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Integrated Thermal Energy Storage for Cooling Applications

Final Report

June 2017

Report Number 17-17

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Serve as a catalyst – advancing energy innovation, technology, and investment; transforming New York's economy; and empowering people to choose clean and efficient energy as part of their everyday lives.

Integrated Thermal Energy Storage for Cooling Applications

Final Report

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Acronyms and Abbreviations

base	baseline (existing) chiller parameters without subcooling
DAQ	data acquisition system
EER	energy efficiency ratio
ExCh	existing chiller
FS	full scale
ITES	Integrated Thermal Energy Storage
ITESS	Integrated Thermal Energy Storage System
kWh	kilowatt hours
NYSERDA	New York State Energy Research and Development Authority
OTS	Optimized Thermal Systems, Inc.
PGW	propylene glycol/water

1 Introduction

Many commercial and industrial facilities are cooled using vapor compression systems. However, the performance of these systems degrades with high outdoor temperatures causing high peak electric demand increase, reduced efficiency, and lower cooling capacity. As the number of installed systems increases and the average summer outdoor temperatures rise, electricity consumption and peak demand requirements will become even greater challenges for the utility grid.

An Integrated Thermal Energy Storage System (ITESS) utilizing chilled water could provide additional subcooling for an air conditioning system's condenser, thereby increasing the capacity of the entire system and providing significant reductions in electric demand and consumption. The ITESS uses a dedicated chiller to cool a thermal storage tank, typically at night when electricity demand and rates are lower. This thermal reservoir is used the following day to subcool refrigerant leaving the condenser. This additional cooling increases the cooling capacity and decreases electrical demand during hot days for an existing or new vapor compression system.

The following report outlines the results of a demonstration of the ITESS, developed by Johnson Controls, Inc. (JCI), at the Bitzer plant in Syracuse, NY. Optimized Thermal Systems, Inc. (OTS) served as the third-party evaluator.

The test results showed that the cooling capacity of the existing chiller increased by 2.2–34.2%, depending on operating conditions, with the addition of subcooling. The ITESS increased existing chiller efficiency between 0.6–28.5% and has the potential to reduce power demand by 0.7–34.3%.[1] Total energy consumption for the system was essentially unchanged, increasing on average by approximately 0.05%, well within the margin of error.

[1] Calculated, based on theoretical savings as compared to a larger baseline chiller with matching capacity.

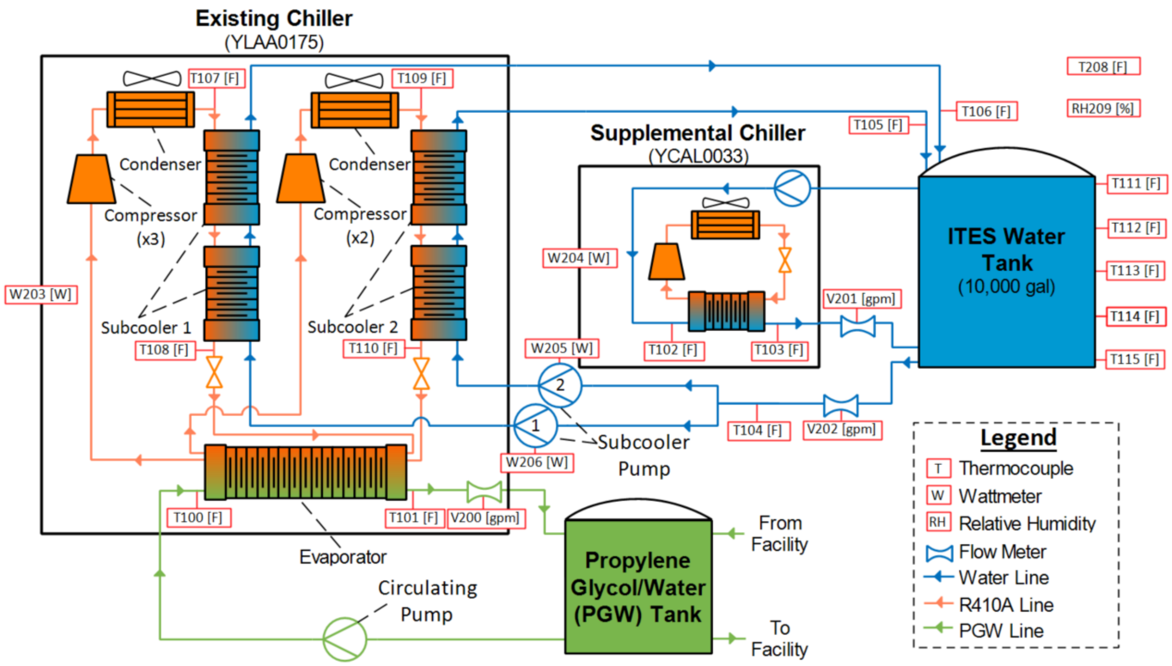
2 Integrated Thermal Energy Storage System (ITESS)

Integrated thermal energy storage (ITES) is a novel concept in improving cooling performance of air-conditioning systems at peak-load conditions. An existing chiller system used for demonstration purposes with the ITESS is illustrated in Figure 1. An additional piping diagram is provided in Appendix A. The existing chiller system at the Bitzer plant includes a 175-ton chiller, a 35% by volume Propylene-Glycol/Water (PGW) storage tank, and a constant-speed circulation pump. The chiller includes two refrigerant circuits, one with two compressors and another with three, to enable maximum flexibility through variable, part-load operation. The chiller is run, as needed, to maintain a desired set point temperature in the PGW tank. PGW solution from the tank is then circulated throughout the building to provide both space conditioning and meet cooling demands from the compressor test facility. Some long-term compressor tests are run 24 hours per day, seven days per week. Thus, the chiller is continuously in operation to meet the cooling demand.

The existing configuration was retrofitted with a 33-ton supplemental chiller, 10,000-gallon supplemental water tank, four subcoolers (plate heat exchangers), and two subcooler pumps for each of the existing chiller's refrigerant circuits. (Each refrigerant circuit has two subcoolers connected in series.) The supplemental chiller operates during off-peak hours to chill water, which is stored in the supplemental water tank. During on-peak hours, chilled water from the tank is circulated through the added plate heat exchangers to subcool the refrigerant, providing a potential capacity and efficiency gain for the main chiller. Measurement points for the system are shown in Figure 1 and discussed in Section 3.1. The system installation and the measurement procedure are described in Sections 4.1 and 4.2, respectively.

It should be noted that a supplemental chiller was used for the demonstration of the ITESS given that the Bitzer plant and chiller system were pre-existing. In a new construction or complete renovation application, use of a supplemental chiller for ITES would not be necessary and could lead to further efficiency gains. Suggested configurations for this "commercial" ITESS are described in Section 7.2.

Figure 1. Schematic of Existing Chiller System with ITESS



3 Data Collection and Control

3.1 Measurement Devices

The ITESS was instrumented with a number of sensors to measure critical parameters to assess the ITESS viability and performance. These measurement devices are depicted in Figure 1 and further details, including manufacturer and equipment accuracy, are listed in Table 1.

Table 1. Measurement devices

Location	Measurement	Device	Part Number	Accuracy
Ambient	Air temperature	Thermistor	Dwyer Inst. RHP-2D11	± 0.4 °F
Ambient	Relative humidity	Relative humidity sensor	Dwyer Inst. RHP-2D11	± 2.0 %
Supplemental chiller	Total power input	Watt meter	Ohio Semitronics PC5-063D	± 0.5 % FS[a]
Existing chiller	Total power input	Watt meter	Ohio Semitronics PC5-081D	± 0.5 % FS
Existing chiller PGW[b] loop	PGW flow rate	Magnetic flow meter	GF Sinet 2551	± 1.0 % RDG
Supplemental chiller water loop	Water flow rate	Magnetic flow meter	GF Sinet 2551	± 1.0 % RDG[c]
Subcooler water loop	Water flow rate	Magnetic flow meter	GF Sinet 2551	± 1.0 % RDG
Supplemental chiller water loop	Water temperature	T-type thermocouple	Omega Eng. TQSS-14G-12	± 0.9 °F
Existing chiller PGW loop	PGW temperature	T-type thermocouple	Omega Eng. TQSS-14G-12	± 0.9 °F
Subcooler water loop	Water temperature	T-type thermocouple	Omega Eng. TQSS-14G-12	± 0.5 °F
Subcooler water loop	Pump power input	Watt meter	Ohio Semitronics GH-001E	± 0.2 % FS
Water Tank	Water temperature	T-type thermocouples	Omega Eng. TT-T-24-SLE	± 0.9 °F

[a] % FS = percent of full scale for the measurement instrument

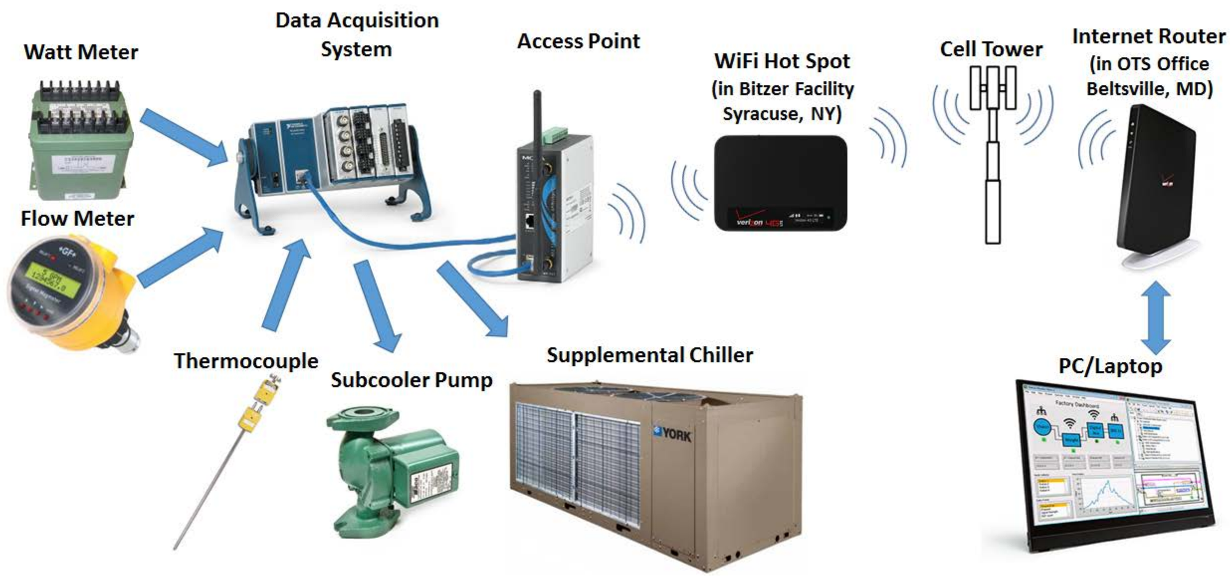
[b] PGW = propylene glycol/water solution

[c] % RDG = percent of reading for the measurement instrument

3.2 Data transfer and control activation

Figure 2 illustrates the schematic diagram of the data collection and control. Data for each of the sensors listed in Table 1 was collected every 30 seconds by a National Instruments, Inc. data acquisition (DAQ) system, which consists of a chassis and various input and output modules. The chassis operated as a stand-alone computer that collected data from measurement devices such as watt meters, flow meters, and thermocouples through their respective input modules. The chassis also activated and deactivated the subcooler pumps and the supplemental chiller though output modules. A WiFi device at the Bitzer facility in Syracuse, NY enabled communication with the DAQ system in order to retrieve data from the OTS office in Beltsville, MD.

Figure 2. Data collection and control



4 System Installation

4.1 ITESS Installation

The supplemental chiller and water storage tank, shown in Figure 3, were installed on steel and wooden pads, respectively. The subcooler pumps were installed in a waterproof box to protect the pumps and the electronics from rain and direct sun light, as shown in Figure 4. Temperature sensors were inserted into the subcooler pipes to measure the water supply and return temperature. The subcooler pumps maintained a set differential temperature between two sensors, which allowed the system to maximize the cooling capacity of the water storage tank. The subcooler heat exchangers were attached to steel fixtures, as shown in Figure 5, and plumbed to the refrigeration lines of the existing chiller. CPVC pipes were installed to transfer cooling water between the supplemental chiller, the storage tank, and the subcoolers (Figure 6). These pipes were left uninsulated, which ultimately resulted in losses in the system.

