DEVELOPMENT OF A MODEL AND OPTIMAL CONTROL STRATEGY FOR THE CAL POLY CENTRAL PLANT AND THERMAL ENERGY STORAGE SYSTEM

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ABSTRACT

Development of a Model and Optimal Control Strategy for the Cal Poly Central Plant and Thermal Energy Storage System

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This thesis develops a calibrated model of the Cal Poly Central Chilled Water Plant with Thermal Energy Storage for use in determining an optimal operating control strategy. The model was developed using a transient systems simulation program (TRNSYS) that includes plant performance and manufacturer data for the primary system components, which are comprised of pumps, chillers, cooling towers, and a thermal energy storage tank. The model is calibrated to the actual measured performance of the plant using the current control strategy as a baseline. By observing and quantifying areas for potential improvement in plant performance under conditions of high campus cooling load demands, alternative control strategies for the plant are proposed. Operation of the plant under each of these control strategies is simulated in the model and evaluated for overall energy and demand-usage cost savings. These results are used to recommend improvements in the plant's current control strategy, as well as to propose an optimal control strategy that may be applied to reduce plant operating costs.

The results of the model identify that the plant can perform more economically by employing more chiller power to charge the Thermal Energy Storage tank to higher capacities during overnight periods when the utility rates are lower. Staging the operation of the different chillers to more precisely follow the tank charges during these off-peak periods can ensure faster tank charging when its capacity may not be sufficient to meet the peak and part-peak cooling load demands. A proposed control strategy to accomplish this breaks the overnight Off-Peak rate period into three periods with separate control setpoints, which are designed to maintain the tank charge capacity at the minimum levels to be able to accommodate the daily campus cooling demands during peak and part-peak hours.

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LIST OF ACRONYMS AND ABBREVIATIONS

BAC	Baltimore Air Coil
CH	Chiller
CHW	Chilled Water
COP	Coefficient of Performance
CT	Cooling Tower
CW	Condenser Water
CWP	Condenser Water Pump
DB	Dry Bulb
DDC	Direct Digital Control
FFLP	Fraction of Full Load Power
GPM	Gallons Per Minute
MINLP	Mixed Integer Linear Programming
MPC	Model Predictive Control
NTU	Number of Transfer Units
PCHWP	Primary Chilled Water Pump
PLR	Part Load Ratio
RH	Relative Humidity
SCHWP	Secondary Chilled Water Pump
TES	Thermal Energy Storage
TOPP	Theoretical Optimum Plant Performance
TRNSYS	TRansient SYstems Simulator
WB	Wet Bulb

1. INTRODUCTION

This thesis develops an optimal control strategy for the Cal Poly central chilled water plant, which includes a Thermal Energy Storage (TES) tank to shift energy demand out of peak periods. The general approach to find an optimal control strategy includes constructing a model of the plant using a simulation program, incorporating a baseline load profile using measured data over a period of time, calibrating the model to the actual energy usage, running the model over a range of operating conditions and control set points, and selecting the optimal control strategy to minimize costs.

1.1 System Overview

A primary function of the Cal Poly Central Plant is to distribute chilled water to the university campus and student housing, in addition to other buildings within the campus property. Chilled water is produced using water-cooled centrifugal chillers, which is either delivered directly to the campus or pumped to the 1.6 million gallon, 19,000 ton-hour TES tank. When the chillers are in operation, condenser water rejects heat and is pumped to cooling towers located outside the building. Chilled water at approximately 40^{o}F is distributed through an underground pipe loop to different buildings; warm water is then returned to the central plant for cooling. Depending on the operating conditions, the chilled water is either distributed to the campus from the chillers, from the TES tank, or from a combination of both when demand is high.

The TES tank was installed at Cal Poly in 2011 and utilizes the concept of generating and storing energy in the form of chilled water for demand-side management and cost reduction. During off-peak energy rate hours in the evenings, the chillers “charge” the tank by producing chilled water and storing it in the tank for future use. When the energy rates are at peak or partial-peak periods, chilled water is delivered to the campus directly from the TES tank, and the chillers are not in operation unless the depleted capacity of the TES tank necessitates their use. This effectively shifts the energy consumption of the chillers from high-demand hours during the day to the low-demand periods at night, resulting in significant energy cost savings.

In addition to the installation of the TES tank, a variable speed 1,350 ton chiller was installed at the Central Plant to accommodate the increasing energy demands of the campus. Based on trend data from the facilities between October 2014 and October 2015, this chiller is the primary means of producing chilled water.

1.2 Objective

The primary objective of this thesis is to develop an optimal control strategy of the chilled-water plant and improve the charging and discharging periods of the TES to yield the minimum energy consumption and/or lowest possible energy costs. This will be done by accomplishing the following objectives:

1. Developing an accurate chilled water plant model for the different operating modes and calibrated to trended power data.
2. Reviewing the current operating strategies used between 10/2014 and 10/2015 to identify if there are any inefficiencies that can be reduced.
3. Exploring different control strategies that improve the performance of the chilled water plant system, including chiller and TES tank sequencing, to minimize energy usage and cost.
4. Developing specific control strategies that the model can simulate for optimal performance.

5. Summarizing 1 – 3 recommendations for the plant facilities to implement that will improve plant performance, minimize partial-peak and full-peak equipment operation, and balance the operating sequence for varying load scenarios; recommendations must be specific, measurable, actionable, realistic, and timely.

Energy rates from the local utility, PG&E, are based on winter and summer schedules. Winter is defined as the period from November through April; summer is defined as the period from May through October. Because rates are higher in the summer, and the campus loads are significantly higher with increased air conditioning requirements, this study focuses on developing an optimal control strategy for the summer rate period.

2. BACKGROUND

2.1 Chilled Water Plant

The Central Plant at Cal Poly distributes chilled water at approximately 40^{o}F to over twenty buildings on campus (as of October 2015) through an underground pipe loop. The chilled water return temperature is designed for 60^{o}F, although because of older cooling coil designs that use three-way valves, flow may be bypassed at the individual buildings and result in lower return water temperatures.

Chilled water is produced utilizing a combination of water-cooled chillers, with variable speed pumps delivering chilled water to the load. The heat rejected in the chiller flows through a condenser water loop, which pumps the warmer water to a cooling tower. Cooler water at the cooling tower sump is then returned back to the chiller for heat rejection. Figure 2.1 provides a simplified layout of the plant. Note that for clarity, only one cooling tower is shown.

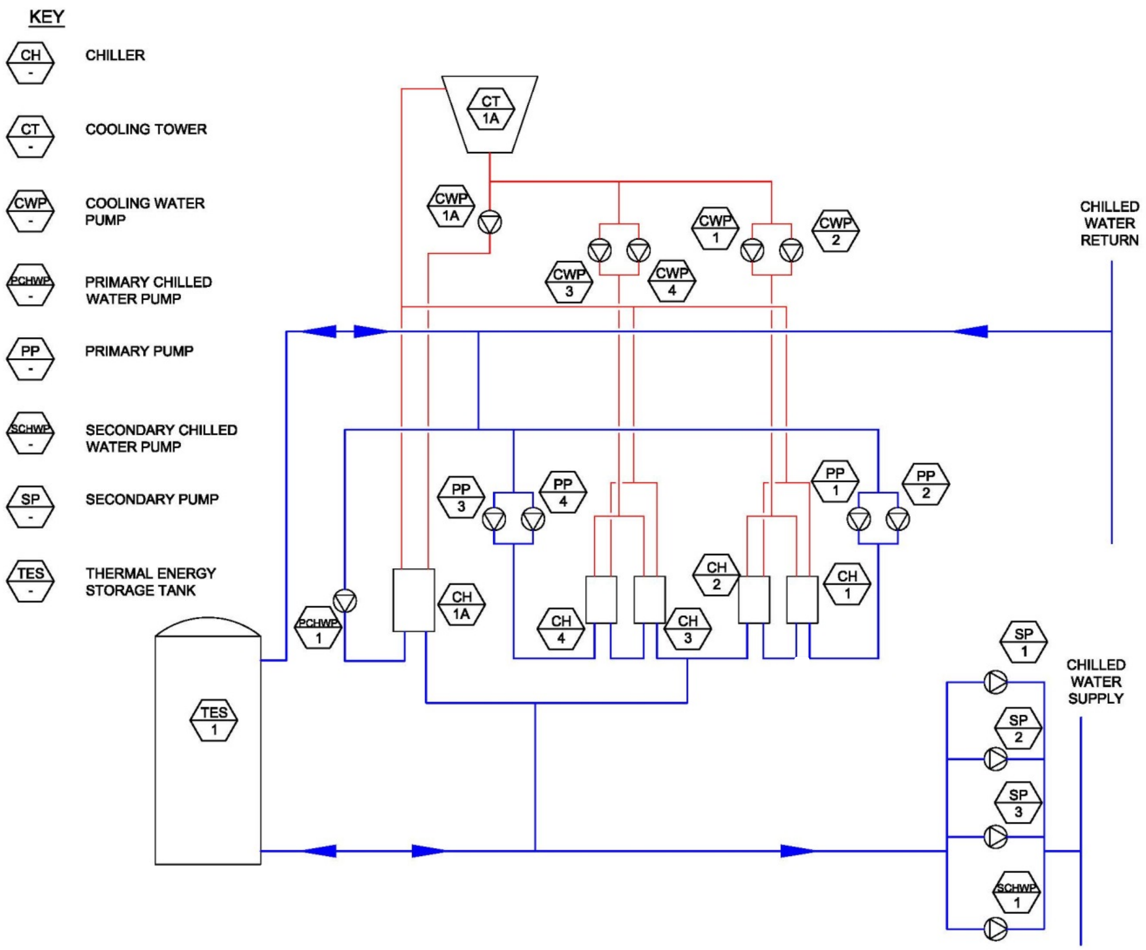


Figure 2.1 Simplified Layout of Central Plant

2.1.1 Primary Equipment

Chillers

As of October, 2015, the central plant has five chillers installed. The most recently installed chiller is a high-efficiency centrifugal chiller with variable speed compressor drive (see Appendix B). The nominal rating for this chiller is 1,350 tons capacity with 6.05 COP at 40^{o}F chilled water setpoint and 80^{o}F entering condenser water temperature. This chiller, designed for a 20^{o}F ΔT (evaporator), is the primary source of chilled water for the campus. There are four additional chillers, which are older and less efficient. These chillers have lower capacities and are occasionally cycled in operation in place of the 1,350 ton chiller. They can operate in parallel with the 1,350 ton chiller when the cooling requirements of the campus are higher. These chillers operate as pairs in series, since they were designed for a 10^o ΔT, and each have a capacity of 300 tons (600 tons per pair or 1,200 tons total).

Pumps

The chilled water is distributed to campus using three variable speed pumps. Return water is delivered back to the chiller by means of a separate variable speed pump. Constant speed pumps are used on the condenser water side.

Cooling Towers

A primary and a backup cooling tower are installed for heat rejection. Both are Baltimore Air Coil (BAC) model 31301C/V [see Appendix C].

2.1.2 Campus Load

Since the cooling requirements of the campus include equipment and server rooms, air conditioning is provided 24 hours a day, with a minimal load in the overnight hours. The load peaks in general during the early afternoon hours, when building air conditioners have their highest demands due to weather and occupancy loads. Figure 2.2 shows a measured campus load profile during a weekday in late September, at the start of the Fall term. Note that in addition to seasonal variations in load profiles and magnitudes, occupancy loads vary considerably based on whether classes are in session as well as which quarter is in session.

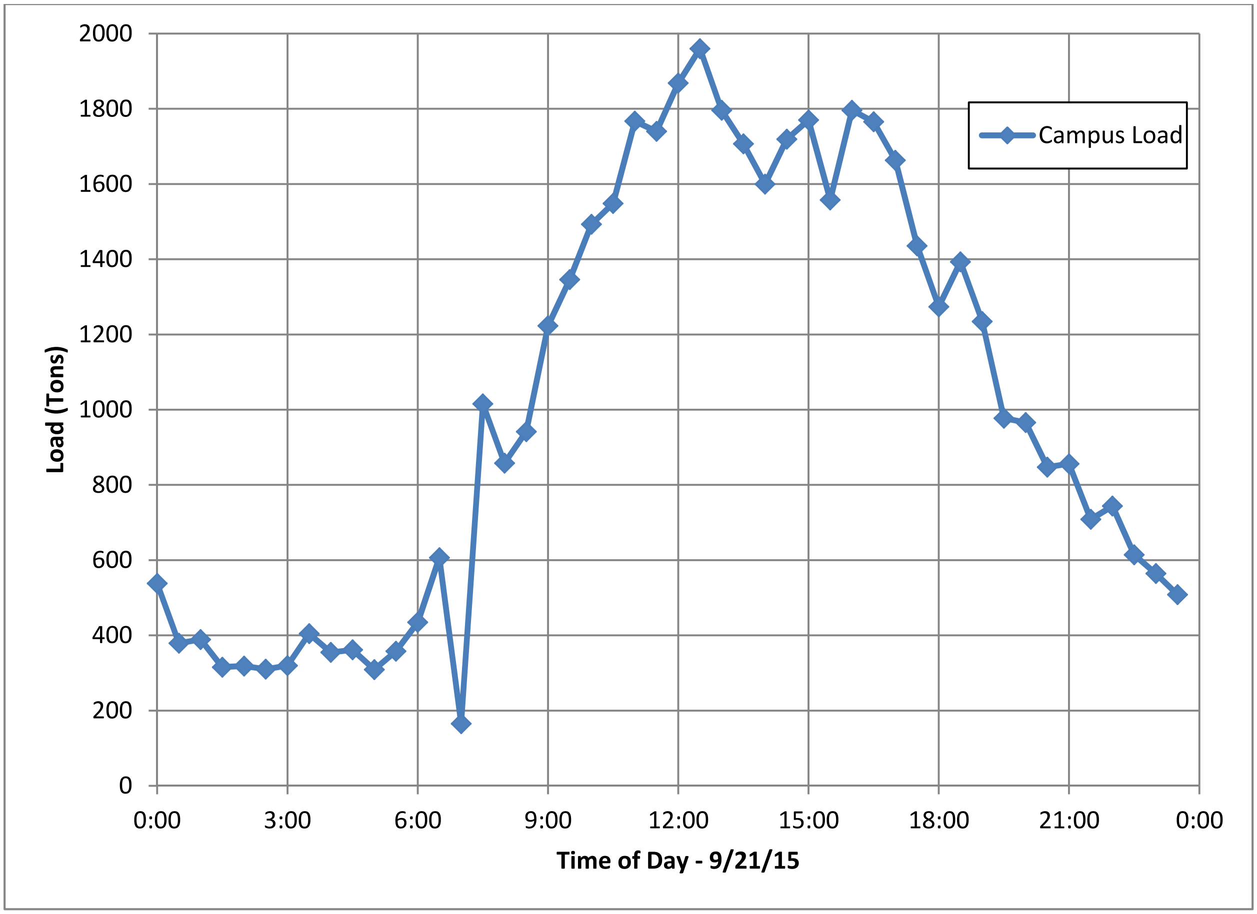


Figure 2.2 Campus Load for September 21, 2015

2.1.3 Energy Rate Schedule

Electric power is supplied to the Cal Poly campus from PG&E, and energy rates vary based on time of the year (summer or winter) and time of day. Energy charges are at their minimum in the overnight hours when demand on the electrical grid is at a minimum, and charges are higher during the late morning, afternoon, and early evening hours when the demand is higher. Additionally, there is a monthly demand charge based on the maximum power usage during the peak and partial peak periods. Table 2.1 identifies the rate schedule for the Cal Poly campus. A copy of the PG&E Electric Schedule is included as part of Appendix A.

Table 2.1 Energy Rate Schedule

Season	Time-of-Use Period	Demand Charges ($/kW)	Energy Charges ($/kWh)
Summer	Max-Peak	$16.74	$0.10132
	Part-Peak	$3.63	$0.08210
	Off-Peak	-	$0.06600
	Maximum	$6.08	-
Winter	Part-Peak	-	$0.08354
	Off-Peak	-	$0.07020
	Maximum	$6.08	-

Notes:

Summer Season (May - October)

Peak Hours: 12:00 noon to 6:00pm, Monday-Friday (except holidays)
Partial-Peak Hours: 8:30am to 12:00 noon AND 6:00 pm to 9:30pm, Monday-Friday (except holidays)

Off-Peak Hours: 9:30pm to 8:30am, Monday-Friday (except holidays), All Day Saturdays, Sundays, and holidays

Winter Season (November - April)

Partial Peak Hours: 8:30am to 9:30pm, Monday-Friday (except holidays)
Off-Peak Hours: 9:30pm to 8:30am, Monday-Friday (except holidays), all day Saturday, Sunday, and holidays

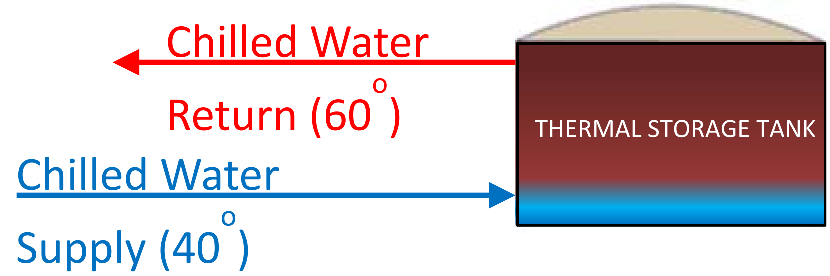
2.2 Thermal Energy Storage

Installed in 2011, the Thermal Energy Storage (TES) tank was designed to reduce energy costs by minimizing the amount of time the chillers operate during peak and partial peak energy rate periods.

The objective of storing cold water in a thermal energy storage tank is to produce utility savings by shifting the operation of pumps, chillers, and cooling towers to off-period rate periods where the energy demand is typically lower. This practice also helps the system to run at a generally higher efficiency due to the cooler ambient temperatures.

The TES tank takes advantage of thermal stratification, in which the warmer, buoyant water rises towards the top of the tank while the denser cold water sinks toward the bottom. This allows for a simple, reliable, and low cost means of operating the system. During TES charging, warm water from the top of the tank is delivered to the chiller, which produces cold water that is sent to the bottom of the tank. During discharge periods, the cold water from the bottom of the tank is distributed to the campus, and the warm return water from the campus is pumped to the top of the tank, maintaining thermal stratification. This is illustrated in Figure 2.3, below.

Charging Mode:



Discharging Mode:

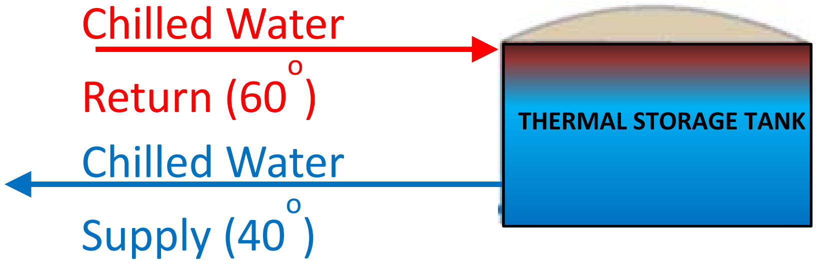


Figure 2.3 Operation of Thermal Energy Storage Tank

2.3 Plant Operation

The operation of a chilled water thermal storage system requires a carefully-defined method of operating for controlling the overall system. Since successful operation of such a system depends on a schedule of charging and discharging based on how loads can be met under different conditions, there is an added level of complexity in controlling these systems compared to instantaneous chilled water systems.

To understand the level of control involved in thermal storage systems, it is necessary to clearly define the difference between "operating modes," "operating strategy," and "control strategy." According to the 2012 ASHRAE Handbook – HVAC Systems and Equipment [30], the following definitions apply:

> **Operating Strategy:** "Defines the overall method of control for the thermal storage system to achieve the design intent. The operating strategy provides the logic used to determine when the various operating modes and control sequences are selected… The operating strategy defines the higher-level logic by which the system operates." [30]
>
> **Control Strategies:** "A thermal storage control strategy is the sequence of operating modes implemented under specific conditions of load, weather, season, etc… For example, a control strategy for a summer design day might specify a discharging mode, using storage-priority control during daytime on-peak hours to minimize or eliminate on-peak chiller operation… The various control strategies implement the specific operating modes." [30]
>
> **Operating Modes:** "A thermal storage operating mode describes which of several possible functions the system is performing at a given time (e.g., charging storage, meeting load directly without storage, meeting load from discharging storage, etc.)." [30]

In short, the operating strategy establishes when the TES tank is expected to charge and discharge, while the control strategy specifies what setpoints initiate the charging and discharging sequences under the various conditions. The operating modes, in turn, describe what the system is actually doing.

Another item to consider is what it means by “full-storage” and “partial-storage” strategies. A full-storage strategy indicates that the TES tank, when fully charged during the off-peak period, has enough capacity to meet the entire peak and part-peak load demand. A partial-storage strategy indicates that even when fully charged during the off-peak period, the TES tank does not have enough capacity to meet the entire load demand during the peak and part-peak periods. For example, currently the Cal Poly campus demands have grown such that the total charge capacity of the TES tank (approx. 19,000 ton-hours) would not be enough to meet the total campus load during the worst-case load conditions (i.e., worst-case loads would be greater than 19,000 ton-hours). Therefore, on the “design day” (when the campus load is at a maximum), only a partial storage strategy is possible.

Operating Strategy

For this system, the Operating Strategy is to charge the TES tank during off-peak periods and discharge during peak and part-peak periods, using a partial-storage strategy on the design day and full-storage strategy on lower-load days. This Operating Strategy will not be modified for the purposes of this study.

Operating Modes

Because of varying demand loads and the inclusion of a TES tank, the chilled water system operates in four different configurations. For the sake of simplicity, this report will refer to them as Modes 1, 2, 3, and 4, as described below. Note that the description ASHRAE uses is listed in parentheses.

Mode 1 – Chillers Serving Load Directly

(ASHRAE: *Meeting Load Directly Without Storage*)

Mode 2 – Chillers Charging TES while Serving Load Directly

(ASHRAE: *Charging Storage While Meeting the Load*)

Mode 3 – TES Serving Load Directly

(ASHRAE: *Meeting Load from Discharging Only*)

Mode 4 – Chillers and TES Both Serving Load

(ASHRAE: *Meeting Load from Discharging and Direct Equipment Operation*)

A discussion of each of these operating modes follows in sections 2.3.1 through 2.3.4. These modes will continue to be employed throughout this study and will not be modified.

Control Strategies

The control strategy currently used for this system utilizes setpoints consisting of time periods (off-peak, part-peak, and peak), percentage charge of TES, and temperatures at different levels of the tank.

The focus of this study will involve adjusting the control strategy for the summer rate period to arrive at an optimal method of control.

2.3.1 Operating Mode 1 – Chiller Serving Load

Figure 2.4 shows the simplest mode of operation in which the chiller, CH-1A, delivers chilled water to the campus, and the warmer chilled water return is delivered back to the chiller. Both pumps SCHWP-1A and PCHWP-1A are employed. Heat is rejected through the cooling water loop from the condenser of the chiller to the cooling tower, CT-1A, served by condenser water pump CWP-1A.

This mode of operation occurs occasionally during the off-peak periods if the TES tank has been charged to near or at its capacity, but the control setpoint has not switched over to TES discharge mode and the chiller continues to serve just the campus.

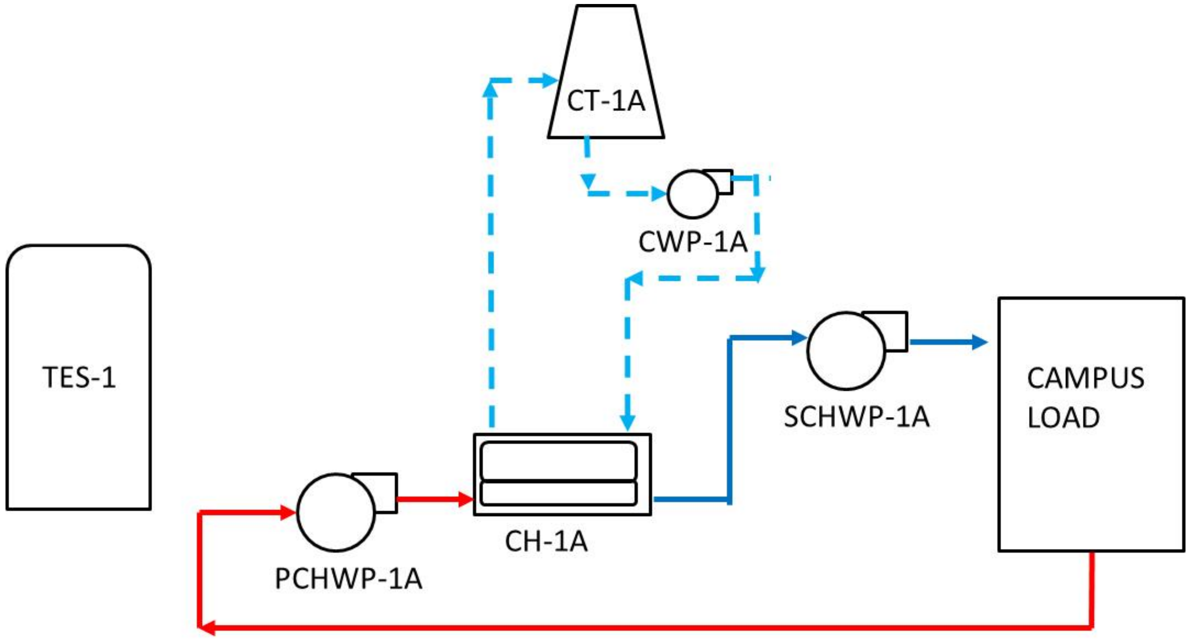


Figure 2.4 Mode 1 - Chiller Serving Load

2.3.2 Operating Mode 2 – Chiller Charging TES while Serving Load

As illustrated in Figure 2.5, the typical off-peak mode of operation has the chiller delivering chilled water to the campus while simultaneously charging the TES tank. Both the return water from the campus and the warm water from the top of the TES tank are pumped to the inlet side of the chiller.

This mode of operation typically occurs during off-peak hours, but may occasionally be initiated during partial-peak periods if the TES tank capacity is depleted. Due to the high energy rates at peak hours, this should never occur during peak periods.

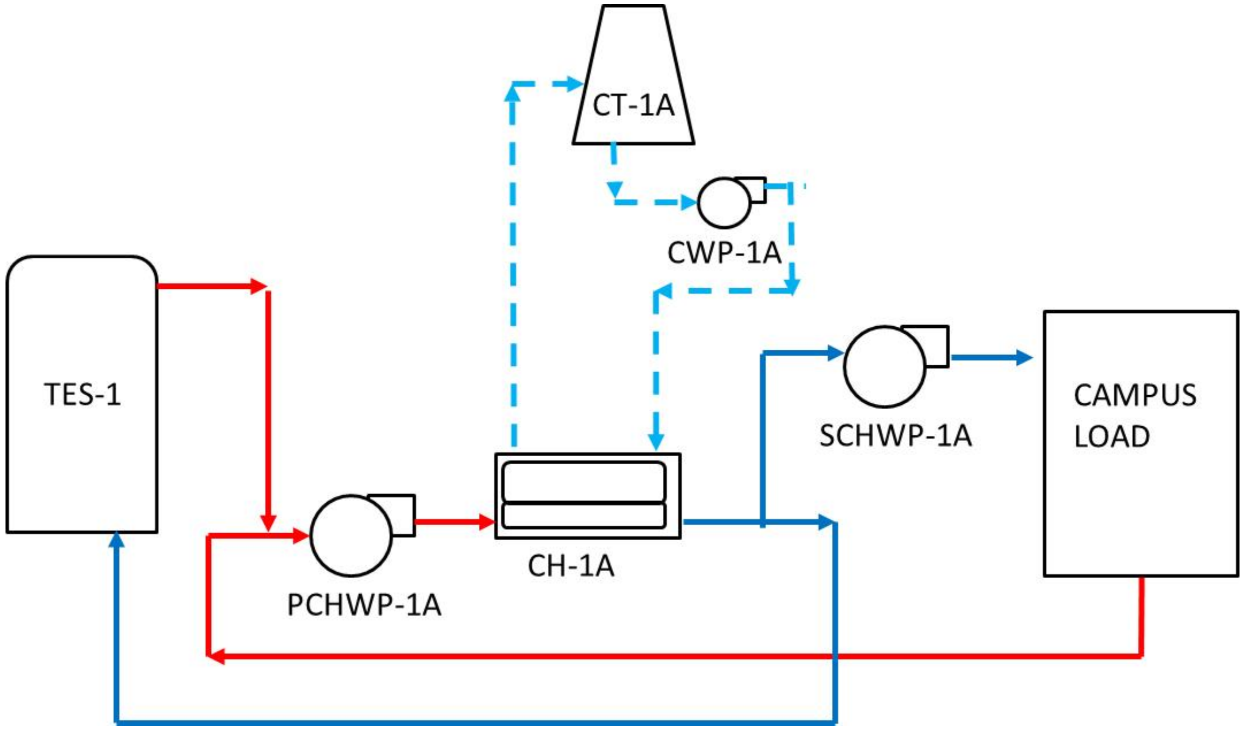


Figure 2.5 Mode 2 - Chiller Charging TES while Serving Load

2.3.3 Operating Mode 3 – TES Serving Load

Figure 2.6 shows that when the TES tank has enough capacity to satisfy the campus loads, cold water from the bottom of the TES tank is pumped via SCHWP-1A to the campus. Return water then gets delivered to the top of the TES tank.

Ideally, this mode of operation would occur during all peak and partial peak periods. However, since the TES capacity may not be sufficient to serve the campus at heavy loads, this is not always sufficient.

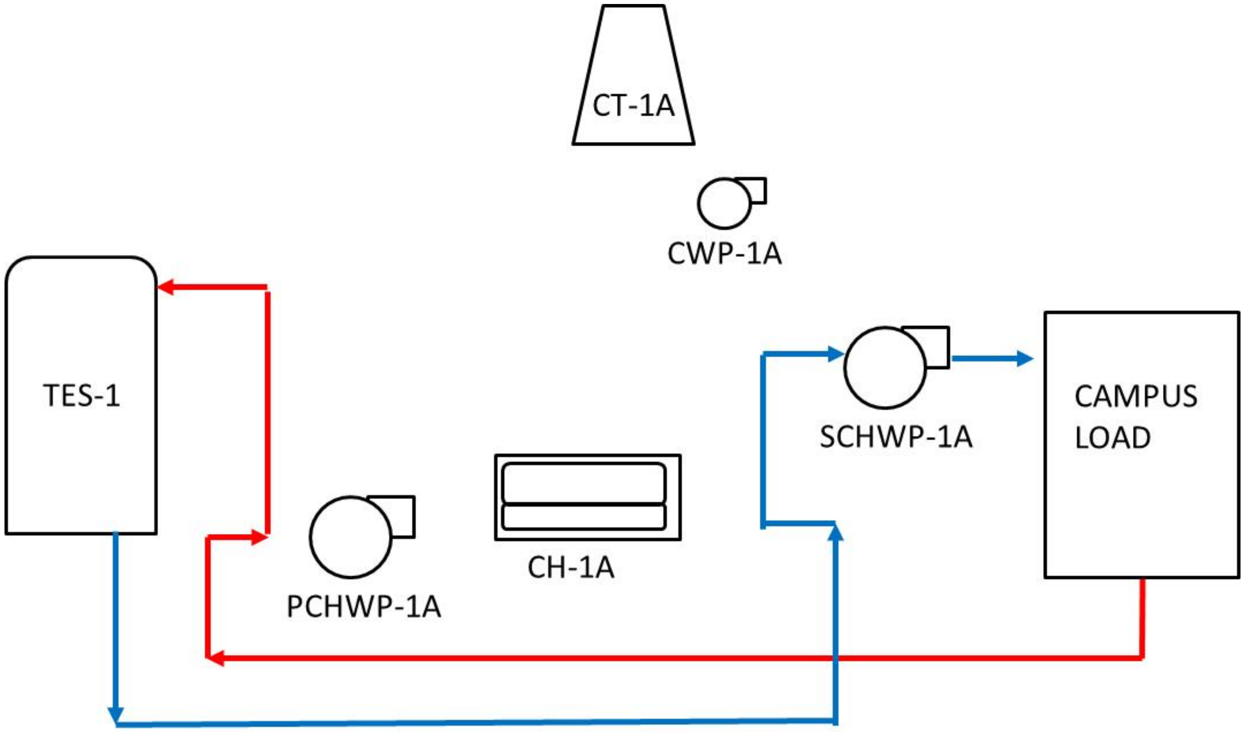


Figure 2.6 TES Serving Load

2.3.4 Operating Mode 4 – Chiller and TES Serving Load

Figure 2.7 shows the plant operation during periods of heavy campus loads, when both the chiller and the TES serve the campus. Chilled water is produced at the chiller, mixes with a cold water stream from the bottom of the TES tank, and is pumped to the campus via SCHWP-1A. The return water from the campus gets cycled back proportionally to the TES tank and to the chiller via PCHWP-1A.

Although this condition is unavoidable when campus cooling demands are especially high, this condition should be minimized to reduce energy costs, especially during peak periods, by ensuring the TES tank has sufficient charge.

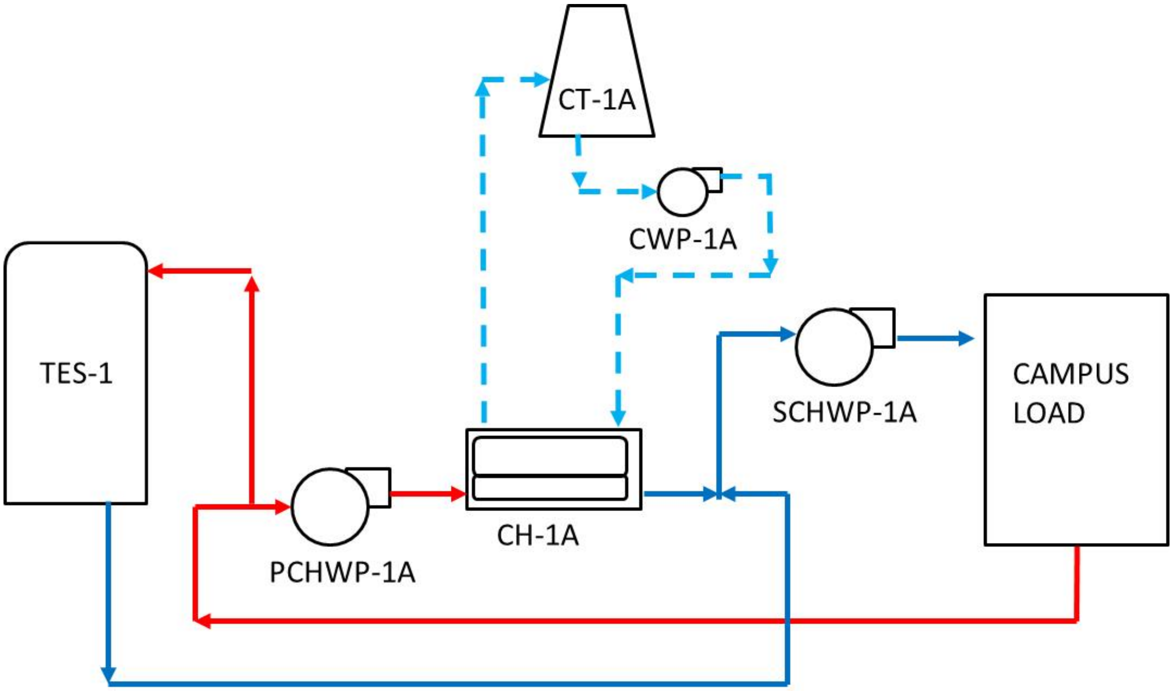


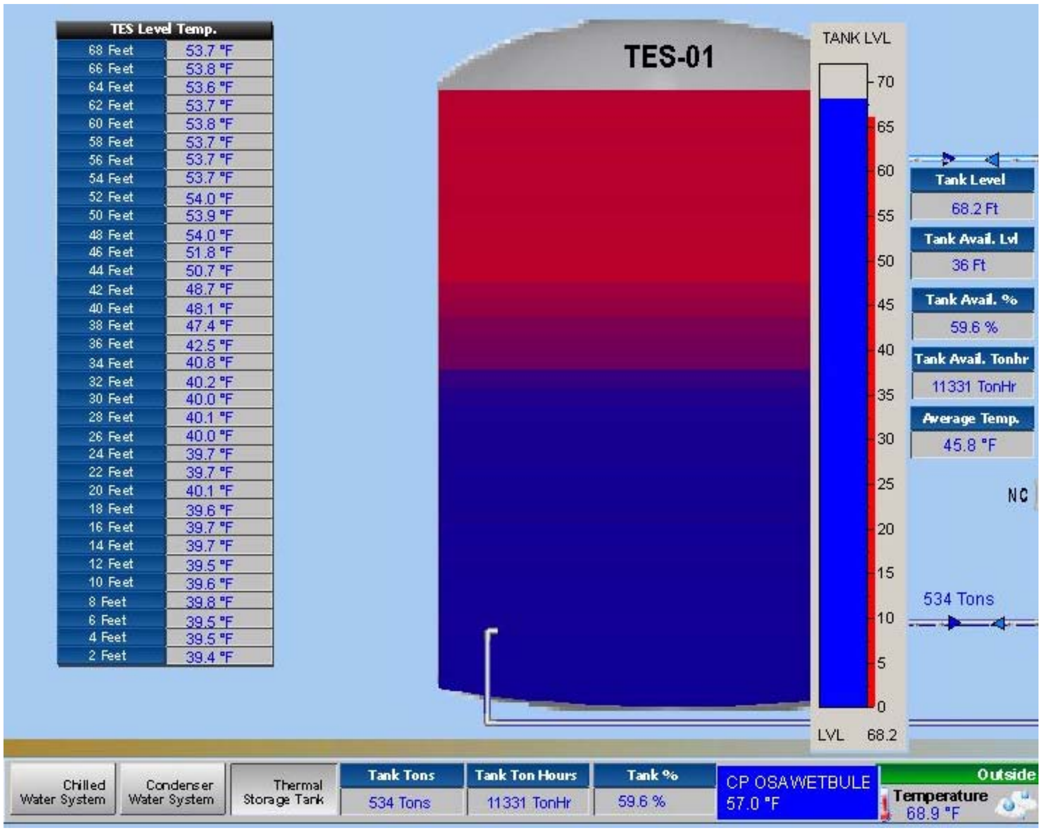
Figure 2.7 Chiller and TES Serving Load

2.3.5 Current Control Strategy

The TES tank is approximately 70 feet tall and has temperature sensors every two feet along the height of the tank (see Figure 2.8), which are also used to compute the charge percentage of the tank. Currently, the mode of operation is determined based on the time of day and either the temperature at a specific level of the TES tank or the charge percentage of the tank. These setpoints, listed below in Table 2.2, were chosen to provide an appropriate balance of system effectiveness (i.e., TES tank charging at night and discharging during the day during moderate load periods) and adequate campus cooling (i.e., chillers operate during the day during periods of high loads).

Table 2.2 Current Control Strategy

Rate Period	Time	Setpoint	
Off-Peak	21:30pm – 8:30am	Regen Start if 56ft Tank sensor is greater than	45^{o}F
		Regen stop if 66ft tank sensor is less than	45^{o}F
Part-Peak 1	8:30am – 12:00pm	Start chillers if 40ft tank sensor is greater than	45^{o}F
		Deplete tank if 60ft tank sensor is less than	45^{o}F
Peak	12:00pm – 18:00pm	Deplete tank if available % is greater than	0%
		Start chillers if 2ft tank sensor is greater than	42^{o}F
Part-Peak 2	18:00pm-21:30pm	Deplete tank if available % is greater than	30%
		Start chillers if available % is less than	30%



TES Level Temp.	
68 Feet	53.7 °F
66 Feet	53.8 °F
64 Feet	53.6 °F
62 Feet	53.7 °F
60 Feet	53.8 °F
58 Feet	53.7 °F
56 Feet	53.7 °F
54 Feet	53.7 °F
52 Feet	54.0 °F
50 Feet	53.9 °F
48 Feet	54.0 °F
46 Feet	51.8 °F
44 Feet	50.7 °F
42 Feet	48.7 °F
40 Feet	48.1 °F
38 Feet	47.4 °F
36 Feet	42.5 °F
34 Feet	40.8 °F
32 Feet	40.2 °F
30 Feet	40.0 °F
28 Feet	40.1 °F
26 Feet	40.0 °F
24 Feet	39.7 °F
22 Feet	39.7 °F
20 Feet	40.1 °F
18 Feet	39.6 °F
16 Feet	39.7 °F
14 Feet	39.7 °F
12 Feet	39.5 °F
10 Feet	39.6 °F
8 Feet	39.8 °F
6 Feet	39.5 °F
4 Feet	39.5 °F
2 Feet	39.4 °F

LVL 68.2

Tank Level
68.2 Ft

Tank Avail. Lvl
36 Ft

Tank Avail. %
59.6 %

Tank Avail. Tonhr
11331 TonHr

Average Temp.
45.8 °F

534 Tons

Tank Tons	Tank Ton Hours	Tank %
534 Tons	11331 TonHr	59.6 %

CP OSAWETBULE
57.0 °F

Outside
Temperature
68.9 °F

Figure 2.8 TES Facility Monitoring Screenshot

3. LITERATURE REVIEW

There has been substantial research in the field of chilled water plant optimization, including studies that include various forms of thermal energy storage.

3.1 Chilled Water Plant Modeling and Optimization Methodology

Optimization techniques pioneered by James Braun utilized mathematical models of the equipment to develop optimal control algorithms for designing chilled water plants ([1], [2], [3]).

Braun's research discussed effective design practices used to reduce energy consumption and increase efficiencies of these systems. Many of these strategies, such as the use of variable speed compressors and the use of chilled water storage, are much more prevalent today. He also recommended using TRNSYS as a system simulation model, while citing limitations in the program that are no longer applicable in today's versions. The simulations recorded in Braun's work involve control of condenser flow rates, tower fan flows, the number of chillers operating, use of thermal storage, and other variables that can be controlled to minimize operational costs. His methodologies for large central chilled water systems consist of: (1) mathematical models for the individual equipment, (2) optimal control algorithms, and (3) general design and control guidelines. Of primary interest are the methods for determining optimal values of the independent control variables. One option involves a component-based optimization algorithm, which simulates the operation of a system over time by minimizing costs at each time increment in response to input variables. The other option is for near-optimal control, which utilizes an empirical cost function for the total power consumption of the plant based on the individual components, which allows for determination of optimal control variables and linear regression techniques. The results showed that the system-based procedure was an effective optimization technique and implementable to actual systems, but inefficiencies may still be present, particularly in the time interval for control decisions [1].

Braun later summarized a number of practices for improved control [3], including:

- For variable speed tower fans, all tower cells should be operated at identical speeds.
- The lowest-speed tower fans should be incremented first when adding tower capacity; the reverse is true for removing capacity.
- To yield peak pump efficiencies for each combination of operating chillers, variable speed pumps should be sequenced so that they are directly coupled to the sequencing of chillers.
- Multiple chillers should have the same chilled water set temperatures, and the flow rates of the evaporator and condenser water should be proportional to the chillers' relative cooling capacities.
- Parallel air handlers should have the same supply air setpoint temperatures.

3.2 Optimal Design and Control of Chilled Water Plants

A series of articles by Steven Taylor in the ASHRAE Journal discuss in depth about optimizing design and control of chilled water plants [5]. These articles reference techniques presented in a 2007 article written by Mark Hydeman, Optimizing Chilled Water Plant Control [4]. Taylor and Hydeman stated that the modeling tools typically used in these applications include advanced programs such as DOE-2, EnergyPlus and TRNSYS, as well as custom models.

Hydeman's techniques [4] include detailed modeling of specific plants to determine the optimum operating sequences, which emphasize three influential factors on system efficiency: equipment efficiency, system configuration, and control sequences. A parametric analysis technique can then be used to optimize the control sequences of chilled water plants. In particular, implementation of guiding principles of good plant design can reduce the number of parameters that needs to be reviewed and modified once a system is modeled and simulated. The plant model can then be run through all of the feasible plant control modes in an effort to identify the combination of control sequences that result in either the lowest energy consumption or cost of operation. According to Hydeman, the general procedure to accomplish this is as follows:

1. Collect a baseline load profile including chilled water flow, chilled water supply temperature, chilled water return temperature, and outside air wet-bulb temperature.
2. Calibrate the models of the chilled water plant equipment.
3. Run the model across the full range of acceptable operating conditions.
4. Calculate the sum of the lowest energy cost (or energy usage) for each hour, called the theoretical optimum plant performance (TOPP) value.
5. Analyze the results to determine the realistic control sequences that approach the TOPP value.

Building upon Hydeman's work, an informative series of articles written by Steven Taylor offers an in-depth discussion of how to optimize the design and control of chilled water plants [5]. Taylor began by offering eight general steps to produce near-optimal plant design. The first seven steps are based on the design of a new system, while the eighth step outlines how to develop and optimize control sequences. Taylor recommended estimating energy usage using modeling programs such as DOE-2, EnergyPlus, and TRNSYS, although he cautioned against the limitations of DOE-2.1 and 2.2 and emphasized the latter options.

The plant model includes numerous equipment and system variables that affect plant performance, including:

- Chillers – full- and part- load efficiencies, heat transfer characteristics of the evaporator and condenser, unloading devices such as variable speed drives, oil management systems, and internal control logic
- Cooling towers – tower efficiency, approach temperatures
- Chilled and condenser water pumps – inclusion of variable speed drives, pump efficiencies, ΔT
- Chilled water distribution systems
- Weather
- Load profile

Optimal control sequences are unique to every plant, climate, and building/campus type, and Taylor referenced the techniques described in Hydeman's article for determining optimized performance. This includes developing and calibrating simulation models of the plant and equipment, and then running simulations with hourly chilled water load profiles and weather data as uncontrolled input data. By modeling all potential control sequences of operation at each hour, the theoretical optimum plant performance (TOPP) can be determined based on either minimum hourly energy usage or minimum costs. Note that the independent variables include plant load and weather, and trends can be acquired using various applications; these trends can in turn be used as predictive input to control the plant through direct digital control (DDC) systems.

Taylor's article followed with a discussion and analysis of the TOPP modeling and control sequences for a chilled water plant model serving a typical office building. Optimized control logic, chiller staging, and DDC programming are addressed as well.

Other articles have been reviewed for applicability to this project, and other strategies to improve performance of chilled water plants looked specifically at optimization of chiller staging, chilled and cooling water temperatures, and chiller on/off running times for effects on plant performance ([5], [9]).

3.3 Chilled Water Plant Optimization with Thermal Energy Storage

The addition of Thermal Energy Storage (TES) to a chilled water plant can result in significant opportunities for optimization, provided the tools and methods adequately address the applicable control parameters. One distinction that must be underscored is that TES is primarily a cost savings measure rather than a technology used for energy savings, although energy savings can certainly result. However, this savings is particularly at the source of electricity generation, where it reduces demand on the grid during peak times, and thus the lower efficiency energy sources would not be used as much [8].

A great deal of research has been done by Kody Powell of the University of Texas in optimizing cooling systems with thermal energy storage ([17],[18], [19], [20]). Powell's studies described how proper design, optimization, and control of thermal energy storage systems can result in increased system flexibility and efficiency, reduced energy consumption and equipment costs, and better independence from utilities. One strategy in particular – model predictive control (MPC) – uses a model of a building and its systems, along with other variables such as weather and occupancy predictions, to look for an optimal trajectory over a period of time. Suggested modeling tools include EnergyPlus and TRNSYS, coupled with other programs such as MATLAB for further analysis. For an active chilled water TES system, MPC functions best as a sort of equipment scheduler rather than changing equipment setpoints. With a prediction of the campus load, the MPC determines how many chillers should operate at each time step to meet the rest of the load, as well as the start and stop times of each chiller [19].

Additional studies by Powell and others ([17], [18], [20]) went into depth on dynamic optimal chiller loading with thermal energy storage to shift the load to the more efficient chillers at each time interval. One applicable outcome of their modeling methodologies found that a system of chillers could be simplified to a single, optimal chiller for given load and ambient conditions to reduce the number of degrees of freedom in the model.

Although not directly related to chilled water thermal energy storage systems, Braun studied ways of modeling and optimizing thermal storage in buildings based on the capacitance of the structure and furnishings [7]. Braun's research focused on applying optimization routines that utilize a building's thermal capacitance to reduce operating costs using dynamic building control. This primarily involved varying the zone setpoints by shifting cooling loads from daytime to nighttime to take advantage of storing thermal energy within the structure and furnishings, thus reducing peak electrical demands and taking advantage of low nighttime rates. In principle, this is similar to what a chilled water thermal energy storage system does, and the optimization strategies that Braun outlined can be modified for alternate methods of thermal storage.

