Emerging Technologies

Evaluation of Direct Energy Savings and Demand Response Potential from Phase Change Materials for Cold Storage Cooling Applications

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EXECUTIVE SUMMARY

The purpose of this study is to evaluate the energy savings and Demand Response (DR) potential of passive Phase Change Materials (PCMs) and supplemental controls in cold storage freezer applications. PCM technology is designed to provide a freezer with a thermal battery effect that allows the space to better participate in DR and bring everyday electric energy and demand cost savings to utility customers. By increasing the freezer's thermal capacity, this battery allows the mechanical cooling equipment to be curtailed during on-peak and critical-peak time periods, providing grid relief when it is needed the most.

Load-shed DR enables load reductions in response to event notifications or signals, which are relayed through various means – some more automated than others. When customers respond to event signals and reduce load only on event days, it is called "event-driven load-shed DR."

Load-shape DR repeats load reductions each summer weekday, and shapes the facility's load profile to avoid high summer on-peak demand charges. By reducing load repeatedly and consistently during all summer weekdays, customers can significantly reduce their on-peak energy use and associated energy and demand charges.

Several types of PCM have been developed, notably from eutectic salts, paraffin wax, and bio-based organic materials. PCMs are proprietary formulas designed and produced so the PCM changes phase (leveraging the material's latent heat value) at a eutectic point matched to the operating temperature in the specific refrigerated space. The PCM absorbs heat as it transitions from a solid to a liquid-like gel state. Various forms of encapsulation and rack mounting are available for installation.

The field evaluation involved assessing the energy savings and DR potential impact on a 4,800 square foot frozen food distribution freezer in SCE territory. The technical approach accounted for variations in ambient conditions throughout the test period. PCM performance was measured by isolating the freezer's system-level energy use.

Each time one of these refrigeration systems cycles off, there are losses associated with the refrigerant being trapped in the lines as system pressures equalize. Also, these systems require a startup runtime while they ramp up to operating capacity. During these ramp times, the equipment efficiency is poor, due to high energy input and low cooling output. Longer compressor runtimes, coupled with fewer operation cycles, lead to higher operational efficiency by limiting the losses associated with these negative efficiency impacts.

The freezer's energy use data, along with key system-level operating parameters (temperatures, cycle timing, etc.), were monitored on a continuous basis throughout the project (please refer to Appendix A for a complete list of points and sensors used in this study). This continuous monitoring provided the greatest accuracy for the targeted performance calculations. In addition, five research questions were established and addressed as part of this study.

1. Energy Efficiency (EE) - is the PCM able to increase EE through improved system operating efficiency (using native or supplemental controls)?

- **Answer: Yes** - the PCM can improve system operating efficiency using both native and supplemental controls.

2. Critical peak load reduction – can PCM be used as a DR strategy to reduce electric loads in cold storage applications during critical peak load conditions?

- **Answer: Yes** – the PCM can be used to reduce electric loads in cold storage applications during critical peak load conditions. The technology can be deployed for load-shape and load-shed DR.

3. Operating costs – can the PCM use its TES properties based on SCE's Time-of-Use (TOU - 4 p.m. - 9 p.m.) rate schedules, and native or supplemental controls, to reduce energy costs?

- **Answer: Yes** - the PCM can reduce energy costs based on SCE's TOU (4 p.m. to 9 p.m.) rate schedules using native and supplemental controls.

4. Required notification times for DR – can cold-storage loads with PCM reduce critical peak loads with day-of notification, or do they require day-ahead notification?

- **Answer: Yes** – cold storage loads with PCM can reduce critical peak loads with day-of or day-ahead notification.

5. Consistency of critical peak load reduction – can cold storage loads with PCM respond to DR event notifications over successive days?

- **Answer: Yes** – cold storage loads with PCM can respond to event notifications over successive days (three or more days in a row).

FIGURE-ES 1: PROJECT RESEARCH QUESTION RESULTS

The following tables summarize the energy savings and DR potential resulting from this study.

TABLE-ES 1: EE ANNUAL ENERGY SAVINGS RESULTS

	Annual Energy Use [kWh]	Annual energy Savings [kWh]	Annual energy Savings [%]
Baseline	294,333	N/A	N/A
PCM with Native Controls	237,539	56,794	19%
PCM with Supplemental Controls[1]	220,570	73,763	31%

Field test results indicate the freezer's annual energy savings potential, with the addition of the PCM, increased by 55,552 kilowatt-hours (kWh) – 19%. The PCM's full functionality, with supplemental controls, increased the annual energy savings potential to 73,763 kWh (31%).

[1] Supplemental control savings are measured from baseline conditions.

TABLE-ES 2: SUMMARY DR LOAD-REDUCTION TESTING (SPACE TEMPERATURE CONTROL STRATEGY)

	MEASURED TEST DEMAND [KW]	MAX SPACE TEMP [°F]	MAX PRODUCT TEMP [°F]	MEASURED TEST DEMAND REDUCTION [KW]
Baseline	16.4	8.8	5.0	n/a
PCM with Native Controls	6.8	6.3	3.9	9.6
PCM with Supplemental Controls	0.9	8.5	6.5	15.5

Field test results indicate the freezer's DR potential, with the PCM added, increased by 9.6 kilowatts (kW). The native controls maintained the freezer cooling systems in a curtailed state for the duration of the DR test events (weekdays from 4 p.m. to 9 p.m.) with the PCM in place[2]. During baseline testing, with no PCM, these same cooling systems cycled on at some point during the test period, limiting the freezer's DR potential. The full functionality of supplemental controls increased the DR potential by an additional 5.9 kW (the additional kW was attributed to evaporator fan cycling, which was not part of the native control system).

TABLE-ES 3: FINANCIAL ANALYSIS RESULTS

	IMPLEMENTATION COST	ANNUAL ELECTRIC COST SAVINGS	SIMPLE PAYBACK (YRS.)
PCM with Native Controls	$36,500	$6,694	5.45
PCM with Supplemental Controls	$52,500	$16,236	3.23

Since there is no Expected Useful Life (EUL) available in the DEER database, an EUL of 20 years was assumed, as presented in the PCM manufacturer literature. Load-shape DR participation significantly reduces summer on-peak demand charges for this customer. This study assumes a highly-responsive load-shape DR profile that does not result in any system failures and removes all normal operational demand charges from the system during summer on-peak periods. This level of return is reasonable, due to the level of response during testing and the response frequency available from this type of customer.

We recommend SCE proceed with adopting PCM technology into its portfolio of load-shed DR products. If customers choose to implement load-shape DR activities, their participation in event-driven load-shed DR programs will be significantly limited, but their return on investment will be greatly improved.

[2] Some additional controls were used: shed start and stop instructions were delivered by the PCM manufacturer's system (rather than requesting manual intervention by site personnel) for the baseline and native control tests. While these test scenarios would have been possible without the controls, using these controls eased the customer burdens associated with participation and repeated testing into the late evening on consecutive days.

ABBREVIATIONS AND ACRONYMS

API	Application Programming Interface
CDD	Cooling Degree Days
CT	Current Transducers
CV(RMSE)	Coefficient of Variation of the Root Mean Squared Error
DEER	Database for Energy Efficient Resources
DR	Demand Response
EE	Energy Efficiency
EP	Emerging Products
ET	Emerging Technology
EUL	Effective Useful Life
IOUs	Investor-Owned Utilities
kW	Kilowatt
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
M&V	Measurement and Verification
NMBE	Normalized Mean Biased Error
PCM	Phase Change Material
R^2	R-squared

SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TES	Thermal Energy Storage
TMY	Typical Meteorological Year Data
TOU	Time of Use
VRE	Variable Renewable Energy

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INTRODUCTION

EE and DR are essential resources for electric grid stability, and more EE and DR solutions are being tested to be included in utility EE and DR programs. The purpose of this study is to evaluate the energy savings and DR potential of passive PCMs in cold storage freezer applications. The investigated measure was a Thermal Energy Storage (TES) system using PCM and intelligent controls for cold storage applications, specifically low-temperature applications (for example, frozen foods). This study was conducted in SCE service territory, at a frozen foods warehouse in Rancho Cucamonga, California.

Several PCMs have been developed, including some consisting of eutectic salts, paraffin wax, and bio-based organic materials. PCMs are proprietary formulas designed and produced so the PCM changes phase (leveraging the material's latent heat value) at a eutectic point matched to the operating temperature of the refrigerated space. As illustrated in Figure 2, the PCM absorbs heat as it transitions from a solid to a liquid-like gel state. The PCM manufacturer's deployment also installs the PCM (represented across the top of the graphic below) in an exposed format of containment cells, much like a heat exchanger, using airflow to absorb heat in the space faster than the packaged food products can.

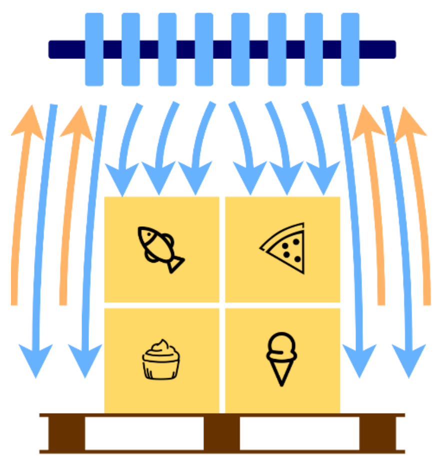

FIGURE 2: PCM OPERATION

Currently, most cold storage applications use conventional refrigeration equipment to maintain space and product temperatures, and use large amounts of energy throughout the day. System operators are reluctant to shut these systems down at any time during the day, due to rising space and product temperatures that occur when the refrigeration equipment is idle for an extended period of time. While other refrigeration system components cycle on and off, evaporator fans run continuously to circulate air in the freezer space and maintain a uniform temperature.

During the course of normal business operations, increased heat in the refrigerated space comes from conductive heat gain through the building envelope, air infiltration through doorway openings, and heat transferred from products introduced to the space. Adding PCM increases thermal mass, reducing the rate at which product temperatures rise while the system operates at minimum power by using evaporator fans only (or any other reduced equipment settings).

Refrigerated space EE is improved by minimizing equipment cycling. Each time these systems cycle off, there are losses due to refrigerant trapped in the lines as pressures equalize. These systems also require a startup runtime while they ramp up to operating capacity. During ramp times, equipment efficiency is poor due to high energy input and low cooling output. Longer compressor runtimes, together with fewer operating cycles, result in better efficiency through reducing losses associated with negative efficiency impacts.

For DR, the PCM acts as a thermal battery by absorbing heat energy, so the product stays cold in the freezer – like ice cubes in a cooler – allowing system owners and operators to idle refrigeration compressors during critical peak periods.

SCE's DR programs give their customers the opportunity to actively manage their energy use during critical peak time periods and lower their energy costs. Participating customers can:

- Reduce electricity usage during critical peak demand periods.
- Receive discounted rates, incentives, or bill credits for participation.
- Get personalized consultation to identify solutions that may be best for their businesses.

When customers participate in DR, they do not just save money – they make a difference by reducing energy consumption during peak demand hours. This can relieve stress on the grid, prevent power shortages in their communities, and help preserve the environment.

There is no incumbent technology associated with PCM. The alternative to this product is the existing mechanical cooling equipment serving the freezer. The base case for the analysis in this report assumes the freezer space with no PCM installed.

DR CATEGORIES

To assess DR potential in California, Lawrence Berkeley National Laboratory (LBNL) conducted a series of California Demand Response Potential Studies with two goals: 1) to bridge analysis Distributed Energy Resources (DER) analysis with grid investment and operation; and 2) to clearly communicate study results to power system policymakers and stakeholders who need to synthesize across those domains.[3] In these studies, LBNL defines the four types of DR:

- **Shape** captures DR that reshapes customer load profiles through price response or behavioral campaigns— "load-modifying DR"—with advance notice of months to days.
- **Shift** represents DR that encourages moving energy consumption from times of high demand to times of day when there is a surplus of Variable Renewable Energy (VRE) generation.
- **Shed** describes loads curtailed to provide peak capacity reduction and support the system in emergency or contingency events with a range in advance notice times.
- **Shimmy** involves using loads to dynamically adjust demand on the system to alleviate short-run ramps and disturbances at timescales ranging from seconds up to an hour.

While most legacy DR programs use traditional Shed DR, it is important to evaluate all categories when calculating the site's DR potential in each study phase. In particular, for Phase 3, the DR potential was also evaluated for its Shape DR potential.

3 https://buildings.lbl.gov/potential-studies

BACKGROUND

HISTORY AND CURRENT GOALS

In 2016, a DR study on PCM technology (project ET16SDG1061), sponsored by the ET program for San Diego Gas & Electric (SDG&E), was conducted at a food bank (low-temperature warehouse) in San Diego[4]. This study builds on the findings of the SDG&E report by analyzing differential savings between the PCM and supplemental controls, to determine their individual contributions to measured savings in a refrigerated warehouse setting. The differentiation was accomplished by isolating the energy savings and DR potential associated with the PCM from the contribution of supplemental controls. The PCM and the PCM with supplemental controls were tested separately from each other, and their performances were independently evaluated.

SITE DESCRIPTION

The system was installed at a frozen foods warehouse in Rancho Cucamonga, California (Figure 3). The site houses two low-temperature, cold-storage, independently-isolated freezers (Freezer A and Freezer B). Each has similar use and equipment providing the required cooling capacity for their operation. We chose Freezer B, at 4,800 square feet with approximately 50 available positions (on top of the rack, above product) to install PCM, for the demonstration project. This freezer's allowable operating range is 0°F to +6°F, and normal operating temperature set point is approximately -1°F. (set point is the value in the native control system delivering the desired operating conditions for the site; normal operating temperatures measured in the freezer vary within a limited range from this setting). The freezer is equipped with a manual door opener, triggered by forklift drivers approaching and activating the mechanism (Figure 4). An industrial strip curtain interior door kit provides an additional air barrier forklift drivers can drive through, while allowing minimal air infiltration to the freezer space.

FIGURE 3: FROZEN FOODS WAREHOUSE, RANCHO CUCAMONGA, CA

[4] https://www.etcc-ca.com/reports/phase-change-material-and-controls-study-low-temp-refrigeration-applications

Two refrigeration compressor and evaporator systems serve Freezer B (Figure 5). Each is capable of providing the required cooling capacity to the space. The second system is primarily for redundancy, but also operates parallel to the other system to provide a uniform distribution of space cooling throughout the freezer.

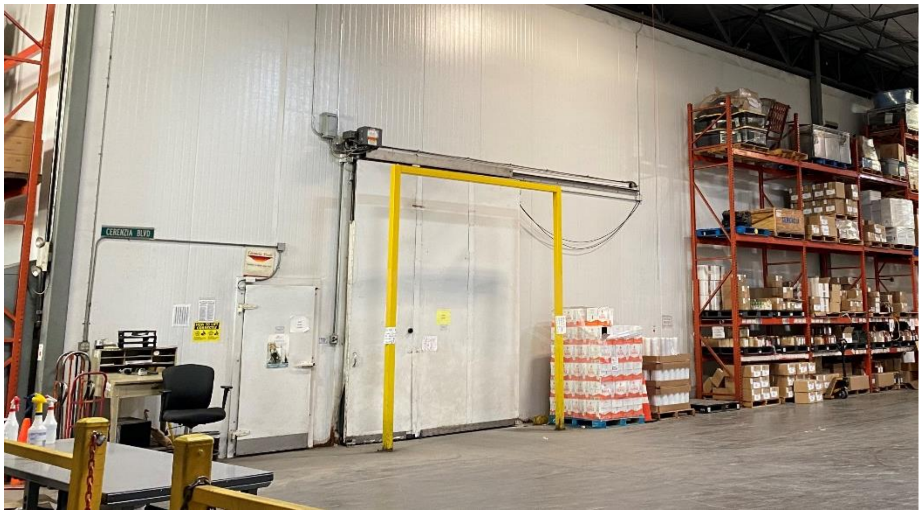

FIGURE 4: FROZEN FOODS WAREHOUSE ENTRY DOOR

FIGURE 5: FROZEN FOODS WAREHOUSE EVAPORATORS

SOLAR ENERGY ARRAY

The warehouse also has a large solar array on the roof, as shown in Figure 6, taken from Google Earth.

FIGURE 6: FROZEN FOODS WAREHOUSE, ROOFTOP SOLAR ARRAY

Solar energy produced at the warehouse offsets much of the facility-level daytime load. Figure 7 presents the typical summer load profile for the utility revenue meter serving the entire site. These 24-hour load profiles demonstrate the load shape apparent to the grid does not represent the customer's actual load shape. In fact, this customer's profiles are fairly flat; they do not vary significantly throughout the day. This grid-apparent load profile has a mid-day trough only because the solar array energy production offsets the grid energy usage. In fact, the solar array overproduces much of the day, between noon and 4 p.m. Overproduction is handled as part of the utility net energy metering agreement.