Figure 3. Supplemental chiller and water storage tank

Figure 4. Subcoolers pumps and Watt meters

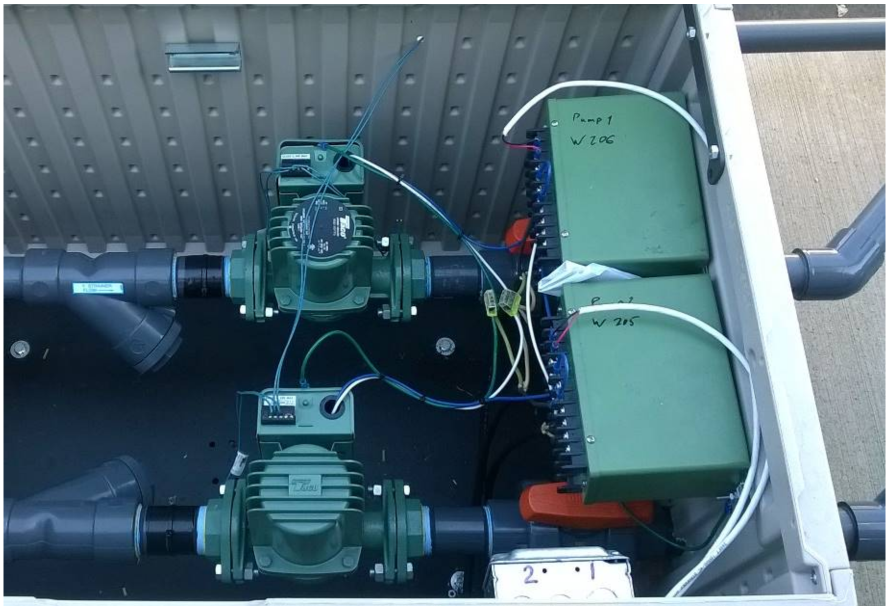
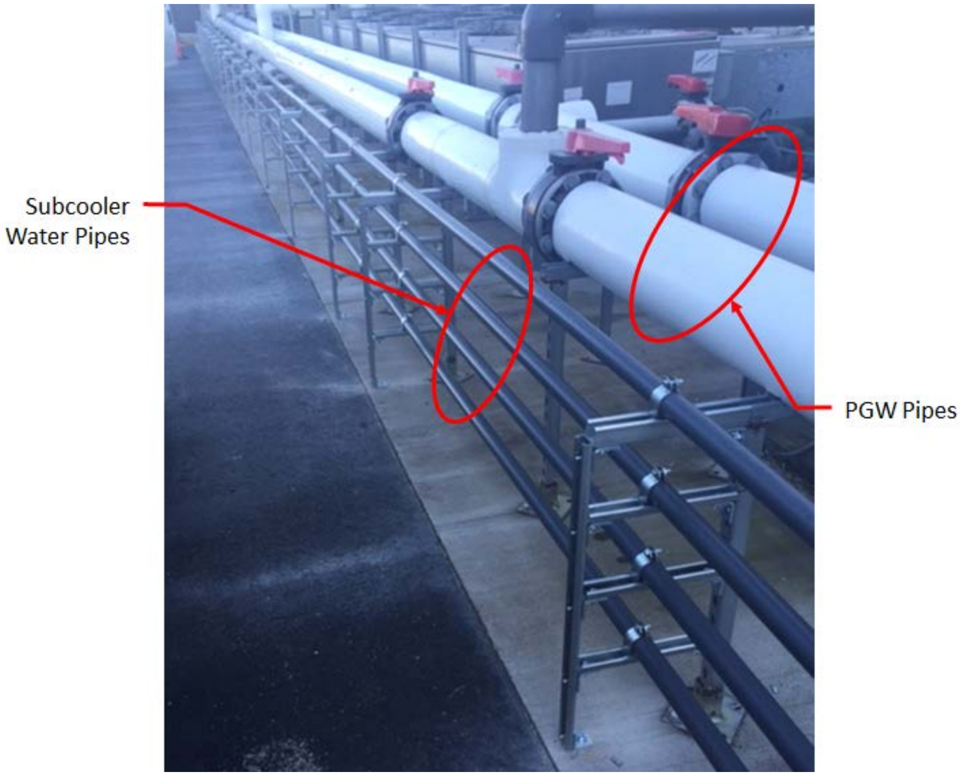


Figure 5. Subcooler plate heat exchangers

Figure 6. Subcooler pipes



4.2 DAQ Installation

The measurement equipment listed in Table 1 and depicted in Figure 1 was installed to collect data for the evaluation of the ITESS. Five thermocouple wires were attached to a CPVC pipe at equal distances, which was lowered into the water storage tank, as shown in Figure 7. To measure the water and PGW temperatures, seven thermocouple probes were inserted into pipes through drilled holes and sealed using compression fittings, as shown in Figures 8 and 9. Figure 9 also shows the dual sensor attached to a support rail to measure the relative humidity and temperature of the ambient air. To measure the refrigerant inlet and outlet temperature at the subcoolers, four thermocouple wires were directly attached to copper tubes using cable ties, as depicted in Figure 10. These connections were also insulated. Three magnetic flow meters were inserted into the water and PGW pipes through pipe fittings (iron strap-on saddles) and mounted to them, as shown in Figure 11. Four Watt meters were installed to measure the power consumption of the existing chiller, supplemental chiller, and the subcooler pumps. These are the green boxes wired to connecting equipment shown in both Figures 4 and 12. The DAQ system, which consists of the DAQ chassis and modules, was installed in an electric enclosure as shown in Figure 13. The measurement devices were connected to the input modules. The output modules were connected to the chiller and subcooler pump contactors to turn them on and off. A 24VDC power supply provided power to the measurement devices, the DAQ chassis, and the access point. The access point served as a bridge between the DAQ chassis and the wireless Wi-Fi hot spot, connecting the DAQ to the internet. Additionally, a cooling fan was installed to cool the DAQ system. While the supplemental chiller was turned off automatically when the set temperature was reached, the chiller and subcooler pumps were tuned off by using the contactors at a set time. The supplemental chiller pump, however, was not controlled using the same settings as the supplemental chiller. As such, the supplemental chiller pump often ran during times when it was not needed. This control deficiency led to unnecessary energy consumption and is an item to be noted for future improvement, as are the uninsulated pipes transferring cold water between the storage tank and subcoolers.

Measurement equipment was installed at the end of April 2016 and the control equipment for the supplemental chiller and the subcooler pumps was installed in the middle of June 2016, as outlined in Table 2. Furthermore, the single speed subcooler pumps were replaced with variable speed pumps in May 2016.

Table 2. Installation dates

Equipment	Date
Supplemental chiller, thermal storage tank, and connecting pipe installation	January–April, 2016
Measurement equipment	April 27-30, 2016
Subcooler pump replacement	May 5, 2016
Control equipment	June 16-17, 2016

Figure 7. Thermocouples attached to CPVC pipe inserted into the water storage tank

Figure 8. Thermocouple probes inserted in the pipes

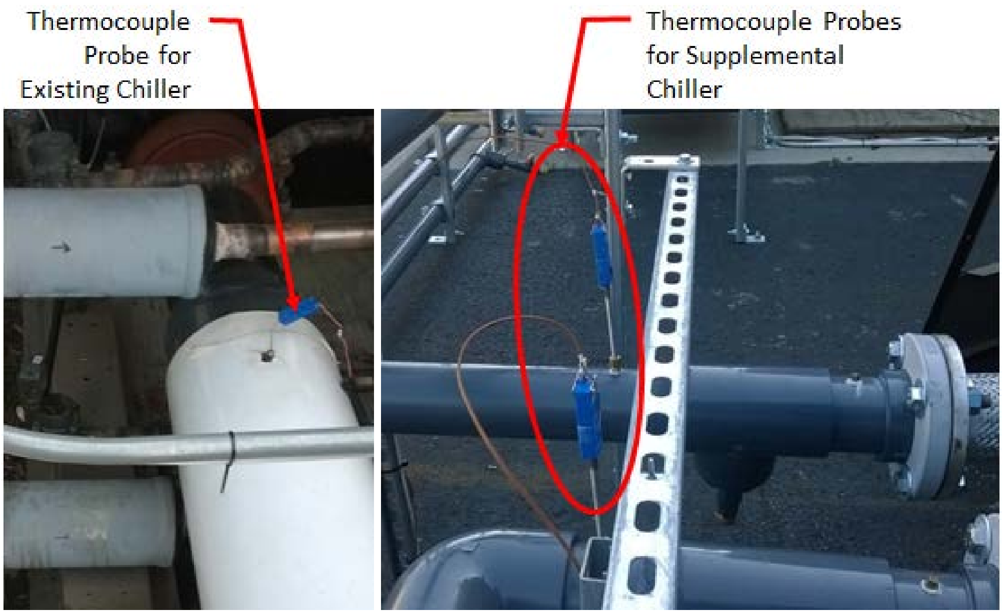


Figure 9. Relative humidity with (ambient) temperature transmitter and subcooler thermocouple probes

Figure 10. Thermocouple attached to the refrigeration copper tube

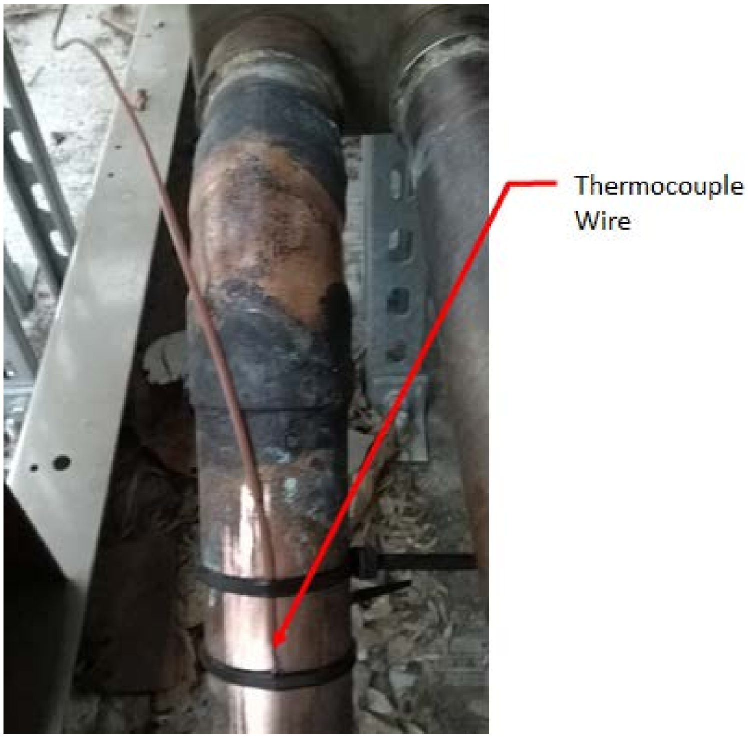


Figure 11. Flow meter inserted into the CPVC pipe

Figure 12. Watt meter installed in the existing chiller

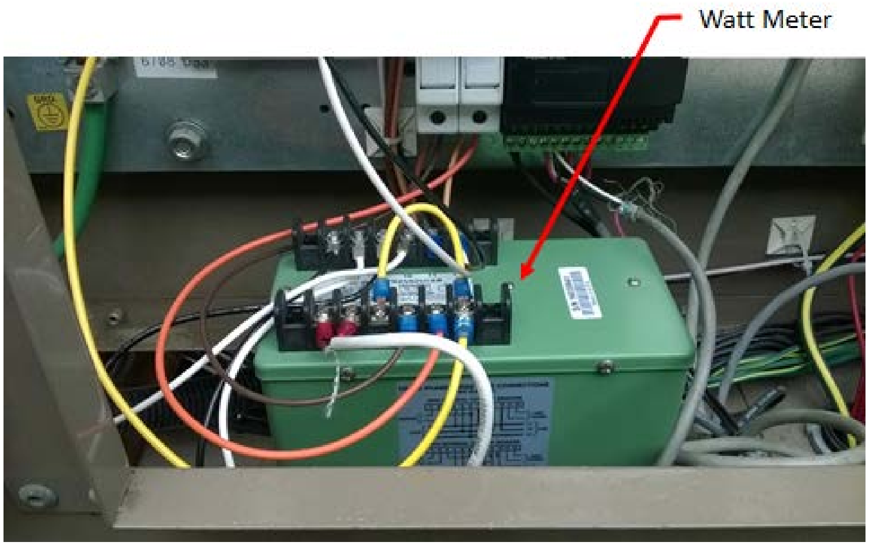
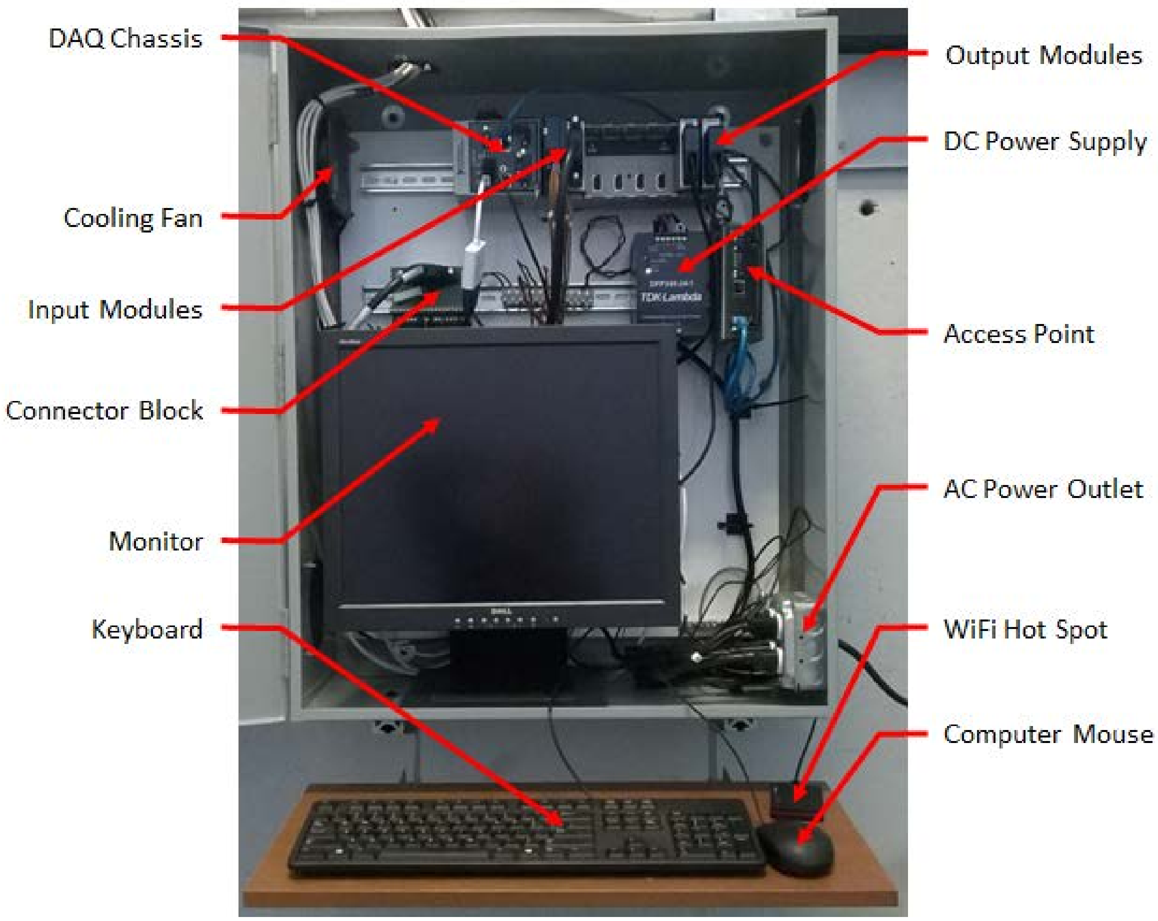