One of the challenges in optimization of thermal energy storage systems is developing a model that takes into account the stratification of the chilled water storage tank. For example, in one model, numerical simulation was used to determine the relationship between tank size and good thermal stratification [15]. Another study discussed a strategy to identify both an optimal tank size and operation strategy using a system model that incorporates the chilled water volume, flow rate, and delta-T as they affect the storage tank [16].

A significant amount of research has used numerical methods. Using such advanced programs as FLUENT to accurately model the chilled water flows, theoretical optimization models can be obtained, as referenced in Rosen’s text on thermal energy storage [10].

Other studies have found that for the optimal chiller dispatch schedule, the most efficient chiller is always operated first, followed by the next most efficient chiller type. The TES system also enables the most efficient chillers to be more fully loaded when the cooling load is lower, which in turn allows for the TES to discharge during periods of high cooling loads, thus eliminating some of the operation time for lower efficiency chillers [12].

3.4 Plant Modeling and Optimization Tools

TRNSYS is a popular choice for modeling and optimizing chilled water systems. Other typical plant modeling tools include DOE-2, EnergyPlus, and custom models. However, the ASHRAE series by Taylor [5] suggested limitations in the DOE-2 programs that would make alternate modeling tools a better choice.

Yu and Chan [22] used TRNSYS to identify an optimal load-sharing strategy for systems that employ multiple chillers to meet cooling load requirements. This was done by first building a TRNSYS chiller model to evaluate how the chiller load interacts with the Coefficient of Performance (COP) under different ambient conditions and control strategies.

Qiang, Wieding, and Min [23] used TRNSYS for modeling and Mathematica for optimization of a chiller plant to find the minimum energy consumption for varied conditions. A regression was completed using cooling load, cooling water supply temperature, cooling water flow rate, and chilled water flow rate. The total energy consumption of the plant was compared under three different control strategies and verified through TRNSYS simulations.

A good overview of how TRNSYS can be used as a model for simulation of a large central cooling and heating plant was done by Monfet and Zmeureanu [24]. The plant model includes chillers with heat recovery, cooling towers, and chilled water pumps. Weather data during a week-long period is collected and used to calibrate the model for testing during a three-month period. The TRNSYS model simulation was run at a time interval of 15 minutes – the same as the monitoring time steps. The simulation results were then validated using correlation-based models developed from other available information. The results found a good agreement between the simulated and monitored data, which stresses the importance of component-level calibration, particularly if the model will be used for plant optimization.

In another study, TRNSYS was used for modeling and simulation of a system with cold thermal energy storage systems in office buildings in Malaysia [25]. This process started with gathering the energy consumption pattern of a typical office building and constructing a baseline model using TRNSYS. After establishing accurate simulation results, TES was added to the model and the new energy consumption pattern is predicted. This simulation showed that while TES does not substantially reduce the total energy consumption, it can reduce energy costs through better balancing of consumption on the power grid.

These studies give ample support for utilization of TRNSYS to model a chiller plant system, calibrating the model to fit actual energy usage trends, and running the simulation at different control strategies to evaluate the optimal strategy.

3.5 Case Study: Thermal Energy Storage System at UC Irvine

As of October of 2015, the University of California, Irvine, utilizes a 4.5-million gallon thermal storage unit to serve a campus that uses approximately 75,000 ton-hours per day [11]. In one research study, Mixed Integer Linear Programming was used to determine optimal chiller plant scheduling [13]. The chillers were operated in ON/OFF modes to charge the TES and supply chilled water. The tank was modeled with two layers of stratification. Two control strategies were compared through MATLAB simulations: a baseline strategy, and one that included the proposed MINLP-based MPC strategy.

Another study was completed to model and optimize the system using TRNSYS [14]. This paper developed a model for the University of California, Irvine Thermal Energy Storage system. For simplicity, only a 24-hour look-ahead period was used to find the optimal values of the plant inputs, which served as the independent variables for the overall plant operating cost function. For the case study given in the paper, the optimization was compared against two baseline operating strategies.

4. METHODOLOGY

Typically, optimization of a chilled water distribution system is most effective if performed first during the design phase of the plant. Since the Cal Poly chilled water plant has already been installed and is operational, optimization for this system is somewhat more limited. The methodology employed for this project follows the optimization processes outlined by Hydeman [4] and Taylor [5].

Of the various modeling tools available such as EnergyPlus, DOE-2, and EnergyPro, TRNSYS (TRansient SYstem Simulator) was selected as a software particularly well-suited for energy analysis applications. TRNSYS is transient systems simulation program that uses a modular structure that models thermodynamic interactions over time. For this system, a number of modules are incorporate to model the various components such as chillers, pumps, cooling towers, and the TES tank. These modules are then connected in the appropriate configuration and parameters for each are set to reflect the operating conditions of the actual system. Optimization can be achieved by evaluating the model’s performance with varying operating parameters.

As explained by Hydeman, the methodology used for this optimization study includes the following steps [4]:

1. Develop a chilled water plant simulation model that incorporates the actual load profile data trended by the facility, including chilled water flow and supply and return temperatures, weather data, and TES flow and supply and return temperatures, as well as the current operating strategy, operating modes, and control strategies (Chapter 4 of this report).

2. Calibrate the model to the actual energy consumption data for the equipment (Chapter 5 of this report).
3. Run the model under different control strategies (varying the charging and discharging scenarios) to seek a feasible optimal strategy (Chapter 6 of this report).
4. Calculate the energy costs for each scenario and determine which control strategies can be realistically implemented to achieve optimal energy costs (Chapter 7 of this report).

It should be noted that the optimization efforts in this study follow Hydeman's approach of determining optimal control strategies. Unlike true mathematical optimization, which involves identifying the maximum or minimum of a real function, Hydeman's process looks for a combination of control sequences that produce the lowest energy cost operation. The specific goal is to "find a practical control strategy that performs close to optimum" [4].

The first step of that methodology will be outlined in greater detail below, with emphasis on how TRNSYS will be utilized.

4.1 Component Model Development

The simulation of the chiller plant is developed using the mathematical models for each of the components. The parameters established for each piece of equipment are then used as input to the TRNSYS model for simulation of the system's performance. While manufacturer nameplate data is used for the rated characteristics of the chiller and cooling tower, actual performance data is used where available from trended data measured from the plant itself.

4.1.1 Chillers

The campus primarily uses a 1,350 ton capacity chiller designed for a 20^{o}F temperature difference. When additional capacity is needed, four other lower capacity chillers, 300 tons each, are available. These usually operate as pairs connected in series, since they were each designed for a 10^{o}F temperature difference. The total capacity of the plant is therefore 2,550 tons if all chillers are operating concurrently. Since the chillers have the highest electrical loads in the chilled water plant, accurate modeling of these is essential to properly simulate the plant performance. The methodology below focuses on the modeling of the 1,350 ton chiller.

Table 4.1 summarizes the parameters used for the chillers.

Table 4.1 Chiller CH-1A Parameters

Chiller	Rated Capacity	Rated COP	Rated Power	Design Chilled Water Temp	Design Entering Cond. Water Temp	Evap. Temp Diff.	Design Flow
	Tons	-	KW	^{o}F	^{o}F	^{o}F	GPM
CH-1A	1,350	6.7	780	40	80	20	1620
CH-1 / 2	300 / 300	5*	200 / 200	50 / 40	-	10/ 10	720 / 720
CH 3 / 4	300 / 300	5*	200 / 200	50 / 40	-	10/ 10	720 / 720

* Data Unavailable – Calculated from trended data

The chillers in this system cool a water stream on the evaporator side (chilled water loop) and reject heat to a water stream on the condenser side (cooling water loop). While limited data is available from the manufacturer, actual performance data can be used to develop an empirical model.

The following variables are used for the methodology of modeling chillers described below [26]:

$Capacity$ = Chiller Capacity at Given Conditions (kW or BTU/hr)

$Capacity_{rated}$ = Chiller Capacity at Rated Conditions (kW)

$Capacity_{ratio}$ = Chiller Capacity Ratio (*dimensionless*)

$c_{p,chw}$ = Chilled Water Specific heat ($1.0\ BTU/lb_m{}^{o}F$)

COP = Coefficient of Performance (*dimensionless*)

COP_{nom} = Nominal COP at Given Conditions (*dimensionless*)

COP_{rated} = COP at Rated Conditions (*dimensionless*)

COP_{ratio} = COP Ratio (*dimensionless*)

$FFLP$ = Chiller Fraction of Full Load Power (*dimensionless*)

$\dot{m}_{chw}$ = Mass Flow Rate of Chilled Water (lb_m/hr)

η = Chiller Efficiency (*dimensionless*)

P = Nominal Chiller Power Draw (*kW or BTU/hr*)

P_{tot} = Power Consumed by Chiller (*kW or BTU/hr*)

PLR = Chiller Part Load Ratio (*dimensionless*)

$\dot{Q}_{load}$ = Load on Chiller Evaporator (*kW*)

$\dot{Q}_{cond}$ = Load on Chiller Condenser (*kW*)

$T_{chw,in}$ = Chilled Water Inlet Temperature (^oF)

$T_{chw,set}$ = Chilled Water Setpoint Temperature (^oF)

$T_{cw,i}$ = Condenser Water Inlet Temperature (^oF)

$T_{cw,o}$ = Condenser Water Outlet Temperature (^oF)

The Coefficient of Performance (COP) for the chiller is defined as:

$$COP = \frac{\dot{Q}_{load}}{P_{tot}}$$

From an energy balance on the evaporator, the chiller load is given by:

$$\dot{Q}_{load} = \dot{m}_{chw} c_{p,chw} (T_{chw,in} - T_{chw,set})$$

The Part Load Ratio (PLR) is found by:

$$PLR = \frac{\dot{Q}_{load}}{Capacity}$$

The chiller's power draw is:

$$P = \frac{Capacity}{COP_{nom}} FFLP$$

where FFLP is the Fraction of Full Load Power.

The heat rejected from the condensers to the cooling water stream is found from an overall energy balance on the chiller:

$$\dot{Q}_{cond} = \dot{Q}_{load} + \eta P_{tot}$$

or an energy balance on the condenser alone:

$$\dot{Q}_{cond} = \dot{m}_{cw} c_{p,cw} (T_{cw,o} - T_{cw,i})$$

TRNSYS uses an empirical model based on trended data for predicting chiller performance under varying part-load and condenser water conditions. Because of this approach, certain parameters must be evaluated and inputted into text-based data files for TRNSYS. At each time step, the TRNSYS chiller module uses the cooling water inlet temperature and chilled water setpoint to determine a COP ratio and capacity ratio at those conditions. The chiller's nominal COP and capacity at those conditions are then calculated using the following equations:

$$COP_{nom} = COP_{rated} * COP_{ratio}$$

$$Capacity = Capacity_{rated} * Capacity_{ratio}$$

Note that the Capacity Ratio and COP Ratio are both 1.000 at the rated conditions, 40°F chilled water set point and 80°F entering condenser water temperature.

Trended data from the Central Plant includes chilled water supply and return temperatures and flow rates, as well as power consumption at 15-minute intervals. From this data, the COP ratio at each time period can be calculated, as well as the capacity ratio at each condition, as tabulated in Table 4.2. In addition, the Fraction of Full Load Power (FFLP) is correlated against the Part Load Ratio (PLR) and included as part of a separate data file, as summarized in Table 4.3.

Table 4.2 Chiller CH-1A Performance Data

Outlet CHW Temp (^{o}F)	**Inlet CW Temp (^{o}F)**	**Capacity Ratio**	**COP Ratio**
38.0	61	1.0415	1.2674
	68	1.0151	1.1265
	77	0.9860	1.0147
	80	0.9745	0.9775
	86	0.9515	0.9031
	95	0.9223	0.8130
40.0	61	1.0668	1.2924
	68	1.0404	1.1544
	77	1.0115	1.0375
	80	1.0000	1.0000
	86	0.9770	0.9249
	95	0.9480	0.8337
41.0	61	1.0791	1.3036
	68	1.0540	1.1566
	77	1.0227	1.0491
	80	1.0122	1.0118
	86	0.9913	0.9371
	95	0.9598	0.8427
42.8	61	1.1702	1.3936
	68	1.1453	1.2663
	77	1.1144	1.1302
	80	1.1040	1.0922
	86	1.0834	1.0160
	95	1.0521	0.9173
44.6	61	1.1248	1.3497
	68	1.0997	1.2224
	77	1.0685	1.0908
	80	1.0581	1.0527
	86	1.0373	0.9766
	95	1.0061	0.8800
46.4	61	1.1474	1.3716
	68	1.1225	1.2444
	77	1.0914	1.1105
	80	1.0810	1.0724
	86	1.0603	0.9963
	95	1.0291	0.8976

Table 4.3 Chiller CH-1A Part Load Ratio (PLR) Data

Part Load Ratio	Fraction of Full Load Power
0.00	0.0000
0.33	0.2168
0.60	0.4631
0.70	0.5654
0.80	0.6931
0.90	0.9010
1.00	1.0000

It should be noted that the Part Load Ratio (PLR) data indicates that the chiller is more efficient at lower loads. This suggests that, where possible, the chiller would consume noticeably less energy if it can be run longer at lower loads, than if it were run shorter at higher loads.

4.1.2 Cooling Tower

The chilled water plant currently has two Baltimore Air Coil (BAC) cooling towers, which serve to provide either additional capacity when needed, or redundancy. Performance data for the BAC cooling towers from the manufacturer is included in Appendix C. The relevant cooling tower performance characteristics are included below in Table 4.4.

Table 4.4 BAC 31301C/V Performance Data

Design Parameter	Value	Units
Flow Rate	3431	GPM
Hot Water Temp	91	^oF
Cold Water Temp	80	^oF
Wet Bulb Temp	73	^oF
Fan Power	100	HP

The following variables are used for the methodology of modeling cooling towers in TRNSYS [26]:

c = Empirical Cooling Tower Coefficient (*dimensionless)*

$c_{p,w}$ = Specific Heat of Water ($1.0\ BTU/lb_m{}^oF$)

C_s = Saturation Specific Heat ($BTU/lb_m{}^oF$)

ε_a = Cooling Tower Effectiveness (dimensionless)

$h_{a,w,i}$ = Enthalpy of Inlet Water (BTU/lb_m)

$h_{a,i}$ = Enthalpy of Inlet Air (BTU/lb_m)

$h_{s,w,i}$ = Saturation Enthalpy of Inlet Water (BTU/lb_m)

$h_{s.w.o}$ = Saturation Enthalpy of Outlet Water (BTU/lb_m)

$\dot{m}_a$ = Mass Flow of Air (lb_m/hr)

$\dot{m}_w$ = Nominal Mass Flow of Water (lb_m/hr)

$\dot{m}_{w,i}$ = Mass Flow of Inlet Water (lb_m/hr)

m^* = Mass Averaged Specific Heat Ratio (*dimensionless*)

n = Cooling Tower Empirical Exponent (*dimensionless*)

NTU = Number of Transfer Units (*dimensionless*)

$\dot{Q}$ = Actual Heat Transfer in Cooling Tower (*kW or BTU/hr*)

$\dot{Q}_{max}$ = Maximum Heat Transfer in Cooling Tower (*kW or BTU/hr*)

$T_{w,i}$ = Temperature of Inlet Water (${}^oF$)

$T_{w,o}$ = Temperature of Outlet Water (${}^oF$)

For a given ambient wet bulb temperature and entering water temperature, the maximum heat transfer in a cooling tower is determined by the following equation:

$$\dot{Q}_{max} = \dot{m}_a(h_{a,w,i} - h_{a,i})$$

The actual heat transfer is determined by an energy balance on either the air or the water. Using the entering and exit water conditions, and neglecting the make-up water,

$$\dot{Q} = \dot{m}_w c_{p,w}(T_{w,i} - T_{w,o})$$

The resulting tower effectiveness, ε_a, is defined as

$$\varepsilon_a = \frac{\dot{Q}}{\dot{Q}_{max}}$$

Cooling tower effectiveness can be shown to be a function of the air and water properties and the number of transfer units, as in sensible heat exchangers, for a cross-flow cooling tower.

$$\varepsilon_a = \frac{1}{m^*}(1 - \exp(-m^*(1 - \exp(-NTU)))$$

Where

$$m^* = \frac{\dot{m}_a C_s}{\dot{m}_{w,i} c_{p,w}}$$

and

$$C_s = \frac{h_{s,w,i} - h_{s.w.o}}{T_{w,i} - T_{w,o}},$$

where C_s is the saturation specific heat.

The NTU can be correlated as follows:

$$NTU = c\left(\frac{\dot{m}_w}{\dot{m}_a}\right)^n,$$

where c and n are empirical coefficients based on manufacturer's data.

Appendix C includes the spreadsheet used to determine these parameters, which are summarized in Table 4.5 below.

Table 4.5 Cooling Tower Parameters

Coefficient	Value
c	30.54
n	-2.4

4.1.3 Stratified Chilled Water Tank

The TES storage tank model consists of the tank divided into separate control volumes, each two feet in height, that apply mass and energy balance equations to each control volume. Thermal Storage is described in depth in the 2012 ASHRAE Handbook – HVAC Systems and Equipment, Chapter 51 [30].

The parameters for the Cal Poly TES tank are given in Table 4.6.

Table 4.6 TES Tank Parameters

Design Parameters	Value	Units
Total Latent Capacity	19,000	Ton-hours
Charging Flow (Max)	4,860	GPM
Charging Tons (Max)	4,050	Tons
Discharging Flow (Max)	6,000	GPM
Discharging Tons (Max)	5,000	Tons
Design Temperatures	40 / 60	^{o}F
Tank Volume	1,600,000	Gallons

One phenomenon of naturally stratified thermal storage tanks is the occurrence of a "thermocline" region, which is the thin thermal transition layer that forms between the warm and cold volumes of water within the tank. Depending on temperature and flow conditions, as well as physical characteristics of the system and the tank, thermocline thicknesses can typically range from 1.5 ft to 6 ft [32]. Direct readings from the Cal Poly TES tank shows a thermocline region of approximately 4 feet (see Appendix D), between which the temperature transitions from the low 40s to the low 50s.

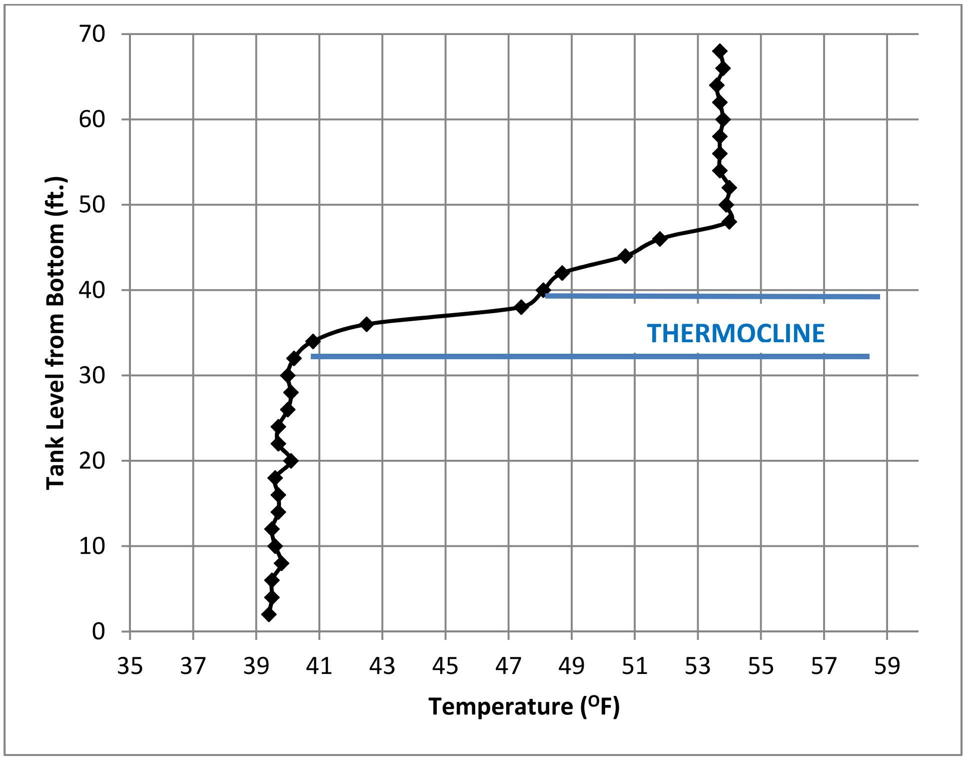


Figure 4.1 Typical Temperature Stratification Profile for TES Tank

The fully charged condition (100% charge) is the state at which no more heat is to be removed from the tank, which occurs when the temperature of the chilled water entering the tank is the same as the temperature leaving the tank [30]. The system is designed for 40ºF chilled water, although the chiller can actually deliver lower temperatures. Therefore, the tank is evaluated as fully charged at 100% capacity when its entire volume is 40ºF. The actual cooling capacity of the tank is computed based on the amount of heat that can be removed at design conditions – in this case, using the entire volume of the tank with a 20ºF temperature difference (40ºF to 60ºF). The Cal Poly TES tank has a nominal capacity of 19,000 ton-hours.

The fully discharged condition (0% charge) is the state when the tank has no more usable cooling capacity, which occurs when the discharge temperature from the tank reaches a pre-defined temperature [30]. According to the facilities engineers, this temperature is 45ºF. Charge percentages in between 0 and 100 are calculated based on the percent usable volume. This is accomplished by taking the temperature at each node and calculating the heat removal of the volume of that node and a temperature difference from 60^{o}F. Nodes with temperatures above the "usable" temperature of 45^{o}F are not counted in the total charge percentage.

For example, to calculate the charge of a 60-ft diameter, 70 foot tall tank with 35 nodes (2 feet each) using the data in Figure 4.1 (with the bottom node temperature of 39.5^{o}F):

$$V_{2ft-node} = \frac{\frac{\pi}{4}D^2H}{35} = \frac{\frac{\pi}{4}60^2 * 70}{35} = 5{,}654.9ft^3 = 42{,}298.4gal$$

$$m_{2ft-node} = \rho_{node}V_{2ft-node} = 62.4\frac{lb}{ft^3} * 5654.9ft^3 = 352{,}863.7lb$$

$$Q_{node1} = m_{2ft-node}c_p(60 - T_{node1}) = 352863.7lb * 1.00\frac{BTU}{lb°F}(60 - 39.5)°F =$$

$$Q_{node1} = 7{,}233{,}706BTU\left(\frac{ton}{12{,}000\ BTU/hr}\right) = 602.8\ ton \cdot hr$$

where

$V_{2ft\text{-}node}$ = Volume of a 2-foot tall segment of the tank (*ft*^{3})

$m_{2ft\text{-}node}$ = Mass of a 2-foot tall segment of the tank (*lb*)

D = Diameter of the tank (*60 ft.*)

H = Height of the tank (*70 ft.*)

ρ_{node} = Density of the water at the node temperature (*62.4 lb/ft*^{3})

c_p = Specific heat of water (*1.00 Btu/lb^{o}F* for water at 40^{o}F)

Q_{node} = Stored energy of tank node (*BTU* or *ton-hr*)

Using the same methodology for the temperatures at each of the nodes (35 total), and evaluating nodes with temperatures above 45°F as zero, the total charge is the sum of all 35 nodes. For the data shown in Figure 4.1, the sum is approximately 10,925 ton-hrs. Dividing that by the capacity of the tank (19,000 ton-hrs), this equates to about a 57.5% charge.

4.1.4 Pumps

Pumps are modelled in TRNSYS based on their rated conditions and an input control signal – ranging from 0 to 1 – that defines the ratio of flow and power for which the pumps operate at any timestep [26]. The output flow is computed as follows:

$$Q_{output} = \gamma * Q_{rated}$$

where

Q_{output} = Actual Flow of Pump (*GPM*)

Q_{rated} = Rated Flow of Pump (*GPM*)

γ = Control Signal (*0-1, dimensionless*)

The control signal is also used in the pump module for determining the amount of power drawn by the pump. If the control signal is greater than 0 (as in, the pump is operating), the power drawn is given by:

$$P = P_{rated}(a_0 + a_1\gamma + a_2\gamma^2 + a_3\gamma^3 + \cdots)$$

Where

P = Actual Pump Power (*kW*)

P_{rated} = Rated Pump Power (*kW*)

and a_0, a_1, etc., are the pump coefficients, which are defined by the user based on either published or correlated data. Since actual plant performance data was taken for the pumps, the coefficients listed in Table 4.7 are correlated to the trended data.

Table 4.7 Pump Parameters

Pump	Design Head	Design Flow	Rated Power	a_0	a_1
	Ft	GPM	HP	-	-
SCHWP 1A	145	2,000	125	0.01	0.49
PCHWP 1	45	1,620	40	0	0.57
CWP 1A	73	3,431	100	0	0.55

4.1.5 Other Equations

Although TRNSYS has modules that model the converging of two fluid streams, some of the parameters were inadequate for the purposes of this model. Fortunately, the program has the flexibility to incorporate custom equations and variables with user-defined inputs and outputs.

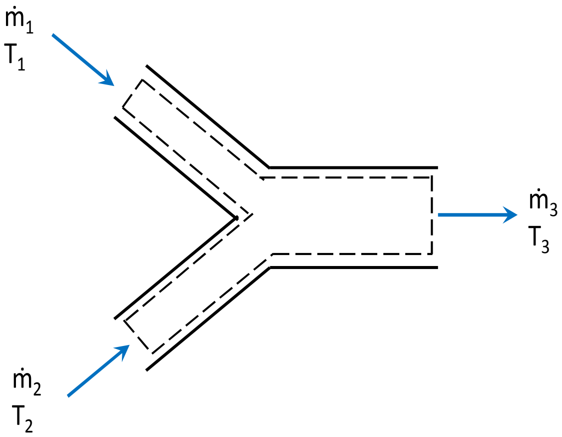


Figure 4.2 Mixing of Two Streams

The mixing of two streams, as illustrated in Figure 4.2, is given by basic continuity and energy balance equations [31]:

Mass Balance: $$\dot{m}_3 = \dot{m}_1 + \dot{m}_2$$

Energy Balance: $\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$

where $\dot{m}$ and h are the mass flow rate and enthalpy, respectively.

Assuming constant specific heat for water, it can be shown that

$$T_3 = \frac{\dot{m}_2 T_2 + \dot{m}_1 T_1}{(\dot{m}_1 + \dot{m}_2)}$$

Using the Equation function on TRNSYS, these equations and parameters were used for the mixing of the campus return and TES return (during charging) to the chiller, as well as the mixing of the chiller supply and the TES supply (during discharge) to the campus load.

4.2 Plant Model Development

With the necessary parameters for the primary system components fully defined, the TRNSYS plant model could be assembled by linking each of the component modules as shown in Figure 4.3.

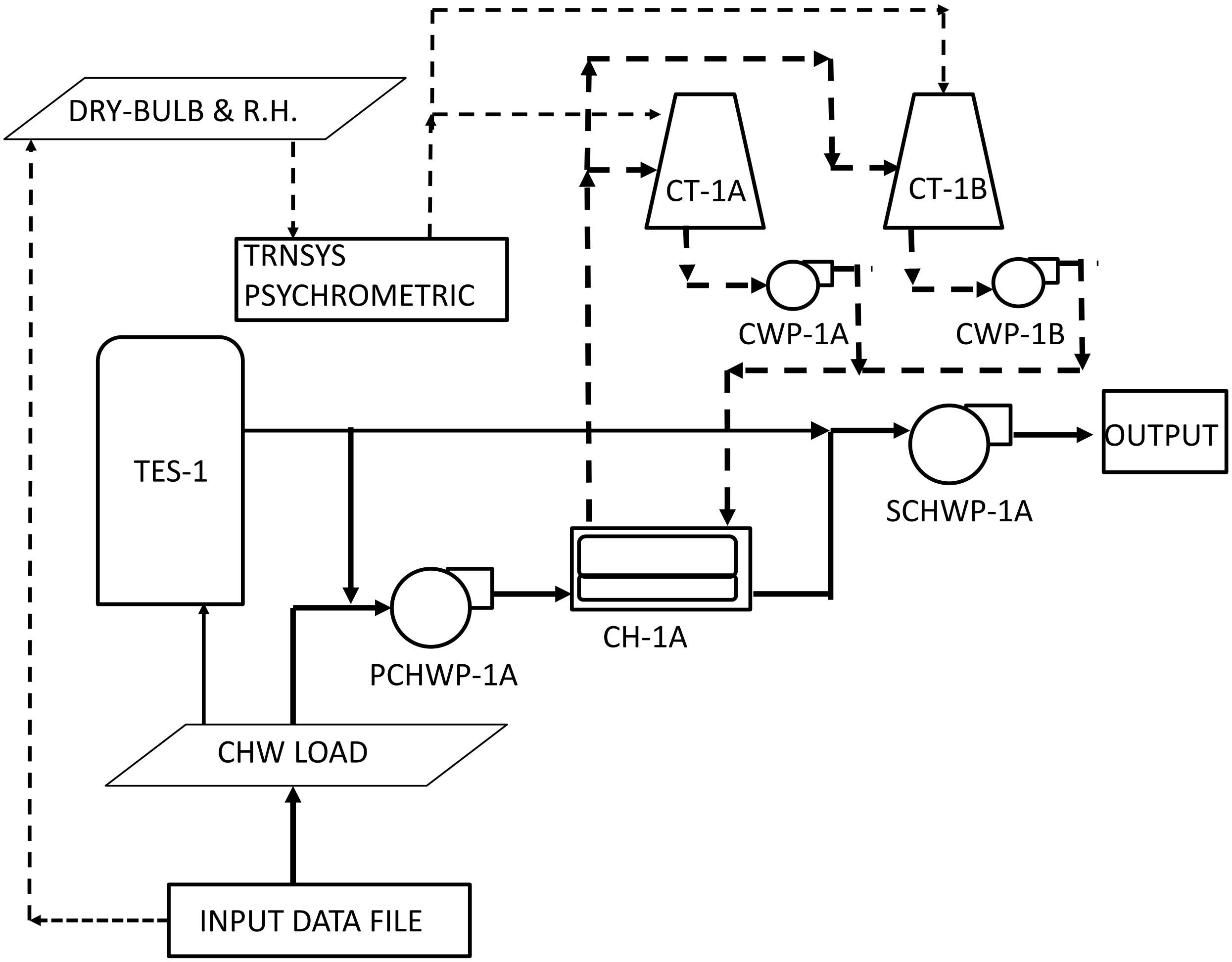


Figure 4.3 General Model Used for TRNSYS

TRNSYS contains a library of component types; Table 4.8 summarizes which ones were used for the Cal Poly central plant model.

Table 4.8 TRNSYS Types Used In the Model

NAME	TRNSYS TYPE
Stratified Thermal Energy Storage Tank	Type60f
Water-Cooled Chiller (CH-1A, CH-1&2, CH-3&4)	Type666
Cooling Tower: user-supplied performance coefficients (CT-1A)	Type51b
Variable speed pumps (PCHWP-1A, SCHWP-1A, CWP-1A)	Type110
Fluid diverting valves	Type11f
Mixing valves for fluids	Equation (*see Sec 4.1.6*)
Weather Data	Excel Module
Load Data	Excel Module
Chilled Water Setpoint (Forcing Function)	Type14
Psychrometrics: dry-bulb and relative humidity known	Type33e
Online plotter	Type65d
Online plotter with data output file	Type65a
Equations / Conversions	Equation Module

Using the plant monitoring software, a campus load profile was trended from October 1, 2014 to October 1, 2015 and incorporated into TRNSYS using the Excel Spreadsheet module. Weather data recorded at the campus was also utilized in the simulation. The trended data used as input to the model are listed in Table 4.9.

Table 4.9 Trended Input Data

ITEM	UNIT
Outdoor air dry-bulb temperature (T_{DB})	^{o}C
Outdoor relative humidity (RH)	%
Chilled water supply temperature (T_{CHWS})	^{o}C
Chilled water return temperature (T_{CHWR})	^{o}C
Chilled water flowrate	kg/hr
TES supply temperature ($T_{CHWS\text{-}TES}$)	^{o}C
TES return temperature ($T_{CHWR\text{-}TES}$)	^{o}C
TES flowrate	kg/hr

Since this data includes the chilled water flowrate and the supply and return temperatures, the campus cooling load can be computed from an energy balance on the campus water loop [34]:

$$q = 500Q\Delta T$$

where

q = Campus Cooling Load (BTU/hr)

Q = Chilled Water Flow Rate (GPM)

ΔT = Chilled Water Temperature Difference (^oF)

This cooling load is calculated for each timestep (6-minute intervals) in the model. The outputs of the model are the energy consumption rates in kW for each piece of equipment. These outputs serve as a baseline using the current operating strategy and can be compared to the actual recorded equipment power for validation of the model.

5. CHILLED WATER PLANT MODEL SIMULATION

Figure 5.1 shows the completed TRNSYS model used for the plant simulations. The TRNSYS model consists of linked modules for each piece of equipment in the plant. The input files for "Plant Data" and "Weather" were prepared from the facility-trended data at 6-minute intervals (a portion of this data, for a week in September, is included as part of Appendix D). The model also includes output devices for calculated data and plotting, which for clarity are not shown in the figure.

As discussed previously in Section 2, the chilled water plant can operate in four different modes based on whether the chillers are operating and whether the TES tank is charging or discharging. TRNSYS simulates these with a logic sequence inputted by the user in Excel, which controls the modules for the specific equipment – chillers, pumps, and cooling towers – as well as the mixing of the chilled water streams (return water to chillers or supply water to campus) and the splitting of supply/return chilled water streams (from the campus to the chillers and TES, or from the chillers to the TES and campus).

Although every effort has been made to accurately model the one-year period of historical plant cooling load data and each of the specific plant components, the TRNSYS output will not precisely match the actual equipment power performance without calibration of the model. As described in Section 4, the second step of Hydeman's referenced methodology is to calibrate the model to the actual energy consumption data for the equipment [4].

Therefore, in addition to the trended input data for the model, the actual power data was also trended by the plant monitoring system during the summer months of 2015 – June through October. This period includes the warmest times of the year as well as a wide range of occupancy loads on campus – the nearly unoccupied breaks between quarters, the less populated summer quarter, and the most populated period at the beginning of Fall quarter.

The calibration process for this study focused on matching the baseline performance of the model with the available summer power data from June 24th through September 30th. This period was specified for two reasons:

(1) While chilled water and weather measurements have been trended since October 2014, actual equipment power data was not trended until June 24th, 2015. Since the TRNSYS model output can be directly compared to the actual equipment power consumption during these dates, it was prudent to focus on them for the sake of accuracy.

(2) The summer utility rate period lasts from May through October, and the focus of this study is to develop an optimal control strategy for this summer rate period. The period from June 24th through September 30th includes a wide range of campus cooling loads: "low" loads when the campus is less-occupied and the temperatures are moderate (i.e., late June); "average" loads with an average campus population and moderate temperatures (i.e., late July); and "high" loads with the campus heavily occupied and near record high temperatures (as in the week of September 21st). Therefore, calibrating the model to the loads experienced from June 24th through September 30th can be assumed to be representative of the entire summer utility rate period.

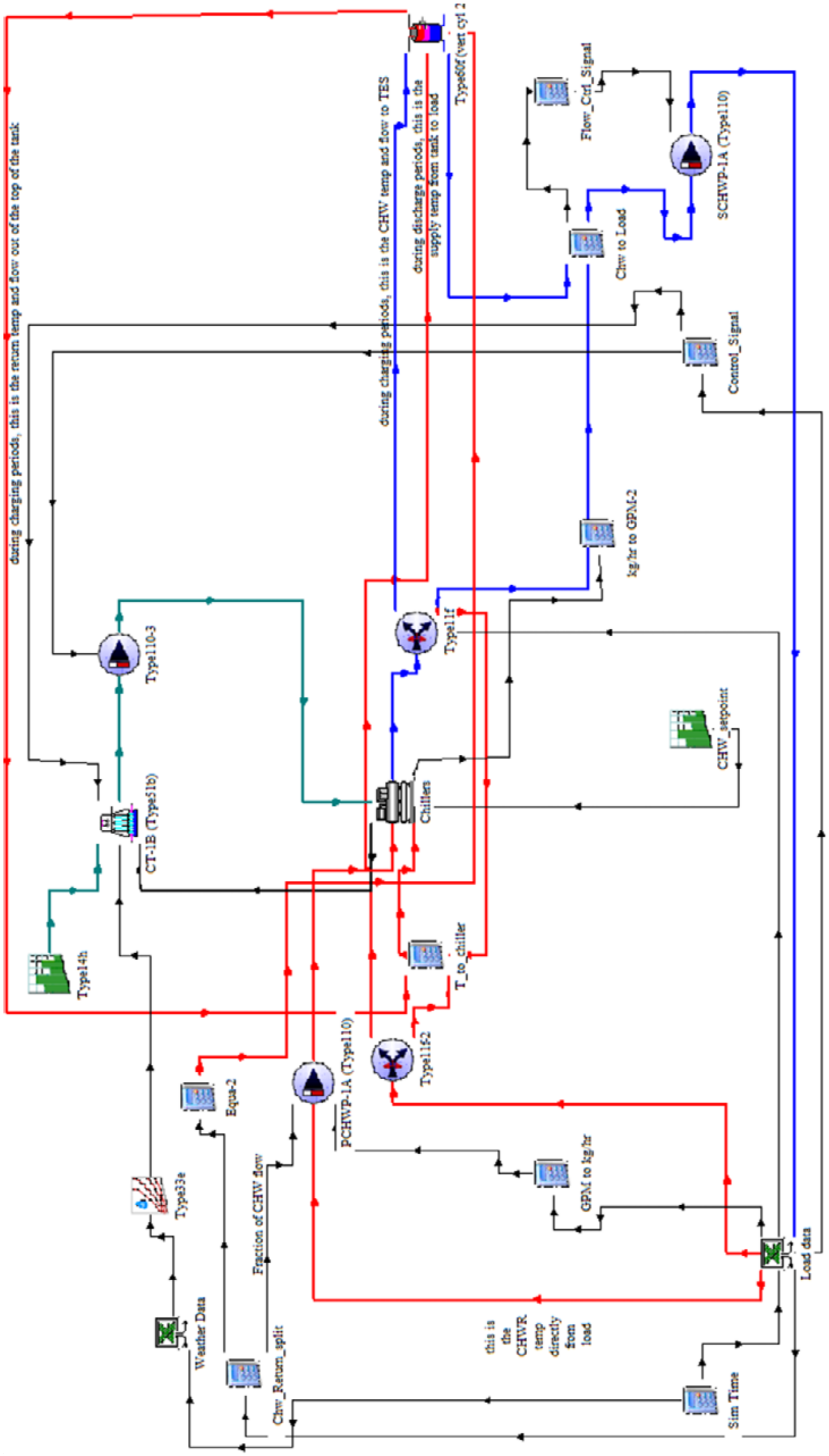


Figure 5.1 TRNSYS Model

There were some gaps in the trend data at the start of each month, resulting in a non-continuous range of performance data. Therefore, the model was run at 168-hour (1 week) intervals for the following weeks listed in table 5.1. (Note that except for the June data, the weeks in the model run from Saturday through Friday; this is because weekends are considered Off-Peak hours and will not be used in the energy/cost savings analysis in this study, but are useful to run in the model for the purposes of the initial conditions on Mondays.)

Table 5.1 Summer Weeks Used in Study

Weeks Modeled
June 24 – June 30
July 4 – July 10
July 11 – July 17
July 18 – July 24
July 25 – July 31
Aug 8 – Aug 14
Aug 15 – Aug 21
Aug 22 – Aug 28
Sept 5 – Sept 11
Sept 12 – Sept 18
Sept 19 – Sept 25

The uncalibrated simulation results showed that the electrical power consumption from the trended data sometimes varied when compared to the model results. Possible reasons for the discrepancies could be due to inaccuracies in the manufacturer's data compared to the actual performance of the equipment, inaccuracies in the measured data, or errors in the initial conditions used in the model.

After comparing the equipment power consumption from TRNSYS to the actual trended power data, the equipment parameters in each module were adjusted iteratively as needed to match the overall model simulation to the actual plant performance. These parameters include the cooling tower and pump coefficients, as well as the chiller part-load ratios. The process by which the model was calibrated to accurately model the current plant performance is described in the subsequent sections.

5.1 Initial Model Calibration – Week of 7/25/15 – 7/31/15

For initial evaluation of the TRNSYS model, the simulation was run with only a small subset of trended data. The objective was to match the model performance with the actual measured plant performance for a one-day period, and then extend that period to one week, and eventually the entire summer trend period of Table 5.1.

As a starting point, data was reviewed over the trended period to find an “average day" to model. Using the methodology to compute the loads in ton-hrs described in Section 4.2, Figure 5.2 summarizes the daily loads in ton-hours using the available data from 6/24/15 to 9/30/15 (note that data was unavailable for some days at the start of each month). The average load was calculated to be approximately 9,500 Ton-hours (depicted as a red line in the figure).

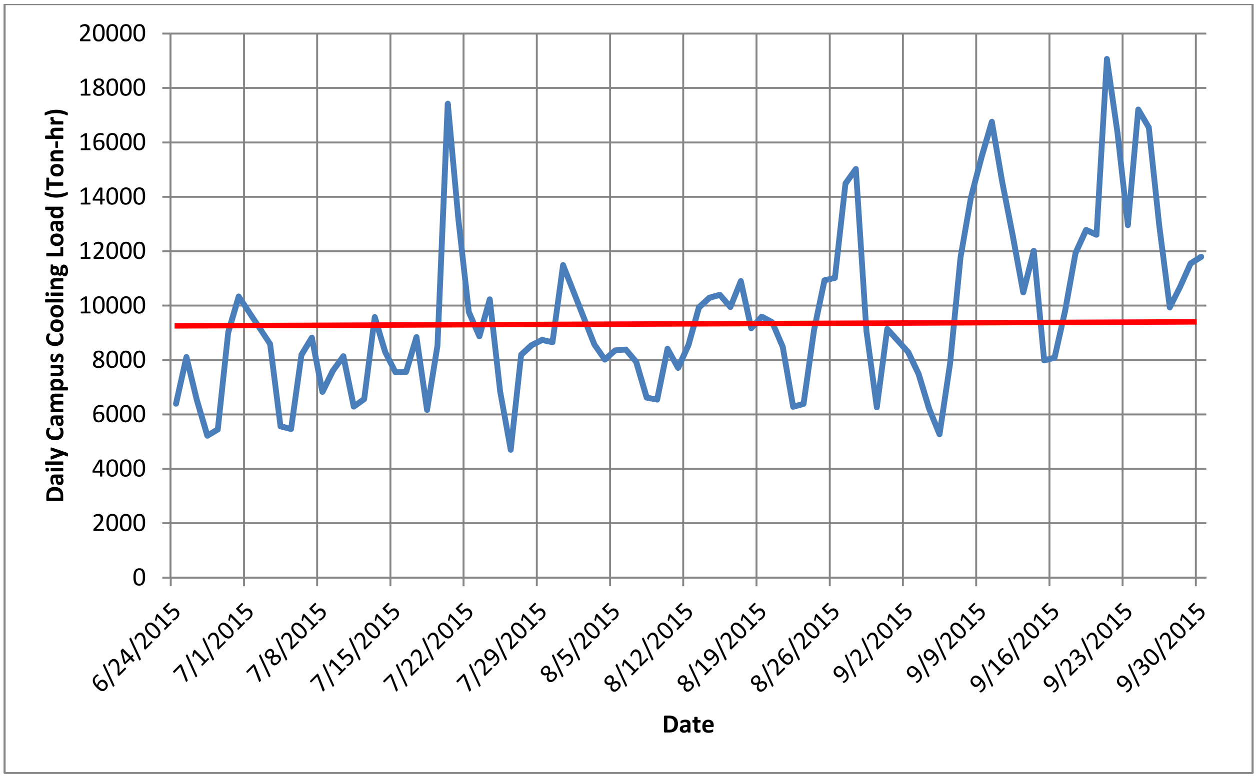


Figure 5.2 Daily Campus Cooling Load from 6/24/15 - 9/30/15

The actual chiller performance for Monday, July 28th 2015 was used, as its load profile is representative of what the campus experiences on an "average" day. The chiller power and the campus load for this 24 hour period are plotted in Figure 5.3 to illustrate an example of effective plant operation: the chiller shuts off during the Part-Peak and Peak periods (the shaded regions of the plot), while the TES satisfies the period with the highest campus cooling requirements.

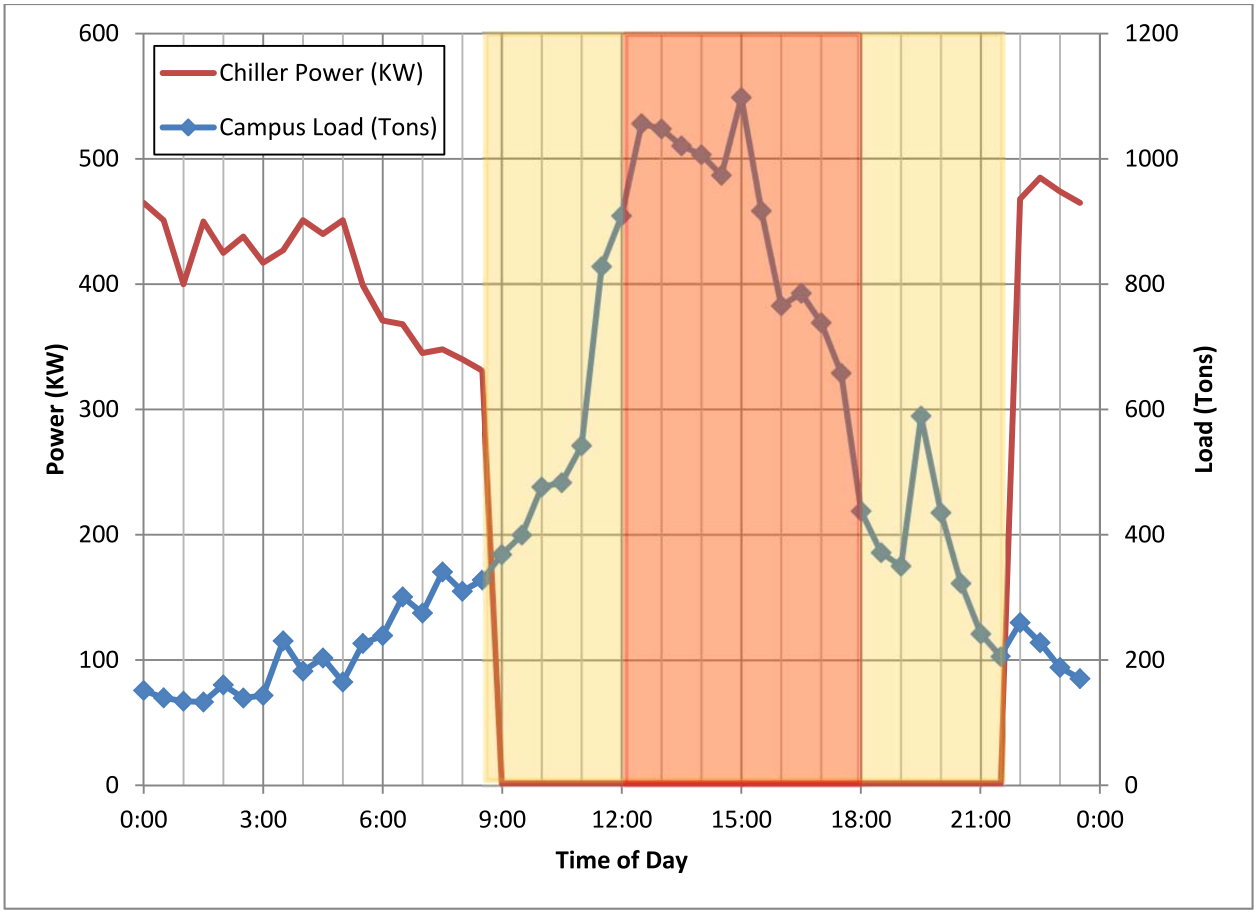


Figure 5.3 Campus Load and Chiller Power for 7/28/15

The model was run during this one-day period and the chiller parameters for Part Load Ratio and Fraction of Full Load Data were adjusted slightly (increased or decreased by a range of approximately 0.05) until the performance matched. Figure 5.4 illustrates the comparison of calibrated simulation and performance data for the 1,350 ton chiller on July 28th.