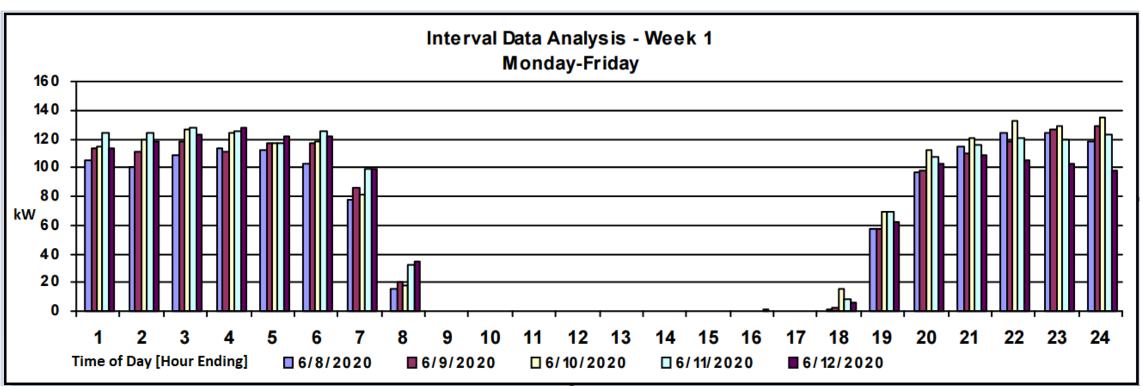

FIGURE 7: FROZEN FOODS WAREHOUSE, TYPICAL SOLAR LOAD PROFILES

While much of the daytime load is offset by the solar array, it does not impact this study data, which is separate from the whole-building utility revenue meter data. Energy and demand data focus on Freezer B, and data was collected using targeted metering on the equipment operating for that section of the frozen foods warehouse only (see Appendix A for a complete list of sensors and locations).

EMERGING TECHNOLOGY/PRODUCT

PCM

The PCM studied for this report is specifically designed for cold storage applications. This type of PCM transitions from solid to liquid at extremely low temperatures, adjustable by its internal chemistry.

The site installation uses a format of wire deck modules to hold the passive cells, filled with a substance with a melting point equivalent to the desired space temperature. The PCM stores or releases latent heat, to help maintain the space temperature setpoint when the mechanical cooling system is curtailed during critical peak times.

To understand PCM application in a cold storage setting, it is necessary to understand the difference between sensible and latent heat. When frozen product temperatures increase and decrease, the quantifiable difference is termed "sensible heat", which can be gauged by a conventional temperature measuring device. Latent heat is the heat energy required to change the material from solid to liquid (phase change). During this transition, the material does not change temperature. After phase change is complete, heat gain becomes "sensible" again (see Figure 8).

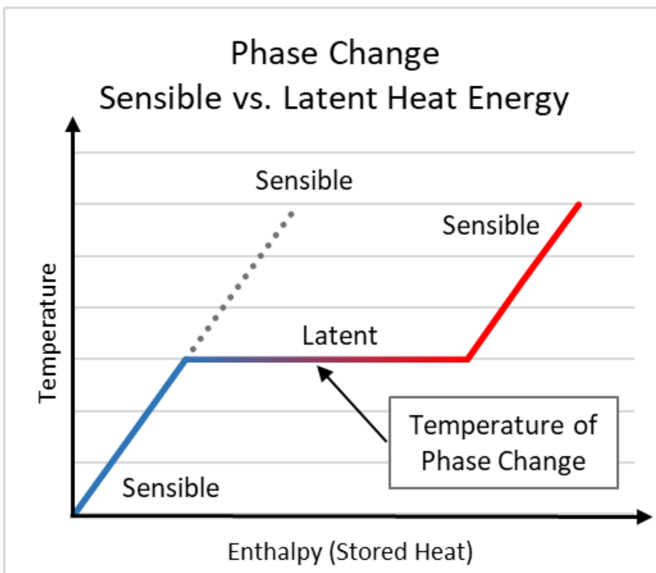

FIGURE 8: PHASE CHANGE DIAGRAM (SENSIBLE VS. LATENT HEAT ENERGY)

Individual PCMs are designed to operate, or phase change, at a specific temperature (eutectic point) or within a limited temperature range. This allows the PCM to have a phase change design point specifically targeted to the control temperature of the space. This design temperature is maintained while the material transitions through the phase change process, and is possible because per unit of PCM mass, more heat transfer capacity is available through latent heat transfer than through sensible transfer.

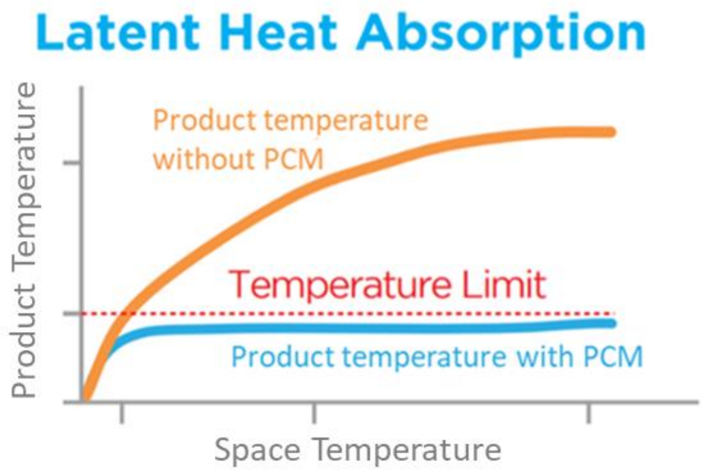

FIGURE 9: PHASE CHANGE DIAGRAM (PRODUCT TEMPERATURE WITH AND WITHOUT PCM); SOURCE: PCM MANUFACTURER

By designing the PCM to change phases in proper relation to the freezer control point, the site can keep the mechanical cooling systems off as space temperatures rise and the material absorbs the thermal energy as latent heat. When PCM capacity is diminished, the systems are turned back on, to resolidify the material and prepare it for its next use.

During the compressor/fan-coil “off” cycle, the PCM provides a passive free-convection effect as it encounters warm rising air, which is cooled and falls back on the product below, and the PCM slowly converts from solid to liquid. During the compressor/fan-coil “on” cycle, the forced convection of cooler air re-charges the PCM back to solid.

During DR periods, the PCM absorbs heat from the surrounding air and stored product, to slow the rate of air and product temperature rise. This heat absorption helps maintain space and product temperatures within acceptable tolerances. The overall impact is a reduction in electrical load while the PCM absorbs heat throughout the DR period.

The PCM manufacturer has a portfolio of products specifically formulated to support each individual application. Operating ranges extend from -25°F to +38°F, and are selected based on the customer’s cooling objectives and operating ranges of the space being controlled. The product selected for this application uses a design melting/freezing point of approximately +4°F, with a latent energy stage of between about +3.5°F to +4.5°F. Using this wide band increases the differential between air and PCM temperature during freezing or melting, maximizing PCM heat transfer.

The PCM manufacturer has a variety of installation mounting formats to address various site-specific installation requirements. For this site, PCM wire deck modules were mounted above the product where available, at the topmost position (under the top pallet) where needed, on idle crossbars of the existing racking system (approximately 20’ above the floor), and in line with the evaporator fan airflow.

FIGURE 10: PCM WIRE DECK MODULES

These PCM modules are designed using micro-encapsulation to increase, the overall surface area and allow for superior, effective heat transfer. The slim wire rack designs include robust hangar systems that allow storage above and below installed modules and do not impact product storage space.

SUPPLEMENTAL CONTROLS

The installation included a supplemental controls package, with monitoring and sensing equipment to support the project objectives, including product temperature sensors, PCM temperature monitoring, a door sensor to detect opening frequency, and Current Transducers (CTs) on equipment such as compressors, condensers, and evaporators, to determine unit power. In addition, the package interfaced with existing (native) controls equipment. The controls and sensing portion of the package were integrated, but operated independently for the different study phases: 1) baseline with no PCM and native controls; 2) PCM with native controls; and 3) PCM with supplemental controls (see Appendix A for a complete list of sensors and locations).

Native control systems are typically operated using space temperature read using a single sensor at the rear of the evaporator fan. This sensor represents the freezer temperature, since the air circulating back to the evaporator is representative of the air circulating throughout the freezer. Since these evaporator fans are typically continuously operated, readings represent the actual space temperature during compressor operation and when the compressor is non-operational (fan-only operation).

Supplemental control system sensor locations were chosen to provide a reasonable determination of the freezer’s highest impact areas. Space, product, and cell temperature sensors were located away from the evaporator fans in areas of minimal air flow, to detect maximum temperature swings. Additional sensors were placed the near main entry, to capture the effects of door openings on these temperatures.

For load-shape DR applications, the supplemental controls can work on a daily basis, shifting refrigeration load to times when the electricity is less expensive. The PCM then maintains the space temperature during hours when electricity is most expensive.

ASSESSMENT OBJECTIVES

The purpose of this study is to evaluate the energy savings and DR potential of passive PCMs and supplemental controls in cold storage freezer applications. The project addresses the following five research questions:

1. EE

Is the PCM able to increase EE through improved system operating efficiency (using native or supplemental controls)?

2. Critical peak load reduction

Can PCM be used as a DR strategy to reduce electric loads in cold storage applications during critical peak load conditions (using native or supplemental controls)?

3. Operating costs

Can the PCM reduce energy costs using its TES properties based on SCE's TOU (4 p.m. to 9 p.m.) rate schedules (using native or supplemental controls)?

4. Required notification times for DR

Can cold storage loads with PCM reduce critical peak loads with day-of notification, or do they require day-ahead notification?

5. Consistency of critical peak load reduction

Can cold storage loads with PCM respond to DR event notifications over successive days (three or more days in a row)?

FIGURE 11: PROJECT QUESTIONS

TECHNOLOGY/PRODUCT EVALUATION

The studied technology was the PCM and supplemental controls installed in a low-temperature, cold-storage field application. By installing the PCM, the freezer's thermal capacity increased considerably, allowing mechanical cooling energy to be stored as latent heat in the PCM. By implementing a supplemental control system along with the PCM, new energy reduction methods (such as evaporator fan cycling) could be implemented, which may not previously have been possible. Combining the PCM and supplemental controls reduced the risk of product temperatures increasing above the customer's allowable tolerance. It also enabled the freezer to operate compressors during off-peak and shoulder hours, and curtail compressors during critical peak times.

The field assessment was conducted in a single freezer at a frozen foods warehouse in Rancho Cucamonga, California. These characteristics made the site ideal for the project:

- Consistent year-round product throughput
- SCE service territory location
- Interest in reducing operating costs
- Customer willingness to take the risk of allowing refrigeration systems to shut down for extended periods of time
- High-quality equipment maintenance and service history
- Supportive customer site personnel
- Complimentary internal freezer rack design

TECHNICAL APPROACH/TEST METHODOLOGY

Baseline and PCM test conditions were established by recording all temperatures, operating states, demand (in kW), and energy (in kWh) at five-minute recording intervals, continuously through all project phases. DR test events were scheduled to occur during SCE peak periods, between 4 p.m. and 9 p.m. on weekdays, excluding holidays. DR events were controlled through the PCM manufacturer Application Programming Interface (API) which administered test event timing signals, initiating and concluding the scheduled test events.

There were three major test methodology phases in this study:

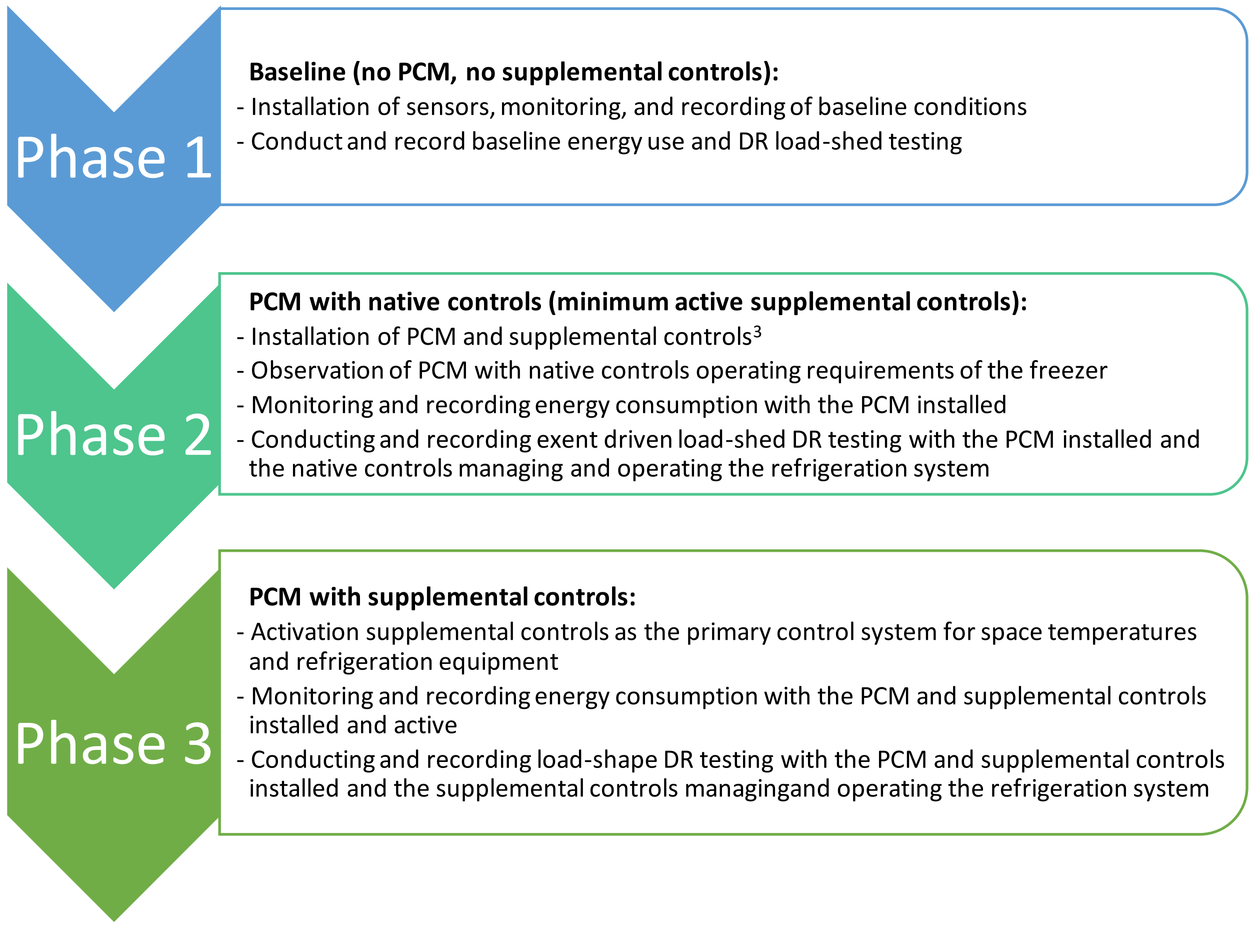

FIGURE 12: TEST METHODOLOGY PHASES

[5] To minimize installation costs, the supplemental controls were installed during this phase of the project. These supplemental controls were used to start and stop the native controls for customer convenience, as they did not have personnel for manual intervention or operation upon a test dispatch event(s). The native controls were exclusively responsible for space temperature and refrigeration equipment control during normal operations.

Phase 1 – Baseline

The baseline data collection phase continued for a six-week period (9/17/2020 through 10/29/2020) following field instrument installation. The initial four weeks (9/17/2020 through 10/18/2020) of this baseline data collection phase was used to establish the facility's typical energy use patterns under normal operations. Preliminary analysis confirmed the initial baseline data accurately represented the facility's typical operations and provided sufficient outside air temperature variation to support developing a baseline annual energy model for the facility. The final two weeks (10/18/2020 through 10/29/2020) of this phase were used for DR load-shed testing (before adding the PCM to Freezer B). During this testing, DR events were initiated to determine the facility's load-shed capabilities prior to installing the PCM. During the first week of DR events, the refrigeration system was operated to maintain the space temperature at below 10°F.

When reviewing the first week of DR test data, researchers noted although the space temperature had risen above the 10°F threshold, which triggered refrigerator system operation, the product temperature sensors indicated much lower readings. Product temperatures did not exceed 5°F during this initial testing. Researchers asked for the controls to be modified to include a space temperature input, to determine the effectiveness of space temperature control on the native system without PCM installed. During the second week of baseline DR testing, the system was operated to maintain the product temperature at below 6°F and space temperature at below 10°F.

Phase 2 – PCM with Native Controls

The PCM was installed in the second phase, along with the supplemental controls (which were not activated during this phase). Measuring the PCM's effect on the space was isolated, to quantify the EE impacts and DR load-reduction potential from the PCM without the supplemental control functionality. During this phase (12/12/2020 through 1/17/2021) the freezer was monitored with the PCM installed and the native controls managing the refrigeration systems. The intended data collection period was modified, due to a maintenance problem that occurred with one of the evaporator units. It was decided that waiting for normal operations to resume with the repaired evaporator was the best course of action.

