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Q-Sync Motor Performance in Walk-in Coolers and Freezers

Field Test for ComEd Emerging Technologies

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INTRODUCTION

For commercial refrigeration applications, the Q-Sync motor - a type of permanent magnet alternating current (PMAC) motor – has recently received attention because of its high efficiency and much improved power factor compared to traditional Shaded-Pole (SP), Permanent Split Capacitor (PSC) motors, and even newer Electronically Commutated (EC) motors. The U.S. Department of Energy (DOE) Oak Ridge National Laboratory (ORNL) and Alternative Energy Systems Consulting have conducted field studies of Q-Sync motors for evaporator fans in refrigerated display cases, walk-in coolers, and walk-in freezers in large supermarkets in Ohio, Vermont, and California. These studies have suggested significant energy savings potential.

Commonwealth Edison Company (ComEd) is a large, investor-owned electric utility covering most of northern Illinois. ComEd has over four million customers; primary sectors include residential customers (31% of total energy usage), small commercial and industrial customers (35% of energy usage), and large commercial and industrial customers (25% of energy usage). ComEd provides energy efficiency programs to customers to meet legislatively-mandated savings goals. The program offerings include incentivizing customers on high-efficiency HVAC and refrigeration equipment. New energy efficiency products such as Q-sync are often evaluated by ComEd's emerging technology (ET) program, which sponsors pilot field studies of commercially available new products on the market.

Under the contract with ComEd, Slipstream has conducted a field study of Q-Sync motors for small commercial refrigeration applications in northern Illinois. This study focused on retrofitting existing walk-in cooler and freezer evaporator fan motors in small convenience stores.

OBJECTIVES

The primary objectives of this project were to:

- Quantify the electrical energy savings and demand reduction from retrofitting original equipment motors with Q-Sync motors in walk-in cooler/freezer applications in small convenience stores
- Investigate issues related to identifying fans eligible for retrofit, and best practices for retrofitting them with Q-Sync motors
- Develop a report describing the methods, results, and conclusions of the study

LITERATURE REVIEW

Historically SP motors were the most commonly used evaporator fan motors in commercial refrigeration display cases, walk-in coolers and freezers, and beverage vending machines and cases. They had been the simplest and least expensive type of small motor but are also not very energy efficient. The motors commonly used for evaporator fans in walk-in coolers and freezers applications are typically less than 20% efficient for SP motors and 25% to 40% efficient for PSC motors (NCI and PNNL, 2011).

Q-Sync motors are new, state-of-the-art permanent magnet alternate current (PMAC) synchronous motors that can achieve higher energy efficiency than existing motor types. The Q-Sync motors have several distinct new design features that contribute to significant energy savings compared to traditional evaporator fan motors used in refrigerated display cases:

1. Q-Sync motors are a type of PMAC motors that rotate synchronously with grid power frequency. The permanent magnets eliminate the need for magnetizing current used in induction motors (such as SP motors) and therefore eliminate induction motor's slip and rotor conductor losses, improving motor energy efficiency.
2. EC Motors use electronics to rectify AC to DC and then use inverters or switching power supplies to produce AC electric current pulses to drive each phase of the motor. Synchronous AC motors can directly use grid-supplied alternating current without these power-consuming electronics and the inverters/switching power supplies, resulting in reduced power draw.
3. Traditional PMAC motors require a Variable Frequency Drive (VFD) to provide a start to the rotation, and they cannot operate directly across the line. Q-Sync motors have a patent-pending new controller design that does not use VFDs. The new control circuit will only be energized during motor start and the circuit, which does consume power, drops out after reaching synchronous speed. The Q-Sync motor then sustains the AC speed. Since evaporator motors usually run continuously for a long time with few starts and stops, this control circuit design improves overall motor energy efficiency.

There was only one formal field study found in our literature search related to Q-Sync retrofit for walk-in applications. The Oak Ridge National Laboratory (ORNL) completed a field study in 2018 (Fricke, Brian A.; Becker, Bryan R., 2018) for 38–50-watt Q-Sync motors used for evaporator fans for walk-in coolers and freezers. In the lab testing, the 38~50-watt Q-Sync motors exhibit a peak efficiency of 82% with a power factor of approximately 0.9 at a power output of 35 watt. The power factor did vary significantly and increased with motor load and power output.

Because Q-Sync motors run at different fan motor rotational speeds (1800 RPM on a 60 Hz AC power) than conventional fan motors (typically 1550 RPM), Q-Sync blades have a slightly lower pitch than typical evaporator fan blades. In another lab testing of air flows vs. motor input power, a series of curves generated show lower pitch blades and higher air flow rates resulted in lower motor input powers. A procedure for the selection of fan blade pitch for 38–50-watt Q-Sync motors is given based on these curves, with the assumption there is no other difference between the incumbent blades and the Q-Sync blades. The Q-Sync motor manufacturer standardized 38~50-watt motor to only two fan blade options: 10-inch fan blade pitch: 22 degrees, and 12-inch fan blade pitch: 18 degrees. The standardized Q-Sync motor /fan assemblies produced equivalent or higher air flow rates than the incumbent motor/fan assemblies tested in the lab.

The 38~50-watt Q-Sync motors were tested at two field test sites in this study. One site is a supermarket located in South Burlington, VT, while the other was the same supermarket chain store located in Colchester, VT. One walk-in cooler and one walk-in freezer were selected for testing at each site. Total of

42 evaporator fan motors were retrofitted. On average, the walk-in evaporator fan powers decreased by 53% and 61% for the coolers and 46% for one of the freezers following the retrofit of the incumbent fan motors with Q-Sync fan motors. The retrofit of the other freezer did not yield conclusive results due to irregular performances of the Q-Sync motor and the researchers were not able to determine the cause of the anomalies. A whole-store Q-Sync motor retrofit was also conducted on 22 display cases and 16 walk-ins. The real power was found to be reduced by 46% following the retrofit of the 262 evaporator fan motors that were monitored, and the simple payback period was calculated to be 5.6 years. The power factors for the Q-Sync motors in the walk-ins had a range of ~0.60 to 0.95.

EXPERIMENTAL FIELD TEST

Our field study was conducted following an experimental plan that included customer acquisition, exploratory site visits, measurement design and installation, Q-Sync motor retrofit, and finally data analysis. Each step is described in detail in the sections below.

CUSTOMER AQUISITION

In this field study, we focused on testing the 38~50 w Q-Sync motors for small commercial refrigeration applications in the ComEd service territory. The ORGNI Group, an Energy Services firm based in Wood Dale, IL, are well connected to local small businesses and helped Slipstream in identifying small business building owners who were willing to participate this field study. Three sites were identified.

Site #1: Dunkin' Donuts Store in Bensenville, IL

This store (Figure 1) is a typical franchised Dunkin' Donuts store that sells Dunkin' Donuts coffee, donuts, bagels, muffins, compatible bakery products, sandwiches, as well as other food items and beverages. Its normal hours of operation are from 4:00 am to 11:00 pm every day. The store has a gross floor area of about 2,100 sq. ft. (50' x 42'.)

Figure 1. Site #1 - Dunkin Donuts Store

Site #2: Mobil Gas Station in McHenry, IL

This gas station/convenience store (
Figure 2) is a small retail business that stocks a range of everyday items such as snack foods, confectionery, soft drinks, tobacco products, beer, and wine, newspapers, and car related items. Its normal hours of operation are from 5:00 am to 11:00 pm every day. The store has a gross floor area of about 3,100 sq. ft. (75' x 45'.)

Figure 2. Site #2 – Gas Station Convenience Store

Site #3: Liquor Store in Joliet, IL

This food and liquor store is also a small retail business that sells everyday snack foods, soft drinks, tobacco products, beer and wine, and other miscellaneous items (Figure 3.) Its normal hours of operation are from 9:00 am to 10:00 pm every day. The store has a gross floor area of about 4,500 sq. ft. (75’ x 60’.)

Figure 3. Site #3 – Liquor Store

All these stores have multiple walk-in coolers and freezers to store foods, liquor, and other items. These coolers and freezers’ evaporator fans use 38~50 w motor & fan assembly in delivering cold air to the inside spaces of the coolers and freezers. Customer agreements for the Q-Sync motor pilot project were signed between the building owner and ComEd. These agreements allowed Slipstream researcher and local service contractors to go into the building and conduct survey and measurement, install power and temperature/relative humidity monitoring devices, and retrofit the cooler/freezer evaporator fan motor and blade assemblies.

EXPLORATARY SITE VISITS

At the beginning of the experimental test, exploratory site visits were conducted to evaluate refrigeration equipment and site configurations. This step is critical in identifying cooler and/or freezer evaporator fan motors that are appropriate for Q-sync motor retrofit, in selecting Q-sync motor and blade assemblies, as well as planning both installation and measurement and verification activities at these sites. We tried to obtain information on:

- Motor types and configurations in use, i.e., EC, SP, or PSC motors, mounting, shaft, and rotation direction.
- Motor models and fan blade types/sizes
- Operations practices such as fan controls or seasonally variable practices
- Practical aspects of performing both installation and measurement and verification

The OGNI Group engineers provided an initial list of evaporator fan motors that the building owners agreed to be included in this field study.

Site #1: Dunkin' Donuts

This Dunkin' Donuts store has a cooler and a freezer to store various food and drink items. They are connected to each other, but a door in between allows staff to enter from the cooler to the freezer. The cooler and freezer are very small in size – approximately 90'(L) x 75' (W) x 90' (H) for the cooler, and 137'(L) x 75' (W) x 90' (H) for the freezer. One side of the cooler/freezer is adjacent to the exterior wall in the back of the store, and a solid door is an entry to the cooler space. Each of the cooler and freezer has a cooling unit on top of the roof. The cooling unit includes both condenser and the evaporator units. A top view of the store that marks locations of the cooler and freezer as well as doors and cooling units are shown in Figure 4.

The manufacturer of both the walk-in cooler and freezer prefabricated panels is Norlake. The cooling unit models cannot be clearly seen, but it was suspected they are one of the celling-mounted Capsule Pak™ series models by Norlake. Both units run on 208 VAC and are controlled by Norlake's digital temperature controllers that are mounted on the front door of the cooler for easy adjustments. The cooler temperature was usually set at 37 ^{o}F, and the freezer temperature was usually set at -5 ^{o}F (Figure 5.)

Both cooling units on top of the roof combine condensers and evaporators into one. Evaporators for both cooling units were uncovered to observe the evaporator fan motor models and fan blade sizes (Figure 8 and Figure 9.) Both motors in the cooler evaporator were YDK-38-4 1550 model that is rated for single phase, 208~230 VAC, 1/20 HP, 0.5 A, and 1550 RPM. The blade size for this evaporator is 10" nominal. One motor in the freezer evaporator was FASCO LR6319 that is rated for single phase, 208~230 VAC, 1/20 HP, 0.84 A, and 1550 RPM, and the other motor was FASCO D1126 that is rated for single phase, 208~230 VAC, 1/15 HP, 1.1 A, and 1550 RPM. The blade size for this evaporator is also 10" nominal. However, *one of these two evaporator fan motors (FASCO LR6319) was found without a fan blade (*Figure 8.) The cold air after the evaporator coil is pushed from the top/ceiling of the cooler and freezer down to the inside of the cooler and freezer spaces. The power to the condenser and the evaporator at both cooling units were not on separate circuits at the main power panel.

Figure 4. Site #1 – Top View


Figure 5. Site #1 – Door 1 and Digital Temperature Controllers

Figure 6. Site #1 – Freezer Inside View

Figure 7. Site #1 – Cooler and Freezer Outside View

Figure 8. Site #1 – Freezer Evaporator

Figure 9. Site #1 – Cooler Evaporator

Site #2: Mobil Gas Station

The Mobil Gas Station's convenience store has one cooler to store various food and drink items. The cooler is roughly rectangular with dimension 335'(L) x 117' (W) x 100' (H), and it is located inside the building. A top view of the store that marks the location of the cooler is shown in Figure 10. There is only one solid door at one end of the cooler as the entry to the cooler space. The cooling unit condenser is on the roof, but the three evaporator units are inside the cooler (Figure 11.) Each evaporator unit has two motor and fan assemblies.

The three evaporator units' model is Heat Craft's Climate Control Low Profile LSC-140-A. All units run on the same circuit on 115 VAC and are controlled by a single Johnson Controls analog temperature controller with the temperature sensor directly connected to the controller. The temperature setting could be seen around 36 ºF during the site visit (Figure 12.)

The evaporator fan motors for these evaporator units were FASCO LR6319 that is rated for single phase, 115 VAC, 1/30 HP, 1.7 A, and 1550 RPM. The blade size is 10” nominal (Figure 13.) The power to the condenser and the evaporator are on separate circuits at the main electrical panel.

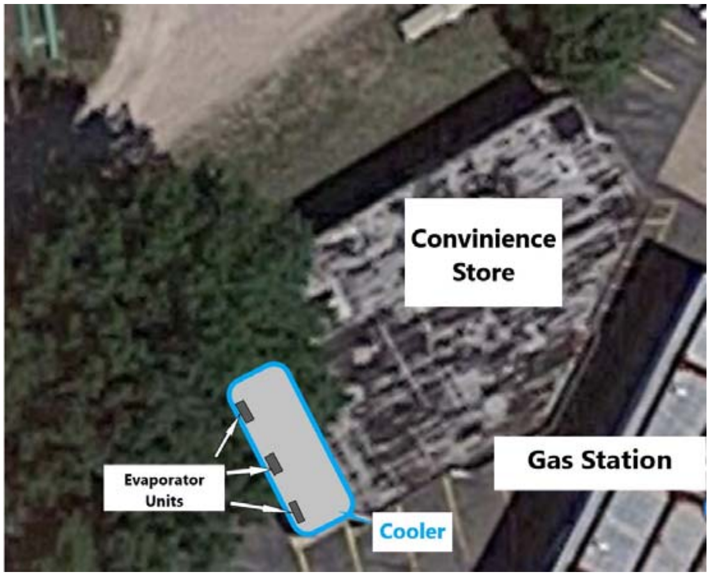


Figure 10. Site #2 – Top View

Figure 11. Site #2 – Cooler Inside View

Figure 12. Site #2 – Cooler Temperature Controller

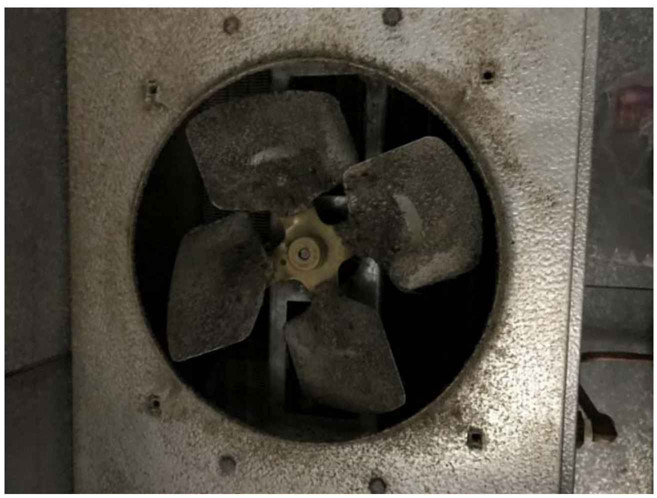


Figure 13. Site #2 – Evaporator Fan

Site #3: Liquor Store

This liquor store has multiple coolers and freezers, but only one walk-in cooler was selected to participate in this study by the store owner. The cooler is also roughly rectangular with dimension 400'(L) x 125' (W) x 90' (H), and it is located inside the building. A top view of the store that marks the location of the cooler is shown in Figure 14. There is only one solid door at one end of the cooler as the entry to the cooler space. The cooling unit condenser is on the roof. There are two evaporator units inside the cooler providing cold air to the space (Figure 15.) Each evaporator unit has four motor and fan assemblies.

The two evaporator units' model is Heat Craft's Larkin Low Profile LCA6185AB. Both units run on the same circuit at 115 VAC, but they were controlled by two independent Johnson Controls analog temperature controllers (Figure 16.) The temperature setting could be seen around 35~40 ºF.

The existing evaporator fan motors for these evaporator units had two different models: 1) FASCO LR6319 that is rated for single phase, 115 VAC, 1/20 HP, 1.8 A, and 1650 RPM; and 2) FASCO D1124 that is rated for single phase, 115 VAC, 1/20 HP, 2.1 A, and 1550 RPM. The blade size for these motors is 12” nominal (Figure 17.) The power to the condenser and the evaporator are on separate circuits at the main electrical panel.

Figure 14. Site #3 – Top View

Figure 15. Site #3 – Cooler Inside View

Figure 16. Site #3 – Temperature Controllers


Figure 17. Site #3 – Evaporator Fan

A summary of the information collected from the exploratory site visits is listed in Table 1.

Table 1. Information Collected from the Exploratory Site Visits

	Site #1	Site #2	Site #3
Store Type	Food/Drink Store	Gas Station Convenience Store	Liquor Store
Location	Bensenville, IL	McHenry, IL	Joliet, IL
Walk-in Cooler/Freezer	1 Cooler & 1 Freezer	1 Walk-In Cooler	1 Walk-In Cooler
Manufacturer	Norlake	Heat Craft	Heat Craft
Evaporator Unit Series	Kold Locker?	Climate Control Low Profile	Larkin Low Profile
Evaporator Unit Model #	Capsule Pak?	LSC-140-A	LCA6185AB
Unit Cooler Defrost Type	Air Defrost	Air Defrost	Air Defrost

Evaporator Unit Quantity	2	3	2
Evaporator Motor Quantity	2x2 = 4	3x2 = 6	2x4 = 8
Evap. Fan. Motor Model#	#1&2: YDK-38-4 1550 rpm (cooler), #3: FASCO 71639383 1550 rpm (freezer, no blade) & #4: FASCO D1126 1550 rpm (freezer)	#1~6: FASCO 71634714 1550 rpm	#1~4: FASCO D1124, 1550 RPM; #5~8: FASCO 71730599 1650 RPM
Evap. Fan Motor Type	PSC (YDK); SP (FASCO)	SP	SP
Evap. Fan Blade	10", 22? Deg, 5/16 Bore, CW (5 blades)	10", 40 Deg, 5/16 Bore, CW (4 blades)	12", 23 Deg, 5/16 Bore, CW (5 blades)
Volt	208-230	115	115
Phase	1	1	1
Hz	60	60	60
HP per Motor	#1&2: 1/20, #3: 1/20; #4:1/15	1/30	1/20
Rated amps per motor	#1&2: 0.5; #3: 0.84; #4: 1.1	#1-6: 1.7	#1-4:2.1; #5-8: 1.8
Temperature Control	Digital (2)	Analog (1)	Analog (2)
Temperature Setpoints	-5ºF (freezer); 40ºF (cooler)	~36ºF	~35ºF

MEASUREMENT DESIGN AND INSTALLATION

The pretest-posttest experimental design was used in this project to compare Q-Sync motor retrofit energy savings and cost effectiveness. Key steps in the measurement plan are shown below.

The experiment began with monitoring system design, procurement, and assemble/setup, before the pre-retrofit monitoring on the field. We collected 3~4 weeks of data for the pre-retrofit period, then followed with the Q-Sync motor retrofit installation on all evaporator fan motors. Post-retrofit monitoring then continued for another 3~4 weeks, and all measurement equipment was removed. The power and temperature monitoring design largely depended on the findings from the exploratory site visits. We want to make sure enough detailed pre- and post-retrofit power and temperature data are collected for energy and cost saving calculations. The pre- and post-retrofit monitoring periods each lasted 3~4 weeks to collect enough data that reflect different weather conditions. However, since most of these evaporator fan motors are inside the cooling units located in the walk-in coolers or freezers, we did not expect the outside weather conditions would have a direct and significant impact on their energy use.