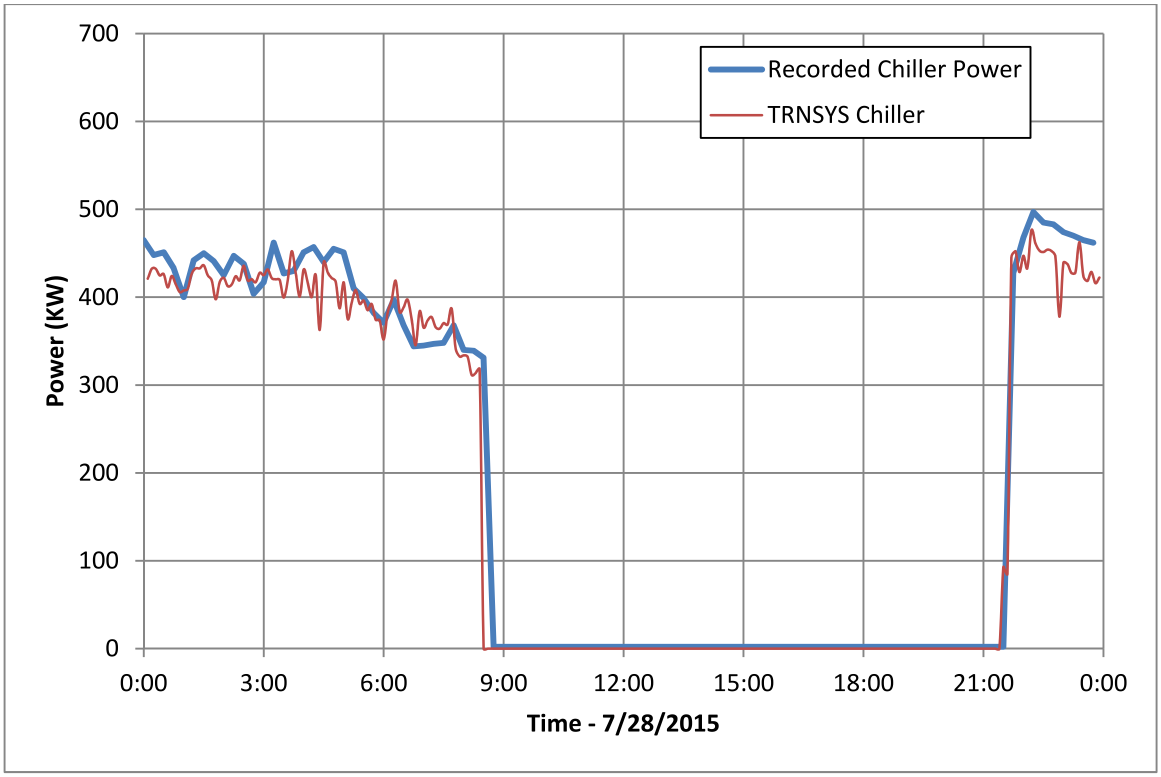


Figure 5.4 Comparison of Chiller Power Usage for Modeled and Trended Data – 7/28/15

With the chiller performance in the model properly matching the recorded performance, the rest of the equipment can be calibrated to the data similarly by adjusting their respective performance parameters to match the measured power loads. Figure 5.5, below, shows the results of this effort for the chiller pump (PCHWP), the chilled water pumps that distributes water to campus (SCHWP), and the primary cooling tower (CT-1A).

For the pumps, their pump coefficients (a_1 , a_2, etc.) as defined in Section 4.1.5 were adjusted by a range of approximately 0.1 in order to match the actual measured pump performance. For the cooling tower, which operates at a constant fan speed, only the TRNSYS control signal needed to be adjusted to reflect the same fraction of rated power that the measured data reflected.

While Figures 5.4 and 5.5 show that the model can accurately represent an “average” day, the accuracy of the model during the entirety of the study period must be attained. With sufficient results for July 28th, the full week starting from 7/25/15 through 7/31/15 were put through a similar calibration process for the chiller. The overall performance of the plant is shown in Figures 5.6 through 5.9.

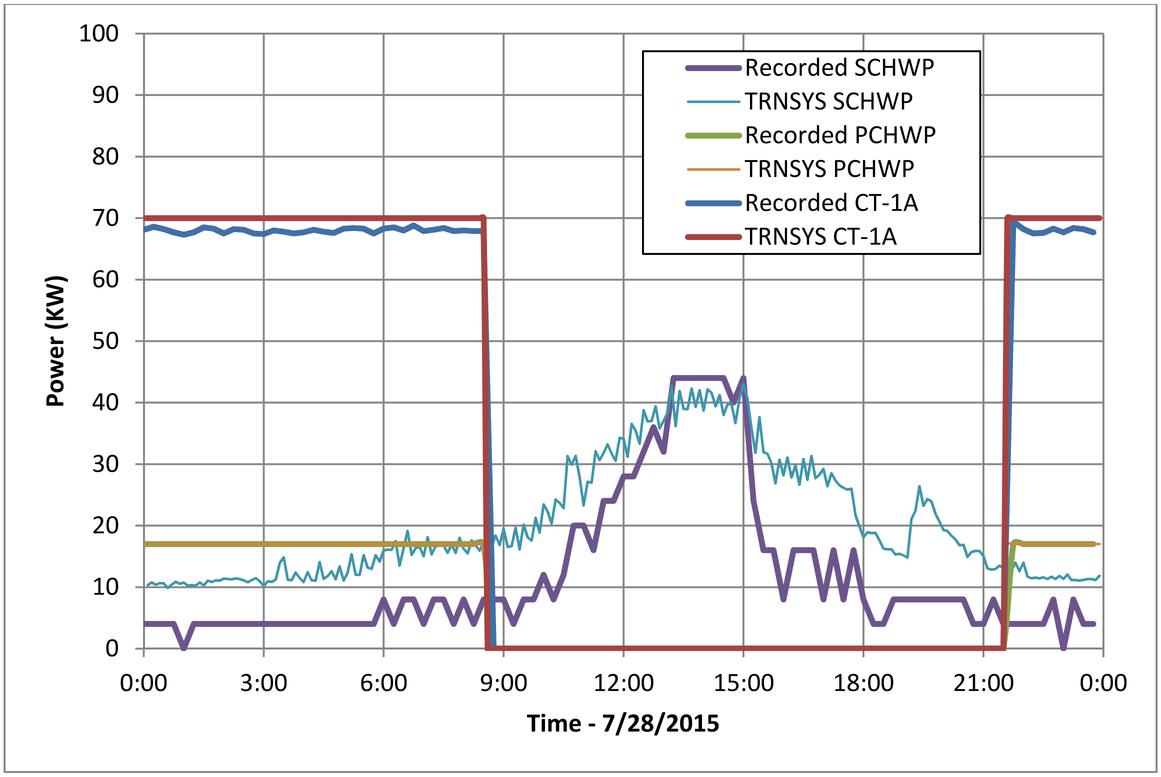


Figure 5.5 Comparison of Pump/Cooling Tower Power for Modelled and Trended Data – 7/28/15

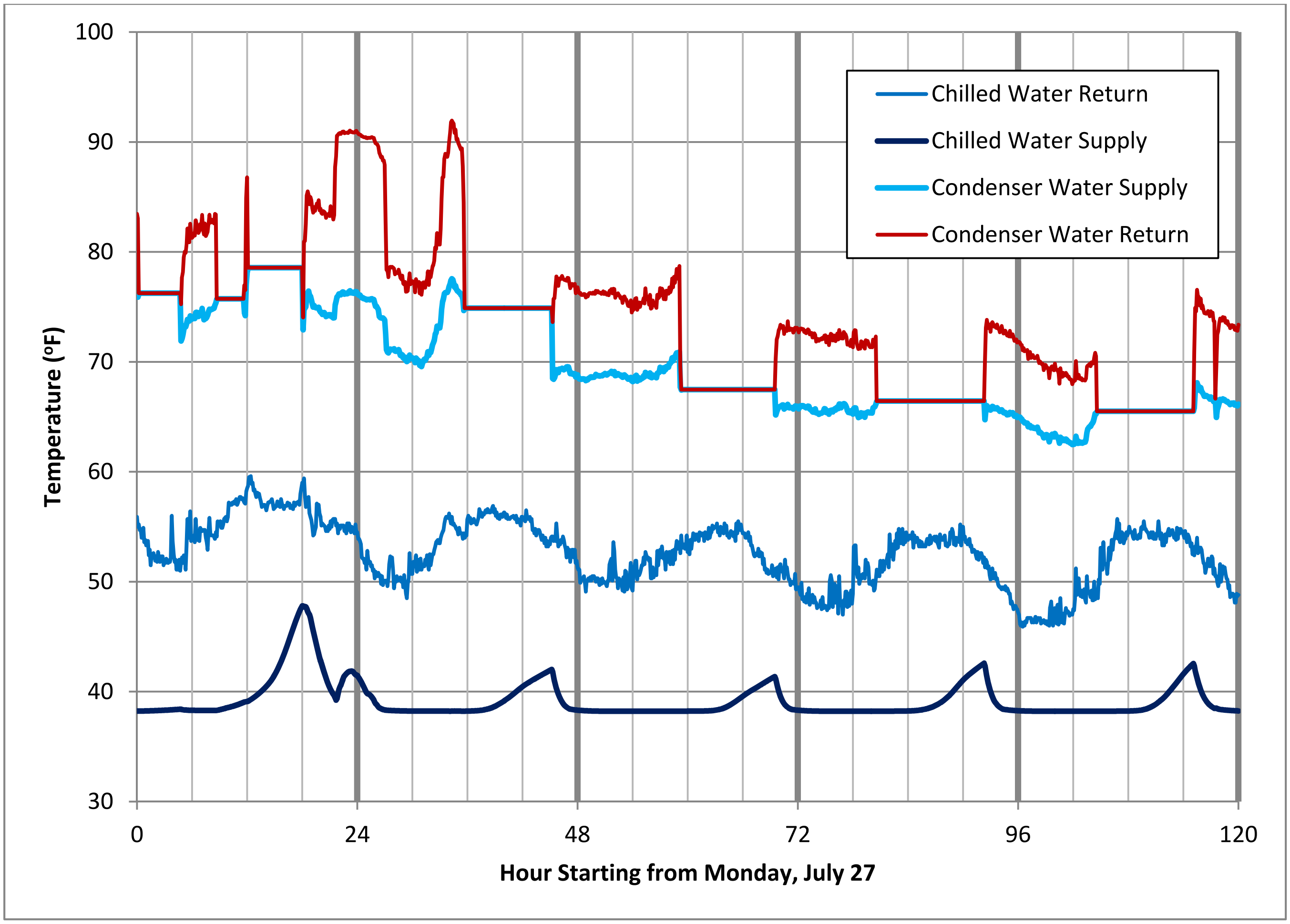


Figure 5.6 Chilled Water and Condenser Water Temperature Outputs in TRNSYS – 7/27 - 7/31/15

Figure 5.6 shows the range of supply and return temperatures over the one-week period for both the chilled water and the condenser water. The chilled water supply temperatures are the temperatures being supplied directly to the campus – either from the chiller(s), the TES tank, or a combination of the two. The peaks in the chilled water plot indicate a rising TES supply temperature from the bottom of the tank. The condenser water supply and return temperatures are more of a function of the ambient wet bulb temperatures. The flat horizontal lines in the condenser water plots are the periods when the chillers and associated equipment are not operating.

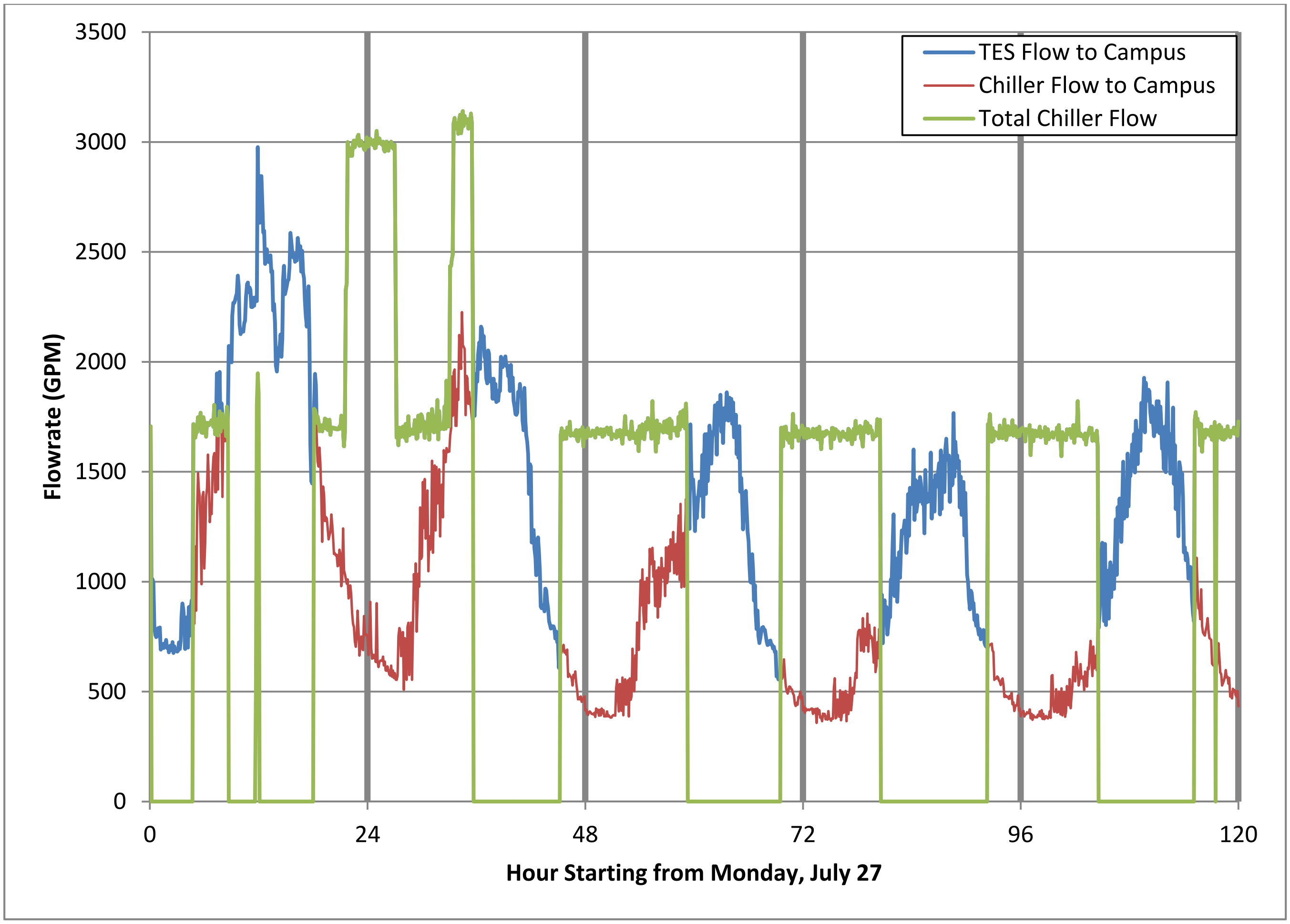


Figure 5.7 Chiller and TES Flow Outputs Modeled in TRNSYS - 7/27 - 7/31/15

In Figure 5.7, both the chiller flow rates and the TES flow rates are plotted. The flow plots are broken up based on whether the campus is being served by the chiller(s) or the TES tank. During chiller operation, the total chiller flow is plotted, along with the portion of the chiller flow to the campus. The difference between the total chiller flow and the flow to campus is equal to the amount of flow directed to charge the TES tank.

When the chiller(s) is/are not in operation, only the TES is serving the campus, as indicated by the plot. Following the two plots that represent the chiller and the TES flow to the campus, the general campus cooling load profile is evident by the lower flows in the overnight hours and the higher flows in the afternoon hours.

While the chillers are operating, the total flow is approximately 1,700 GPM when only the 1,350 ton chiller is running, while the flow jumps to about 3,000 GPM with the addition of another chiller pair.

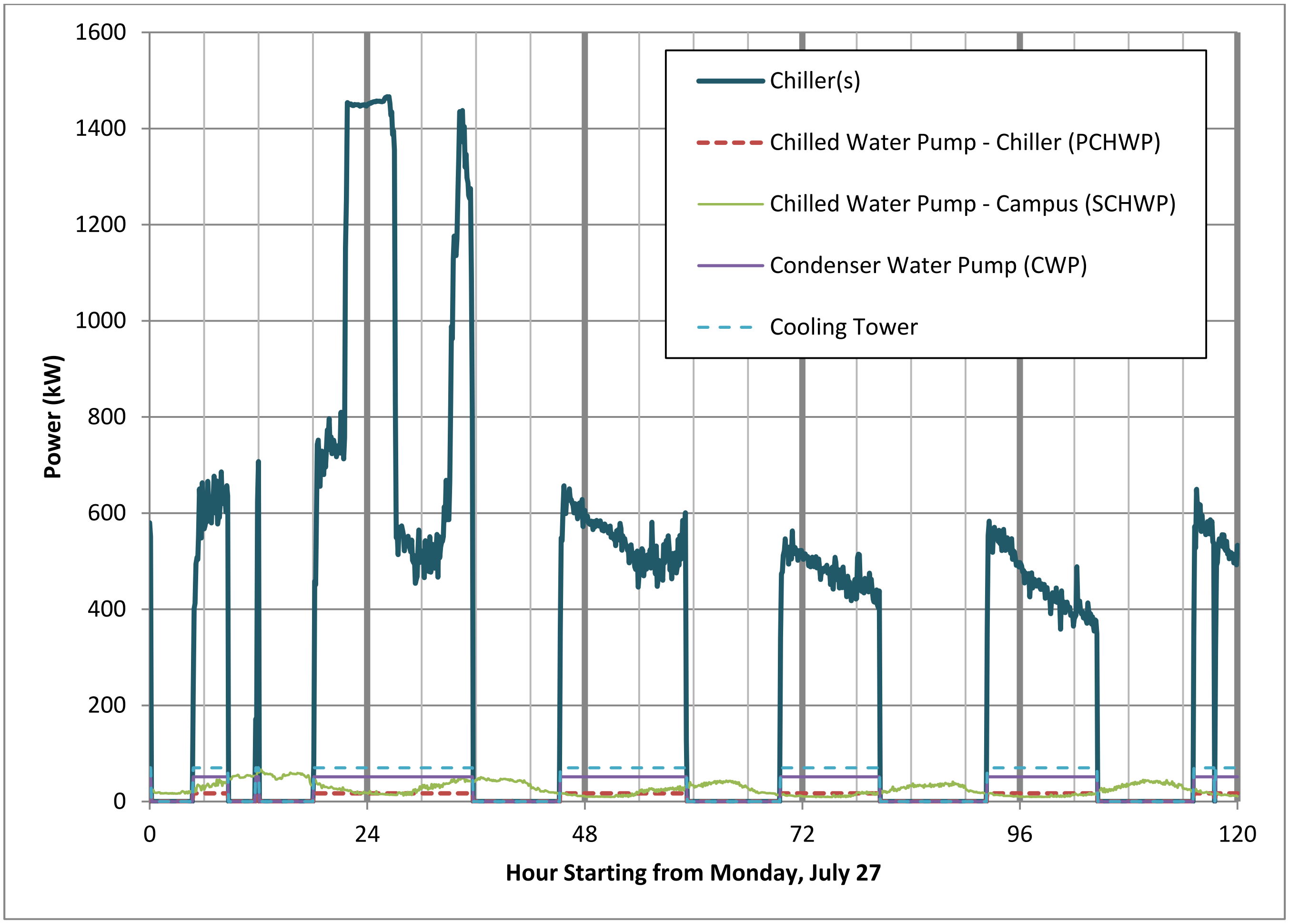


Figure 5.8 Equipment Power Usage Modeled in TRNSYS - 7/27 - 7/31/15

Figure 5.8 plots the chiller power over the week-long period, as well as the other components including pumps and cooling tower fans. The plot clearly illustrates the how significant the power usage is of the chiller(s) compared to the rest of the equipment.

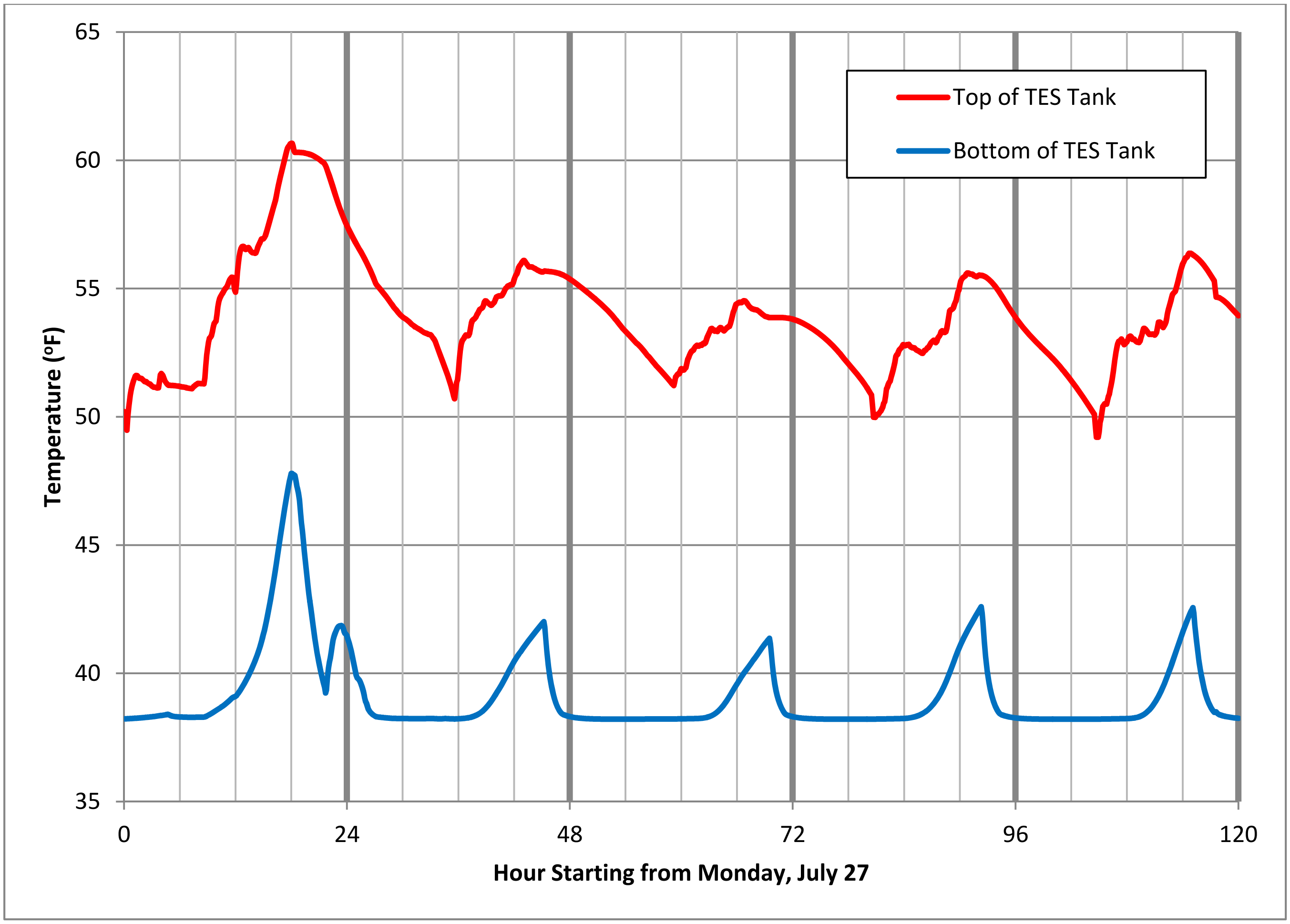


Figure 5.9 TES Tank Temperatures - 7/27 - 7/31/15

The temperatures at the bottom and the top of the TES tank over the modelled period are plotted in Figure 5.9. Note that the temperatures steadily rise in the afternoon as the TES tank depletes in capacity.

5.2 Model Calibration – 6/24/15 – 9/30/15

With the model accurately following the performance for an average week in July, it can next be calibrated to periods of lower and higher loads. Using Figure 5.2 again as a reference, it is clear that the week of June 24-30 encompasses relatively low loads (a low of about 5,200 Ton-hours on 6/27/15), while the week of September 19-25 has the highest loads (over 19,000 Ton-hours on 9/21/15). These weeks therefore effectively capture the full range of summer load data.

Using the same calibration process described in Section 5.1, the equipment parameters were adjusted slightly for these periods to fit the measured power data. Figures 5.10 and 5.11 show the calibrated simulation results for the 1,350 ton chiller.

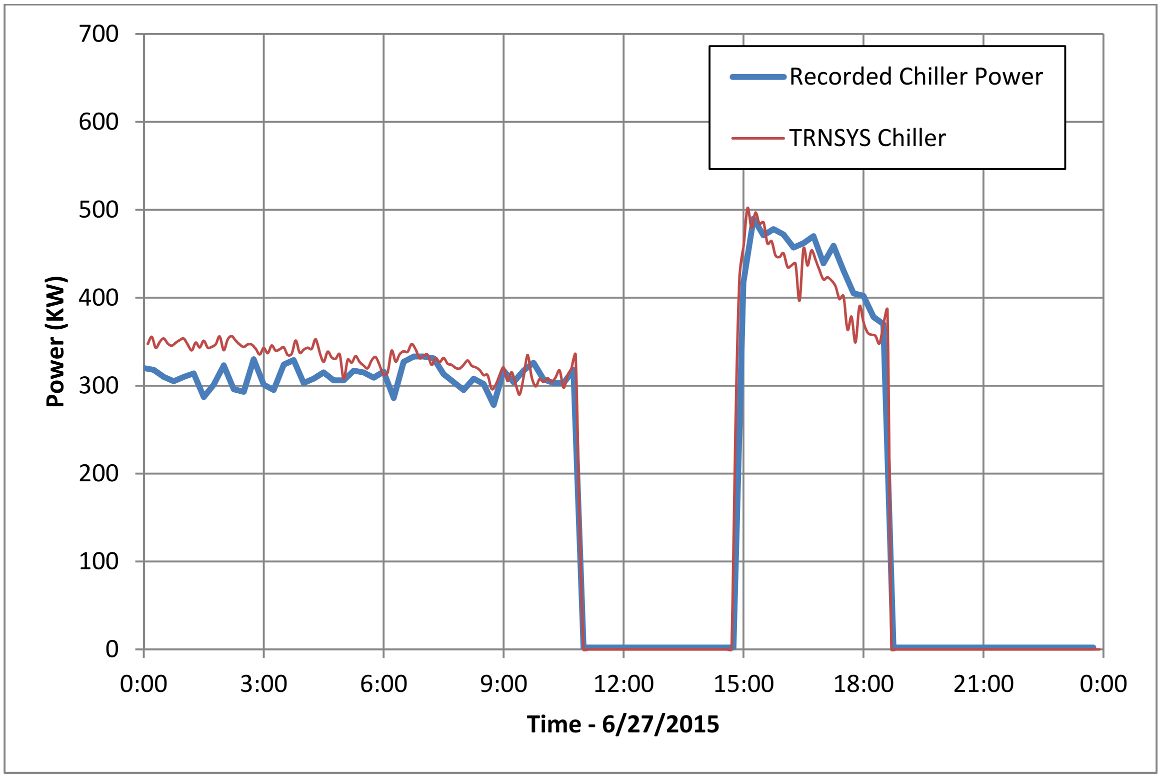


Figure 5.10 Comparison of Chiller Power Usage for Modelled and Trended Data - 6/27/15

The low campus cooling loads in late June were the result of particularly moderate summer weather and with the campus less populated than other quarters. June 27th – a Saturday – used a range of 300 to 500 KW from CH-1A.

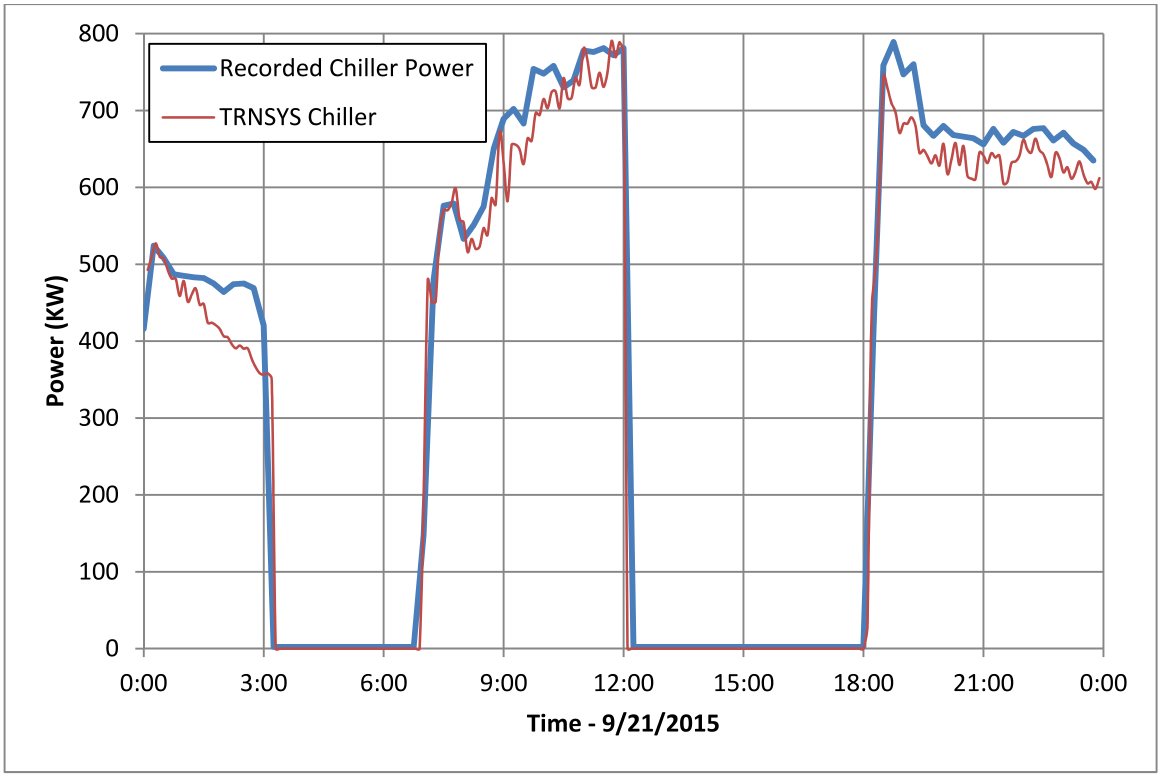


Figure 5.11 Comparison of Chiller Power Usage for Modeled and Trended Data - 9/21/15

The first week of Fall quarter is traditionally a period of very high loads, particularly because of it's the week with the most number of students on campus. During this week in September of 2015, the outdoor temperature also hit near-record highs, making for the loads to be even higher. On September 21st, 2015, which was a Monday, CH-1A used a range of about 450 KW to nearly 800 KW.

Although the campus is less populated during the summer quarter, the campus loads can still be quite high with the warm weather, as seen in Figure 5.2 for 7/20/15 (over 17,000 Ton-hours). On Monday, July 20th, 2015, CH-1A consumed up to its maximum of about 800 KW. Then, at the start of the off-peak periods at 21:30pm, another pair of chillers was taken on-line for added capacity to charge the TES tank. Combined, CH-1A and the other two chillers consumed about 1400 KW. The TRNSYS model, which has been shown to accurately match the performance of

CH-1A, also has to model the performance of CH-1A working in parallel with another chiller pair.

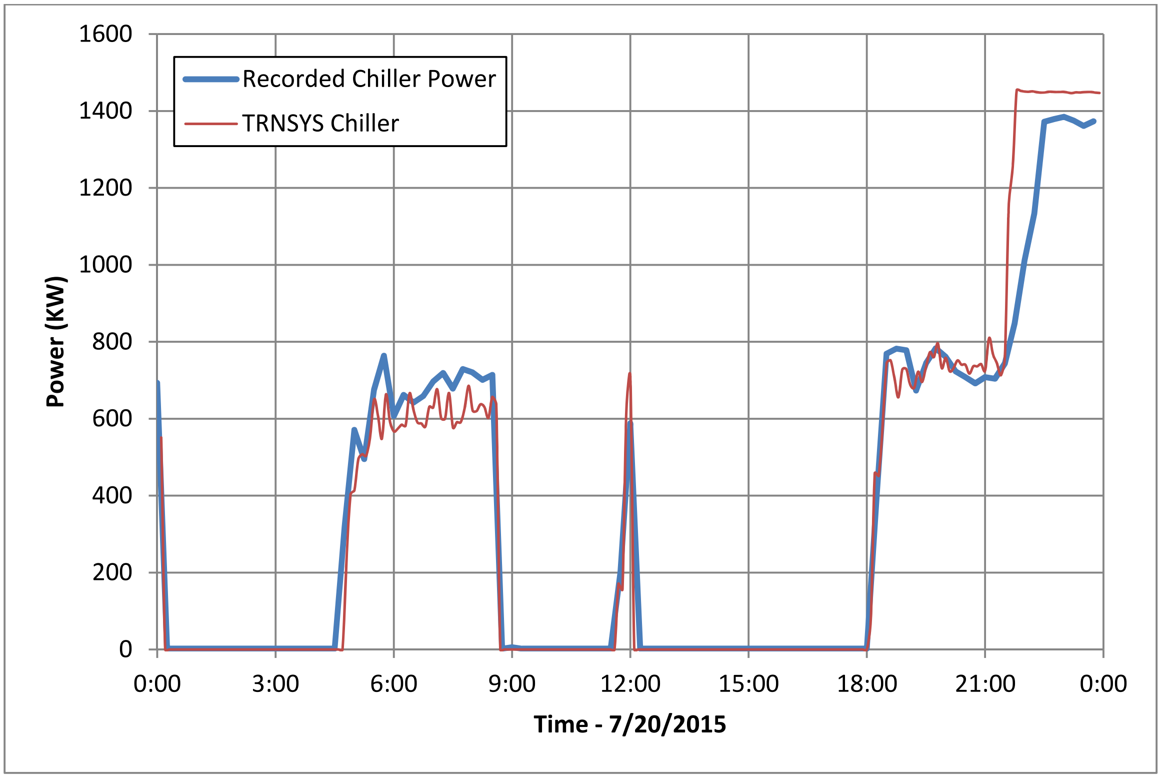


Figure 5.12 Comparison of Chiller Power Usage for Modeled and Trended Data - 7/20/15

As Figure 5.12 shows, the model outputs a slightly higher rate of power consumption at this point. This is due to lack of performance data on the older chillers, which meant that conservative assumptions had to be made for their COP and PLR data. Despite the fact that the modelled power usage for the other chiller pairs is slightly overstated compared to the measured data, the results still fit for the purposes of comparing different control strategies.

Since the model has now been shown to compare favorably to the trended data for the full range of summer campus loads, it can therefore be used as a baseline model for evaluating the effects of applying different control strategies. Plots of the trended chiller power data with the calibrated

TRNSYS power output from June 24th, 2015 to September 30th, 2015 can be found in Appendix E.

6. CONTROL STRATEGY OPTIMIZATION

The goal of the optimization for the chilled-water storage tank and chiller operation is to minimize utility costs of the chiller plant by a combination of chiller sequencing and shifting of chilled water production and storage periods. The end result should be minimized utility costs of the chiller plant over a set billing period by shifting the as much chilled water production to off-peak or part-peak periods as possible [Ref. 28]. Following Hydeman's methodologies, this involves the third step referenced in Section 4 of this report: running the model under different control strategies by varying the charging and discharging scenarios to seek a feasible optimal strategy [4].

Obtaining the optimal control and sequencing scheme of the equipment power in the chiller plant under varied conditions begins with determining the optimal operating parameters first. Parameters that affect the total power consumption of the plant include the supply chilled water temperature and flow rate, the condenser water and flow rate, and the cooling load.

James Braun's Methodologies for Optimal Control of Chilled Water Plants provides useful suggestions for optimization ([1], [2], and [3]). Using his general criteria and including the added variable of thermal energy storage, the process by which the optimization efforts were executed for this project consists of the following:

1) Review the baseline plant performance over the subject summer timeframe and identify trends where TES charging/discharging modes could have been improved to minimize chiller operation during Peak and Part-Peak periods

2) Review the campus cooling load profile from the trended data and determine the capability of the TES tank capacity to satisfy the demands during the Peak and Part-Peak periods
3) Using the baseline performance and the computed campus loads, propose a new control strategy for charging and discharging the TES tank during the different rate periods; specifically, the control strategy should be defined so that the chiller usage during Peak and Part-Peak periods should be minimized
4) Using the proposed new control strategy, establish a number of feasible operating scenarios with different control setpoints, and run the model in each of these to identify the optimal scenario with the minimum operating costs.

The area of optimization in the subsequent sections will focus on the summer period from June 24th, 2015 through September 30th, 2015, as this is the period for which the power data was trended. Optimization efforts will focus on periods of high loads, adjusting the control strategy to best minimize power consumption during peak/part-peak periods.

The optimization strategy here begins with evaluating the current control strategy, which includes reviewing the overall power consumption trends and the TES tank capacity profiles over time (Section 6.1). Next, the actual campus loads will be computed for the peak and part-peak periods throughout this summer period to assess the charge percentages the 19,000 ton-hour TES tank can potentially reach prior to the part-peak and peak periods; this will identify the minimum operational requirements of the chillers during the peak/part-peak periods and serve as a foundation for the new control strategy (Section 6.2). With the campus load profiles and current performance evaluated, a new control strategy can be proposed using setpoints observed to improve the charging/discharging sequence, and actual energy cost savings will be evaluated for this scenario (Section 6.3). The model can then be re-run under different scenarios, each with varying values for each setpoint, to determine the optimal control strategy setpoints (Section 6.4).

Since the week of September 21st has the highest load, these days (September 21st through the 24th) will be used to illustrate the optimization process throughout the report.

6.1 Evaluation of Current Control Strategy

As stated in Section 2.3.5, the current control strategy was designed to ensure that the chillers and TES tank meet their primary functions during the majority of load periods. Specifically, the sequence results in the chillers functioning primarily during the off-peak periods to both serve the campus loads and charge the TES tank, while the TES tank serves the campus primarily during the partial-peak and max-peak periods.

6.1.1 Review of Overall Chiller Power Consumption Trends

In reviewing the trend data from October 2014 to October 2015 (Appendix D), the current control strategy results in the desired off-peak charging and peak/part-peak discharging modes effectively during most periods of low to moderate cooling loads, as in Figure 5.2 for July 28th. However, during periods of especially high loads, the equipment does not necessarily perform at the optimal level. In particular, at times when the TES does not have sufficient capacity to satisfy the full campus loads, the chillers are designed to operate to add capacity. In reviewing instances where this occurs, there were a number of times where a better balance of TES tank and chiller operation could have been attained. In short, opportunities are available where operation of the chiller during part-peak and max-peak periods could be minimized under a modified control strategy. This is well-illustrated in plots of chiller power usage during the week of September

21st, as shown in Figures 6.1 through 6.5. Since this was the first week of the Fall 2015 quarter, the campus loads were particularly high (as discussed in Section 5), added to the fact that the temperatures were also exceptionally high.

To support the efforts to minimize the operation of the chillers during peak and part-peak periods, it is helpful to also plot the capacity of the TES tank during these periods to identify how the charging and discharging sequence can be improved. Calculation of the percentage charge of the TES requires that the model accurately represents the proper thermal stratification profile (see Section 4.1.4). Since the plant trend data does not include temperature readings throughout the height of the TES tank, initial conditions of the thermal stratification profile within the tank at time t=0 in the model are unknown. This issue can be mitigated by running the model for a 24 to 48 hour simulation time before the start of the day(s) of interest. For example, since weekdays are of primary interest for this study, a simulation of a one-week period should start with Saturday so that by Monday the thermal stratification profile has "caught up" to the correct initial conditions. This ensures more accurate modeling of the Monday through Friday periods, while weekends are inconsequential to the optimization efforts.

The computed charges of the TES are plotted along with the recorded chiller powers in Figures 6.1 through 6.5.

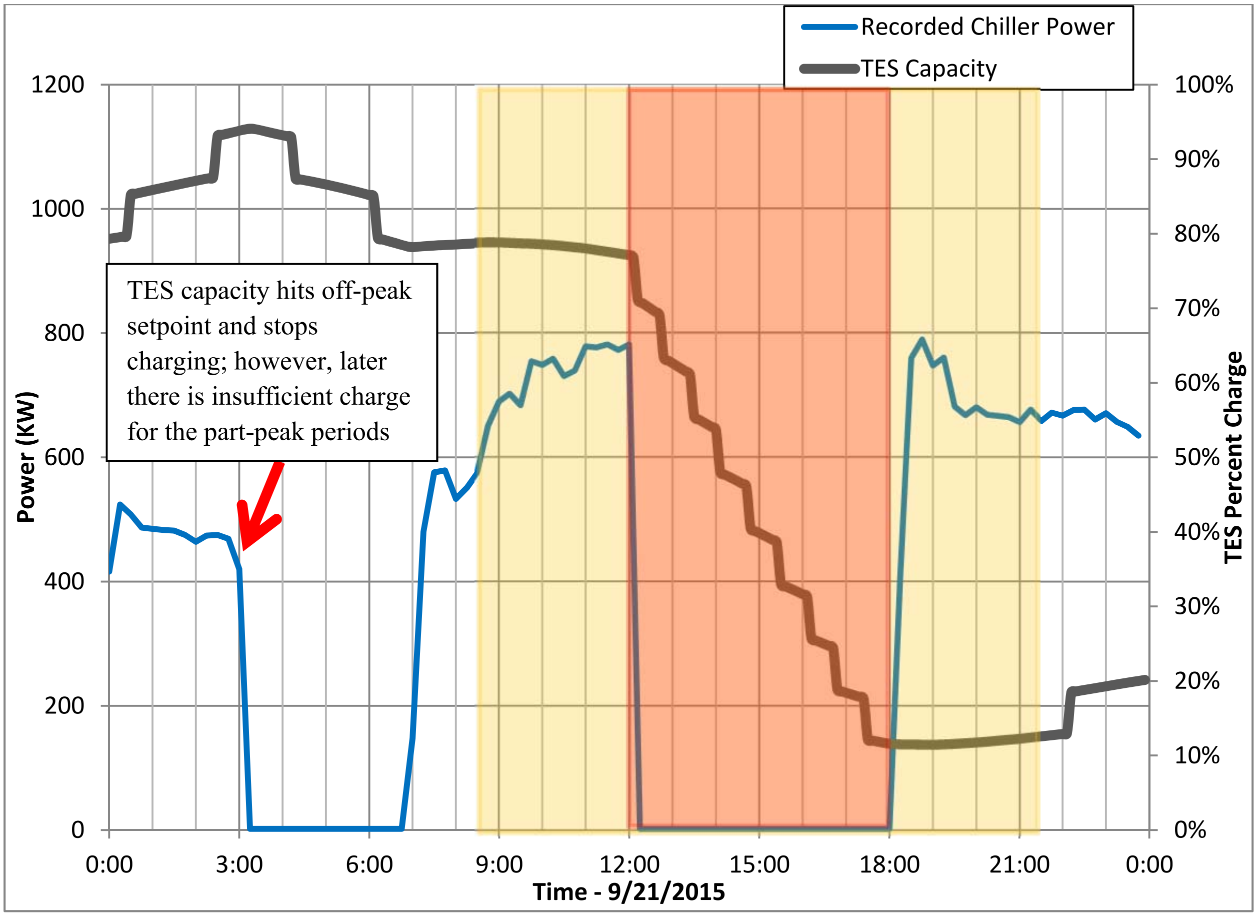


Figure 6.1 Chiller Performance for Monday, Sept 21st, 2015

As Figure 6.1 illustrates, the TES tank reached its Off-Peak setpoint around 3am Monday morning and switched to a discharge mode for about 4 hours before resuming charging. While the tank was almost fully charged by 3am, it had depleted to less than 80% by 7am. This resulted in the chiller running through the entire Part Peak 1 (8:30am-noon) period as the campus load increased. During the Peak period, there was sufficient charge in the TES tank to satisfy campus loads without the support of the chillers, but by the Part-Peak 2 period there was insufficient tank charge (less than 30%) to continue to satisfy campus loads. It can be concluded that an 80% tank charge at 8:30am was not enough to accommodate the Peak and Part-Peak periods.

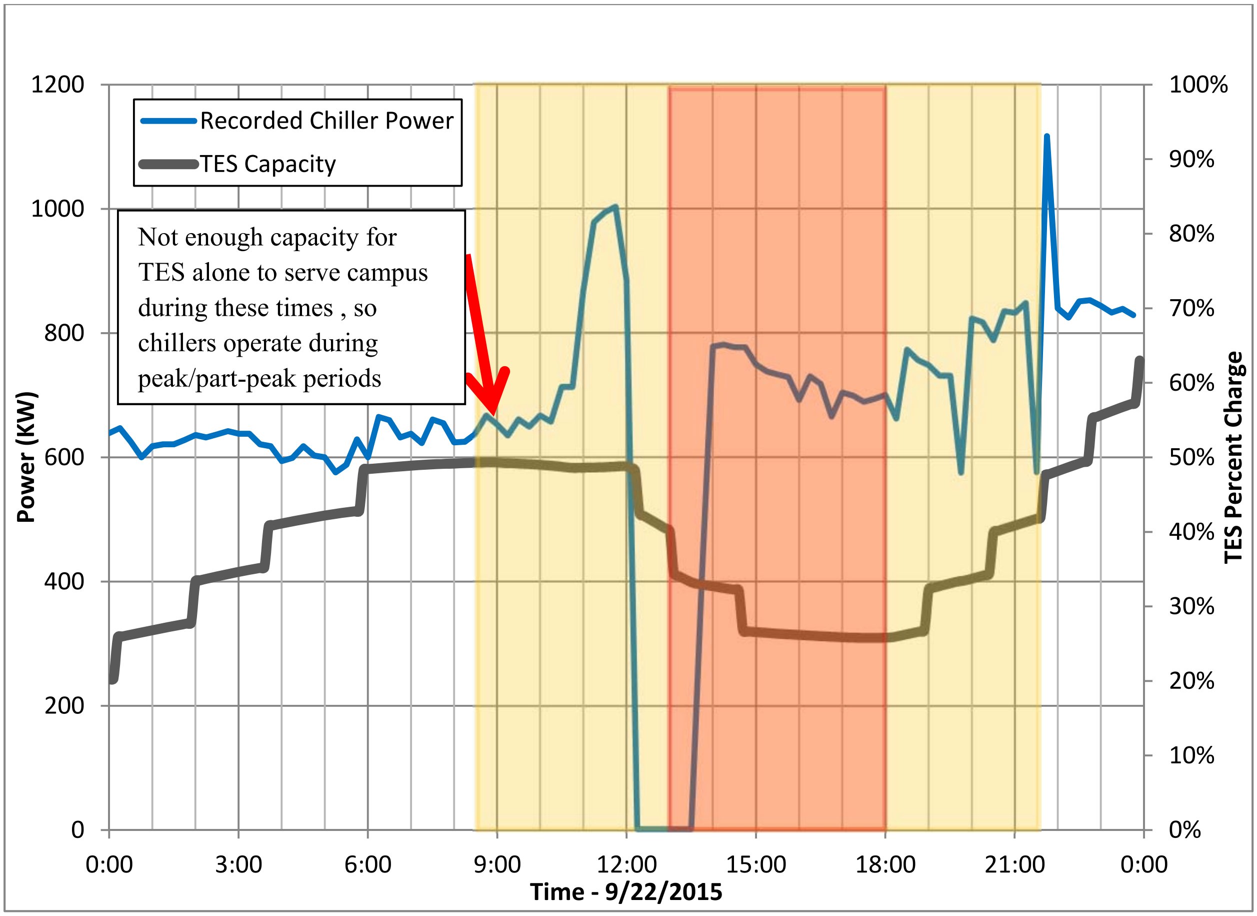


Figure 6.2 Chiller Performance for Tuesday, September 22nd, 2015

With Monday having exceptionally high campus loads, the setpoints during Tuesdays Part-Peak 1 period resulted in the chiller continuing to charge the tank all the way until the start of the Peak period. During the Peak period, however, there was insufficient charge after only an hour, and the tank was charged throughout the rest of the Peak and Part-Peak 2 periods.

The TES capacity plot showed that the tank had only enough charge to be able to serve the campus load for about 2 hours during the Peak period (from 12pm to 2pm). As the plot illustrates, despite non-stop charging overnight, the tank could not even reach a 50% charge by the start of the Part-Peak 1 period; put simply, it could not "catch up."

Alternatively, a more effective control strategy might have identified such a low charge and triggered another chiller pair to add charging capacity for the TES.

