

Phase Change Materials for Building Cooling Applications

Analysis of Energy Performance in a Quick Service Restaurant

ET15SCE1050 Report



Prepared by:

*Emerging Products
Customer Service
Southern California Edison*

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EXECUTIVE SUMMARY

The purpose of this study is to determine the effectiveness of passive phase change materials (PCMs) for controlling room temperatures in buildings and reducing the need for mechanical cooling. The PCM technology is designed to absorb heat during the daytime, and release heat overnight. This function is expected to help reduce the cooling requirements of the facility by mitigating heat gain into the conditioned spaces. This product is becoming more popular in building and refrigeration applications, and this report is necessary to help determine if the technology is resulting in a significant energy savings.

Currently, PCM use in Southern California is limited to a few pilot installations. There is no incumbent technology equivalent to this product installed. By installing the PCM in the attic, heat is expected to be absorbed when the temperature rises above the melting point, preventing it from reaching the occupied space. This, in theory, will require less energy for the Heating, Ventilation, and Air Conditioning (HVAC) system to cool the building in the proposed case as opposed to the base case.

While PCMs are relatively new, the concept of passively storing heat in a building has been around for centuries. Early iterations of passive heat transfer are not very functional in the summer when cooling is required. PCMs however have both heating and cooling applications, and are far more versatile as they can be integrated into the building envelope during new construction or placed in plenum/attic space in retrofit applications. In addition, the PCMs can be designed to an ideal melting/freezing temperature for most applications.

The purpose of this demonstration project is to evaluate the energy saving capabilities of the PCM used in the attic space in a fast food restaurant located in Irvine, California. The technical approach for this field test ensured that any environmental or loading differences between the two cases, baseline and retrofit, be identified and accounted for in order to effectively compare the performance data of the two cases on an equitable basis.

The field test for this study monitored the impact of the PCM on a fast food restaurant's HVAC related electrical load. This location is served by two rooftop package units serving the kitchen (7.5 ton unit) and dining areas (10 ton unit). The store operates from 10:00 AM to 10:30 PM every day of the week, and is typically occupied by employees for an hour or two before and after closing for prep and clean up. The test site is estimated at 2,176 square feet.

Table-ES 1 summarizes the energy savings results obtained in this study. It should be noted that there were no peak demand savings associated with the PCM technology, as the HVAC unit ran at full capacity during both the baseline and post implementation periods when needed.

TABLE-ES 1. SUMMARY OF ANNUAL ENERGY SAVINGS

	HVAC ENERGY BASELINE [kWh]	HVAC ENERGY POST [kWh]	ANNUAL HVAC ENERGY SAVINGS [kWh]	NORMALIZED ANNUAL SAVINGS [kWh/SF]	HVAC ENERGY SAVINGS [%]
Dining Room	48,421	46,981	1,440	1.61	3.0
Kitchen	45,164	44,896	268	0.21	0.6
Totals	93,585	91,877	1,708	0.78	1.8

The technology reduced the cooling loads of the dining room as expected. There was a definite temperature shift within the attic space after the installation of the PCM that caused the space to remain significantly cooler on hot days for a longer period of time than it did without the PCM installed. However, only minimal energy savings were seen at the kitchen HVAC units.

Analysis shows the location may not have been the optimal testing facility for this technology, as the heat loads in the attic space were less significant overall when compared to the heat loads from the excessive windows in the dining room and the internal gains from the kitchen food preparation. PCM placement needs to be strategic in order to optimally leverage the thermal capacity of the material.

The PCM was installed over approximately 60% of the attic space above the ceiling tiles in both the dining room and the kitchen. In order to determine the efficiency of the PCM with respect to the heat load reduction, the PCM properties are referenced and used to calculate the quantity of energy that the PCM is designed to remove from the attic through the phase change process. Table-ES 2

TABLE-ES 2. PCM EFFICIENCY

	SPACE SF	SPACE KWH	INSTALLED ANNUAL PCM-BTU	ANNUAL ENERGY SAVED [BTU]	PCM EFFICIENCY
Dining Room	896	1,440	5,180,314	4,914,720	95%
Kitchen	1,280	268	7,400,448	914,684	12%
Totals	2,176	1,708	12,580,762	5,829,404	46%

The dining room installation delivered the expected energy reduction to the space. The kitchen did not have as much of an impact since there was much internal heat gain from cooking. The kitchen ventilation system may have also limited PCM efficiency in the kitchen. More understanding is needed on how infiltration, internal heat gains and exhaust hoods impact PCM efficiency.

Based on the results of this assessment, the product can be recommended for customized utility energy efficiency programs. The PCM demonstrated that it was able to affect the overall space temperature of the attic area and reduce energy consumption for the dining room. However, since there was no significant reduction in the kitchen area, future installations are cautioned to consider their applications, the internal gains as well as how those internal gains will work in conjunction with PCM.

ABBREVIATIONS AND ACRONYMS

BTU	British Thermal Unit
BTU/lb	British Thermal Unit per pound
CDD	Cooling Degree Day
CDDO	Cooling Degree Day Open
ECM	Energy Conservation Measure
EE	Energy Efficiency
HDD	Heating Degree Day
HVAC	Heating, Ventilation, and Air Conditioning
kW	Kilowatt (Demand)
kWh	Kilowatt Hour (Energy)
PCM	Phase Change Material
RMS	Root-mean-square
SCE	Southern California Edison

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INTRODUCTION

The purpose of this study is to determine the effectiveness of phase change materials (PCMs) for alleviating the need for mechanical cooling through the use of latent heat storage. The PCM technology is designed to absorb heat during the daytime, and release heat overnight when ambient temperatures drop. This function is expected to help reduce the cooling demand for the facility by mitigating heat gain into the conditioned building spaces. This product is becoming more popular in building, refrigeration, and thermal energy storage applications. This report is necessary to help determine if the technology is resulting in significant energy savings.