Figure 13. DAQ system in the electric enclosure



4.3 System Commissioning

Following installation, the accuracy of the measurement devices was verified using secondary devices and/or was compared to applicable design parameters. The voltage and current of the chillers and pumps were measured using a multimeter such that power demand was calculated and then compared to the measured power meter data. All thermocouples were verified by measuring temperatures with an external multimeter. The PGW and water flow rates were compared to design flow rates. In addition, the calculated cooling capacities and efficiencies of the chillers were compared against estimated specifications provided by the manufacturer and found to be in good agreement (Table 3).

Table 3. Measured and manufacturer's data comparison at part-load operation

	Existing Chiller		
	Measured Data	**Manufacturer's Data**	**Difference**
Cooling Capacity [ton]	47.28	49.04	3.73%
Power Consumption [kW]	75.40	76.58	1.57%
EER [Btu/W-h]	7.52	7.68	2.13%
	Supplemental Chiller		
	Measured Data	**Manufacturer's Data**	**Difference**
Cooling Capacity [ton]	29.66	30.10	1.48%
Power Consumption [kW]	27.65	26.40	-4.54%
EER [Btu/W-h]	12.87	12.79	-0.65%

5 Data Analysis

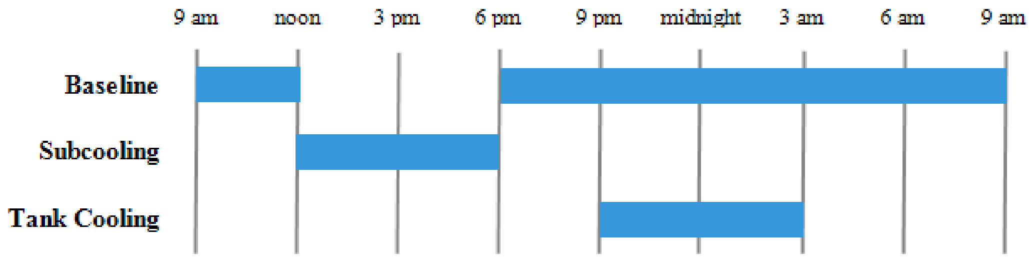
OTS conducted a detailed evaluation of the ITESS including a comparison between the operational data collected for the proposed technology and the established baseline. The goal of the analysis was to compare the following parameters important to the overall performance of the cooling system:

- Cooling capacity
- Peak power demand
- Existing chiller efficiency
- Energy consumption

Data was collected every 30 seconds and averaged over a 24-hour period from 9 a.m. to 9 a.m. This period, illustrated in Figure 14, included two baseline test periods (9 a.m. to noon and 6 p.m. to 9 a.m.), the subcooling period (noon to 6 p.m.), and the tank cooling period (9 p.m. to 3 a.m.). In the baseline mode, the existing chiller operated without any additional subcooling. In the subcooling mode, the subcooler pump(s) moved chilled water from the tank through the subcoolers. In the tank cooling mode, the supplemental chiller cooled down water in the tank and the existing chiller operated normally. On certain days, the subcooling period was extended beyond 6 p.m. to maximize utilization of the ITESS. The tank cooling period ended when the water inlet temperature to the supplemental chiller reached 44°F, which was often before 3 a.m.

Due to technical difficulties with the existing chiller at the beginning of the demonstration project, the testing schedule was adjusted to maximize the amount of data collected for evaluation of the ITESS. As such, a pure baseline test period with only the existing chiller running was not established. Alternately, baseline performance is dependent on both measured data for the baseline periods (Figure 14) and calculated performance during the subcooling periods. Baseline performance during the subcooling periods is calculated using an efficiency curve dependent on the ambient temperature. This curve was derived using measured data of the existing chiller and applied to estimate existing chiller power consumption without additional subcooling. Additional details of this approach are outlined herein and graphically depicted in Section 6.

Figure 14. Testing periods



- Baseline = operation of existing chiller without additional subcooling
- Subcooling = operation of existing chiller with additional subcooling
- Tank Cooling = water cooling in tank using supplemental (33-ton) chiller

The net cooling capacity [Btu/h] for the existing chiller was calculated using the PGW temperatures, PGW flow rate, and PGW properties for the evaporator entering and leaving conditions, per Equation (1).

Equation 1 $$\mathbf{q_{ExCh.base}\ and\ q_{ExCh.sb} = K2 \cdot \rho \cdot V \cdot c_p \cdot (T_e - T_l)}$$

Where:

- $K2 = 8.0209$, ft^3/h-gpm
- ρ = PGW density, lbm/ft^3
- V = PGW volumetric flow rate, gpm
- c_p = specific heat at the average of the entering and leaving PGW temperatures, Btu/lbm-°F
- T_e = measured existing chiller evaporator entering PGW temperature, °F
- T_l = measured existing chiller evaporator leaving PGW temperature, °F

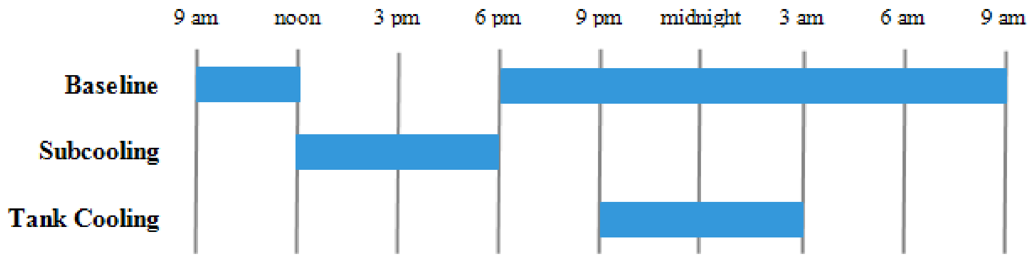
Assuming that the additional cooling capacity [Btu/h] of the existing chiller is the same as the subcooler capacity (the amount of heat removed from the refrigerant in the subcoolers), the cooling capacity increase was calculated as follows:

Equation 2 $$\mathbf{q_{sb} = K2 \cdot \rho \cdot V \cdot c_p \cdot (T_e - T_l)}$$

Where:

- $K2 = 8.0209$, ft^3/h-gpm
- ρ = water density, lbm/ft^3
- V = water volumetric flow rate, gpm
- c_p = specific heat at the average of entering and leaving water temperatures, Btu/lbm-°F
- T_e = measured subcooler entering water temperature, °F
- T_l = measured subcooler leaving water temperature, °F

Figure 14. Testing periods



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Where:

- $K2 = 8.0209$, $ft^3/h\text{-}gpm$
- ρ = water density, lbm/ft^3
- V = water volumetric flow rate, gpm
- c_p = specific heat at the average of entering and leaving water temperatures, Btu/lbm-°F
- T_e = measured subcooler entering water temperature, °F
- T_l = measured subcooler leaving water temperature, °F

Equation 7 $$\mathbf{W}^{*}_{\mathbf{ExCh,sb}} = \mathbf{EFF_{base}} \cdot \mathbf{K3} \cdot \mathbf{q_{ExCh,sb}}$$

Where:
EFF_{base} = estimated baseline efficiency of the existing chiller during the subcooling period, kW/ton (per Equation 4)
K3 = 12,000 ton-h/Btu
$q_{ExCh,sb}$ = cooling capacity of the existing chiller during the subcooling period, Btu/h (per Equation 2)

The power demand change was then calculated per Equation 8.

Equation 8 $$\Delta\mathbf{W} = \frac{(\mathbf{W_{ExCh,sb}} - \mathbf{W}^{*}_{\mathbf{ExCh,sb}})}{\mathbf{W}^{*}_{\mathbf{ExCh,sb}}} \cdot \mathbf{100}\%$$

Equation 9 was applied to calculate the total energy consumption (kWh) of the existing chiller using measured data and the calculated performance during the subcooling period.

Equation 9

$$\mathbf{E_{base}} = \sum_{\mathbf{t=9am}}^{\mathbf{t=noon}} \mathbf{W_{ExCh,base}} \cdot \mathbf{t_{ExCh,base}} + \sum_{\mathbf{t=noon}}^{\mathbf{t=6pm}} \mathbf{W}^{*}_{\mathbf{ExCh,sb}} \cdot \mathbf{t_{SubCool}} + \sum_{\mathbf{t=6pm}}^{\mathbf{t=9am}} \mathbf{W_{ExCh,base}} \cdot \mathbf{t_{ExCh,base}}$$

Where:
- $W_{ExCh,base}$ = measured power demand of the existing chiller during baseline period, kW
- $W^{*}_{ExCh,sb}$ = estimated power demand of the existing chiller during the subcooling period (per Equation 7)
- $t_{ExCh,base}$ = time during baseline period, h
- $t_{SubCool}$ = time during subcooling period, h

The total ITESS power demand (kW) was calculated using Equation 10. If the supplemental chiller and the subcooler pumps did not operate, their power terms were zero.

Equation 10 $$\mathbf{W_{ITESS}} = \mathbf{W_{ExCh}} + \mathbf{W_{SubPump}} + \mathbf{W_{SupCh}}$$

Where:
- W_{ExCh} = measured power demand of existing chiller, kW
- $W_{SubPump}$ = measured power demand of subcooler pump(s), kW
- W_{SupCh} = measured power demand of supplemental chiller, kW

The net ITESS energy consumption (kWh) over a full 24-hour period was calculated using Equation 11. The energy consumption for the ITESS was based entirely on measured data for the power draw of each component and actual run time.

Equation 11

$$\mathbf{E_{ITESS}} = \sum_{\mathbf{t=9am}}^{\mathbf{t=9am}} \mathbf{W_{ITESS}} \cdot \mathbf{t} = \sum_{\mathbf{t=9am}}^{\mathbf{t=9am}} \mathbf{W_{ExCh}} \cdot \mathbf{t} + \sum_{\mathbf{t=SubCoolStart}}^{\mathbf{t=SubCoolStop}} \mathbf{W_{SupPump}} \cdot \mathbf{t_{SubCool}} \sum_{\mathbf{t=SupChStart}}^{\mathbf{t=SupChStop}} \mathbf{W_{SupCh}} \cdot \mathbf{t_{TankCool}}$$

Where:

- t = total run time of ITESS/existing chiller, h
- $t_{TankCool}$ = time during tank cooling period, h

The change in enery consumption (%) was calculated per Equation 12.

Equation 12 $$\Delta\mathbf{E} = \frac{\mathbf{E_{base}} - \mathbf{E_{ITESS}}}{\mathbf{E_{base}}} \cdot \mathbf{100}\%$$

6 Test Results

Testing with the ITESS was conducted from the beginning of July 2016 until the end of October 2016. The collected data was evaluated on a daily basis. Analysis for a select day is presented in Section 6.1 and a summary of results for each month is presented in Section 6.2.