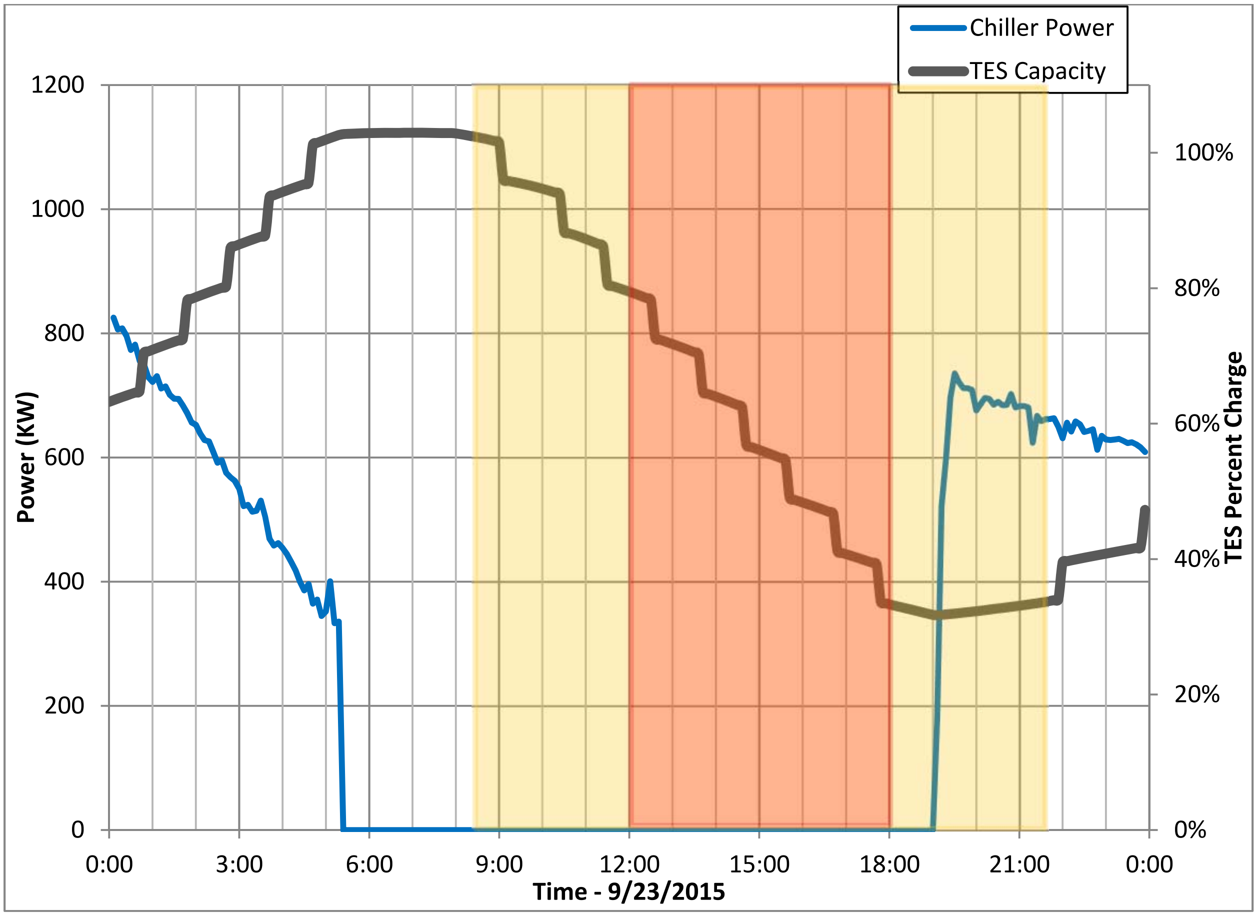


Figure 6.3 Chiller Performance for Wednesday, September 23rd, 2015

With the tank continually being charged since around 3pm Tuesday, it eventually reached its Off-Peak setpoint around 5am Wednesday, and the discharge mode began. The tank continued to discharge until it ran out of capacity during the Part-Peak 2 period (meaning less than 30% charge), at which point charging resumed.

The TES capacity plot aligns with the power plot at the point where the Off-Peak charging setpoint was reached, around 5am. Here the charge exceeds 100% (due to a chilled water temperature of 38^{o}F, rather than the design temperature of 40^{o}F). Despite the high loads of the day, there was sufficient charge to avoid chiller operation in the Part-Peak 1 and Peak periods. However, during Part-Peak 2, the tank capacity depleted to 30%, at which point it resumed charging.

Since the tank outlet temperature was still acceptable to serve the campus (approximately 41^{o}F), this suggests that a 30% Part-Peak 2 setpoint may be higher than necessary; also, once the chiller started running during the Part-Peak 2 period, it would have been more effective to run it at a lower part-load condition and wait to charge the tank until off-peak.

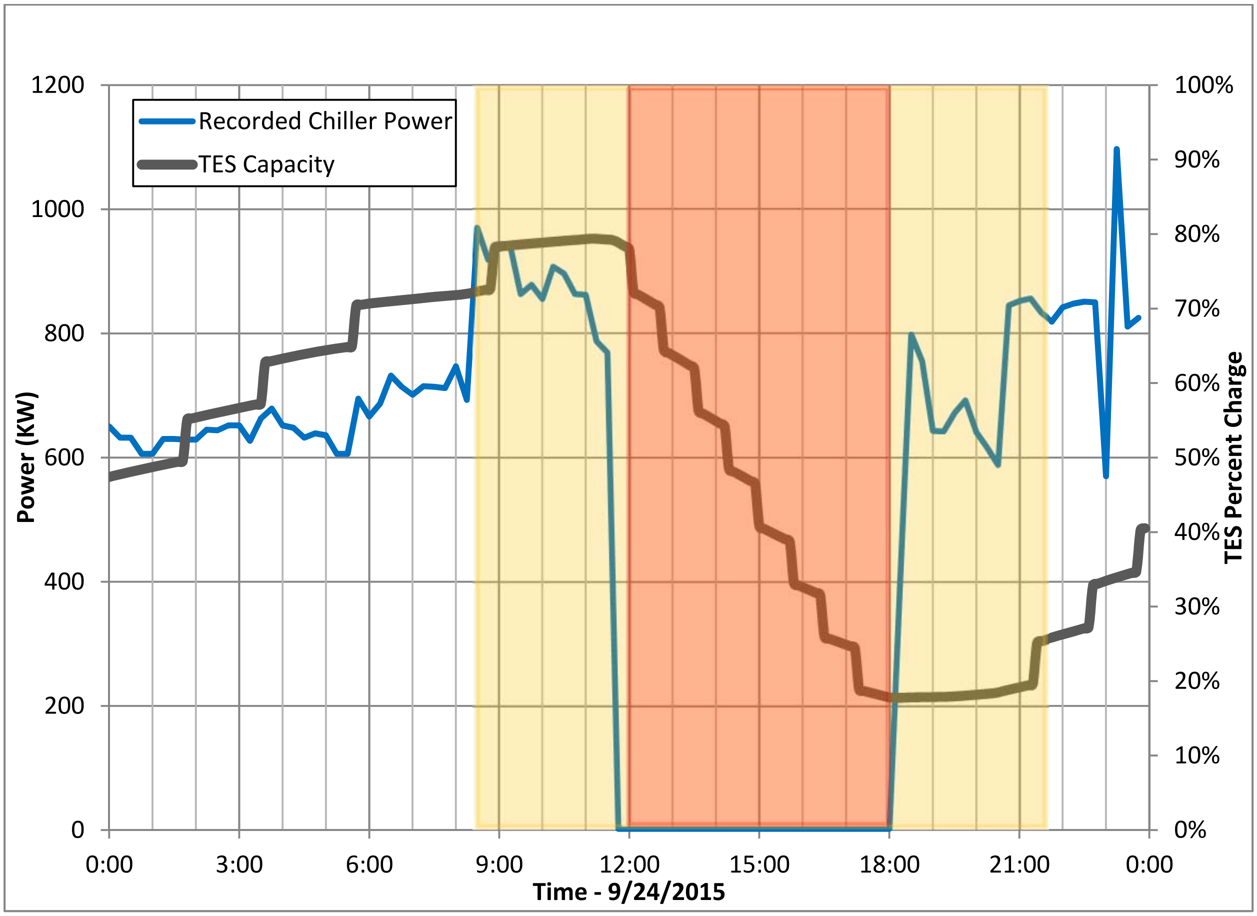


Figure 6.4 Chiller Performance for Thursday, September 24th, 2015

On Thursday, as has been the trend through much of the week, the TES tank did not reach its discharge setpoint during the Part-Peak 1 period. While it managed to discharge through the duration of the Peak Period, it depleted to less than 30% by the start of the Part-Peak 2 period, and charging resumed.

Once again, the TES plot is shown to have insufficient capacity to meet the campus loads during the Part-Peak periods. Additional charging capacity from another chiller pair could have helped bring the tank to a suitable charge prior to 8:30am. It is worth noting that the charge was below 50% at midnight, and below 70% at 4am.

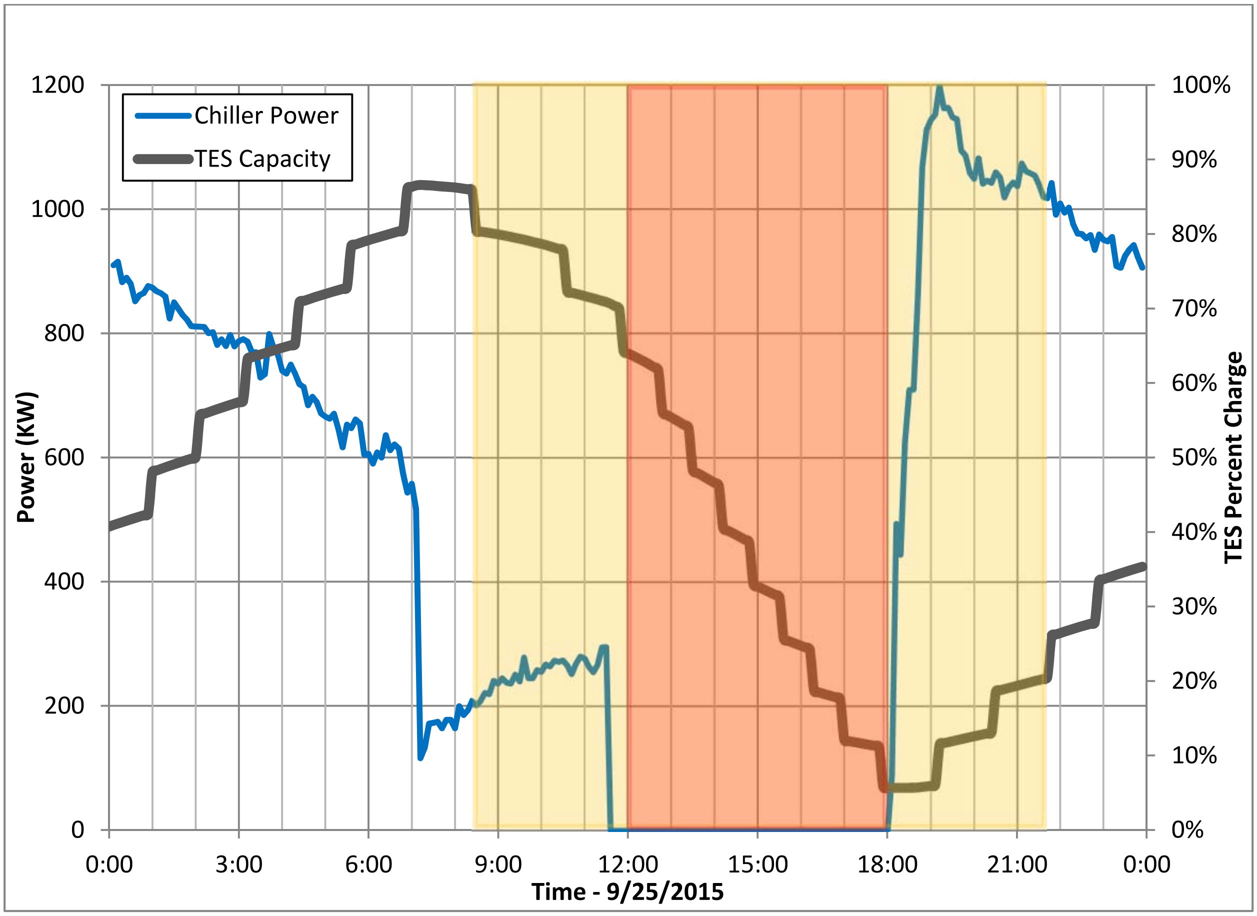


Figure 6.5 Chiller Performance for Friday, September 25th, 2015

Friday's performance followed a similar pattern as Thursday’s, except that in the Part-Peak 2 period, the charge was so low that a second pair of chillers were operated to add capacity to CH-1A (note the 1, 200 KW of power used).

While the week of September 21st represents the peak load week, other weeks during the summer have similar areas for improvement in the charge/discharge periods. Since the week of July 20th – July 24th was another period of high campus cooling loads, performance plots for this week using the same optimization methodologies can be in Appendix E.

The TES capacity plot indicates that for this high-load day, even an 85% charge at the start of Part-Peak 1 was not enough to serve the campus until the next Off-Peak period. Another item to note is the rate at which the tank can be charged when CH-1A and another chiller pair are operating, which occurs after 9:30pm: approximately 10% per hour.

Given the above plots – as well as review of plant performance plots from June through September found in Appendix E – a few conclusions can be drawn:

- Based upon the rate of decline in capacity during the peak/part-peak periods, it is clear that the TES tank should have as high a charge as possible prior to the part-peak period at 8:30am. Figure 6.10 suggests that greater than 85% would be needed.
- Although the current Part-Peak 2 period strategy is for the chillers to charge the TES tank when it reaches 30%, operating experience shows that the tank can adequately serve the campus at lower charges, as it does during Peak periods. For this reason, a setpoint of 30% may be overly conservative and can result in unnecessary initiation of the chiller(s) during the Part-Peak 2 period, as seen in Figure 6.8.
- During Part-Peak 2, when the TES tank reaches its charge setpoint, it may be more economical to instead cease discharging the tank but wait until the Off-Peak period to resume charging it.

- Figures 6.7 and 6.9 show instances when even with continuous charging of the TES tank by CH-1A during off-peak hours, the capacity it reaches at the start of Part-Peak 1 was still insufficient to meet the campus loads during the Part-Peak periods. Additional charging capacity from another pair of chillers could have helped bring the tank to a suitable charge by 8:30. Specifically, a charge below 50% at midnight and below 70% at 4am could warrant adding more charging capacity.
- During the early morning (midnight to 8:30am) hours, it takes an average of about 90 minutes to charge the TES tank 10% with just CH-1A operating; with both CH-1A and another chiller pair operating concurrently, the TES tank can charge about 10% in about one hour .

6.2 Assessment of Actual Campus Loads

Since actual campus data is available from June through September (see Appendices D and E), the actual loads in ton-hours can be computed (see Section 4.2) for each Peak and Part-Peak Period as described in Section 4.2. Since the purpose of thermal storage systems is to meet the loads during these periods, these loads can be directly compared to the actual TES tank capacity – 19,000 ton-hr. Identifying how much of this capacity is consumed during the Part-Peak 1 period, the Peak Period, and the Part-Peak 2 period can serve as a foundation for a new control strategy. Because some days might have loads greater than the total capacity of the tank, the tank may need to be charged more during the Part-Peak 1 period. In these cases, it is beneficial to evaluate how much capacity is consumed during just the Peak and Part-Peak 2 periods.

Using the methodology to compute the loads in ton-hrs described in Section 4.2, Table 6.1 summarizes the rate period breakdown of these loads using the available data from 6/24/15 to

9/30/15 (note that data was unavailable for some days at the start of each month). The "Total" column mirrors the Campus Cooling Load plot in Figure 5.2

Table 6.1 Evaluation of Load Demands

	Part-Peak 1	Peak	Part-Peak 2	Peak + Part-Peak 2	Total
Date	ton-hr	ton-hr	ton-hr	ton-hr	ton-hr
6/24/2015	1311	3937	1145	5082	6393
6/25/2015	1723	4875	1514	6389	8112
6/26/2015	1465	4011	1059	5070	6535
6/27/2015	1147	2961	1108	4069	5216
6/28/2015	1308	2896	1244	4140	5447
6/29/2015	1783	5323	1904	7227	9010
6/30/2015	2405	5852	2078	7929	10335
7/3/2015	1824	5142	1626	6768	8591
7/4/2015	1260	3161	1142	4303	5563
7/5/2015	1066	3319	1080	4400	5465
7/6/2015	1918	4562	1710	6272	8190
7/7/2015	1917	4986	1921	6906	8823
7/8/2015	1378	4100	1353	5453	6831
7/9/2015	1576	4550	1476	6026	7602
7/10/2015	1789	4664	1689	6353	8141
7/11/2015	1582	3250	1457	4707	6290
7/12/2015	1619	3448	1495	4943	6562
7/13/2015	2222	5550	1806	7356	9578
7/14/2015	2070	4701	1535	6236	8305
7/15/2015	1294	4701	1559	6260	7554
7/16/2015	1701	4444	1417	5861	7562
7/17/2015	2231	5092	1519	6611	8843
7/18/2015	1137	3632	1396	5029	6165
7/19/2015	1645	3975	2906	6881	8526
7/20/2015	5195	9187	3040	12226	17422
7/21/2015	3889	7317	1954	9270	13159
7/22/2015	2449	5722	1597	7319	9767
7/23/2015	2219	5117	1536	6653	8873
7/24/2015	2430	6051	1751	7802	10233
7/25/2015	1825	3789	1226	5015	6840
7/26/2015	982	2585	1135	3720	4702
7/27/2015	1643	5202	1346	6548	8191
7/28/2015	1859	5369	1317	6686	8545
7/29/2015	1999	5063	1676	6739	8738
7/30/2015	2322	4843	1492	6335	8657
7/31/2015	3214	6437	1841	8278	11492
8/3/2015	2315	4705	1548	6253	8568
8/4/2015	1738	4544	1733	6277	8015
8/5/2015	2139	4729	1487	6216	8355

Table 6.1 (Continued)

	Part-Peak 1	Peak	Part-Peak 2	Peak + Part-Peak 2	Total
Date	ton-hr	ton-hr	ton-hr	ton-hr	ton-hr
8/6/2015	1849	5033	1503	6536	8385
8/7/2015	1445	4669	1819	6488	7933
8/8/2015	1423	3742	1450	5191	6614
8/9/2015	1311	3539	1696	5235	6546
8/10/2015	1995	5001	1419	6420	8415
8/11/2015	1627	4592	1488	6080	7708
8/12/2015	1790	4915	1853	6768	8557
8/13/2015	2142	5817	1974	7791	9933
8/14/2015	2609	5683	1996	7679	10289
8/15/2015	2138	5853	2405	8259	10397
8/16/2015	2146	5857	1947	7805	9950
8/17/2015	2748	6008	2145	8152	10900
8/18/2015	2068	5499	1603	7102	9170
8/19/2015	2307	5399	1893	7292	9599
8/20/2015	2400	5132	1861	6993	9394
8/21/2015	1686	5025	1777	6802	8487
8/22/2015	1043	3919	1321	5240	6283
8/23/2015	1148	3711	1527	5238	6386
8/24/2015	2122	5345	1650	6995	9116
8/25/2015	2470	6442	2022	8464	10933
8/26/2015	2772	5972	2277	8248	11021
8/27/2015	3930	7620	2936	10556	14486
8/28/2015	3991	8293	2739	11033	15024
8/29/2015	2376	4796	1898	6694	9070
8/30/2015	1513	3512	1234	4746	6259
8/31/2015	2654	5156	1332	6488	9142
9/2/2015	1765	5004	1525	6529	8294
9/3/2015	1861	4480	1153	5633	7494
9/4/2015	1267	3892	1050	4942	6209
9/5/2015	919	3188	1165	4353	5272
9/6/2015	1978	4377	1525	5902	7880
9/7/2015	2650	7018	2098	9116	11766
9/8/2015	3100	8195	2676	10871	13971
9/9/2015	3805	8853	2793	11646	15451
9/10/2015	4198	9207	3352	12559	16757
9/11/2015	4032	7994	2517	10511	14542
9/12/2015	3270	6998	2291	9289	12559
9/13/2015	2243	6108	2137	8244	10487
9/14/2015	3451	6435	2127	8563	12013
9/15/2015	2662	4112	1211	5322	7984
9/16/2015	1654	4903	1530	6433	8087
9/17/2015	2273	5707	1836	7543	9816
9/18/2015	3014	6803	2122	8924	11939

Table 6.1 (Continued)

	Part-Peak 1	Peak	Part-Peak 2	Peak + Part-Peak 2	Total
Date	ton-hr	ton-hr	ton-hr	ton-hr	ton-hr
9/19/2015	3146	6902	2734	9637	12783
9/20/2015	3263	6703	2640	9343	12607
9/21/2015	5261	10171	3633	13804	19065
9/22/2015	4792	9142	2428	11570	16361
9/23/2015	2808	7209	2941	10150	12958
9/24/2015	4653	9166	3389	12554	17207
9/25/2015	3826	9319	3405	12724	16550
9/26/2015	3293	7018	2642	9660	12953
9/27/2015	2111	5743	2079	7822	9933
9/28/2015	2256	6174	2262	8436	10692
9/29/2015	2323	6676	2548	9224	11547
9/30/2015	2359	6959	2474	9433	11792

Table 6.2 summarizes the range of loads experienced during this data trending period. Put in terms of TES tank percent charge (dividing each ton-hr value by 19,000 ton-hrs, the capacity of the tank), Table 6.3 shows the range of percentage charged.

Table 6.2 Range of Campus Load Demands

Load Range	Part-Peak 1	Peak	Part-Peak 2	Peak + Part-Peak 2	Total
	ton-hr	ton-hr	ton-hr	ton-hr	ton-hr
min	919	2585	1050	3720	4702
avg	2293	5476	1871	7347	9640
max	5261	10171	3633	13804	19065

Table 6.3 Range of Campus Load Demands in Terms of TES Percent Charge

Load Range	Part-Peak 1	Peak	Part-Peak 2	Peak + Part-Peak 2	Total
	ton-hr	ton-hr	ton-hr	ton-hr	ton-hr
min	4.8%	13.6%	5.5%	19.6%	24.7%
avg	12.1%	28.8%	9.8%	38.7%	50.7%
max	27.7%	53.5%	19.1%	72.7%	100.3%

Note that the maximum percent charge in Table 6.3 is slightly above 100%. This indicates that there will be times that the chiller(s) will need to run to add capacity during the Peak/Part-Peak periods. Also, since the thermal energy storage system is not 100% efficient, some of the charge will inevitably be lost during discharge (i.e., pipe friction losses, heat transfer through the piping and components, etc.). Therefore, even a 19,000 ton-hr total charge – 100% of the TES tank – will require use of the chillers for added chilled water capacity. Nevertheless, the TES charge requirements in Tables 6.2 and 6.3 serve as a starting point for determining a more optimal control strategy.

6.3 Development of Proposed New Control Strategy

With the campus load profiles and current performance evaluated, a new control strategy can be proposed using setpoints observed to improve the charging/discharging sequence.

As evidenced by the available capacity of the TES tank and the range of load demands from the campus, one aspect of the control strategy that can be improved is to ensure the tank is charged to specific percentages prior to the different rate periods. The data in Table 6.2 suggests – as a starting point – that the TES tank should be charged to 100% (19,000 ton-hr) by 8:30am to meet the peak and part-peak loads for the peak design day of 9/21/15 (19,065 ton-hr).

Another observation that warrants further consideration is that to minimize operation of the chillers during Part-Peak periods, the TES discharge settings should be designed to deplete the tank as fully as possible by the end of the second part-peak period (from 6:00pm to 9:30pm). Currently the setpoint is to charge the TES tank during that period when the charge percentage is at or below 30%. Also, since the Off-Peak period is approaching next, there is little benefit in the chiller(s) both serving the campus loads and charging the TES during that period when the setpoint is reached; instead, it would be more economical for the chillers to wait to charge the TES tank until the Off-Peak period begins.

A limiting factor in achieving a desired charge percentage prior to a rate period change is in how fast the chiller(s) can charge the TES. As stated in Section 6.1, CH-1A can charge the TES 10% in approximately 90 minutes, while CH-1A operating with another pair of chillers can charge the TES 10% in about one hour. Since one goal is to almost fully deplete the tank by the end of the second part-peak period, it will be important to establish how fast the chiller(s) can recover the charge during the 11 hour Off-Peak period up to the first Part-Peak period (9:30pm to 8:30am). Specifically, the control strategy must take into account how depleted the tank is and how fast it would take to bring the charge up to an appropriate level utilizing either CH-1A or a combination of CH-1A and another pair of chillers. This is a dynamic problem because the chiller will also be serving a reduced but variable campus load during these off-peak periods. Consequently, the charge rate (i.e., 10% per 90 minutes) at one point in time during the off-peak period could be much higher or lower at another point in time due to the campus load.

Therefore, some way of implementing a time component into the control strategy must be considered. For example, a statement such as "if the TES charge is less than 60% within 2 hours of the first part-peak period (8:30am), charge the tank with both CH-1A and a second pair of chillers" must be translated to a workable control sequence. Baseline setpoints – as in specific charge percentages the TES should reach at different intervals of time within the off-peak period – must also be established.

Based on the way the current facility control system works, the most effective way of implementing this facet of a new control strategy is to divide the off-peak period up into distinct periods. For the sake of feasibility, the new control strategy will distinguish the off-peak period between weekday off-peak and weekend off-peak. Also, the 11-hour weekday off-peak period will be divided into three periods: 9:30pm to midnight, midnight to 4:00am, and 4:00am to 8:30am. Each period will have its own separate setpoints. The peak and part-peak periods will follow the same time intervals.

The following notation will be used for these rate periods:

Table 6.4 Definition of Setpoint Periods

Name	Time Period
Weekend Off-Peak	Weekends
Off-Peak 1	Weekdays 12:00am – 4:00am
Off-Peak 2	Weekdays 4:00am – 8:30am
Part-Peak 1	Weekdays 8:30am – 12:00pm
Peak	Weekdays 12:00pm – 18:00pm
Part-Peak 2	Weekdays 18:00pm – 21:30pm
Off-Peak 3	Weekdays 21:30pm – 12:00am

Next a sequence of setpoints for each period must be established. Since the starting point is to reach a 100% TES charge by 8:30am, we will start development of the setpoints with Off-Peak 2.

6.3.1 Off-Peak 2: Weekdays from 4:00am to 8:30am

Since the goal for this rate period is to reach a TES charge of 100% by 8:30am, this period provides a maximum of 4-1/2 hours to reach that charge.

During the early morning hours, the campus load is at a minimum and the charge rate can more reliably reach the previously-noted rates of 10% per hour for concurrent operation of CH-1A and another chiller pair, and 10% per 90 minutes for CH-1A.

For just CH-1A to run the full 4-1/2 hours, the average amount of charge it could provide at 10% per 90 minutes would be 30%. This implies that both CH-1A and a second chiller pair would be needed to provide greater than 30% charge to the TES from the start of this time period to the start of the part-peak period. Accordingly, the first setpoint can be summarized as follows:

- CHARGE TES with both CH-1A and CH-1/2 or CH-3/4 if available percentage is less than 70%

Since the desired charge at 8:30am is 100%, the second setpoint should be 100% or only slightly less; 95% can be used as an initial value (which will be addressed during optimization):

- CHARGE TES with CH-1A if available percentage is less than 95%

Since the desired charge at 8:30am is 100%, no discharge will be allowed during this time. Should the tank reach 100%, the chiller CH-1A will operate in "Mode 1," serving only the campus load.

What this control strategy does is ensures that the TES has sufficient charge by the end of the off-peak period to enable the chillers to charge it up to 100%.

6.3.2 Off-Peak 1: Weekdays from 12:00am to 4:00am

As previously determined, CH-1A alone can provide about 30% charge in the 4-1/2 hours following the end of this off-peak interval period. This establishes a minimum desired charge of 70% by the end of this period. Therefore, the first setpoint is as follows:

- CHARGE TES with CH-1A if available % is less than 70%

At the start of this rate period, there are four hours available to reach the 70% desired end-of-period charge. With CH-1A alone, that means that it can charge approximately 27% (at the established rate of 10% per 90 minutes, for four hours) during this period. Therefore, any charge less than about 43% would need both CH-1A and another chiller pair to be able to meet the 70% charge by 4:00am. This yields the next setpoint:

- CHARGE TES with CH-1A and a second chiller pair if available % is less than 45%

Finally, a discharge setpoint should be selected, since as long as the charge is at 70% by 4:00am there is sufficient time to bring the tank up to 100% at the end of the off-peak period. A deadband in the range of 10-20% brings this setpoint to:

- DISCHARGE TES if available % is more than 80%

6.3.3 Off-Peak 3: Weekdays from 9:30pm to 12:00am

It was established in the previous section that CH-1A can charge the TES tank to 100% in 8-1/2 hours if it has a charge of about 43% or more. Very conservatively rounding up:

- CHARGE TES with CH-1A if available % is less than 50%

Next, the setpoint for using CH-1A and another chiller pair must be determined. Given that this period has 3-1/2 hours to reach a charge of 43%, CH-1A alone can provide about 23% of charge (at the aforementioned rate of 10% per 90 minutes). Therefore, a charge at 9:30pm of 20% or less would require an additional chiller pair to CH-1A. Adding conservatism:

- CHARGE TES with CH-1A and another chiller pair if available % is less than 30%

Finally, the discharge setting will include the same 10-20% deadband as the previous section:

- DISCHARGE TES if available % is more than 65%

6.3.4 Part-Peak 2: Weekdays from 6:00pm to 9:30pm

As previously mentioned, the current setpoint of charging the TES tank at 30% has been observed to run the chillers much more than desired during the part-peak rate period, since the goal is to try and deplete the tank as much as possible prior to the off-peak hours. Therefore, this setpoint will be lowered:

- Discharge TES if available % is more than 15%
- Run chillers in "Mode 1" (do not charge TES) if available % is less than 15%

Since the off-peak period is the next rate period, there is no benefit to charging the TES tank during the part-peak period once it is depleted; the chiller(s) can charge the TES starting at 9:30pm once the energy rates are at their lowest.

6.3.5 Peak: Weekdays from 12:00pm to 6:00pm

The peak period – when the energy and demand rates are at the highest, should be controlled to eliminate any use of the chillers except in cases where the TES absolutely cannot meet the campus demand. The first existing setpoint will continue to be utilized:

- Deplete tank if available % is greater than 0%

The second setpoint allows for the chillers to start if the temperature at the bottom of the tank (2ft level) exceeds 42^{o}F. Reviewing the plant performance found that this setpoint initiated the chillers during a few periods of exceptionally high loads – for instance, September 22nd (Figure 6.2). For the chiller alone – which operated at approximately 780 KW – this equates to a possible contribution to the monthly peak demand charge in excess of $12,000. Clearly the avoidance of greater than a 42^{o}F chilled water temperature does not warrant such a high demand cost.

Therefore, the recommendation is to increase that 42^{o}F setpoint to a value the plant can approach without compromising the cooling of vital areas (such as server rooms). Running the simulation at different temperatures and at the new control strategy found that a temperature of 43^{o}F avoided initiation of the chillers during the peak period throughout the weeks simulated:

- Start chillers in "Mode 1" (no charging of TES) if the 2ft tank sensor is greater than 43^{o}F

6.3.6 Part-Peak 1: Weekdays from 8:30am to 12:00pm

The last period for which to establish an appropriate control strategy is the first part-peak period. The challenge with this period is in determining what minimum percentage charge the TES tank should have by the end of the rate period, and whether to charge it during this period despite the increased usage and demand rates.

Table 6.3, reproduced below, offers some basis for how much depletion to expect during this time:

Table 6.5 Range of Campus Load Demands in Terms of TES Percent Charge

Load Range	Part-Peak 1	Peak	Part-Peak 2	Peak + Part-Peak 2	Total
	ton-hr	ton-hr	ton-hr	ton-hr	ton-hr
min	4.8%	13.6%	5.5%	19.6%	24.7%
avg	12.1%	28.8%	9.8%	38.7%	50.7%
max	27.7%	53.5%	19.1%	72.7%	100.3%

In particular, the "Peak + Part-Peak 2" column indicates a range of approximately 20% to 75% depletion beginning at 12:00pm. However, to suggest maintaining a charge of 75% in the Part-

Peak 1 period, simply to ensure enough capacity for the worst-case Peak and Part-Peak 2 periods, would likely produce an inefficient cycling of chiller operation. Also, the energy and demand rates are the same during Part-Peak 1 and Part-Peak 2, so charging more in Part-Peak 1 just to gain capacity for Part-Peak 2 does not offer any benefit. Therefore, it would be more appropriate to look specifically at the Peak Period column.

According to the historical data, the Peak period consumes a maximum capacity of 53.5%. Since the Peak period is designed to discharge as long as the capacity is above 0%, the minimum charge the tank should have at the start of the Peak period (and the end of the Part-Peak 1 period) would be 53.5%. Rounding up, the Part-Peak 1 setpoints are:

- DISCHARGE if available % is more than 55%
- CHARGE if available % is less than 55%

6.3.7 Summary

The new summer control strategy setpoints are summarized below as follows:

Table 6.6 New Proposed Control Strategy (Not Optimized)

Rate Period	Time	Setpoint	
Off-Peak 1	12:00am – 4:00am	CHARGE TES with CH-1A and a second chiller pair if available % is less than	45%
		CHARGE TES with CH-1A if available % is less than	70%
		DISCHARGE TES if available % is more than	80%
Off-Peak 2	4:00am – 8:30am	CHARGE TES with both CH-1A and another chiller pair if available percentage is less than	70%
		CHARGE TES with CH-1A if available percentage is less than	95%
		Run Chillers in “Mode 1” (no charging of TES) if available percentage is greater than	100%
Part-Peak 1	8:30am – 12:00pm	CHARGE if available % is less than	55%
		DISCHARGE if available % is more than	55%
Peak	12:00pm – 18:00pm	Deplete tank if available % is greater than	0%
		Start chillers in "Mode 1" (no charging of TES) if the 2ft tank sensor is greater than	43^{o}F
Part-Peak 2	18:00pm-21:30pm	Discharge TES if available % is more than	15%
		Run chillers in "Mode 1" (do not charge TES) if available % is less than	15%
Off-Peak 3	21:30pm – 12:00am	CHARGE TES with CH-1A and another chiller pair if available % is less than	30%
		CHARGE TES with CH-1A if available % is less than	50%
		DISCHARGE TES if available % is more than	65%
Weekend Off-Peak	Weekends	Regen Start if 56ft Tank sensor is greater than	45^{o}F
		Regen stop if 66ft tank sensor is less than	45^{o}F

6.4 Additional Control Strategy Setpoints

With a new control strategy established, optimization of some of the key setpoints can be performed. However, most of the setpoints were established relative to others (i.e., cascaded setpoints of charging to 100% in Off-Peak 2, charging to 70% in Off-Peak 1, and charging to 50% in Off-Peak 3). Therefore, following the methodology described by Hydeman [4] and Braun

([1], [2], and [3]), the model will be run under a number of different control strategies to assess the effectiveness of varying charging and discharging setpoints.

In addition to the scenario defined in Table 6.6 above ("Alternative 2"), three other alternatives will be defined – two with higher setpoints (more rigorously charging) and one with lower setpoints (less rigorous charging). The model will be run in all four scenarios, and the best of the four will be selected. These are summarized in Table 6.7.

Note that as previously mentioned, the setpoints for the Peak and Part-Peak 2 were defined to ensure that the TES is as fully depleted as possible by the end of these periods; accordingly, these setpoints do not leave margin for optimization.

While these four alternatives provide a range of possible charging and discharging strategies, other combinations of setpoints could also be considered. However, in keeping with Hydeman's strategies, the scope of this study is directed to evaluating a number of discrete control strategies. Using the results of this study as a foundation, future efforts may explore additional control setpoint options.

Table 6.7 Optimization Scenarios

Rate Period	Setpoint	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Off-Peak 1	CHARGE TES with CH-1A and a second chiller pair if available % is less than	40%	45%	50%	55%
	CHARGE TES with CH-1A if available % is less than	65%	70%	70%	75%
	DISCHARGE TES if available % is more than	75%	80%	80%	85%
Off-Peak 2	CHARGE TES with both CH-1A and another chiller pair if available percentage is less than	65%	70%	70%	75%
	CHARGE TES with CH-1A if available percentage is less than	95%	95%	95%	100%
	Run Chillers in “Mode 1” (no charging of TES) if available percentage is greater than	100%	100%	100%	100%
Part-Peak 1	CHARGE if available % is less than	50%	55%	60%	65%
	DISCHARGE if available % is more than	50%	55%	60%	65%
Peak	Deplete tank if available % is greater than	0%	0%	0%	0%
	Start chillers in "Mode 1" (no charging of TES) if the 2ft tank sensor is greater than	43^oF	43^oF	43^oF	43^oF
Part-Peak 2	Discharge TES if available % is more than	15%	15%	15%	15%
	Run chillers in "Mode 1" (do not charge TES) if available % is less than	15%	15%	15%	15%
Off-Peak 3	CHARGE TES with CH-1A and another chiller pair if available % is less than	25%	30%	40%	45%
	CHARGE TES with CH-1A if available % is less than	45%	50%	60%	65%
	DISCHARGE TES if available % is more than	60%	65%	70%	75%

The results of these four strategies will be discussed in Section 7.

7. RESULTS

With different control strategies established, the last step in Hydeman's optimization methodology – the fourth step described in Section 4 – is to calculate the energy costs for each scenario and determine which control strategies can be realistically implemented to attain the optimal energy costs.

7.1 Determining the Optimal Control Strategy

The four control strategies from Table 6.7 were run for the weekdays of the subject period (June 24th through September 30th, 2015), and the total weekly costs were calculated, as summarized below in Table 6.1 and Figure 6.1.

Table 7.1 Weekly Energy Charge for Each Optimization Scenario

Scenario	Energy Charge
Baseline	$ 6,705.53
Alternative 1	$ 6,285.99
Alternative 2	$ 6,271.21
Alternative 3	$ 6,241.48
Alternative 4	$ 6,264.62

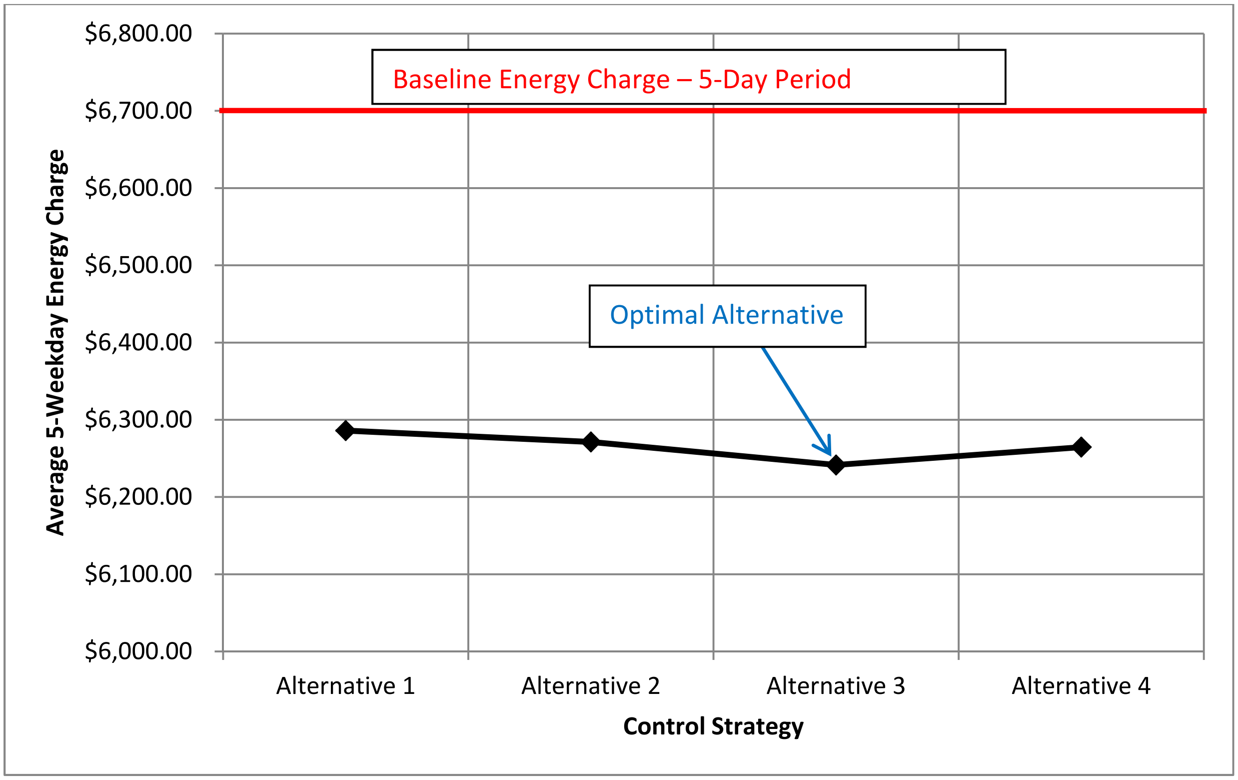


Figure 7.1 Optimal Control Strategy Results - Weekly Energy Charge

The energy charges listed are the sum of the charges for the Peak, Part-Peak, and Off-Peak periods from Monday through Friday. Demand charges – both Peak and Part-Peak – were nearly equal for each of the four scenarios (approximately $4,300 total). While Alternative 3 shows the best cost savings, the sensitivity for varying the control setpoints is not very significant, with a range of cost savings of only about $45 between all four alternatives. More significant is the savings associated with adjusting the control strategy from the baseline to any one of the new alternatives – a savings of between $400 and $500 per week.

It can be reasonably concluded that there is some flexibility in the exact setpoints chosen for the proposed new control strategy. Results for Alternative 3 are discussed in Section 7.2.

7.2 Optimal Control Strategy Results

The optimal control strategy ("Alternative 3") was run over the period from June 24th through September 30th, 2015, using the campus loads that had been trended over that date range. As discussed in Section 6.1.2, only the Monday through Friday periods are of concern for optimization. Also, since there were some gaps in the trend data at the start of each month, a continuous load profile from June through September could not be obtained, as noted in Section 5. Figures 7.2 through 7.6 show the comparison between Alternative 3 and the baseline power usage for the chillers during the week of September 21-25, 2015.

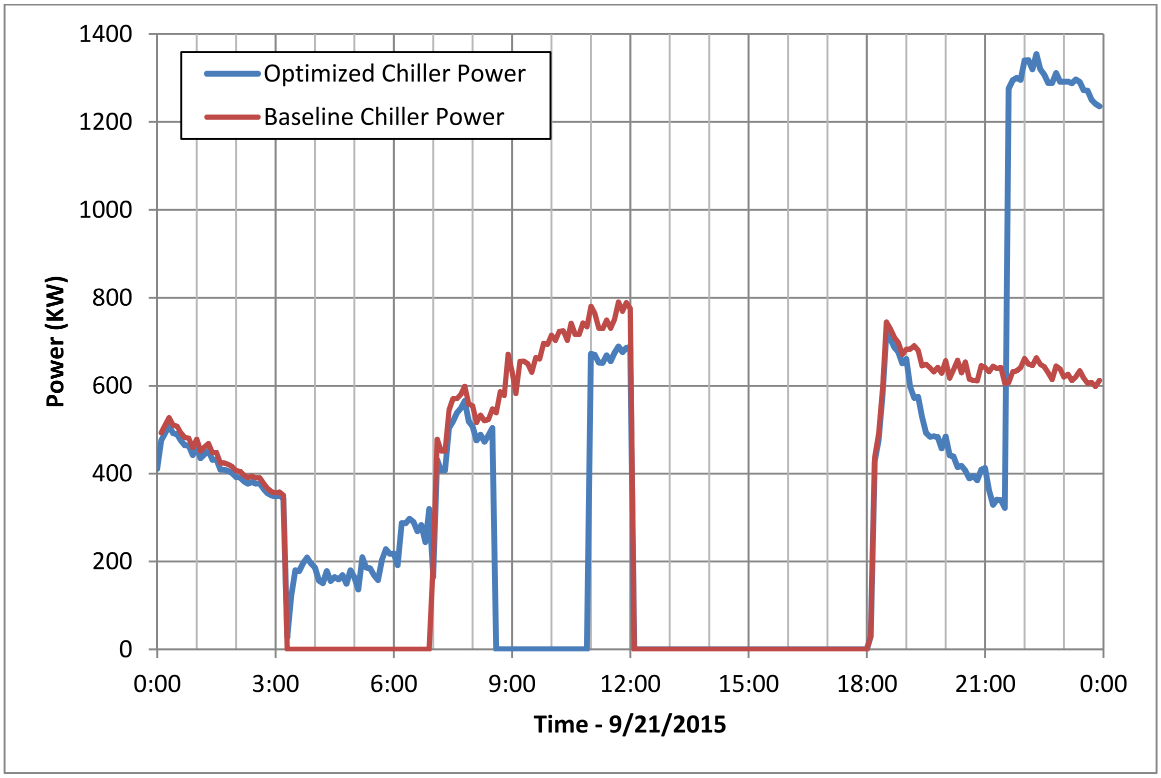


Figure 7.2 Optimized Chiller Power - 9/21/15

The baseline power plot in Table 7.2 indicates that the chiller stopped charging around 3am, only to resume at about 7am and continue on until the 12:00pm Peak Period. The new control strategy established a greater charge requirement during the Off-Peak hours, which resulted in the chiller charging all the way up to the Part-Peak 1 period. After discharging for a few hours, additional charge was needed in the tank prior to the Peak Period, so the chiller resumed charging for about an hour before noon. After the Peak Period, the depleted tank called for the chiller to take on the campus load, but it did not concurrently charge the tank – resulting in decreased power during Part-Peak 2. Finally, at the Off-Peak period, another chiller pair was brought online for additional capacity.

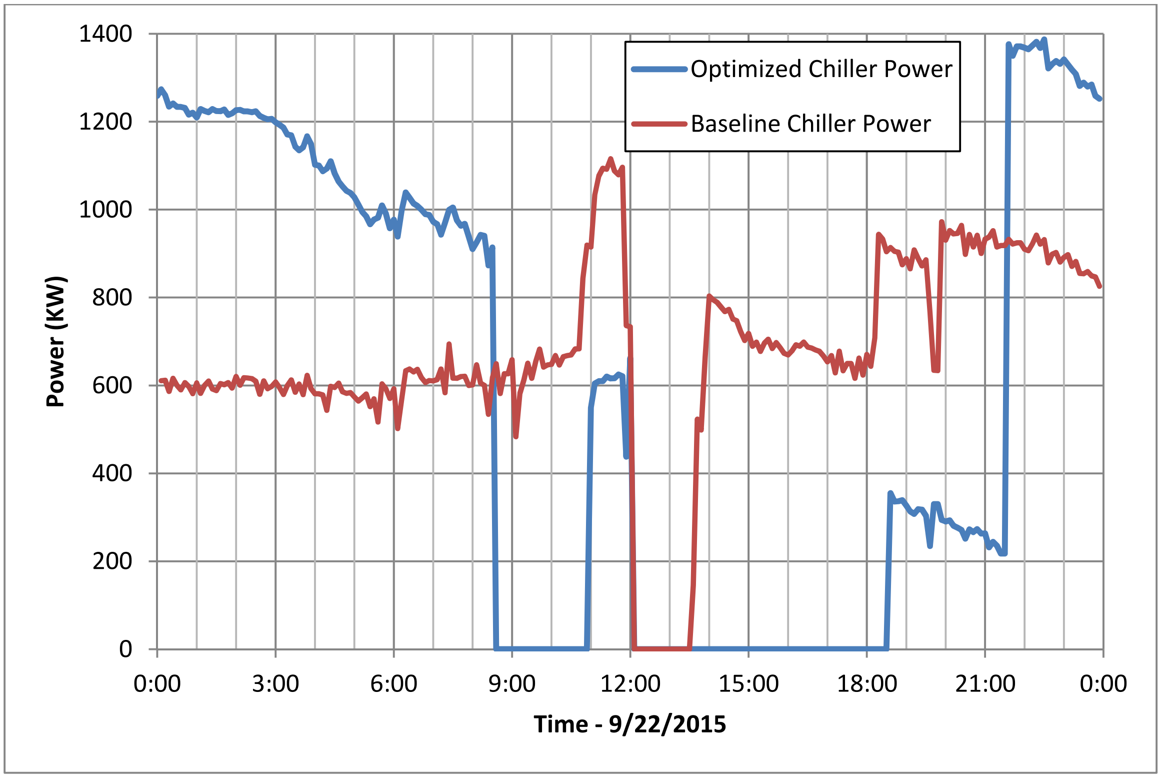


Figure 7.3 Optimized Chiller Power - 9/22/15

The baseline power profile in Figure 7.3 shows that the chiller(s) ran almost the entire day, with only a short time during the Peak period where they were off-line. The new control strategy called for another chiller pair during the Off-Peak periods due to the low charge level of the tank. The result is significantly less run-time of the chillers, except for about an hour during the Part-Peak 1 period and a “Mode 1”-only Part-Peak 2 operation.