SCE contracted an engineering firm to conduct a measurement and verification analysis for PCM in order to determine if the technology is viable for adoption in future utility incentive programs. The PCM vendor selected a typical fast food restaurant building in Irvine, California as the test facility for this analysis (located in California Climate Zone 8). The PCM was installed above the drop ceiling of the restaurant in both the dining and kitchen areas.

Currently, PCM use in Southern California is limited to few installations. It is anticipated that the initial markets prime for PCM installations are those with diurnal swing characteristics that will aid in passively charging and recharging materials. There is no incumbent technology equivalent to this product installed. The alternative to this product is not having any PCMs installed in the walls or ceiling. The base case for the analysis in this report assumes a regular building with no heat transfer material in the attic area. By installing the PCM in the attic, heat is expected to be absorbed when the temperature rises above the melting point, preventing it from reaching the occupied space. This, in theory, will require less energy for the Heating, Ventilation, and Air Conditioning (HVAC) system to cool the building in the proposed case as opposed to the base case.

BACKGROUND

HISTORY

While PCMs are relatively new, the concept of passively storing heat in a building has been around since the 1800s¹. One of the earliest iterations of this technology is referred to as a Trombe wall. The Trombe wall is a wall that has an external layer of glass and a high heat capacity internal layer separated by a layer of air. Heat from the sun penetrates the glass in the form of ultraviolet radiation and is absorbed the internal layer of the wall. The heat is then re-emitted from the wall as infra-red radiation, which does not pass back through the glass layer as easily and becomes trapped. Upper and lower vents are located in the internal wall layer to allow the air between the wall and glass to flow into the building space. This technology was first created in 1881 by Edward Morse, and was fully developed by Felix Trombe in 1964. The main drawback of the Trombe wall is that it is not very functional in the summer when cooling is required. PCMs, however, have both heating and cooling applications, and are far more versatile as they can be placed in both walls and ceilings. In addition, the PCMs can be designed to an ideal melting/freezing temperature for most applications.

Over the years several materials have been considered and tested as applications for PCM in buildings. Some notable materials are eutectic salts, paraffin wax, and bio-based organic materials. The material under study in this report is a bio-based PCM. These bio-PCMs maintain their melting temperatures between 70°F and 80°F adjustable by their internal chemistry. This makes them ideal for building cooling applications.

The earlier versions of PCM technology used macro-encapsulation, which reduced the surface area contact to the PCM. As a result, when it was time to regain the heat from the liquid phase, the PCM would solidify only on the edges, and prevent effective heat transfer from the rest of the material in the capsule. At the time, the material available was also either toxic or flammable, which posed unsafe conditions and possible health risks for the buildings in which they were used. The PCM technology has since evolved to incorporate micro-encapsulation as opposed to macro-encapsulation. This increases the overall surface area and allows for superior effective heat transfer. Non-toxic and ignition resistant PCMs have also been developed.

SITE DESCRIPTION

The field test for this study monitored the impact of the PCM on a fast food restaurant's HVAC related electrical load. The building is served by two Carrier rooftop package units comprising of 17.5 tons of cooling capacity. The store operates from 10:00 AM to 10:30 PM every day of the week, and is typically occupied by employees for an hour or two before and after closing for prep and clean up. The test site is approximately 2,176 square feet. The satellite imagery from Google Earth can be seen in Figure 1.

¹ Introduction to Phase Change Materials: Building Applications, Theo Pacson, 2011



FIGURE 1. GOOGLE EARTH IMAGE OF RESTAURANT

ROOFTOP UNITS

The restaurant is served by two 48HJD Series Carrier rooftop units. These are typical rooftop units with gas heating and electric cooling. The dining room is served by a 7.5 ton unit, and the kitchen is served by a 10 ton unit. The two units in question are circled in Figure 1. Additional equipment on the roof serves the freezer area, which was not part of the energy study. A diagram of a typical rooftop unit can be seen in the Figure 2, and the nameplate of one of the rooftop units is shown in Figure 3.