Equipment Setup

For the three test sites, the following table shows the general monitoring data points and the data collection sampling rates:

Table 2. Monitoring Data Points

Sampling Rate	Site #1	Site #2	Site #3
Continuous (1 sample/minute pre- and post-retrofit)	- Cooler evap. fan motor power, current, power factor, voltage (two motors;) - Freezer evap. fan motor power, current, power factor, voltage (at the motor level)	- Cooler evap. fan motor power, current, power factor, voltage (at the circuit level - 6 motors)	- Cooler evap. fan motor power, current, power factor, voltage (at the cooling unit level - 4 motors)
Continuous (1 sample/minute pre- and post-retrofit)	- Cooler space temperature and RH%; - Freezer space temperature and RH%.	- Cooler space temperature and RH%	- Cooler space temperature and RH%
One Time (pre- and post-retrofit)	- Air velocity at cooler unit discharge (7 points); - Air velocity at freezer unit discharge (7 points);	- Air velocity at cooler unit discharge (12 points);	- Air velocity at cooler unit discharge (16 points);
One Time (pre-retrofit)	- Cooler space temperatures at multiple locations; - Freezer space temperatures at multiple locations.	- Cooler space temperatures at multiple locations.	- Cooler space temperatures at multiple locations;
Continuous (1 sample/hour pre- and post-retrofit)	- Local outside temperature	- Local outside temperature	- Local outside temperature

For the evaporator fan motor power, current, power factor, and voltage monitoring points, we used eGauge Systems' "eGauge Core" energy meters. The "eGauge Core" is a 15-channel energy meter with 0.5% revenue grade accuracy compliance and the ability to measure residential or commercial circuit panels, up to 3-phase 277/480VAC and 6900A. The embedded web server allows the user to connect to a user interface over the internet or on a local area network through an on-board Ethernet port. The meter has a data logger that can store 1-minute interval data for up to 64 variables over a period of at least a year before over-writing any values, and the user can access data remotely as granular as 1-second. The detailed energy meter specifications and setup are listed in Appendix A eGaguge Core Specifications and Setup. The current transducers used in connection with the eGauge Core energy meters were high-accuracy AC split-core Accu-CT models from Continental Control Systems. These current transducer's specifications are listed in Appendix B Current Transducer Specifications.

The continuous cooler and freezer space temperature and relative humidity measurement data were collected using the ONSET HOBO external temperature/RH sensor data logger model MX2302. These weatherproof data loggers are battery-powered, can measure temperature from -40 to 158 ^oF with ±0.45 ^oF or better accuracy and 0.07 ^oF resolution. They can also measure relative humidity from 0 to 100% RH with ±2.5% from 10% to 90% RH (typical) to ±5% below 10% RH and above 90% RH (typical) with 0.01% resolution. For the 1-minute sampling rate, these data logger can store approximately 1 month of data. They use Bluetooth Smart (Bluetooth Low Energy, Bluetooth 4.0) wireless communication standard to communicate with any smart phone with HOBO app installed. Data can be downloaded wirelessly in various common formats such as .csv format. Figure 18 shows the actual data loggers used for the three test sites.

Figure 18. HOBO Temp/RH% Data Loggers

Because these evaporator fan motor powers may vary over time, change with cooler/freezer space temperatures, or potentially have correlations with outside air temperature, we monitored these variables continuously throughout the pilot period. Local outside temperature data are obtained by downloading hourly weather data files from the nearest local weather stations.

We also did one-time field measurements of air velocity, space temperature and relative humidity values at several locations inside the coolers/freezer. The one-time measurements gave us some estimates on the space temperature uniformity and before and after retrofit air flow rates comparisons. These measurements were done using the TSI 9545-A VelociCalc air velocity meter. This meter simultaneously measures and records several ventilation parameters using a single probe with multiple sensors. It measures velocity, temperature, and relative humidity; and calculates flow, wet bulb and dew point temperature. The accuracy of its air velocity measurement is ±3% of reading plus 3 ft/min when measuring air within 0 to 6,000 ft/min range. Temperature measurement accuracy is ±5 ºF, and relative humidity measurement accuracy is ±3% RH. Measurement data can be recorded manually or automatically at specified sampling intervals (1 second to 1 hour,) and stored in the meter storage before being downloaded to a computer using its proprietary LogDat2 software and a USB cable. Figure 19 is the photo of such a meter, and its full specification and calibration certificate for the meter used are in Appendix C Air Flow Meter Specifications. It's worth mentioning that airflows are difficult to measure accurately in the field.

Figure 19. TSI 9545-A Air Velocity Meter

The replacement Q-Sync motors and blades selection was based on the exploratory site visit findings. The existing and replacement motor and blade model number and other key parameters are listed in Table 3.

Table 3. Existing and Replacement Motor and Blade Comparison

	Site #1	Site #2	Site #3
Evap. Fan. Motor Model#	#1&2: YDK-38-4 1550 rpm (cooler), #3: FASCO 71639383 1550 rpm (freezer, no blade) & #4: FASCO D1126 1550 rpm (freezer) vs. #1~4: Q-Sync QSM50-2A-CC 1800 rpm	#1~6: FASCO 71634714 1550 rpm vs. #1~6: Q-Sync QSM50-1A-C1-F 1800 rpm	#1~4: FASCO D1124, 1550 RPM; #5~8: FASCO 71730599 1650 RPM vs. #1~8: Q-Sync QSM50-1A-C1-F 1800 rpm
Evap. Fan Motor Type	PSC (YDK) & SP (FASCO) vs. PMS	SP vs. PMS	SP vs. PMS
Evap. Fan Blade	10", 22? Deg, 5/16 Bore, CW (5 blades) vs. New 10", 22 Deg, 5/16 Bore, CW (5 blades)	10", 40 Deg, 5/16 Bore, CW (4 blades) vs. New 10", 22 Deg, 5/16 Bore, CW (5 blades)	12", 23 Deg, 5/16 Bore, CW (5 blades) vs. New 12", 18 Deg, 5/16 Bore, CW (5 blades)
Volt	208-230	115	115
Rated amps per motor	#1&2: **0.5**; #3: **0.84**; #4: **1.1** vs. Q-Sync #1~4: **0.28** (max)	#1~6: **1.7** vs. Q-Sync #1~6: **0.55** (max)	#1~4:**2.1;** #5~8: **1.8** vs. Q-Sync #1~8: **0.55** (max)
Power Monitoring CT range per monitoring circuit	CT1: 0~5A (1 freezer motor;) CT2: 0~5A (1 freezer motor;) CT3: 0~5A (2 cooler motors.)	CT1: 0~20A (6 motors).	CT1: 0~20A (4 motors); CT2: 0~15A (4 motors).

Pre-retrofit Monitoring

Pre-retrofit monitoring activities include power and temperature/RH% monitoring equipment/instrument installation and setup at the test sites, as well as remote data collection and monitoring during the 3~4 weeks of the pre-retrofit period.

SITE #1: DUNKIN' DONUTS

The cooling units for both the cooler and the freezer at this site are on top of the roof, and they are relatively close to each other. Our power monitoring equipment with the NEMA-4 weather proof enclosure was put nearby the two cooling units on top of the roof. Current transducers were installed to measure two freezer evaporator fan motors separately (Figure 20) and two cooler evaporator fan motors in one circuit. The power to these evaporator motors are ~208 VAC and come from the unit condensers (Figure 21.) The HOBO temperature/RH% data loggers were placed nearby the doors of the cooler and freezer, respectively. After the installation and setup of the power and temperature/RH% monitoring instrument, data were checked on-site to assess their reasonableness.

Figure 20. Site #1 – CTs for the Freezer Evaporator Fan Motors

Figure 21. Site #1 – Condenser for the Cooler Cooling Unit

There were several observations for this site:

- One of the freezer cooling unit's evaporator fan motor blade was missing – though the motor can still run.
- The two evaporator fan motors for the freeze were not the same model.
- The freezer evaporator has a lot of ice accumulated on one side of the evaporator heat exchanger – the side with the missing fan blade (Figure 20.)

- The 208 VAC power to both units are from two hot lines/phases, with each hot line having ~120 VAC when measured to the ground/neutral line.

SITE #2: MOBIL GAS STATION

The three identical cooling unit evaporators inside the cooler space are very far apart (Figure 11.) The power to these evaporators are on a single circuit from the main electrical panel, and no other loads are on this circuit. Furthermore, the three evaporators were controlled using one Johnson Controls' temperature controller, so all cooling units will run the same way. We decided to monitor the power of all three evaporators at the circuit level instead of individual motors to reduce the complexity and cost of the power monitoring system. The power monitoring equipment with the NEMA-4 weather proof enclosure was installed on the wall besides the main electrical panel (Figure 22.) The power to these evaporators is ~120 VAC, and the current transducer measuring the current of the circuit was installed inside the main electrical panel. The HOBO temperature/RH% data loggers were installed close to the temperature controller on the wall (Figure 23.) After the installation and setup, data were checked on-site to assess their reasonableness.

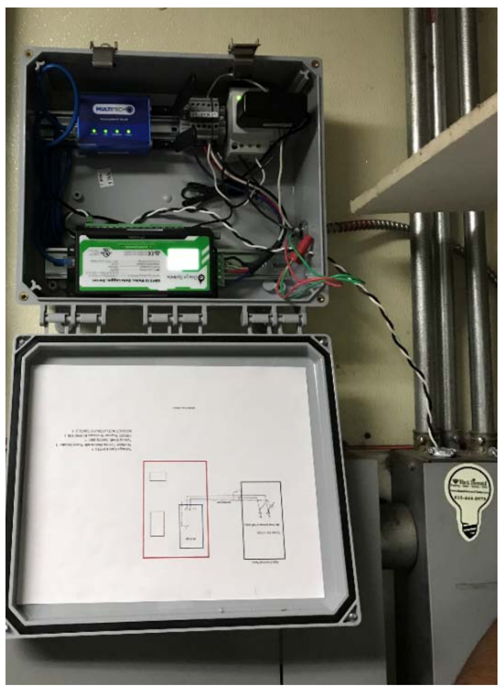


Figure 22. Site #2 – Power Monitoring Equipment

Figure 23. Site #2 – HOBO Temperature/RH% Data Logger

SITE #3: LIQUOR STORE

The two identical cooling unit evaporators inside the cooler space are relatively close to each other. The power to these evaporators are on a single circuit from the main electrical panel. However, these two evaporators are controlled separately using two different Johnson Controls temperature controllers. We mounted our power monitoring equipment near the two evaporator units and monitored the power to each unit separately (Figure 24.) The line voltages to these evaporator units are ~120 VAC, and the current transducers were installed inside the evaporators – bypass the temperature controllers – so the powers measured are for the evaporator fan motors only and not include the small powers consumed by the temperature controllers. The HOBO temperature/RH% data loggers were installed close to the power monitoring equipment (Figure 24.)


Figure 24. Site #3 – Power Monitoring Equipment and HOBO Datalogger

Figure 25. Site #3 – Current Transducer Inside the Evaporator Unit

Observations for this site:

- The evaporator unit #2 (the right-side unit on Figure 24) contains one evaporator fan motor that runs in cycles (On for ~15 minutes then Off for ~5 minutes) instead of constantly like the other 3 motors on the same unit.
- The temperature settings on the two controllers were slightly different and cannot be clearly seen. These are analog temperature controllers and the dial are small, so it is no guarantee the two temperature settings match perfectly.

During the pre-retrofit period, power monitoring data at these sites were remotely downloaded and monitored periodically. No major issues occurred during the period. Detailed the data analysis for this period is presented in the "Data Analysis" section.

Q-SYNC MOTOR RETROFIT

The Q-Sync motor retrofit activities include a trip to these sites to 1) remove existing evaporator motors and blades; 2) install new Q-Sync motors and blades; and 3) took measurements of air velocities at multiple points, dimensions inside the walk-in coolers and the freezer, and multiple temperatures and relative humidity points within the spaces. A local refrigeration technician was hired to implement the retrofits. He has multiple years of experience in repairing and maintaining various refrigeration equipment including these walk-in cooler and freezer cooling units.

SITE #1: THE DUNKIN' DONUTS STORE

Four existing evaporator fan motors (two for the cooler and two for the freezer) were replaced with four Q-Sync motors (model # QSM50-2A-CC) (Figure 26.) The existing fan blades were also replaced with new Q-Sync fan blades (Figure 27) including the motor with the original blade missing. Both cooling units are on the roof, and the refrigeration technician had to open the insulated top covers of the cooling unit evaporator sections to conduct the retrofit. The retrofit process was pretty straightforward: 1) disconnecting the power cables to the motors; 2) removing the support bar with the existing motor and blades from the cooling unit; 3) disconnecting existing motors and blades; 4) installing new motors and blades on the support bar (Figure 28;) 5) putting the support bar with new motors and blades back to the unit and screwing it tight; 6) reconnecting the motor power cable. The retrofit process took about 1 hour and 10 minutes. The refrigeration technician also spent some additional time in disconnecting/connecting power monitoring equipment and conducting some maintenance work on the freezer evaporator coil (cleaning up the ice accumulated near the coil using hot water.) Figure 29 and Figure 30 show the freezer and cooler evaporator units after the retrofit.

Figure 26. Site #1 – 208 VAC Q-Sync Motor

Figure 27. Site #1 – Existing Blade (Left) vs. Q-Sync Blade (Right)

Figure 28. Site #1 – Assembling New Fan Blades

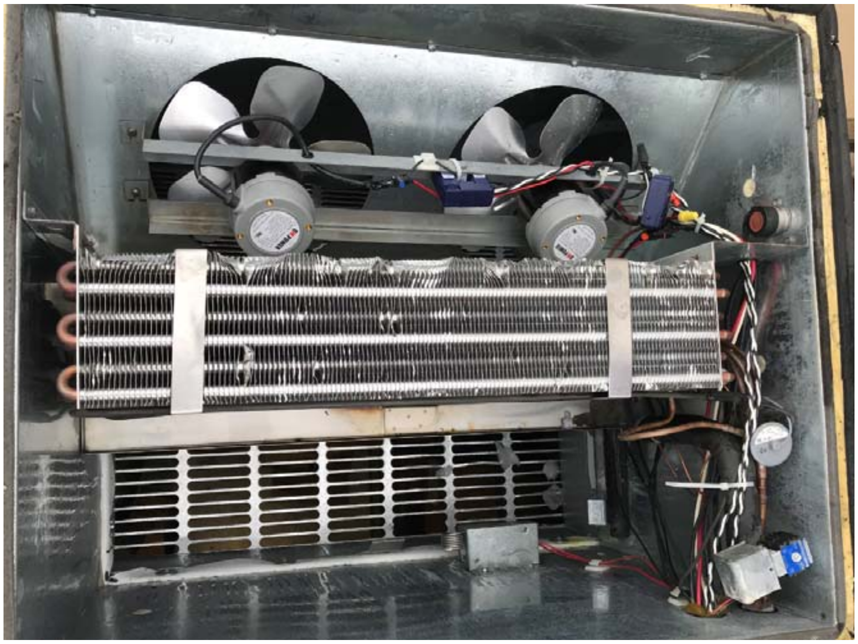


Figure 29. Site #1 – Freezer Cooling Unit After Retrofit

Figure 30. Site #1 – Cooler Cooling Unit After Retrofit

Air velocity, temperature and RH% measurements were taken using a newly purchased TSI 9545-A meter at 7 points – each point at the middle of the supply air outlets, about 6-inch away (Figure 31.) The air velocity measurement settings included a 20-second average sampling rate and actual air velocity, which compensate for temperature, pressure, and humidity compared to standard air velocity readings.

Figure 31. Site #1 – Supply Air Grills

The one-time space temperature and RH% readings were also taken using the TSI meter at three different locations inside the cooler and freezer to assess the temperature and RH% uniformity (Figure 32.) The dimensions of the inside spaces of the cooler and the freezer were taken as well (Figure 33.)

Figure 32. Site #1 – One-time Space Temperature/ RH% Measurement

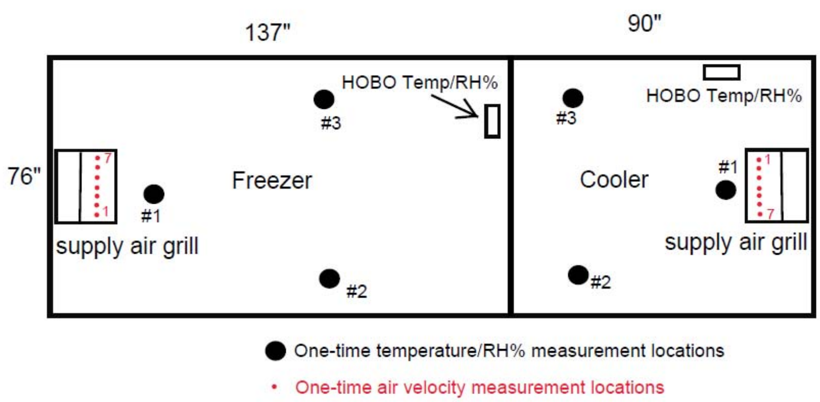


Figure 33. Site #1 – Cooler & Freezer Layout and One Time Measurement Locations

SITE #2: THE MOBIL GAS STATION

Six existing evaporator fan motors were replaced with new Q-Sync motors (model # QSM50-1A-C1-F) (Figure 34) during the first retrofit trip for Site #2. The existing fan blades, however, were not replaced in this trip, due to the fact that new Q-Sync blade size (12”) ordered was bigger than that of the existing blades (10”) (Figure 35.) After consulting with the Q-Sync motor manufacturer, a temporary solution was to use the existing fan blades with the new Q-Sync motors, while six new smaller 10” size Q-Sync fan blades were immediately ordered for future replacement.

The three cooling evaporator units, each with two fan motor/blade assemblies, are all inside the cooler. The retrofit steps involved: 1) removing the protective fan grills and blades and exposing the motor with its supporting bar (Figure 36); 2) disconnecting existing motor power cable; 3) removing the existing motor and installing a new Q-Sync motor (Figure 37;) 4) connecting the motor power cable; 5) installing the blade; and 6) putting back the fan grills. The overall retrofit time for these three units, six motor/blade assemblies was about 2 hours and 10 minutes.

Figure 34. Site #2 – 120 VAC Q-Sync Motor

Figure 35. Site #2 – Fan Blade Comparisons

Figure 36. Site #2 – An Existing Evaporator Fan Motor

Figure 37. Site #2 – A New Fan Motor Installed

The six existing fan blades were replaced with six new 10” Q-Sync fan blades in a second retrofit trip. We found two of the six Q-Sync motors failed to work after several hours when paired with the original fan blades, which is much heavier with a much higher pitch than the new Q-Sync blades (40 deg. vs. 22 deg.) With Q-Sync motors run at 1800 rpm (vs. 1550 for the original fan motors), the load on the Q-Sync motors with the original blades probably exceeded Q-Sync motors’ design load, resulting in burned out motors. Photos of a new blade and the evaporator unit after the second retrofit are shown in Figure 38 and Figure 39.

Figure 38. Site #2 – A New Fan Blade Installed

Figure 39. Site #2 – A Cooling Unit After the Retrofit

For this site, air velocity, temperature, and RH% measurements were taken using the newly purchased TSI 9545-A meter at 12 points – two points for each of the six fans as shown in Figure 40, with measuring sensor tip about 6-inch away from the fan grill. The air velocity measurement settings included a 20-second average sampling rate and actual air velocity. The one-time space temperature and RH% readings were also taken using the TSI meter at six different locations inside the cooler (Figure 40.) The dimensions of the cooler were taken as well.

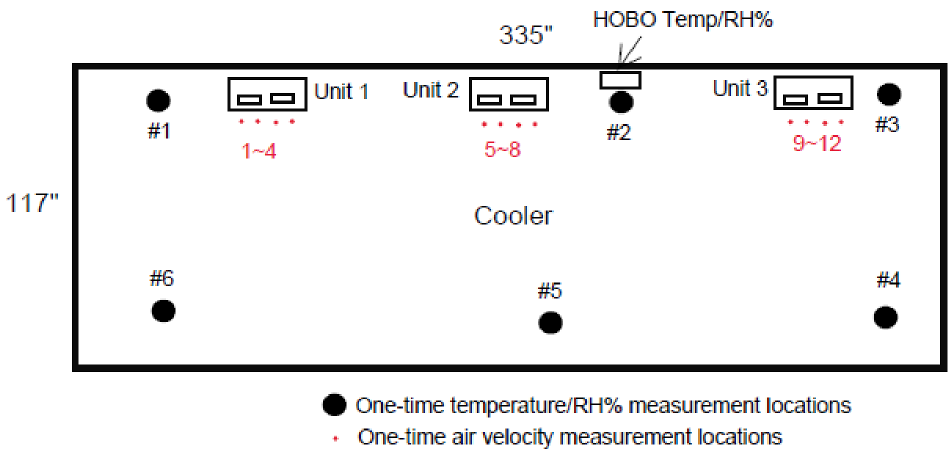


Figure 40. Site #2 – Cooler Layout and One-Time Measurement Locations

SITE #3: THE LIQUOR STORE

Eight existing evaporator fan motors were replaced with new Q-Sync motors (model # QSM50-1A-C1-F) (Figure 34) at this site. A comparison of an existing and the new motor is shown in Figure 41, and a comparison of an existing and the new fan blade is shown in Figure 42.