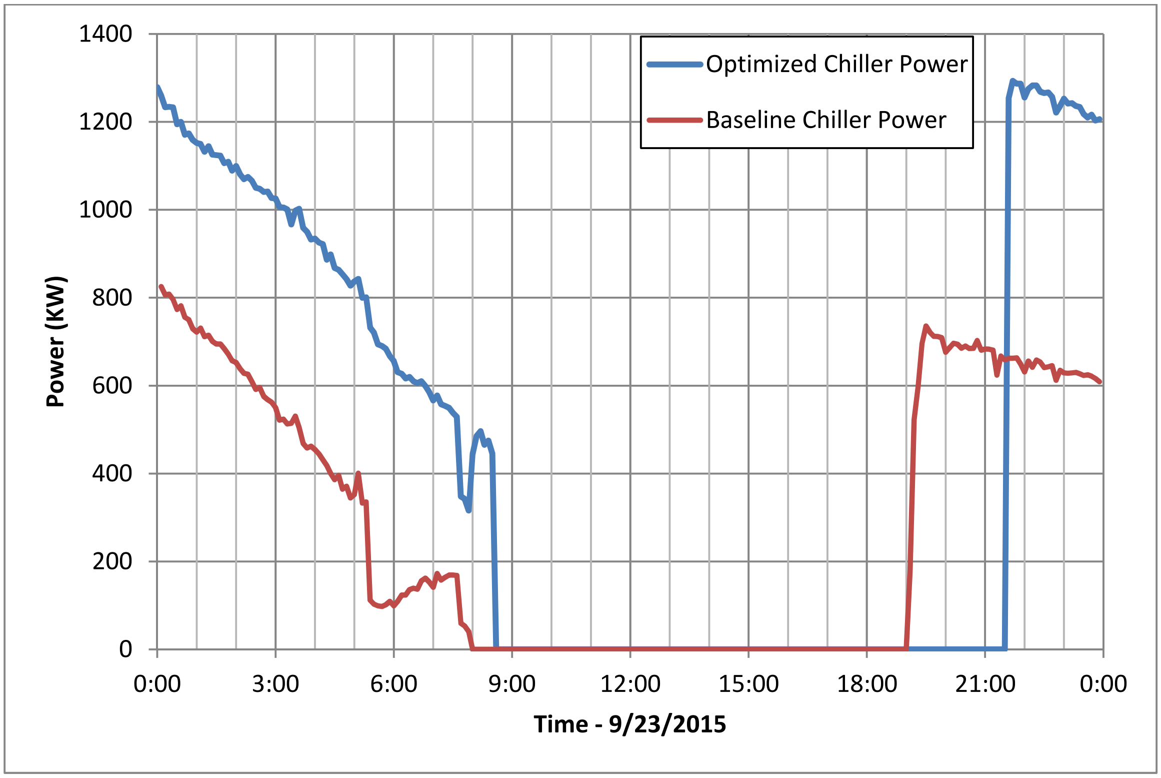


Figure 7.4 Optimized Chiller Power - 9/23/15

Compared to the baseline in Figure 7.4, the new control strategy used additional chiller capacity during the Off-Peak periods and therefore eliminated chiller operation during Peak and Part-Peak periods.

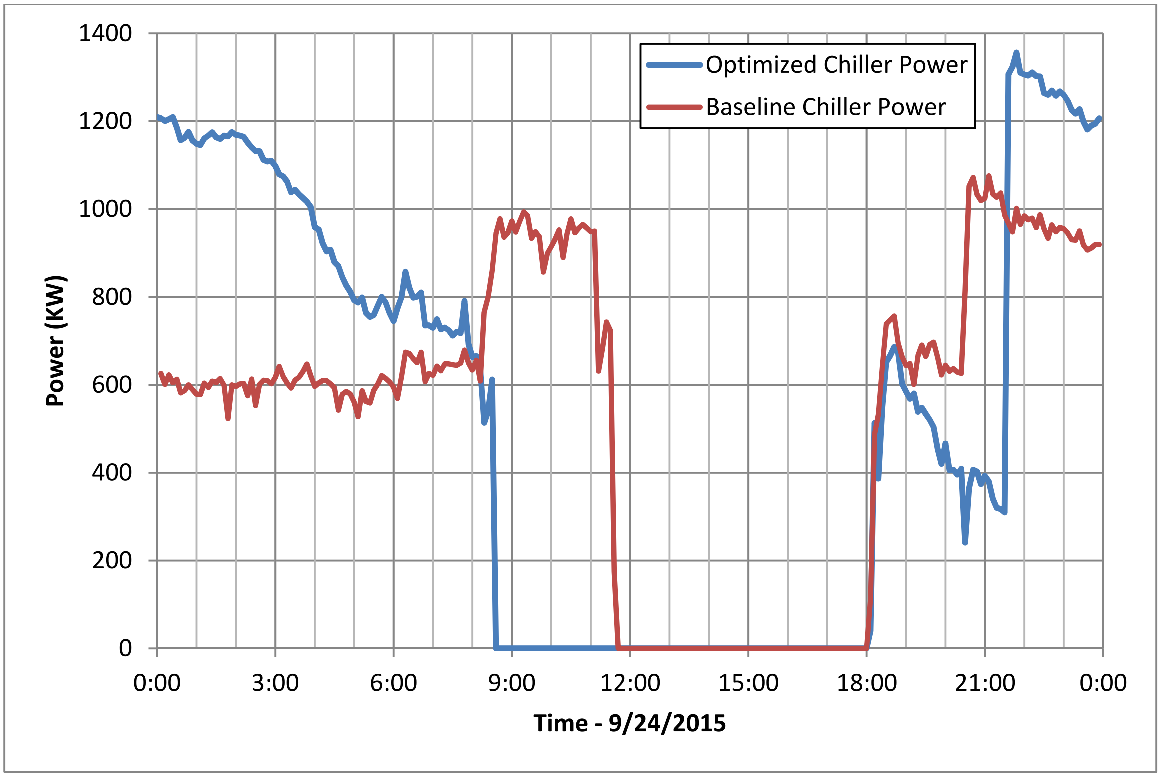


Figure 7.5 Optimized Chiller Power - 9/24/15

As has been shown in previous figures, Figure 7.5 illustrates the improvement of the new control strategy by invoking greater chiller capacity during Off-Peak and restricting charging of the TES tank during Part-Peak 2, resulting in significantly less Peak/Part-Peak chiller operation compared to the baseline.

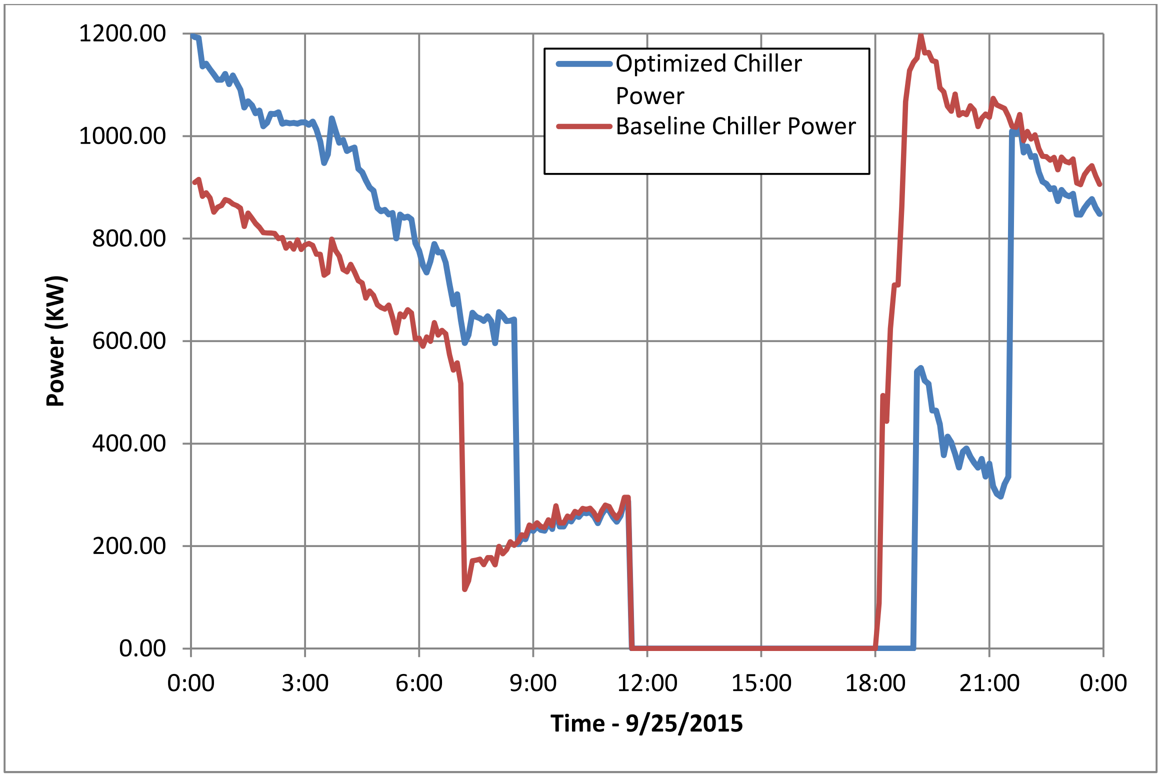


Figure 7.6 Optimized Chiller Power - 9/25/15

Figure 7.6 again shows the reduction in Part-Peak 2 operation by increasing the number of chillers used during the Off-Peak period.

The TES tank capacity profiles for the new control strategy are plotted along with the baseline strategy in Figures 7.7 through 7.11. As expected, the new charging/discharging profiles follow a more consistent cycle as compared to the baseline. Since the setpoints were devised so that the tank maintains a higher charge in the early morning Off-Peak hours – and it more fully depletes during the Peak and Part-Peak 2 periods – the result is a better balance for the full week. For example, the profile for Tuesday in the optimized scenario (Figure 7.7) shows the tank approaching a 90% charge at the start of the Part-Peak 1 period (despite the significant depletion that occurred the day before), whereas originally the tank charge reached less than 50%, resulting in considerable chiller operation during the Part-Peak and Peak hours.

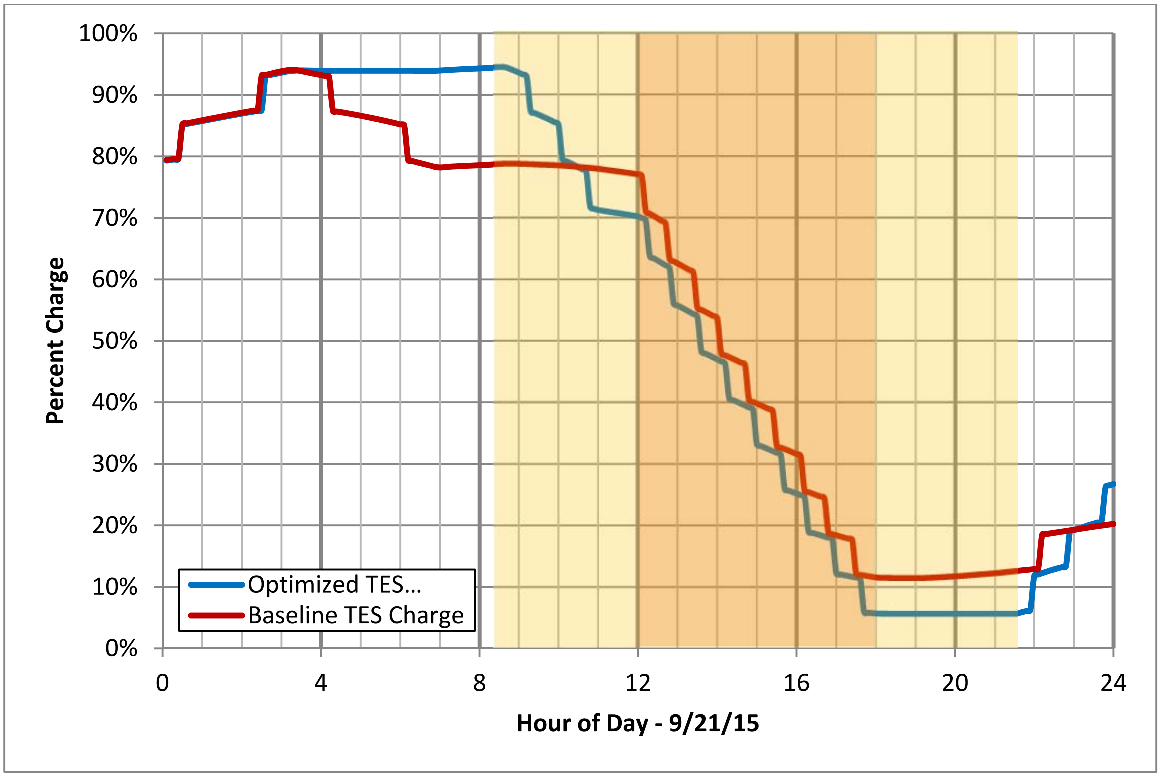


Figure 7.7 Optimized TES Tank Capacity Profile for Monday, Sept 21st, 2015

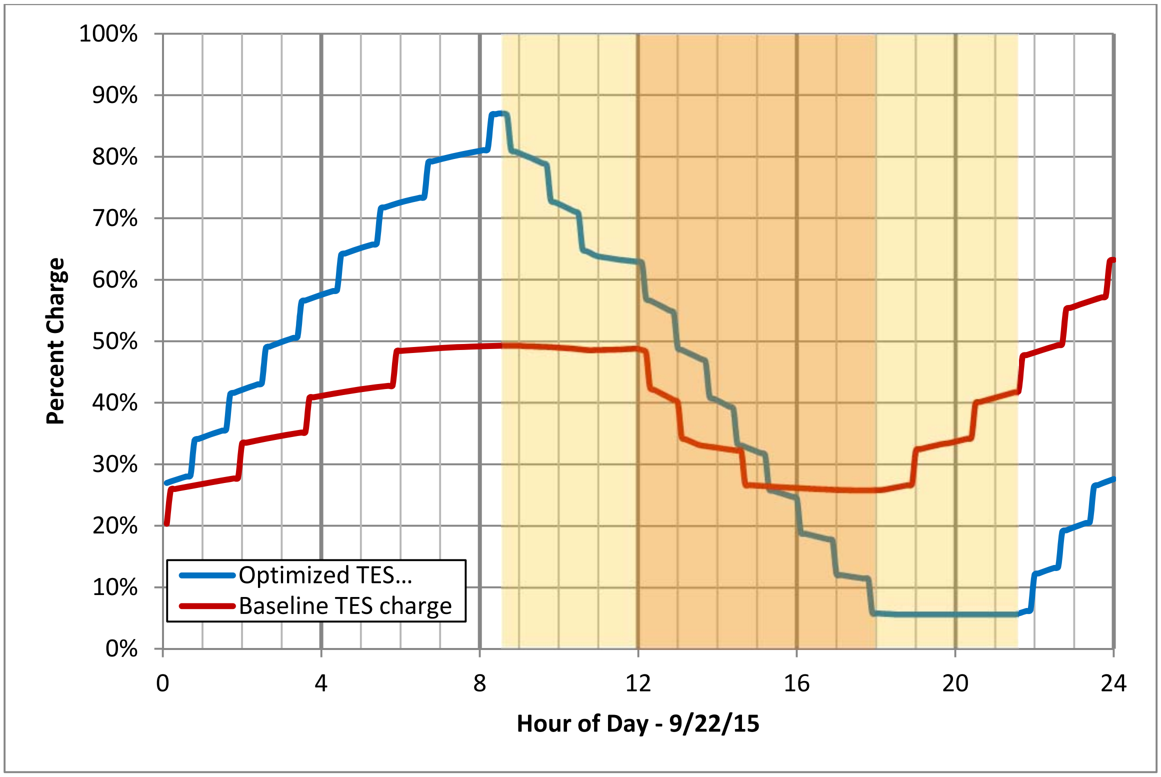


Figure 7.8 Optimized TES Tank Profile for Tuesday, Sept 22nd, 2015

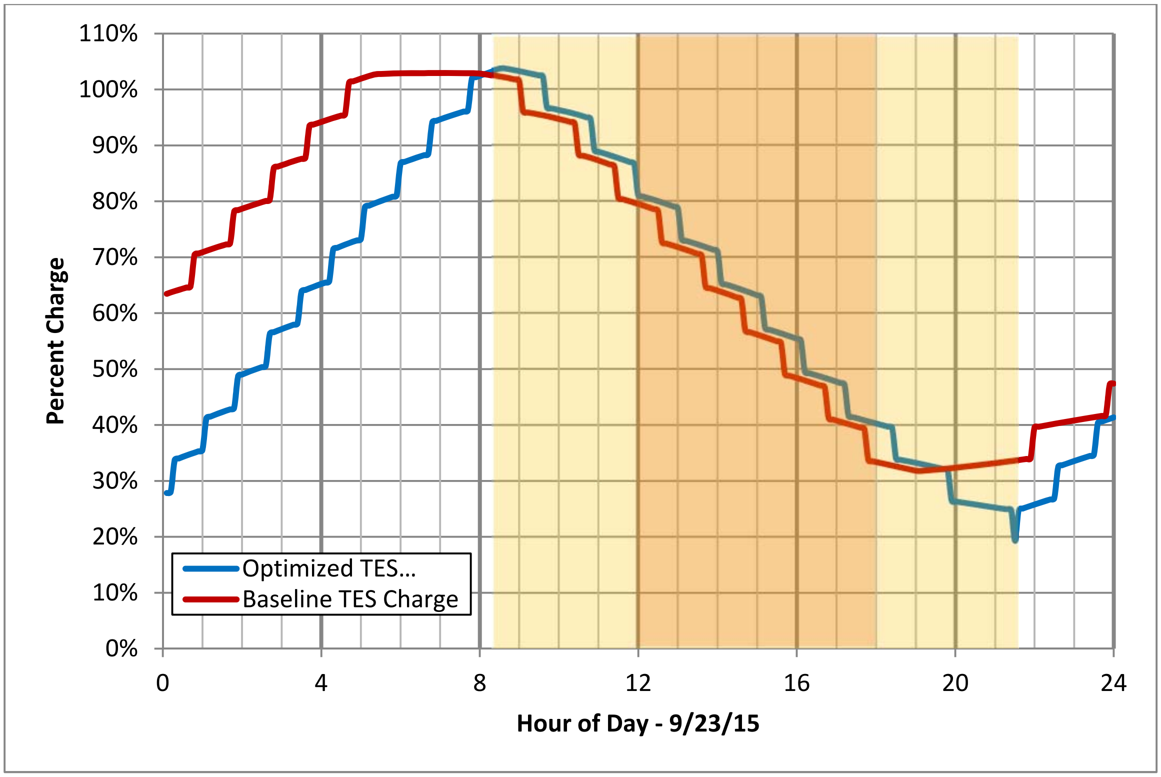


Figure 7.9 Optimized TES Tank Profile for Wednesday, Sept 23rd, 2015

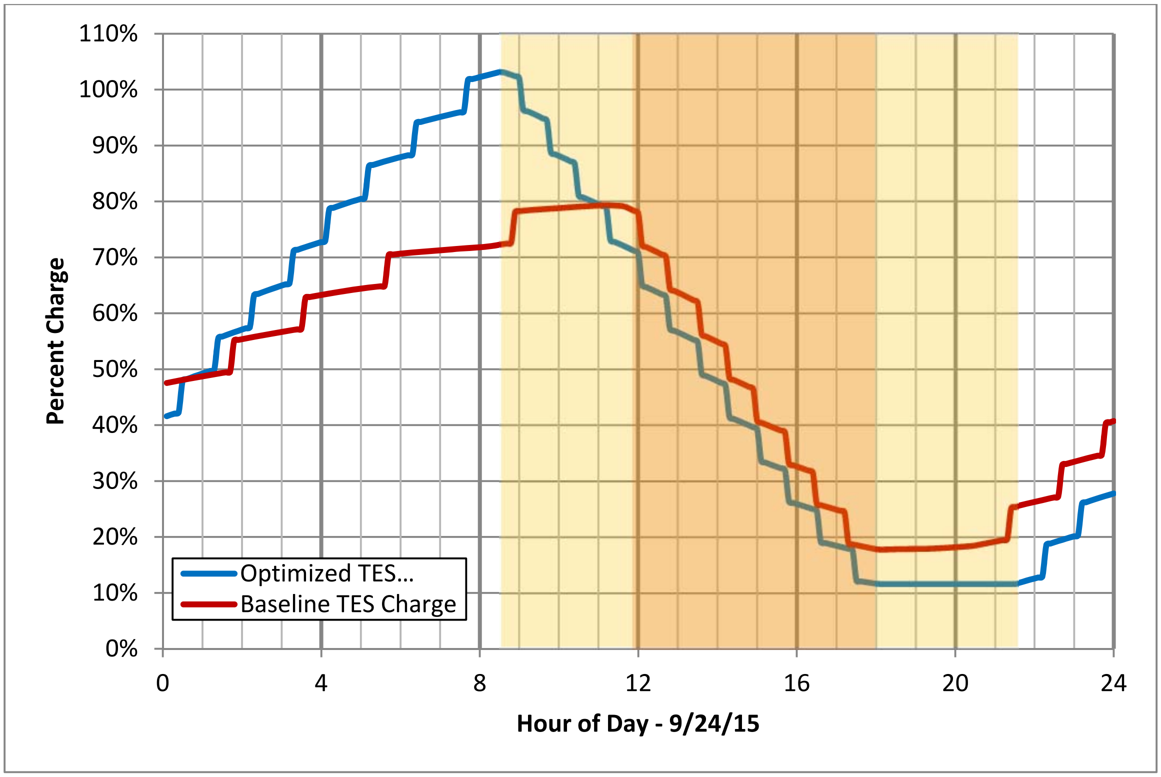


Figure 7.10 Optimized TES Tank Profile for Thursday, Sept 24th, 2015

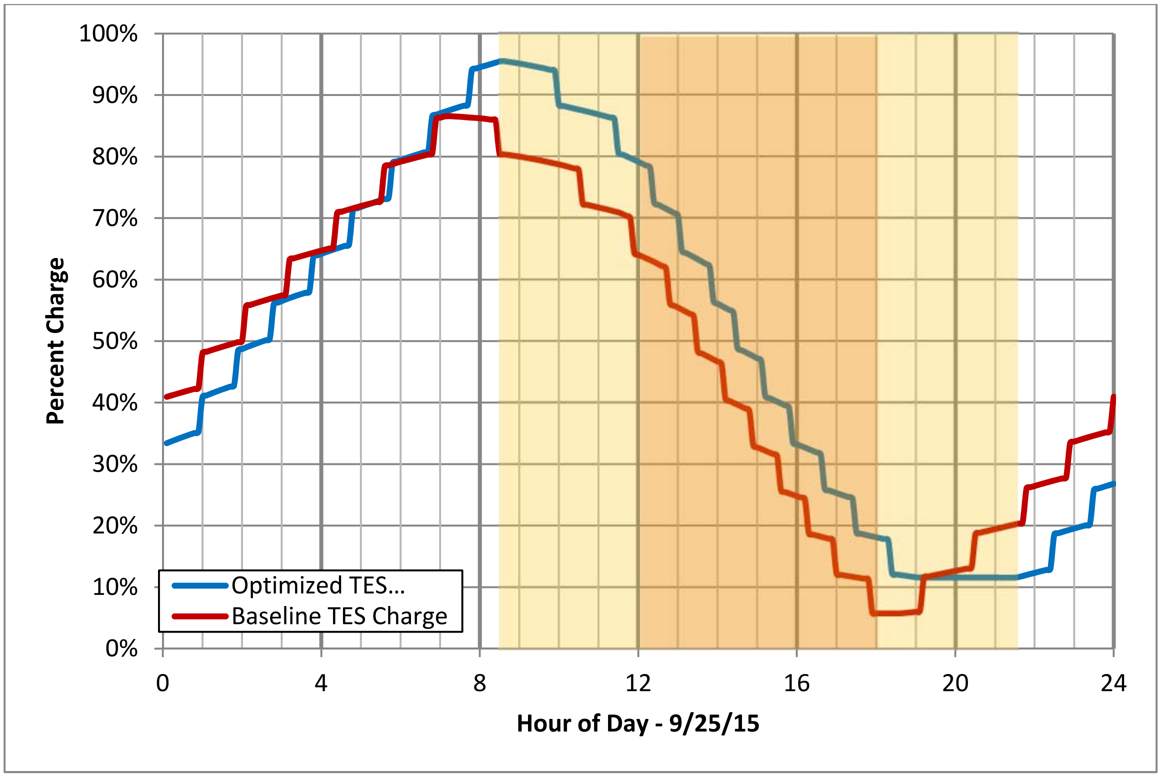


Figure 7.11 Optimized TES Tank Profile for Friday, Sept 25th, 2015

For further comparison of the proposed control strategy as compared to the baseline, Figure 7.12 shows the net changes in power consumption, broken down to their off-peak, part-peak, and peak periods.

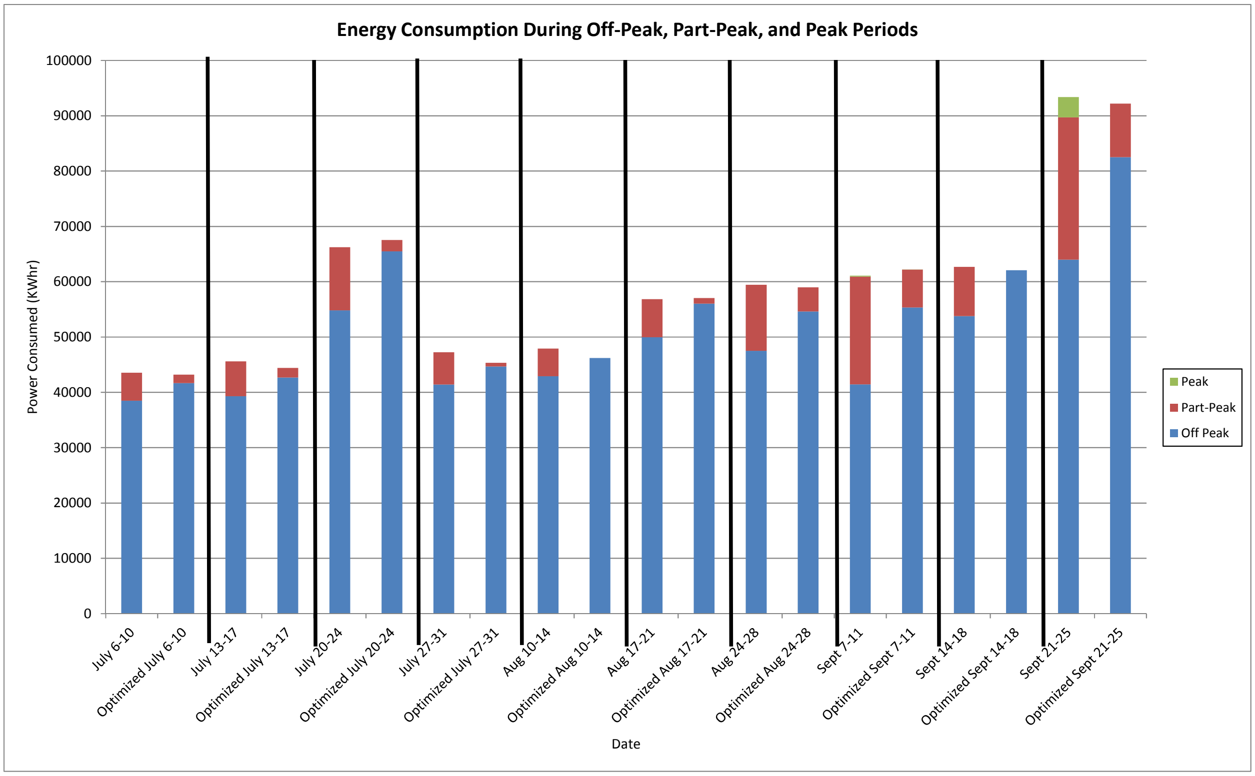


Figure 7.12 Energy Consumption Breakdown

Note that while the total power consumption increased for some weeks, the increase was in the off-peak periods, while the peak and part-peak reduced considerably, resulting in a net cost savings. Any increases in overall power are actually the result of using the less-efficient chillers for added chiller capacity during Off-Peak hours to reduce the operation of the more efficient chiller CH-1A during the Peak/Part-Peak hours. The result is still an overall cost savings.

This savings, broken down by each week-long simulation, is shown in Table 7.2 below.

Table 7.2 Weekly Energy Rate Savings, July through September

Date	Energy Charge		
	Baseline	New	Savings
July 6-10	$ 2,954.14	$ 2,876.17	**$ 77.97**
July 13-17	$ 3,109.91	$ 2,959.50	**$ 150.41**
July 20-24	$ 4,555.03	$ 4,491.13	**$ 63.90**
July 27-31	$ 3,213.39	$ 3,002.99	**$ 210.40**
Aug 10-14	$ 3,240.97	$ 3,049.88	**$ 191.09**
Aug 17-21	$ 3,862.54	$ 3,780.38	**$ 82.16**
Aug 24-28	$ 4,115.51	$ 3,963.76	**$ 151.75**
Sept 7-11	$ 4,350.68	$ 4,216.77	**$ 133.91**
Sept 14-18	$ 4,280.34	$ 4,096.39	**$ 183.94**
Sept 21-25	$ 6,705.53	$ 6,246.76	**$ 458.77**

In addition, Table 7.3 shows the breakdown of the potential demand charge savings for the Peak and Part-Peak periods during these months.

Table 7.3 Weekly Potential Peak and Part-Peak Demand Savings, July through September

Date	Peak Demand Charge			Part-Peak Demand Charge		
	Baseline	New	Savings	Baseline	New	Savings
July 6-10	$ 619.81	$ 619.81	$ -	$ 2,421.26	$ 2,432.75	$ (11.49)
July 13-17	$ 685.04	$ 685.04	$ -	$ 2,643.11	$ 2,625.77	$ 17.34
July 20-24	$ 1,017.18	$ 1,046.78	$ (29.59)	$ 5,645.38	$ 2,976.58	$ 2,668.80
July 27-31	$ 765.78	$ 765.78	$ -	$ 2,869.02	$ 2,500.49	$ 368.53
Aug 10-14	$ 664.94	$ 664.94	$ -	$ 2,687.65	$ 146.40	$ 2,541.25
Aug 17-21	$ 791.17	$ 791.17	$ -	$ 2,923.53	$ 1,830.77	$ 1,092.76
Aug 24-28	$ 802.45	$ 802.45	$ -	$ 4,460.64	$ 3,314.71	$ 1,145.92
Sept 7-11	$ 13,878.46	$ 2,586.62	$ 11,291.84	$ 4,519.72	$ 3,469.56	$ 1,050.16
Sept 14-18	$ 720.65	$ 720.65	$ -	$ 2,957.49	$ 145.53	$ 2,811.96
Sept 21-25	$ 15,452.90	$ 949.49	$ 14,503.41	$ 4,770.69	$ 3,137.64	$ 1,633.05

To summarize, the optimized control strategy was implemented for the period from June through September and resulted in a slight overall increase in energy, but with significant shifts from peak and part-peak power to the off-peak rate period; the end result is an overall cost savings, as tabulated in Table 7.4. The Demand Savings columns are calculated by taking the maximum value for the subject month from the Baseline column in Figure 7.3 and subtracting the maximum value from the same month in the New column.

Table 7.4 Estimated Monthly Savings, July through September

	Energy Savings	Peak Demand Savings	Part-Peak Demand Savings
July	$ 502.67	$ (29.59)	$ 2,668.80
August	$ 566.65 *	$ -	$ 1,145.92
September	$ 1,035.50 *	$ 12,866.28	$ 1,301.13

*Note: Due to gaps in the campus load data, only three weeks were simulated with the new control strategy; energy savings for August and September have been adjusted by taking the average savings for three weeks and multiplying it by four weeks

Discussion of Accuracy

Every effort was made to ensure the accuracy of the TRNSYS plant model and the simulation results for both the baseline and the optimization runs. However, a variety of factors may contribute to results that might vary from the actual plant performance. In an effort to avoid overstating the potential energy cost savings, conservative estimates were used could affect the plant model results:

- Performance data for the other chiller pairs (CH-1 & 2, CH 3&4) was not available; chiller part-load ratios and capacity/COP ratios were conservatively estimated based on the trended performance. As a result, their actual performance is probably more efficient than what is represented in the model.
- The TRNSYS model of the TES tank uses 35 “nodes” with depths of 2-feet each, which matches the configuration of the temperature sensors in the actual tank. However, the actual physical stratification phenomenon is a continuous temperature distribution through the entire height of the tank, so the TES model is more accurate with more nodes

used in the model. Therefore, using a discrete number of nodes may not necessarily reflect the actual TES capacity percentages in the physical tank at each time step. The results with this limited number of nodes is expected to be more conservative because the lower "resolution" of the stratification profile – particularly in the thermocline region – causes the calculated model capacities to deplete faster and charge more slowly; in actuality, the tank will likely deplete more slowly and charge more quickly, which is more beneficial to the system.

- The redundant flow measurements from the trended data did not always agree. Facilities personnel indicated that this may have to do with calibrations of the flow meters used. For the purposes of the model, the higher flow rates were used in determining campus loads. Therefore, the campus loads may be computed as higher in the model than they actually were.

8. CONCLUSIONS AND RECOMMENDATIONS

Based on the optimization process outlined in this report, the following general recommendations for the control strategy have been shown to improve TES tank performance and operating costs:

1) Adjust the charging strategy so that the TES tank is always as fully charged as possible prior to the summer Part-Peak 1 (8:30am-12:00pm) period; in particular, it is suggested to restrict discharging of the tank during the hours before 8:30am
2) Adjust the discharge strategy to allow for near-complete discharge of the TES tank during the Peak and Part-Peak 2 periods; specifically, establish setpoints that reduce the TES tank to as close to 0% capacity as is feasible in the Part-Peak 2 period
3) Restrict the charging of the TES tank during the Peak and Part-Peak 2 periods; if chilled water capacity to the campus is required from the chiller(s) during these periods, it is recommended that the chillers do not also charge the tank, so that they operate in “Mode 1” rather than “Mode 2” to minimize the amount of power drawn
4) During the late night and early morning Off-Peak periods, the TES tank should be charged as much as possible at the start of the rate period, using chiller capacity that is proportional to the amount of charge required to bring it back to 100%; for example, a fully depleted tank should use CH-1A and another chiller pair at the start of the Off-Peak period, while a minimally depleted tank should only use CH-1A to charge.

By simulating various possible control strategies and optimizing the setpoints, an effective summer control strategy for the Cal Poly Central Plant is summarized in Table 8.1:

Table 8.1 Recommended Control Strategy

Rate Period	Time	Setpoint	
Off-Peak 1	12:00am – 4:00am	CHARGE TES with CH-1A and a second chiller pair if available % is less than	50%
		CHARGE TES with CH-1A if available % is less than	70%
		DISCHARGE TES if available % is more than	80%
Off-Peak 2	4:00am – 8:30am	CHARGE TES with both CH-1A and another chiller pair if available percentage is less than	70%
		CHARGE TES with CH-1A if available percentage is less than	95%
		Run Chillers in “Mode 1” (no charging of TES) if available percentage is greater than	100%
Part-Peak 1	8:30am – 12:00pm	CHARGE if available % is less than	60%
		DISCHARGE if available % is more than	60%
Peak	12:00pm – 18:00pm	Deplete tank if available % is greater than	0%
		Start chillers in "Mode 1" (no charging of TES) if the 2ft tank sensor is greater than	43^{o}F
Part-Peak 2	18:00pm-21:30pm	Discharge TES if available % is more than	15%
		Run chillers in "Mode 1" (do not charge TES) if available % is less than	15%
Off-Peak 3	21:30pm – 12:00am	CHARGE TES with CH-1A and another chiller pair if available % is less than	40%
		CHARGE TES with CH-1A if available % is less than	60%
		DISCHARGE TES if available % is more than	70%
Weekend Off-Peak	Weekends	Regen Start if 56ft Tank sensor is greater than	45^{o}F
		Regen stop if 66ft tank sensor is less than	45^{o}F

This control strategy has been applied to the calibrated TRNSYS plant model. Since the baseline performance of the model matches the actual plant performance using the current control strategy, it can be reasonably concluded that the simulated results of this new control strategy accurately reflects what can be expected from the actual plant performance.

The resultant energy cost savings using actual campus load data for the month of September exceeds $1,000 per month, while savings using load data for the months of July and August is over $500 per month. Part-Peak energy demand savings was determined to be between $1,000 to $3,000 per month, while savings for peak demand in September was determined to be nearly $13,000.

REFERENCES

1. Braun, Klein, Beckman, and Mitchell, "Methodologies for Optimal Control of Chilled Water Systems Without Storage," *ASHRAE Transactions*, 1989

2. Braun, Klein, Mitchell, and Beckman, "Applications of Optimal Control to Chilled Water Systems Without Storage," *ASHRAE Transactions*, 1989

3. Braun, James, "Methodologies for the Design and Control of Central Cooling Plants," Ph.D. Dissertation, Mechanical Engineering Department, University of Wisconsin, Madison, WI, 1988

4. Hydeman, Mark, "Optimizing Chilled Water Plant Control," *ASHRAE Journal*, June, 2007

5. Taylor, Steven T., "Optimizing Design and Control of Chilled Water Plants," *ASHRAE Journal,* June, 2012

6. Peterson, Kent, "Improving Performance of Large Chilled Water Plants," *ASHRAE Journal*, January, 2014

7. Braun, James, "Reducing Energy Costs and Peak Electrical Demand through Optimal Control of Building Thermal Storage," *Controls Research, Johnson Controls*, Inc., 1989

8. Rutberg, Hastbacka, Cooperman, and Bouza, "Emerging Technologies: Thermal Energy Storage," *ASHRAE Journal*, June, 2013.

9. Wei, Xu, and Kusiak, "Modeling and Optimization of a Chiller Plant," *Energy 73*, 2014

10. Rosen, Marc and Ibrahim, Dincer*, Thermal Energy Storage: Systems and Applications, 2nd Edition*, Wiley, 2010

11. “UCI Microgrid: Thermal Storage,” DOE Global Energy Storage Database [Online], available: http://www.energystorageexchange.org/projects/1343

12. Henze, Biffar, Kohn, and Becker, "Optimal Design and Operation of a Thermal Storage system for a Chilled Water Plant Serving Pharmaceutical Buildings," *Energy and Buildings 40*, 2008

13. Deng, Sun, Chakraborty, Lu, Brouwer, and Mehta, "Optimal Scheduling of Chiller Plant with Thermal Energy Storage using Mixed Integer Linear Programming," *American Control Conference*, *Washington, DC*, 2013

14. Chandan, Vikas, et al. "Modeling and optimization of a combined cooling, heating and power plant system." *American Control Conference (ACC), 2012*. IEEE, 2012

15. Osman, Khaireed, Ariffin, and Senawi, "Dynamic Modeling of Stratification for Chilled Water Storage Tank," *Energy Conversion and Management 49.11*, 2008

16. Zhang, Turner, Chen, Xu, and Deng, "Tank Size and Operating Strategy Optimization of a Stratified Chilled Water Storage System," *Applied Thermal Engineering 31.14*, 2011

17. Powell, Cole, Ekarika, and Edgar, "Dynamic Optimization of a Campus Cooling System with Thermal Energy Storage," *European Control Conference, Zurich, Switzerland*, 2013

18. Powell Powell, Kody M., and Thomas F. Edgar. "Modeling and control of a solar thermal power plant with thermal energy storage." *Chemical Engineering Science 71*, 2012

19. Cole, Wesley J., Kody M. Powell, and Thomas F. Edgar. "Optimization and advanced control of thermal energy storage systems," 2012

20. Powell, Cole, Ekarika, Edgar, "Optimal Chiller Loading in a District Cooling System with Thermal Energy Storage," *Energy Journal*, Vol. 50, 2012

21. Ma, Zhenjun and Wang, Shengwei, “An Optimal Control Strategy for Complex Building Central Chilled Water Systems for Practical and Real Time Applications,” *Building and Environment 44*, 2009

22. Yu, F.W. and Chan, K.T., “Optimum Load Sharing Strategy for Multiple Chiller Systems Serving Air-Conditioned Buildings,” *Building and Environment*, Vol 42, 2007

23. Xiao-Qiang, J., Weiding, L., and Min, L., “Optimum Control Strategy for All-Variable Speed Chiller Plant,” Central South University Press, 2011

24. Monfet and Zmeureanu, "Simulation of a Large Central Cooling and Heating Plant Using TRNSYS and Calibration with Monitored Data*," Eleventh International IBPSA Conference, Glasgow, Scotland*, July 2009

25. Rismanchi, Saidur, Masjuki, and Mahlia, "Modeling and Simulation to Determine the Potential Energy Savings By Implementing Cold Thermal Energy Storage System In Office Buildings," *Energy Conversion and Management*, 2013

26. Klein, S.A. et al, “TRNSYS 16: A Transient System Simulation Program,” Solar Energy Laboratory, University of Wisconsin, Madison, USA, http://sel.me.wisc.edu/trnsys., 2010

27. Ortiz, Mammoli, and Vorobieff, "A TRNSYS Model of a Solar Thermal System with Thermal Storage and Absorption Cooling," *American Society for Engineering Education*, 2008

28. Zhang, Turner, Li, Deng, "Optimal Operation of a Chilled-Water Storage System with a Real-Time Pricing Rate Structure," *ASHRAE*, 2011

29. Huang, Zuo, "Optimization of the Water-Cooled Chiller Plant System Operation," *ASHRAE*, 2014

30. *2012 AHSRAE Handbook – HVAC Systems and Equipment*, Chapter 51: Thermal Storage, 2012

31. Moran, Michael and Shapiro, Howard, *Fundamentals of Engineering Thermodynamics, 5th Edition*, John Wiley & Sons, Inc., 2004

32. Bahnfleth,William P., "Thermal Performance of a Full-Scale Stratified Chilled Water Thermal Storage Tank," *ASHRAE Transactions*, V 104 Pt. 2, 1998

33. Zheng, Turner, Chen, Xu, Deng, "A Method to Determine the Optimal Tank Size for a Chilled Water Storage System Under a Time of Use Electricity Rate Structure," *Proceedings of the Tenth International Conference for Enhanced Building Operations, Kuwait,* October, 2010

34. Lindeburg, Michael R., *Mechanical Engineering Reference Manual, 12th Edition*, Professional Publications, Inc., 2012

Pacific Gas and Electric Company
San Francisco, California
U 39

	Revised	*Cal. P.U.C. Sheet No.*	35159-E
Cancelling	Revised	*Cal. P.U.C. Sheet No.*	34700-E

ELECTRIC SCHEDULE E-20

Sheet 3

SERVICE TO CUSTOMERS WITH MAXIMUM DEMANDS of 1000 KILOWATTS or MORE

3. RATES: Total bundled service charges are calculated using the total rates shown below. Direct Access (DA) and Community Choice Aggregation (CCA) charges shall be calculated in accordance with the paragraph in this rate schedule titled Billing.

TOTAL RATES

	Secondary Voltage	Primary Voltage	Transmission Voltage
Total Customer/Meter Charge Rates			
Customer Charge Mandatory E-20 ($ per meter per day)	$32.85421	$49.28131	$65.70842
Optional Meter Data Access Charge ($ per meter per day)	$0.98563	$0.98563	$0.98563
Total Demand Rates ($ per kW)			
Maximum Peak Demand Summer	$18.53 (I)	$18.15 (I)	$16.74
Maximum Part-Peak Demand Summer	$4.03	$3.79	$3.63
Maximum Demand Summer	$14.71 (I)	$12.05 (I)	$6.08 (I)
Maximum Part-Peak Demand Winter	$0.27	$0.29	$0.00
Maximum Demand Winter	$14.71 (I)	$12.05 (I)	$6.08 (I)
Total Energy Rates ($ per kWh)			
Peak Summer	$0.14772 (R)	$0.14709 (R)	$0.10132 (R)
Part-Peak Summer	$0.10275 (R)	$0.10132 (R)	$0.08210 (R)
Off-Peak Summer	$0.07311 (R)	$0.07455 (R)	$0.06600 (R)
Part-Peak Winter	$0.09636 (R)	$0.09614 (R)	$0.08354 (R)
Off-Peak Winter	$0.07431 (R)	$0.07871 (R)	$0.07020 (R)
Power Factor Adjustment Rate ($/kWh/%)	$0.00005	$0.00005	$0.00005

PDP Rates			
PDP Charges ($ per kWh)			
All Usage During PDP Event	$1.20	$1.20	$1.20
PDP Credits			
Demand ($ per kW)			
Peak Summer	($6.05)	($6.50)	($5.90)
Part-Peak Summer	($1.23)	($1.19)	($1.28)
Energy ($ per kWh)			
Peak Summer	$0.00000	$0.00000	$0.00000
Part-Peak Summer	$0.00000	$0.00000	$0.00000

Total bundled service charges shown on customers' bills are unbundled according to the component rates shown below. PDP charges and credits are all generation and are not included below.