Data collection originally started at the beginning of May 2016, however, no baseline could be established due to several issues with the existing chiller. One of the condensers was found to have a refrigerant leak and had to be replaced. One of the compressors was also replaced. Furthermore, pollen accumulated on the condensers, reducing overall chiller performance. Cleaning was conducted on a weekly basis during the month of June to minimize such performance degradation.

6.1 Daily Test Results

The cooling capacity of the existing chiller was calculated using Equation 1. Several days with different cooling capacity profiles were selected as examples for the evaluation. Data for August 27, 2016 is presented as an example. Additional examples are provided in Appendix B. As an example of the evaluation, Figure 15 shows the existing chiller cooling capacity calculated using Equation 1 for a 24-hour period on August 27, 2016. As can be seen in the figure, when the subcoolers are activated between 12 p.m. and 7 p.m. (hours 12 and 19), the cooling capacity increases. The fluctuation in the cooling capacity during the subcooling period is attributed to the cycling of compressors in the existing chiller, meaning that more capacity is provided than necessary so the chiller doesn’t constantly run at full capacity. When compressors turn off, the capacity is reduced, hence the reduction in capacity during the subcooling period. The cooling capacity below the baseline performance was not included in the calculation to determine the cooling capacity increase. The small fluctuations in the cooling capacity are attributed to the fluctuations in PGW flow measurements. The red lines in the graph represent the average values for the selected time period.

Figure 16 shows the directly measured power demand of the existing chiller during baseline and ITESS operating modes. The power demand of the existing chiller significantly decreased during the subcooling period. As with the capacity curve, the power demand fluctuation is attributed to compressor cycling. The power demand of the existing chiller was lower during the subcooling period for short periods of time because the ITESS shifted some of the demand to off-peak hours when the cooling tank was recharged.

The supplemental chiller water pump circulated water between the supplemental chiller and the water storage tank even after the supplemental chiller was turned off, as noted previously. This unfortunately caused unnecessary energy consumption, which could have been avoided by integrating the pump control into the supplemental chiller control. The power demand of the subcooler pumps, however, is very small (around 0.13kW) compared to the total power demand of the system (above 100 kW during the subcooling period).

Figure 15. Calculated (Equation 1) existing chiller cooling capacity on 08/27/2016

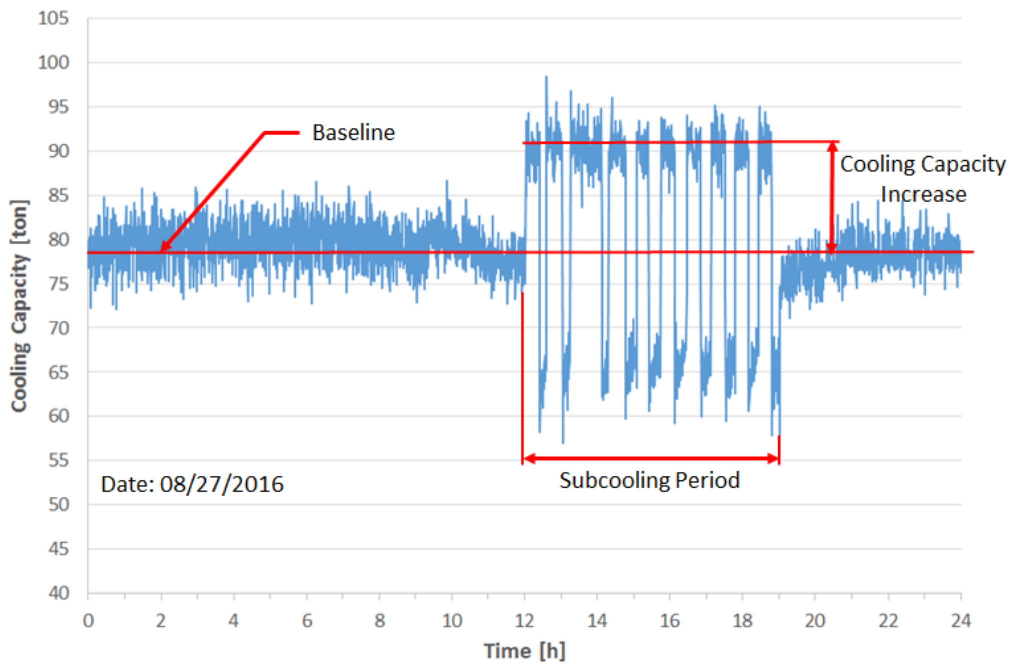
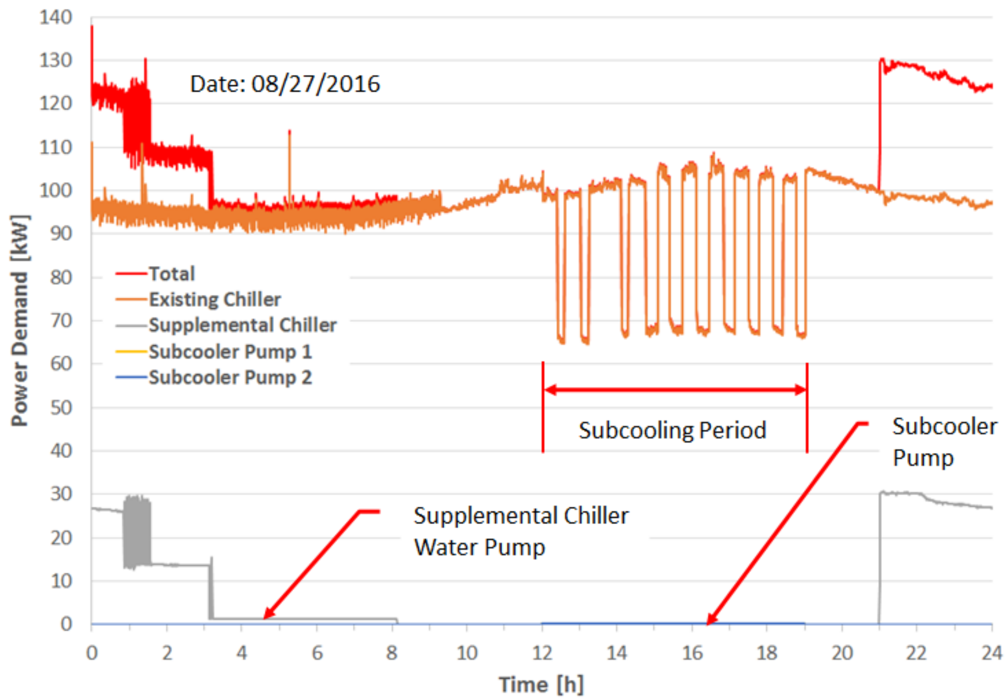


Figure 16. Measured power demand of existing chiller with ITESS on 08/27/2016



The power demand of the existing chiller was normalized over its cooling capacity to calculate its efficiency, which is expressed in kW of electrical input to the chiller per ton of cooling capacity provided by the chiller (kW/ton). More efficient chillers have lower kW/ton ratings, indicating they use less electricity to deliver the same amount of cooling. The existing chiller efficiency was plotted vs. ambient temperature, as shown in Figure 17. During the baseline and subcooling periods, the efficiency increases with rising temperatures due to a higher refrigerant rejection temperature. The efficiency is lower during the subcooling period as compared to the baseline period due to the increased refrigerant subcooling. For the baseline period, Equation 4 was used to calculate the chiller efficiency such as that depicted in Figure 17. Figure 18 shows the fitted line for the baseline chiller efficiency, which was calculated by using data taken from multiple days and covers a wide range of ambient temperatures that occurred during the test period (from 37°F to 94°F). The equation was used to estimate the normalized power demand of the existing chiller at higher ambient temperatures, which usually occurred during the subcooling period. As shown in Figure 19, the ambient temperature during the subcooling period is approximately 4-23°F higher than that during the baseline period on 08/27/2016. A similar trend was observed during the entire testing period. The estimated efficiency curve calculated using Figure 18 was then used for the calculation of baseline chiller power demand during the average temperature during the subcooling period, as outlined in Equation 7.