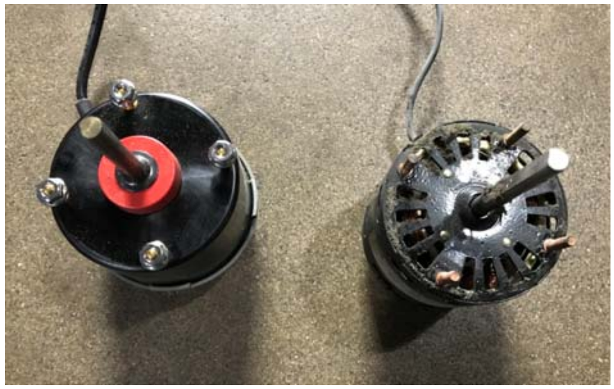


Figure 41. Site #3 – Existing (Right) vs. New Q-Sync (Left) Motors

Figure 42. Site #3 – Existing (Right) vs. New (Left) Fan Blades

After removing the protective fan grills and the fan blades, it can be seen the existing evaporator fan motors were mounted on mounting brackets on the cooling unit (Figure 43.) To replace these motors with new Q-Sync motors, these mounting brackets were unscrewed from the cooling unit for easy uninstallation of the existing motors and reinstallation of the new motors (Figure 44.) Other retrofit steps involved with temporary disconnecting and then reconnecting the motor power wires. Figure 45 shows a cooling unit after the retrofit. The overall retrofit time for these 2 units, 8 motor/blade assemblies was about 2 hours.

Figure 43. Site #3 – An Existing Evaporator Fan Motor with Mounting Bracket

Figure 44. Site #3 – New Q-Sync Motors on the Mounting Brackets

Figure 45. Site #3 – One Cooling Unit after the Retrofit

One-time air velocity, temperature, and RH% measurements were taken using the TSI 9545-A meter at 16 points – two points for each of the eight fans as shown in Figure 46, with measuring sensor tip about 6-inch away from the fan grill. The air velocity measurement settings included a 20-second average sampling rate and actual air velocity. The one-time space temperature and RH% readings were also taken at six different locations inside the cooler. The dimensions of the cooler were taken as well.

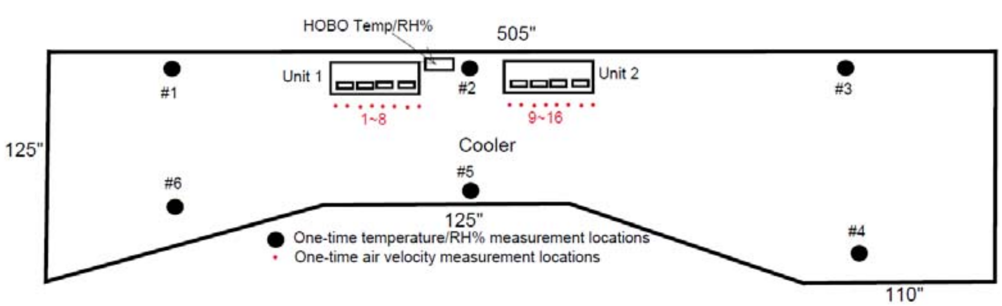


Figure 46. Site #3 – Cooler Layout and One-Time Measurement Locations

After the Q-Sync motor and blade retrofits, motor powers and space temperatures and RH%s were continuously monitors and data collected for at least four weeks at each site. The following table lists the pre-retrofit and post-retrofit periods for each of the three sites.

Table 4. Pre-retrofit and Post-retrofit Periods

	Site #1	Site #2	Site #3
Monitoring equipment installation	8/28/2018	8/28/2018	8/29/2018
Pre-retrofit	08/29 – 9/27/2018	08/29 – 9/27/2018	08/30 – 9/27/2018
Retrofit	9/28/2018	9/28/2018	9/28/2018
Post-retrofit	9/29/2018 – 12/1/2018	9/29/2018 – 12/1/2018	9/29/2018 – 12/5/2018
Notes	One of the four Q-Sync motors found failed on 11/18/2018.	9/29 – 10/18/2018: Q-Sync motors installed with original blades; 10/18 – 12/1/2018: Q-Sync motors installed with Q-Sync blades; 11/3: Replaced two failed Q-Sync motors with new ones.	

During the post-retrofit periods, there are a couple of issues found. One issue with paring Q-Sync motors with the original fan blades in Site #2 (as a temporary solution) has been discussed in the previous section. The other issue found was a failed Q-Sync motor at Site #3 on November 18. Figure 47 showed the condition when the cooling unit for the freezer was uncovered. The left-side motor (motor#2) no longer run, and there was a lot of ice on the Q-Sync motor as well as inside the unit. It is suspected that the top insulated cover was not sealed very tight, and water/snow could leak into the cooling unit causing ice build-up. With the fan running, the water vapor with high moisture content could enter the inside of the motor.

Figure 47. Site #1 – Freezer Evaporator Unit in Winter

All the monitoring equipment were removed after enough post-retrofit data have been collected.

DATA ANALYSIS

Pre- and post- retrofit data were processed and analyzed to calculate energy savings and other statistical characteristics of the savings. Data analysis are presented in this section by site and by walk-in cooler/freezer unit, since these units are of different manufacturers and models, and their installations, operations, and working conditions are also quite different.

Site #1: Dunkin' Donuts Store

The two freezer evaporator fan motors were monitored separately. The overall freezer motor power monitoring chart for the whole project period is shown in Figure 48. In this figure, motor#1 is the right-side motor in Figure 8; the motor#2 is the left-side motor. During the pre-retrofit period, the lower motor power level for motor#1 reflected the fact that this motor did not have a fan blade installed. While both the motors were SP motors and were manufactured by FASCO, the exact motor models and specification were different (Table 1.) It was apparent that one or both of these two motors had been replaced before.

After the Q-Sync motor retrofit, it was apparent that the new Q-Sync motor power levels were significantly lower. The motor power reductions for Q-Sync motors were **54%** for motor#1 and **69%** for motor#2 (refer to Table 5 at the end of this section.) The energy savings for motor#1 compares Q-Sync motor with a blade to an SP motor without a blade, so actual saving percentage should be much higher if the existing SP motor#1 had a fan blade installed.

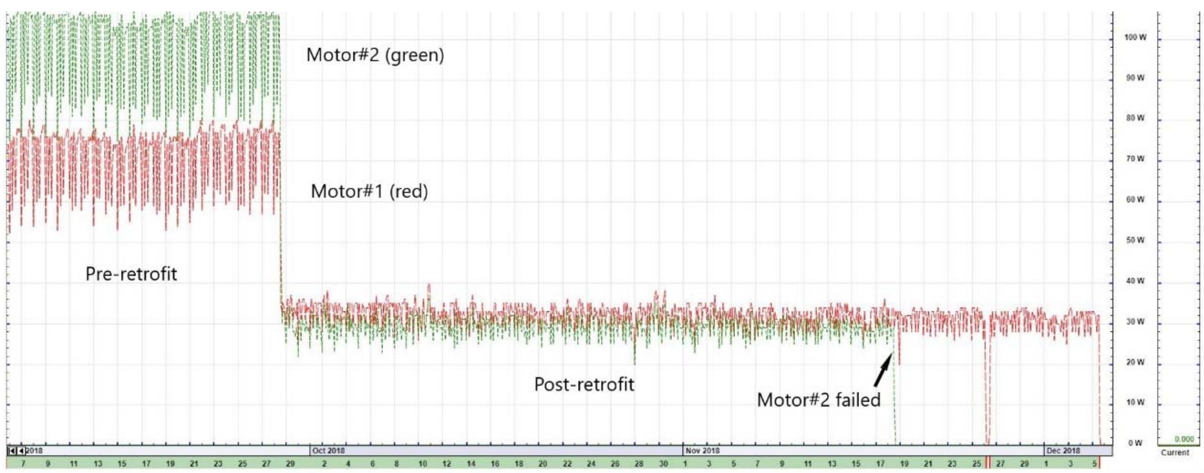


Figure 48. Site #1 – Freezer Motor Power Comparisons

Comparing these motor powers for a typical Wednesday in the pre-retrofit period and a typical Wednesday in the post-retrofit period reveals more interesting details (Figure 49.) In this chart, pre- and post-retrofit motor powers (red for freezer motor#1 and green for freezer motor#2) can be read from the left y-axis, and the freezer space temperature in blue can be read from the right y-axis. All these motors stopped running for a period of time between 20 to 30 minutes three times a day, due to the air defrost cycle to melt the ice on the evaporator coil. The time periods stopped for Q-Sync motors were shorter (close to 20 minutes) than the original SP motors (close to 30 minutes.) The space temperature controlled were more stable after the retrofit (also see Figure 53.) The store staff do often enter the freezer to pick up or store food items several times a day. The higher freezer space temperature rises in the pre-retrofit period could because of a longer time for store staff to store or pickup items that day and could also partly contributed by the fact that one of the two evaporator fan blades were missing thus the actual cold airflow rate were much lower than designed. For Q-Sync motor#1 after the retrofit, there were also additional 12 times of power dips during the day – each lasted about 3 to 4 minutes for unknown reasons.

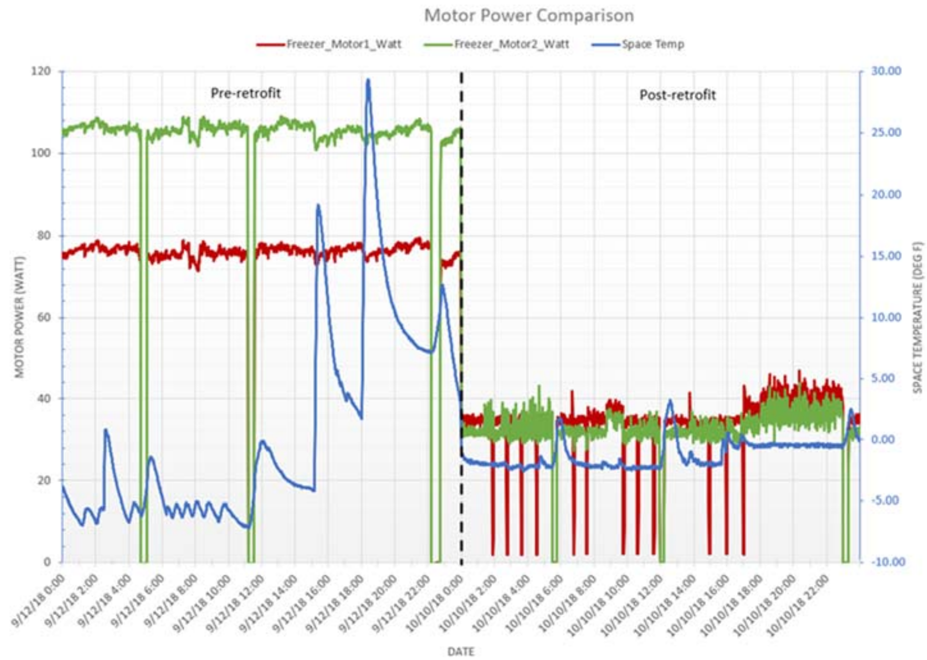


Figure 49. Site #1 – Freezer Motor Power One Day Comparisons

The hourly outside air temperature data from a nearby airport (Chicago O'Hare International Airport) were downloaded from the National Centers for Environmental Information (NOAA) website. A scatter plot of freezer motor power vs. outside air temperature (Figure 50) shows that there was no direct correlation either before or after the retrofit - even though the three-sides of the freezer walls are directly exposed to outside, and the evaporator and condenser units for the cooling unit were both on top of the roof.

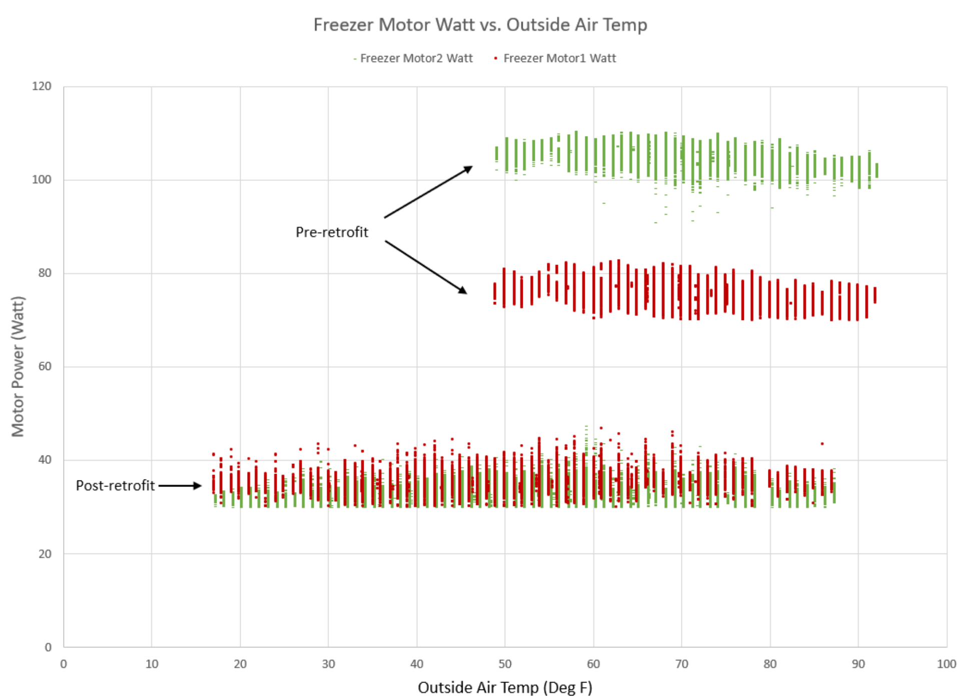


Figure 50. Site #1 – Freezer Motor Power vs. Outside Air Temperature

The motor current reductions (Figure 51) were also significant: **67%** for motor#1 and **70%** for motor#2 (refer to Table 6 at the end of this section.) The percentage reduction for motor#1 should be even higher had the original motor#1 fan blade installed. The measured motor currents for the original motors were 0.75 amp and 0.85 amp, respectively. These values are slightly lower than the rated motor current of 0.84 amp and 1.0 amp. After the retrofit, both Q-Sync motors averaged 0.25 amps each (Table 6) and were very close to (but still slightly lower) than the rated number of 0.28 amps at full load condition.

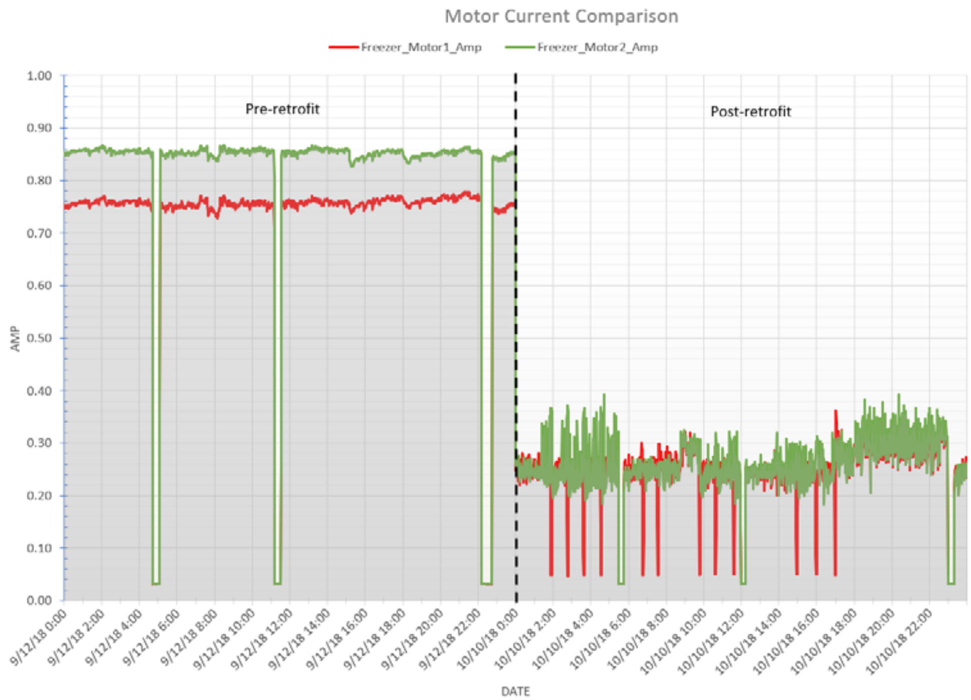


Figure 51. Site #1 – Freezer Motor Current One Day Comparisons

Figure 52 illustrates the comparisons of motor power factors in two typical days before and after the retrofit. Before the retrofit, motor#1 (without a fan blade) had a lower power factor (0.48) compared to motor#2 (0.59), even though both were SP motors. After the retrofit, Q-Sync motor#1 has a slightly higher (0.67) power factor than motor#2 (0.61.) Since two Q-Sync motors were identical, the difference in the power factors may be due to their physical positions/configurations within the evaporator unit and thus airflows/loads. More statistical data on freezer motor power factor comparisons can be found in Table 7. It is worth mentioning that the measured Q-Sync motor power factors (0.61 and 0.67) were both much lower than the rated power factor by the manufacturer (0.93). However, the manufacturer specification is for full load condition, and the Q-Sync motors in this freezer were not at full load.

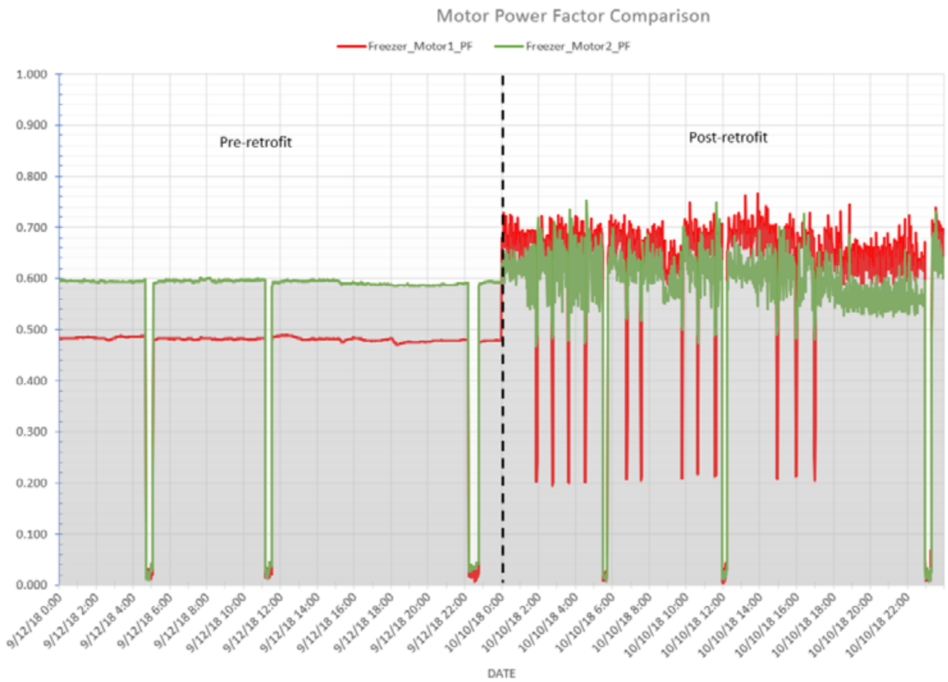


Figure 52. Site #1 – Freezer Motor Power Factor One Day Comparisons

The freezer inside space temperature and relative humidity values were recorded using a HOBO data logger. There were two short periods (a few days each) of missing data in the post-retrofit period due to site visit scheduling issues, and the HOBO data logger used to record the data started to overwrite the old data with new data when its storage was full. Figure 53 shows the freezer inside space temperature and relative humidity during the project period. It can be seen the space temperature and relative humidity were mostly maintained before and after the retrofit. The space temperature before the retrofit had more spikes, perhaps due to the fact that one of the two evaporator motor fan blades was missing. After the retrofit, the temperature was controlled better (tighter range, less oscillation, and less frequent temperature spikes) overall.