(Continued)

Advice Letter No: 4596-E	*Issued by*	*Date Filed*	February 27, 2015
Decision No.	***Steven Malnight***	*Effective*	March 1, 2015
	Senior Vice President	*Resolution No.*	
3C8	*Regulatory Affairs*		

CH-1A DATA IN F

Rated Conditions
40 outlet CHWT
80 inlet CWT

38.0	**40.0**	**41**	**42.8**	**44.6**	**46.4**	**!Chilled**	**water**	**leaving**	**temperature**	**(F)**
60.8	**68.0**	**77.0**	**80.0**	**86.0**	**95.0**	**!Cooling**	**water**	**inlet**	**temperature**	**(F)**

1.0415	1.2674	!Capacity	ratio	and	COP	ratio	at	**38**	F	oulet	CHWT	and	**61**	F	inlet	CWT
1.0151	1.1265	!Capacity	ratio	and	COP	ratio	at	**38**	F	oulet	CHWT	and	**68**	F	inlet	CWT
0.986	1.0147	!Capacity	ratio	and	COP	ratio	at	**38**	F	oulet	CHWT	and	**77**	F	inlet	CWT
0.9745	0.9775	**!Capacity**	**ratio**	**and**	**COP**	**ratio**	**at**	**38**	**F**	**oulet**	**CHWT**	**and**	**80**	**F**	**inlet**	**CWT**
0.9515	0.9031	!Capacity	ratio	and	COP	ratio	at	**38**	F	oulet	CHWT	and	**86**	F	inlet	CWT
0.9223	0.813	!Capacity	ratio	and	COP	ratio	at	**38**	F	oulet	CHWT	and	**95**	F	inlet	CWT
1.0668	1.2924	!Capacity	ratio	and	COP	ratio	at	**40**	F	oulet	CHWT	and	**61**	F	inlet	CWT
1.0404	1.1544	!Capacity	ratio	and	COP	ratio	at	**40**	F	oulet	CHWT	and	**68**	F	inlet	CWT
1.0115	1.0375	!Capacity	ratio	and	COP	ratio	at	**40**	F	oulet	CHWT	and	**77**	F	inlet	CWT
1	1	**!Capacity**	**ratio**	**and**	**COP**	**ratio**	**at**	**40**	**F**	**oulet**	**CHWT**	**and**	**80**	**F**	**inlet**	**CWT**
0.977	0.9249	!Capacity	ratio	and	COP	ratio	at	**40**	F	oulet	CHWT	and	**86**	F	inlet	CWT
0.948	0.8337	!Capacity	ratio	and	COP	ratio	at	**40**	F	oulet	CHWT	and	**95**	F	inlet	CWT
1.0791	1.3036	!Capacity	ratio	and	COP	ratio	at	**41**	F	oulet	CHWT	and	**61**	F	inlet	CWT
1.054	1.1566	!Capacity	ratio	and	COP	ratio	at	**41**	F	oulet	CHWT	and	**68**	F	inlet	CWT
1.0227	1.0491	!Capacity	ratio	and	COP	ratio	at	**41**	F	oulet	CHWT	and	**77**	F	inlet	CWT
1.0122	1.0118	**!Capacity**	**ratio**	**and**	**COP**	**ratio**	**at**	**41**	**F**	**oulet**	**CHWT**	**and**	**80**	**F**	**inlet**	**CWT**
0.9913	0.9371	!Capacity	ratio	and	COP	ratio	at	**41**	F	oulet	CHWT	and	**86**	F	inlet	CWT
0.9598	0.8427	!Capacity	ratio	and	COP	ratio	at	**41**	F	oulet	CHWT	and	**95**	F	inlet	CWT
1.1702	1.3936	!Capacity	ratio	and	COP	ratio	at	**42.8**	F	oulet	CHWT	and	**61**	F	inlet	CWT
1.1453	1.2663	!Capacity	ratio	and	COP	ratio	at	**42.8**	F	oulet	CHWT	and	**68**	F	inlet	CWT
1.1144	1.1302	!Capacity	ratio	and	COP	ratio	at	**42.8**	F	oulet	CHWT	and	**77**	F	inlet	CWT
1.104	1.0922	**!Capacity**	**ratio**	**and**	**COP**	**ratio**	**at**	**42.8**	**F**	**oulet**	**CHWT**	**and**	**80**	**F**	**inlet**	**CWT**
1.0834	1.016	!Capacity	ratio	and	COP	ratio	at	**42.8**	F	oulet	CHWT	and	**86**	F	inlet	CWT
1.0521	0.9173	!Capacity	ratio	and	COP	ratio	at	**42.8**	F	oulet	CHWT	and	**95**	F	inlet	CWT
1.1248	1.3497	!Capacity	ratio	and	COP	ratio	at	**44.6**	F	oulet	CHWT	and	**61**	F	inlet	CWT
1.0997	1.2224	!Capacity	ratio	and	COP	ratio	at	**44.6**	F	oulet	CHWT	and	**68**	F	inlet	CWT
1.0685	1.0908	!Capacity	ratio	and	COP	ratio	at	**44.6**	F	oulet	CHWT	and	**77**	F	inlet	CWT
1.0581	1.0527	**!Capacity**	**ratio**	**and**	**COP**	**ratio**	**at**	**44.6**	**F**	**oulet**	**CHWT**	**and**	**80**	**F**	**inlet**	**CWT**
1.0373	0.9766	!Capacity	ratio	and	COP	ratio	at	**44.6**	F	oulet	CHWT	and	**86**	F	inlet	CWT
1.0061	0.88	!Capacity	ratio	and	COP	ratio	at	**44.6**	F	oulet	CHWT	and	**95**	F	inlet	CWT
1.1474	1.3716	!Capacity	ratio	and	COP	ratio	at	**46.4**	F	oulet	CHWT	and	**61**	F	inlet	CWT
1.1225	1.2444	!Capacity	ratio	and	COP	ratio	at	**46.4**	F	oulet	CHWT	and	**68**	F	inlet	CWT
1.0914	1.1105	!Capacity	ratio	and	COP	ratio	at	**46.4**	F	oulet	CHWT	and	**77**	F	inlet	CWT
1.081	1.0724	**!Capacity**	**ratio**	**and**	**COP**	**ratio**	**at**	**46.4**	**F**	**oulet**	**CHWT**	**and**	**80**	**F**	**inlet**	**CWT**
1.0603	0.9963	!Capacity	ratio	and	COP	ratio	at	**46.4**	F	oulet	CHWT	and	**86**	F	inlet	CWT
1.0291	0.8976	!Capacity	ratio	and	COP	ratio	at	**46.4**	F	oulet	CHWT	and	**95**	F	inlet	CWT

Chiller CH-1A Performance Data - from Eqpt. Schedule

Load %	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**33**
Input kW	784	628	512	404	316	248	198	170
Power (Btu/hr)	2674638	2142440	1746702	1378257	1078043	846059	675482.6	579959.8
Capacity (Tons)	1350	1215	1080	945	810	675	540	445.5
kW/ton	0.580741	0.516872	0.474074	0.427513	0.390123	0.367407	0.366667	0.381594
COP	6.056894	6.805326	7.419695	8.227781	9.016339	9.573801	9.593142	9.217881
Capacity ratio	1	0.9	0.8	0.7	0.6	0.5	0.4	0.33
COP ratio	1	1.123567	1.225	1.358416	1.488608	1.580645	1.583838	1.521882
Evap								
LWT (F)	40	40	40	40	40	40	40	40
EWT (F)	60	60	60	60	60	60	60	60
Press Drop	23	19.1	15.5	12.2	9.3	6.8	4.6	3.3
Flow	1620	1458	1298	1134	972	810	648	535
(BTU/HR)	16200000	14580000	12980000	11340000	9720000	8100000	6480000	5350000
(Tons)	1350	1215	1081.667	945	810	675	540	445.8333
Cond								
LWT (F)	91	87	84	80	76	73	69	67
EWT (F)	80	78	75	73	70	68	65	63
Press Drop	26	26	26	26	26	27	27	27
Flow	3431	3431	3431	3431	3431	3431	3431	3431

FFLP - CH1A

0.0000	**Fraction of Full Load Power at PLR=0.00**
0.2168	**Fraction of Full Load Power at PLR=0.33**
0.4631	**Fraction of Full Load Power at PLR=0.60**
0.5654	**Fraction of Full Load Power at PLR=0.70**
0.6931	**Fraction of Full Load Power at PLR=0.80**
0.8510	**Fraction of Full Load Power at PLR=0.90**
1.0000	**Fraction of Full Load Power at PLR=1.00**

Baltimore Aircoil Company, Inc.

Cooling Tower Selection Program

Version:	8.6.0 NAPG03
Product data correct as of:	March 18, 2014

Project Name:	
Selection Name:	
Project State/Province:	California
Project Country:	United States
Date:	October 09, 2015

Model Information

Product Line:	PG S3000 (2009-2013)
Model:	31301C/V
Number of Units:	1
Fan Type:	Standard Fan
Fan Motor:	(1) 100.00 = 100.00 HP/Unit
Total Standard Fan Power:	Full Speed, 100.00 BHP/Unit
Intake Option:	None
Internal Option:	None
Discharge Option:	None

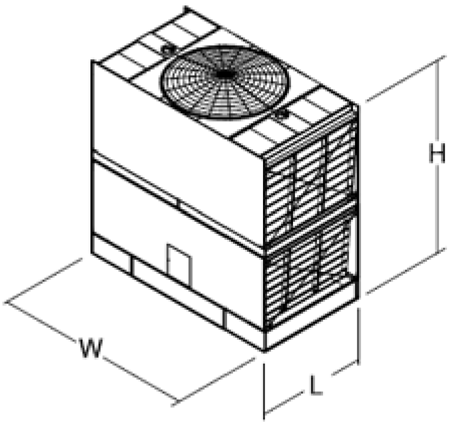
Design Conditions

Flow Rate:	3,431.00	USGPM
Hot Water Temp.:	91.00	°F
Cold Water Temp.:	80.00	°F
Wet Bulb Temp.:	73.00	°F
Tower Pumping Head:	9.00	psi
Reserve Capability:	3.13	%

Thermal performance at design conditions and standard total fan motor power is certified by the Cooling Technology Institute (CTI).

Engineering Data, per Unit

Unit Length:	13' 11.12"	
Unit Width:	24' 00.50"	
Unit Height:	25' 09.75"	
Air Flow:	314,078	CFM
Approximate Shipping Weight:	24,450	pounds
Heaviest Section:	14,230	pounds
Approximate Operating Weight:	48,680	pounds



Minimum Distance Required

From Solid Wall:	9	ft.
From 50% Open Wall:	3	ft.

Energy Rating:

47.72 per ASHRAE 90.1, ASHRAE 189 and CA Title 24.

Note: These unit dimensions do not account for any options/accessories. Please contact your local BAC sales representative for dimensions of units with options/accessories.

Warning

1. CTI Certification was maintained on this model during its production.

Baltimore Aircoil Company, Inc.

Cooling Tower Selection Program

Version: 8.6.0 NAPG03
Product data correct as of: March 18, 2014

Project Name:
Selection Name:
Project State/Province: California
Project Country: United States
Date: October 09, 2015

Model & Fan Motor

Product Line:	PG S3000 (2009-2013)
Model:	31301C/V
Number of Units:	1
Fan Motor:	(1) 100.00 = 100.00 HP/Unit
Total Standard Fan Power:	Full Speed, 100.00 BHP/Unit

Model Accessories

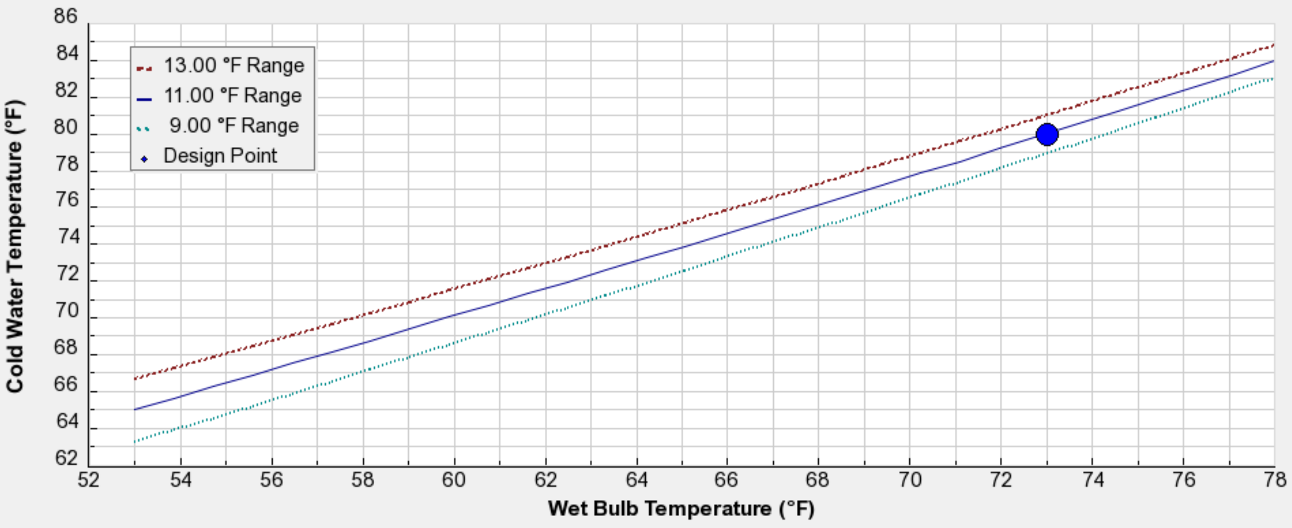
Intake Option:	None
Internal Option:	None
Discharge Option:	None
Fan Type:	Standard Fan

Design Conditions @ Standard Total Fan Motor Power per Unit (100.00 HP)

Thermal performance at design conditions and standard total fan motor power is certified by the Cooling Technology Institute (CTI).

Flow Rate:	3,431.00	USGPM
Hot Water Temp.:	91.00	°F
Cold Water Temp.:	80.00	°F
Wet Bulb Temp.:	73.00	°F

Predicted Performance
Fan Motor Alternative = Full Speed, 100.00 BHP
Flow Rate = 3431.00 USGPM (100.00% of Design)



These performance curves are based on constant fan power.

Warning	Applies to Design Conditions	Applies to Off Design Conditions
1. One or more selection parameters are outside of CTI Certification limits.	No	Yes

Baltimore Aircoil Company, Inc.

Cooling Tower Selection Program

Version:	8.6.0 NAPG03
Product data correct as of:	March 18, 2014

Project Name:	
Selection Name:	
Project State/Province:	California
Project Country:	United States
Date:	October 09, 2015

Model Information

Product Line: PG S3000 (2009-2013)
Intake Option: None
Model: 31301C/V
Internal Option: None
Number of Units: 1
Discharge Option: None
Fan Type: Standard Fan
Fan Motor: (1) 100.00 = 100.00 HP/Unit
Total Standard Fan Power: Full Speed, 100.00 BHP/Unit

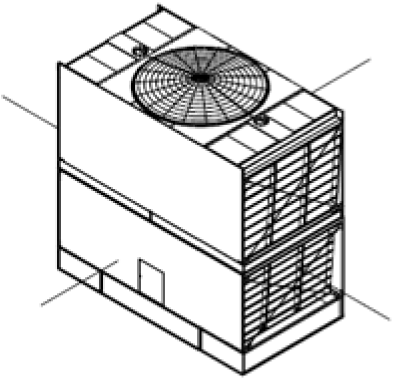
Octave band and A-weighted sound pressure levels (Lp) are expressed in decibels (dB) reference 0.0002 microbar. Sound power levels (Lw) are expressed in decibels (dB) reference one picowatt. Octave band 1 has a center frequency of 63 Hertz.

Top
Sound Pressure (dB)

Octave	Distance	
Band	5 ft.	50 ft.
1	88	77
2	89	77
3	88	77
4	84	70
5	81	66
6	75	61
7	71	57
8	70	54
A-wgtd	**86**	**73**

Air Inlet
Sound Pressure (dB)

Octave	Distance	
Band	5 ft.	50 ft.
1	82	71
2	84	70
3	83	72
4	76	68
5	70	63
6	63	54
7	58	48
8	54	45
A-wgtd	**78**	**69**



End
Sound Pressure (dB)

Octave	Distance	
Band	5 ft.	50 ft.
1	83	77
2	83	71
3	80	73
4	73	67
5	69	62
6	61	53
7	54	48
8	51	43
A-wgtd	**76**	**69**

End
Sound Pressure (dB)

Octave	Distance	
Band	5 ft.	50 ft.
1	83	77
2	83	71
3	80	73
4	73	67
5	69	62
6	61	53
7	54	48
8	51	43
A-wgtd	**76**	**69**

Air Inlet
Sound Pressure (dB)

Octave	Distance	
Band	5 ft.	50 ft.
1	82	71
2	84	70
3	83	72
4	76	68
5	70	63
6	63	54
7	58	48
8	54	45
A-wgtd	**78**	**69**

Sound Power (dB)

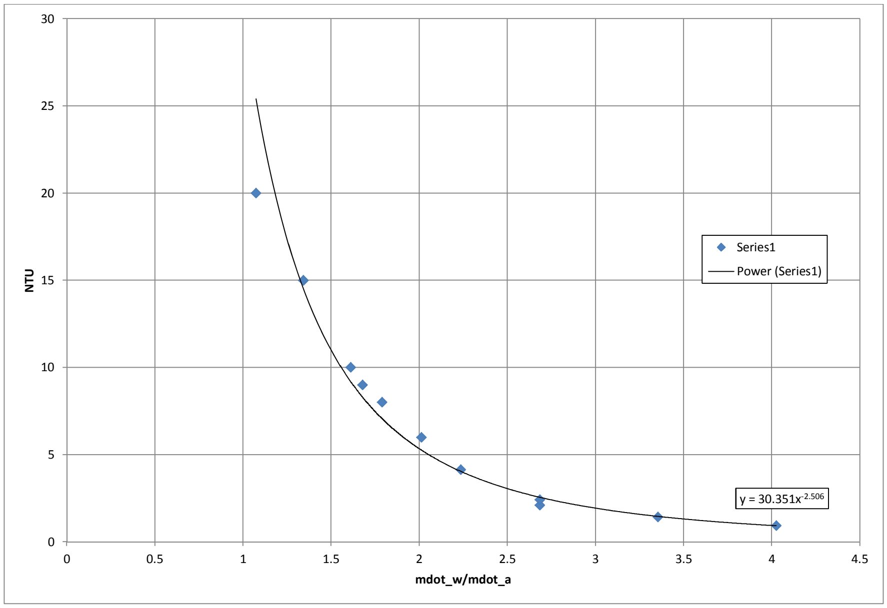
Octave Band	Center Frequency (Hertz)	Lw
1	63	107
2	125	105
3	250	106
4	500	100
5	1000	95
6	2000	88
7	4000	84
8	8000	81

Note: The use of frequency inverters (variable frequency drives) can increase sound levels.

	mdotw/mdota	NTU
3	1.341755937	15
5	1.677194921	9
10	2.236259894	4.136592
11	3.354389841	1.422928
1	1.073404749	20
2	1.341755937	15
6	1.789007915	8
9	2.683511873	2.41747
4	1.610107124	10
7	2.012633905	6
8	2.683511873	2.097041
12	4.02526781	0.935385

	mdotw/mdota	**NTU**
1	1.073404749	20
2	1.341755937	15
3	1.341755937	15
4	1.610107124	10
5	1.677194921	9
6	1.789007915	8
7	2.012633905	6
8	2.683511873	2.097041
9	2.683511873	2.41747
10	2.236259894	4.136592
11	3.354389841	1.422928
12	4.02526781	0.935385

c	30.35
n+1	-2.506
n	-3.506



Appendix D - Selected Cal Poly Plant Data - Sept 21st - Sept 25th

Date	Time	CHW-S Temp	CHW-R Temp	CHW Flow	OA Enthalpy	OA Humidity	OA DB Temp	TES FLOW	TES CHW-R	TES CHW-S	CH1 Energy	CH2 Energy	CH3 Energy	CH4 Energy	CH1A Energy	CH1A Power
		deg. F	deg. F	GPM	BTU/lbm	%	deg F	GPM	deg. F	deg. F	KWH	KWH	KWH	KWH	KWH	KW
9/20/2015	11:30:00	38.4	56	1728	29.85	22	91.8	-259	51.2	38.6	143118	116889	66675	41327	3998697	716
9/20/2015	12:00:00	38.2	55.2	1736	30.22	21	92.9	-298	51.1	38.2	143118	116889	66675	41327	3999052	687
9/20/2015	12:30:00	39.1	58.5	1722	30.59	22	93.6	-183	51.2	38.2	143118	116889	66675	41327	3999424	775
9/20/2015	13:00:00	39.5	59	1739	30.81	23	93.1	-315	51	39.5	143118	116889	66675	41327	3999813	786
9/20/2015	13:30:00	39.8	58	1691	30.93	23	93.2	0	53.2	39.5	143118	116889	66675	41327	4000194	785
9/20/2015	14:00:00	39.5	57.5	1741	30.58	24	91.7	0	57	39.9	143118	116889	66675	41327	4000592	781
9/20/2015	14:30:00	38.8	56.9	1712	30.48	23	92.5	-175	48.7	39.9	143118	116889	66675	41327	4000980	772
9/20/2015	15:00:00	38.6	56.9	1728	30.27	24	91.4	-165	50.7	38.8	143118	116889	66675	41327	4001369	778
9/20/2015	15:30:00	38.3	57.1	1723	30.41	25	90.9	-368	50.9	38.8	143118	116889	66675	41327	4001748	774
9/20/2015	16:00:00	38.4	56.4	1720	30.24	25	90.2	-382	50.7	38.3	143118	116889	66675	41327	4002124	719
9/20/2015	16:30:00	38.8	56.2	1719	29.91	26	89.2	-384	50.5	38.3	143118	116889	66675	41327	4002486	651
9/20/2015	17:00:00	38.2	56.5	1718	29.74	26	88.8	-373	50.3	38.2	143118	116889	66675	41327	4002836	718
9/20/2015	17:30:00	38.9	56.4	1731	29.1	26	87.9	-336	50.1	38.2	143118	116889	66675	41327	4003187	647
9/20/2015	18:00:00	38.4	56	1679	28.84	25	87.5	-365	50	38.4	143118	116889	66675	41327	4003524	672
9/20/2015	18:30:00	38.3	56.2	1725	28.7	23	88.9	-398	49.9	38.4	143118	116889	66675	41327	4003854	672
9/20/2015	19:00:00	38.3	56	1680	28.03	28	84.3	-478	49.7	38.4	143118	116889	66675	41327	4004180	620
9/20/2015	19:30:00	38.1	56.5	1706	27.26	28	82.8	-720	48.6	38.4	143118	116889	66675	41327	4004482	570
9/20/2015	20:00:00	39	55.6	0	27.03	30	81.2	938	55.1	39.1	143118	116889	66675	41327	4004620	2
9/20/2015	20:30:00	39.1	55.1	0	26.73	33	79.2	757	54.5	39.1	143118	116889	66675	41327	4004621	2
9/20/2015	21:00:00	39.1	55.1	0	26.48	33	78.6	705	54.5	39.2	143118	116889	66675	41327	4004622	2
9/20/2015	21:30:00	39.1	54.9	0	26.22	34	77.6	689	54.5	39.2	143118	116889	66675	41327	4004623	2
9/20/2015	22:00:00	39.1	54.5	0	26.06	35	76.7	712	54.2	39.2	143118	116889	66675	41327	4004624	2
9/20/2015	22:30:00	39.1	54.1	0	25.85	37	75.7	649	53.7	39.2	143118	116889	66675	41327	4004625	2
9/20/2015	23:00:00	39	53.4	0	25.51	37	74.9	705	53.3	39.2	143118	116889	66675	41327	4004626	2
9/20/2015	23:30:00	39	53	0	25.45	38	74.6	694	52.8	39.2	143118	116889	66675	41327	4004627	2
9/21/2015	0:00:00	39.8	52.5	1743	25.63	39	74.4	-726	53.5	39.9	143118	116889	66675	41327	4004701	416
9/21/2015	0:30:00	38.2	51.7	1678	25.18	39	73.4	-1004	53.5	39.9	143118	116889	66675	41327	4004949	508
9/21/2015	1:00:00	38.3	50.7	1668	25.07	39	73.3	-915	53.5	38.4	143118	116889	66675	41327	4005196	485
9/21/2015	1:30:00	38.2	49.9	1668	25.07	42	72.4	-1021	53.5	38.4	143118	116889	66675	41327	4005436	482
9/21/2015	2:00:00	38.4	50.3	1681	24.75	42	71.7	-1039	53.4	38.6	143118	116889	66675	41327	4005672	464
9/21/2015	2:30:00	38.2	50.4	1709	24.87	40	72.2	-1099	53.3	38.6	143118	116889	66675	41327	4005909	475
9/21/2015	3:00:00	38	50.6	1683	24.63	38	72.7	-1074	50.9	38.5	143118	116889	66675	41327	4006142	420
9/21/2015	3:30:00	39	51	0	24.89	38	73.2	679	50.7	38.5	143119	116889	66675	41327	4006185	2
9/21/2015	4:00:00	39	50.4	0	24.77	38	72.9	621	50.5	39.2	143119	116889	66675	41327	4006186	2
9/21/2015	4:30:00	39	49.9	0	24.63	39	72.3	670	50	39.2	143119	116889	66675	41327	4006187	2
9/21/2015	5:00:00	39	49.4	0	24.37	42	70.7	606	49.6	39.2	143119	116889	66675	41327	4006188	2
9/21/2015	5:30:00	39	49.4	0	24.54	45	70.2	721	49.4	39.2	143119	116889	66675	41327	4006189	2
9/21/2015	6:00:00	39	50.4	0	24.76	46	70	791	50.2	39.2	143119	116889	66675	41327	4006190	2
9/21/2015	6:30:00	39	52.2	0	24.98	49	69.7	984	52.2	39.2	143119	116889	66675	41327	4006191	2
9/21/2015	7:00:00	48.9	52.3	1655	24.9	50	69.3	-490	51.8	48.7	143119	116889	66675	41327	4006197	148
9/21/2015	7:30:00	38.5	54.8	1662	25.32	51	69.4	-167	51.4	48.7	143119	116889	66675	41327	4006426	576
9/21/2015	8:00:00	38.2	53	1681	26.93	50	72.8	-290	51.3	38.5	143119	116889	66675	41327	4006703	533
9/21/2015	8:30:00	38.8	54.1	1655	28.52	52	74.8	-178	51.1	38.5	143119	116889	66675	41327	4006978	575
9/21/2015	9:00:00	38.3	54.9	1768	29.16	48	77.2	77	54.6	38.7	143119	116889	66675	41327	4007296	689
9/21/2015	9:30:00	38.4	55	1946	29.63	43	80.1	190	54.7	38.7	143119	116889	66675	41327	4007630	683
9/21/2015	10:00:00	38.5	55.7	2083	29.91	36	83.6	286	55.3	39.3	143119	116889	66675	41327	4007998	748
9/21/2015	10:30:00	38.6	55.6	2186	30.29	29	88	373	55.1	39.3	143119	116889	66675	41327	4008365	730
9/21/2015	11:00:00	38.9	56.6	2396	30.88	23	93.2	543	56.3	39.3	143119	116889	66675	41327	4008750	778
9/21/2015	11:30:00	39.1	56.9	2346	29.33	13	98.5	547	56.5	39.3	143119	116889	66675	41327	4009140	781
9/21/2015	12:00:00	39.6	57.5	2505	33.11	23	97.4	694	57.1	39.3	143119	116889	66675	41327	4009529	781
9/21/2015	12:30:00	39.3	56.6	0	31.68	30	90	2356	56.2	39.3	143119	116889	66675	41327	4009553	2
9/21/2015	13:00:00	39.3	56.2	0	31.94	33	88.6	2235	55.8	39.3	143119	116889	66675	41327	4009554	2
9/21/2015	13:30:00	39.3	55.9	0	30.84	30	88.4	2135	55.6	39.3	143119	116889	66675	41327	4009555	2

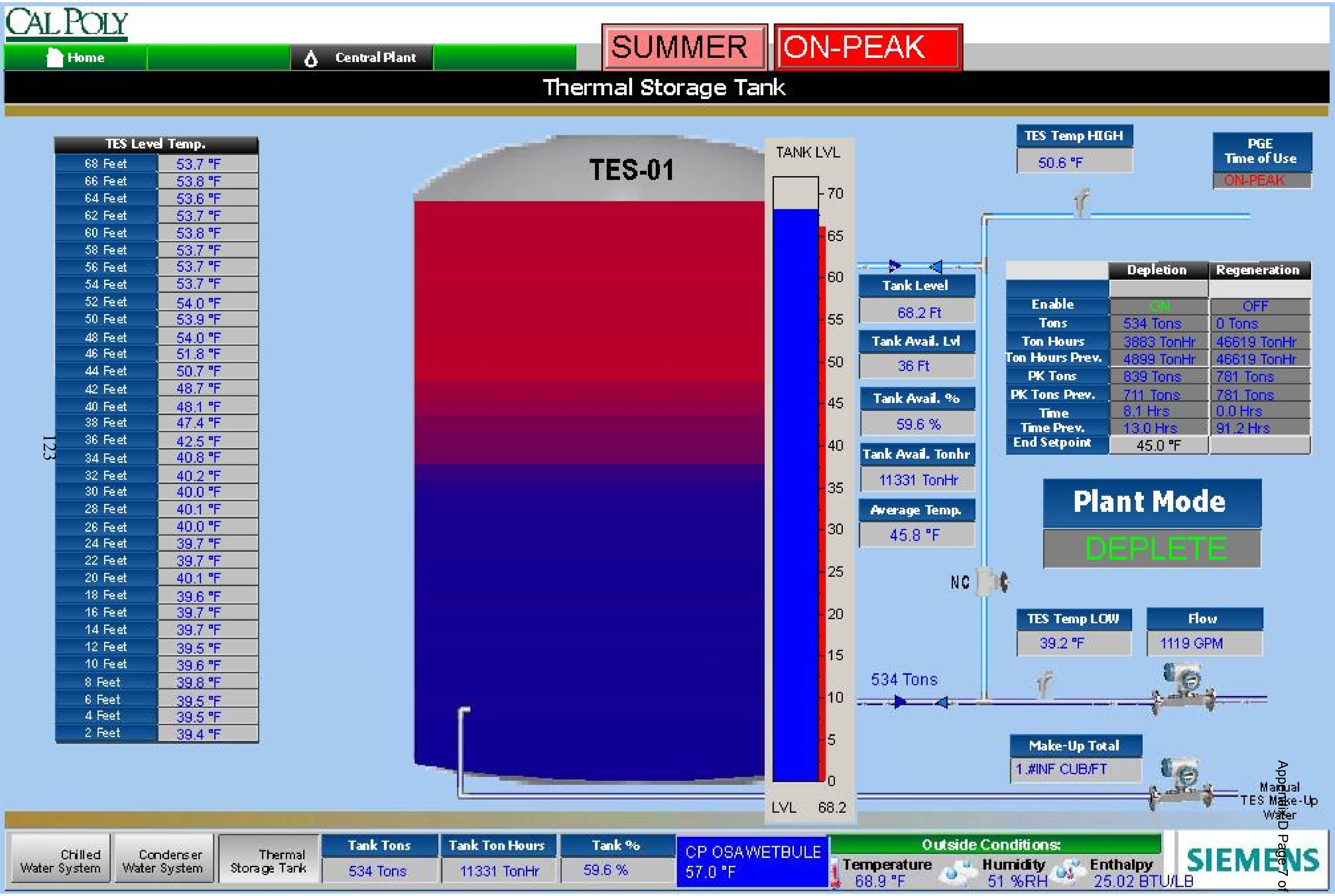
Date	Time	CHW-S Temp	CHW-R Temp	CHW Flow	OA Enthalpy	OA Humidity	OA DB Temp	TES FLOW	TES CHW-R	TES CHW-S	CH1 Energy	CH2 Energy	CH3 Energy	CH4 Energy	CH1A Energy	CH1A Power
		deg. F	deg. F	GPM	BTU/lbm	%	deg F	GPM	deg. F	deg. F	KWH	KWH	KWH	KWH	KWH	KW
9/21/2015	**14:00:00**	39.4	55.9	0	29.15	23	90	1999	55.5	39.4	143119	116889	66675	41327	4009556	2
9/21/2015	**14:30:00**	39.4	56.4	0	31.19	30	89	2149	56.1	39.4	143119	116889	66675	41327	4009557	2
9/21/2015	**15:00:00**	39.5	56.7	0	31.91	37	86.7	2156	56.4	39.5	143119	116889	66675	41327	4009558	2
9/21/2015	**15:30:00**	39.6	55.7	0	29.29	27	87.3	1954	55.4	39.5	143119	116889	66675	41327	4009559	2
9/21/2015	**16:00:00**	39.6	56.2	0	33.86	48	84.5	2261	55.8	39.7	143119	116889	66675	41327	4009560	2
9/21/2015	**16:30:00**	39.7	55.7	0	33.07	53	81.4	2318	55.4	39.7	143119	116889	66675	41327	4009561	2
9/21/2015	**17:00:00**	39.9	55.1	0	32.61	55	80.2	2245	54.8	40	143119	116889	66675	41327	4009562	2
9/21/2015	**17:30:00**	40.1	55.2	0	32.28	59	78.4	2021	55	40	143119	116889	66675	41327	4009563	2
9/21/2015	**18:00:00**	40.4	55.6	0	31.61	62	76.4	1751	55.3	40.5	143119	116889	66675	41327	4009564	2
9/21/2015	**18:30:00**	38.6	56.3	1889	31.55	62	76.4	128	55.9	40.5	143119	116889	66675	41327	4009758	759
9/21/2015	**19:00:00**	38.2	55.6	1703	31.16	66	74.5	0	55.2	40.7	143119	116889	66675	41327	4010132	747
9/21/2015	**19:30:00**	38.4	54.5	1736	30.92	70	73.1	-279	55.2	40.7	143119	116889	66675	41327	4010500	681
9/21/2015	**20:00:00**	38.3	54.4	1752	30.6	70	72.5	-312	55.5	38.4	143119	116889	66675	41327	4010836	680
9/21/2015	**20:30:00**	38.3	54.3	1737	30.5	71	72	-466	55.5	38.4	143119	116889	66675	41327	4011172	666
9/21/2015	**21:00:00**	38.2	53.9	1738	30.45	71	72.1	-429	55.5	38.3	143119	116889	66675	41327	4011495	656
9/21/2015	**21:30:00**	38.2	53.7	1650	30.46	73	71.5	-553	55.5	38.3	143119	116889	66675	41327	4011828	658
9/21/2015	**22:00:00**	38.1	54.4	1716	30.56	72	71.9	-621	55.5	38.3	143119	116889	66675	41327	4012163	667
9/21/2015	**22:30:00**	38.2	53.6	1714	30.54	72	72	-757	55.5	38.3	143119	116889	66675	41327	4012505	677
9/21/2015	**23:00:00**	38.3	53.3	1679	30.65	71	72.5	-776	55.5	38.4	143119	116889	66675	41327	4012837	671
9/21/2015	**23:30:00**	38.3	52.8	1690	30.52	71	72.2	-849	55.5	38.4	143120	116889	66675	41327	4013161	649
9/22/2015	**0:00:00**	38.3	52.5	1699	30.48	71	72.1	-906	55.5	38.5	143120	116889	66675	41327	4013480	639
9/22/2015	**0:30:00**	38.4	52	1686	30.67	72	72.2	-904	55.5	38.5	143120	116889	66675	41327	4013798	625
9/22/2015	**1:00:00**	38.4	51.1	1718	30.64	72	72	-1007	55.5	38.5	143120	116889	66675	41327	4014109	618
9/22/2015	**1:30:00**	38.4	51.7	1657	30.59	73	71.8	-961	55.5	38.5	143120	116889	66675	41327	4014415	621
9/22/2015	**2:00:00**	38.3	51.9	1710	30.52	74	71.4	-1024	55.5	38.4	143120	116889	66675	41327	4014730	636
9/22/2015	**2:30:00**	38.3	52.1	1679	30.53	74	71.5	-1013	55.5	38.4	143120	116889	66675	41327	4015049	637
9/22/2015	**3:00:00**	38.2	51.9	1684	30.13	78	69.9	-1021	55.5	38.4	143120	116889	66675	41327	4015370	638
9/22/2015	**3:30:00**	38.2	51.7	1683	30.08	78	69.9	-862	55.5	38.4	143120	116889	66675	41327	4015687	621
9/22/2015	**4:00:00**	38.3	51.5	1696	29.96	78	69.6	-865	55.5	38.8	143120	116889	66675	41327	4015999	594
9/22/2015	**4:30:00**	38.2	51.7	1710	29.8	78	69.5	-901	55.5	38.8	143120	116889	66675	41327	4016305	618
9/22/2015	**5:00:00**	38.3	51.5	1686	29.96	78	69.6	-860	55.4	38.5	143120	116889	66675	41327	4016602	600
9/22/2015	**5:30:00**	38.4	51.6	1711	29.83	78	69.5	-760	55.4	38.5	143120	116889	66675	41327	4016894	588
9/22/2015	**6:00:00**	38.3	52.7	1712	29.64	79	68.9	-675	55.4	38.5	143120	116889	66675	41327	4017198	600
9/22/2015	**6:30:00**	38.3	54	1744	29.86	75	70.3	-364	55.3	38.5	143120	116889	66675	41327	4017512	660
9/22/2015	**7:00:00**	38.3	53.8	1717	29.96	75	70.3	-347	55.3	38.4	143120	116889	66675	41327	4017835	638
9/22/2015	**7:30:00**	38.3	54.7	1665	29.88	77	69.8	-159	54.9	38.4	143120	116889	66675	41327	4018155	661
9/22/2015	**8:00:00**	38.4	53.6	1738	30.04	75	70.5	-231	55	38.5	143120	116889	66675	41327	4018480	624
9/22/2015	**8:30:00**	38.4	54	1740	30.33	73	71.3	-183	55	38.5	143120	116889	66675	41327	4018785	638
9/22/2015	**9:00:00**	38.5	54.9	1764	30.24	75	70.7	0	54.4	38.6	143120	116889	66675	41327	4019113	653
9/22/2015	**9:30:00**	38.8	55	1864	30	72	71.1	172	54.6	38.6	143120	116889	66675	41327	4019441	661
9/22/2015	**10:00:00**	38.4	54.3	1964	30.52	65	73.9	173	54.1	39	143120	116889	66675	41327	4019785	667
9/22/2015	**10:30:00**	38.2	54.6	2240	31.03	60	76.2	461	54.4	39	143120	116889	66675	41327	4020123	713
9/22/2015	**11:00:00**	40	55	2422	31.32	52	79.2	-139	53.5	39	143120	116889	66681	41374	4020465	655
9/22/2015	**11:30:00**	39.2	55.6	2495	32.04	50	81.1	-207	53.6	41	143120	116889	66749	41450	4020812	706
9/22/2015	**12:00:00**	38.8	56.2	2183	32.3	52	80.9	394	55.9	39.3	143120	116889	66800	41501	4021170	773
9/22/2015	**12:30:00**	39	55.9	0	31.91	50	80.8	1940	55.7	39.3	143120	116889	66800	41501	4021196	2
9/22/2015	**13:00:00**	38.9	55.5	0	31.86	48	81.8	1894	55.3	39	143120	116889	66800	41501	4021197	2
9/22/2015	**13:30:00**	38.9	55.6	0	32.55	45	84	1919	55.4	39	143120	116889	66800	41501	4021198	2
9/22/2015	**14:00:00**	39.2	57.2	2546	32.46	48	82.6	703	56.9	39	143120	116889	66800	41501	4021394	778
9/22/2015	**14:30:00**	38.9	56.5	2373	32	48	81.9	543	56.2	39	143120	116889	66800	41501	4021788	777
9/22/2015	**15:00:00**	38.4	55.5	2184	31.16	55	78	391	55.2	39.1	143120	116889	66800	41501	4022170	749
9/22/2015	**15:30:00**	38.5	55.5	2101	30.8	58	76.6	322	55.1	39.1	143120	116889	66800	41501	4022533	733
9/22/2015	**16:00:00**	38.6	55.1	2056	30.71	58	76.3	295	54.8	39.1	143120	116889	66800	41501	4022899	692

Date	Time	CHW-S Temp	CHW-R Temp	CHW Flow	OA Enthalpy	OA Humidity	OA DB Temp	TES FLOW	TES CHW-R	TES CHW-S	CH1 Energy	CH2 Energy	CH3 Energy	CH4 Energy	CH1A Energy	CH1A Power
		deg. F	deg. F	GPM	BTU/lbm	%	deg F	GPM	deg. F	deg. F	KWH	KWH	KWH	KWH	KWH	KW
9/22/2015	16:30:00	38.3	55.1	2069	30.43	60	75.3	299	54.7	39.1	143121	116889	66800	41501	4023258	718
9/22/2015	17:00:00	38.5	54.8	1974	29.91	63	73.4	218	54.6	39.1	143121	116889	66800	41501	4023613	704
9/22/2015	17:30:00	38.5	55.1	1879	29.61	63	73.1	159	54.7	39.1	143121	116889	66800	41501	4023957	689
9/22/2015	18:00:00	38.3	55.4	1724	29.29	65	72	0	54.9	38.5	143121	116889	66800	41501	4024301	700
9/22/2015	18:30:00	40.3	55.1	2339	28.64	69	69.9	-1050	55.4	38.5	143121	116934	66800	41501	4024620	617
9/22/2015	19:00:00	40.5	54.6	2372	27.89	74	67.5	-1136	55.4	40.6	143121	117010	66800	41501	4024923	596
9/22/2015	19:30:00	40.5	54.5	2373	27.28	77	66.1	-1214	55.4	40.6	143121	117086	66800	41501	4025214	575
9/22/2015	20:00:00	39	53.7	2387	27.12	78	65.4	-1327	55.4	40.6	143121	117091	66826	41527	4025510	595
9/22/2015	20:30:00	39.5	53.1	2397	27.24	79	65.4	-1405	55.4	39.2	143121	117091	66890	41600	4025793	516
9/22/2015	21:00:00	38.9	53.1	2418	27.46	79	65.7	-1422	55.4	39.2	143121	117091	66951	41674	4026077	564
9/22/2015	21:30:00	39.1	53.3	2375	27.28	80	65.3	-1552	55.4	39.2	143121	117091	66982	41711	4026217	576
9/22/2015	22:00:00	39	53.2	2370	27.52	80	65.6	-1564	55.4	39.2	143121	117091	67074	41824	4026645	568
9/22/2015	22:30:00	39	53.6	2388	27.35	81	65	-1723	55.4	39.3	143121	117091	67136	41899	4026929	575
9/22/2015	23:00:00	39	53.1	2373	27.11	81	64.7	-1720	55.4	39.2	143121	117091	67198	41976	4027214	568
9/22/2015	23:30:00	39	52.1	2379	27.08	81	64.9	-1762	55.4	39.2	143121	117091	67259	42053	4027491	559
9/23/2015	0:00:00	38.9	52.6	2354	27.11	81	64.6	-1793	55.4	39.2	143121	117091	67319	42129	4027770	559
9/23/2015	0:30:00	39	50.7	2367	26.75	82	64.1	-1836	55.4	39.2	143121	117091	67379	42205	4028042	516
9/23/2015	1:00:00	39	50.3	2346	26.89	82	64.1	-1833	55.4	39.2	143121	117091	67409	42243	4028178	532
9/23/2015	1:30:00	38.9	50.1	2375	26.94	81	64.6	-1895	55.3	39.4	143121	117091	67496	42353	4028581	542
9/23/2015	2:00:00	39	50.5	2367	27.06	79	64.9	-1909	55.3	39.3	143121	117091	67554	42426	4028853	540
9/23/2015	2:30:00	39.4	50.2	2355	26.72	80	64.4	-1909	52.3	39.3	143121	117091	67611	42495	4029102	422
9/23/2015	3:00:00	38.9	50.4	2358	26.62	78	64.6	-1900	51	39.3	143121	117091	67669	42549	4029300	394
9/23/2015	3:30:00	39	51.9	2368	26.46	76	64.7	-1773	50.6	39.3	143121	117091	67698	42575	4029397	371
9/23/2015	4:00:00	38.7	50.1	2374	26.72	78	64.8	-1860	49.1	39.3	143121	117091	67756	42628	4029585	366
9/23/2015	4:30:00	38.5	48.9	2372	26.51	78	64.4	-1898	43.6	38.9	143121	117091	67827	42698	4029810	273
9/23/2015	5:00:00	37.6	49.6	2372	26	81	63.1	-1916	40.8	38.9	143121	117091	67874	42698	4029920	202
9/23/2015	5:30:00	40.5	48.6	738	26.03	80	63.3	-264	40.1	39.2	143122	117091	67923	42698	4029981	2
9/23/2015	6:00:00	41.1	49.1	718	25.88	81	62.8	-243	40	39.2	143122	117091	67952	42698	4029981	2
9/23/2015	6:30:00	41	50.9	744	25.44	84	61.5	0	40.5	41.3	143122	117091	68020	42698	4029982	2
9/23/2015	7:00:00	40.5	51.3	693	25.51	83	61.8	0	40.2	41.3	143122	117091	68100	42718	4029983	2
9/23/2015	7:30:00	40.7	52.7	809	25.48	84	61.6	64	52.5	41	143122	117091	68161	42773	4029984	2
9/23/2015	8:00:00	42.1	53.5	612	25.67	82	62.3	520	53.5	41	143130	117091	68204	42815	4029985	2
9/23/2015	8:30:00	39.2	53	0	25.52	79	62.7	601	53.4	40.8	143141	117091	68204	42815	4029986	2
9/23/2015	9:00:00	39	52.5	0	25.84	72	64.9	733	52.5	40.8	143141	117091	68204	42815	4029987	2
9/23/2015	9:30:00	39	53.7	0	26.6	66	67.5	795	53.3	39.4	143141	117091	68204	42815	4029988	2
9/23/2015	10:00:00	39	54.7	0	26.73	55	70.7	970	54.6	39.4	143141	117091	68204	42815	4029989	2
9/23/2015	10:30:00	39	54.6	0	25.72	37	75.3	1045	54.4	39.4	143141	117091	68204	42815	4029990	2
9/23/2015	11:00:00	39	56.3	0	25.83	27	80.3	1294	58.2	39.4	143141	117091	68204	42815	4029991	2
9/23/2015	11:30:00	39.1	58.1	0	28.36	31	83.1	1236	57.3	39.4	143141	117091	68204	42815	4029992	2
9/23/2015	12:00:00	39.1	58	0	27.87	27	84.7	1222	57.8	39.4	143141	117091	68204	42815	4029993	2
9/23/2015	12:30:00	39.1	57.8	0	28.79	30	84.5	1248	57.7	39.4	143141	117091	68204	42815	4029995	2
9/23/2015	13:00:00	39.1	58.1	0	28.93	31	84.6	1289	57.8	39.4	143141	117091	68204	42815	4029995	2
9/23/2015	13:30:00	39.2	58.6	0	29.47	37	82.7	1336	58.3	39.4	143142	117091	68204	42815	4029997	2
9/23/2015	14:00:00	39.2	58.1	0	29.37	38	81.8	1340	58	39.4	143142	117091	68204	42815	4029997	2
9/23/2015	14:30:00	39.2	57.4	0	28.95	35	82.3	1318	57.2	39.4	143142	117091	68204	42815	4029998	2
9/23/2015	15:00:00	39.2	58	0	28.28	31	83.5	1356	57.7	39.4	143142	117091	68204	42815	4029999	2
9/23/2015	15:30:00	39.3	57.8	0	28.27	29	84.4	1392	57.5	39.5	143142	117091	68204	42815	4030001	2
9/23/2015	16:00:00	39.3	58.1	0	28.51	33	82.5	1331	57.9	39.5	143142	117091	68204	42815	4030001	2
9/23/2015	16:30:00	39.3	57.7	0	28.21	30	83.5	1330	57.4	39.5	143142	117091	68204	42815	4030003	2
9/23/2015	17:00:00	39.3	57.8	0	28.25	32	82.8	1386	57.6	39.5	143142	117091	68204	42815	4030003	2
9/23/2015	17:30:00	39.3	58	0	28.19	35	80.9	1323	57.7	39.5	143142	117091	68204	42815	4030004	2
9/23/2015	18:00:00	39.4	57.7	0	28.34	41	78.8	1211	57.5	39.6	143142	117091	68204	42815	4030005	2
9/23/2015	18:30:00	39.4	57.2	0	28.31	46	76.7	1043	57.1	39.6	143142	117091	68204	42815	4030006	2