DR events were initiated during the following two-week period (1/18/2021 through 1/29/2021) to determine the facility's load-shed capabilities with the PCM installed. Similar to Phase 1, the first week used space temperature to control the refrigeration system, and the second week used product temperature. This phase provided the data needed to evaluate the impacts of the PCM without active supplemental controls, and showed its operations aligned with the facility's typical operations. Space temperature setpoint, loading dock temperature (outside the freezer walls), and door operation were consistent with baseline conditions throughout this second study phase.

Phase 3 – PCM with Supplemental Controls

In Phase 3, the supplemental controls were enabled, and the entire system (PCM and supplemental controls) was evaluated for its EE and load-shape DR potential. No additional evaluation was required to evaluate the impacts of the PCM, so during this data collection phase (2/8/2021 through 4/8/2021), the focus was the load-shape DR potential using the PCM and supplemental controls. The system was curtailed during weekdays of the on-peak period from 4 p.m. to midnight on weekdays, with normal operations on weekends, to simulate a customer implementing a load-shape DR to avoid summer on-peak demand charges. The contractor initiated the extended timeframe of 9 p.m. to midnight to demonstrate PCM capabilities and supplemental controls, and how they could perform beyond the 4 p.m. to 9 p.m. timeframe.

The load-shape DR supplemental control strategy initiated a compressor shutdown during the on-peak time periods from 4 p.m. to 9 p.m., and extended that shutdown to midnight. These shutdowns continued for eight and a half consecutive weeks (2/8/2021 through 4/8/2021) on weekdays, and added evaporator fan control to minimize evaporator fan operation during these compressor shutdowns. This operational strategy minimized freezer energy consumption during summer on-peak time periods, to avoid the associated time-related demand charges.

Implementing this type of load-shape DR strategy excludes the freezer's loads from taking part in any event-driven DR programs. While there is potential for winter season participation in load-shed DR programs, winter months have minimal value in these annual programs as compared to the summer months.

FIELD TESTING OF TECHNOLOGY

The frozen foods warehouse is open 24 hours a day, and has a medium-sized freezer warehouse of 4,800 square feet and a setpoint temperature of -1°F. Forklifts often enter the freezer throughout the day. The freezer door is equipped with strip curtains, to minimize heat loss when employees enter and exit.

Data loggers were installed, primarily to monitor the refrigeration system energy, space temperature, and product temperature. Loggers recorded data throughout the baseline period, and were left in place during PCM and control system installation and set-up phases.

DATA CHAIN OF CUSTODY

Due to COVID-19 restrictions, minimal site access was allowed. The PCM manufacturer was responsible for installing and calibrating the monitored data collection system, including all sensors. Consulting firm D+R verified installations and downloaded data directly from the vendor's API. The data collection points and locations were specified, and any plans submitted by the vendor were approved. D+R was also responsible for providing secure data through a single-user download user ID and password, which granted direct access to the supplemental control data collection API, where all applicable project data was downloaded directly from the API without transitioning the data through the PCM manufacturer or any other entity. D+R was responsible for downloading the data from the API access point provided by the PCM manufacturer, and developing quality control and verification protocols to screen the data for acceptability and use in the analysis and delivery for SCE. D+R was also responsible for analyzing, archiving, and reporting the data.

QUALITY ASSURANCE

Quality assurance procedures were used for the baseline and post-implementation Measurement and Verification (M&V) data collection. Procedures included inspecting the data at regular intervals, to ensure measured values fell within expected parameters. Quality assurance work was conducted by D+R staff engineers and reviewed by senior engineers.

EVALUATION PERIODS

Evaluation periods were independently determined for the three phases – baseline, PCM with native controls, and PCM with supplemental controls – as each occurred. The length of each period was determined based on data viability; the data had to provide sufficient independent evaluation characteristics for each phase, along with sufficient regression characteristics correlating the phases together. Correlation data from each phase was sufficient to support projecting each phase to the broad spectrum of events that occur during a typical DR season. The periods coincided with data collection periods, which were adjusted for anomalies due to equipment breakdowns and seasonal events such as holidays.

CALCULATION METHODOLOGY AND ANALYSIS PROCEDURE

Having established that each phase could be normalized to a typical DR season, the key metric for consideration was measured test demand, which is defined as load (demand in kW) that remains operational during a DR test event. This load is either unavailable for curtailment using existing controls, or management deems it critical to operations. In either case, measured test demand remains operational during DR load-shed testing, and defines the customer's minimum load threshold during load-shed testing scenarios.

TEST METHODOLOGY

This M&V project leveraged the Retrofit Isolation option (Option B) of the International Performance Measurement & Verification Protocol (IPMVP). This option best fit the project due to the following facts:

- Performance reporting was not at facility level; the performance of specific systems affected by the measure was the only area of concern for this study.
- Other systems at the facility (office systems, forklifts, battery chargers, other freezers, etc.) outside the purview of the study were assumed to be unaffected and operate the same during the pre- and post-monitoring periods.
- Interactive effects (if any) with other site systems and facility equipment not under study were assumed to be immaterial.
- The independent variables that affect DR and associated energy use were not complex, or excessively difficult or expensive, to monitor.

To avoid duplicate monitoring data collection equipment, research data was collected by the supplemental control system monitoring data collection system, because that system required many of the same data collection points as the study. Two targeted points not part of the supplemental control system – evaporator temperatures and stratified space temperatures – were added, and were monitored using external data loggers connected to the central data collection system. The energy savings and DR from this measure only affected the equipment monitored in this project (the Freezer B refrigeration systems). Anything beyond the measurement boundary was excluded from the analysis. A complete list of instrumentation and placement diagrams is found in Appendix B, Field Instrumentation.

Temperature and energy measurements were logged during all phases of the study (baseline, PCM with native controls, and PCM with supplemental controls) using energy sensors at the various compressors and fans as well as temperature sensors at various elevations strategically located in the freezer. Product and space temperatures were located at mid-height and top-of-rack elevations. Previous studies indicated greater temperature stratification was not required (see Appendix A for a complete list of sensors and locations).

All data was processed to determine if there were any data issues, or recorded data not within guidelines of expectations for specific monitored points. Data from both sources (calibrated kW and temperatures) was used to independently perform all of these actions for each project phase:

1. EE regression analysis
2. DR analysis
3. Product temperature analysis
4. Final report chart and graph development

EE Regression Analysis Procedure

The procedure to determine annual energy use in each of the three phases involved using collected data to define dependent variables influencing energy use in the freezer, then performing a multiple-regression analysis on independent variables. This identified the formula applied to the annual data set and project annual energy use.

Since there was a limited number of days in the data set for each phase, we had to use that limited data set to project it across the entire year using multiple-regression analysis, a technique using several independent variables to predict the state of a dependent variable. Simply put, multiple regression uses the relationship between the independent variables and the dependent variable to predict the relative state of the dependent variable at each corresponding point in time, relative to conditions described by the independent variables. Using the three previously-described independent variables in this multiple-regression analysis provided a good prediction of energy use in each study phase.

Three independent variables were found to primarily influence the freezer's energy use:

1. Outside air temperature – this impacted cooling equipment efficiency and heat load to the cooled space.
2. Door openings – the number of times the door was opened, or the percent of each hour the door was open, was related to infiltration into the space from the dock area, and impacted cooling loads in the space, as well as energy use.
3. Evaporator fan runtime – while this variable is largely constant in the first two phases (baseline and PCM with native controls) the evaporator fan control implemented by the supplemental controls in Phase 3 directly impacted energy use and cooling loads in the space. Cycling the evaporator fans off during on-peak hours reduced runtime and associated energy use.

When using the multiple-regression technique for predictive data analysis, the coefficient of determination (R-squared) is an important statistical metric. R-squared (R^2) is used as a measure of the variation in the independent variables. R^2 values range from zero (0) to one (1) where a value of 0 indicates none of the independent variables are indicators of the dependent variable, and a value of 1 indicates the predicted outcome has no errors. Therefore, these multiple-regression analyses target R^2 values that approach or exceed 0.80, and R^2 values exceeding 0.90 are considered excellent predictors. However, a high R^2 value does not guarantee a regression model should be used, or that it provides an accurate prediction of the dependent variable. Therefore, both the IPMVP and ASHRAE guideline 14 define the acceptable level of savings uncertainty. The defined method is most commonly described as "goodness of fit" [6] and describes the model's usefulness and validity using metrics that include (but are not limited to) R^2.

FACILITY OPERATING CONDITIONS

The freezer space temperature setpoint remained the same throughout the project. The customer was asked to shift electric defrost time schedules (which occurred every six hours for 30 minutes) to ensure they did not occur during the DR timeframe of 4 p.m. to 9 p.m. The number of door openings was also consistent during baseline and each testing phase.

TABLE 4: SUMMARY DR LOAD-REDUCTION TESTING (SPACE TEMPERATURE CONTROL STRATEGY)

PROJECT PHASE	DAILY AVERAGE DOOR OPENING [% OPEN]
Baseline	9.0 %
PCM with Native Controls	10.8 %
PCM with Supplemental Controls	9.0 %

Independent variables used to calculate annual cooling energy consumption included door openings, evaporator fan status, and outside air temperature. Summertime temperatures were higher during the baseline data collection phase, whereas fall and winter temperatures were considerably lower during the PCM with native controls and the PCM with supplemental control phases.

The change in outside air temperature directly correlates to the warehouse compressor power consumption. Figure 13 shows the average power used between 4 p.m. and 9 p.m. plotted against the number of Cooling Degree Days[7] (CDD-65) for the same data.

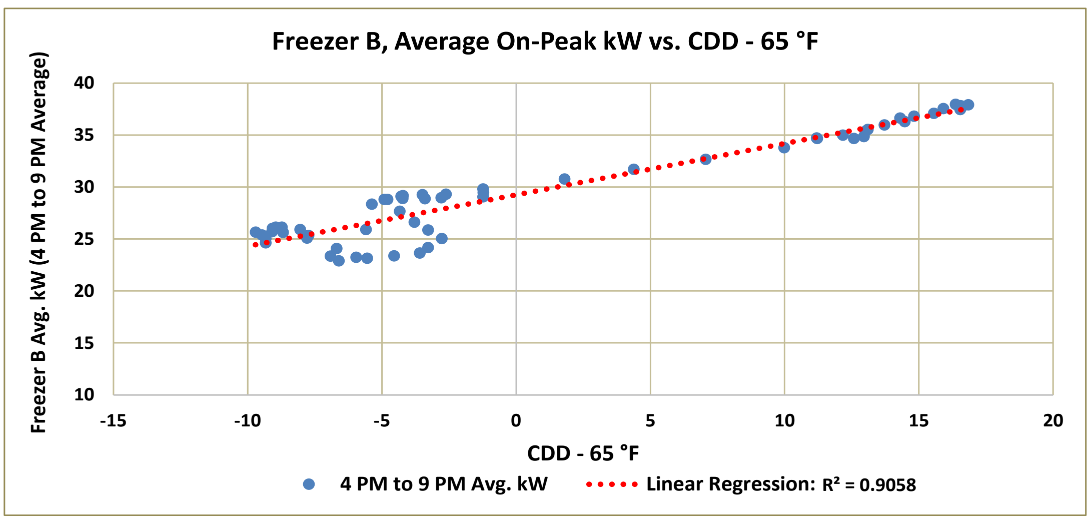

FIGURE 13: FREEZER POWER REGRESSION ANALYSIS

[6] Please see: Site-Level NMEC Technical Guidance, page 15, which can be found at the following link: https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/energy-efficiency/rolling-portfolio-program-guidance

[7] Cooling Degree Days (CDD-65) are calculated as the difference between the average temperature for a given day, and 65°F. If the average temperature is 75°F, the number of CDD-65 is the difference between 75°F and 65°F or 10.

This regression analysis demonstrates that while outside air temperatures varied throughout the testing phases of this project, the impacts on the freezer's cooling equipment was predictable. The results of the off-season testing conducted in the fall and winter can be scaled and compared to the collected summer baseline data.

DR Load-Reduction Analysis Procedure

The "normal operations" baseline analysis provided the DR baseline load profiles used to calculate the DR load-reduction results[8] in subsequent phases of the project (PCM with native controls and PCM with supplemental controls). In cases such as refrigerated warehouse spaces, DR potential is measured as the difference between a typical operational load profile and a minimum operating load profile during a DR load-reduction event.

[8] Please see: Calculating Load Shed from System Test, Section 3.13.1, https://www.sce.com/sites/default/files/inline-files/Auto-DR%20Program%20Handbook%200919_1.pdf

PHASE 1 - BASELINE TESTING

BASELINE (WITHOUT LOAD SHED, NORMAL OPERATIONS)

The freezer's typical energy use patterns were established during the baseline testing phase. These patterns were monitored during a four-week period, to determine if there was sufficient operational consistency to normalize and annualize the results and estimate the freezer's baseline annual energy use. After this period, we determined there was sufficient consistency in the energy use data, as well as adequate variability in the outside air temperature data, to develop a robust baseline energy profile and estimate baseline annual energy consumption.

The following chart represents the baseline data collection period and associated profiles to validate the freezer's baseline energy use profiles[9]. The profiles were produced using a space temperature control strategy to operate the freezer.

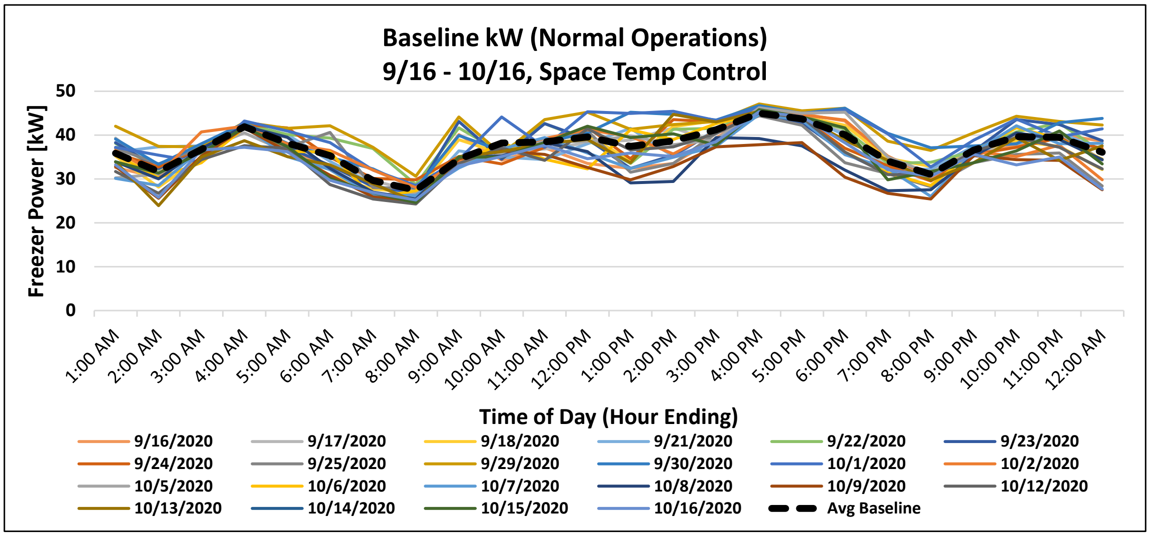

FIGURE 14: BASELINE NORMAL OPERATIONS KW (SPACE TEMPERATURE CONTROL)

Throughout the baseline monitoring period, the refrigeration systems maintained freezer space temperatures, and there was little variation from the space temperature setpoint.

BASELINE MULTIPLE-REGRESSION ANALYSIS

Baseline data was collected during the period from September 17, 2020, to October 18, 2020. These dates included outdoor air temperatures from 57°F to 105°F, with an average temperature of 79°F. This temperature range sufficiently covered 73% of outside air temperatures seen in a typical year for this climate zone. Within this 73% temperature range were 86% of the hours in a year, meaning 86% of annual operating hours could be estimated using data from this 73% temperature coverage range.

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[9] The average kW presented in the chart represents the baseline for DR events at the site, and is developed using PG&E's 10-day baseline morning-of adjustment procedure. (https://www.pge.com/includes/docs/pdfs/mybusiness/energysavingsrebates/demandresponse/10-day_baseline_morning-of_adjustment.pdf)

The independent variables used for the baseline multiple-regression analysis were derived from the three independent variables previously described. For the baseline, the square of the door openings was added, to improve the R^2 value of the result. These independent variables were the analysis inputs:

- Outside air temperature
- Door openings
- Square of door openings (provides more model emphasis on door openings)
- Evaporator fan runtime

Table 5 shows the resulting statistical output (Excel) from the analysis:

TABLE 5: MULTIPLE-REGRESSION STATISTICAL ANALYSIS RESULTS (BASELINE DATA)

Regression Statistics	
Multiple R	0.9653
R Square	0.9317
Adjusted R Square	0.9216
Standard Error	19.0813
Observations	32

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-90.97	208.82	-0.44	6.67E-01
X Variable 1	3.91	0.58	6.74	3.11E-07
X Variable 2	1412.64	102.65	13.76	1.02E-13
X Variable 3	-3135.18	324.67	-9.66	2.99E-10
X Variable 4	600.35	224.69	2.67	1.26E-02

Where:

- X Variable 1 corresponds to average daily outside air temperature
- X Variable 2 corresponds to average daily door openings (% open)
- X Variable 3 corresponds to the square of average daily door openings (% open)
- X Variable 4 corresponds to average daily evaporator fan runtime (% operating)

The R^2 value (labeled "R Square" in Table 5) is a measure of how well the regression line fits the source data. It is a number between 0 and 1 – the closer to 1, the better the fit. A linear relationship between degree days and energy usage is expected, and a high R^2 value is anticipated; the higher the R^2, the better.