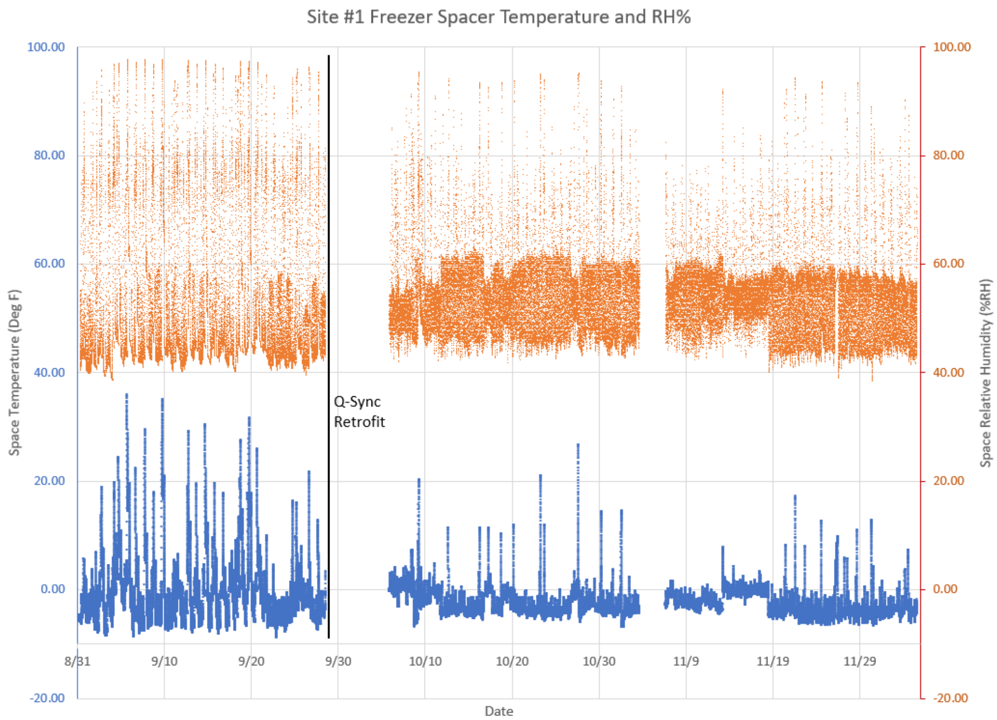


Figure 53. Site #1 – Freezer Space Temperature/RH% Comparisons

The two cooler evaporator fan motors were monitored in one circuit, as both were PSC motors with the same model number. The overall motor power monitoring chart for the whole project period is shown in Figure 54. Detailed motor specifications are shown in Table 1.

The new Q-Sync motors use significant less power than the original PSC motors. The motor power reductions for Q-Sync motors were **52**% (Table 5, 116.83 watt vs. 55.61 watt.) The daily comparison chart (Figure 55) reveals a few power dips each day for the Q-Sync motors during the post-retrofit period. A scatter plot of cooler motor power vs. outside air temperature (Figure 56) shows that there was no direct correlation between them.

Figure 54. Site #1 – Cooler Motor Power Comparison

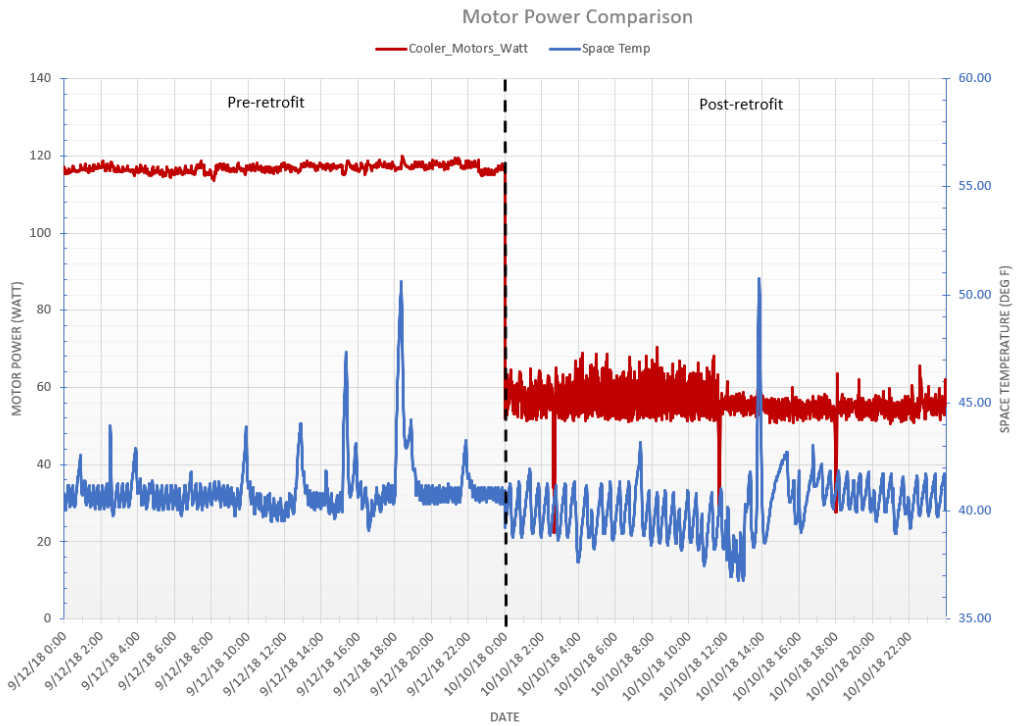


Figure 55. Site #1 – Cooler Motor Power One Day Comparison

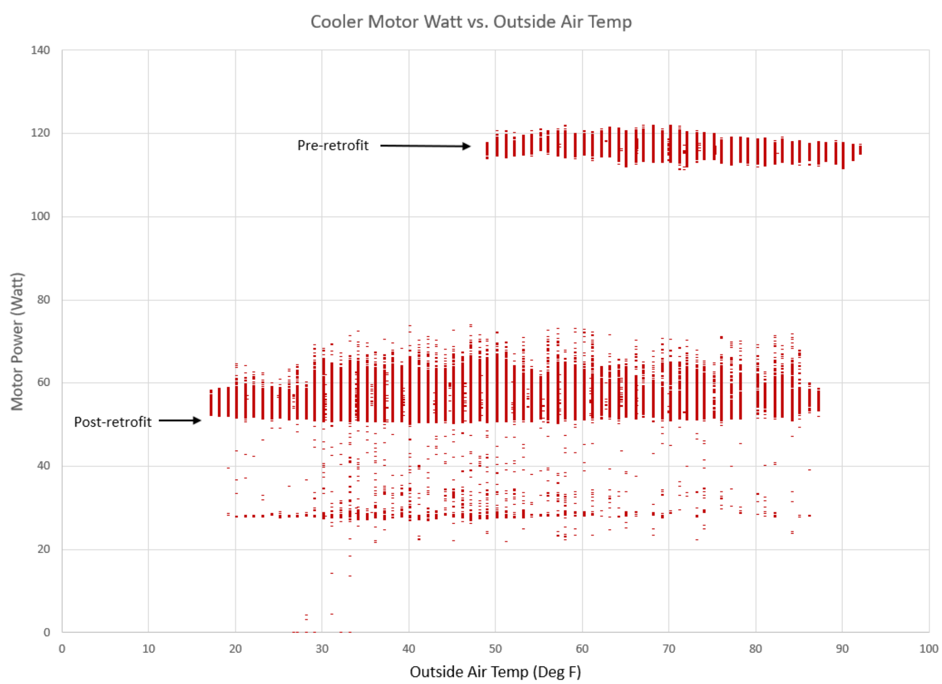


Figure 56. Site #1 – Cooler Motor Power vs. Outside Air Temperature

The two motors' current reduction was also significant at **53%** (Table 6.) This is at the similar level as the power reduction. The measured motor currents for the two original PSC motors were 0.71 amp, resulting in 0.355 amp for each. Compared with their rated 0.5 amp (Table 1) number, it indicates that these motors were not at full loads. Similarly, the Q-Sync motors' actual measured current of 0.33 Amp (0.165 amp each) were also significantly lower than the rated number of 0.28 amp each by the manufacturer. It was also observed that the standard deviations for the Q-Sync motors' power and current (Table 5 and Table 6) were much larger than those of the original motors, indicating the new motors may run less stably. It is not clear this is due to motor itself, the combination of the motor and the matching Q-Sync blade.

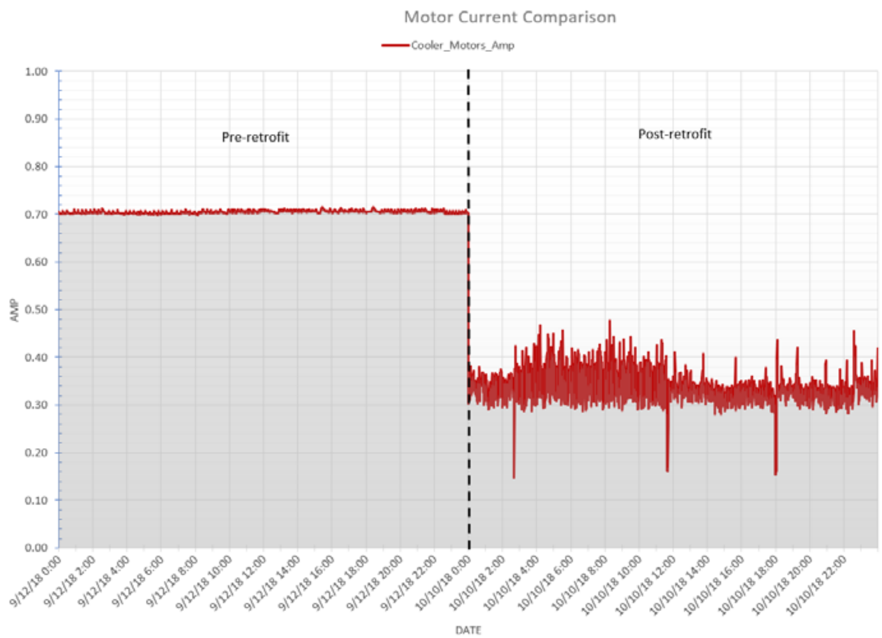


Figure 57. Site #1 – Cooler Motor Current One Day Comparison

Figure 58 illustrates the comparison of motor power factor before and after the retrofit. There was no significant increase in power factor (0.79 vs. 0.80,) and the Q-Sync motors' power factor (0.80) was significantly lower than manufacturer's specified number (0.93.) We believe this is also due to these two Q-Sync motors' loads were significantly lower than full loads. More statistical data on cooler motor power factor comparisons can be found in Table 7.

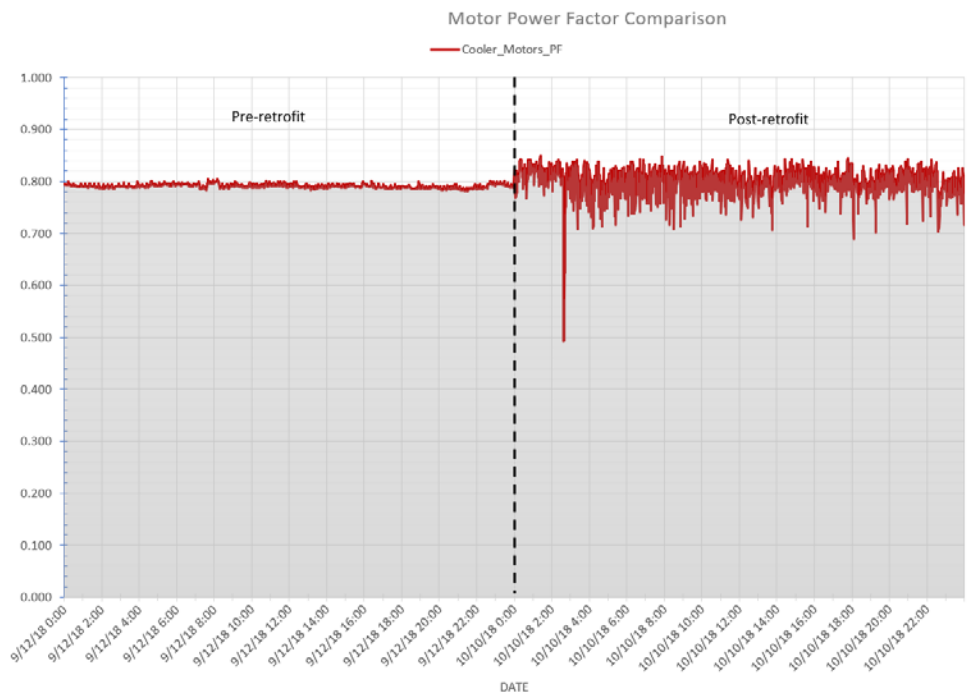


Figure 58. Site #1 – Cooler Motor Power Factor One Day Comparison

The cooler inside space temperature and relative humidity chart (Figure 59) indicates consistent space temperature control pre-retrofit and post-retrofit but somewhat lower relative humidity level (not controlled) in the post-retrofit period.

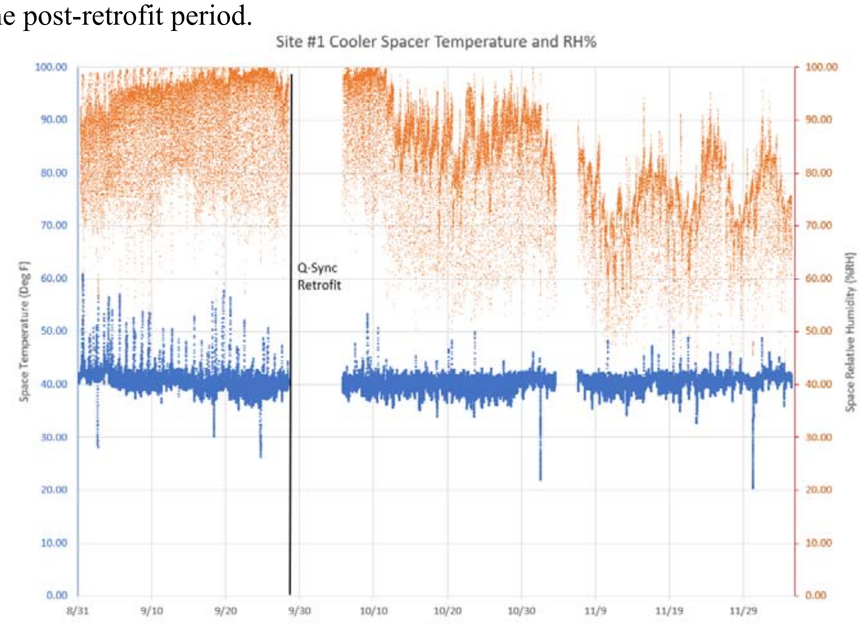


Figure 59. Site #1 – Cooler Space Temperature/RH% Comparisons

Table 5 to Table 7 list average measured data and standard deviations for evaporator motor power, current, and power factor for the freezer and cooler motors. The pre-retrofit period for the original motors is 8/29/2018 0:00 ~ 9/27/2018 23:59 (29 days.) The post-retrofit period for the freezer motor#1 and the two cooler motors is 9/29/2018 0:00 ~ 12/4/2018 23:59 (67 days.) The post-retrofit period for the freezer motor#2 is 9/29/2018 0:00 ~ 11/17/2018 23:59 (50 days) due to motor failure on 11/18/2018.

Table 5. Site #1 Motor Power Energy Savings

Site #1 Motor Power Reductions			
	Pre-retrofit Power (Watt)	Post-retrofit Power Avg. (Watt)	**Power Reduction (%)**
Two Cooler Motors	116.83	55.61	**52.4%**
Freezer Motor #1*	75.89	34.58	**54.4%***
Freezer Motor #2	105.15	31.98	**69.6%**
	Pre-retrofit Power Std. Dev. (Watt)	Post-retrofit Power Std. Dev. (Watt)	
Two Cooler Motors	1.45	4.25	
Freezer Motor #1*	3.26	2.57	
Freezer Motor #2	4.12	2.48	
* Freezermotor#1 was without a fan blade in the pre-retrofit period.			

Table 6. Site #1 Motor Current Reductions

Site #1 Motor Current Comparisons			
	Pre-retrofit Current (Amp)	Post-retrofit Current Avg. (Amp)	**Current Reduction (%)**
Two Cooler Motors	0.71	0.33	**53.1%**
Freezer Motor #1*	0.75	0.25	**67.3%**
Freezer Motor #2	0.85	0.25	**70.4%**
	Pre-retrofit Current Std. Dev. (Amp)	Post-retrofit Current Std. Dev. (Amp)	
Two Cooler Motors	0.005	0.029	
Freezer Motor #1*	0.025	0.021	
Freezer Motor #2	0.027	0.023	
* Freezermotor#1 was without a fan blade in the pre-retrofit period.			

Table 7. Site #1 Motor Power Factor Increases

Site #1 Motor Power Factor Comparisons			
	Pre-retrofit Power Factor Avg.	Post-retrofit Power Factor Avg.	**PF Increase (%)**
Two Cooler Motors	0.79	0.80	**1.2%**
Freezer Motor #1*	0.48	0.67	**39.7%***
Freezer Motor #2	0.59	0.61	**3.2%**

	Pre-retrofit Power Factor Std. Dev.	Post-retrofit Power Factor Std. Dev.	
Two Cooler Motors	0.005	0.033	
Freezer Motor #1*	0.006	0.045	
Freezer Motor #2	0.009	0.038	
* Freezermotor#1 was without a fan blade in the pre-retrofit period.			

As indicated in the “Q-Sync Motor Retrofit” section, one-time manual field measurements of air velocity were conducted during the Q-sync retrofit trip and a post-retrofit trip. Manual field measurement data are used as empirical evidence of air flow change before and after the retrofit in this study. However, due to human factors and field measurement limitations, these data (especially the air velocity values) may not be very accurate at every point. Table 8 and Table 9 list these measured data for the freezer and the cooler. The point numbers and their locations can be found in Figure 33.

The average air velocity for the freezer fans almost doubled from 140 ft/min to 264 ft/min after the retrofit. This was due to a new fan blade was installed on motor#1. It implied similar air flow rates before and after the retrofit if motor#1 had a blade installed before the retrofit. For the cooler fans, the average air velocity after the retrofit (201 ft/min) was lower than before (278 ft/min) by about 27%. This might explain why the Q-Sync motors for the cooler were significantly less than full load and had a lower than specified power factor. This also implies that the air flow rate after a Q-Sync retrofit may be difficult to match perfectly with the original evaporator motor air flow.

Table 8. Site #1 Freezer Field Measurement

	Point#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	Average
Air velocity (ft/min)	Pre-retrofit (9/28/2018)	72	101	124	201	183	161	140	**140.3**
	Post-retrofit (11/03/2018)	294	296	323	278	266	239	157	**264.7**

Table 9. Site #1 Cooler Field Measurement Results

	Point#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	Average
Air velocity (ft/min)	Pre-retrofit (9/28/2018)	147	502	278	362	181	165	314	**278.4**
	Post-retrofit (11/03/2018)	203	249	235	223	241	213	46	**201.4**

Site #2: The Mobil Gas Station

Because the three cooling units are the same model and they were controlled by one single temperature controller, the power of the six evaporator fan motors was monitored at the circuit level. It has been verified onsite that this circuit does not have other loads such as walk-in cooler lights. The overall power monitoring chart for the whole project period are shown in Figure 60.

Due to an error in identifying the fan blade size and model number during the first site visit, the six Q-Sync motors were paired with the original fan blades during the first retrofit trip on 9/28/2018 – as a temporary solution. While waiting for the matching Q-Sync blades to be ordered and delivered on-site, it was discovered that one of the six Q-Sync motors was burned out after about 3 hours and 20 minutes (Figure 61.) Another motor was burned out as well two hours later (Figure 61.) Fortunately, the other four Q-Sync motors continued to run with the original fan blades for another 18 days before the matching Q-

Sync blades were installed. The two failed Q-Sync motors were replaced with good ones 13 days later. The reason for the Q-Sync motor burn-out is probably because they were significantly overloaded when paired with the original fan blades. The original fan blades were very heavy and with a 40 degree pitch (Table 3 and Figure 13,) while the new Q-Sync motors were designed to match with much lighter with much lower 18 or 22 degree pitch blades because they run at higher speed (1800 rpm vs. 1550 rpm) than traditional SP or PSC motors. In theory, motor power use should be proportional to the third power of motor speed. The combination of higher speed, heavier blades with much higher fan blade pitch caused the problem of Q-Sync motor overload and burn-out when paired with the original fan blades. Figure 60 also showed that after replacing the original blades with the Q-Sync blades, the four Q-sync motor power decreased significantly – an indication of the impact of lighter blades with much lower pitch. After the two failed Q-Sync motors were replaced with good ones, the six new Q-Sync motor (with matching Q-Sync blades) power were **83%** lower than the original motor and blade assemblies (Table 10.)