Date	Time	CHW-S Temp	CHW-R Temp	CHW Flow	OA Enthalpy	OA Humidity	OA DB Temp	TES FLOW	TES CHW-R	TES CHW-S	CH1 Energy	CH2 Energy	CH3 Energy	CH4 Energy	CH1A Energy	CH1A Power
		deg. F	deg. F	GPM	BTU/lbm	%	deg F	GPM	deg. F	deg. F	KWH	KWH	KWH	KWH	KWH	KW
9/23/2015	19:00:00	39.4	57	1210	28.09	48	75.4	1013	56.5	57.1	143142	117091	68204	42815	4030008	66
9/23/2015	19:30:00	38.3	56.7	1722	28.42	63	71.3	-502	57.1	57.1	143142	117091	68204	42815	4030089	437
9/23/2015	20:00:00	38.1	55.7	1659	28.29	66	70.2	-541	57.2	57.1	143142	117091	68204	42815	4030451	779
9/23/2015	20:30:00	38.3	55.5	1707	28.17	64	70.5	-647	57.3	38.3	143142	117091	68204	42815	4030824	771
9/23/2015	21:00:00	38.2	55.1	1708	27.99	63	70.7	-688	57.3	38.5	143142	117091	68204	42815	4031204	724
9/23/2015	21:30:00	38.2	53.9	1704	27.72	63	70.1	-834	57.3	38.5	143142	117091	68204	42815	4031573	732
9/23/2015	22:00:00	38.2	53	1675	27.28	64	69.1	-905	57.3	38.5	143142	117091	68204	42815	4031928	707
9/23/2015	22:30:00	38.2	53.2	1677	26.75	63	68.5	-972	57.3	38.5	143142	117091	68204	42815	4032278	696
9/23/2015	23:00:00	38.2	52.8	1668	26.95	64	68.6	-961	57.3	38.4	143142	117091	68204	42815	4032616	670
9/23/2015	23:30:00	38.1	51.8	1692	26.03	61	67.8	-1016	57.3	38.4	143142	117091	68204	42815	4032949	632
9/24/2015	0:00:00	38.4	52.9	1636	23.16	37	70.1	-994	57.3	38.9	143142	117091	68204	42815	4033273	650
9/24/2015	0:30:00	38.2	51.9	1686	23.09	30	72.5	-1073	57.3	38.9	143142	117091	68204	42815	4033601	632
9/24/2015	1:00:00	38.1	50.9	1655	22.75	28	72.8	-1032	57.3	38.4	143142	117091	68204	42815	4033911	606
9/24/2015	1:30:00	38.2	51.7	1687	22.85	16	79.5	-1058	57.2	38.4	143142	117091	68204	42815	4034222	630
9/24/2015	2:00:00	38.2	52.2	1648	23.44	14	82	-1041	57.2	38.4	143142	117091	68204	42815	4034533	629
9/24/2015	2:30:00	38.2	52.3	1573	23.62	15	82.2	-916	57.2	38.4	143142	117091	68204	42815	4034857	644
9/24/2015	3:00:00	38.1	52.6	1684	24.16	18	81.7	-1069	57.2	38.4	143142	117091	68204	42815	4035182	652
9/24/2015	3:30:00	38.3	53.5	1684	24.41	20	80.7	-908	57.2	38.4	143142	117091	68204	42815	4035673	663
9/24/2015	4:00:00	38.3	53	1672	24.42	20	80.6	-991	57.2	38.6	143142	117091	68204	42815	4036006	652
9/24/2015	4:30:00	38.2	53	1689	24.41	22	79.9	-930	57.2	38.6	143142	117091	68204	42815	4036337	632
9/24/2015	5:00:00	38.2	52.4	1669	24.49	23	79.3	-887	57.1	38.4	143142	117091	68204	42815	4036655	636
9/24/2015	5:30:00	38.3	53	1741	24.96	24	79.7	-751	57.1	38.4	143142	117091	68204	42815	4036961	606
9/24/2015	6:00:00	38.3	54.4	1683	25.14	24	80.3	-688	57	38.6	143142	117091	68204	42815	4037288	666
9/24/2015	6:30:00	38.3	56.2	1705	25.12	25	79.8	-516	56.9	38.6	143142	117091	68204	42815	4037637	732
9/24/2015	7:00:00	38.3	55.5	1679	25.18	27	78.8	-481	56.9	38.5	143142	117091	68204	42815	4037994	701
9/24/2015	7:30:00	38.4	55.9	1714	25.37	26	79.6	-475	56.9	38.5	143142	117091	68204	42815	4038348	714
9/24/2015	8:00:00	38.2	55.6	1706	25.43	26	79.6	-509	56.8	38.4	143142	117091	68204	42815	4038709	747
9/24/2015	8:30:00	40	55.7	2358	25.17	25	79.9	-1019	56.5	38.4	143151	117127	68204	42815	4039055	790
9/24/2015	9:00:00	38.7	56.7	2362	25.84	26	80.6	-929	55.7	38.9	143230	117199	68204	42815	4039389	639
9/24/2015	9:30:00	38.6	54.8	2400	25.68	22	82.9	-345	55.1	38.9	143311	117269	68204	42815	4039696	567
9/24/2015	10:00:00	39	55.3	2362	26.45	22	84.7	-403	54.8	39.1	143388	117332	68204	42815	4039984	583
9/24/2015	10:30:00	38.6	55.1	2444	26.7	18	87.4	-422	54.5	39.1	143466	117395	68204	42815	4040279	616
9/24/2015	11:00:00	38.7	54.7	2464	27.12	16	90	-446	54.2	38.8	143545	117459	68204	42815	4040577	578
9/24/2015	11:30:00	38.5	56.3	1979	27.69	15	92.7	211	55.9	38.8	143565	117476	68204	42815	4040907	769
9/24/2015	12:00:00	39.1	57	0	27.89	13	94.9	2038	56.6	39.1	143565	117476	68204	42815	4040973	2
9/24/2015	12:30:00	39.1	55.9	0	28.44	12	97.2	1843	55.5	39.1	143565	117476	68204	42815	4040974	2
9/24/2015	13:00:00	39.2	55.9	0	28.63	11	98.4	1928	55.5	39.1	143565	117476	68204	42815	4040975	2
9/24/2015	13:30:00	39.2	55.6	0	28.53	10	99.1	1983	55.1	39.1	143565	117476	68204	42815	4040976	2
9/24/2015	14:00:00	39.2	55.5	0	31.35	20	96.4	1986	55.1	39.1	143565	117476	68204	42815	4040977	2
9/24/2015	14:30:00	39.2	55.5	0	31.46	23	94.3	2068	55	39.1	143565	117476	68204	42815	4040978	2
9/24/2015	15:00:00	39.2	55.1	0	30.6	24	91.6	2087	54.5	39.1	143565	117476	68204	42815	4040979	2
9/24/2015	15:30:00	39.2	56	0	29.23	21	91.2	1834	55.5	39.1	143565	117476	68204	42815	4040980	2
9/24/2015	16:00:00	39.2	55.1	0	28.71	19	91.2	1831	54.7	39.2	143565	117476	68204	42815	4040981	2
9/24/2015	16:30:00	39.2	55.7	0	28.43	20	90	1887	55.4	39.2	143565	117476	68204	42815	4040982	2
9/24/2015	17:00:00	39.2	55.7	0	27.13	17	89.6	1864	55.4	39.2	143565	117476	68204	42815	4040983	2
9/24/2015	17:30:00	39.3	56.1	0	26.58	17	88.2	1857	55.8	39.2	143565	117476	68204	42815	4040984	2
9/24/2015	18:00:00	39.5	56.1	0	26.06	16	87.8	1490	55.7	39.6	143565	117476	68204	42815	4040985	2
9/24/2015	18:30:00	38.5	57	1741	26.39	18	87.3	-121	54.8	39.6	143565	117476	68204	42815	4041172	798
9/24/2015	19:00:00	38.6	55.1	1739	26.54	21	85.1	-76	55.2	38.4	143565	117476	68204	42815	4041544	643
9/24/2015	19:30:00	38.4	55.7	1701	26.18	23	82.9	-220	55.2	38.4	143565	117476	68204	42815	4041866	672
9/24/2015	20:00:00	38.2	54.7	1723	25.84	25	81.1	-318	55.3	38.4	143565	117476	68204	42815	4042200	641
9/24/2015	20:30:00	43.7	54.3	2412	26.63	31	79.7	-1189	55.5	38.4	143565	117476	68204	42815	4042513	588
9/24/2015	21:00:00	39.3	54.9	2404	27.17	41	76.7	-1110	55.4	39.5	143565	117476	68266	42889	4042799	568

Date	Time	CHW-S Temp	CHW-R Temp	CHW Flow	OA Enthalpy	OA Humidity	OA DB Temp	TES FLOW	TES CHW-R	TES CHW-S	CH1 Energy	CH2 Energy	CH3 Energy	CH4 Energy	CH1A Energy	CH1A Power
		deg. F	deg. F	GPM	BTU/lbm	%	deg F	GPM	deg. F	deg. F	KWH	KWH	KWH	KWH	KWH	KW
9/24/2015	21:30:00	39	53.9	2406	25.77	36	76	-1288	55.4	39.5	143565	117476	68327	42969	4043086	553
9/24/2015	22:00:00	39.1	53.8	2424	27.54	50	73.8	-1269	55.3	39.3	143565	117476	68387	43046	4043362	570
9/24/2015	22:30:00	38.9	52.6	2416	28.23	57	72.7	-1444	55.3	39.3	143565	117476	68450	43122	4043648	571
9/24/2015	23:00:00	38.9	53.3	2394	27.12	51	72.7	-1525	55.2	39.3	143565	117476	68482	43160	4043786	570
9/24/2015	23:30:00	39.2	52.7	2393	27.83	57	72	-1529	55.2	39.1	143565	117476	68575	43273	4044198	543
9/25/2015	0:00:00	39.1	52.7	2379	28.12	63	70.8	-1597	55.1	39.2	143565	117476	68636	43348	4044472	552
9/25/2015	0:30:00	39.3	51.8	2396	28.16	64	70.7	-1567	55.1	39.2	143565	117476	68697	43422	4044744	520
9/25/2015	1:00:00	39.1	51.2	2420	27.89	62	70.6	-1603	55.1	39.2	143565	117476	68758	43493	4045008	534
9/25/2015	1:30:00	38.9	50.7	2415	26.31	56	70	-1632	55.1	39.2	143565	117476	68818	43564	4045270	491
9/25/2015	2:00:00	39.4	50	2411	26.32	56	69.7	-1647	55	39.5	143565	117476	68879	43631	4045515	478
9/25/2015	2:30:00	39.1	49.7	2366	27.57	69	68.2	-1591	55	39.5	143565	117476	68939	43697	4045763	495
9/25/2015	3:00:00	39	49.9	2392	27.77	73	67.6	-1619	55	39.2	143565	117476	68999	43763	4046016	517
9/25/2015	3:30:00	39	49.3	2405	28.04	71	68.5	-1419	55	39.2	143565	117476	69061	43828	4046269	479
9/25/2015	4:00:00	39.1	50.6	2362	28.24	73	68.2	-1507	55	39.3	143566	117476	69123	43893	4046523	514
9/25/2015	4:30:00	38.9	49.9	2410	27.43	71	67.6	-1495	54.9	39.3	143566	117476	69185	43958	4046779	495
9/25/2015	5:00:00	39	49.1	2422	27.08	68	67.6	-1478	54.9	39.3	143566	117476	69215	43989	4046904	485
9/25/2015	5:30:00	38.7	49.7	2391	26.2	66	67	-1542	54.9	39.4	143566	117476	69306	44081	4047258	490
9/25/2015	6:00:00	39.2	49.4	2406	25.19	62	66.1	-1598	54.8	39.7	143566	117476	69365	44144	4047496	421
9/25/2015	6:30:00	39	51.1	2380	25.61	61	67.2	-1477	54.3	39.7	143566	117476	69425	44204	4047717	474
9/25/2015	7:00:00	39	50.1	2393	25.42	62	66.5	-1470	51.9	39.3	143566	117476	69484	44263	4047931	383
9/25/2015	7:30:00	40.2	51.2	1123	26.74	68	67	298	51	39.3	143566	117476	69542	44316	4047969	2
9/25/2015	8:00:00	40	50.7	1149	27.25	65	68.7	346	50.9	39.3	143566	117476	69573	44343	4047969	2
9/25/2015	8:30:00	40	52.7	1321	28.22	67	69.9	494	52.6	39.4	143566	117476	69665	44430	4047971	2
9/25/2015	9:00:00	39.8	53.6	1437	28.65	63	71.8	548	53.5	39.4	143566	117476	69727	44497	4047972	2
9/25/2015	9:30:00	39.8	53.8	1623	29.29	61	73.2	736	53.7	39.4	143566	117476	69789	44567	4047973	2
9/25/2015	10:00:00	39.7	53.9	1875	29.47	53	76.1	946	53.8	39.4	143566	117476	69851	44640	4047974	2
9/25/2015	10:30:00	39.9	54.5	1935	28.88	41	79.6	964	54.4	39.4	143566	117476	69914	44716	4047975	2
9/25/2015	11:00:00	39.6	54.8	2025	29.48	37	82.6	1084	54.7	39.4	143566	117476	69976	44792	4047976	2
9/25/2015	11:30:00	39.7	55	2044	28.78	29	85.1	1046	54.8	39.4	143566	117476	70006	44830	4047976	2
9/25/2015	12:00:00	40.2	56.3	0	28.56	25	87.2	1624	56.1	39.4	143566	117476	70030	44860	4047978	2
9/25/2015	12:30:00	40.3	56	0	32.69	38	87.2	1847	55.7	39.4	143566	117476	70030	44860	4047979	2
9/25/2015	13:00:00	40.4	56.3	0	32.08	43	83.9	1875	56.1	39.4	143566	117476	70030	44860	4047980	2
9/25/2015	13:30:00	40.5	56.6	0	32.51	46	83.7	1987	56.3	39.4	143566	117476	70030	44860	4047981	2
9/25/2015	14:00:00	40.5	56.3	0	32.75	42	85.6	1940	56	39.5	143566	117476	70030	44860	4047982	2
9/25/2015	14:30:00	40.6	56.6	0	32.58	39	86.5	2063	56.3	39.5	143566	117476	70030	44860	4047983	2
9/25/2015	15:00:00	40.7	56.8	0	32.45	39	86.3	2031	56.5	39.5	143566	117476	70030	44860	4047984	2
9/25/2015	15:30:00	40.4	56.4	0	32.34	40	85.7	1957	56.2	39.5	143566	117476	70030	44860	4047985	2
9/25/2015	16:00:00	40.3	56.3	0	31.93	42	84.4	1945	55.9	39.7	143566	117476	70030	44860	4047986	2
9/25/2015	16:30:00	40.4	56.7	0	31.34	42	83.6	1941	56.4	39.7	143566	117476	70030	44860	4047987	2
9/25/2015	17:00:00	40.8	56.6	0	31.03	44	82.1	1880	56.3	40.1	143566	117476	70030	44860	4047988	2
9/25/2015	17:30:00	40.9	56.4	0	30.46	49	79	1655	56.2	40.1	143566	117476	70030	44860	4047989	2
9/25/2015	18:00:00	41.5	56.3	0	29.9	53	76.7	1547	56.1	40.7	143566	117476	70030	44860	4047990	2
9/25/2015	18:30:00	38.8	56.6	1732	29.34	61	73.4	0	56.3	40.7	143566	117476	70030	44860	4048180	749
9/25/2015	19:00:00	39.1	55.8	2430	29.04	69	70.6	-769	56.2	40.7	143566	117476	70072	44914	4048531	669
9/25/2015	19:30:00	39	55	2470	28.61	71	69.3	-1052	56.2	39.3	143566	117476	70135	45001	4048864	649
9/25/2015	20:00:00	39	54.2	2424	28.32	74	68.1	-1081	56.2	39.3	143566	117476	70196	45087	4049174	623
9/25/2015	20:30:00	38.9	54.4	2412	28.27	76	67.8	-1162	56.2	39.3	143566	117476	70256	45173	4049488	625
9/25/2015	21:00:00	38.9	54.4	2397	28.06	76	67.3	-1176	56.2	39.1	143566	117476	70316	45258	4049800	622
9/25/2015	21:30:00	38.8	54.3	2409	27.89	77	66.8	-1254	56.2	39.1	143566	117476	70376	45343	4050118	623
9/25/2015	22:00:00	39	53.4	2421	27.81	77	66.6	-1464	56.2	39.2	143566	117476	70436	45428	4050416	603
9/25/2015	22:30:00	39	52.6	2394	27.91	76	67.1	-1515	56.2	39.2	143566	117476	70495	45511	4050717	592
9/25/2015	23:00:00	39	52.7	2384	27.91	75	67.4	-1568	56.1	39.3	143566	117476	70553	45593	4051006	586
9/25/2015	23:30:00	38.9	51.9	2389	27.83	74	67.3	-1626	56.1	39.3	143567	117476	70612	45673	4051292	576

Date	Time	CHW-S Temp	CHW-R Temp	CHW Flow	OA Enthalpy	OA Humidity	OA DB Temp	TES FLOW	TES CHW-R	TES CHW-S	CH1 Energy	CH2 Energy	CH3 Energy	CH4 Energy	CH1A Energy	CH1A Power
		deg. F	deg. F	GPM	BTU/lbm	%	deg F	GPM	deg. F	deg. F	KWH	KWH	KWH	KWH	KWH	KW
9/26/2015	0:00:00	38.9	51.4	2383	27.92	73	67.6	-1712	56.1	39.2	143567	117476	70672	45751	4051583	584
9/26/2015	0:30:00	39.2	52.1	2359	27.59	74	67.1	-1607	56.1	39.2	143567	117476	70733	45828	4051866	540
9/26/2015	1:00:00	39	50	2399	27	74	66.1	-1741	56	39.4	143567	117476	70793	45904	4052141	525
9/26/2015	1:30:00	38.8	49.2	2378	26.73	76	65.2	-1714	56	39.4	143567	117476	70852	45979	4052409	535
9/26/2015	2:00:00	38.9	49.1	2376	26.62	77	64.8	-1629	55.9	39.1	143567	117476	70912	46050	4052671	512
9/26/2015	2:30:00	38.9	50.3	2384	26.6	79	64.3	-1752	55.8	39.1	143567	117476	70972	46121	4052937	536
9/26/2015	3:00:00	38.9	49.8	2395	26.59	80	64.2	-1828	55.6	39.1	143567	117476	71032	46194	4053204	532
9/26/2015	3:30:00	38.9	48.4	2383	26.71	78	64.9	-1761	55.3	39.2	143567	117476	71091	46264	4053456	499
9/26/2015	4:00:00	38.8	49.5	2363	26.68	78	64.9	-1781	54.9	39	143567	117476	71151	46332	4053711	511
9/26/2015	4:30:00	39.3	49.4	2390	26.36	78	64.3	-1828	54.2	39	143567	117476	71212	46399	4053953	472
9/26/2015	5:00:00	39.4	49.9	2375	26	70	65.5	-1795	53.9	39.6	143567	117476	71270	46463	4054185	446
9/26/2015	5:30:00	39	49.6	2364	25.08	58	67.1	-1774	53.5	39.6	143567	117476	71328	46525	4054407	430
9/26/2015	6:00:00	38.7	49.3	2356	24.21	47	68.7	-1725	51.9	39	143567	117476	71388	46582	4054614	390
9/26/2015	6:30:00	46.1	50.4	714	23.57	31	73.3	0	46.9	39	143567	117476	71440	46634	4054765	2
9/26/2015	7:00:00	40.3	50.6	1052	23.77	31	73.7	253	50.5	39	143567	117476	71499	46689	4054766	2
9/26/2015	7:30:00	40.3	51.6	973	23.44	33	72.4	221	51.5	39.6	143567	117476	71561	46744	4054767	2
9/26/2015	8:00:00	40.2	52.4	1014	24.73	37	73.3	241	52.2	39.5	143567	117476	71621	46804	4054768	2
9/26/2015	8:30:00	40	53	1093	25.02	32	76	288	52.9	39.5	143567	117476	71683	46868	4054769	2
9/26/2015	9:00:00	40	53.9	1168	24.72	27	77.6	326	53.9	39.4	143567	117476	71744	46931	4054770	2
9/26/2015	9:30:00	39.9	54.2	1371	25.05	25	79.4	617	54	39.4	143567	117476	71805	47001	4054771	2
9/26/2015	10:00:00	39.9	54.4	1456	25.5	24	81.1	607	54.3	39.4	143567	117476	71867	47077	4054772	2
9/26/2015	10:30:00	39.9	54.8	1537	26.26	22	83.8	606	54.8	39.4	143567	117476	71928	47155	4054773	2
9/26/2015	11:00:00	39.9	56.6	1621	26.94	20	87	752	56.4	39.4	143568	117476	71992	47238	4054774	2
9/26/2015	11:30:00	39.7	56.7	1740	27.53	18	90	799	56.5	39.4	143568	117476	72063	47325	4054775	2
9/26/2015	12:00:00	39.8	56.4	1740	27.97	17	91.6	864	56.1	39.4	143568	117476	72135	47411	4054776	2
9/26/2015	12:30:00	39.7	57.5	1762	31.38	33	87.7	861	57.3	39.4	143568	117476	72171	47454	4054776	2
9/26/2015	13:00:00	43.1	56.3	2372	31.8	36	87	-455	56.2	39.4	143568	117476	72292	47584	4054852	406
9/26/2015	13:30:00	39.1	56.5	2410	31.13	33	87.1	-474	56.1	43.2	143568	117476	72369	47671	4055206	738
9/26/2015	14:00:00	40	57.3	1719	30.83	38	84.5	813	56.9	39.6	143568	117476	72444	47758	4055247	2
9/26/2015	14:30:00	39.9	56.4	1816	30.5	37	84.3	928	56	39.6	143568	117476	72515	47845	4055248	2
9/26/2015	15:00:00	40.1	56.1	1679	30.63	41	82.8	803	55.8	39.6	143568	117476	72581	47932	4055249	2
9/26/2015	15:30:00	40	56.3	1727	29.5	38	82.1	845	56	39.6	143568	117476	72649	48019	4055250	2
9/26/2015	16:00:00	40	56.3	1684	28.99	37	81.7	776	55.9	39.6	143568	117476	72716	48107	4055251	2
9/26/2015	16:30:00	40	56.5	1622	30.34	46	80.3	768	56.2	39.6	143568	117476	72783	48195	4055252	2
9/26/2015	17:00:00	40	55.9	1618	30.6	52	78.3	746	55.5	39.6	143568	117476	72850	48283	4055253	2
9/26/2015	17:30:00	42.8	55.9	2432	30.41	51	78.1	-556	55.6	39.6	143568	117476	72913	48371	4055295	400
9/26/2015	18:00:00	39	55.8	2438	29.87	52	76.9	-910	55.7	39.2	143568	117476	72978	48459	4055596	689
9/26/2015	18:30:00	38.9	54.5	2424	29.77	59	74.5	-1046	55.7	39.2	143568	117476	73040	48546	4055926	650
9/26/2015	19:00:00	39.1	55.3	2445	29.24	61	72.9	-1050	55.7	39.2	143568	117476	73101	48634	4056248	642
9/26/2015	19:30:00	39	54.6	2383	28.87	64	71.7	-1289	55.7	39.2	143568	117476	73163	48720	4056568	623
9/26/2015	20:00:00	39.1	54.9	2414	28.69	64	71.4	-1303	55.7	39.2	143568	117476	73223	48805	4056872	625
9/26/2015	20:30:00	38.9	54.6	2405	28.44	65	70.8	-1411	55.7	39.2	143568	117476	73284	48889	4057185	624
9/26/2015	21:00:00	38.9	53.9	2397	28.08	70	68.9	-1511	55.6	39.1	143568	117476	73344	48973	4057492	610
9/26/2015	21:30:00	39.1	54.2	2376	28.09	69	69.3	-1531	54.4	39.1	143568	117476	73404	49053	4057786	566
9/26/2015	22:00:00	39.1	52.7	2350	27.91	70	68.5	-1553	53.1	39.3	143568	117476	73461	49122	4058054	494
9/26/2015	22:30:00	39.2	51.8	2374	27.68	70	68.3	-1662	49	39.3	143568	117476	73520	49179	4058272	366
9/26/2015	23:00:00	40.4	51.3	770	27.68	71	68	-65	46.1	39.3	143568	117476	73574	49232	4058339	2
9/26/2015	23:30:00	40.7	51.3	678	27.73	72	67.9	0	44.9	40.9	143568	117476	73632	49284	4058340	2
9/27/2015	0:00:00	40.3	51.5	674	27.86	72	68	-80	44.3	40.9	143568	117476	73689	49336	4058341	2
9/27/2015	0:30:00	40.5	51.1	756	27.72	73	67.7	-73	43.9	40.9	143568	117476	73743	49388	4058342	2
9/27/2015	1:00:00	40.6	50.5	675	27.2	75	66.2	-124	43.8	41	143568	117476	73795	49439	4058343	2
9/27/2015	1:30:00	40.6	49.7	765	27.22	75	66.3	-138	43.7	41	143568	117476	73845	49491	4058344	2
9/27/2015	2:00:00	40.6	50.2	893	26.85	75	65.7	-286	43.8	41.1	143568	117476	73893	49542	4058345	2



TES Level Temp.	
68 Feet	53.7 °F
66 Feet	53.8 °F
64 Feet	53.6 °F
62 Feet	53.7 °F
60 Feet	53.8 °F
58 Feet	53.7 °F
56 Feet	53.7 °F
54 Feet	53.7 °F
52 Feet	54.0 °F
50 Feet	53.9 °F
48 Feet	54.0 °F
46 Feet	51.8 °F
44 Feet	50.7 °F
42 Feet	48.7 °F
40 Feet	48.1 °F
38 Feet	47.4 °F
36 Feet	42.5 °F
34 Feet	40.8 °F
32 Feet	40.2 °F
30 Feet	40.0 °F
28 Feet	40.1 °F
26 Feet	40.0 °F
24 Feet	39.7 °F
22 Feet	39.7 °F
20 Feet	40.1 °F
18 Feet	39.6 °F
16 Feet	39.7 °F
14 Feet	39.7 °F
12 Feet	39.5 °F
10 Feet	39.6 °F
8 Feet	39.8 °F
6 Feet	39.5 °F
4 Feet	39.5 °F
2 Feet	39.4 °F

TES Temp HIGH: 50.6 °F

PGE Time of Use: ON-PEAK

Tank Level: 68.2 Ft

Tank Avail. Lvl: 36 Ft

Tank Avail. %: 59.6 %

Tank Avail. Tonhr: 11331 TonHr

Average Temp.: 45.8 °F

	Depletion	Regeneration
Enable	ON	OFF
Tons	534 Tons	0 Tons
Ton Hours	3883 TonHr	46619 TonHr
Ton Hours Prev.	4899 TonHr	46619 TonHr
PK Tons	839 Tons	781 Tons
PK Tons Prev.	711 Tons	781 Tons
Time	8.1 Hrs	0.0 Hrs
Time Prev.	13.0 Hrs	91.2 Hrs
End Setpoint	45.0 °F	

Plant Mode: DEPLETE

TES Temp LOW: 39.2 °F

Flow: 1119 GPM

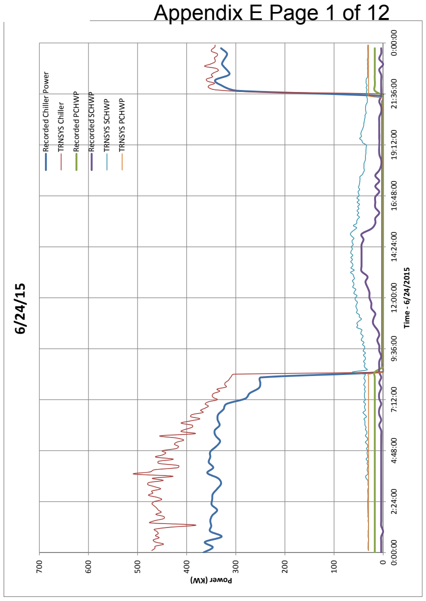
Make-Up Total: 1.#INF CUB/FT

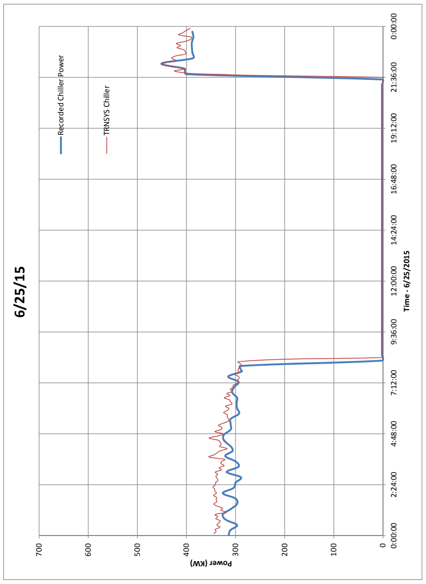
Tank Tons	Tank Ton Hours	Tank %	CP OSAWETBULE
534 Tons	11331 TonHr	59.6 %	57.0 °F

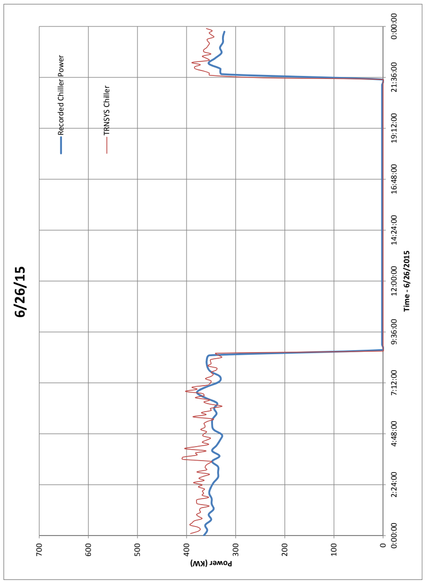
Outside Conditions:

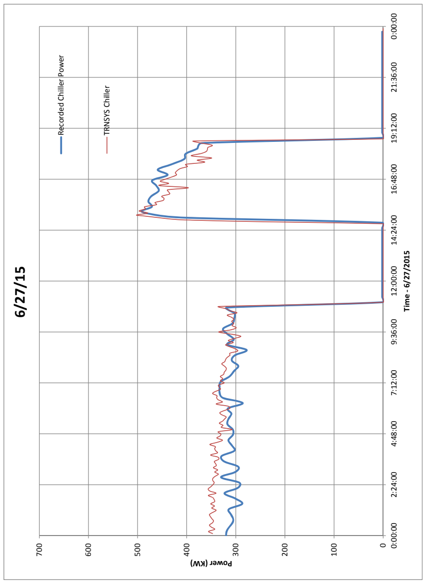
Temperature	Humidity	Enthalpy
68.9 °F	51 %RH	25.02 BTU/LB

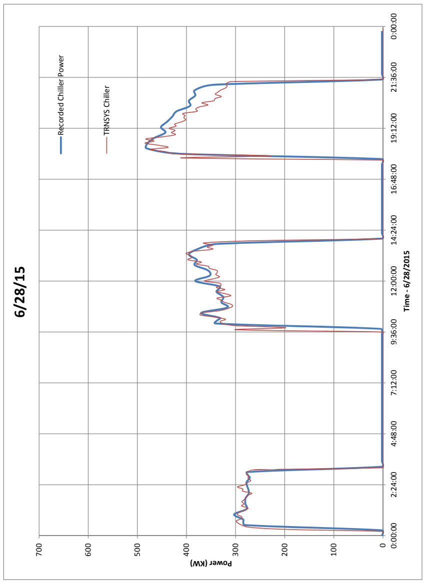
Appendix E - Chiller Performance Plots - 6/24/15 - 9/30/15

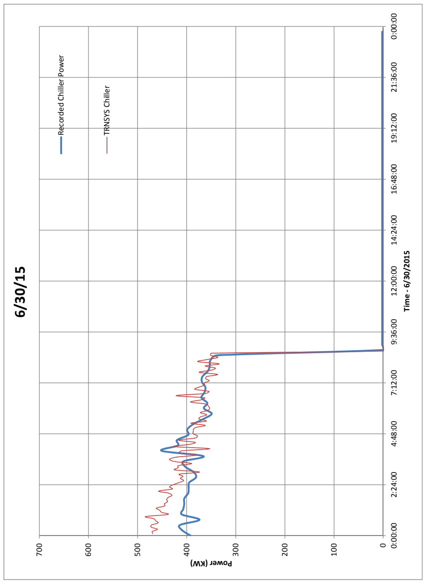


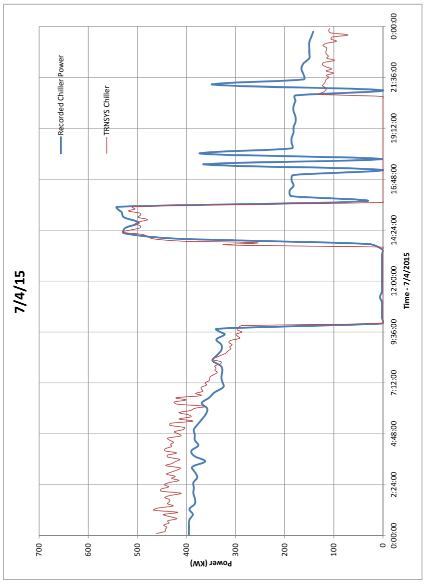


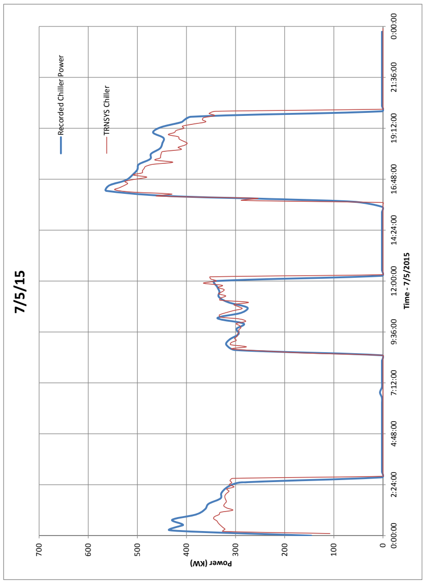


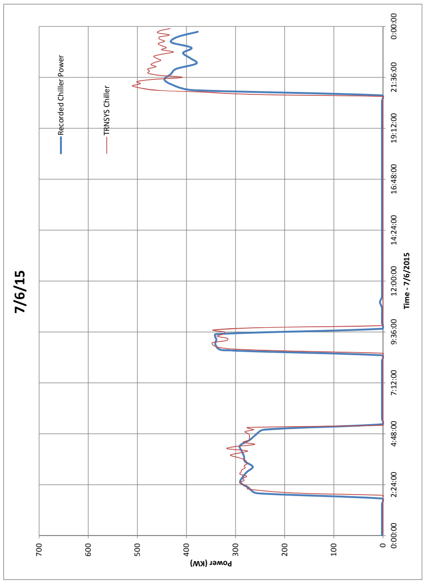


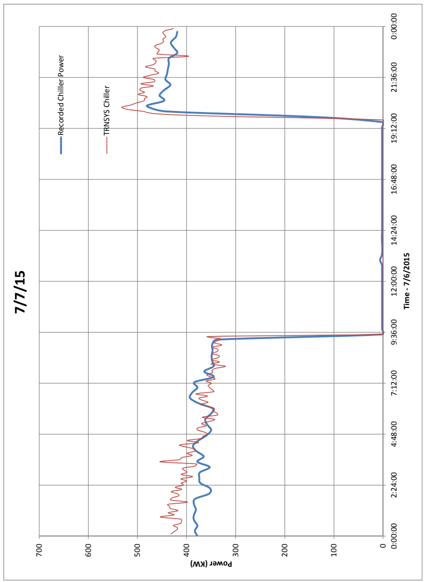


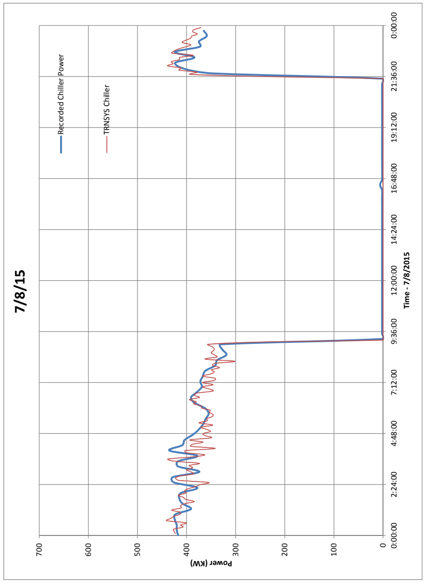


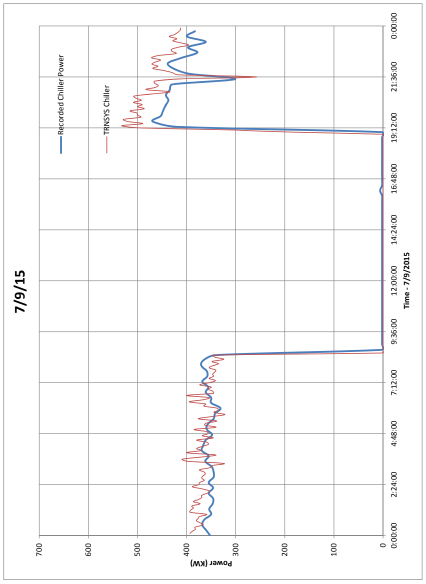

7/4/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/4/2015

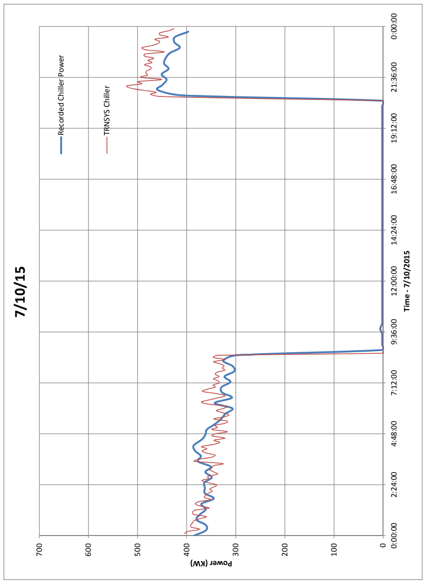

7/5/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/5/2015

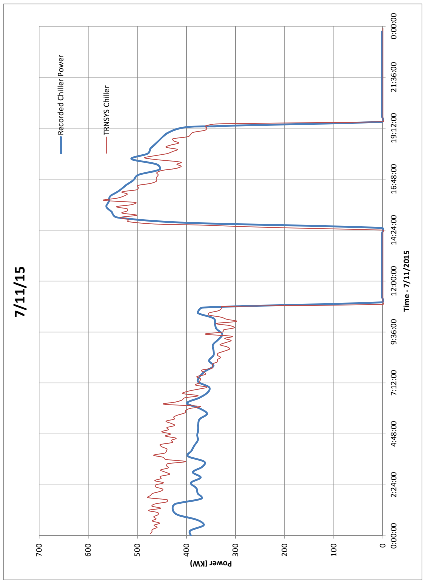

7/6/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/6/2015

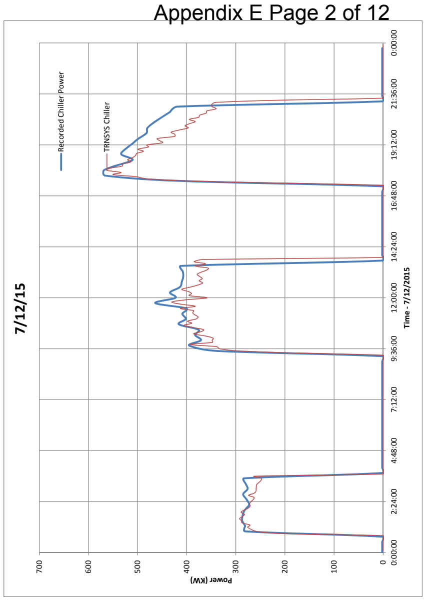

7/7/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/6/2015

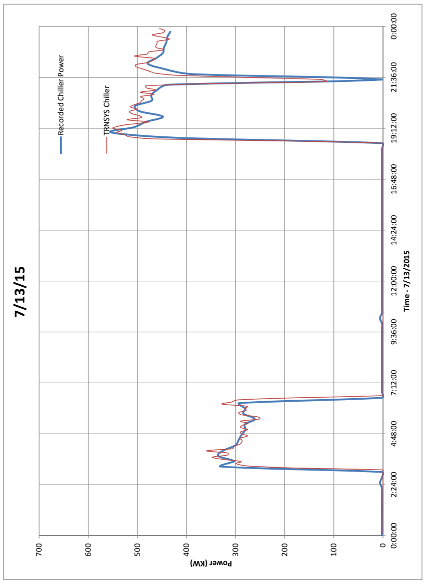

7/8/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/8/2015

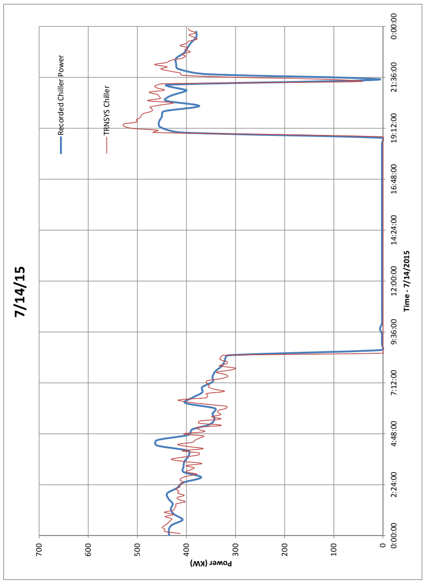

7/9/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/9/2015

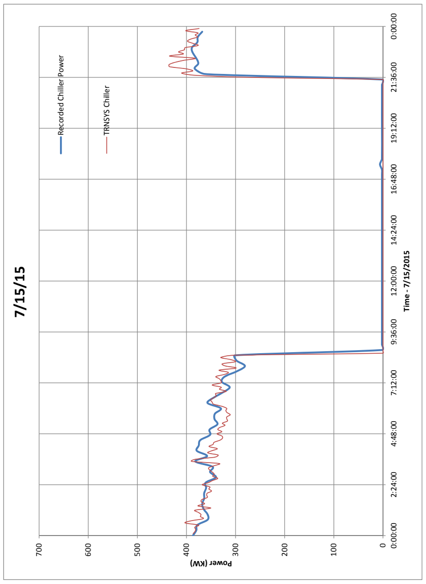

7/10/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/10/2015

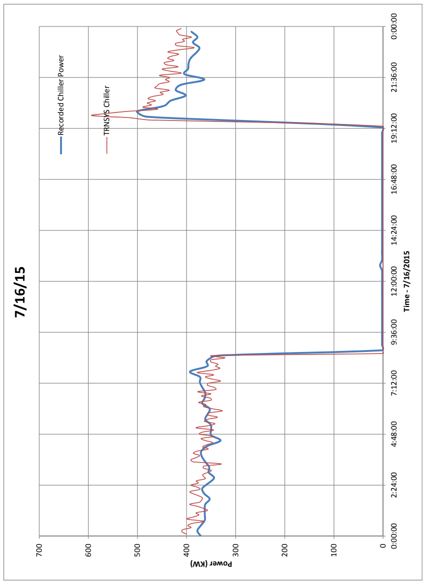

7/11/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/11/2015

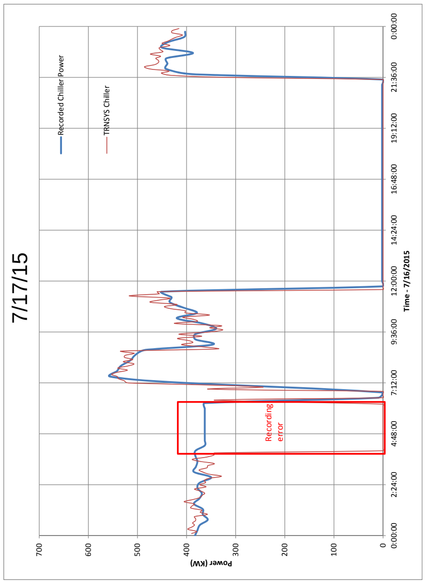

7/12/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/12/2015

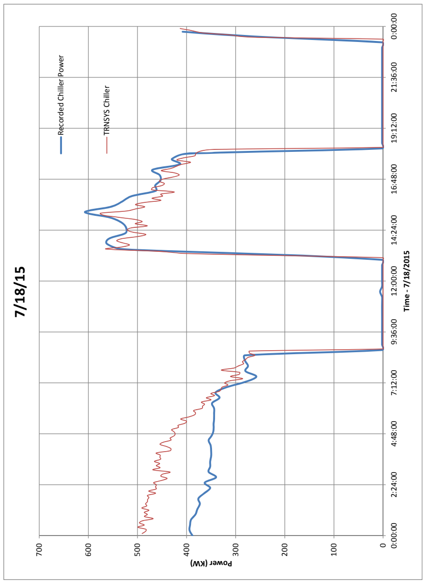

7/13/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
100
200
300
400
500
600
700
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/13/2015

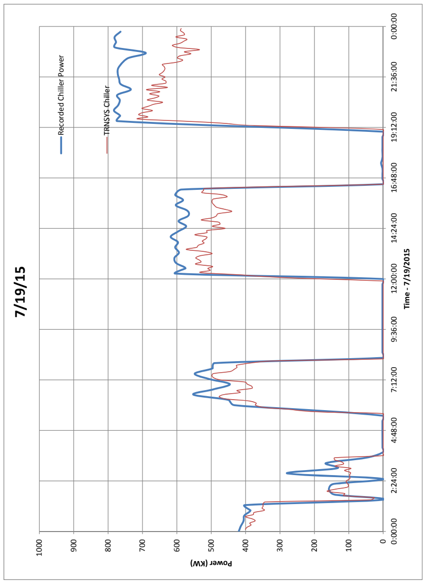

7/14/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
100
200
300
400
500
600
700
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/14/2015

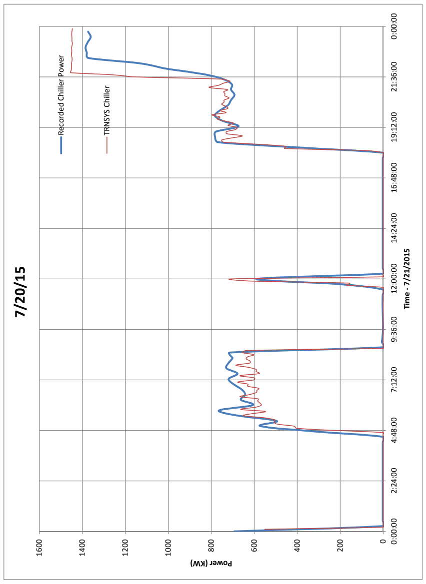

7/15/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
100
200
300
400
500
600
700
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/15/2015

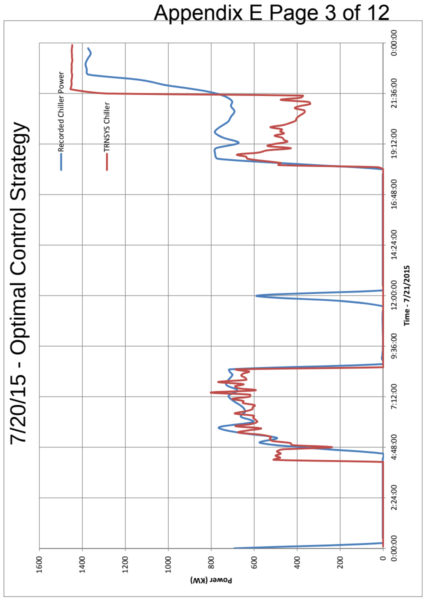

7/16/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
100
200
300
400
500
600
700
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/16/2015


7/17/15
Recorded Chiller Power
TRNSYS Chiller
Recording error
Power (KW)
0
100
200
300
400
500
600
700
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/16/2015

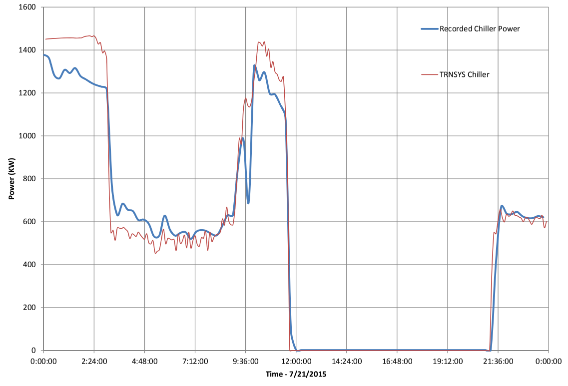

7/18/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
100
200
300
400
500
600
700
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/18/2015


7/19/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/19/2015

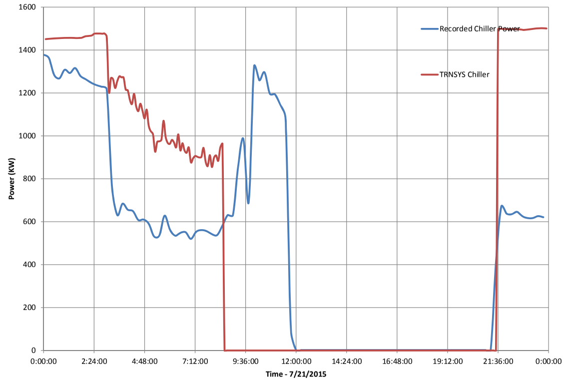

7/20/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
200
400
600
800
1000
1200
1400
1600
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/21/2015


7/20/15 - Optimal Control Strategy
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
0
200
400
600
800
1000
1200
1400
1600
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/21/2015