Goodness of fit was determined using multiple metrics, the first being Coefficient of Variation of the Root Mean Squared Error, or CV(RMSE), in which the calculated value had to be greater than 25%. The second metric was Normalized Mean Biased Error (NMBE), for which the calculated value had to be between -0.5% and 0.5%. The third metric was R^2, which required the calculated value to be greater than 0.7.

Calculated factors and goodness-of-fit requirements for these variables are shown in Table 6:

TABLE 6: MULTIPLE-REGRESSION GOODNESS OF FIT RESULTS (BASELINE DATA)

Summary of Fitness Metrics		Requirements
CV(RMSE)	2%	< 25%
NMBE	0.00%	-0.5% > NMBE < 0.5%
R^2	0.93	> 0.7

Converting a P-Value to a Relative Precision or Error Bound

When program savings is estimated through regression analysis, a "p-value" is sometimes used to assess the estimate's statistical precision. Most standard regression software packages report the estimate itself, the standard error, a statistic called the "t-value", and the p-value. If the p-value is less than 0.10, the corresponding estimate is usually regarded as statistically significant at the 90% confidence level. Statistical precision should also be reported as an error bound and relative precision at the 90% level of confidence. The error bound can usually be calculated as 1.645 times the reported standard error. Relative precision can be calculated as the error bound divided by the absolute value of the estimate.

The resulting predictive calculation formula for this multiple regression is as follows:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i4} + \varepsilon$$

Where:

Y_i = daily kWh fit

ß = constants from regression analysis results

X_i = independent variables from regression analysis inputs

ε = residual error for each daily result

Comparing fit results to the original data and adding a trendline (as shown in Figure 15) the quality of the baseline data multiple-regression analysis can be seen:

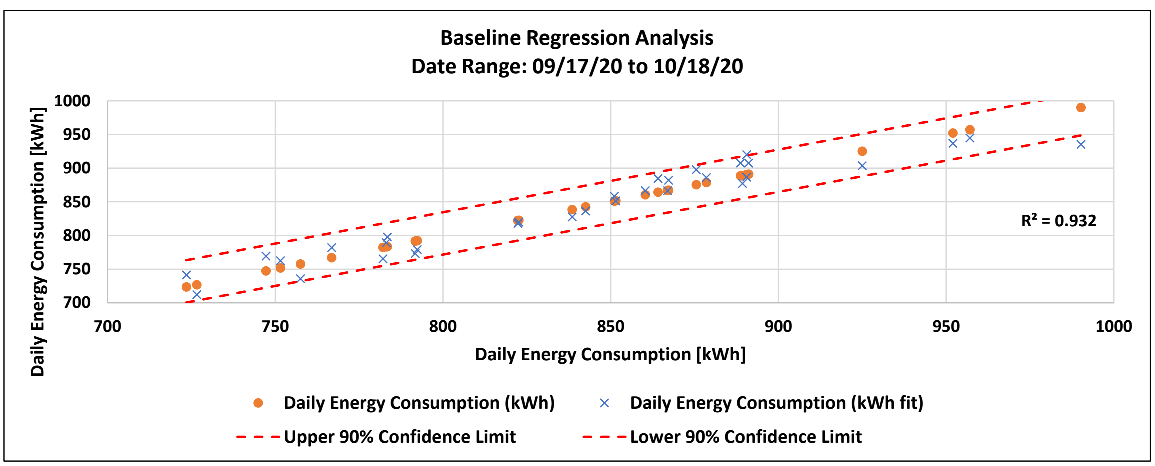


FIGURE 15: BASELINE REGRESSION ANALYSIS (DAILY KWH FIT WITH CONFIDENCE INTERVALS)

Additionally, comparing the two data sets(actual vs. fit) with respect to average outside air temperature shows the fit closely predicts actual values.

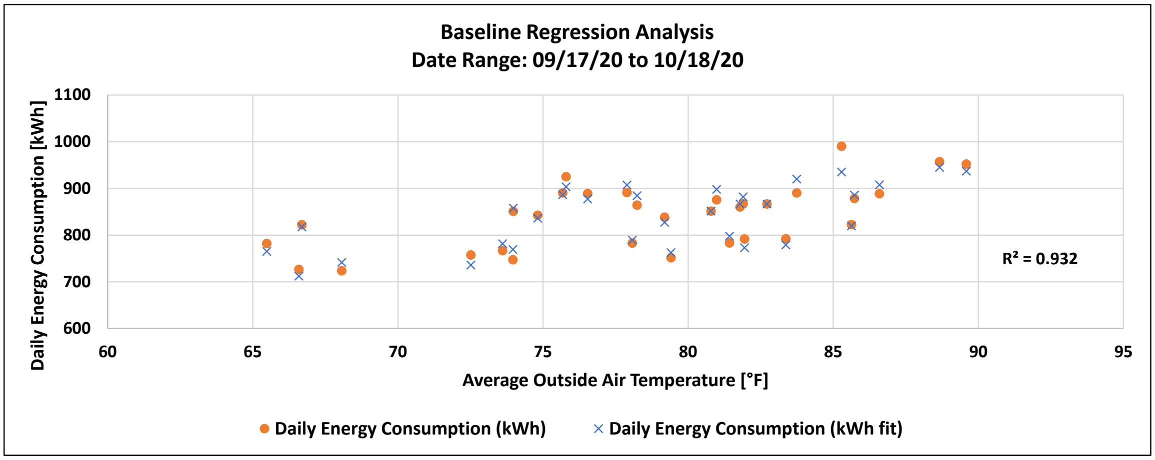


FIGURE 16: BASELINE REGRESSION ANALYSIS (DAILY KWH VS. OUTSIDE AIR TEMPERATURE)

Applying the predictive formula to Typical Meteorological Year (TMY) data for this climate zone provides annual energy consumption for the baseline phase of the study. The values used for the door openings were held constant, at the average of the values found in all data sets. The values used for the evaporator fan run time were held constant at the average of the values found for the baseline and PCM with native control data sets. Evaporator fan control was part of the supplemental control phase implemented strategy and, as such, excludes Phase 3 evaporator fan control data from being averaged into these results. The applicable constant values were:

- Average door openings (% open) = 9.4%
- Average evaporator fan runtime = 90.2%

BASELINE (WITH LOAD-SHED EVENT)

To establish the load-shed test event performance difference among phases, it was necessary to examine the measured load-shed event test demand during the scenarios in each test phase. In the baseline phase, the site was tested to determine DR load reductions using the native control strategy without PCM. The baseline control strategy used space temperature to control the mechanical cooling equipment. If any of the space temperature sensors registered readings above 10°F, that sensor's mechanical cooling system would be started, regardless of DR event status. Figure 17 shows the five DR test days corresponding to the baseline phase using the space temperature control strategy.

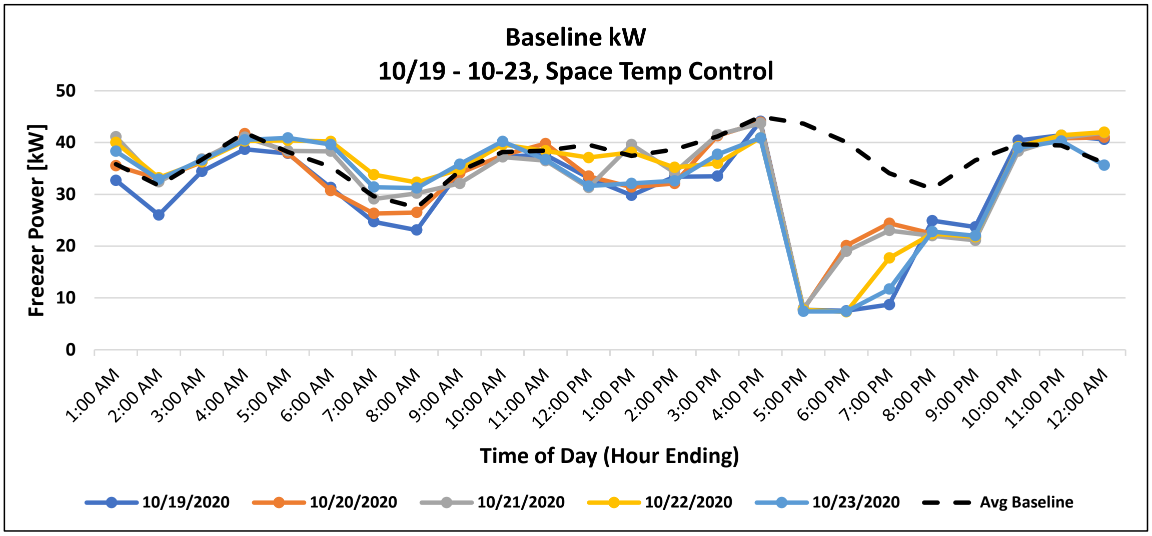


FIGURE 17: BASELINE LOAD-SHED TEST EVENT KW (SPACE TEMPERATURE CONTROL)

During the baseline DR load-shed test events, using the native space temperature control, the average measured test demand was 16.4 kW.

While the space temperature had reached the activation threshold temperature of 10°F for one of the mechanical cooling systems, product temperatures remained within acceptable tolerances. Figure 18 shows the product temperatures corresponding to the baseline, space temperature, load-shed test events presented in Figure 17.

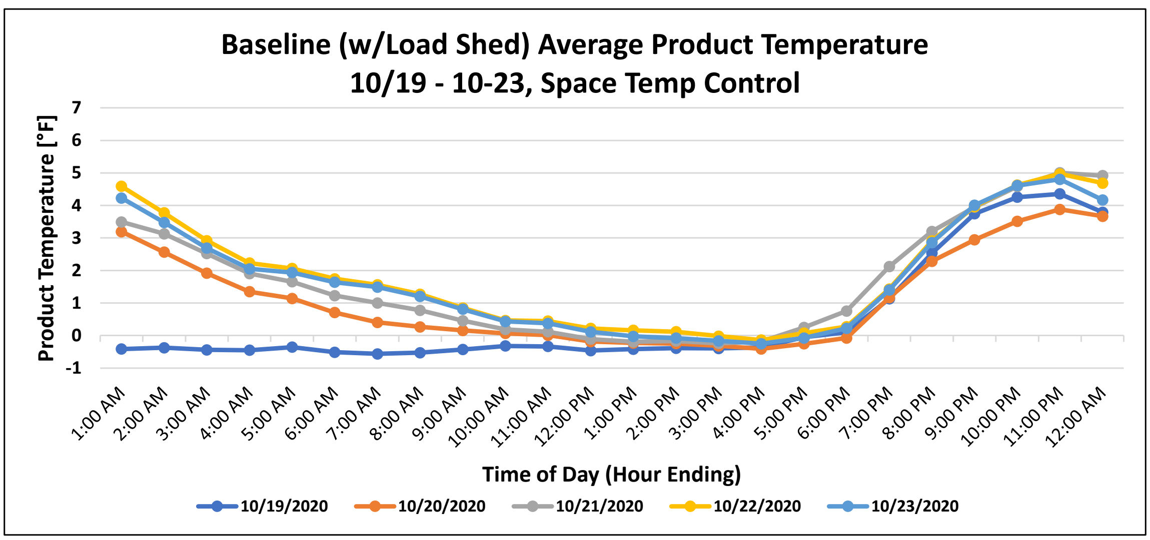


FIGURE 18: BASELINE LOAD-SHED TEST EVENT PRODUCT TEMPERATURE (SPACE TEMPERATURE CONTROL)

While mechanical cooling system activation kept the product temperatures low during the second half of these events, data indicated the product temperatures were well within the safe range (below 10°F) for frozen meats. For products with vitamin content, temperatures above 0°F can lead to accelerated vitamin depreciation[10]; however, in this case, the product

[10] https://blog.liebherr.com/appliances/us/what-makes-0f-the-ideal-freezer-temperature/

types are not subject to these concerns. Trends prior to mechanical cooling system activation indicated product temperatures were not in danger of rising to levels that might compromise product quality or longevity. Management targets a maximum product temperature of 8°F in this freezer, to ensure adequate safety margins against product thaw.

A week after the space temperature-controlled events and subsequent data review, at the recommendation of D+R, we conducted additional baseline testing using product temperatures as the cooling system control instead of the standard space temperature-control strategy, to implement a product temperature control strategy. Using the product temperature sensors installed as part of the study instrumentation package, the strategy was implemented for five consecutive days. Figure 19 presents the five DR test days corresponding to the baseline phase using the product temperature control strategy overlaid with the five days that correspond to the space temperature control strategy.

A product temperature trend is shown in Figure 18, with a lower product temperature during the early morning hours. This was a Monday when ample time was provided for the product temperature to drop and the DR strategy was inactive over the weekend.

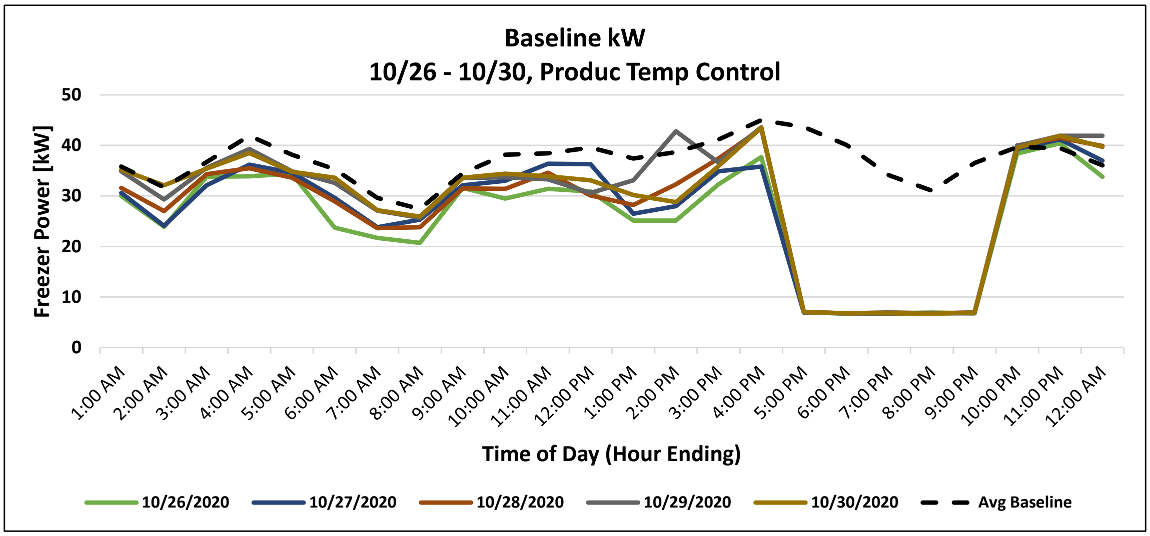


FIGURE 19: BASELINE FREEZER KW DURING DR (SPACE AND PRODUCT TEMPERATURE CONTROL STRATEGIES)

The data shows measured test demand using the product temperature control strategy averaged 6.8 kW. Further examination shows loads operating in support of the warehouse during product control strategy testing were primarily related to evaporator fans, which operate continuously under the native controls. These fans are set to operate continuously, to maintain circulation throughout the freezer regardless of compressor operation and sustain equal product temperature distribution. Figure 20 shows the product temperatures corresponding to the baseline, product temperature, load-shed test events presented as part of Figure 19.

https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/food-safety-basics/freezing-and-food-safety

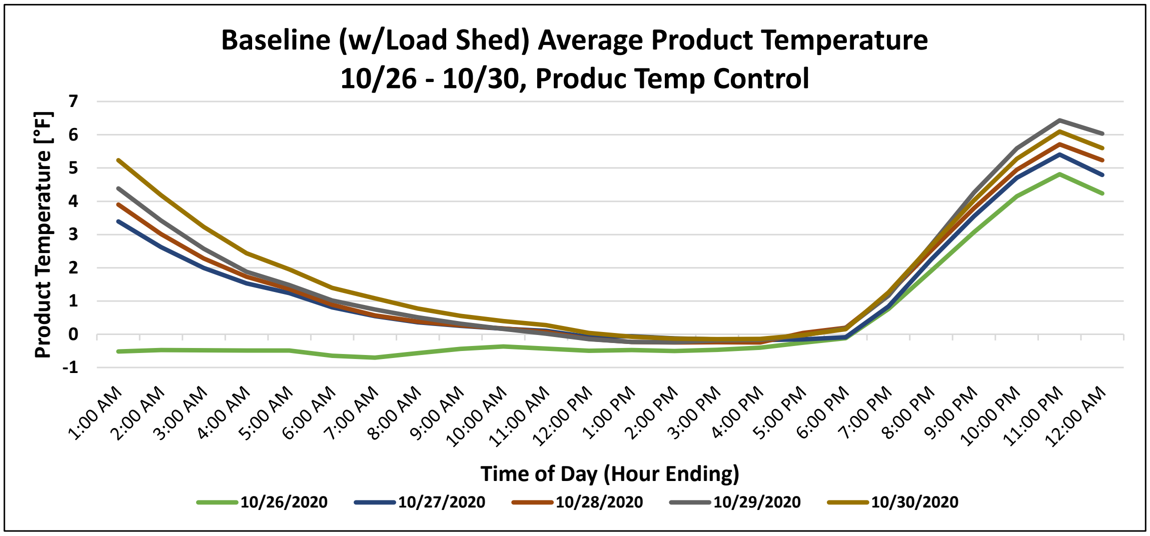


FIGURE 20: BASELINE TEST EVENT PRODUCT TEMPERATURE (PRODUCT TEMPERATURE CONTROL)

This figure shows the average product temperature rose an additional 1.5°F during the test using this control strategy. This additional product temperature rise is within the customer's defined operating thresholds of 0°F to +6°F.