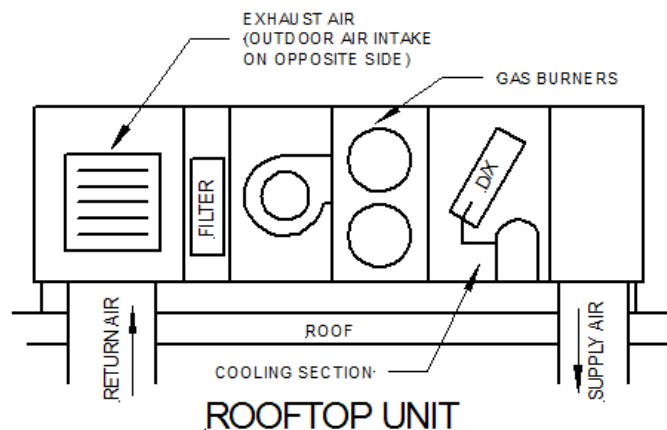


FIGURE 2. TYPICAL ROOFTOP UNIT DIAGRAM

Carrier Corporation TYLER, TEXAS		MODEL 48HJD012---571--		SERIAL 0205G40339			
FACTORY CHARGED		REF. SYSTEM R-22		TEST PRESSURE GAGE			
COMPR	1	208-230	3	60	17.6	125	9.6 LBS
COMPR	1	208-230	3	60	17.6	125	10.6 LBS
FAN MTR	1	208-230	3	60	17.6	125	10.6 LBS
OUTDOOR	2	208-230	1	60	1.4		
INDOOR	1	208-230	3	60	10.6		
OTHER							
COMBUST	1	208-230	1	60	0.57		
CHARGE SYSTEM PER INSTALLATION INSTRUCTIONS FOR OUTDOOR INSTALLATION ONLY		POWER SUPPLY		208/230		3 PH 60 HZ	
		TESTABLE VOLTAGE AT UNIT		254		MAX 187 MIN	
MINIMUM CLEARANCES TO COMBUSTIBLE MATERIALS							
TOP		BOTTOM		SIDES		FLUE SIDE	
DOWN SUPPLY	0 IN 0 MM	1 IN 25.4MM	0 IN 0 MM	48 IN 1219M			
SIDE SUPPLY							
* FOR INSTALLATION ON COMBUSTIBLE FLOORING OR CLASS A,B, OR C ROOFING MATERIAL							
** 18 INCHES(457mm) WITH ACCESSORY FLUE DISCHARGE DEFLECTOR							
MIN WKT AMPS	53	MAX FUSE OR HACR BREAKER	60	MINIMUM UNIT DISCONNECT FLA	55.9	341	COMBINATION COOLING AND HEATING UNIT
DEVICE CERTIFIED AS A FORCED AIR FURNACE WITH COOLING UNIT CSA APPROVED FOR NON-RESIDENTIAL USE TO -40 F AMBIENT.							
DESIGNED MAXIMUM OUTLET AIR TEMPERATURE				165F 74C			
AIR TEMP RISE		MAX EXTERNAL STATIC PRESSURE					
35-65F		1.0WC 0.25KPA					
19.4-36.1C							
INPUT MIN		INPUT MAX		OUTPUT CAP		THERMAL EFFICIENCY	
120000		180000		98400/147600		82	
35.2		52.8		28.8/43.2		NATURAL GAS	
GAS SUPPLY PRESSURE		13WC 3.23KPA		MAX 4WC 0.99KPA		MIN	
MANIFOLD PRESSURE		1.8/3.5WC .45/.87KPA					

FIGURE 3. DINING ROOM AC UNIT NAMEPLATE

BUILDING SCIENCE

THERMAL ENERGY STORAGE

Energy storage is the capture of energy produced at one time for use at a later time. Thermal energy storage is the temporary storage or removal of heat. Latent heat thermal energy storage systems work with materials with high latent heat capacity, which are commonly referred to as PCMs. The main advantage of these materials is that their latent heat storage capacity is much more than sensible heat. Phase changes from solid to liquid absorb a large amount of thermal energy for later use. Typically, buildings store energy as sensible heat and there is not a latent storage element unless there is a storage system that utilizes latent heat transfer, such as an ice storage system. Typically, these systems are found underground or above ground in large tanks or in a series of smaller tanks. The PCM allows for a much simpler alternative to underground storage tanks, as it can be inserted into conditioned space out of plan site without any major alterations to the existing facility.

HEAT GAIN

Heat gains, or additions to the building's cooling load, can come from several sources including:

- Windows
- Lighting
- Equipment
- Walls and Roof
- The Human Body

For the restaurant site, all of these heat gain sources apply. By adding PCM into the attic, the overall thermal mass of the restaurant is increased. Thermal mass has a significant effect in tempering heat gains. Studies show energy-use estimates of high-thermal-mass buildings vary with insulation placement. With the PCM being installed in the attic area, the PCM is expected to mitigate the heat gain from the roof. Figure 4 shows a diagram of typical heat gain sources.