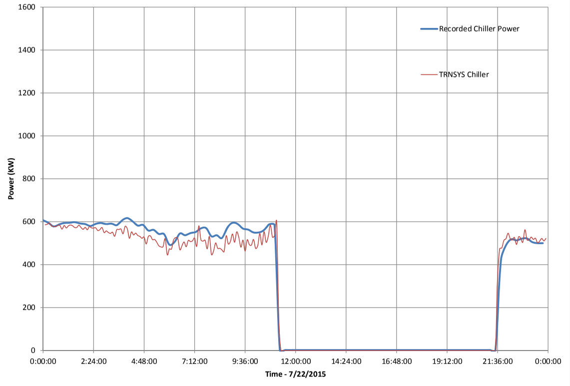
7/21/15



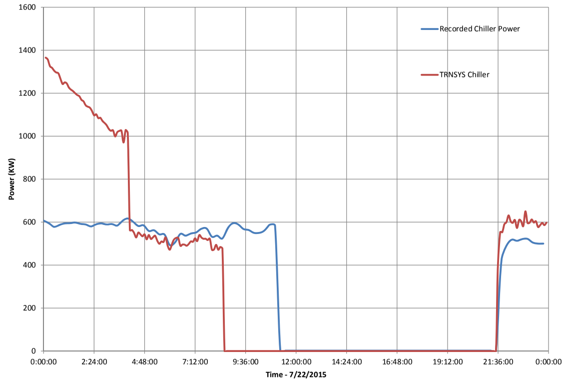
7/21/15 - Optimal Control Strategy



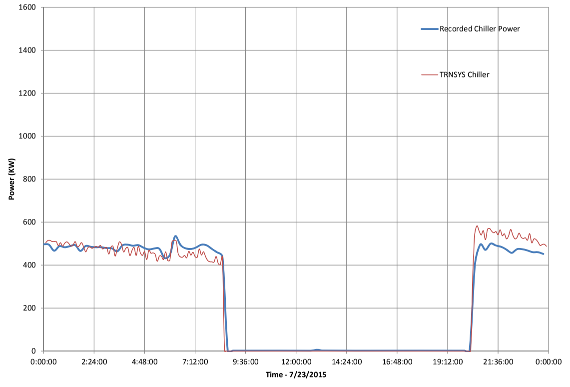
7/22/15



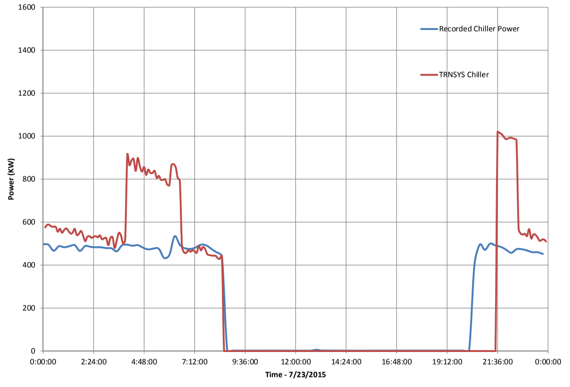
7/22/15 - Optimal Control Strategy



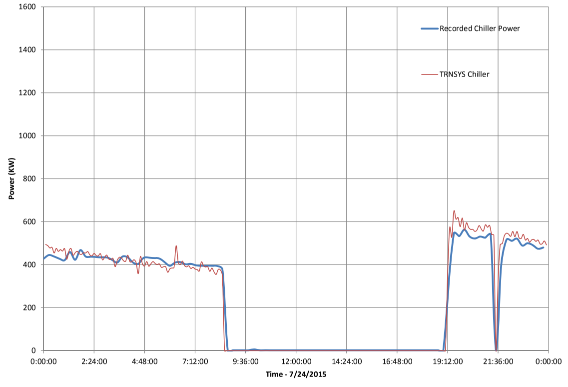
7/23/15



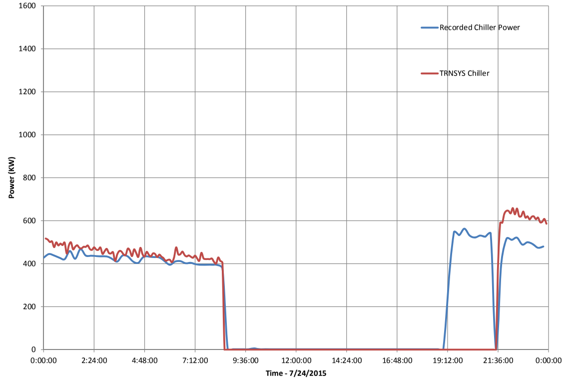
7/23/15 - Optimal Control Strategy



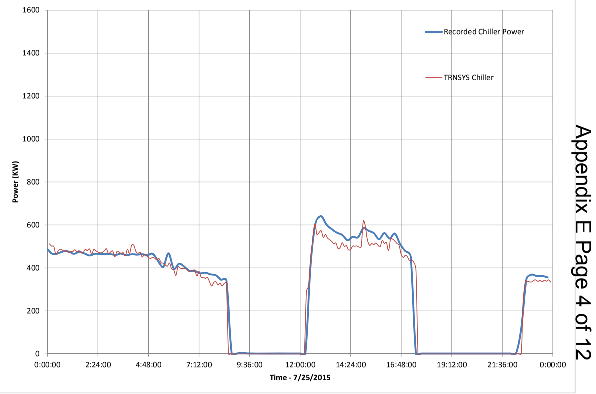
7/24/15

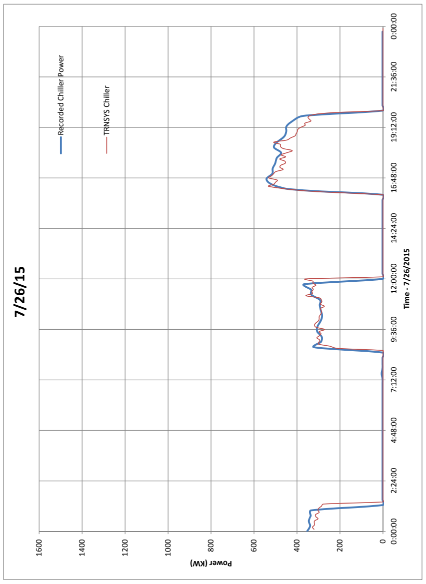


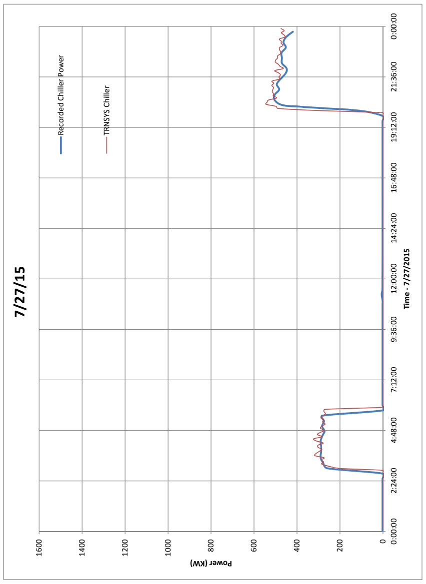
7/24/15 - Optimal Control Strategy

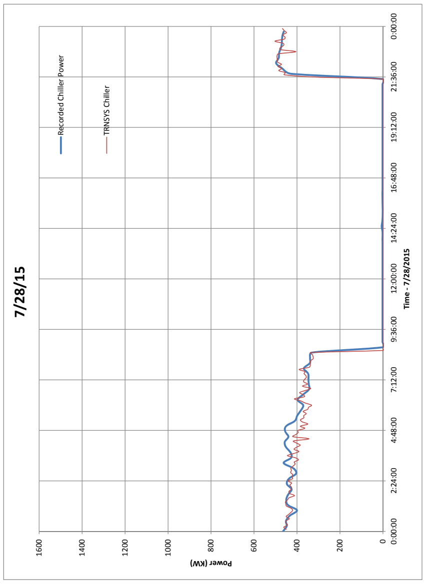


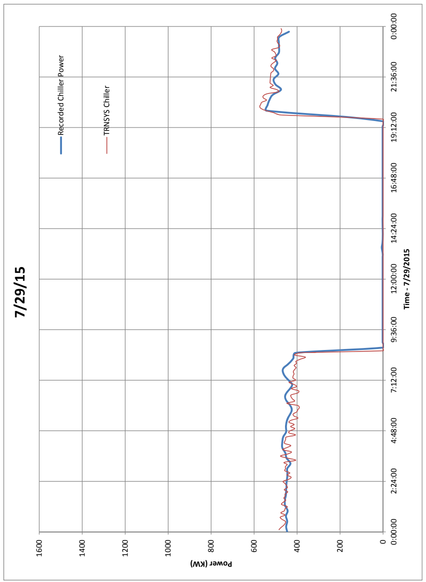
7/25/15

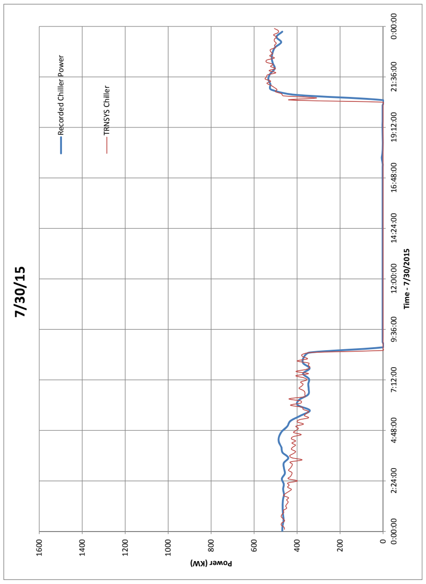


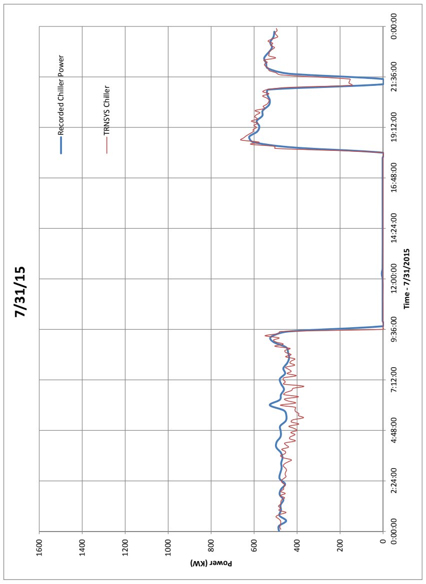

7/26/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/26/2015

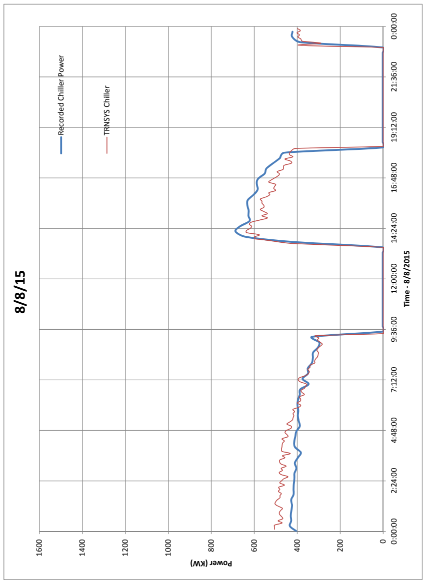

7/27/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/27/2015

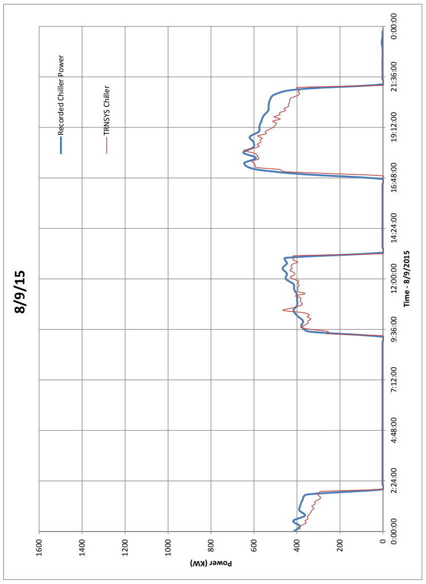

7/28/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/28/2015

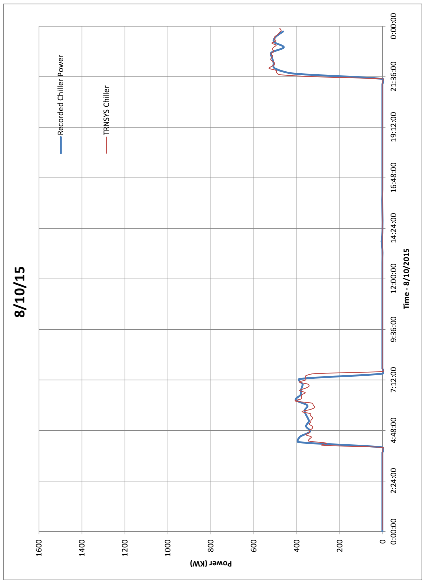

7/29/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/29/2015

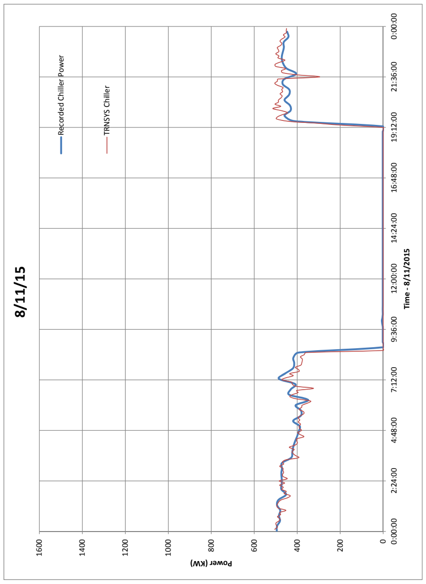

7/30/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/30/2015

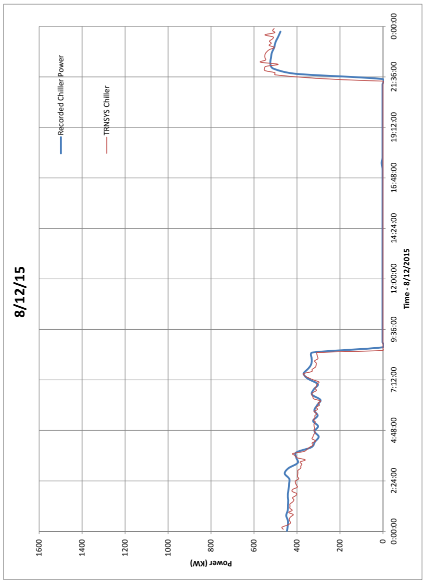

7/31/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 7/31/2015

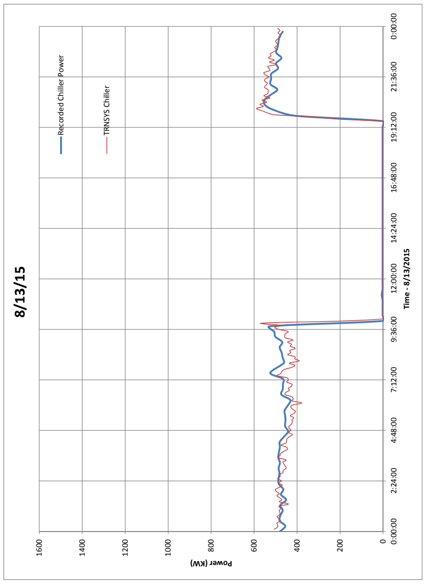

8/8/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/8/2015

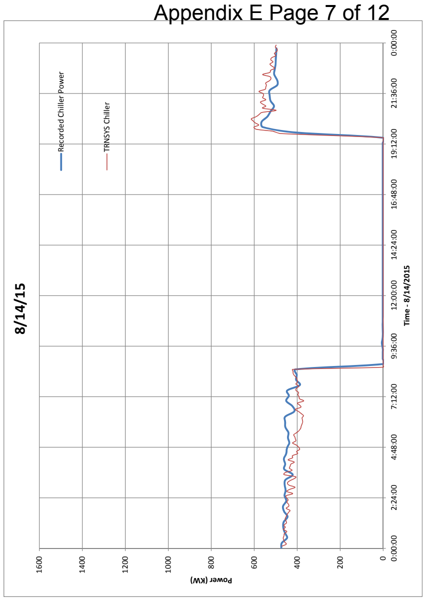

8/9/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/9/2015

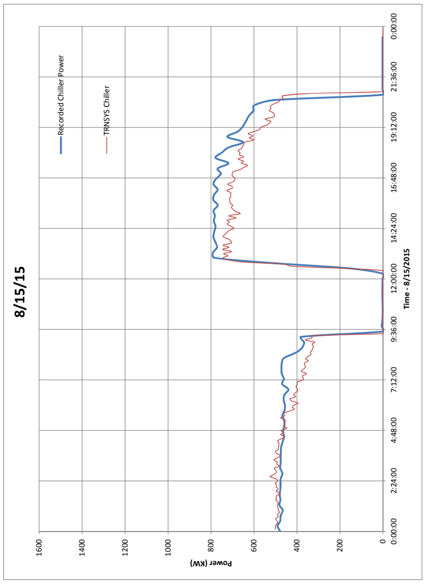

8/10/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/10/2015

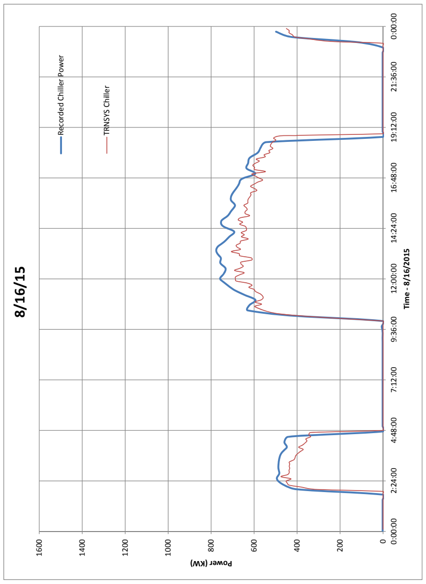

8/11/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/11/2015

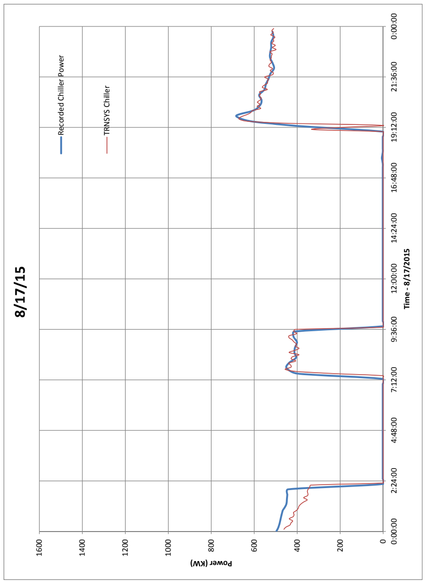

8/12/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/12/2015

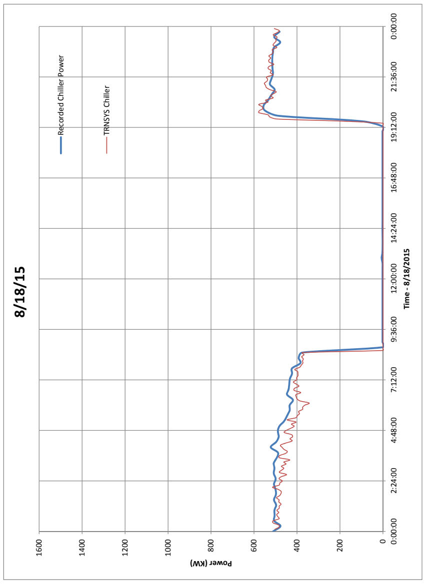

8/13/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/13/2015

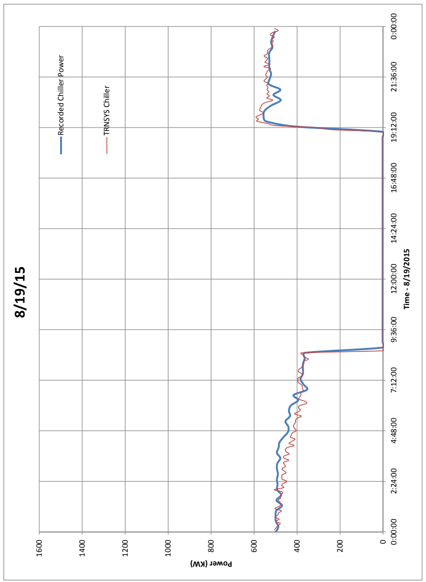

8/14/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/14/2015

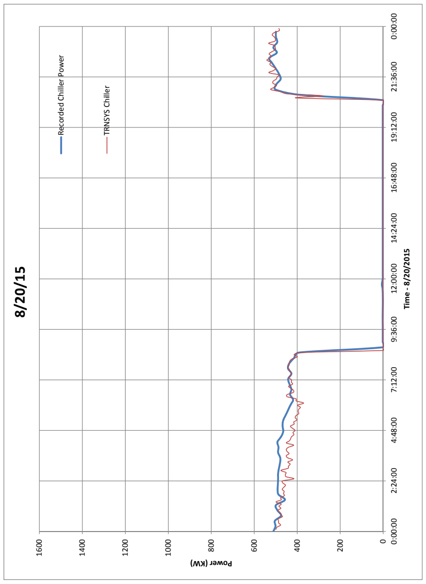

8/15/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/15/2015

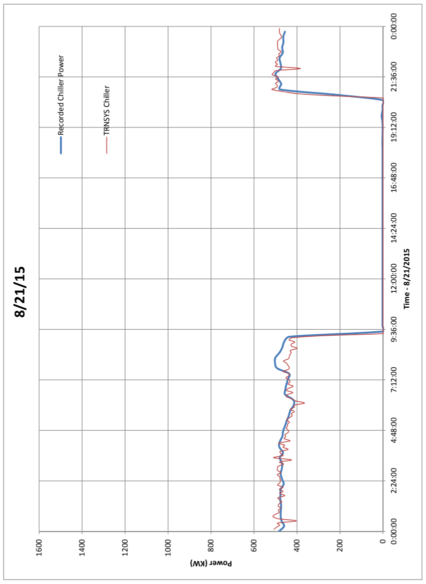

8/16/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/16/2015

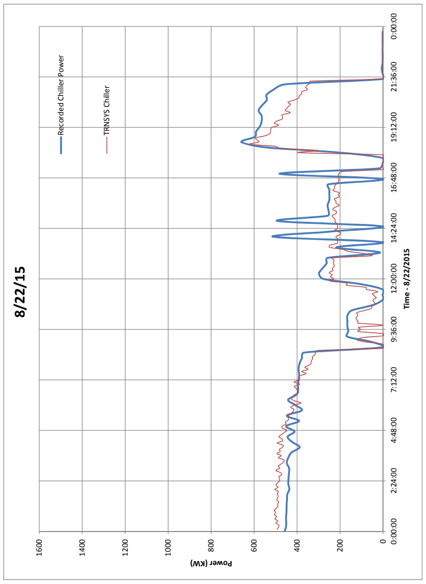

8/17/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/17/2015

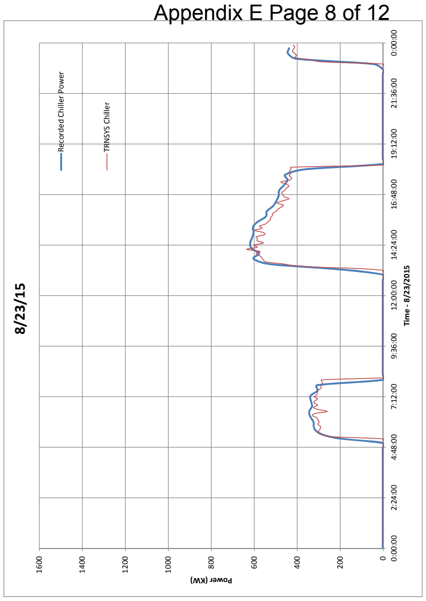

8/18/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/18/2015

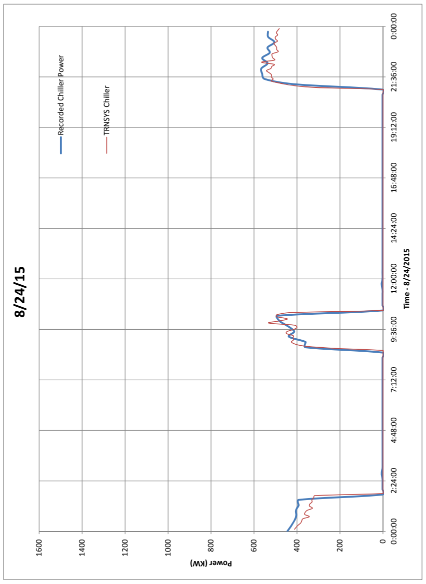

8/19/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/19/2015

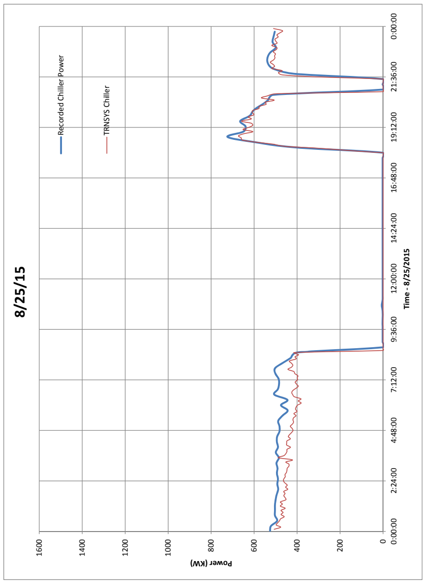

8/20/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1600
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 8/20/2015

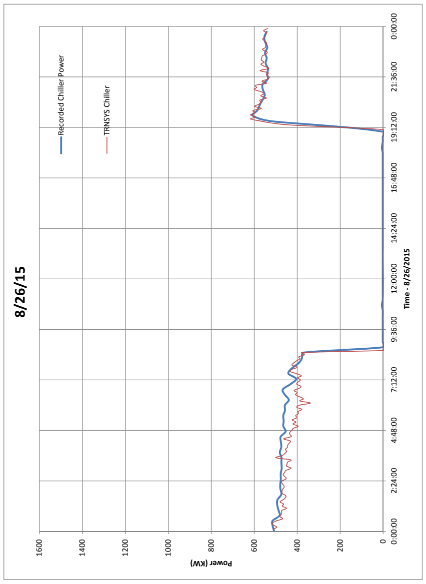

8/21/15

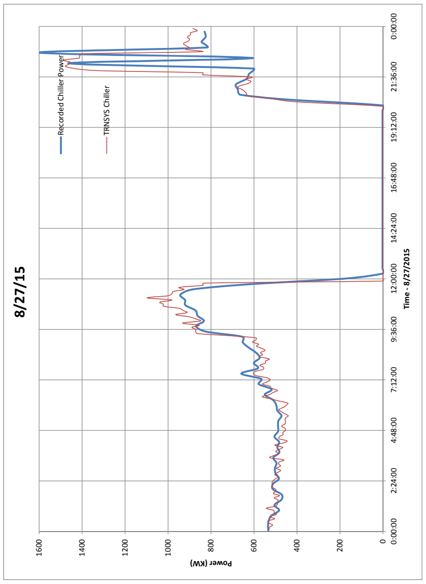

8/22/15

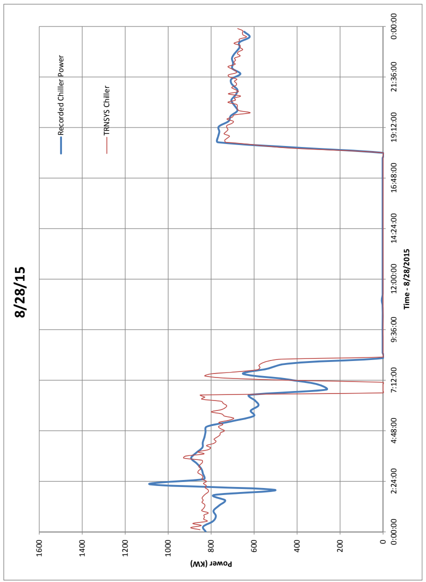

8/23/15

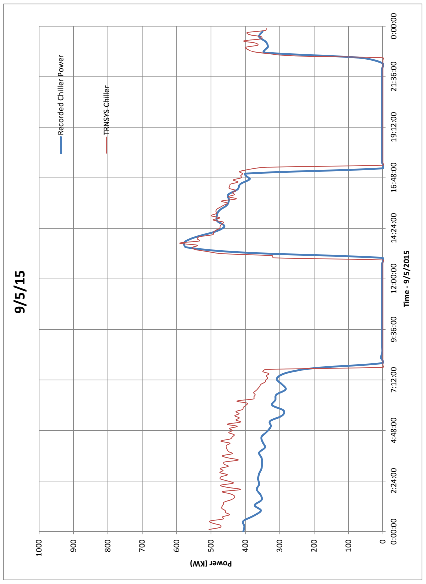

8/24/15

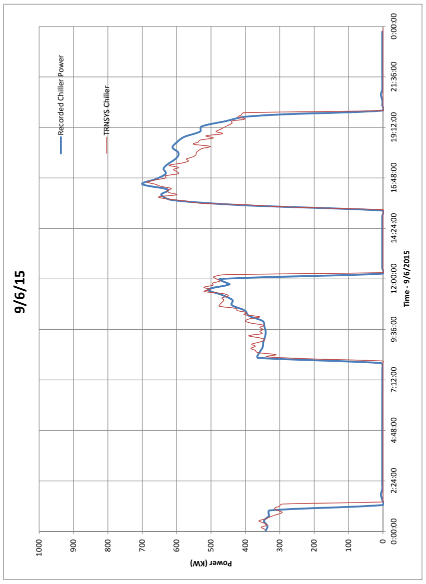

8/25/15

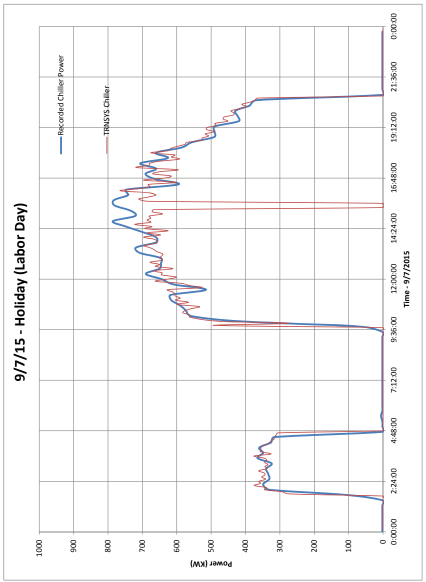

8/26/15

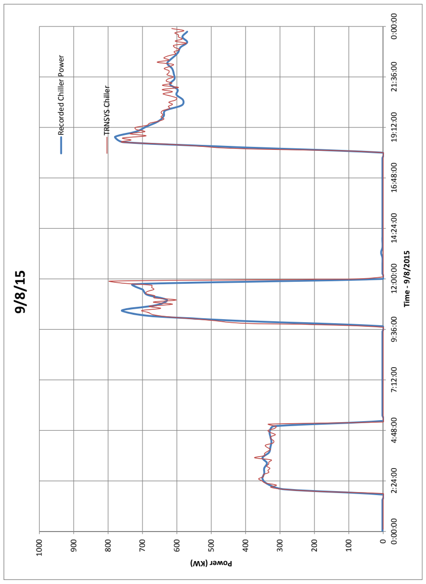

8/27/15

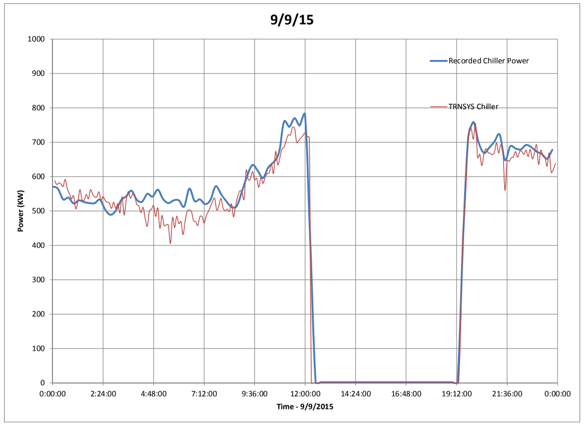

8/28/15

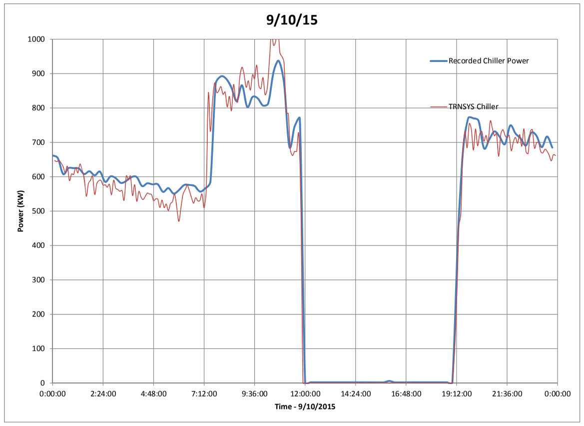

9/5/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/5/2015

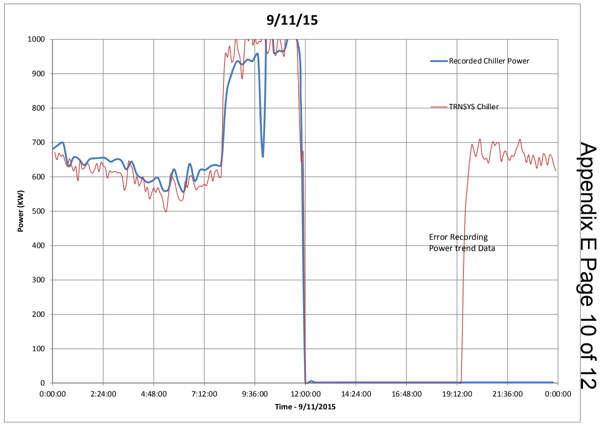

9/6/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/6/2015

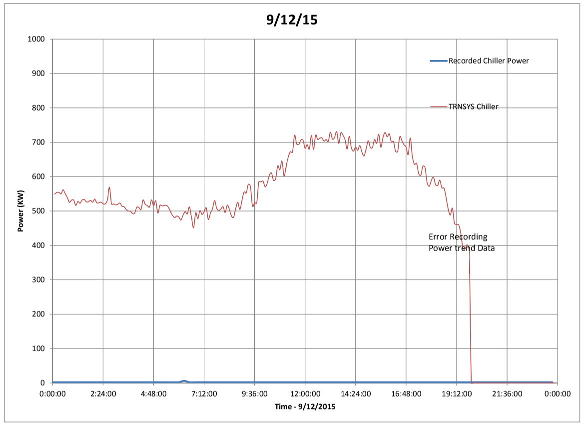

9/7/15 - Holiday (Labor Day)
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/7/2015

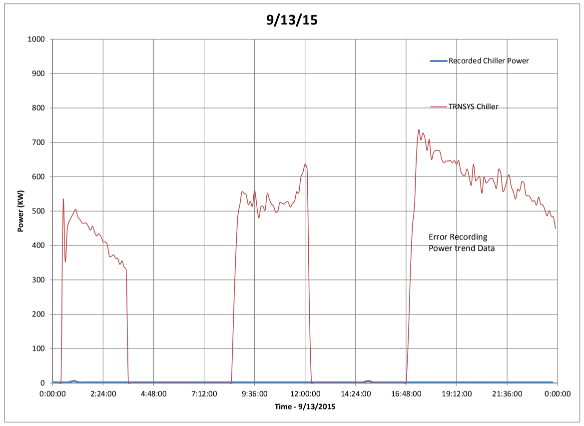

9/8/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/8/2015

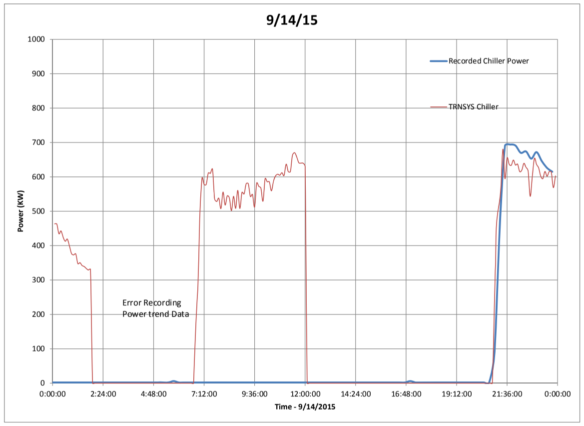

9/9/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/9/2015
Recorded Chiller Power
TRNSYS Chiller

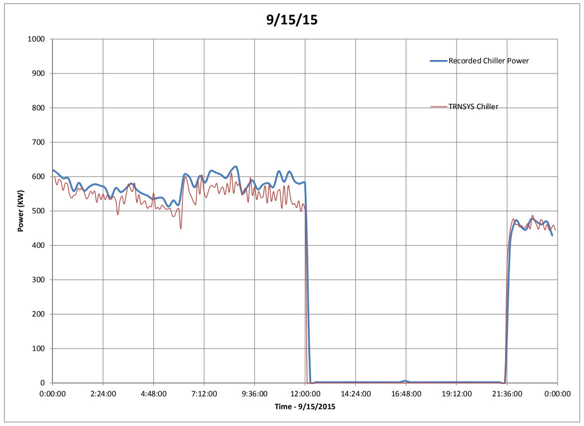

9/10/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/10/2015
Recorded Chiller Power
TRNSYS Chiller

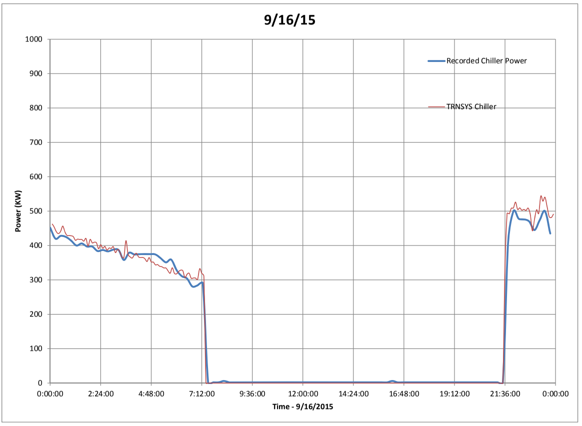

9/11/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/11/2015
Recorded Chiller Power
TRNSYS Chiller
Error Recording
Power trend Data

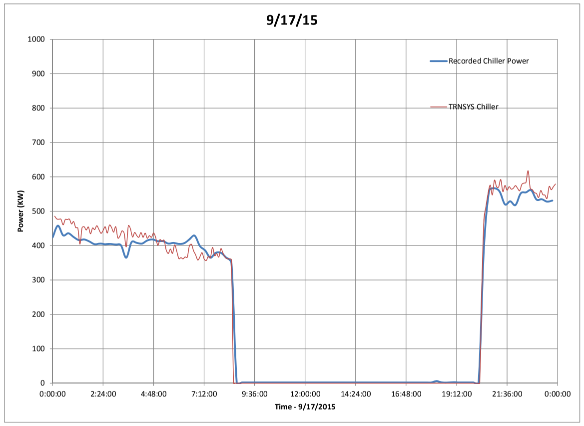

9/12/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/12/2015
Recorded Chiller Power
TRNSYS Chiller
Error Recording
Power trend Data

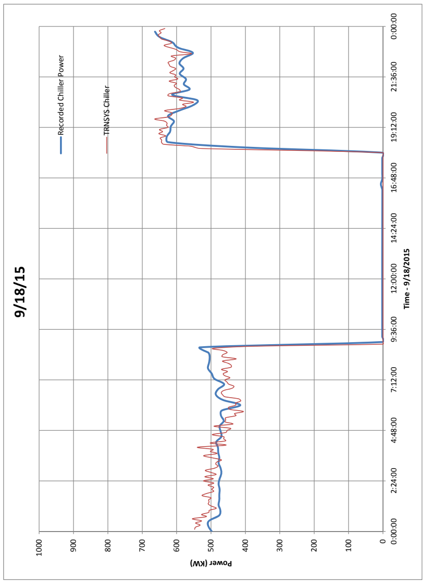

9/13/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/13/2015
Recorded Chiller Power
TRNSYS Chiller
Error Recording
Power trend Data

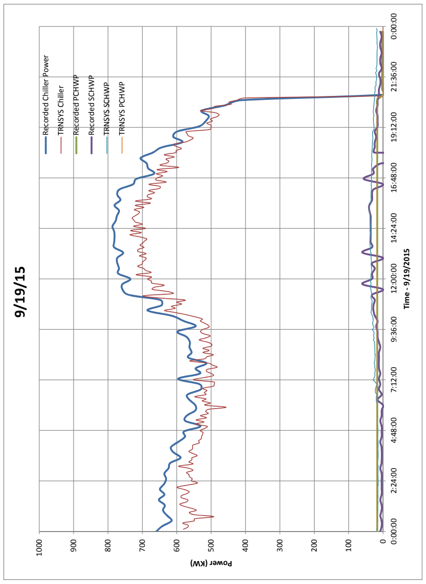

9/14/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/14/2015
Recorded Chiller Power
TRNSYS Chiller
Error Recording
Power trend Data

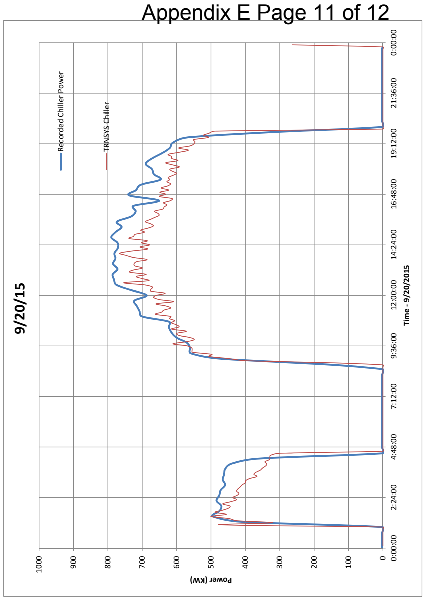

9/15/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/15/2015
Recorded Chiller Power
TRNSYS Chiller

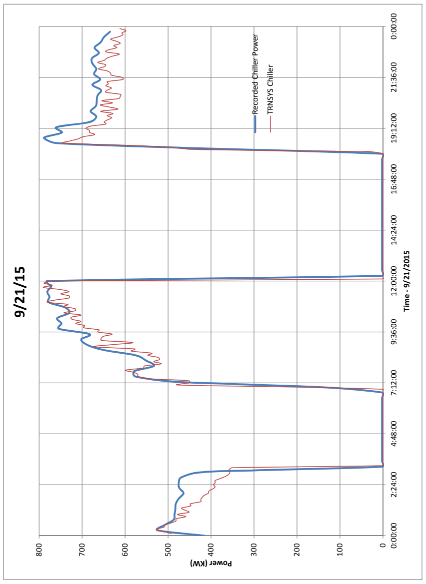

9/16/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/16/2015
Recorded Chiller Power
TRNSYS Chiller

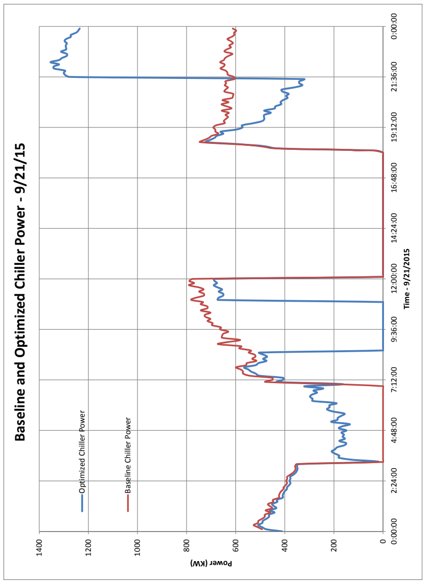

9/17/15
Power (KW)
0
100
200
300
400
500
600
700
800
900
1000
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/17/2015
Recorded Chiller Power
TRNSYS Chiller

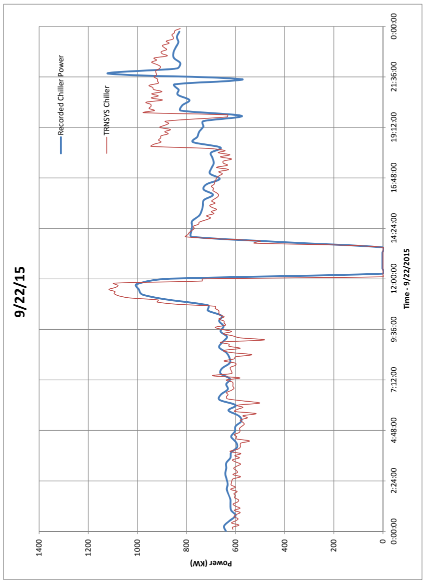

9/18/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/18/2015

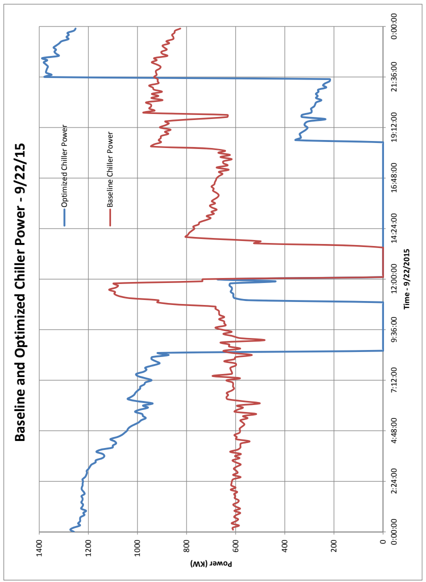

9/19/15
Recorded Chiller Power
TRNSYS Chiller
Recorded PCHWP
Recorded SCHWP
TRNSYS SCHWP
TRNSYS PCHWP
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/19/2015

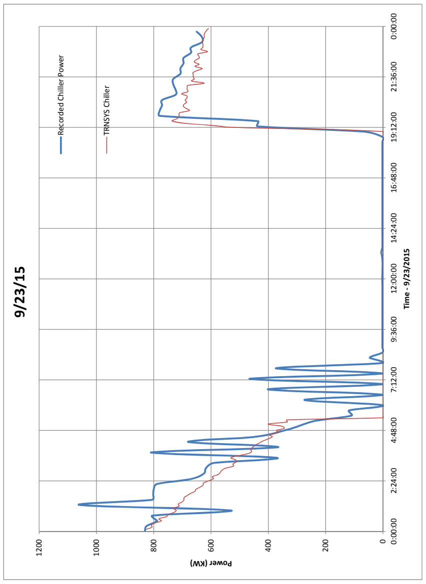

9/20/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1000
900
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/20/2015

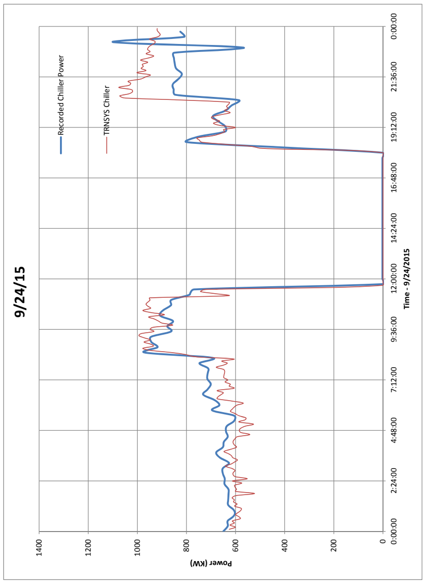

9/21/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
800
700
600
500
400
300
200
100
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/21/2015

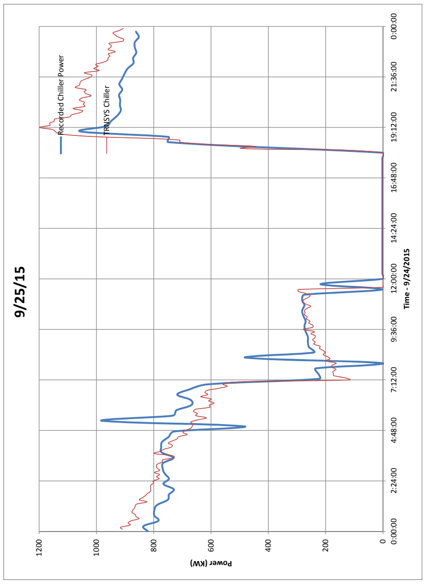

Baseline and Optimized Chiller Power - 9/21/15
Optimized Chiller Power
Baseline Chiller Power
Power (KW)
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/21/2015

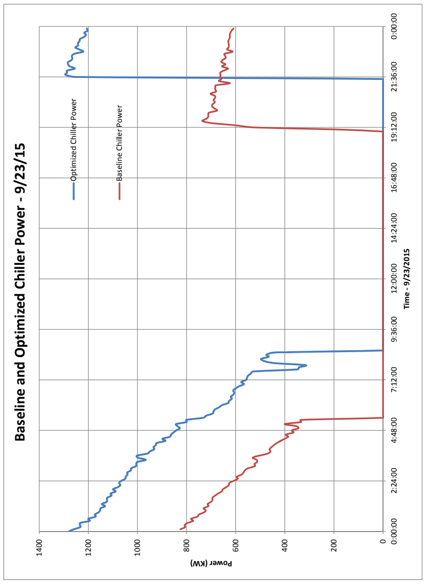

9/22/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/22/2015

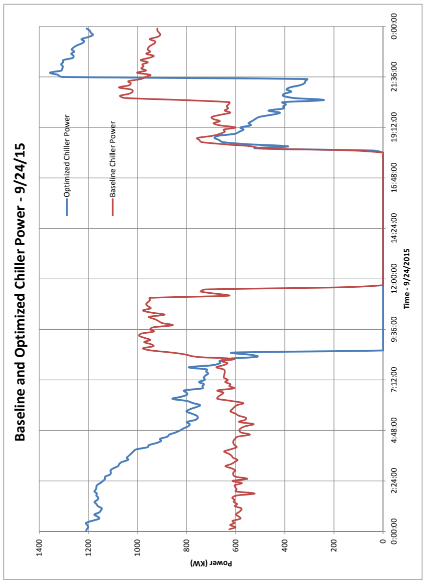

Baseline and Optimized Chiller Power - 9/22/15
Optimized Chiller Power
Baseline Chiller Power
Power (KW)
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/22/2015

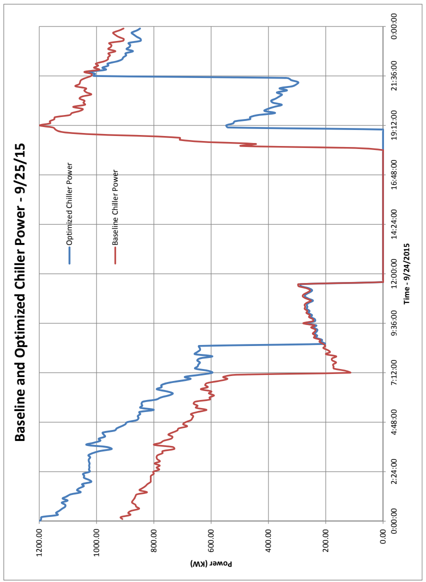

9/23/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/23/2015


9/24/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/24/2015


9/25/15
Recorded Chiller Power
TRNSYS Chiller
Power (KW)
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/24/2015


Baseline and Optimized Chiller Power - 9/23/15
Optimized Chiller Power
Baseline Chiller Power
Power (KW)
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/23/2015


Baseline and Optimized Chiller Power - 9/24/15
Optimized Chiller Power
Baseline Chiller Power
Power (KW)
1400
1200
1000
800
600
400
200
0
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/24/2015


Baseline and Optimized Chiller Power - 9/25/15
Optimized Chiller Power
Baseline Chiller Power
Power (KW)
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
2:24:00
4:48:00
7:12:00
9:36:00
12:00:00
14:24:00
16:48:00
19:12:00
21:36:00
0:00:00
Time - 9/24/2015