.5	66.0
50%	7%	0.53	73.8	66.5
55%	5%	0.53	73.8	67.0
60%	5%	0.54	75.8	69.0
65%	5%	0.53	77.1	71.0
70%	3%	0.55	77.4	72.0
75%	2%	0.56	77.8	73.0
80%	1%	0.57	78.1	73.5
85%	1%	0.58	78.7	74.0
90%	1%	0.63	81.6	77.0
95%	0%	0.66	83.5	80.0
100%	0%	0.69	84.7	80.8
Average annual plant efficiency			**0.56**	**kW/ton**

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