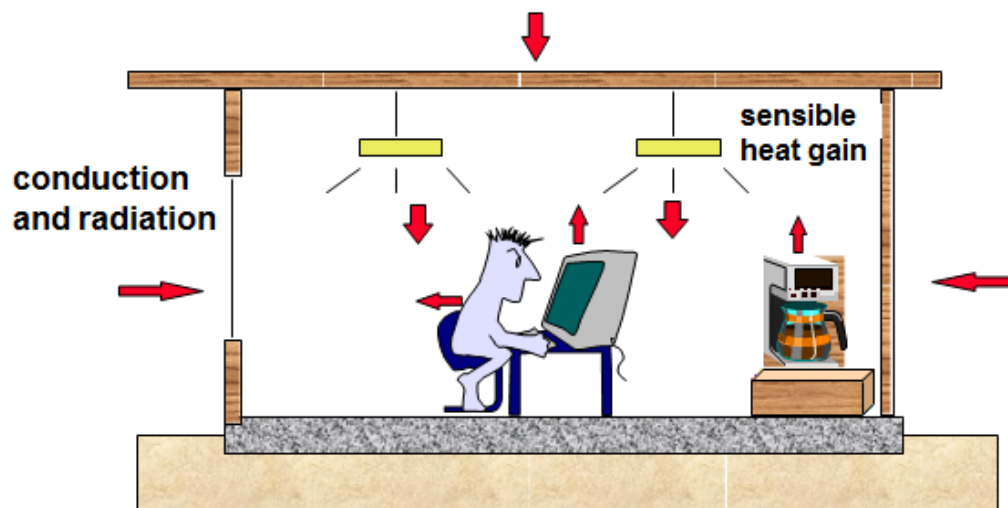


FIGURE 4. DIAGRAM OF TYPICAL HEAT GAIN SOURCES

HEAT LOSS

The majority of heat loss is due to conduction. Conduction is a function of area, U-value, and the difference between indoor and outdoor temperatures. Perimeter heat loss is a function of the perimeter F-factor, perimeter length, and indoor/outdoor temperature difference. Convection heat loss occurs around windows and doors and is dependent on the infiltration air flow volume and temperature differences. An example diagram can be seen in Figure 5.

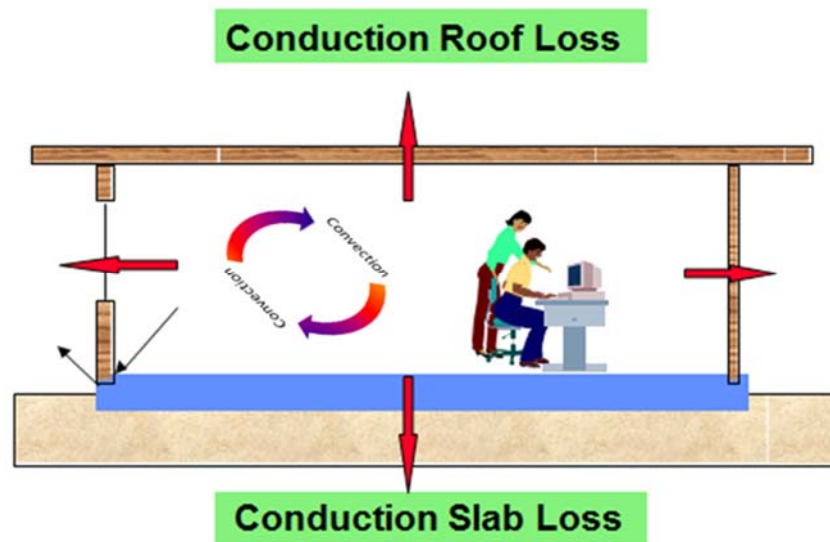


FIGURE 5. CONDUCTIVE AND CONVECTIVE HEAT LOSS

NATURAL VENTILATION

Natural ventilation relies on uncontrolled pressure differences (stack and wind) to determine the ventilation rates. In terms of air leakage, infiltration roughly equals exfiltration. Locations of the leaks in the structure dictate where and how much ventilation occurs. If the outdoor air is cooler than the indoor air, the air that is heated in the building will rise within the structure. As the heated air rises, a positive pressure (with respect to the outside) is created high in the building and a negative pressure low in the building.

Stack effect generally refers to the pressure difference created by warm air inside a building rising.

Stack effect leakage is driven by:

- Height of building spaces that are open to each other
- Thermal stratification in the building
- Distribution of leakage area high in the building

The total pressure effects on the building are a combination of all the pressures being applied to the building, including mechanical ventilation. Figure 6 shows an air movement diagram.

Sealing the building envelope penetrations high in the building is an effective way to control air leakage.

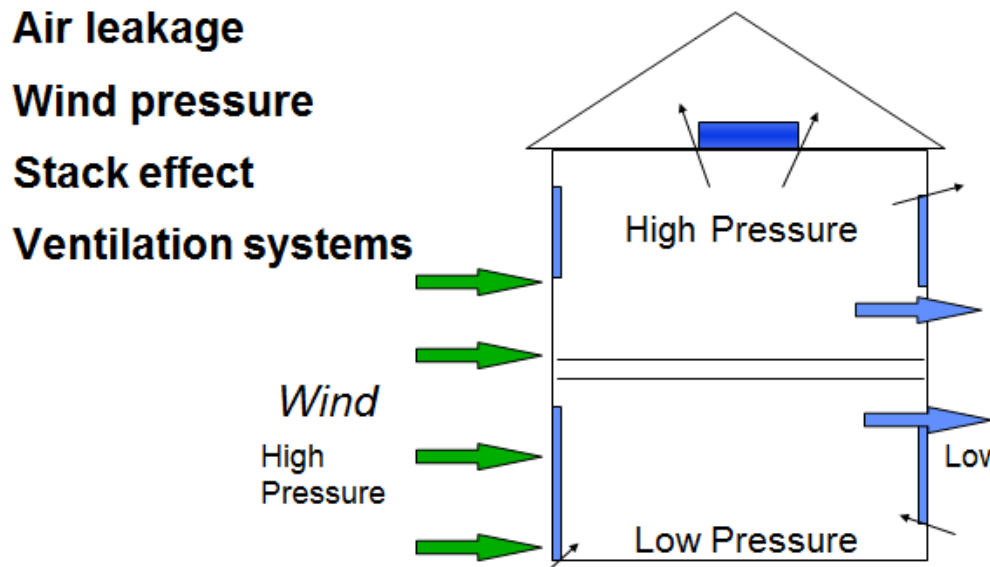


FIGURE 6. AIR MOVEMENT DIAGRAM

TECHNOLOGY DESCRIPTION

PCMs are materials that have the capability to store and release latent heat. When used for building applications, the latent thermal storage capacity of PCMs should offset cooling and heating loads in a building. This is because the PCM increases the thermal mass within the interstitial space, which allows it to maintain a lower temperature and reduce the heat gain from this space into the conditioned space. This reduction in heat gain allows the conditioned space below to maintain its desired temperature, as it would without the PCM installed, while utilizing less mechanical cooling.