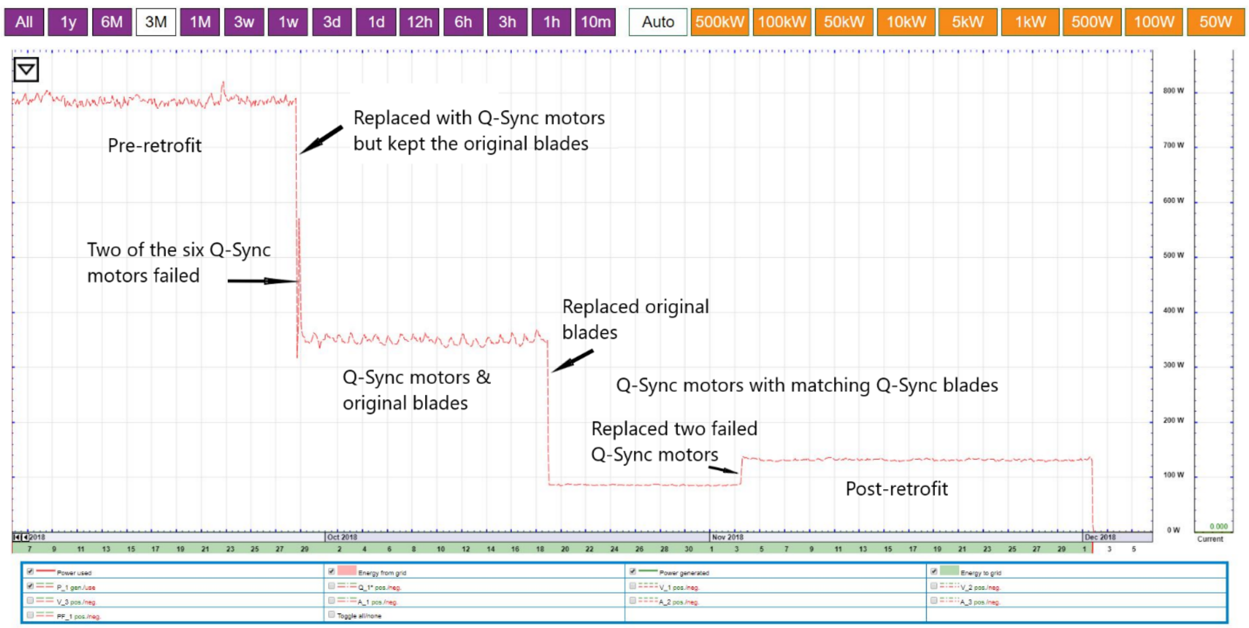


Figure 60. Site #2 – Cooler Motor Power Comparison

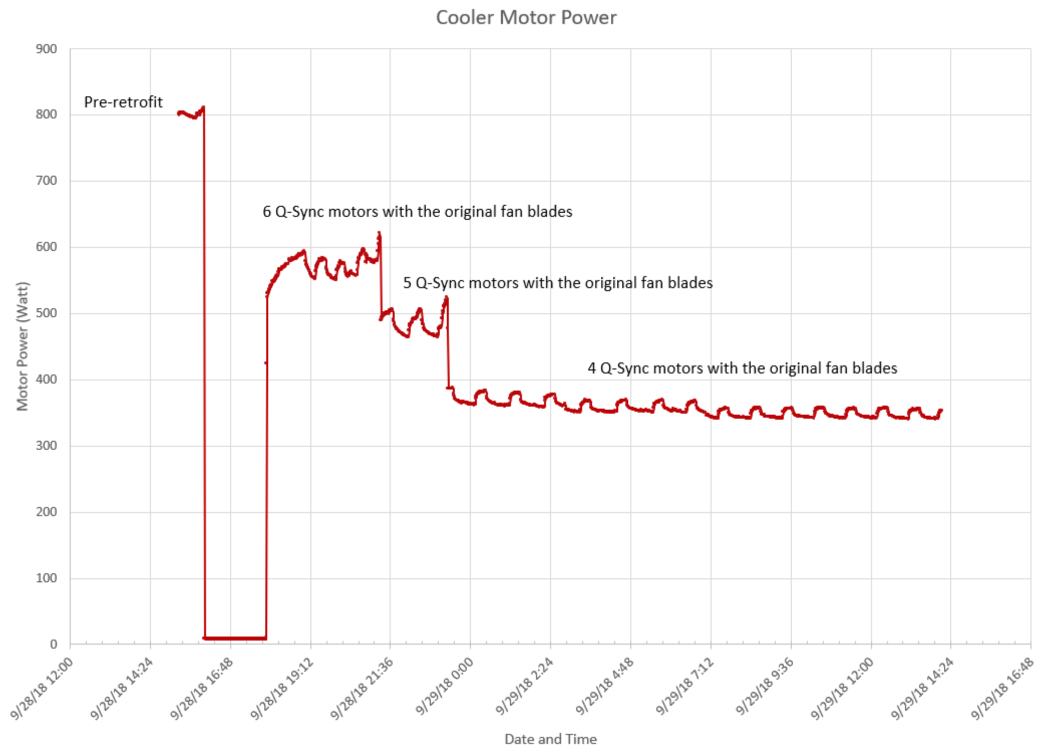


Figure 61. Site #2 – Cooler Motor Power Comparison – Q-Sync Motor with Original Blades

The difference in motor powers and the impact of Q-Sync motor retrofit to the cooler space temperature can better be seen from daily chart comparison in Figure 62. The space temperature can be maintained around 37 to 38 ^{o}F on average during pre-retrofit and post-retrofit. The original motors (and blades) cooled down the temperature faster than the Q-Sync motors (and Q-Sync blades.) This could be due to evaporator cold discharge air airflow difference, or there was an internal load changes in the cooler. As a result, the evaporator unit's temperature controller controlled the evaporator compressor fan on/off *less frequently* after the retrofit. A scatter plot of cooler motor power vs. outside air temperature (Figure 63) shows that there was no direct correlation between them.

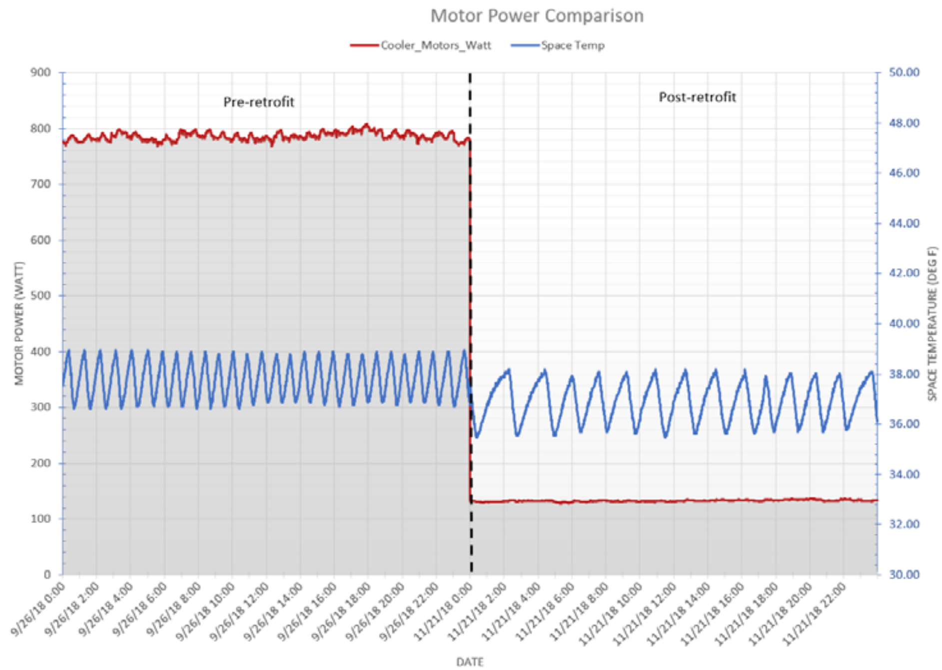


Figure 62. Site #2 – Cooler Motor Power One Day Comparison

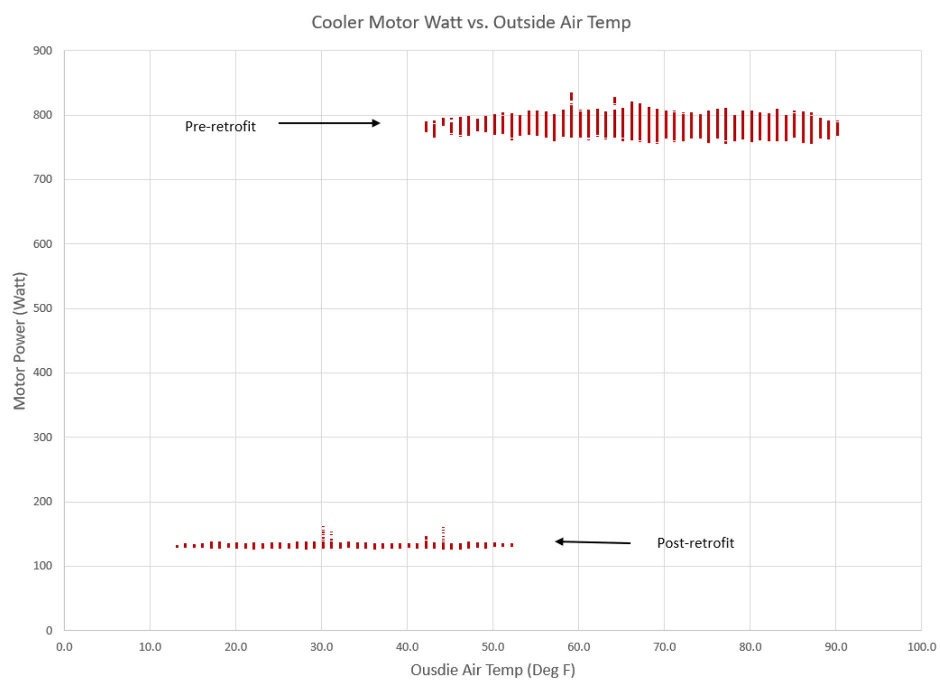


Figure 63. Site #2 – Cooler Motor Power vs. Outside Air Temperature

Figure 64 and Table 11 show that comparing with the original motor and blade assemblies, the Q-Sync motors with matching Q-Sync blades reduced the current draw by **84%** (9.87 amp vs. 1.6 amp for six motors.) This is partly because the Q-Sync motors are more energy efficient, and partly because the Q-Sync blades are also lighter with much lower pitch. Compared with their respected current rating of 1.7 amp (original) and 0.55 amp (Q-Sync) at full load condition, the measured values (1.645 amp each for the originals and 0.26 amp each for the Q-Sync motors) indicate that the Q-Sync setup were only at less than 50% of full load, while the original motor was almost at full load. This could be because of the much lighter Q-Sync blades with much lower pitch, compared to the original fan blades.

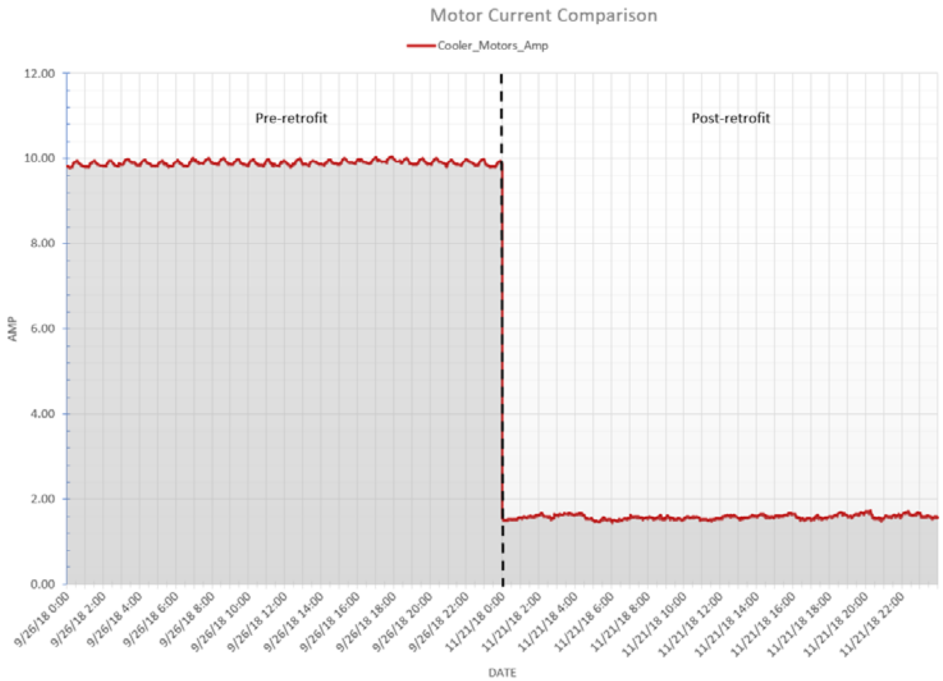


Figure 64. Site #2 – Cooler Motor Current One Day Comparison

The motor power factor comparison charts (Figure 65 and Figure 66) are interesting. From the daily comparison of one day performance in the pre-retrofit and post-retrofit period, the Q-Sync motor power factor only increased slightly by **3.5%** from 0.65 to 0.68. Again, the reason is that Q-Sync motors were not run at full load condition. However, looking at the period when the four Q-Sync motors run with the original fan blades, the power factor become ~0.98. This number exceeded manufacturer's specified power factor of 0.93 at full load condition, because these Q-Sync motors run at more than full load condition.

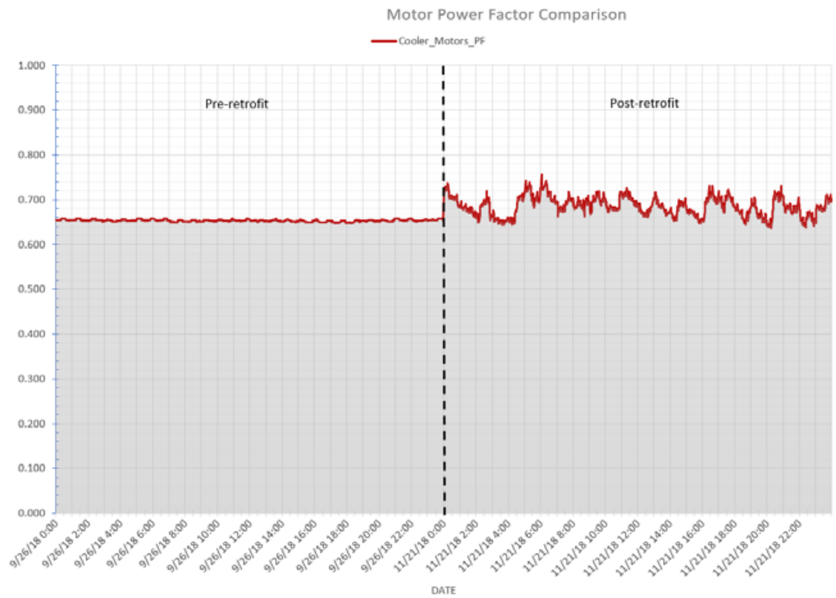


Figure 65. Site #2 – Cooler Motor Power Factor One Day Comparison

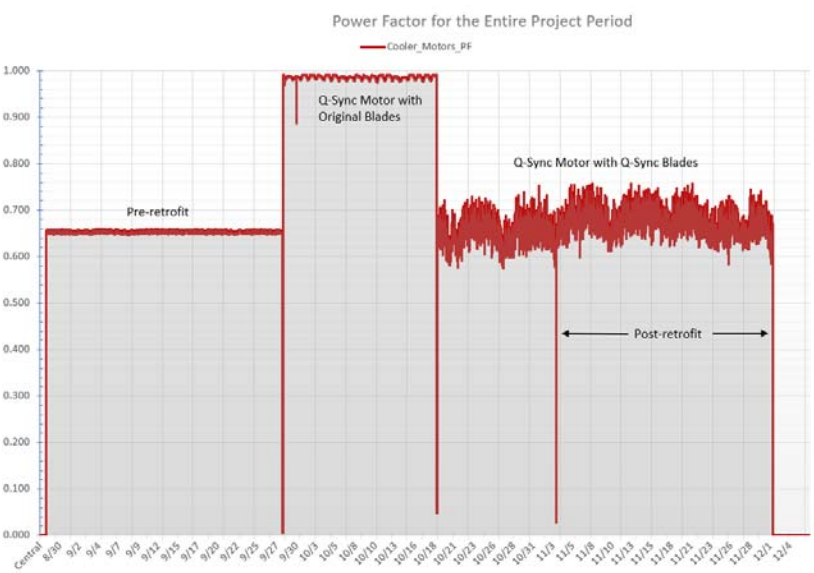


Figure 66. Site #2 – Cooler Motor Power Factor Comparison

The cooler inside space temperature and relative humidity chart (Figure 67) indicates consistent space temperature control pre-retrofit and post-retrofit. It was noted that during the pre-retrofit period, the thermostat setting may be adjusted by the building owner lower by a couple of degrees lower, though.

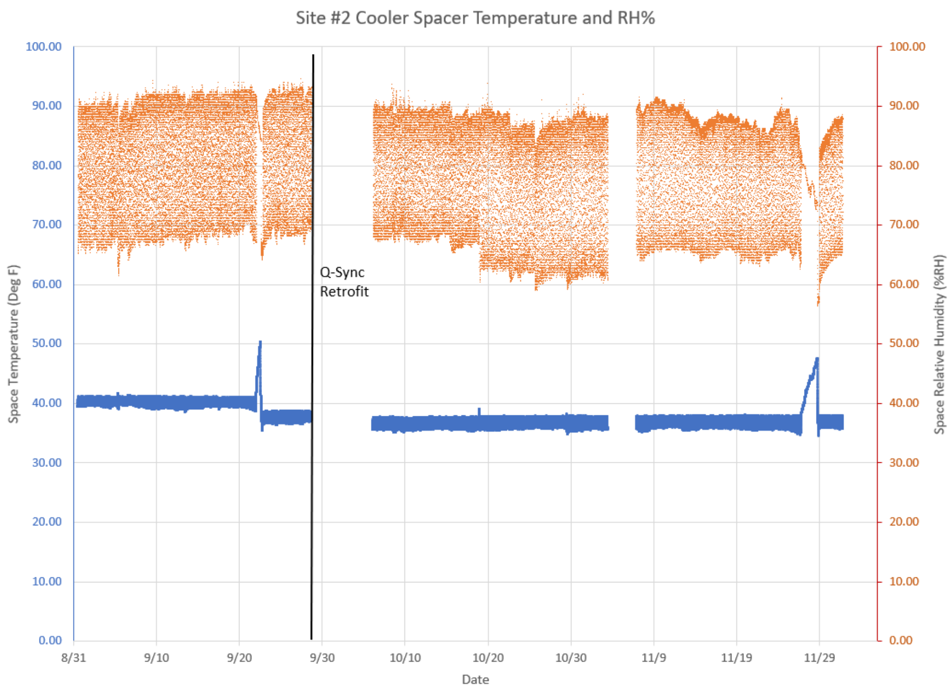


Figure 67. Site #2 – Cooler Space Temperature/RH% Comparisons

Table 10 to

Table 12 list average measured data and standard deviations of motor power, current, and power factor for the six cooler evaporator motors. The pre-retrofit period for the original motors is 8/29/2018 0:00 ~ 9/27/2018 23:59 (29 days.) The post-retrofit period is 11/04/2018 0:00 ~ 11/30/2018 23:59 (27 days) when six Q-Sync motors run with the matching Q-Sync blades.