Figure 17. Calculated (Equation 4) efficiency of existing chiller on 08/27/2016

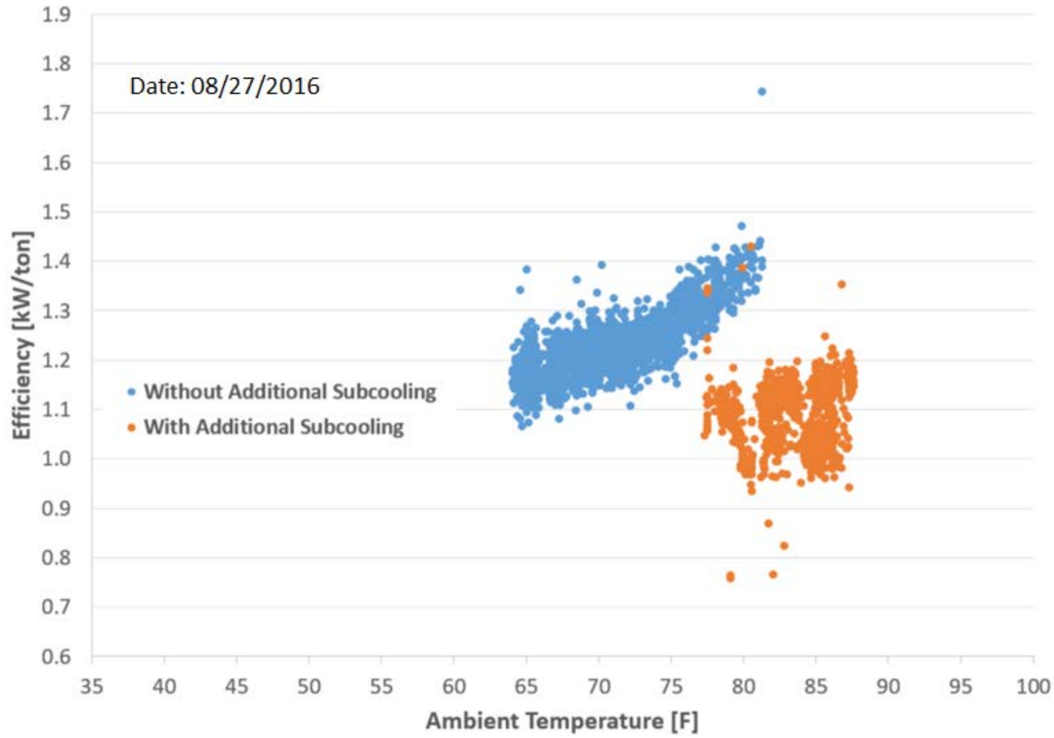


Figure 18. Baseline efficiency

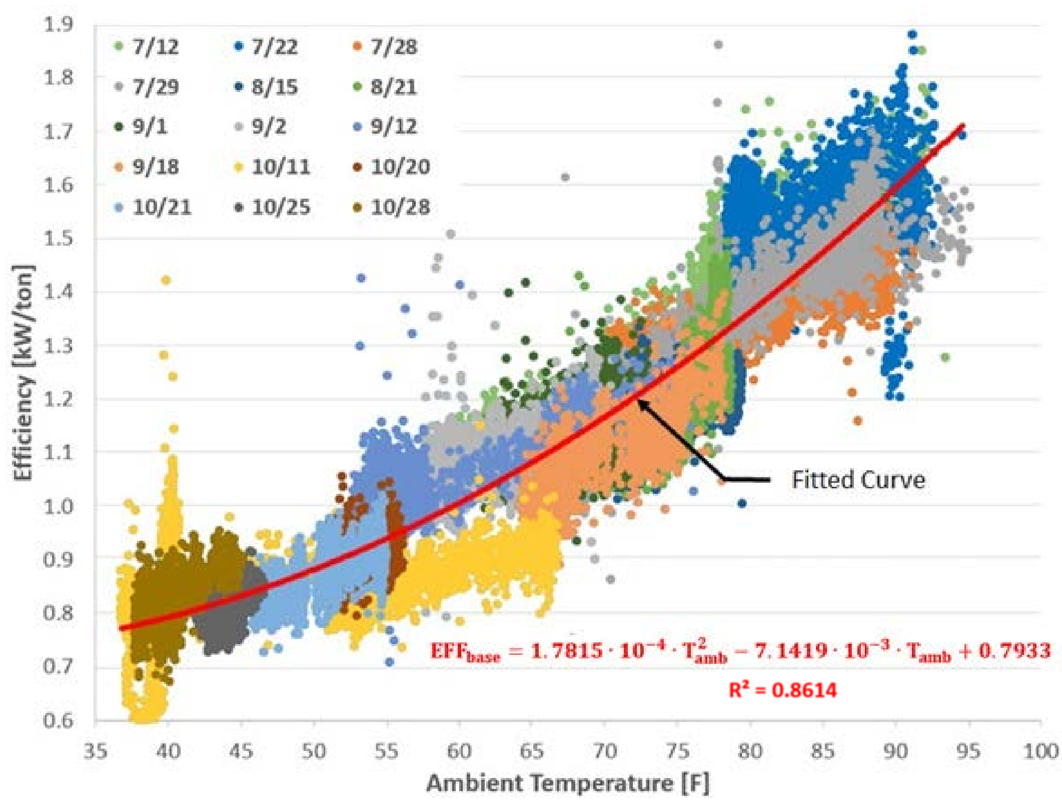
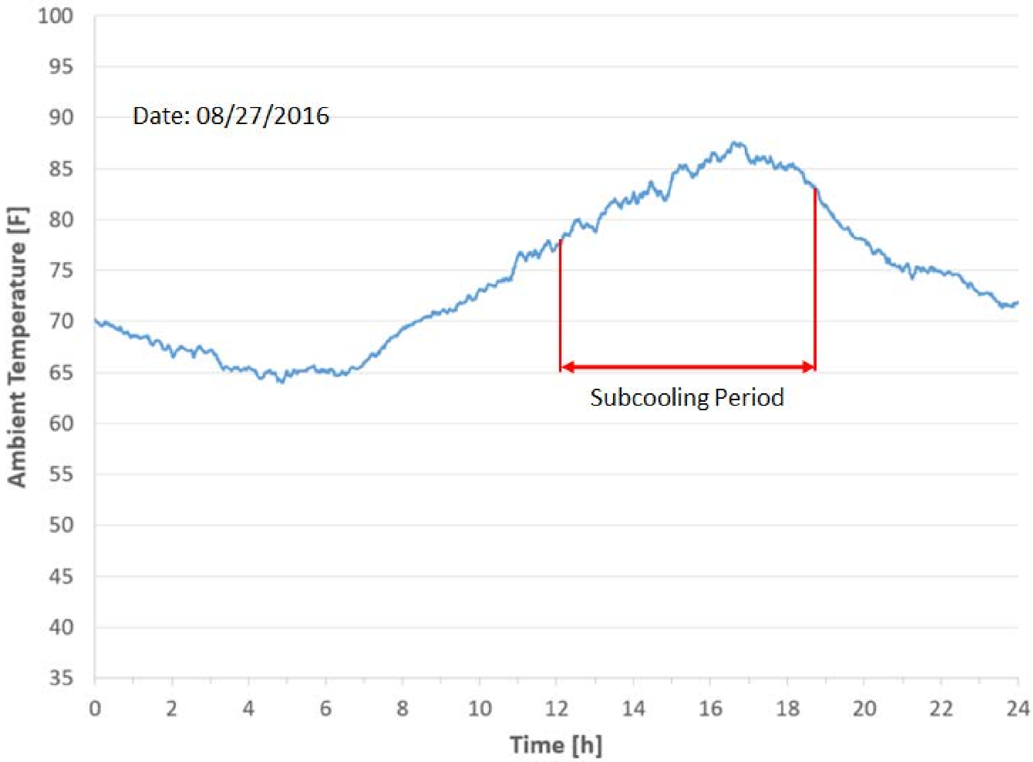


Figure 19. Measured ambient temperature on 08/27/2016



6.2 Monthly Test Results

Daily test data were summarized and evaluated for a total of 80 days for the test period from July to October 2016. Figure 20 through Figure 23 show relative changes in cooling capacity, efficiency, power demand, and energy usage of the existing chiller as a result of the use of additional subcooling. Table 4 and Table 5 summarize the daily average, minimum, and maximum values for each parameter. It should be noted that the listed power demand is based on the theoretical calculation presented in Section 5.[3] For the sake of completeness, all data are shown in the graphs including those for the days when the existing chiller was shut down for repairs and days in late October when the additional subcooling did not result in gained capacity due to lower ambient temperatures. However, these data were not included in the final evaluation.

[3] Actual peak demand using the ITESS increased due to use of the supplemental chiller overnight. As described below, this additional demand would not occur in the proposed commercial solution.

The results clearly show the increase in the cooling capacity and efficiency as well as the reduction in the power demand of the existing chiller. However, the results also show a marginal increase in the average energy usage. This can be attributed to heat losses though the uninsulated subcooler water pipes, which account for 5-8% of the supplemental chiller thermal energy;[4] heat losses through the water tank; and the extended run time of the water pump for the supplemental chiller. Thus, the energy usage could be reduced by insulating water pipes, providing better insulation to the water storage tank, and integrating water pump control with the supplemental chiller control.

Table 4. Daily average, minimum, and maximum values with uncertainty for ITESS performance gains

	Average	Minimum	Maximum
Cooling Capacity [ton]	11.01 ± 3.31	0.75 ± 0.23	19.26 ± 5.78
Efficiency [kW/ton]	0.195 ± 0.059	-0.353 ± 0.112	0.390 ± 0.117
Estimated Power Demand [kW][5]	-10.0 ± 1.98	-0.50 ± 2.44	-25.8 ± 2.90
Energy Usage [kWh]	-71.6 ± 11.5	-276 ± 7.0	419 ± 15.0

Table 5. Daily average, minimum, and maximum values with uncertainty as a percentage for ITESS performance gains

	Average	Minimum	Maximum
Cooling Capacity [%]	17.74 ± 5.32	2.20 ± 0.66	34.21 ± 10.26
Efficiency [%]	15.01 ± 4.50	0.60 ± 0.18	28.50 ± 8.55
Estimated Power Demand [%][7]	-13.99 ± 2.92	-0.65 ± 2.78	-34.31 ± 3.85
Energy Usage [%]	0.05 ± 0.007	-5.51 ± 0.13	4.75 ± 0.16

4 NAIMA 3E software was used to estimate pipe heat losses.

5 Calculated, per Section 5, and estimated against operation of a comparably larger chiller offering the same capacity.

Figure 20. Differences Between Baseline and ITESS Performance in July

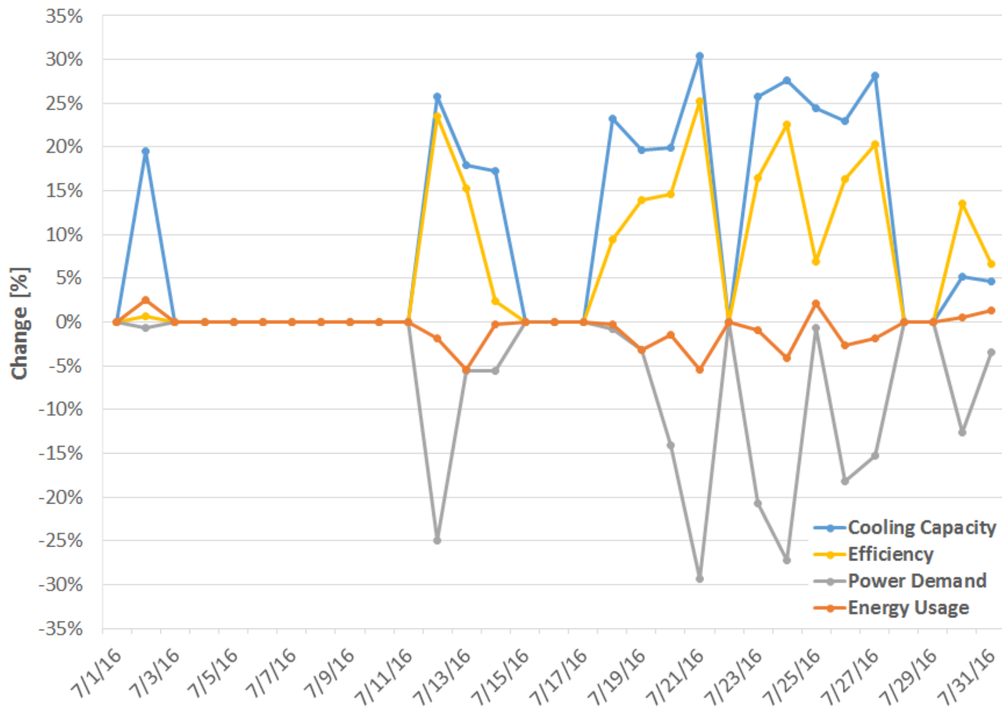


Figure 21. Differences Between Baseline and ITESS Performance in August

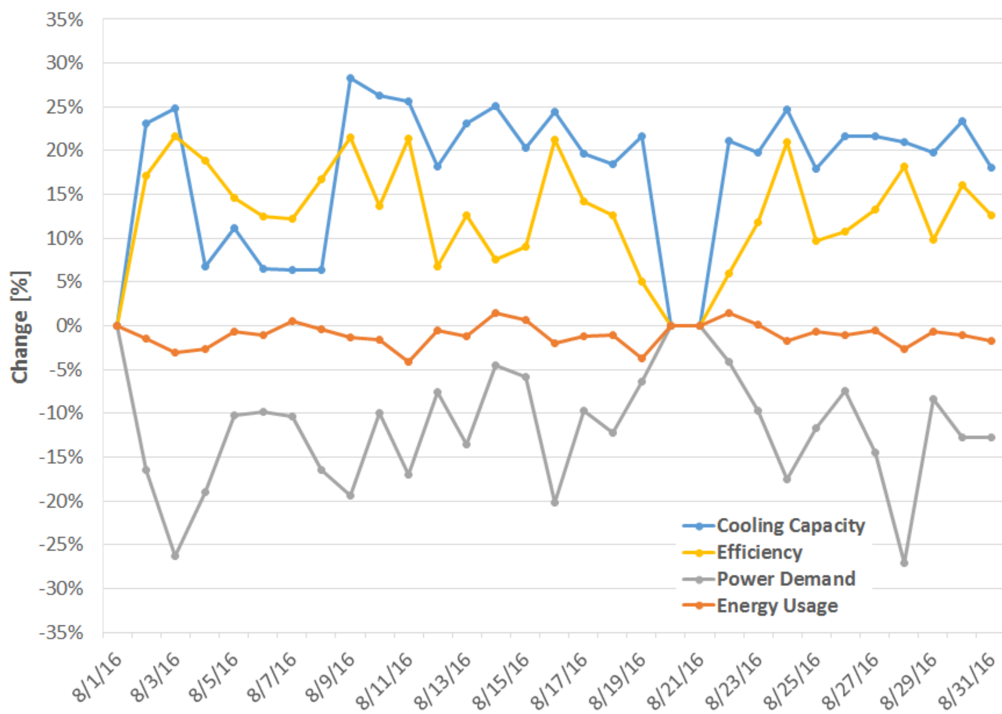


Figure 22. Differences Between Baseline and ITESS Performance in September

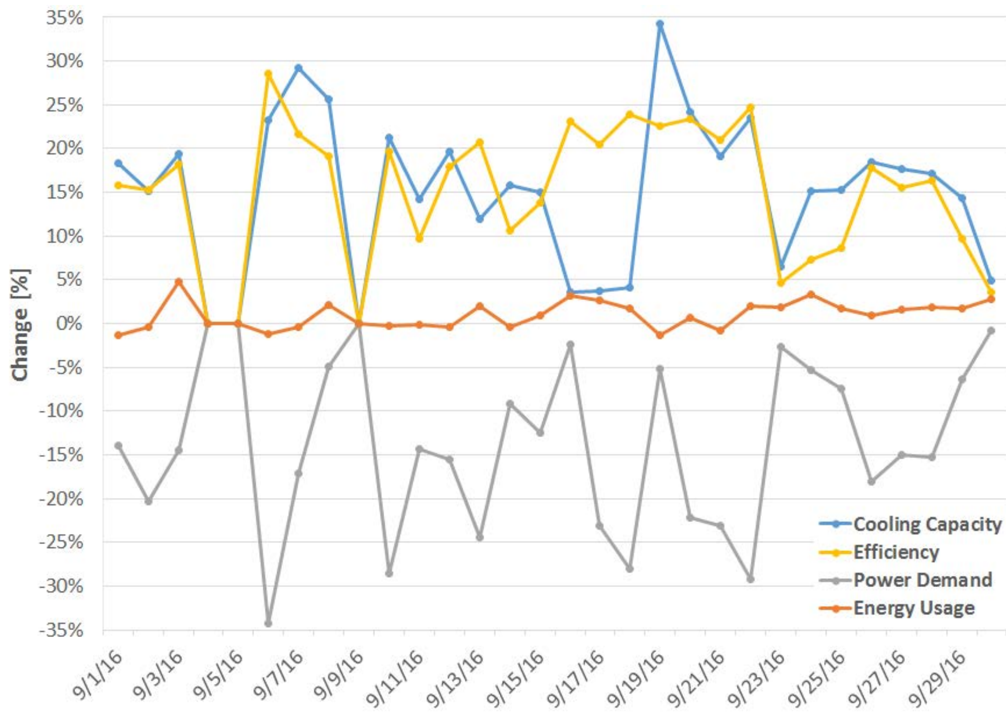
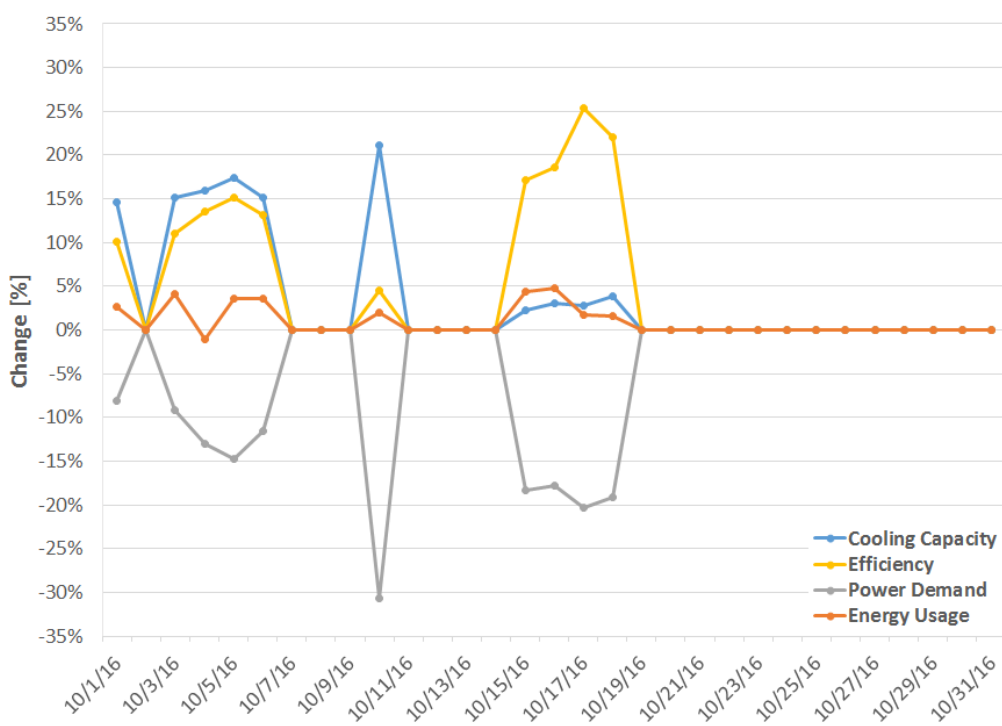