HOW IT WORKS

PCMs store heat by undergoing a solid-liquid phase transformation. Once the temperature surrounding the PCM rises to its designed melting point, the PCM will absorb the heat in the plenum as it melts and maintain a near-constant temperature until it has fully changed phases (melted). The PCM will remain in this melted state until the temperature of the space drops sufficiently to begin the phase change back to the solid state. At that time the PCM will release heat back into the surrounding space until it has solidified, or the temperature shifts back in the warmer direction causing another melting cycle. Figure 7 helps illustrate this process.

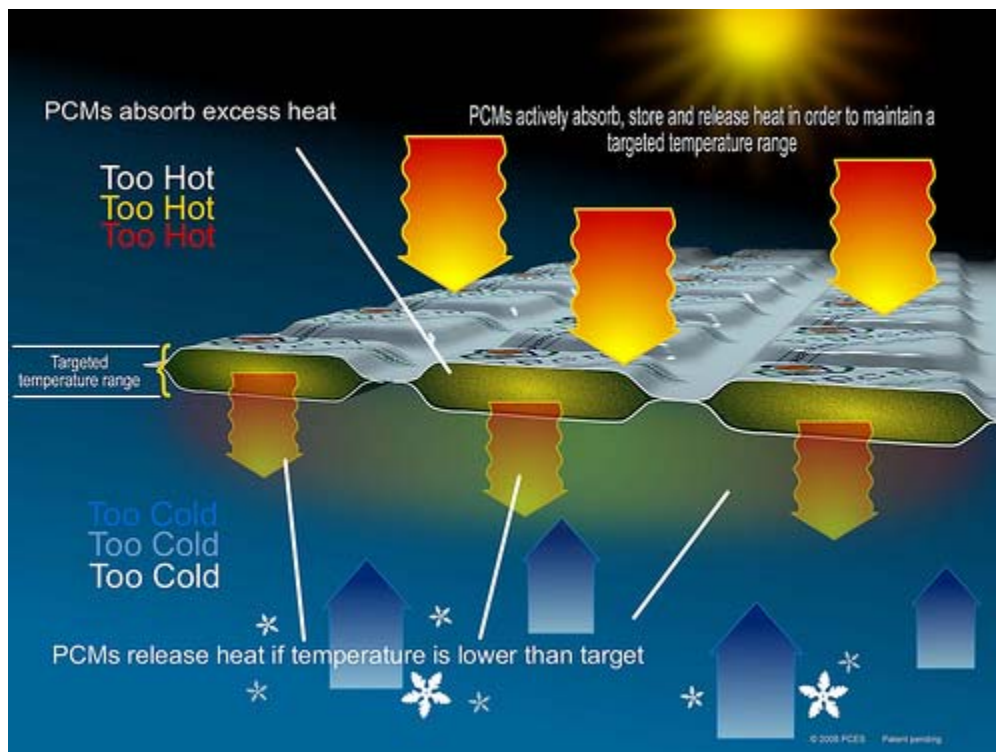


FIGURE 7. HOW PCMS WORK (IMAGE PROVIDED BY PHASE CHANGE ENERGY SOLUTIONS)

PCMs can be packaged in micro- or macro-encapsulated cells for application in interior wall construction (adjacent to insulation and wallboard), between attic joists, above ceiling panels in a drop ceiling, or integrated directly within wallboard, ceiling panels, and floor tiles. The addition of the material above the ceiling grid creates a heat barrier that the PCM will maintain until all of the PCM has fully changed phases. This added benefit reduces the heat transfer from the space above the ceiling grid into the conditioned space. Figure 8 shows a typical PCM installation.

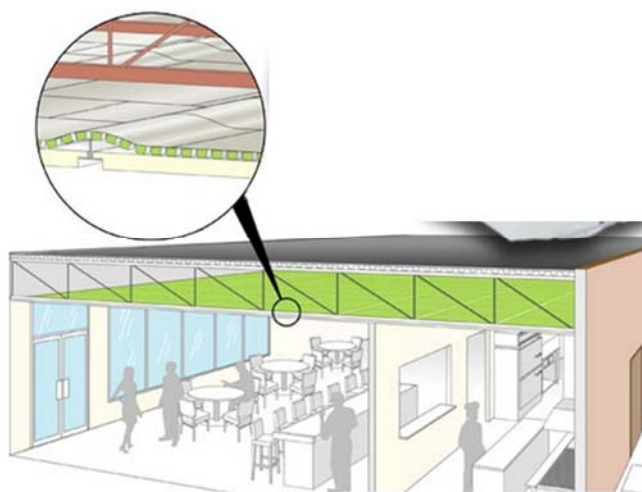


FIGURE 8. PCM EXAMPLE INSTALLATION (IMAGE PROVIDED BY PHASE CHANGE ENERGY SOLUTIONS)

ASSESSMENT OBJECTIVES

This project is a technology assessment that ultimately aims to analyze the potential energy and demand savings potential for PCMs. Specifically, the assessment objectives include:

- Using temperature loggers, verify space and attic temperatures remained within an acceptable range.
- Analyze the interval data for noticeable changes in energy-use between pre and post installation timeframes.
- Identify potential energy and demand savings.
- Using EnergyPlus™, simulate the building and analyze the baseline heat loads as well as the heat loads associated with the PCM measure installed.