Table 10. Site #2 Motor Power Reductions

Site #2 Motor Power Comparisons			
	Pre-retrofit Power (Watt)	Post-retrofit Power Avg. (Watt)	**Power Reduction (%)**
Six Cooler Motors	785.31	132.53	**83.1%**
	Pre-retrofit Power Std. Dev. (Watt)	Post-retrofit Power Std. Dev. (Watt)	
Six Cooler Motors	8.85	1.73	

Table 11. Site #2 Motor Current Reduction

Site #2 Motor Current Comparisons			
	Pre-retrofit Current (Amp)	Post-retrofit Current Avg. (Amp)	**Current Reduction (%)**
Six Cooler Motors	9.87	1.60	**83.8%**
	Pre-retrofit Current Std. Dev. (Amp)	Post-retrofit Current Std. Dev. (Amp)	

Six Cooler Motors	0.05	0.06	

Table 12. Site #2 Motor Power Factor Increase

Site #2 Motor Power Factor Comparisons			
	Pre-retrofit Power Factor Avg.	Post-retrofit Power Factor Avg.	**PF Increase (%)**
Freezer Motor #2	0.65	0.68	**3.5%**
	Pre-retrofit Power Factor Std. Dev.	Post-retrofit Power Factor Std. Dev.	
Two Cooler Motors	0.002	0.024	

The average air velocity for the cooler fans more than doubled from 290 ft/min to 681 ft/min after the retrofit with both Q-Sync motors and matching Q-Sync blades. This reflects significant differences in two types of blades' shape, weight, material, configuration (4 blades vs. 5 blades), and blade pitch (40 degree vs. 22 degree,) beside the fact the new Q-Sync motors run 16% faster (1800 rpm vs. 1550 rpm.) This is another example that matching the original evaporator unit air flow rate may be difficult without making any adjustment of the blade size because there are many different existing fan blade models and only one standardized Q-Sync blade model for the 10" size Q-Sync blade and one for the 12" size Q-Sync blade. However, the space temperature seems under control with a significantly higher air flow rate because the thermostat controller will turn on/off the compressor based on its space temperature measurements.

Table 13. Site #2 Cooler Field Measurement Results

	Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Avg.
Air velocity (ft/min)	Pre-retrofit 9/28/2018	340	368	362	253	241	430	296	285	245	391	94	174	**289.9**
	Post-retrofit 11/03/2018	771	521	222	854	588	716	239	901	707	688	858	1101	**680.5**

Site #3: The Liquor Store

The two cooling units at this liquor store, each with four evaporator fans, were separately controlled by two independent temperature controllers. We monitor the fan motor powers at the unit level – each of the power lines in Figure 68 representing the wattage of the four motors in the cooling units.

The new Q-Sync motors power levels were **62%** (unit #1) and **55%** (unit #2) lower than the original SP motors (Table 14.) A closer examination of the daily power comparison charts (Figure 69 and Figure 70) and field observation showed that one of the four motors in unit #2 run intermittently (on for 15 minutes and then off for 5 minutes) during the pre-retrofit period. The refrigeration technician who serviced these cooling units said this was because of the motor failed due to overheating and could recover to run again after it stopped and cooled down. Both cooling units were not in very good conditions – they were very old and there were a lot of dirt inside and outside the units. The power data for the unit #2 pre-retrofit period removed the power levels when the failed motor stopped running for a fair comparison with the Q-Sync motors that were always running normally after the retrofit. Figure 69 also indicated the motor powers dipped when the compressor was off, causing space temperature rose and air density lower, so the motor loads were lower during those periods. It also appeared the compressor was turned on/off the same three times in each of these two sample days. So, it is an anecdotal evidence (though we did not directly monitor it) that there were not significantly different compressor operations before and after the retrofit. We did observe the larger variation in post-retrofit power for unit #2 over the two-month period. However, since we did not monitor the evaporator coil or the condenser, it is hard to explain the strange pattern shown in Figure 68. The cooler motor power vs. outside air temperature scatter plot did not show any significant correlation between the power and outside air temperature (Figure 71.)

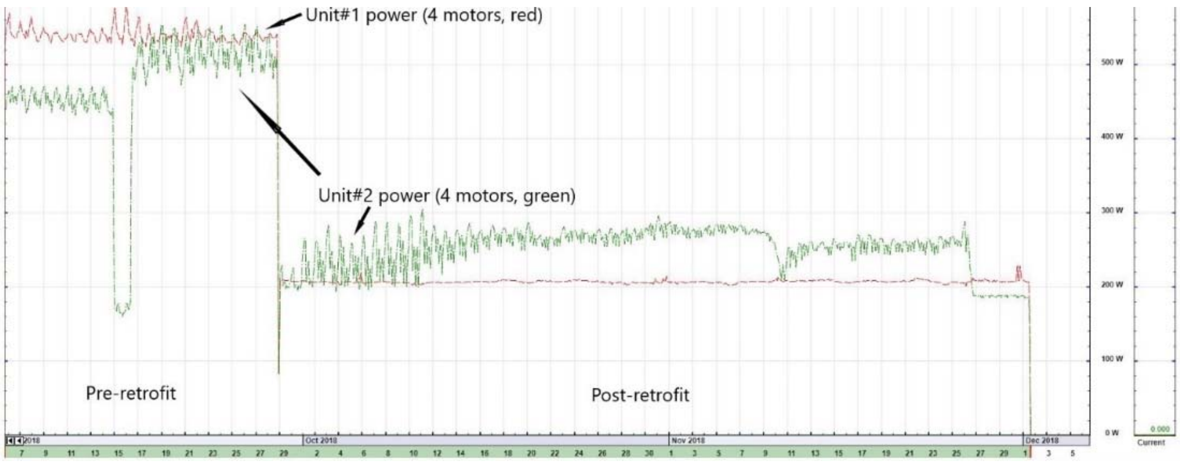


Figure 68. Site #3 – Cooler Motor Power Comparisons

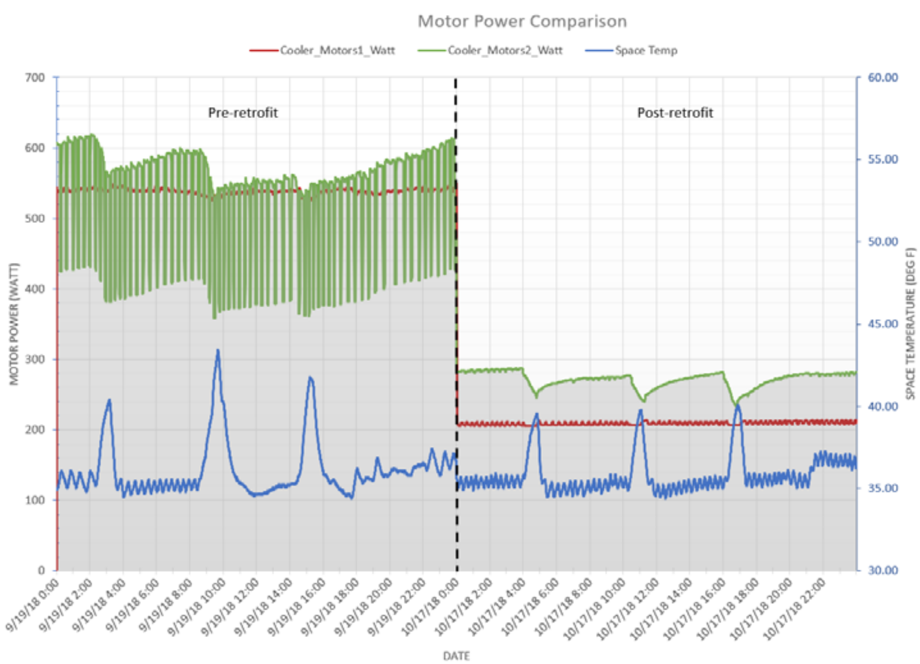


Figure 69. Site #3 – Cooler Motor Power One Day Comparisons

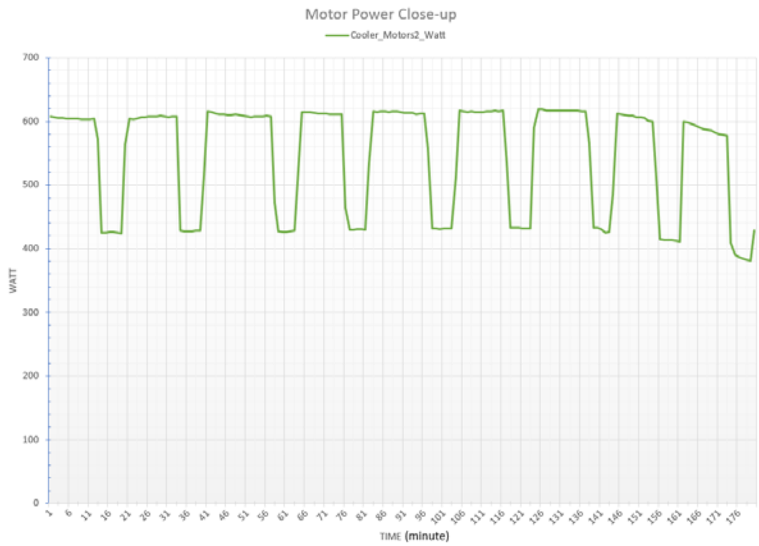


Figure 70. Site #3 – Cooler Unit #2 Pre-retrofit Motor Power Close-Up

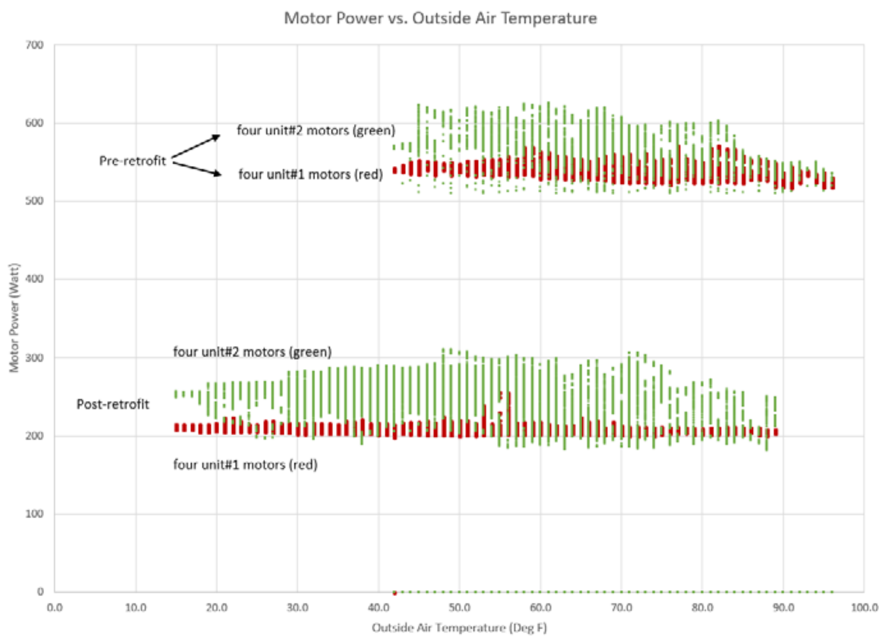


Figure 71. Site #3 – Cooler Motor Power vs. Outside Air Temperature

Figure 72 and Table 15 show that the Q-Sync motors reduced the current draw by **74%** (7.1 amp vs. 1.8 amp for four motors) for unit #1 and **71%** (7.6 amp vs. 2.2 amp for four motors) for unit #2. For unit #2, the 7.6 amp number did not count the current dip when the failed motor stopped running. Compared with their current rating of 1.8 amp (unit #1) and 2.1 amp (unit #2) (Table 3) for the original motors, the measured values (1.78 amp each for unit #1, and 1.9 amp each for unit #2) indicate both were run at close to full loads. The measured Q-Sync motors' current of 0.45 amp (unit #1) and 0.55 amp (unit #2) were also close to the manufacturer's specified 0.55 amp.

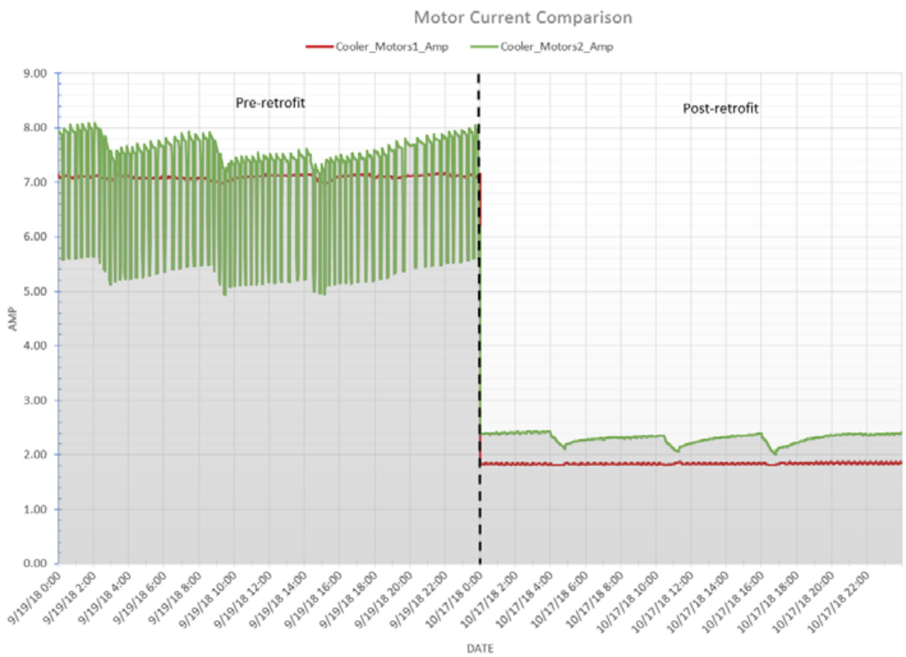


Figure 72. Site #3 – Cooler Motor Current One Day Comparisons

With pre-retrofit and post-retrofit motors run at close to full loads, the power factors (Figure 73 and Table 16) were much improved after the retrofit. The Q-Sync motor power factors were 0.92 and 0.95 respectively, very close to manufacture specified number of 0.93. These numbers are ~50% increase to the original power factors of 0.62 and 0.63 for the original SP motors. The cooler inside space temperature and relative humidity (Figure 74) also did not change much after the retrofit.

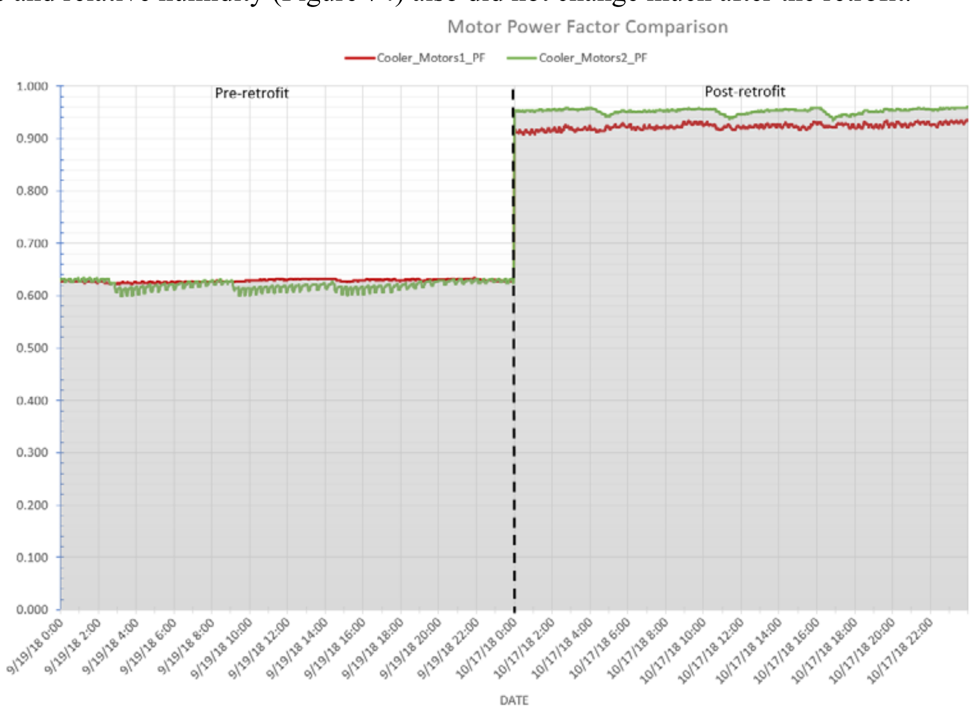


Figure 73. Site #3 – Cooler Power Factor Comparison

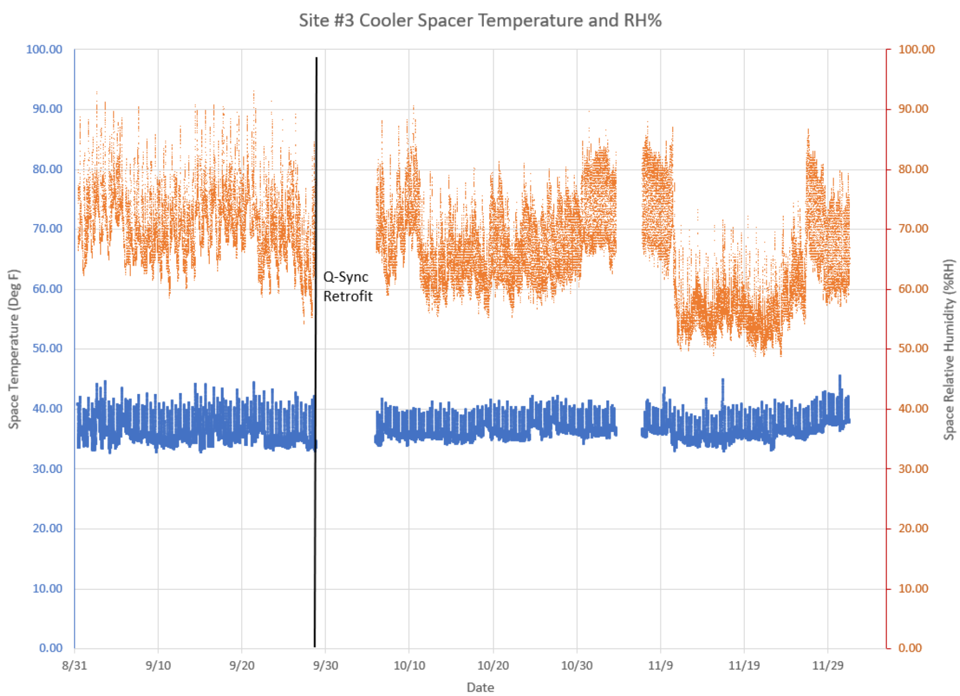


Figure 74. Site #3 – Cooler Space Temperature/RH% Comparisons

Table 14 to

Table 16 list average measured data and standard deviations of motor power, current, and power factor for the eight cooler evaporator motors. The pre-retrofit period for the original motors is 8/29/2018 0:00 ~ 9/27/2018 23:59 (29 days) for unit #1, and 9/17 0:00 ~ 9/27 23:59 (11 days) for unit #2. The post-retrofit period is 9/29 0:00 ~ 11/25 23:59 (58 days) for both units.

Table 14. Site #3 Motor Power Reduction

Site #3 Motor Power Comparisons			
	Pre-retrofit Power (Watt)	Post-retrofit Power Avg. (Watt)	**Power Reduction (%)**
Four Unit #1 Motors	540.93	207.71	**61.6%**
Four Unit #2 Motors	568.83	258.64	**54.5%**
	Pre-retrofit Power Std. Dev. (Watt)	Post-retrofit Power Std. Dev. (Watt)	
Four Unit #1 Motors	10.37	2.82	
Four Unit #2 Motors	21.70	22.85	

Table 15. Site #3 Motor Current Reduction

Site #3 Motor Current Comparisons			
	Pre-retrofit Current (Amp)	Post-retrofit Current Avg. (Amp)	**Current Reduction (%)**
Four Unit #1 Motors	7.11	1.82	**74.4%**

Four Unit #2 Motors	7.58	2.21	**70.9%**
	Pre-retrofit Current Std. Dev. (Amp)	Post-retrofit Current Std. Dev. (Amp)	
Four Unit #1 Motors	0.12	0.02	
Four Unit #2 Motors	0.21	0.17	

Table 16. Site #3 Motor Power Factor Increase

Site #3 Motor Power Factor Comparisons			
	Pre-retrofit Power Factor Avg.	Post-retrofit Power Factor Avg.	**PF Increase (%)**
Four Unit #1 Motors	0.62	0.92	**49.5%**
Four Unit #2 Motors	0.63	0.95	**50.9%**
	Pre-retrofit Power Factor Std. Dev.	Post-retrofit Power Factor Std. Dev.	
Four Unit #1 Motors	0.085	0.007	
Four Unit #2 Motors	0.002	0.013	

The average air velocity for the cooler fans were very similar before and after the retrofit (Table 17.) From the field visit photo (Figure 42) the Q-Sync blades were very similar to the original fan blades.