A product temperature trend can be seen in Figure 20, which displays a lower product temperature during the early morning hours. This day corresponded to a Monday, when enough time was provided for product temperature to drop when the DR strategy was inactive during the weekend.

PHASE 2 - PCM WITH NATIVE CONTROLS

The PCM was installed on November 18, 2020, and the freezer was drawn down in temperature to ensure the PCM formed the necessary crystal structures required for freezing. The initial freeze began well below the PCM's normal operating temperature. To initiate this initial freeze ("nucleation") the space temperature was lowered three to four degrees below the PCM's normal freeze point, and held for an extended period of time. Once the initial crystals formed, nucleation began, and the PCM freezing process continued at this reduced temperature until a "hard charge" (completely-solidified) state was reached, at which point the PCM was considered ready for service.

PCM nucleation is only required at installation, and does not need to be repeated as the PCM cycles through usage patterns on DR days or in other more-frequent usage scenarios. Re-nucleation is only required if all ice crystals within a cell are melted in a completely-discharged state.

After installing the PCM in Freezer B, holiday schedules and equipment malfunctions delayed data collection and DR testing. Once these issues were resolved, testing resumed.

PCM with native controls multiple-regression analysis/PCM with native controls-representative data was collected during the period from December 12, 2020, to January 17, 2021. These dates included outdoor air temperatures from 41°F to 88°F, with an average temperature of 58°F. This temperature range provided sufficient coverage for 73% of outside air temperatures seen in a typical year for this climate zone. 85% of the hours in a year were within this 73% range (85% of annual operating hours could be estimated using data contained in this 73% temperature coverage range).

Independent variables used for the PCM with native controls multiple-regression analysis were derived from the three independent variables previously described. For PCM with native controls, as with the baseline data set, the square of the door openings was added, to improve the R^2 value. These independent variables were inputs to the PCM with native controls multiple-regression analysis.

- Outside air temperature
- Door openings
- Square of door openings (provides more model emphasis on door openings)
- Evaporator fan runtime

Table 7 shows the statistical output (Excel) from the multiple-regression analysis for the PCM with native controls data.

TABLE 7: MULTIPLE-REGRESSION STATISTICAL ANALYSIS RESULTS (PCM WITH NATIVE CONTROLS DATA)

Regression Statistics	
Multiple R	0.9453
R Square	0.8937
Adjusted R Square	0.8799
Standard Error	16.6141
Observations	36

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-5175.92	2337.85	-2.21	3.43E-02
X Variable 1	4.92	0.46	10.69	6.36E-12
X Variable 2	545.69	68.67	7.95	5.69E-09
X Variable 3	-453.48	92.56	-4.90	2.86E-05
X Variable 4	6045.95	2579.82	2.34	2.57E-02

Where:

- X Variable 1 corresponds to average daily outside air temperature
- X Variable 2 corresponds to average daily door openings (% open)
- X Variable 3 corresponds to the square of average daily door openings (% open)
- X Variable 4 corresponds to average daily evaporator fan runtime (% operating)

The R^2 value (labeled "R Square" in Table 7) is a measure of how well the regression line fits the source data. It is a number between 0 and 1, and the closer it is to 1, the better the fit. A linear relationship is expected between degree days and energy usage; therefore, a high R^2 value is anticipated – the higher the R^2, the better.

Goodness of fit was determined using multiple metrics. The first is CV(RMSE). The requirement for the CV(RMSE) is for the calculated value to be greater than 25%. The second metric is NMBE. The requirement for the NMBE is for the calculated value to be between -0.5% and 0.5%. The third metric used for evaluating these regression models is R^2. The requirement for R^2 is for the calculated value to be greater than 0.7.

The calculated factors and goodness of fit requirements for these variables is found below.

TABLE 8: MULTIPLE-REGRESSION GOODNESS-OF-FIT RESULTS (PCM WITH NATIVE CONTROLS DATA)

Summary of Fitness Metrics		Requirements
CV(RMSE)	3%	< 25%
NMBE	0.00%	-0.5% > NMBE < 0.5%
R^2	0.89	> 0.7

Comparing the fit results to the original data and adding a trendline in the following chart, the quality of the PCM with native controls data multiple-regression analysis can be seen in this graphical format.

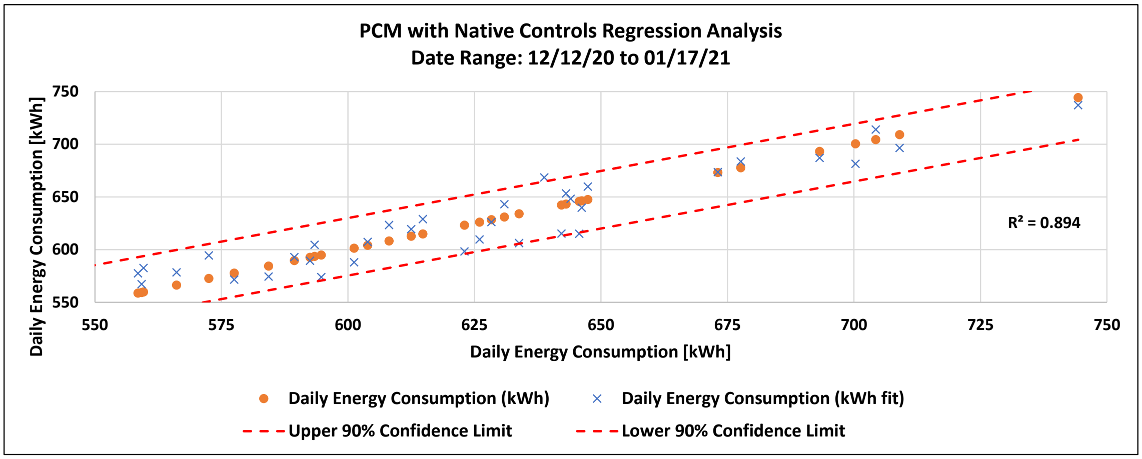


FIGURE 21: PCM WITH NATIVE CONTROLS REGRESSION ANALYSIS (DAILY KWH FIT WITH CONFIDENCE INTERVALS)

Additionally, by comparing the two data sets with respect to average outside air temperature, the fit can be seen to predict actual values closely.

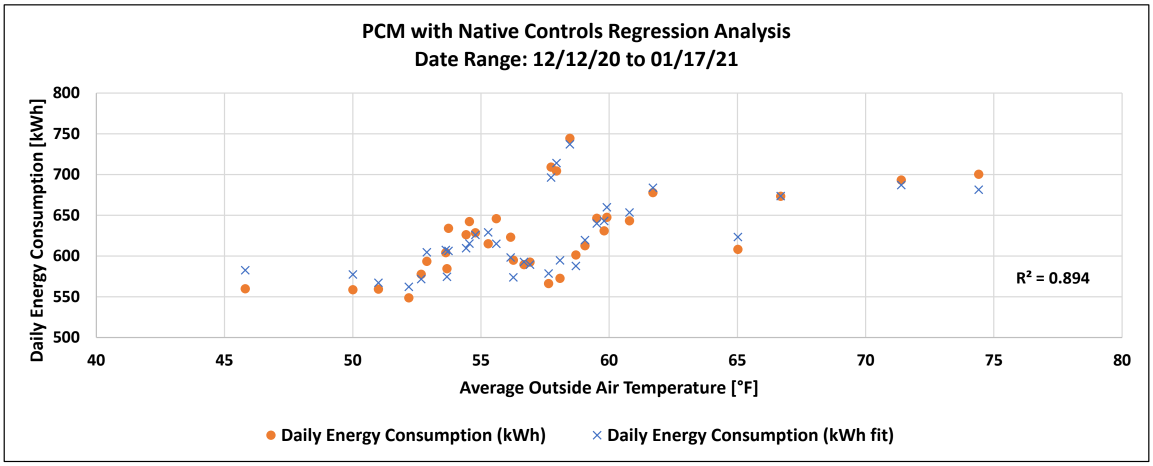


FIGURE 22: PCM WITH NATIVE CONTROLS REGRESSION ANALYSIS (DAILY KWH VS. OUTSIDE AIR TEMPERATURE)

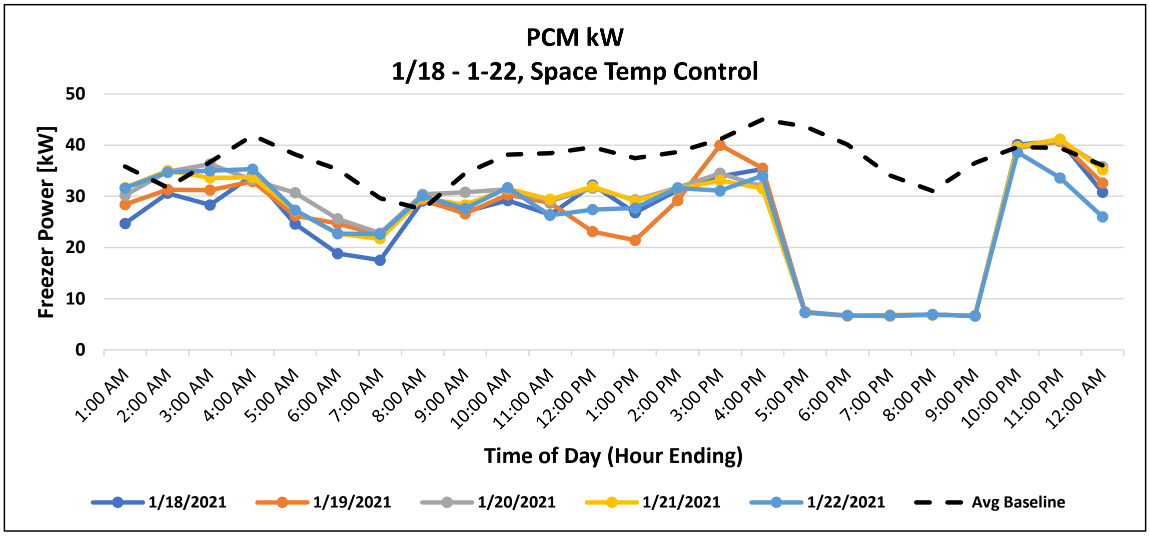
Applying the predictive formula to TMY data for this climate zone provides annual energy consumption for the PCM with native controls phase of the study. The values used for the door openings are held constant at the average of the values found in all data sets. The values used for the evaporator fan run time are held constant at the average of the values found for the baseline and PCM with native control data sets. Evaporator fan control was part of the supplemental control phase implemented strategy and, as such, excludes the Phase 3 evaporator fan control data from being averaged into these results. The applicable constant values are as follows:

- Average door openings (% open) = 10.8%
- Average evaporator fan runtime = 90.5%

DR TESTING (PCM WITH NATIVE CONTROLS)

PCM with native controls scenario events were initiated following PCM ready-state confirmation. As with the baseline testing phase, five consecutive days of testing were initiated using each of the control strategies (space temperature control and product temperature control). However, during the PCM with native controls testing phase, there was no appreciable difference in the measured test demand during the individual test events. During all test events, freezer power was reduced to minimum levels, only operating evaporator fans.

The following chart presents the frozen foods warehouse power during the ten DR test days that correspond to the PCM with native controls phase: five days using the space temperature control strategy and five days using the product temperature control strategy.



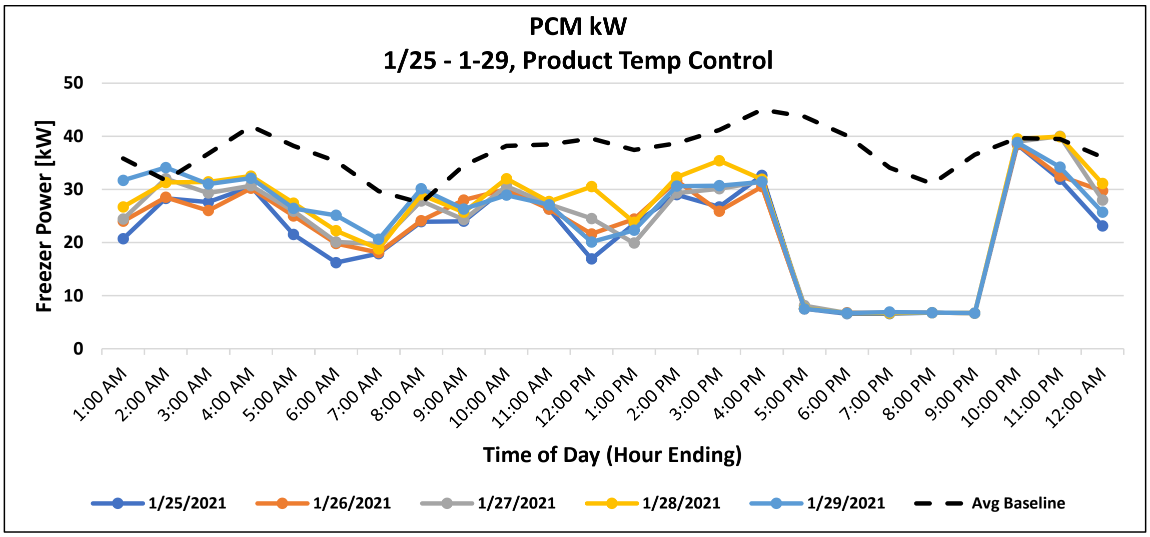


FIGURE 23: PCM WITH NATIVE CONTROLS FREEZER KW DURING DR (SPACE AND PRODUCT TEMPERATURE CONTROL STRATEGIES)

The PCM with native controls testing data shows measured test demand using the space and product temperature control strategies were effectively the same. The measured test demand while implementing the space temperature control strategy averaged 6.8 kW, and the measured test demand while implementing the product temperature control strategy averaged 6.9 kW. As with the baseline testing associated with the product temperature control strategy (average measured test demand = 6.8 kW) the only significant operating loads during these two testing strategies were the evaporator fans. The following chart presents the product temperatures that correspond to the PCM with native controls load-shed test events presented as part of the figure above.

These events correspond to both space temperature and product temperature control strategies.

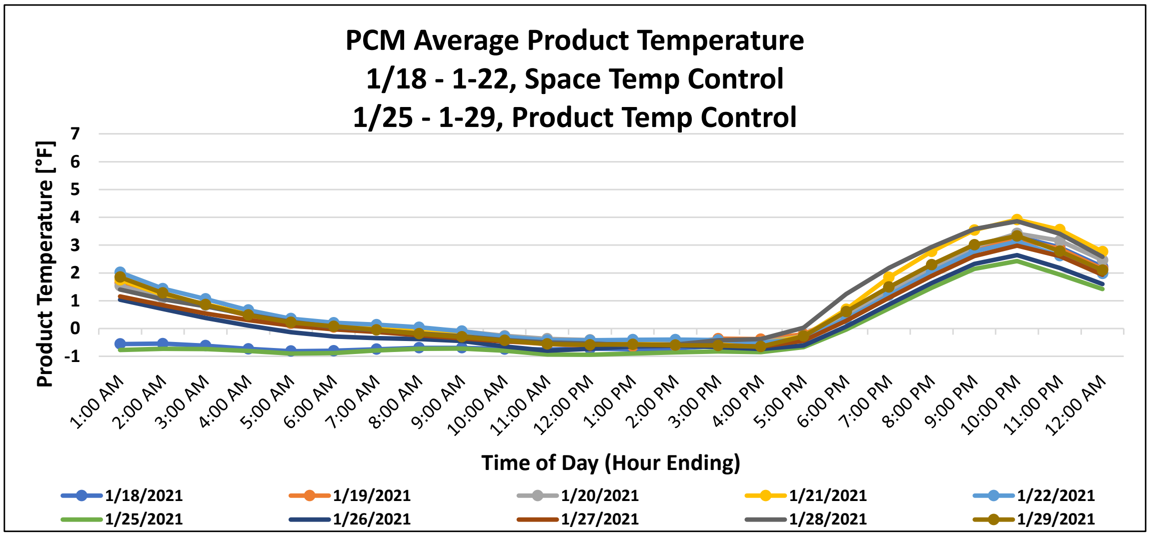


FIGURE 24: PCM WITH NATIVE CONTROLS TEST EVENTS (SPACE AND PRODUCT TEMPERATURE CONTROL STRATEGIES)

The figure above demonstrates that the product temperatures rose similarly during this testing phase, regardless of the control strategy implemented. Minor variations can be attributed to forklift traffic, as indicated by door openings.