TECHNOLOGY EVALUATION

The purpose of this demonstration project is to evaluate the energy saving capabilities of the PCM used in the interstitial space in a fast food restaurant located in Irvine, California. PCMs are materials that have the capability to store and release latent heat. When used for building applications, the latent thermal storage capacity of PCMs should offset cooling and heating loads in a building.

The technical approach for this type of field test must focus on ensuring that any environmental or loading differences between the two cases can be identified and accounted for in order to effectively compare the performance data for the two cases on an equitable basis.

SCE contracted an engineering firm to conduct a field technology assessment at a fast food restaurant in Irvine, California. This location was agreed upon by the restaurant corporate management and the product vendor. The location was selected due to the building size, business type, geographical location, HVAC functionality, and because the restaurant corporate management expressed interest in installing the technology.

TEST METHODOLOGY

FIELD TESTING OF TECHNOLOGY

The field test for this study monitored the impact of the PCM on a fast food restaurant's HVAC related electrical load. This facility is served by two rooftop package units. The dining room is served by a 7.5 ton unit, and the kitchen is served by a 10 ton unit. The store operates from 10:00 AM to 10:30 PM every day of the week, and is typically occupied by employees for an hour or two before and after closing from prep and clean-up. The store is approximately 2,176 square feet.

In order to establish the baseline data for the store, temperature loggers were placed in the attic and return air registers throughout the dining room and kitchen areas. Current loggers were also installed on legs A and C of both HVAC units on the roof. The current loggers were calibrated against instantaneous power measurements to ensure accurate analysis.

Material was installed while leaving all of the data loggers in place. The first PCM installation took place on September 10th, 2015 at 10:00 PM. The installation covered the majority of the drop ceiling areas in the dining room and kitchen, and the total coverage area was approximately 60% of the store. The store operated under the same operating conditions for both the baseline and installed periods. On October 13th, 2015 at 10:00 PM, the uninstallation of the phase change material occurred to create a secondary baseline. This way the analysis was able to have two analysis periods with different weather data. The material was removed until November 12th, 2015 at 10:00 PM, when the installation team returned to the site and replicated the original installation to the best of their ability in terms of location and amount of product used. The material has remained in place since this final installation, and the final data collection date was on December 18, 2015 at 10:00 PM. Historical weather data was obtained from Weather Underground and matched against the corresponding temperature and current readings, using John Wayne Airport (approximately 3 miles away) as the local weather station.

HEAT LOAD SIMULATION MODELING

The heat load calculations were completed by constructing a model that could be simulated using EnergyPlus software. EnergyPlus has been developed through funding provided by the U.S. Department of Energy. The software is a whole building energy simulation program that is used to model energy consumption for heating, cooling, ventilation, lighting, and plug and process loads. EnergyPlus operates by reading inputs from and writing outputs to text files. For this reason it is useful to utilize additional software when running simulations through EnergyPlus. Many front end user interfaces are available at varying costs and each has its own benefits.

Lawrence Berkeley National Laboratories (LBNL) has led a team that developed a free graphical user interface to EnergyPlus that allows users to create buildings and prepare them for simulation with EnergyPlus. The evaluation team selected the combination of EnergyPlus and Simergy™ to build and simulate the heat loads at the Irvine restaurant. The building model was created in Simergy and all building details were modeled to reflect, as closely as practical, the actual conditions found at the site. The complicated roof structure was not explicitly modeled and was instead replaced with a standard flat roof construction to expedite this process. The following are diagrams from the Simergy model created for the heat load simulation.

The baseline heat loads were then simulated by running the model through the EnergyPlus simulation engine. Internal gains were simulated using default ASHRAE 90.1 values for lighting and plug loads as well as occupancy and kitchen equipment. Occupancy schedules were adjusted to reflect the actual operations of the facility. Next, the input files for the simulation were altered to add the PCM to the attic space directly above the ceiling tiles. The properties of the material were added and the construction of the ceiling layers were also updated to include the additional layer of material (BioPCM-Q25 27M). The simulation was repeated using the altered ceiling construction and the results compared to the baseline design. The 3-D Simulation can be seen in Figure 9.