Figure 23. Differences Between Baseline and ITESS Performance in October



The changes in cooling capacity, efficiency, power demand, and energy usage of the existing chiller are depicted in Figures 24 through 27. For reference, curves are included that show the theoretical benefit from cooling refrigerant liquid temperature leaving the condenser at 5°F above the ambient temperature to 48°F. The theoretical benefit from subcooler operation should result in an increase of about 25% in both capacity and efficiency at 90°F, which is the summer design condition for Syracuse, NY. It is obvious that the cooling capacity gains primarily occurred at higher ambient temperatures because of the cooling load of the building and the higher refrigerant heat rejection temperatures (Figure 24). The small cooling capacity changes (up to 10%) at high ambient temperatures could be attributed to compressor cycling.

In general, the measured data agree with the theoretical benefit within the uncertainty of the data. The increase in efficiency primarily accrued at higher ambient temperatures due to the increase in the cooling capacity (Figure 25). Power demand and energy usage decreased with the increasing ambient temperatures as shown in Figures 26 and 27 respectively.

Figure 24. Cooling capacity change vs. ambient temperature

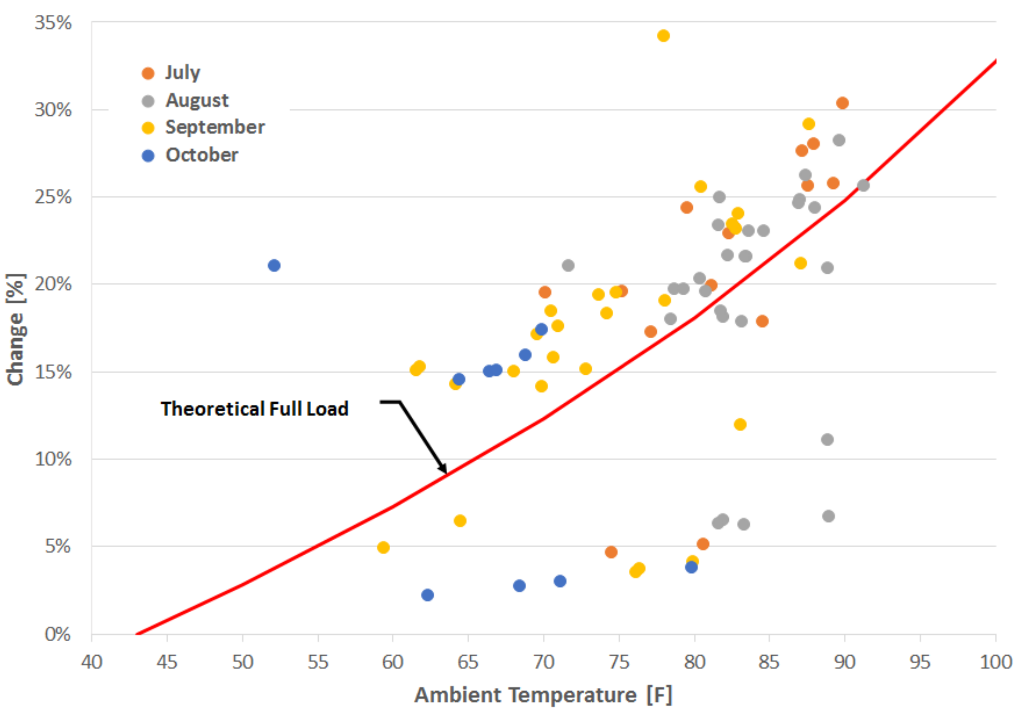


Figure 25. Efficiency change vs. ambient temperature

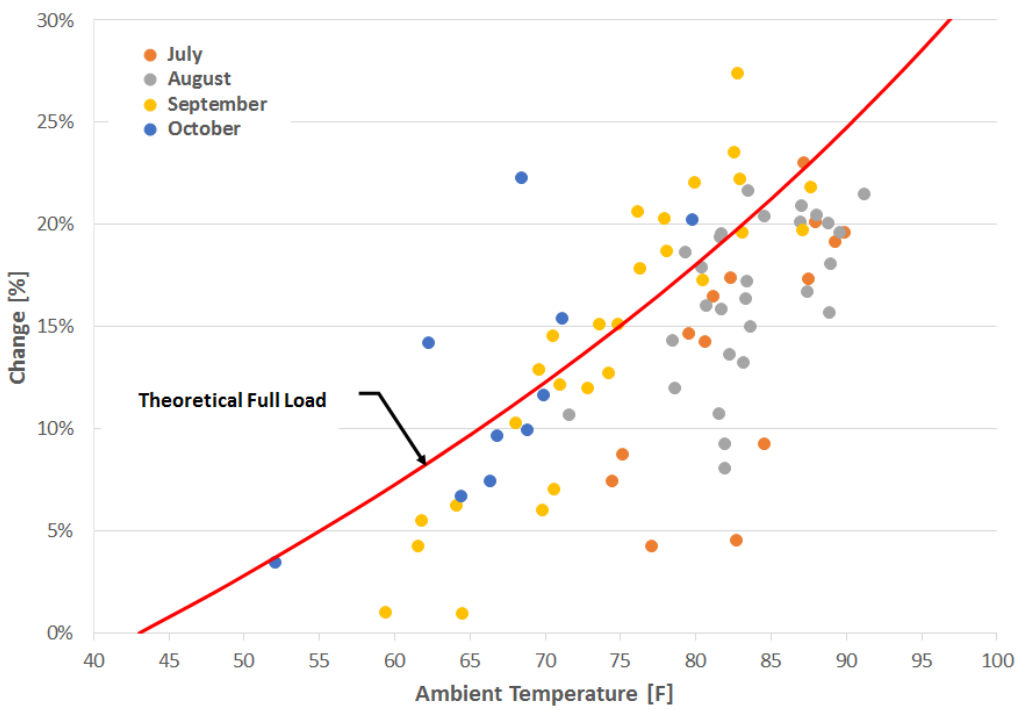


Figure 26. Power demand change vs. ambient temperature

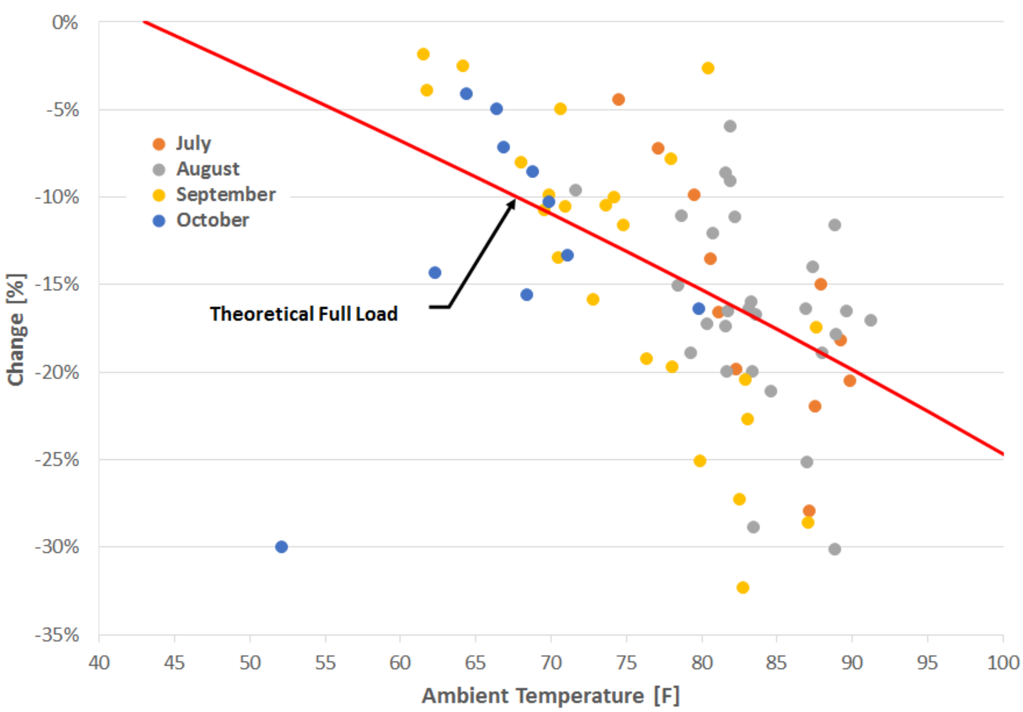
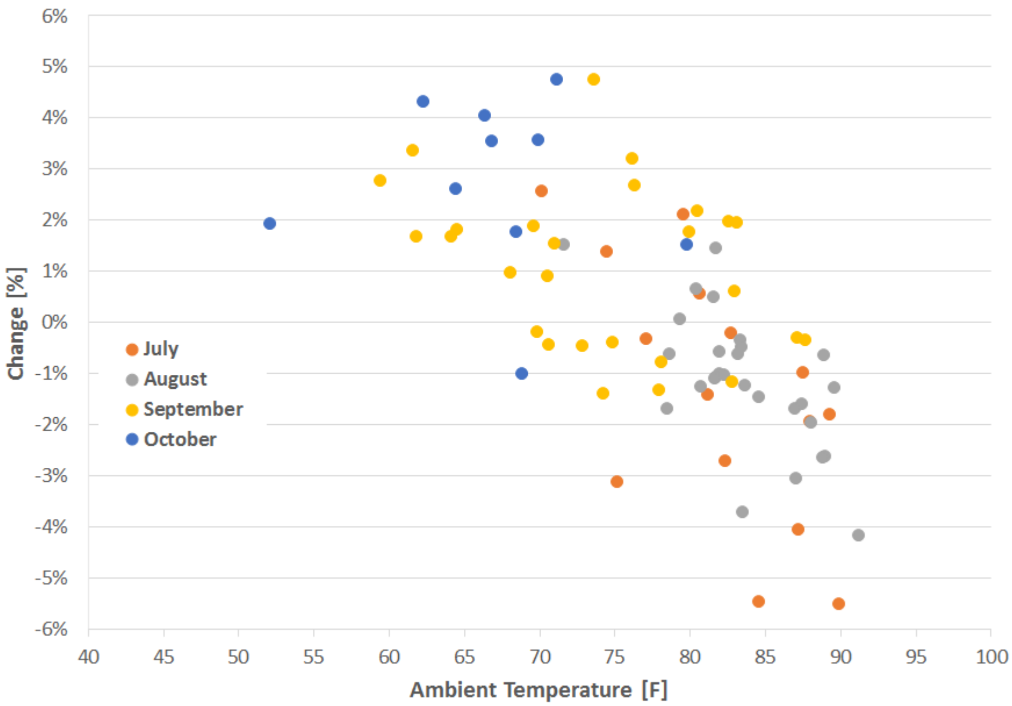


Figure 27. Energy usage change vs. ambient temperature



7 System Cost Analysis

The use of the ITESS has the potential to not only increase system capacity without the installation of a larger chiller system, but potential to reduce utility charges as a result of peak power demand reduction and energy consumption savings. Installation of an ITESS can be considered for two basic scenarios: a retrofit application, like the Bitzer demonstration project; or a new construction installation.