Table 17. Site #3 Cooler Field Measurement Results

	Point#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	Average
Air velocity (ft/min)	Pre-retrofit 9/28/18	591	332	276	617	222	644	291	619	666	426	127	78	701	623	244	284	**421.3**
	Post-retrofit 11/3/18	676	728	310	341	281	749	262	1063	303	415	250	349	282	378	206	365	**434.9**

T

To investigate if there were significant space temperature differences inside the coolers and the freezer, space temperatures were taken manually using the TSI 9545-A meter at multiple locations during the retrofit trips to three pilot sites. The point# locations are illustrated in Figure 33, Figure 40, and Figure 46. **Table 18** shows that the space temperatures within these coolers and the freezer were fairly consistent.

Table 18. Space Temperature Distributions

		Point#	1	2	3	4	5	6	Average	Range
Site #1	Freezer Temp (ºF)	Pre-retrofit (9/28/2018)	7.2	5.2	5.8				6.1	**5.2~7.2**
	Cooler Temp (ºF)	Pre-retrofit (9/28/2018)	37.2	37.8	38.6				37.9	**37.2~38.6**

Site #2	Cooler Temp (ºF)	Pre-retrofit (9/28/2018)	35.2	35.7	35.3	35.1	35	34.5	35.1	**34.5~35.7**
Site #3	Cooler Temp (ºF)	Pre-retrofit (9/28/2018)	32.2	32.7	33.6	33.5	33.3	33.6	33.2	**32.2~33.6**

RESULTS

ENERGY AND COST SAVINGS SUMMARY

The net energy savings are calculated based on the power reductions measured, projected to an annual basis. For the freezer motors at Site #1, the difference in motor daily run times (due to defrost control) are also factored in the calculation. For other motors, annual operating hours of 8760 hours are used. Since it has been shown that motor power did not correlate to outdoor temperature, no corrections are made based on weather. Table 19 list the annual net energy and cost savings summary for each site on the per motor basis.

Table 19. Annual Energy and Cost Savings Summary

		Pre-retrofit Annual (kWh/Motor)	**Post-Retrofit Annual (kWh/Motor)**	**Annual Energy Savings (kWh/Motor)**	**Annual Energy Savings (% /Motor)**	**Annual Energy Cost Savings ($/Motor)**
Site #1	Two Freezer Motors**	907.80	273.54	634.26	69.9%	$76.11
	Two Cooler Motors	511.72	242.35	269.37	52.6%	$32.32
Site #1 Average**		709.76	257.95	**451.82**	**61.3%**	**$54.22**
** It is assumed in the pre-retrofit period motor #1 was with a fan blade installed.						
Site #2	Six Cooler Motors	1,146.55	193.49	953.06	83.1%	$114.37
Site #2 Average		1146.55	193.49	**953.06**	**83.1%**	**$114.37**
Site #3	Four Cooler Motors (unit #1)	1,184.64	454.88	729.75	61.6%	$87.57
	Four Cooler Motors (unit #2)	1,245.74	566.42	679.32	54.5%	$81.52
Site #3 Average		1,215.19	510.65	**704.53**	**58.0%**	**$84.54**

Note: cost saving calculations use **$0.12/kWh** as the rate for electricity.

These results show that Q-Sync motor retrofits can save **52%~83%** evaporator fan energy for the walk-in coolers and freezers in this filed study. Each Q-Sync motor's annual energy saving ranged from **269 kWh to 953 kWh**, and annual cost saving ranged from **$32.3 to $114.4**. These large ranges in energy and cost savings are due to differences in exisiting evaporator design, evaporator motor and blade type and model, cooler and freezer internal loads, and current evaporator unit conditions.

Based on the Illinois TRM (Illinois Energy Efficiency Stakeholder Advisory Group, 2017), for walk-in cooler/freezer applications, the 1/15 to 1/20 horsepower (38 watt to 50 watt) EC motors can save 1,064 kWh energy annually. However, this number was based on theoretical calculation and used SP motor running 8760 hours continuously as the benchmark. It also assumed all evaporator fan motors always run at rated full load conditions and EC motors have 66% efficiency. We know from this field study that these motors may not always run at full load conditions and thus real energy savings could be much less. In terms of percentage energy savings, Q-Sync motors with 82% peak efficiency ((Fricke, Brian A.; Becker, Bryan R., 2018) should provide more energy savings than EC motors with 66% efficiency.

ECONOMIC ANALYSIS

We also conducted economic analysis based on energy cost saved and the first cost of installing new Q-sync motors at these three stores. For materials, the cost for a new Q-Sync motor with matching blade was $50. For labor, the hours used for a refrigeration technician to conduct the Q-Sync motor retrofit at each of the three pilot test sites were recorded, and hourly labor rates obtained from the OGNI Group. Based on the projected energy and cost savings in Table 19, the total costs and resulting paybacks were calculated and are summarized in Table 20.

Table 20. Simple Paybacks for Q-Sync Retrofit

	Number of Motors Retrofitted	Q-Sync Motor and Blade Cost	Retrofit Time (hour)	Travel Time (hour)	Total Hours (hour)	Labor rate ($/hour)	Total Retrofit Cost	Annual Energy Cost Savings ($)	Simple Payback (year)
Site #1	4	$200.00	2.00	1.00	3.00	65.00	395.00	$216.87	1.82
Site #2	6	$300.00	2.17	1.00	3.17	65.00	506.05	$686.20	0.74
Site #3	8	$400.00	2.00	1.00	3.00	65.00	595.00	$676.35	0.88

These simple payback calculations did not take into account regular annual maintenance cost, as our pilot project only monitored the Q-Sync motor performance for about 30 to 60 days. From the conversation with the experienced refrigeration technician, these small business owners very rarely call for regular repair and maintenance of these walk-in coolers and freezers, unless there were total failure of the equipment and the space temperature was not under control. That’s why many of the evaporator units we observed on the filed were in poor condition. The simple payback may also vary depending on differing electricity rates and labor rates. Nevertheless, these simple payback numbers, ranging from 0.77 to 1.82 years, suggest a highly cost-effective measure.

OTHER OBSERVATIONS

Other observations from the pilot project are listed below:

- Among the 18 motors being retrofitted, only two are PSC motors and the rest are SP motors. There were no EC motors at the three pilot test sites for the walk-in coolers and freezers. The energy saving percentage for the two PSC motors was 52%, and the energy saving percentages for the SP motors varied widely from 54% to 84%. The variations were largely due to the differences in how the motors were configured in the existing evaporators, the fan blade size and material, and whether motors typically run close to their rated airflow and power.
- The Q-Sync motor’s power factor can potentially reach its designed value of ~0.93 in the field. However, in many cases, the power factor may only be in the 0.60 to 0.80 range, if a motor does not run close to its rated airflow and power.

- For walk-in coolers, these motors typically run 24 hours per day, 365 days per year. For walk-in freezers, these motors may stop running 3 to 4 times a day for defrost cycles, each lasting approximately 30 minutes.
- It may be difficult to match the original designed airflow rate after the Q-Sync motor (and blade) retrofit, even though the Q-Sync motor manufacturer has factored in the new matching blade design to account for the Q-Sync motor speed increase (1800 rpm vs. 1550 rpm.) There are limited Q-Sync blade design options (one for each of the two blade sizes 10" and 12" nominal) and it is likely impossible in some cases to match the existing airflow.
- However, not matching the original designed airflow rate did not seem to affect the space temperature control much. In all cases, the space temperatures were controlled well – even when one of the two fan blades was missing at Site #1, or two of the six motors were not working at Site #2. For walk-in freezer applications, if there were significant air flow rate changes after the retrofit, the actual operating hours for Q-Sync motors may be impacted slightly due to the defrost cycle. Further study is needed on how the refrigeration compressor energy may also be impacted by this secondary effect.
- The evaporator fan motor power has little correlation with outside air temperature, even when the unit is located adjacent to the outdoors.
- One of the two Q-Sync motors inside the freezer evaporator unit located on top of the roof failed after ~50 days running in cold and humid weather conditions. It may be that moisture entered the inside of the motor because the evaporator unit was not sealed very well.
- The overall Q-Sync motor retrofit process was straight forward. As long as the technician conducting the retrofit had prior refrigeration service experiences and requisite tools, the retrofits went smoothly and quickly.

CONCLUSIONS AND RECOMMENDATIONS

This pilot project is one of the first couple of field studies on Q-Sync motor retrofits for walk-in cooler and freezer applications. Our field study was focused on small businesses in northern Illinois.

Our study's results show that retrofitting existing 38~50-watt evaporator fan motors with Q-Sync motors could save fan energy use by **52~84%** compared to typical existing PSC and/or SP motors, with an average energy savings of **67.8%**. This equates to a range of **269 – 953 kWh per motor**, with an average energy savings of **731 kWh per motor**. For the two existing PSC motors, the energy saving and current reduction percentage was at the low end of the ranges; the sixteen existing SP motors were at the high end of the ranges.

Q-Sync motor retrofit projects can provide excellent simple payback: in most cases under two years, with one site's retrofit paying back as quickly as nine months. On average, for walk-in coolers and freezers, the annual cost savings for retrofitting existing evaporator fan motors with new Q-Sync motors ranged from **$32 ~ $114 per motor**, assuming a $0.12/kwh electricity rate. A summary of all annual energy and cost savings for the three pilot sites is listed in Table 19**Error! Reference source not found.**, and the simple paybacks in Table 20.

It was observed that the new air flow rates after retrofit may not match the original air flows closely in every instance. Also, motor power factor did not reach its rated value of 0.93 in some cases. However, the walk-in cooler or freezer space temperature were not affected by these anomalies.

We would make the following recommendations for evaporator fan motor replacement measures in ComEd's energy efficiency portfolio:

- Q-sync motors should be added as a measure for both display case and walk-in evaporator applications. The savings and incentives should be increased from that of the EC motor measure based on this study and the corresponding previous literature. This measure is still very new in the market, so marketing support should be added for both end-use consumers and refrigeration service providers.
- Update the Illinois TRM to expand the Q-Sync motor measure to include 38~50 watt Q-Sync motor for walk-in cooler and freezer applications.
- Any refrigeration service provider who conducts a Q-Sync motor retrofit should be trained and qualified to do walk-in cooler and freezer maintenance and repair and is familiar with the equipment on site.
- Before the retrofit, the refrigeration service provider should check the existing motor and blade models, voltage, and sizes, to make sure the new Q-Sync motor and blade can physically fit in the existing evaporator and operate with its electrical circuit.
- For the retrofit, it's highly recommended to replace both the existing motors and their corresponding blades with the new Q-Sync motors and their matching blades. Caution should be exercised when only replacing the existing motors with the Q-Sync motors but using the existing fan blades. Note that we observed one instance of two Q-sync motors operating with heavy, higher pitch (more than 22 degrees) existing blades, and those two motors burned out after a few hours.
- There may be some longevity concerns in installing Q-Sync motors in evaporator units located outside the building.

- Since Q-Sync motor retrofits provide very good simply payback as an energy efficiency measure, but the product is rarely known, ComEd should provide marketing support and incentives to promote the adoption of Q-Sync motors in walk-in cooler and freezer applications.

FUTURE STUDY

Some further study is needed to understand the potential for the Q-sync measure more broadly:

- The temperatures we measured inside the walk-ins indicated that there was little change from pre- to post-retrofit, and therefore the load on the system was likely not impacted in a major way. However, there was some indication that small changes in airflow from the Q-sync motors could have led to changes in coil heat transfer and possibly cycling of the compressors. Therefore, some study may of impacts on compressor power use may be useful.

- The overall impact of a measure like Q-sync motors in a given utility territory, such as ComEd's, will be dependent on the wattage and type (SP, PSC, EC) of motors currently in place throughout the territory. Such a characterization was not part of this scope but would be very useful in program planning and possibly TRM improvement.

REFERENCES

Fricke, Brian A.; Becker, Bryan R. (2018). *Permanent Magnet Synchronous Motors for Commercial Refrigeration: Final Report.* Oak Ridge National Laboratory.

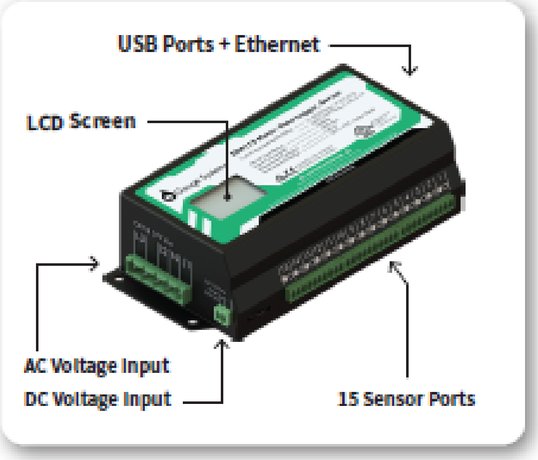
Illinois Energy Efficiency Stakeholder Advisory Group. (2017). *Illinois Statewide Technical Reference Manual for Energy Efficiency version 6.0, Volume 2: Commercial and Industrial Measures.* Technical Report.

NCI and PNNL. (2011). *Preliminary Technical Support Document (TSD): Energy Conservation Program for Certain Commercial and Industrial Equipment: Commercial Refrigeration Equipment.* Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program,.

APPENDIX A EGAGUGE CORE SPECIFICATIONS AND SETUP

eGauge Core Specifications

Model: EG4115



Measurement

AC Voltage: (Y: L-N, Δ: L-L)	L1: 85-277 Vrms L2: 0-277 Vrms L3: 0-277 Vrms
DC Voltage:	42 Vrms Power: 9-60 Vdc Measurement: -60-60Vdc
Current:	15 sensor ports 6900A max Sensor ports isolated from digital and high voltage
Frequency:	50 or 60 Hz
Logging Values:	V, A, W, Wh, Hz, VA VAr, THD, deg
Power Draw:	12W max, 2W typical 2 5V USB Ports @ 1A max
Accuracy:	ANSI C12.2 - 0.5% Compliant

Environment Conditions

Operating Temp:	-30° to 70°C (-22° to 158°F)
Max Altitude:	4000m (13,123ft)
Max Humidity:	80% up to 31°C
Meas. Category:	Overvoltage Category III
Location:	Open type indoor device
Pollution Degree:	2

Data Logger Capacity

Register Count:	64 (data storage points)
Granularity: *(duration/avg)*	1 hr/1 sec 1 yr/1 minute 10 yrs/15 minute Device Lifetime/1 day

Safety and Regulatory

Safety:	IEC/UL 61010-1 Ed. 3.0 B:2010
CE:	IEC 61000-6-1 Ed. 3.0 B:2016 IEC 61000-6-3 Ed. 2.1 B:2011
FCC:	FCC Title 47 CFR Part 15-Subpart B Class B ICES-003 Information Technology-Equipment Class B

eGauge Core Specifications

General

Warranty: 2 years, 5 years

Network Connection

Homeplug AV: Compatible with HomePlug AV adapter within ~100ft. on same phase as L1 terminal

Ethernet: IEEE 802.3 - LAN

WiFi/Cellular: Optional with USB accessory

Data Communication

Import: Modbus RTU, Modbus TCP,

Export: Modbus RTU, Modbus TCP, BACnet/IP, XML

User Interface

Compatible browsers:
(Only up-to-date versions supported)

Google Chrome
Firefox
Safari
Internet Explorer

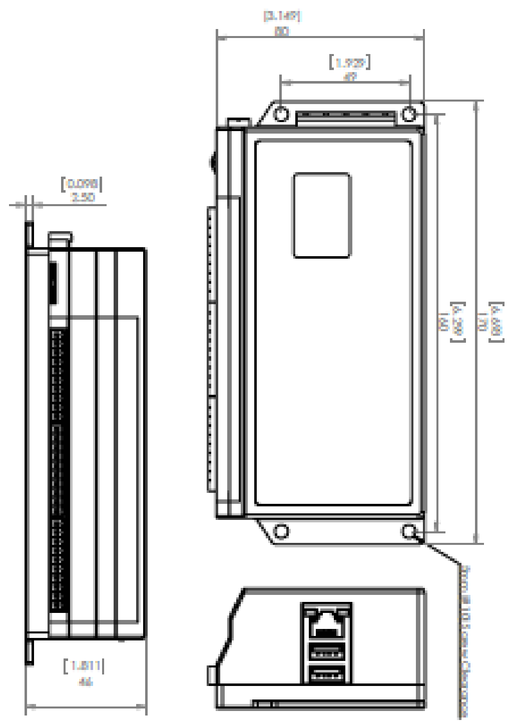
Enclosure

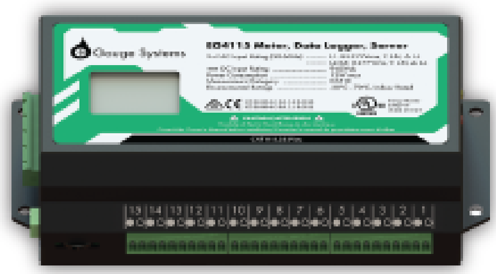
Material: FRABS

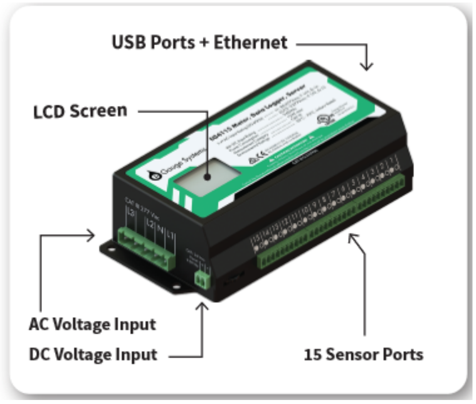
Dimensions: 17 x 8 x 4.6cm (6.7 x 3.15 x 1.81in)

Weight: 300g (0.66lbs)

Dimensions *([in.] mm)v*







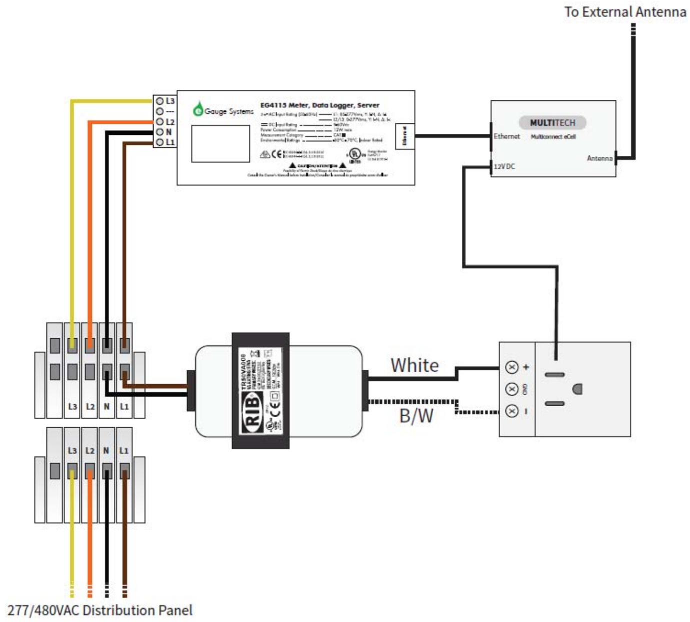
eGauge Core Energy Meter

The current transducers used in connection with the eGauge Core energy meters were high-accuracy AC split-core Accu-CT models from Continental Control Systems.

Continental Control Systems Accu-CT Current Transducer

Multitech's eCell cellular to Ethernet bridge MTE-LAT2-B07 was used to connect to "eGauge Core" energy meters and provide remote connectivity via AT&T LTE cellular network service. Total of three sets of such remote power monitoring systems was assembled for this project, one used in each of the field test sites.