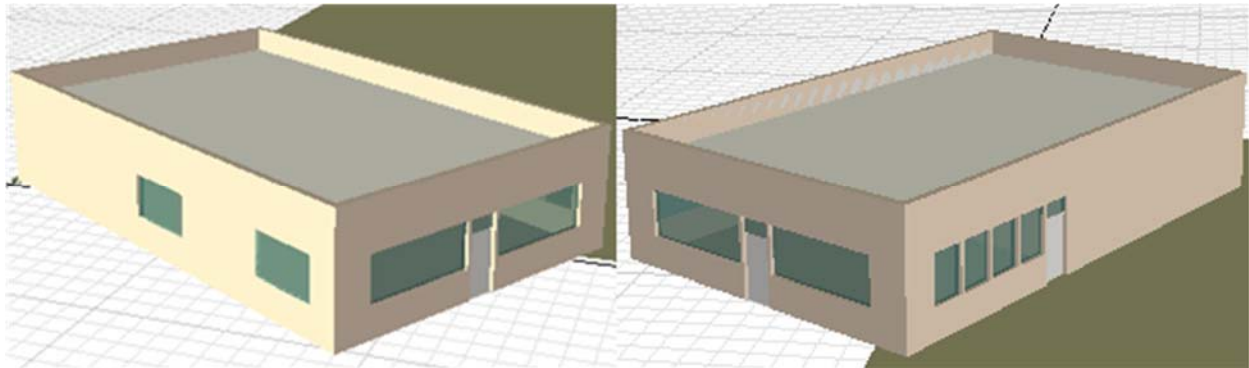


FIGURE 9. SIMERGY BUILDING 3-D GEOMETRY SIMULATION

TABLE 3. HEAT LOAD ANALYSIS RESULTS FROM ENERGY PLUS

	KITCHEN ZONE DESIGN LOAD [TONS]	DINING ZONE DESIGN LOAD [TONS]
No PCM	8.26	7.33
With PCM	8.23	7.29
Percent Difference (%)	0.4%	0.5%

As seen in the data presented in Table 3, there is little change in the peak cooling load. A possible explanation of this 'minimal-impact' is the timing of the phase change transition. The phase change transition time may not be coincident with the peak cooling loads for the facility. During the peak cooling loads for the facility, the PCM may be transitioned to its sensible heat gain state and no longer changing phase.

TEST PLAN

This test plan was performed under the Retrofit Isolation option (Option B) of the International Performance & Verification Protocol (IPMVP). Under Option B, full measurement of the impact of the energy conservation measure is required, but only the systems affected by the ECM are of any concern. By measuring the space temperatures and AC unit current, the study can focus only on the HVAC system and not have to pay attention to the lighting system, miscellaneous plug loads, or other extraneous factors that would be present in whole building meter data.

Almost all conditions, including hours of operation, staff, and temperature setpoints, were held the same between the two baseline and two installed periods, ensuring a fair comparison between the two scenarios. The only condition that could not be controlled was the outside air temperature. In order to account for the differing temperatures throughout the evaluation period, two cycles of baseline/installation were utilized to provide varying weather data in each period. The baseline and installation periods' data was then compared by evaluating data points where the outside air conditions were similar.

The air filters were changed out and the package units were serviced at the start of the project to ensure that the units were fully functioning and would not impact the study negatively. Performance was determined mainly by evaluating the amperage of the two rooftop units, but was also seen by comparing the pre and post attic temperatures against each other. Each monitoring period was approximately 30 days long. Data was collected at the end of each monitoring period, concurrently with the installations and uninstallations. Temperature data was logged every 5 minutes, and current data was logged every 1 minute. Due to the storage capacity of the 1-minute current loggers, current data could only be stored for up to a total of 30 days, which became the limiting factor for each test period.

INSTRUMENTATION PLAN

The instrumentation for this energy study consists of:

- 15 HOBO® Data Loggers (U12-001)
- 22 Temperature Probes TMC6-HD
- 4 CTV-B 50 A Current Transducers
- 1 Power Meter (Powersight 3000)

Temperature measurement accuracy: $\pm 0.25^{\circ}\text{C}$ from 0° to 50°C ($\pm 0.45^{\circ}\text{F}$ from 32° to 122°F) with 5-minute sample times. Two temperature sensors were attached per HOBO logger, allowing for 75 days of continuous data collection without needing to be reset.

Current measurement accuracy: $\pm 4.5\%$ of Full Scale with 1-minute sample times. Current measurements are calibrated against instantaneous power meter readings. One current transducer was attached per HOBO logger, allowing for 30 days of continuous data collection without needing to be reset.

The HOBO loggers were launched and retrieved using HOBOWare 3.7.1 through a USB cable connected to a laptop.

The current transducers were placed on legs A and C of both rooftop units. The temperature logger locations can be seen in the Figure 10.

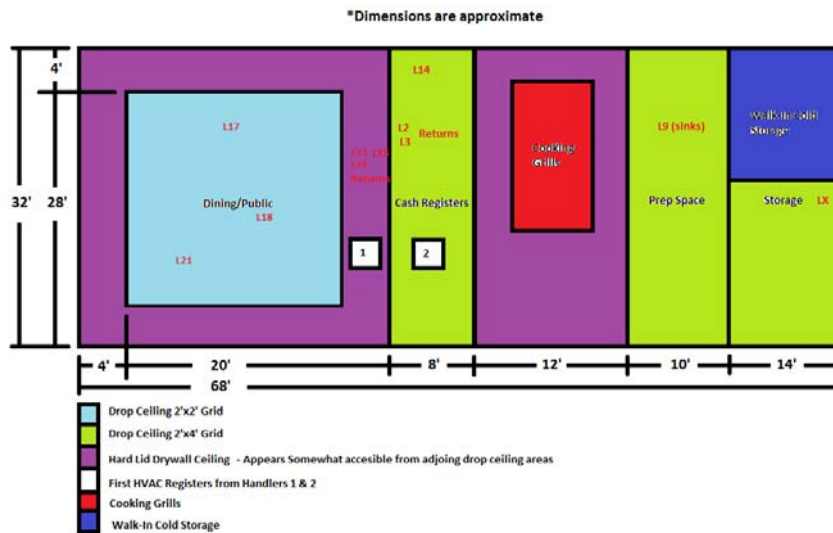


FIGURE 10. LOGGER INSTALLATION FLOORPLAN AND BUILDING DIMENSIONS

Table 4 shows where each logger was installed, what type of measurement each logger was recording, and how many channels were associated with each logger.