Product temperature trends display a lower product temperature during the early morning hours. These days correspond to Mondays, when time was provided for the product temperature to drop while the DR strategy was inactive during weekends.

PHASE 3 - PCM WITH SUPPLEMENTAL CONTROLS

After Freezer B Phase 2 testing was complete, supplemental controls were enabled, and new control strategies initiated. The difference with the supplemental control strategy is threefold. First, the supplemental control strategy added evaporator fan controls to minimize their energy consumption during DR events. Second, the supplemental control strategy continued the DR operation sequence beyond the DR event window. Third, the supplemental control strategy was implemented each weekday, regardless of DR event status.

PCM WITH SUPPLEMENTAL CONTROLS MULTIPLE-REGRESSION ANALYSIS

PCM with native controls representative data was collected during the period from February 8, 2021, to April 8, 2021. These dates included outdoor air temperatures from 37°F to 88°F, with an average temperature of 57°F. This range provided sufficient coverage for 78% of the outside air temperatures seen in a typical year for this climate zone. Contained within this 78% temperature range coverage were 97% of the hours in a year – that is, 97% of the annual operating hours could be estimated using the data contained in this 78% temperature coverage range.

The independent variables used for the PCM with supplemental controls multiple-regression analysis were derived from the three independent variables previously described. In the case of the PCM with supplemental controls, as with the baseline data set, the square of the door openings was added, to improve the R^2 value of the result.

The following independent variables were the inputs to the PCM with native controls multiple-regression analysis:

- Outside air temperature
- Door openings
- Square of door openings (provides more model emphasis on door openings)
- Evaporator fan runtime

The following is the resulting statistical output from the multiple-regression analysis Excel for the PCM with supplemental controls data:

TABLE 9: MULTIPLE-REGRESSION STATISTICAL ANALYSIS RESULTS (PCM WITH SUPPLEMENTAL CONTROLS DATA)

Regression Statistics	
Multiple R	0.8857
R Square	0.7845
Adjusted R Square	0.7685
Standard Error	50.8870
Observations	59

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-76.71	100.19	-0.77	4.47E-01
X Variable 1	3.75	1.16	3.22	2.18E-03
X Variable 2	-1,244.62	684.55	-1.82	7.46E-02
X Variable 3	7,719.67	3,443.78	2.24	2.91E-02
X Variable 4	619.85	102.03	6.08	1.29E-07

Where:

- X Variable 1 corresponds to average daily outside air temperature
- X Variable 2 corresponds to average daily door openings (% open)
- X Variable 3 corresponds to the square of average daily door openings (% open)
- X Variable 4 corresponds to average daily evaporator fan runtime (% operating)

The R^2 value (labeled "R Square" in Table 9) is a measure of how well the regression line fits the source data. It is a number between 0 and 1, and the closer it is to 1, the better the fit. A linear relationship is expected between degree days and energy usage, therefore a high R^2 value (the higher the R^2, the better).

The goodness of fit was determined using multiple metrics: CV(RMSE), required to be greater than 25%; NMBE, required to be between -0.5% and 0.5%; and R^2, required to be greater than 0.7.

Calculated factors and goodness-of-fit requirements for these variables are in Table 10.

TABLE 10: MULTIPLE-REGRESSION GOODNESS OF FIT RESULTS (PCM WITH SUPPLEMENTAL CONTROLS DATA)

Summary of Fitness Metrics		Requirements
CV(RMSE)	10%	< 25%
NMBE	0.00%	-0.5% > NMBE < 0.5%
R^2	0.78	> 0.7

Comparing the fit results to the original data and adding a trendline shows the quality of the PCM with supplemental controls data multiple-regression analysis in a graphical format.

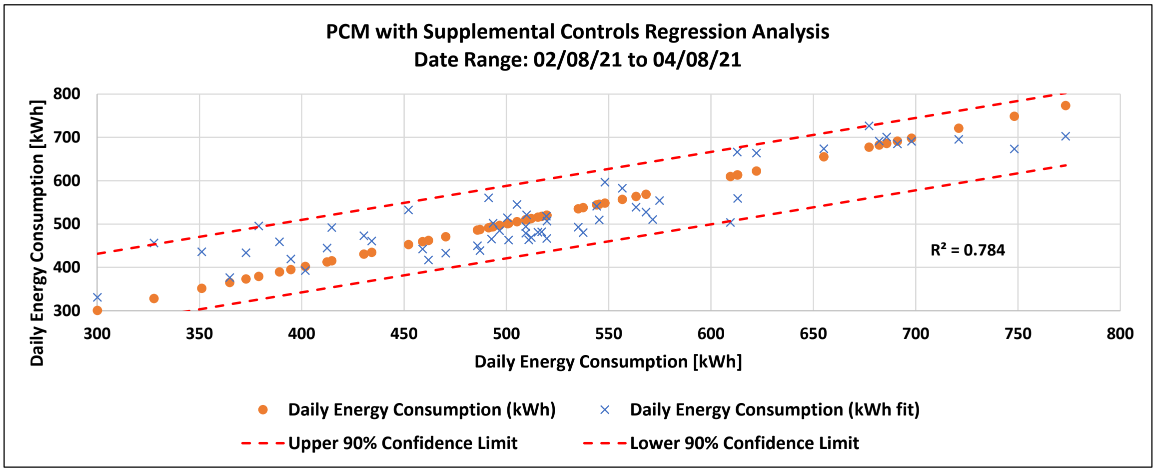


FIGURE 25: PCM W/ SUPPLEMENTAL CONTROLS REGRESSION ANALYSIS (DAILY KWH FIT W/ CONFIDENCE INTERVALS)

Comparing actual vs. fit, with respect to average outside air temperature, shows the fit closely predicted actual values.

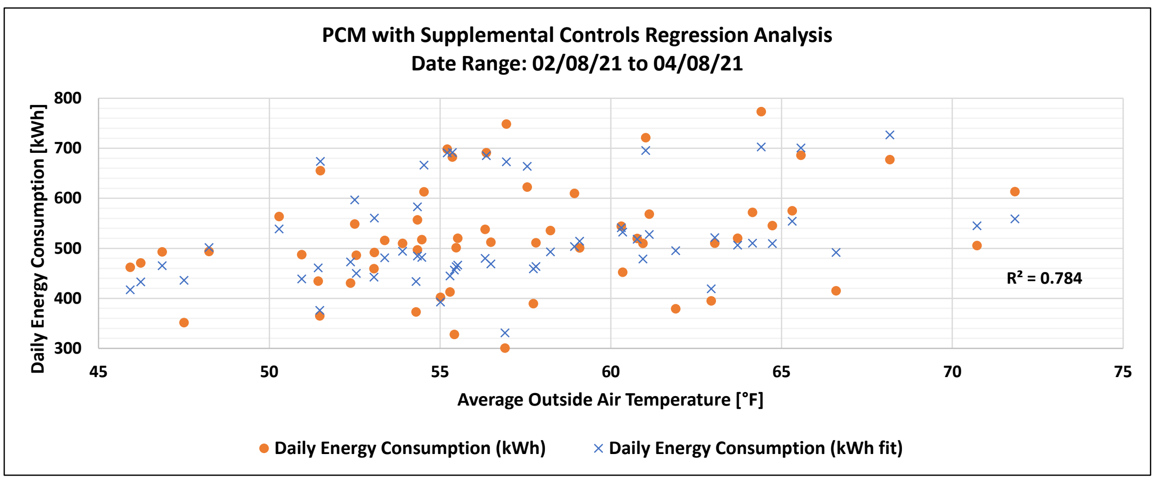


FIGURE 26: PCM WITH SUPPLEMENTAL CONTROLS REGRESSION ANALYSIS (DAILY KWH VS. OUTSIDE AIR TEMPERATURE)

Applying the predictive formula to TMY data for this climate zone provides the annual energy consumption for the PCM with supplemental controls phase. The values used for the door openings are held constant at the average of the values found in all data sets. The values used for the evaporator fan run time are held constant at the average of the values found for this PCM with supplemental control data sets. Evaporator fan control was part of the supplemental control phase implemented strategy, so included averaging only the Phase 3 evaporator fan control data into the results.

Applicable constant values are as follows:

- Average door openings (% open) = 9.0%
- Average evaporator fan runtime = 66.3%

DR TESTING (PCM WITH SUPPLEMENTAL CONTROLS)

As with the baseline and PCM with native controls testing phases, PCM with supplemental control events occurred for five consecutive weekdays.

The following figure presents three consecutive weeks (weekdays only) of the Freezer B power with PCM using the supplemental controls. It can be clearly seen that the PCM with supplemental controls strategy had a significant impact on overall site energy consumption during all hours from 4:00 p.m. through midnight on all weekdays, regardless of DR test event status[11].

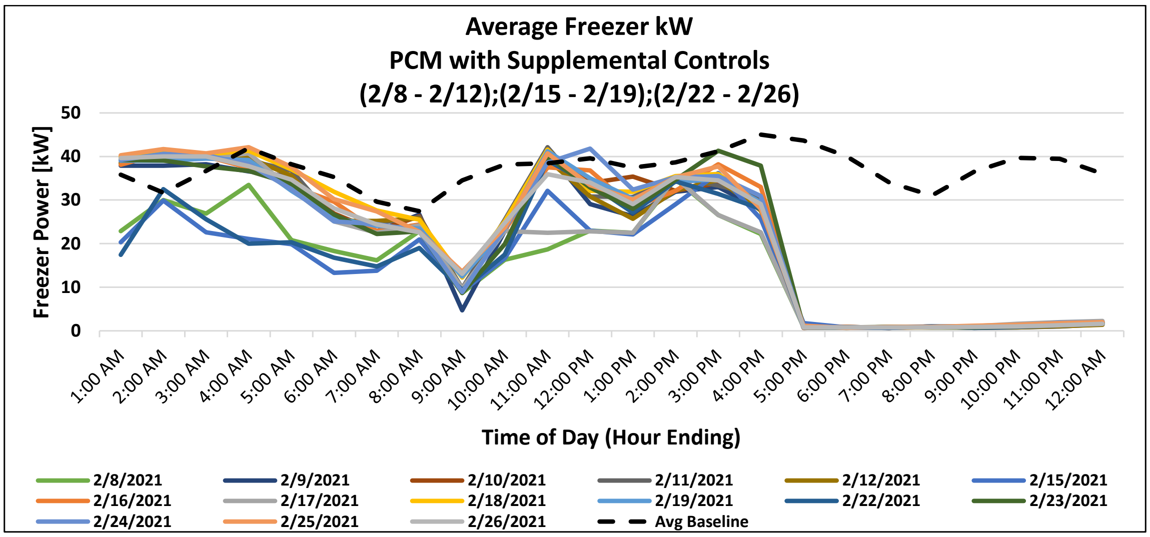


FIGURE 27: PCM WITH SUPPLEMENTAL CONTROLS (WEEKDAY TEMPERATURE CONTROL STRATEGY)

The PCM with supplemental controls test data shows measured test demand was extremely low, averaging 0.9 kW. The only operating loads during the testing strategy were the evaporator fans. Unlike the previous testing scenarios, the supplemental controls cycled the fans to minimize their hourly average kW and still maintain sufficient air circulation to sustain space and product temperatures within acceptable tolerances. The following chart presents product temperatures that correspond to the PCM with supplemental controls load-shed test events shown in the figure above. These events correspond to the continued control strategy implemented on weekdays.

[11] DR programs typically calculate load reductions from baseline conditions. This magnitude of load-shape DR effectively removes the load-shed and load-shift DR potential.

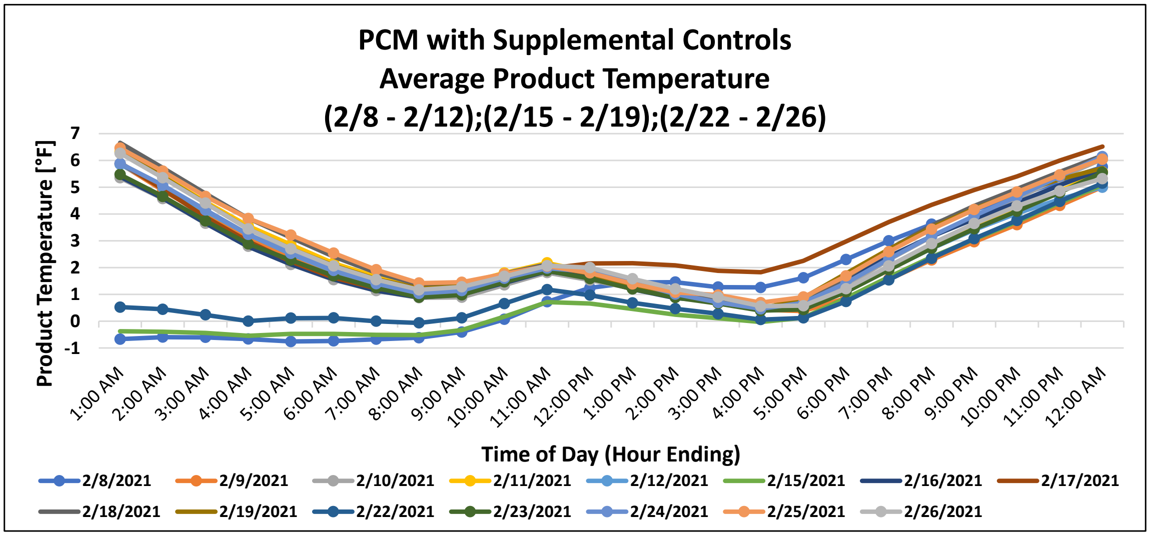


FIGURE 28: PCM WITH SUPPLEMENTAL CONTROLS (DAILY OPERATING STRATEGY, WEEKDAYS ONLY)

While it is clear that these results are significant reductions from normal operations, the fact that these operating scenarios are implemented daily show the repeatability and consistency of the results. DR load reductions are defined as load reductions that can occur on a consistent, repeated basis.

Product temperature trends can be seen in the above chart, and display a lower product temperature during the early morning hours. These days correspond to Mondays, when adequate time was provided for the product temperature to drop when the DR strategy was inactive over the weekend.

RESULTS

The purpose of this project was to explore the EE and DR potential from PCMs for cold storage applications. The following five questions have been answered:

1. EE - is the PCM able to increase EE through improved system operating efficiency (using native or supplemental controls)?

- **Answer: Yes** - the PCM can improve system operating efficiency using both native and supplemental controls.

2. Critical peak load reduction – can PCM be used as a DR strategy to reduce electric loads in cold storage applications during critical peak load conditions?

- **Answer: Yes** – the PCM can be used to reduce electric loads in cold storage applications during critical peak load conditions. The technology can be deployed for load-shape and load-shed DR.

3. Operating costs – can the PCM use its TES properties based on SCE's TOU (4 p.m. to 9 p.m.) rate schedules, and native or supplemental controls, to reduce energy costs?

- **Answer: Yes** - the PCM can reduce energy costs based on SCE's TOU (4 p.m. to 9 p.m.) rate schedules using native and supplemental controls.

4. Required notification times for DR – can cold storage loads with PCM reduce critical peak loads with day-of notification, or do they require day-ahead notification?

- **Answer: Yes** – cold storage loads with PCM can reduce critical peak loads with day-of or day-ahead notification.

5. Consistency of critical peak load reduction – can cold storage loads with PCM respond to DR event notifications over successive days?

- **Answer: Yes** – cold storage loads with PCM can respond to event notifications over successive days (three or more days in a row).

FIGURE 29: PROJECT RESEARCH QUESTION RESULTS

DATA ANALYSIS RESULTS

The results of the EE data analysis demonstrated reduced energy use for Freezer B with the PCM using native controls, and additional energy savings when the supplemental controls were activated. Three data collection periods were isolated for the EE analysis – baseline, PCM with native controls, and PCM with supplemental controls.

Baseline data was collected from September 17 to October 18, 2020. After the standard operation baseline data was collected, DR testing was conducted under baseline conditions. DR test data was removed from the EE analysis, except where it impacts daily operations.