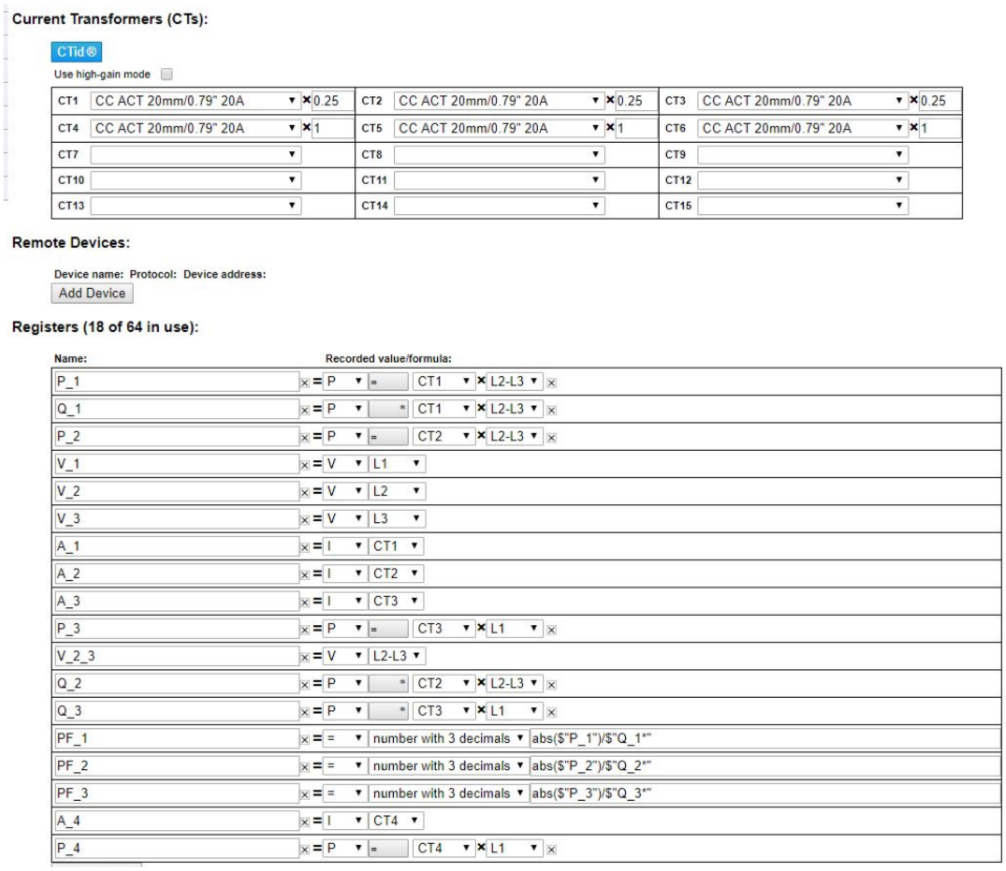
Multitech eCell Modem



Remote Power Monitoring System Line Diagram

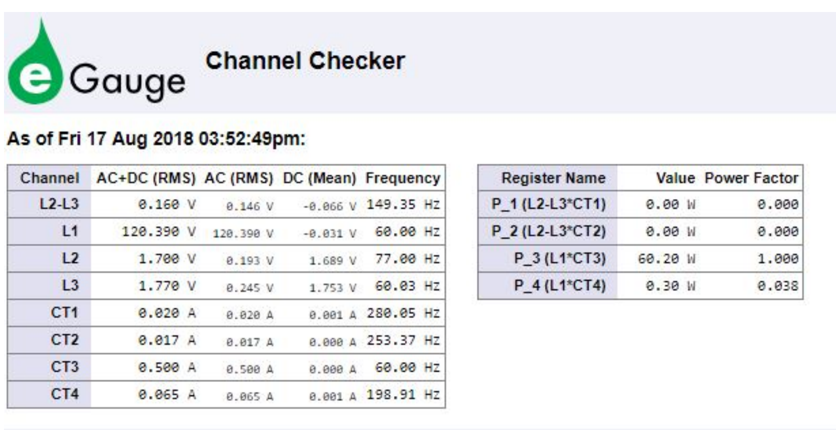

Remote Power Monitoring System

The power monitoring equipment and other components (eGauge energy meter, current transducers, eCell modems, and weather proof enclosure) were procured and assembled into three independent systems – one for each test site. They were then setup and tested fully working properly in the office before installed in the field. The eGauge setup includes proper settings for the current transducers, as well as creating registers to record and calculate current, voltage, real power, apparent power, and power factors for the circuits being measured. A sample setup page is shown below:



A Sample eGauge Energy Meter Settings

Each power monitoring circuit was double-checked in the office by measuring a known 120VAC, 60W incandescent light bulb. The following figure shows a sample test power reading of 60.20 watts and power factor of 1.000.



Channel	AC+DC (RMS)	AC (RMS)	DC (Mean)	Frequency
L2-L3	0.160 V	0.146 V	-0.066 V	149.35 Hz
L1	120.390 V	120.390 V	-0.031 V	60.00 Hz
L2	1.700 V	0.193 V	1.689 V	77.00 Hz
L3	1.770 V	0.245 V	1.753 V	60.03 Hz
CT1	0.020 A	0.020 A	0.001 A	280.05 Hz
CT2	0.017 A	0.017 A	0.000 A	253.37 Hz
CT3	0.500 A	0.500 A	0.000 A	60.00 Hz
CT4	0.065 A	0.065 A	0.001 A	198.91 Hz

Register Name	Value	Power Factor
P_1 (L2-L3*CT1)	0.00 W	0.000
P_2 (L2-L3*CT2)	0.00 W	0.000
P_3 (L1*CT3)	60.20 W	1.000
P_4 (L1*CT4)	0.30 W	0.038

eGauge Energy Meter Readings of a 60 W Light Bulb

The eCell modems were all setup and tested before the pre-retrofit monitoring installation in the field to make sure they can communicate with the energy meters ok and establish internet connectivity through

AT&T cellular network. Python scripts were written and customized for each test site to test the remote data collection/downloading capability from the researcher's laptop.

APPENDIX B CURRENT TRANSDUCER SPECIFICATIONS

ACTL-0750 Split-Core CT

The series of current transducers are revenue grade and offer outstanding linearity and very low phase angle error with easy one-handed opening and closing operations. The standard Accu-CT meets IEEE C57.13 class 1.2. When ordered option C0.6 these transducers meet class 0.6 accuracy standards.

Accuracy

The accuracy specifications apply over the full operating temperature range (-30°C to 55°C) unless otherwise noted. Standard models are calibrated for optimum accuracy at 60 Hz. For use with 50 Hz services, we recommend ordering with Option 50Hz. The following accuracy specifications may vary when other CT options are specified. For details, refer to the individual option descriptions.

Standard Accuracy

These specifications are for 60 Hz operation or for 50 Hz when Option 50Hz is specified.
Accuracy: ±0.75% from 1% to 120% of rated primary current
Phase angle: ±0.50 degrees (30 minutes) from 1% to 120% of rated current
IEEE C57.13 accuracy: class 1.2 from 1% to 120% of rated current
IEC 60044-1 accuracy: class 1.0 from 1% to 120% of rated current

Revenue Grade Accuracy

With Option C0.6, the Accu-CT is calibrated and verified to meet IEEE/ANSI C57.13-2008 class 0.6 accuracy and IEC 60044-1 class 0.5 S accuracy and each CT is shipped with a certificate of calibration.

When used on 50 Hz services, Option C0.6 must be ordered with Option 50Hz.
Accuracy: ±0.50% from 1% to 120% of rated primary current
Phase angle: ±0.25 degrees (15 minutes) from 1% to 120% of rated current; ±0.50 degrees (30 minutes) below 0°C from 1% to 10% of rated current
IEEE C57.13 accuracy: class 0.6 from 1% to 120% of rated current
IEC 60044-1 accuracy: class 0.5 and 0.5 S from 1% to 120% of rated current
Available Models: Option C0.6 is available for all models except ACTL-0750-005

Electrical

Primary rating: 5 to 250 amps nominal, 600 Vac, 60 Hz nominal
Maximum continuous primary amps: varies with model and options
Maximum primary conductor gauge: 4/0, 250 kcmil (see Wire Gauge Table)

Output: 0.333 Vac or 1.00 Vac (with Option 1V)
Output lead wires:
Style: Two conductor, white and black twisted pair (equivalent to about one #8 AWG 0.213″ dia.)
Standard length: 8 ft (2.4 m)
Gauge: #18 AWG
Type: MTW, UL 1015
Voltage: 600 Vac

Certificate of Calibration

Continental Control Systems, LLC
2150 Miller Dr., Suite A, Longmont, CO, 80501, USA
https://www.ctlsys.com
+1 303-444-7422

Continental Control Systems, LLC

Current Transformer

Model: ACTL-0750-020 Opt C0.6
Serial Number: C0270994N1
Rated Primary Current: 20 A
Manufacture Date: 2018-Jul-24
Calibration Date: 2018-Jul-24
Calibration Due Date: 2034-Jul-24 (sixteen year recommended calibration interval)

Traceable Test Equipment

Traceability is to national standards administered by U.S. NIST and/or Euromet members (U.K. NPL, etc.).

Equipment	Manuf.	Model	Cal Due Date	Serial Number
Electrical Power Standard	FLUKE	6105A-50A	2018-Dec-05	288868553

Calibration

Temperature: 23 ± 5°C
Line Frequency: 60 Hz

Operator: Adam Stein
Calibration Station: CALSYS12

Condition (% Rated Current)	Test Current (Amps)	Accuracy Limit (Percent)	Measured Accuracy (Percent)	Phase Limit (Degrees)	Measured Phase (Degrees)	TCF Limit	Measured TCF	Result
120%	24.0	± 0.50%	-0.07%	± 0.25°	-0.13°	1.0 ± 0.006	1.0036	PASS
100%	20.0	± 0.50%	-0.07%	± 0.25°	-0.12°	1.0 ± 0.006	1.0034	PASS
90%	18.0	± 0.50%	-0.08%	± 0.25°	-0.12°	1.0 ± 0.012	1.0035	PASS
75%	15.0	± 0.50%	-0.08%	± 0.25°	-0.11°	1.0 ± 0.012	1.0034	PASS
50%	10.0	± 0.50%	-0.08%	± 0.25°	-0.10°	1.0 ± 0.012	1.0031	PASS
30%	6.0	± 0.50%	-0.08%	± 0.25°	-0.09°	1.0 ± 0.012	1.0028	PASS
20%	4.0	± 0.50%	-0.08%	± 0.25°	-0.08°	1.0 ± 0.012	1.0027	PASS
15%	3.0	± 0.50%	-0.08%	± 0.25°	-0.07°	1.0 ± 0.012	1.0025	PASS
10%	2.0	± 0.50%	-0.08%	± 0.25°	-0.07°	1.0 ± 0.012	1.0024	PASS
5%	1.0	± 0.50%	-0.07%	± 0.25°	-0.07°	No Limit	1.0022	PASS
3%	0.6	± 0.50%	-0.06%	± 0.25°	-0.06°	No Limit	1.0020	PASS
1.5%	0.3	± 0.50%	-0.06%	± 0.25°	-0.06°	No Limit	1.0019	PASS
1%	0.2	± 0.50%	-0.07%	± 0.25°	-0.06°	No Limit	1.0021	PASS

This device meets IEEE C57.13 class 0.6 accuracy (TCF) limits.

This device meets IEC 60044-1 class 0.5 and 0.5 S accuracy limits for error and phase displacement.

Positive measured phase corresponds to the output signal leading the primary current.

For more information about IEEE C57.13, IEC 60044-1, and TCF (transformer correction factor) visit: https://ctlsys.com/support/ct-accuracy-standards/.

Certificate of Calibration

Continental Control Systems, LLC
2150 Miller Dr., Suite A, Longmont, CO, 80501, USA
https://www.ctlsys.com
+1 303-444-7422

CCS | Continental Control Systems, LLC

Current Transformer

Model: ACTL-0750-020 Opt C0.6
Serial Number: C0270993N1
Rated Primary Current: 20 A
Manufacture Date: 2018-Jul-24
Calibration Date: 2018-Jul-24
Calibration Due Date: 2034-Jul-24 (sixteen year recommended calibration interval)

Traceable Test Equipment

Traceability is to national standards administered by U.S. NIST and/or Euromet members (U.K. NPL, etc.).

Equipment	Manuf.	Model	Cal Due Date	Serial Number
Electrical Power Standard	FLUKE	6105A-50A	2018-Dec-05	288868553

Calibration

Temperature: 23 ± 5°C
Line Frequency: 60 Hz

Operator: Adam Stein
Calibration Station: CALSYS12

Condition (% Rated Current)	Test Current (Amps)	Accuracy Limit (Percent)	Measured Accuracy (Percent)	Phase Limit (Degrees)	Measured Phase (Degrees)	TCF Limit	Measured TCF	Result
120%	24.0	± 0.50%	+0.00%	± 0.25°	-0.10°	1.0 ± 0.006	1.0023	**PASS**
100%	20.0	± 0.50%	+0.00%	± 0.25°	-0.09°	1.0 ± 0.006	1.0021	**PASS**
90%	18.0	± 0.50%	-0.02%	± 0.25°	-0.09°	1.0 ± 0.012	1.0023	**PASS**
75%	15.0	± 0.50%	-0.02%	± 0.25°	-0.08°	1.0 ± 0.012	1.0021	**PASS**
50%	10.0	± 0.50%	-0.02%	± 0.25°	-0.07°	1.0 ± 0.012	1.0018	**PASS**
30%	6.0	± 0.50%	-0.02%	± 0.25°	-0.06°	1.0 ± 0.012	1.0016	**PASS**
20%	4.0	± 0.50%	-0.02%	± 0.25°	-0.05°	1.0 ± 0.012	1.0013	**PASS**
15%	3.0	± 0.50%	-0.02%	± 0.25°	-0.05°	1.0 ± 0.012	1.0012	**PASS**
10%	2.0	± 0.50%	-0.01%	± 0.25°	-0.04°	1.0 ± 0.012	1.0011	**PASS**
5%	1.0	± 0.50%	-0.00%	± 0.25°	-0.04°	No Limit	1.0008	**PASS**
3%	0.6	± 0.50%	-0.01%	± 0.25°	-0.03°	No Limit	1.0007	**PASS**
1.5%	0.3	± 0.50%	-0.01%	± 0.25°	-0.03°	No Limit	1.0008	**PASS**
1%	0.2	± 0.50%	-0.00%	± 0.25°	-0.02°	No Limit	1.0006	**PASS**

This device meets IEEE C57.13 class 0.6 accuracy (TCF) limits.

This device meets IEC 60044-1 class 0.5 and 0.5 S accuracy limits for error and phase displacement.

Positive measured phase corresponds to the output signal leading the primary current.

For more information about IEEE C57.13, IEC 60044-1, and TCF (transformer correction factor) visit:
https://ctlsys.com/support/ct-accuracy-standards/.

APPENDIX C AIR FLOW METER SPECIFICATIONS

Specifications

Specifications are subject to change without notice.

Velocity Probe:
Range: 0 to 6000 ft/min (0 to 30 m/s)
Accuracy[1&2]: ±3% of reading or ±3 ft/min (±0.015 m/s), whichever is greater
Resolution: 1 ft/min (0.01 m/s)

Duct Size:
Range: 1.0 to 500 inches in increments of 0.1 in. (2.5 to 1270 cm in increments of 0.1 cm)

Volumetric Flow Rate:
Range: Actual range is a function of actual velocity, and duct size

Temperature from Velocity Probe:
Range: 14 to 140°F (-10 to 60°C)
Accuracy[3]: ±0.5°F (±0.3°C)
Resolution: 0.1°F (0.1°C)

Relative Humidity from Velocity Probe:
Range: 5 to 95% RH
Accuracy[4]: ±3% RH
Resolution: 0.1% RH

Wet Bulb Temperature from Velocity Probe:
Range: 40 to 140°F (5 to 60°C)
Resolution: 0.1°F (0.1°C)

Instrument Temperature Range:
Operating (Electronics): 40 to 113°F (5 to 45°C)
Operating (Probe): 14 to 140°F (-10 to 60°C)
Storage: -4 to 140°F (-20 to 60°C)

Instrument Operating Conditions:
Altitude up to 4000 meters
Relative humidity up to 80% RH, non-condensing
Pollution degree 1 in accordance with IEC 664
Transient over voltage category II

Data Storage Capabilities:
Range: 12,700+ samples and 100 test IDs (one sample can contain fourteen measurement types)

Logging Interval:
Intervals: 1 second to 1 hour

Time Constant:
User selectable

Response Time:
Velocity: 200 msec
Temperature: 2 minutes (to 66% of final value)
Humidity: <1 minute (to 66% of final value)

External Meter Dimensions:
3.3 in. × 7.0 in. × 1.8 in. (8.4 cm × 17.8 cm × 4.4 cm)

Meter Probe Dimensions:
Probe length: 40 in. (101.6 cm)
Probe diameter of tip: 0.28 in. (7.0 mm)
Probe diameter of base: 0.51 in. (13.0 mm)

Articulating Probe Dimensions:
Articulating section length: 6.0 in (15.24 cm)
Diameter of articulating knuckle: 0.38 in (9.5 mm)

Meter Weight:
Weight with batteries: 0.6 lbs (0.27 kg)

Power Requirements:
Four AA-size batteries (included) or AC adapter (optional) 9 VDC, 300 mA min.

1 Temperature compensated over an air temperature range of 40 to 150°F (5 to 65°C).
2 The accuracy statement of ±3.0% of reading or ±3 ft/min (±0.015 m/s), whichever is greater, begins at 30 ft/min through 6000 ft/min (0.15 m/s through 30 m/s).
3 Accuracy with instrument case at 77°F (25°C), add uncertainty of 0.05°F/°F (0.03°C/°C) for change in instrument temperature.
4 Accuracy with probe at 77°F (25°C). Add uncertainty of 0.1% RH/°F (0.2% RH/°C) for change in probe temperature. Includes 1% hysteresis.

Certificate of Calibration and Testing

TSI Incorporated, 500 Cardigan Road, Shoreview, MN 55126 USA
Tel: 1-800-874-2811 1-651-490-2811 Fax: 1-651-490-3824 http://www.tsi.com

Environment Conditions		
Temperature	73.6 (23.1)	°F (°C)
Relative Humidity	47	%RH
Barometric Pressure	28.71 (972.2)	inHg (hPa)

Model	9545-A
Serial Number	9545A1826005

☒ As Left
☐ As Found

☒ In Tolerance
☐ Out of Tolerance

– Calibration Verification Results –

Temperature Verification — System T-100 — *Unit: °F (°C)*

#	Standard	Measured	Allowable Range
1	32.0 (0.0)	32.3 (0.2)	31.5–32.5 (−0.3–0.3)
2	140.0 (60.0)	140.2 (60.1)	139.5–140.5 (59.7–60.3)

Humidity Verification — System H-100 — *Unit: %RH*

#	Standard	Measured	Allowable Range
1	10.0	9.4	7.8–12.2
2	30.0	29.3	27.8–32.2
3	50.0	49.7	47.8–52.2
4	70.0	69.5	67.8–72.2
5	90.0	89.0	87.8–92.2

Velocity Verification — System V-102 — *Unit: ft/min (m/s)*

#	Standard	Measured	Allowable Range
1	0 (0.00)	0 (0.00)	−3–3 (−0.02–0.02)
2	35 (0.18)	35 (0.18)	32–38 (0.16–0.19)
3	64 (0.33)	64 (0.32)	61–67 (0.31–0.34)
4	99 (0.50)	98 (0.50)	96–102 (0.49–0.52)
5	160 (0.81)	160 (0.81)	155–165 (0.79–0.84)
6	330 (1.67)	331 (1.68)	320–340 (1.62–1.73)
7	654 (3.32)	654 (3.32)	635–673 (3.22–3.42)
8	997 (5.07)	1001 (5.08)	967–1027 (4.91–5.22)
9	1468 (7.45)	1482 (7.53)	1423–1512 (7.23–7.68)
10	2497 (12.68)	2509 (12.75)	2422–2572 (12.30–13.07)
11	4499 (22.86)	4536 (23.04)	4364–4634 (22.17–23.54)
12	5783 (29.38)	5763 (29.28)	5610–5957 (28.50–30.26)

TSI does hereby certify that the above described instrument conforms to the original manufacturer's specification (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to the United States National Institute of Standards and Technology (NIST) or has been verified with respect to instrumentation whose accuracy is traceable to NIST, or is derived from accepted values of physical constants. TSI's calibration system is registered to ISO-9001:2015.

Measurement Variable	System ID	Last Cal.	Cal. Due
Temperature	E003617	01-03-18	07-31-18
Humidity	E003296	08-07-17	08-31-18
Temperature	E001594	04-09-18	10-31-18
Pressure	E001264	04-12-18	10-31-18
Temperature	E003305	01-03-18	07-31-18
DC Voltage	E001662	01-31-18	07-31-19
Pressure	E001563	04-12-18	10-31-18
Velocity	E005916	08-14-17	08-31-20

Calibrated

July 2, 2018
Date

Doc. ID: CERT_GEN_WCC