A retrofit ITESS with the addition of a small capacity chiller is suggested if an existing chiller already operates at full capacity at all times and does not have any additional capacity to cool water in the tank for subcooling. This was exactly the case for the Bitzer demonstration. Alternate retrofit configurations, however, are feasible if an existing chiller has some excess cooling capacity during off-peak hours of operation, e.g., at night. In these cases, a supplemental chiller is not needed and water for subcooling can be directly cooled by the existing chiller.

For a new construction application, the ITESS would generally be installed with a single chiller that requires the benefits of subcooling for peak load operation, but has excess capacity during off-peak hours to cool tank water for later subcooling. This would be appropriate for commercial office buildings and similar applications where the main cooling loads occur during standard business hours. ITESS can still be applied for new construction in 24/7 facilities, but may require an additional supplemental chiller or alternate control strategy to ensure all cooling needs are met.

In addition to summarizing the cost impacts for the Bitzer demonstration project, payback analyses are considered for the above described commercial installation approaches.

7.1 Retrofit ITESS

The ITESS installation costs for the Bitzer demonstration project accumulated to $109,277 with high labor costs due to a high degree of customization, per Table 6.

Table 6. ITESS component price

Component	Price
10,500-gal water tank	$8,837
Insulation blanket	$2,780
Supplemental chiller and subcoolers	$20,000
Labor and other components	$77,660
Total	$109,277

In addition to the high installation cost, several factors prevent Bitzer from realizing utility cost savings from the ITESS. These include the following:

- The Bitzer facility is currently charged based on the National Grid (Large General SC3[6]), which does not provide for on-peak/off-peak or time of day pricing for energy supply or demand. Shifting energy usage from day to night time periods does not result in any direct financial gain.
- As noted in Section 2, the demonstration system relied on a separate supplemental chiller in order to cool the water to sufficient temperatures to enable subcooling during day time periods. A supplemental chiller was required for implementation with an existing chilled water system. In this instance, the use of the supplemental chiller actually increased peak power demand when considering the full 24-hour period. New construction or full renovation installations would not require the use of a supplemental chiller and could result in higher energy savings.
- The installed system experienced unnecessary energy losses due to uninsulated water pipes, an uninsulated top of the water tank, and improper control of the supplemental chiller pump. These deficiencies in installation contributed to minor increases in energy consumption and ultimately, energy supply charges.

The main advantage of the ITESS for the Bitzer plant is the added cooling capacity without having to replace the existing chiller with a larger one. While a supplemental chiller was installed, this installation was feasible with minimal interruption to regular cooling operation. As outlined above, on average, use of the ITESS resulted in 17.74% more cooling capacity than without it.

7.2 Commercial ITESS

The intent of the ITESS demonstration is to support Johnson Controls, Inc. in developing a commercial solution for future ITESS installations. A more typical design of an ITESS has been developed, and as previously outlined, unlike the retrofit ITESS at the Bitzer facility, a commercial ITESS will not have a supplemental chiller. Instead, the primary chiller will include an integrated subcooler connected to a storage tank using simple hose connections in the field, as depicted in Figure 28. This eliminates several of the energy losses identified in the Bitzer demonstration.

As shown in Figure 28, the proposed commercial installation of the ITESS includes the subcooler in the chiller refrigerant circuit between the condenser and the expansion valve and is connected in a water loop with a water tank and a subcooler pump. As with the demonstration at the Bitzer facility, the subcooler is

[6] Source: National Grid, 2016

a counterflow (typically brazed-plate) heat exchanger with approximately equal fluid temperature change on both the water and refrigerant sides. For air-cooled systems, the water temperature change can be 60°F to 80°F (33 to 44 K) or even greater, which is several times the available temperature change for conventional chilled-water storage systems.

Valves allow chilled water from the existing chiller to cool the tank at night or during other low-load conditions. The high temperatures of the warm water in the tank combined with lower nighttime air temperatures reduce the energy required to cool the tank and improve overall system efficiency in addition to shifting electric load. When the system is in subcooling mode, valves V2 and V3 are closed and valves V1 and V4 are open. The subcooler and chilled water pumps are both in operation. Chilled water is pumped through the subcooler heat exchanger and warm water is returned to the top of the tank. The flow rate of water through the subcooler is a small fraction of the flow rate through the cooler providing active cooling for the space. At night, when ambient temperatures are cooler and electric rates are lower, the system is recharged. To do so, valves V1 and V4 are closed and valves V2 and V3 are opened. The subcooler pump is off, but the chilled water pump is on. The chiller gradually cools the water in the tank using its comparably large flow rate (Kopko, 2016).

Figure 29 shows the top and side views of the proposed more-standard configuration for a 175-ton chiller with thermal storage tank. This commercial ITESS version will further reduce the foot print and material installation costs of the system by eliminating the supplemental chiller. This configuration will also increase the cooling capacity to 224 tons, providing a significant reduction in installation costs.

Figure 28. Schematic of the commercial ITESS

Source: Kopko (2016)

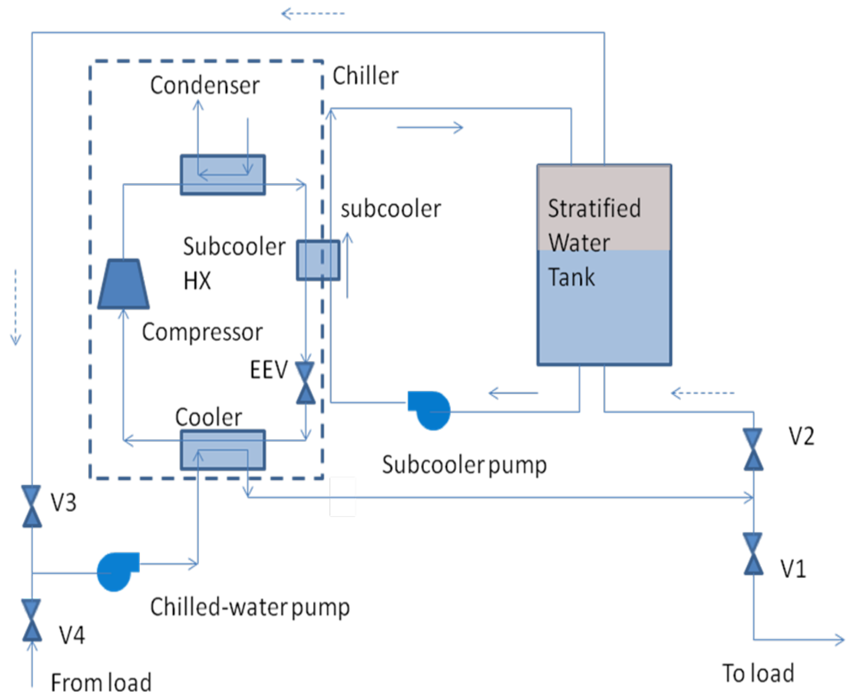
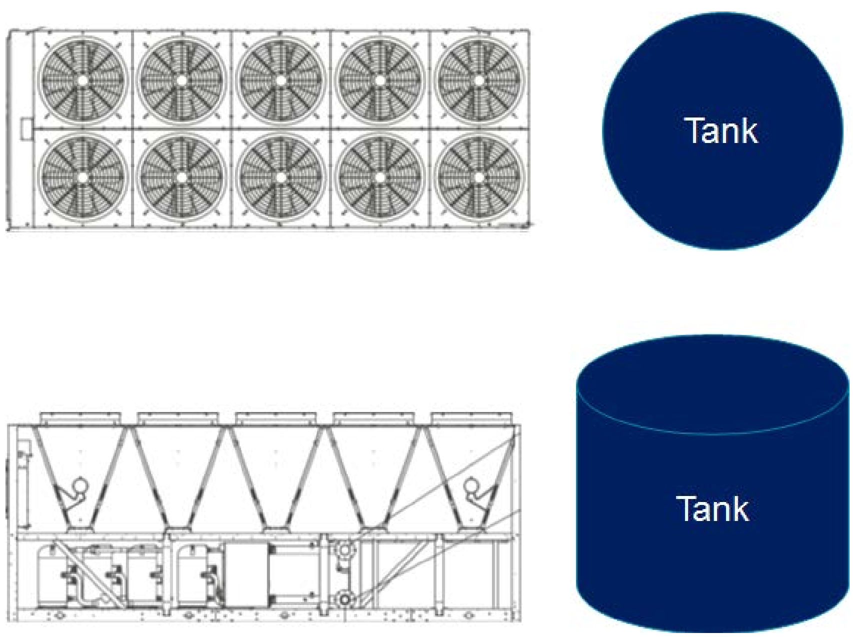


Figure 29. Commercial ITESS a) top view; b) side view

Source: Johnson Controls, Inc.



Energy and utility cost savings were calculated for the proposed commercial ITESS based on observations and calculations from the demonstration project results and use of a utility rate providing for on-peak/off-peak demand pricing. Such rates exist, including, as an example, NYSEG Rate SC7, Large General Service Time-of use Rates, but are not necessarily common, depending on facility size, utility company and territory. As such, it is important that utility rates are identified and negotiated up front to gain maximum cost benefit before any new installation.

The benefits of the ITESS are summarized in Table 7 considering two references: 1) a retrofit case where ITESS adds needed capacity to an existing chiller during on-peak hours, and 2) a new construction case in which installation of a larger chiller can be avoided due to the installed ITESS. As can be seen in the table, the estimated installation cost for a new 175-ton chiller system is $105,000 based on a cost of $600/ton.[7] Similarly, the cost to install a traditional chiller system with 224-ton capacity would be a total of $134,400. Additional costs to provide an integrated ITESS, capable of providing a peak capacity of 224 tons, is $40,000[8] including the water storage tank, subcoolers, subcooler pumps, and additional piping. Thus, for a pure retrofit scenario, the incremental cost for the ITESS is an additional $40,000. For a new construction comparison, however, the incremental cost is reduced to $10,600.

In terms of energy savings, for a retrofit scenario, there is no net change in peak demand (existing chiller versus ITESS with increased capacity in Table 7). Efficiency, however, will improve and total cooling capacity increase without installation of a new chiller. Efficiency improvements will result in consumption savings. Given the variable nature of potential energy consumption savings based on operating conditions, as observed in the Bitzer demonstration, this gain has not been estimated. Providing additional cooling capacity, however, is the main intent of this type of installation and may improve overall building operations. Depending on application, this may result in thermal comfort and/or other business performance improvements that have a value needing evaluation on a case-by-case basis.

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[7] This value is also estimated by Johnson Controls. It could linked to footnote 12 instead. I am not sure anymore what the correct footnote convention is when two pieces of information are from the same source.

[8] As estimated by Johnson Controls, Inc.

For the new construction comparison, however, the ITESS results in a peak demand savings of approximately 65 kW, based on assumed efficiencies (28% increase in cooling capacity). Over the course of the cooling season, using a rate of $8.14/kW based on utility charges, this would provide a utility cost savings of $526 per month. Given the estimated peak demand cost savings and the $10,600 incremental cost outlined above, the payback for this system is just over five years.[9] As with a retrofit installation, additional cost savings from reduced energy consumption is feasible. Any actual energy consumption savings would further reduce the payback period for the ITESS. Energy consumption should not significantly change or increase as a result of the ITESS.

9 Additional maintenance considerations are difficult to estimate and are not included in payback calculations.

Table 7. Benefits of ITES*with 175-ton chiller[10]

	Existing Chiller Reference	Larger Chiller New Construction Reference	ITESS	Units	Formula	Notes
Capacity	175	224	224	tons	A	Baseline and larger chiller efficiencies and capacities are estimated based on values observed from a prior laboratory demonstration (Kopko, 2016). ITESS cooling capacity and efficiency are assumed to be 28% and 30% higher than the baseline based on observations from Bitzer and prior laboratory demonstrations. EER is obtained from the manufacturer at rated conditions.
EER at peak	9.6	9.6	12.5	Btu/hr/W	B	
Peak Power Demand	219	280	215	kW	C=A/B*12	
Peak Demand Savings			65	kW	D=C(Larger)-C(ITESS)	Savings over a larger chiller installation.
Peak Demand Charge			$8.14	kW	E	Based on NYSEG SC7 Time-of-Use Rates,[11] Secondary Voltage.
Months Savings Realized			4	months	F	Assumed cooling period June–September.
Value of Peak Demand Savings			$2,104	/year	G=D*E*F	
Base Cost	$105,000	$134,400	$105,000		H	Based on $600/ton, per Johnson Controls, Inc.
Additional Installed Cost	-	-	$40,000		J	Estimated per Johnson Controls, Inc. for water storage tanks, subcoolers, subcooler pumps, and additional piping.
Total Cost	$105,000	$134,400	$145,000		M = H + J	
Net Incremental Cost	-		$10,600		N=M(ITESS)-M(Larger)	The value of additional capacity is greater than the cost of the proposed commercial ITESS.
Payback			5.04	years	P=N/G	

10 Based on the chiller performance at 95°F ambient 54/44°F chilled water temperature.

11 Source: NYSEG, 2016.

8 Conclusions and Recommendations

An Integrated Thermal Energy Thermal Storage System (ITESS), which provides additional subcooling for an air conditioning system's condenser by utilizing chilled water, was installed at the Bitzer Plant in Syracuse, NY in April 2016 and monitored from July to October 2016. The collected data were analyzed. The application of the additional subcooling showed the following advantages and disadvantages:

- The cooling capacity of the existing chiller increased between 2.2% and 34.2% depending on the cooling load and ambient temperatures.[12] The cooling capacity increases primarily occurred at higher ambient temperatures and is consistent with the theoretical 25% increase at 90°F ambient conditions.
- The efficiency of the existing chiller increased between 0.6% and 28.5% due to the increased cooling capacity.[13]
- The power demand of the existing chiller has the theoretical potential to decrease between 0.7% and 34.3% as compared to a chiller system with comparable increased capacity. Actual power demand increased with the demonstration ITESS due to use of a supplemental chiller and poor control of supplemental equipment.[14]
- The energy usage fluctuated between a 4.7% increase and 5.5% decrease with an average increase of 0.05%.[15] The fluctuation in energy usage is attributed to heat gains though the subcooler pipes and water storage tank as well as longer-than-necessary operating time of the supplemental chiller water pump. This increased energy consumption occurred during the supplemental chiller operation during off-peak hours (8 p.m. to 9 a.m.). In addition, the low energy consumption changes are within the margin of error of the Watt meters.