The following energy and demand data represents the projected annual baseline energy use and demand conditions for the freezer under study:

TABLE 11: BASELINE FREEZER B ENERGY (KWH) AND PEAK DEMANDS (KW)

Month	kWh	Facility Peak kW	On/Mid-Peak Max kW (4-9 PM)
1	23,837	55.5	55.5
2	21,677	55.6	55.6
3	24,225	55.9	55.9
4	23,514	56.4	56.4
5	25,235	58.8	58.8
6	25,042	59.8	59.8
7	26,408	61.5	61.5
8	26,585	61.6	61.6
9	25,515	60.9	60.9
10	25,280	58.9	58.9
11	23,151	55.3	55.3
12	23,864	55.3	55.3
Totals	294,333	61.6	61.6

The PCM was installed and operated in conjunction with the native controls, with data collected from December 12, 2020, to January 17, 2021. After this data was evaluated and determined to also represent standard operations, load-shift DR testing was initiated with the PCM installed using native controls.

The energy and demand data in Table 12 represents the projected annual PCM with native controls energy use and demand conditions for the freezer under study.

TABLE 12: PCM WITH NATIVE CONTROLS FREEZER B ENERGY (KWH) AND PEAK DEMANDS (KW)

Month	kWh	Facility Peak kW	On/Mid-Peak Max kW (4-9 PM)
1	18,714	53.4	49.6
2	17,088	53.7	49.9
3	19,202	54.3	50.5
4	18,671	54.9	51.0
5	20,473	58.4	54.3
6	20,594	60.3	56.1
7	21,948	62.6	58.3
8	22,170	63.0	58.6
9	21,189	62.0	57.7
10	20,530	58.6	54.5
11	18,214	53.3	49.6
12	18,748	53.2	49.5
Totals	237,539	63.0	58.6

After PCM with native controls load-shift DR testing, supplemental controls were activated, and additional control strategies were implemented through the supplemental controls. A key strategy was adding an evaporator fan control, which limited fan operation during DR event windows. The final control action initiated by the supplemental control system enabled DR load reduction from 4 p.m. to midnight each weekday, regardless of whether there was a DR event notification. The following energy and demand data represents the projected annual PCM with supplemental controls energy use and demand:

TABLE 13: PCM WITH SUPPLEMENTAL CONTROLS FREEZER B ENERGY (KWH) AND PEAK DEMANDS (KW)

Month	kWh	Facility Peak kW	On/Mid-Peak Max kW (4-9 PM)
1	18,714	53.4	49.6
2	17,088	53.7	49.9
3	19,202	54.3	50.5
4	18,671	54.9	51.0
5	20,473	58.4	54.3
6	16,547	59.1	4.7
7	17,607	59.8	4.8
8	17,777	60.9	4.9
9	17,000	60.7	4.8
10	20,530	58.6	54.5
11	18,214	53.3	49.6
12	18,748	53.2	49.5
Totals	220,570	60.9	54.5

DR actions taken during on-peak times on all summer weekdays were classified as load-shape DR activities, which impact facility EE and DR load profiles. Table 14 shows the EE impacts, and the subsequent section of this document discusses DR impacts.

TABLE 14: EE ANNUAL ENERGY SAVINGS RESULTS

	ANNUAL ENERGY USE [KWH]	ANNUAL ENERGY SAVINGS [KWH]	ANNUAL ENERGY SAVINGS [%]
Baseline	294,333	N/A	N/A
PCM with Native Controls	237,539	56,794	19%
PCM with Supplemental Controls[12]	220,570	73,763	31%

LOAD-SHED DR DATA ANALYSIS RESULTS

SPACE TEMPERATURE CONTROL STRATEGY LOAD-SHED TEST RESULTS

Two separate DR control strategies were evaluated during the DR testing phases. The first was the space temperature control strategy, which curtailed compressor operations during DR test events, as long as the space temperature did not reach 10°F. Space temperature control is widely used in the industry, so it was the primary focus of the initial testing plan. The following figure presents three key results measured during space temperature control strategy testing:

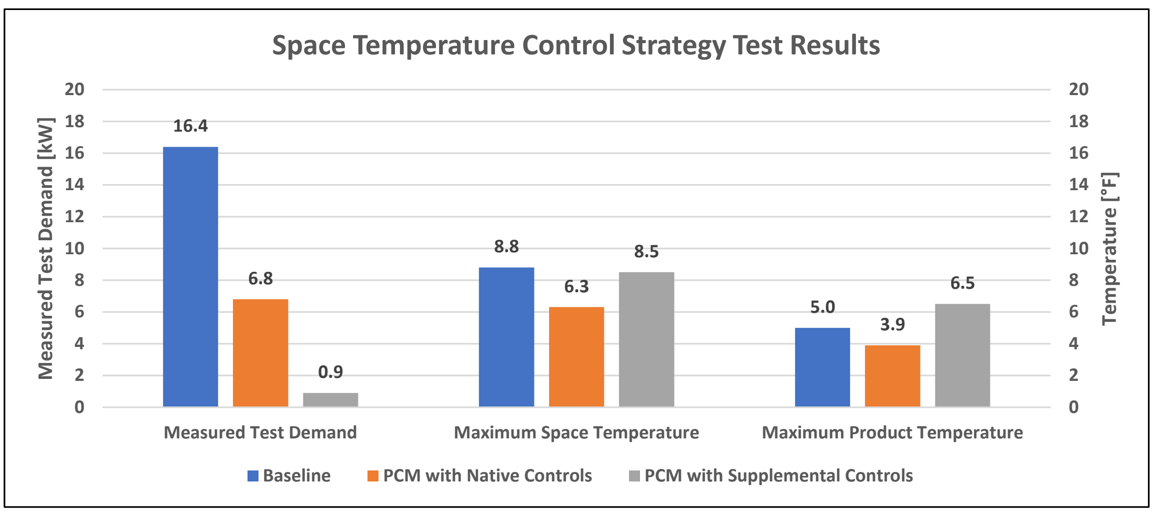


FIGURE 30: SPACE TEMPERATURE CONTROL STRATEGY LOAD-SHED TEST RESULTS

During space temperature control strategy testing, measured demand reductions were attributed to the PCM with native controls. Adding the PCM allowed us to reduce measured test demands by an average of 9.6 kW. When measured test demands were reduced, the

12 Supplemental control savings are in excess of savings from PCM with native controls.

space temperatures were maintained at a maximum of 2.5°F lower than the corresponding baseline space temperatures, and the maximum product temperature was maintained at 1.1°F lower than the corresponding baseline product temperatures. Reducing space and product temperatures during DR test events, without mechanical cooling power, is a direct result of the PCM installation.

Similarly, activating the supplemental control systems reduced measured test demands during load-shed test events by an average of 15.5 kW compared to baseline demands. The additional demand reduction was attributed to evaporator fan cycling, which was not possible using the native control systems. While measured test demands were further reduced using supplemental controls, the maximum space temperature was maintained at 0.3°F lower than the corresponding baseline space temperatures, and the maximum product temperature was maintained at 1.5°F higher than the corresponding baseline product temperatures. The increase in product temperature was attributed to less air circulation. The similarities in space and product temperature differentials between the two phases (PCM with native controls and PCM with supplemental controls) demonstrates temperature was maintained within the customer's defined operating thresholds of 0°F to +6°F.

TABLE 15: SUMMARY DR LOAD-SHED TESTING (SPACE TEMPERATURE CONTROL STRATEGY)

	MEASURED TEST DEMAND [KW]	MAX SPACE TEMP [°F]	MAX PRODUCT TEMP [°F]	MEASURED TEST DEMAND SAVINGS [KW]
Baseline	16.4	8.8	5.0	n/a
PCM with Native Controls	6.8	6.3	3.9	9.6
PCM with Supplemental Controls	0.9	8.5	6.5	15.5

These results show adding PCM allowed the mechanical cooling systems to reduce runtime during DR events, improving load-shed potential by using this control strategy. Supplemental controls also provided additional capabilities for further demand reductions, resulting in maximum DR for the refrigerated space.

PRODUCT TEMPERATURE CONTROL STRATEGY LOAD-SHED TEST RESULTS

Secondary testing was conducted using a product temperature control strategy, which curtailed compressor operations during DR test events, provided the product temperature did not reach the 10°F critical cutoff control setpoint. Figure 31 shows the key measured results:

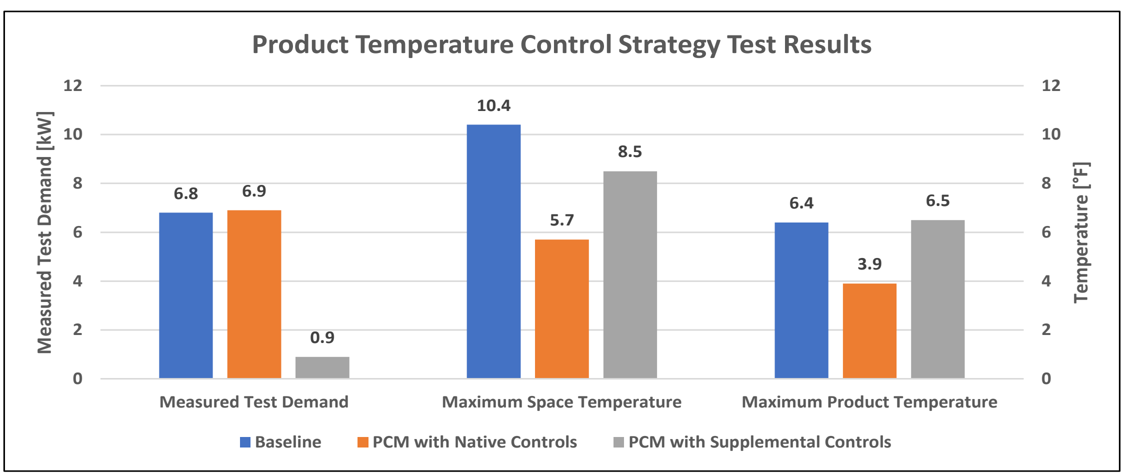


FIGURE 31: PRODUCT TEMPERATURE CONTROL STRATEGY LOAD-SHED TEST RESULTS

When the product control strategy was active, there was no significant difference between measured test demand during baseline test events and PCM with native controls test events. Mechanical cooling systems were not operated in either case, due to the product temperature sensors registering readings below the 10°F threshold during any test event. While the maximum space temperature did reach 10.4°F shortly after the end of one of the baseline test event windows, mechanical cooling was active at the time, and the overrun was brief. Using the product temperature control strategy with PCM, the maximum space temperature was reduced by 4.7°F. There was a corresponding reduction in product temperature associated with this scenario. The maximum product temperature was reduced by 2.5°F.

Activating supplemental control systems reduced measured test demands during the load-shed test events by an average of 5.9 kW compared to baseline demands. The additional demand reduction was attributed to evaporator fan cycling, which did not occur with the native control systems. While measured test demands were further reduced using supplemental controls, the maximum space temperature was maintained at 1.9°F lower than the corresponding baseline space temperatures, and the maximum product temperature was maintained at 0.1°F higher than the corresponding baseline product temperatures. The increase in space temperature was attributed to less air circulation. The similarities in space and product temperature differentials between the two phases remained within the customer's defined operating range.

TABLE 16: SUMMARY DR LOAD-SHED TESTING (PRODUCT TEMPERATURE CONTROL STRATEGY)

	MEASURED TEST DEMAND [KW]	MAX SPACE TEMP [°F]	MAX PRODUCT TEMP [°F]	MEASURED TEST DEMAND SAVINGS [KW]
Baseline	6.8	10.4[13]	6.4	n/a
PCM with Native Controls	6.9	5.7	3.9	-0.1[14]
PCM with Supplemental Controls	0.9	8.5	6.5	5.9

As with the space temperature control strategy, these results demonstrate adding PCM in the freezer allowed the mechanical cooling systems to reduce runtime during DR events and improve load-shed potential. Supplemental controls also provided additional capabilities for further demand reduction, resulting in maximum DR for the refrigerated space.

FINANCIAL ANALYSIS (PCM WITH NATIVE CONTROLS)

Based on pricing provided by the PCM manufacturer, together with projections of potential revenues from DR program participation, the following financial analysis was conducted to determine the cost effectiveness of the PCM with native controls. Since the DEER database has no defined EUL for this material, this analysis assumes a 20-year life expectancy, and literature from the PCM manufacturer indicates a 20-year lifecycle. There is no evidence that a shorter life expectancy should be used.

There is no incumbent technology that would offset the implementation cost or set a code baseline for this technology upgrade. PCM installation costs were determined from the PCM manufacturer's project documentation, as follows:

[13] Maximum reading occurred outside the DR test window (4 PM to 9 PM)

[14] The measured test demand savings for the baseline and PCM with native controls are essentially equal. The difference is due to minor variations in evaporator fan power which is attributed to the amount of ice on the fan coils.

- 121 TES PCM Modules - $22,000
- TES Module Installation - $8,500
- Shipping - $6,000 (estimated PCM shipping fraction)

Financial analysis results of PCM with native controls testing are listed in the table below:

TABLE 17: FINANCIAL ANALYSIS RESULTS (PCM WITH NATIVE CONTROLS)

	Electric Energy Charges	Electric Demand Charges	Total Electric Charges
Baseline	$33,121	$23,416	$56,537
PCM with Native Controls	$27,271	$22,453	$49,724
Annual Electric Cost Savings	$5,850	$ 963	$6,813

	Implementation Cost	Annual Electric Cost Savings	Simple Payback (yrs.)
PCM with Native Controls	$36,500	$6,813	5.36

FINANCIAL ANALYSIS (PCM WITH SUPPLEMENTAL CONTROLS)

Based on the PCM manufacturer's pricing and projections of potential revenues from participation in DR programs, the following financial analysis was conducted to determine the cost effectiveness of the PCM with native controls. Since there is no EUL defined in the DEER database for this material, this analysis assumes a 20-year life expectancy, since literature from the PCM manufacturer indicates a 20-year lifecycle and there is no evidence a shorter life expectancy should be used.

There is no incumbent technology to offset implementation costs or set a code baseline for this technology. We determined PCM installation costs based on the PCM manufacturer's project documentation:

- 121 TES PCM Modules - $22,000
- TES Module Installation - $8,500
- Energy Management and Control Sensors - $10,000
- Energy Management and Control Sensor Installation - $6,000
- Shipping - $6,000 (estimated PCM and controls shipping fraction)

Table 18 provides financial analysis results of PCM with supplemental controls testing:

TABLE 18: FINANCIAL ANALYSIS RESULTS (PCM WITH SUPPLEMENTAL CONTROLS)

	Electric Energy Charges	Electric Demand Charges	Total Electric Costs
Baseline	$33,121	$23,416	$56,537
PCM with Supplemental Controls	$24,975	$15,088	$40,063
Annual Electric Cost Savings	$8,146	$8,328	$16,474

	Implementation Cost	Annual Electric Savings	Simple Payback (yrs.)
PCM with Supplemental Controls	$52,500	$16,474	3.19

DISCUSSION

The space temperature and product temperature control strategy results demonstrate adding PCM in the freezer allowed the mechanical cooling systems to reduce runtime during DR events, thereby reducing energy consumption and improving load-shed DR potential. Adding supplemental controls provided the capacity for reduced evaporator fan operation during load reduction, and presented opportunities for consistent, repeated load reduction to reduce summer on-peak demand charges and increase energy savings.

Adding the PCM gave the owners and operators a significant level of comfort with regard to product safety. Increased thermal mass in the freezer provided a thermal battery effect beyond that of the stored product, and remained in place regardless of the throughput or amount of product present at any given time. This thermal battery acted as a barrier to rising product temperatures and potential product loss.

The supplemental controls provided capabilities for load-shape DR, which resulted in maximum DR potential for the refrigerated space. However, if the freezer were to contain products sensitive to vitamin depreciation, concerns over increased product temperatures during weekday load-shape DR activities would have to be addressed.

CONCLUSIONS

The results of this study demonstrate adding PCM to the freezer reduced its energy consumption by 19%, and supplemental controls and a load-shape DR strategy increased annual energy savings to 31%. Additionally, there are load-shape and load-shed DR potential benefits from the PCM with native controls, and those capabilities are further enhanced by adding supplemental controls. The PCM increased baseline load-shed DR potential by 9.6 kW, and supplemental controls boosted that potential by an additional 5.9 kW, for an increase of 15.5 kW above baseline load-shed DR potential.

Load-shed DR was available for day-ahead or day-of dispatch, since no extended lead time was necessary to prepare the space for events. Steady-state operations were sufficient to maintain participation during test events.

Load-shed test results were not impacted by events on consecutive days – events were conducted repeatedly for successive days, without any measurable effect on results. Each daily test event was followed by a complete recovery using normally-operated standard cooling equipment. Freezer recovery time was not excessive, nor did it require disproportionate runtime to return space, product, and PCM temperatures to normal prior to testing the next day.

Supplemental controls were able to implement load-shape DR for extended time periods, with timeframes for PCM with supplemental controls extended until midnight each weekday. This control strategy minimized compressor and evaporator fan runtimes from 4 p.m. to midnight each weekday as a normal operating control strategy. This load-shape DR can be effective in avoiding high summer on-peak demand charges for customers on rates with TOU demand charges.

The PCM performed as expected, and our results show there are quantifiable benefits associated with installing PCMs and supplemental controls in freezers such as the one we studied at the frozen foods warehouse.

RECOMMENDATIONS

Based on the results of this study, we recommend SCE proceed with adopting PCM technology into its DR product portfolio, because adding PCM in the freezer space increased potential load-shed DR capabilities.

Further investigating the benefits of this technology for frozen food storage customers who are on other SCE rate schedules would provide a road map to help them determine if this technology may be right for them. While current test results show efficiency gains and benefits for these customers, it would be an effective exercise to demonstrate the cost savings potential across multiple customer sizes and business types.

It is possible to leverage this study data into a broader research paper by applying these results to a variety of currently-published rate schedules, to determine financial impacts.

APPENDIX A: INSTRUMENTATION PLAN

INSTRUMENTATION PLAN

For this project, D+R monitored the points discussed in the table below for the different project phases (non-PCM baseline, non-PCM load shed, PCM baseline, PCM load shed, and PCM with controls load shed).

TABLE 19: INSTRUMENTATION DATA POINTS AND DESCRIPTIONS

DATA POINTS	DESCRIPTIONS
CND1 and CND2 Compressors	Combined kW and kWh for both refrigeration unit compressors. These were used to determine the peak load that could be shifted during load shed.
CND1 and CND2 Evaporator Fans and Defrost	Combined kW and kWh for both refrigeration unit fans and defrost in the space. These were also used to determine the peak load that could be shifted during load shed. In addition, if defrost was not used during the first load-shed test event, it could be checked to make sure that it was also not used during the subsequent test events.
CND1 Cooling Runtime	Runtime given in number of seconds out of 300 (5-minute intervals). These were used in conjunction with the power readings to check the status of the systems during the load-shed test events.
CND2 Cooling Runtime	
CND1 Evaporator Fans Runtime	
CND2 Evaporator Fans Runtime	
CND1 Defrost Runtime	
CND2 Defrost Runtime	
Door Status	Amount of time the door to the space was left open. This allowed us to see if any large increases in space temperature were due to increased loading/unloading activity.
Outside Air Temperature	Used to determine the correlation between refrigeration unit power and ambient temperature.
CND1 Product Temperature	When doing the load-shed test events, one week the refrigeration units were controlled based on space temperature, and the next week they were controlled based on product temperature.
CND2 Product Temperature	
CND1 Space Temperature	
CND2 Space Temperature	
CND1 Cell Temperature	Used to verify that the PCM had been fully charged and was operating as it should during the load-shed test events.
CND2 Cell Temperature	
CND1 Evaporator Coil Temperature	These temperatures were another means of checking to make sure defrost was not being used during the load-shed test events.
CND2 Evaporator Coil Temperature	
CND1 Evaporator Return Temperature	
CND2 Evaporator Return Temperature	

The duration set for these points was two to four weeks, based on weather and any issues that arose. Each phase was scoped to be expanded (but not reduced to fewer than two weeks) depending on the weather during the first two weeks of data collection or any abnormal operation.

It was necessary for the data collection periods to encompass a significantly-broad range of data to support a regression analysis that defined the freezer load shape as a function of the dependent variables, of which a primary independent variable was outside air temperature. If there was sufficient variability in outside air temperature during the first two weeks of data collection to define a supporting baseline for this independent variable, it was assumed the remaining independent variables would also support the required regression analysis, as daily operations were understood to be consistent and not seasonal or weather dependent.

If a sufficient range of data was not recorded to represent a meaningful phase analysis, additional time was required until sufficient data was collected to define a reasonable, accurate phase profile. Data was examined routinely, to determine when the next phase could begin.

The following specifies the spot and continuous metering used to gather M&V data:

- WattNode® Revenue Meter
    - Model RWND-M1-MB (option HW. 9.6K, AD=2, CT=100)
    - Accuracy +/- 0.5% (device meets ANSI C12 1-2014 Classes 1.0 and 0.5 and C12 20-2015 Class 0.5 accuracy limits)
    - Calibration conducted by Continental Controls Systems, LLC (03/17/2020)
        - Recommended calibration interval = eight years
- BAPI 3K XP Thermistor
    - Temperature sensors
    - Accuracy +/- 0.1°C (0 to 70°C)
- Data transfers were direct from the control system API, apart from the space temperature outside of the freezer, which was taken from a separate data logger. All data was in five-minute intervals, and the universal translator was used to ensure the timing between the data points was consistent.

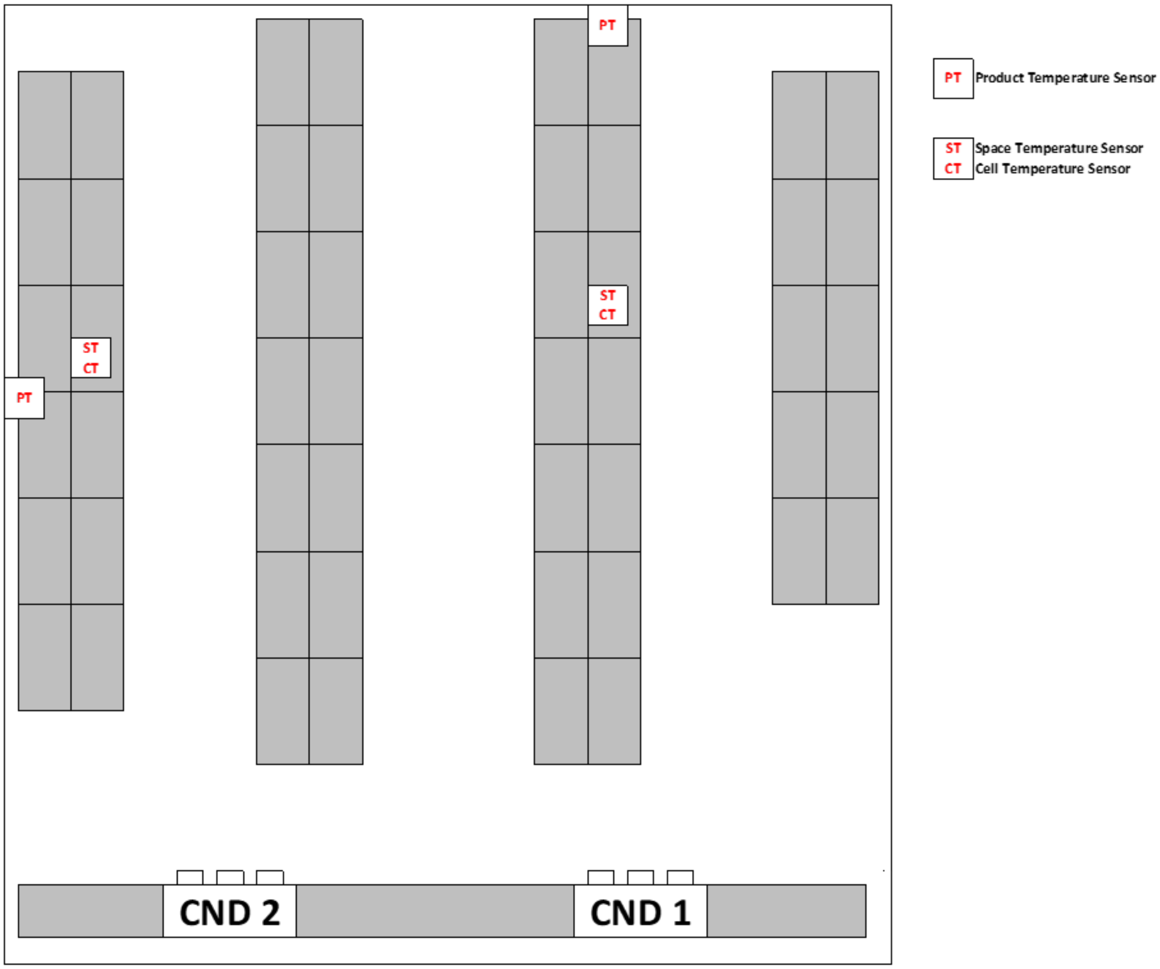


FIGURE 32: FROZEN FOODS FREEZER SENSOR LOCATIONS

TABLE 20: INSTRUMENTATION DATA POINTS, EQUIPMENT, AND ACCURACY

DATA POINTS	EQUIPMENT USED	ACCURACY
CND1 and CND2 Compressors CND1 and CND2 Evaporator Fans and Defrost CND1 Cooling Runtime CND2 Cooling Runtime CND1 Evaporator Fans Runtime CND2 Evaporator Fans Runtime CND1 Defrost Runtime CND2 Defrost Runtime	WattNode Revenue Meter: RWND-M1-MB Opt HW, 9.6K, AD=2, CT=100	±0.5%
Door Status	Magnetic Door Switch	N/A
CND1 Product Temperature	Thermistor: 3K XP (High Accuracy) Sensor in Glycol	±0.1°C
CND2 Product Temperature	Thermistor: 3K XP (High Accuracy) Sensor in Glycol	±0.1°C
CND1 Space Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND2 Space Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND1 Cell Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND2 Cell Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND1 Evaporator Coil Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND2 Evaporator Coil Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND1 Evaporator Return Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C
CND2 Evaporator Return Temperature	Thermistor: 3K XP (High Accuracy) Sensor	±0.1°C

APPENDIX B: SAFETY DATA SHEET

SECTION 2 - Hazards Identification*

Classification of the Substance or Mixture

GHS07

Eye Irritant: 2A H319 Causes serious eye irritation

Label Elements

GHS Label Elements: The product is classified and labeled according to the Globally Harmonized System (GHS)

Hazard Pictograms:

GHS07

Signal Word: Warning

Hazard Statements: Causes serious eye irritation

Precautionary Statements

Eye: If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.

Skin: Liquid can cause skin irritation. Wear gloves and protective clothing if liquid is outside of element.

Ingestion: Liquid can cause gastric disturbances

Inhalation: Temporary discomfort due to inhalation of liquid aerosol.

Chronic (Cancer Info.): No specific dangers known

Teratology: None identified.

Reproduction Info.: None identified.

Target Organs: None identified.

Classification System:

NFPA Ratings (scale 0-4)

Health = 1 Fire = 1 Reactivity = 0

HMIS-Ratings (scale 0-4)

Health = 1 Fire = 1 Reactivity = 0

SECTION 3 – Composition/Information on Ingredients*

Substance Trivial Name Phase change material solution		**Formal Name** Aqueous salt solution	**Chemical Family** Mixture
Component Ammonium Chloride	**Chemical Formula** NH_4Cl	**CAS No.** 12125-02-9	**% by Weight** 5-20%

The specific chemical identity and/or exact percentage of composition of one or more ingredients has been withheld as a trade secret.

SECTION 4 - First Aid Measures

Inhalation: Remove to fresh air. If symptoms persist, seek medical attention.

Ingestion: If swallowed, do not induce vomiting. Rinse mouth with water. Drink plenty of water. Seek medical attention in event of large quantity ingestion.

Eyes: Immediately flush lightly with plenty of water for at least 5 minutes. Remove contact lenses and continue rinsing. If symptoms develop, seek medical attention.

Skin: Wash with soap and water. If symptoms persist, seek medical attention.

Advice to Physicians
Treat symptomatically for lung or eye irritation, if present.

SECTION 5 - Fire Fighting Measures

Extinguishing Media Foam, water spray, dry powder	**Unsuitable Media** Do not use high volume water jet	**Flash Point** >650 °F	**Flash Point Method** ASTM E136
Lower Explosive Limit Not Applicable	**Upper Explosive Limit** Not Applicable	**Ignition in Air** >650 °F	
Flammability Classification Flammable		**Flame Propagation in Air** Not Applicable	
Fire Fighting Procedure Cool surroundings with water to localize the fire zone		**Combustion Hazards** Combustion or thermal decomposition will evolve toxic and irritant vapors.	
Protective Equipment Firefighters should wear positive-pressure, self-contained breathing apparatus (SCBA) and protective firefighting clothing.		**Unusual Fire Hazards** Can melt and burn in a fire. Molten material tends to flow or drip and will propagate fire. Dense Smoke	
Sensitivity to Impact Not Applicable		**Static Discharge Effects**	

	Not Applicable

SECTION 6 - Accidental Release Measures

Personal Precautions
Wear goggles if release creates conditions where eye contact is probable. Use personal protective clothing

Spill Cleanup Measures
Spills may be collected, preferably by vacuum, and placed in suitable container for disposal.

Environmental Precautions
Do not discharge into drains/surface waters/groundwater. This product is regulated by CERCLA.

SECTION 7 - Handling and Storage

Handling & Storage Precautions
Handling: Avoid contact with skin and eyes.

Storage: Product should be stored dry away from alkalis and alkalizing substances. Segregate from nitrites and oxidants. Do not store with sodium nitrate

Hygienic Practices
Avoid eye and skin contact. Wash exposed skin frequently. Good practices should be followed in regard to work clothing.

Special Precautions
Clean up spills promptly.

SECTION 8 - Exposure Controls/Personal Protection

Inhalation Standards
Not applicable

Eye-Face Protection	Skin Protection	Protective Clothing
Safety glasses with side shields or goggles recommended to prevent eye contact.	Chemical resistant gloves	None required.

Respiratory Protection
Approved dust/mist respirator recommended

Engineering Controls
Use general or local exhaust ventilation

Other Protective Measures
Wash exposed skin frequently. Good practices should be followed in regard to work clothing.

SECTION 9 - Physical and Chemical Properties

Physical State Liquid solution in a plastic container	**Color** Black solution in plastic container	**Odor** none
Odor Threshold Not Applicable	**pH** 5-8	**Boiling Point** 100 °C
Evaporation Rate >1 (Butyl acetate=1.0)	**Melting/Freezing Point** -15 to 0 °C	**% Volatile by Volume** 60-95
Solubility in Water Not applicable	**Specific Gravity** 1.02-1.07 g/cm^3	**Vapor Density** 0.694
Vapor Pressure 1 Bar at 100 °C	**Reid Vapor Pressure** Not Applicable	**Water/Oil Distribution** Not Applicable
Viscosity Not Applicable	**Pour Point** Not Applicable	

SECTION 10 - Stability and Reactivity

Chemical Stability Stable	**Conditions to Avoid** Do not overheat	**Incompatible Materials** Nitrites, nitrates, oxidizing materials
Reactivity Reacts with oxidizers and nitrites	**Hazardous Decomposition** Hydrogen chloride, ammonia	**Hazardous Polymerization** None

SECTION 11 - Toxicological Information

Routes of Exposure Ingestion, aerosol inhalation, eye and skin contact.	**Acute Inhalation Effect** No data available	**Acute Ingestion Effect** Of moderate toxicity after single ingestion
Acute Eye Effect May cause irritation.	**Acute Skin Effect** Non-irritant	
Chronic Ingestion Effect None expected.	**Chronic Eye Effect** None expected.	**Chronic Skin Effect** None expected.
Sensitization to Material None expected.	**Medical Conditions Aggravated** None known.	**Synergistic Materials** None expected.
Mutagenicity None known.	**Reproductive Toxicity** None known.	**Teratogenicity** None known.
Carcinogenicity Carcinogenic effects not observed		
LD_{50} for Material >10,000 mg/kg oral, rat (male/female) >15,000 mg/kg dermal, rat (male/female)	**LC_{50} for Material** Toxicological studies have not been conducted.	

SECTION 12 - Ecological Information

Mobility	Persistence/Degradability	Bio-Accumulation
Soluble. Adsorption to solid soil phase is possible	Inorganic product which cannot be eliminated from water by biological purification processes. Can be oxidized to nitrate or reduced to nitrogen by microorganisms	Accumulation in organisms is not expected

Ecotoxicity
Acutely harmful for aquatic organisms. The inhibition of the degradation activity of activated sludge is not anticipated when introduced to biological treatment plants in appropriate low concentrations.

SECTION 13 - Disposal Considerations

Legal Classification
Dispose of in accordance with European and/or USA, federal, state, and local laws and regulations

SECTION 14 - Transport Information*

UN Number	UN Proper Shipping Name	Transport Hazard Class
Not classified	Not classified	Not classified
Packing Group	**Transport in Bulk According to Annex II of MARPOL73/78 and the IBC Code**	**US Rail Regulations**
Not classified	Not hazardous	Not classified

SECTION 15 - Regulatory Information

This material should only be handled by properly trained personnel familiar with its physical and chemical characteristics.

Registration status:
Chemical TSCA, USA released/listed
EPCRA 311/312 (Hazard categories): Acute

CERCLA RQ	CAS Number	Chemical name
5,000 lbs.	12125-02-9	ammonium chloride

Reportable quantity for release: 5,000 lbs. (as NH4Cl), 25,000 lbs. (as PCM solution)

State RTK	CAS Number	Chemical Name
MA, NJ, PA	12125-02-9	ammonium Chloride

NFPA Hazard Codes
Health: 1 Fire: 1 Reactivity: 0 Special:

HMIS III rating
Health: 1 Fire:1 Physical hazard: 0

SECTION 16 - Other Information

Revision Indicator
This is an original version of this format SDS. Revised sections of the SDS will be indicated by an asterisk (*) in front of the section affected.

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