In general, the advantages of the additional subcooling were higher at higher ambient temperatures due to higher refrigerant heat rejection temperature in the condenser.

Based on the lessons learned from the demonstration project, future installations of the ITESS should:

- Leverage installations with built-in subcooling components to simplify the design and reduce unnecessary auxiliary power and losses.
- Adequately insulate the water storage tank and any water pipes carrying cooled water to maximize the subcooling advantage.
- Properly control all equipment to eliminate unnecessary energy consumption.
- Install equipment only for sites where on-peak/off-peak or time-of-day pricing can be realized.

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12 See Table 5 for uncertainties.

13 See Table 5 for uncertainties

14 See Table 5 for uncertainties

15 See Table 5 for uncertainties

References

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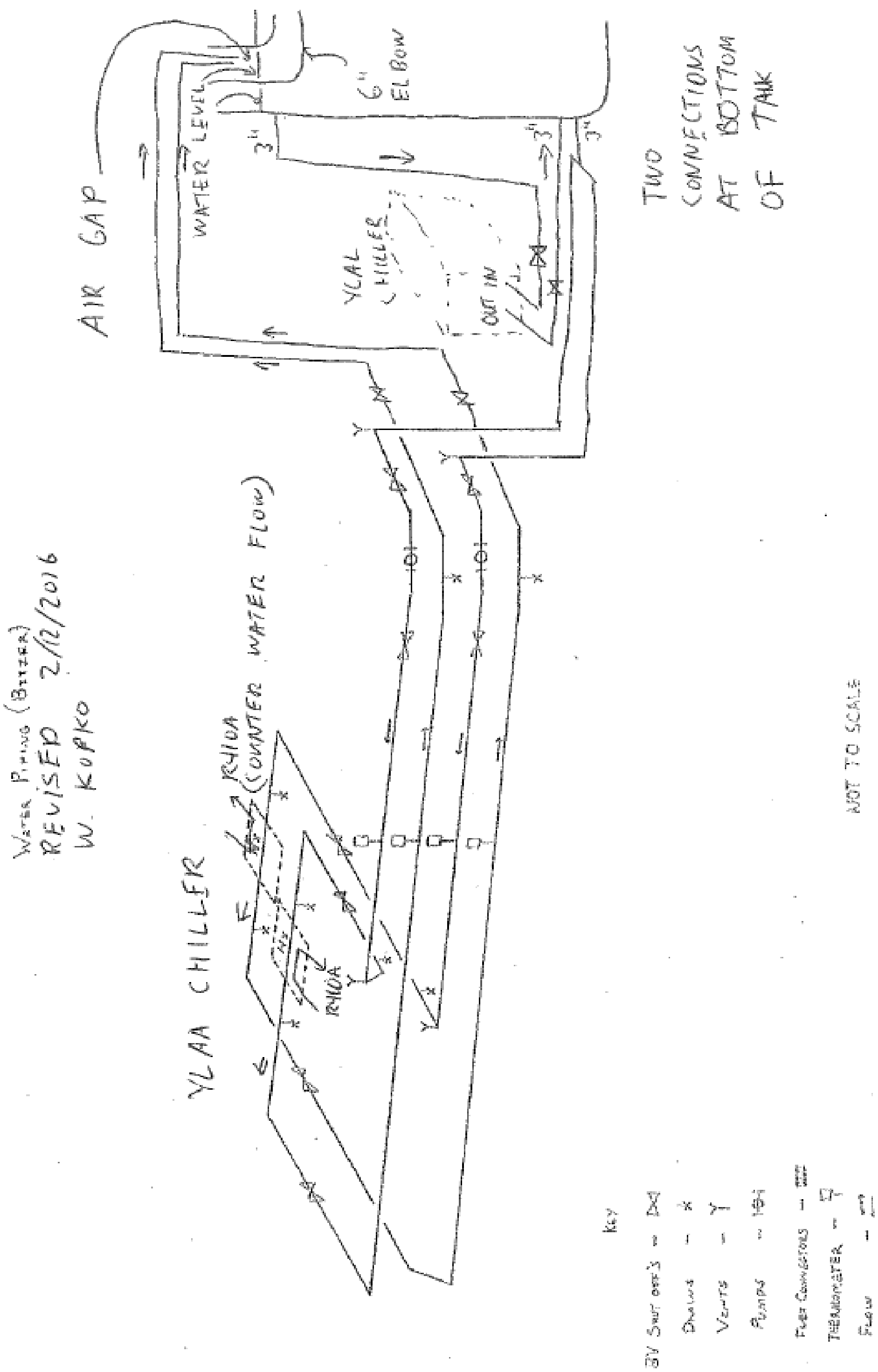
Appendix A: ITES Piping Diagram

Figure A-1. ITES piping diagram



Appendix B: Example Chiller Capacity Profiles

Figure B-1. Existing chiller cooling capacity on 07/27/2016

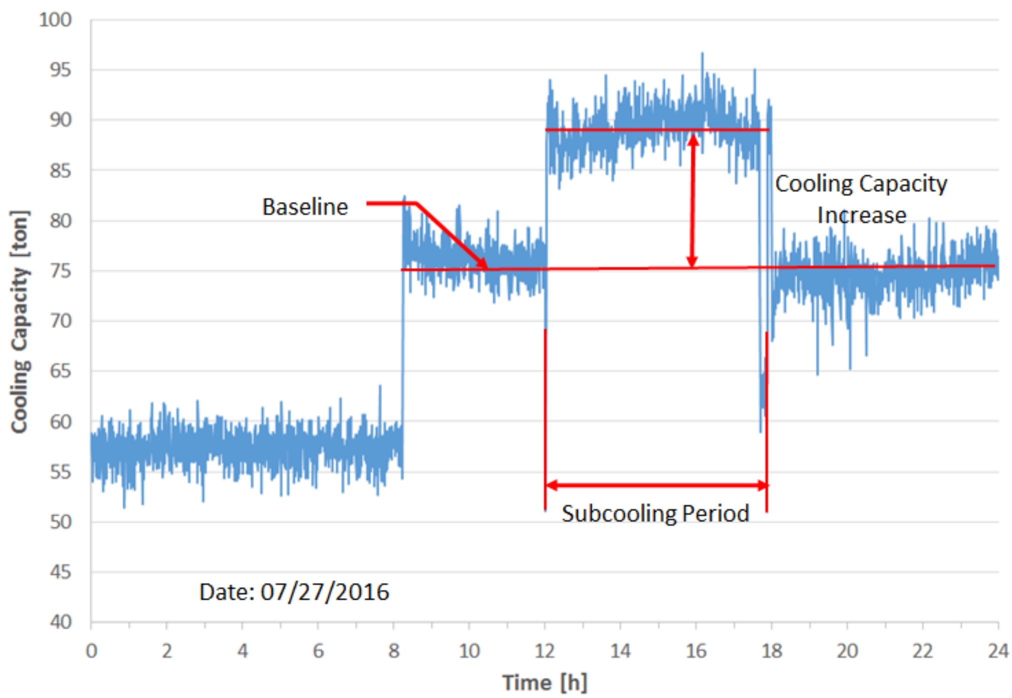


Figure B-2. Existing chiller cooling capacity on 09/06/2016

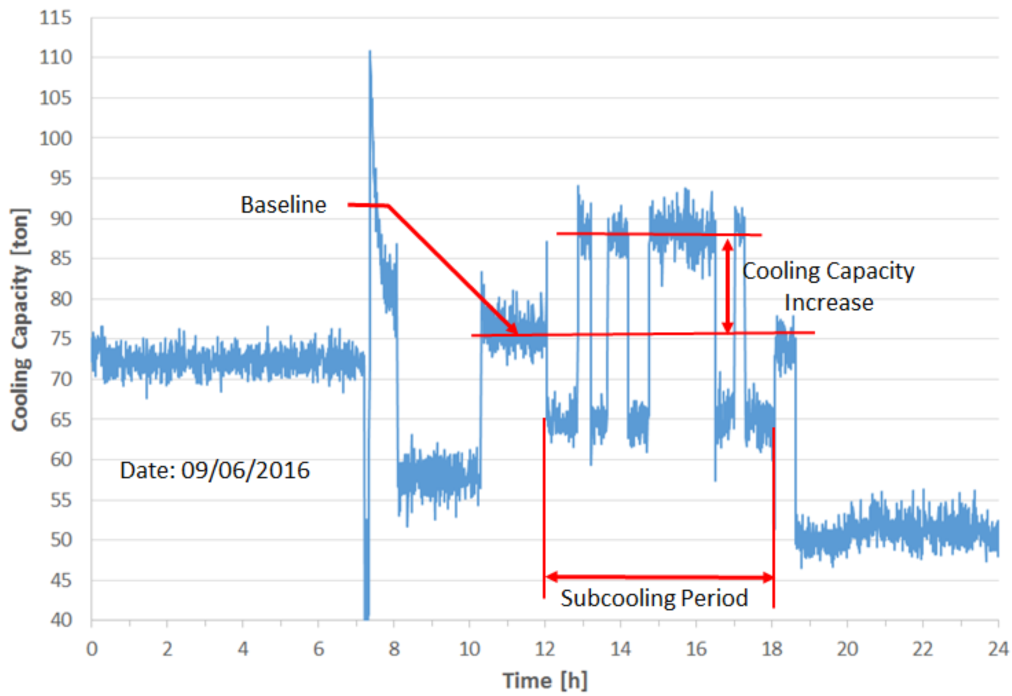
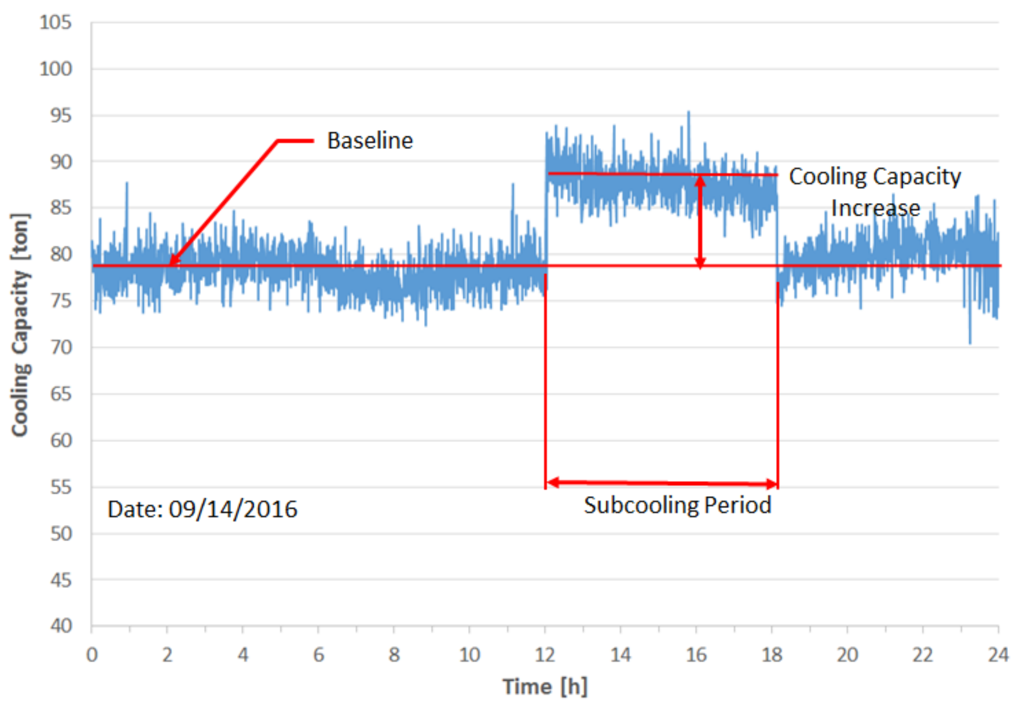


Figure B-3. Existing chiller cooling capacity on 09/14/2016



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