TABLE 4. DATA LOGGER INSTALLATION SHEET

LOGGER NUMBER	LOGGER LOCATION	MEASUREMENT TYPE	NUMBER OF CHANNELS
17	Dining Room Attic	Temperature	2
18	Dining Room Attic	Temperature	2
21	Dining Room Attic	Temperature	2
12	Dining Room Return Grill	Temperature	2
15	Dining Room Return Grill	Temperature	2
16	Dining Room Return Grill	Temperature	2
2	Kitchen Return Grill	Temperature	2
3	Kitchen Return Grill	Temperature	2
9	Kitchen Attic (Sinks)	Temperature	2
10	Kitchen Attic (Storage)	Temperature	2
14	Kitchen Attic (Drive thru)	Temperature	2
7	Dining AC Unit - A	Current	1
20	Dining AC Unit - C	Current	1
6	Kitchen AC Unit - A	Current	1
100	Kitchen AC Unit - C	Current	1

CURRENT DATA CALIBRATION

In order to calculate accurate power consumption for the kitchen and dining AC units, two CTV-B 50A amp loggers were installed on two of the legs within each unit and were programmed to record their amperage every minute. The amp readings these loggers recorded were correlated in order to represent accurate values to be used within any future calculation. The correlation was achieved by establishing the measured power and the average current for each AC unit. During the initial site visit, the information in Table 5 and Table 6 for each AC unit was measured using a Powersight Energy Analyzer and 4 Onset CTV-B 50A loggers.

TABLE 5. DATA RECORDED FROM AC-1 DINING UNIT

LEG	POWERSIGHT [AMP]	CTV-B LOGGER [AMP]	VOLTAGE LABEL	VOLTAGE [V]
A	32.0	33.26	V _{ab}	203.3
B	29.8	No Logger	V _{bc}	204.5
C	34.8	36.34	V _{ca}	204.6
			Total Power Factor = 0.86	True RMS Power = 9.85 kW

TABLE 6. DATA RECORDED FROM AC-2 KITCHEN UNIT

LEG	POWERSIGHT [AMP]	CTV-B LOGGER [AMP]	VOLTAGE LABEL	VOLTAGE [V]
A	24.0	24.9	V _{ab}	205.0
B	24.0	No Logger	V _{bc}	204.0
C	28.0	29.7	V _{ca}	205.3
			Total Power Factor = 0.86	True RMS Power = 7.74 kW

Using the average amp readings from the logger and the measured power from the energy analyzer, it is possible to determine a conversion factor that can be applied to any future amp readings. This correlation factor will, therefore, convert logger amp readings into “correlated amps”, which are then used to calculate the correlated kilowatts (kW). The method used to achieve the correlated kW value is widely accepted within the HVAC industry and will be the method applied to all Amp/Power calculations.

RESULTS

DATA ANALYSIS

There was an observed impact in the attic space above the ceiling grid where the PCM was installed. The space was not as readily heated by the outside ambient conditions and as such, the heat that moved from the attic into the space was reduced accordingly. Figure 11 shows the baseline attic space hourly bin-averaged temperature above the dining room and outside air temperature before the addition of the PCM.

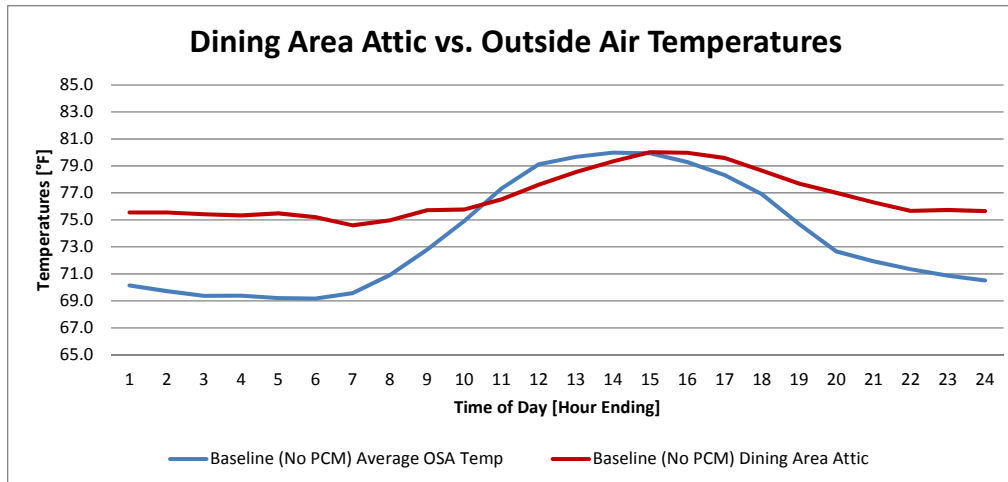


FIGURE 11. DINING ATTIC VS. OUTSIDE AIR TEMPERATURES - BASELINE

It can be seen in Figure 11 that the attic temperature is directly influenced by the outside air temperatures and that there is little 'lag' between the rise in outside air temperatures and the attic temperatures in these average daily profiles.

When the PCM was added to the space, the relationship was altered. The attic temperature rose but there was a lag that can be attributed to the installation of the PCM. Figure 12 shows the post-installation attic space hourly bin-averaged temperature above the dining room after the addition of the PCM.

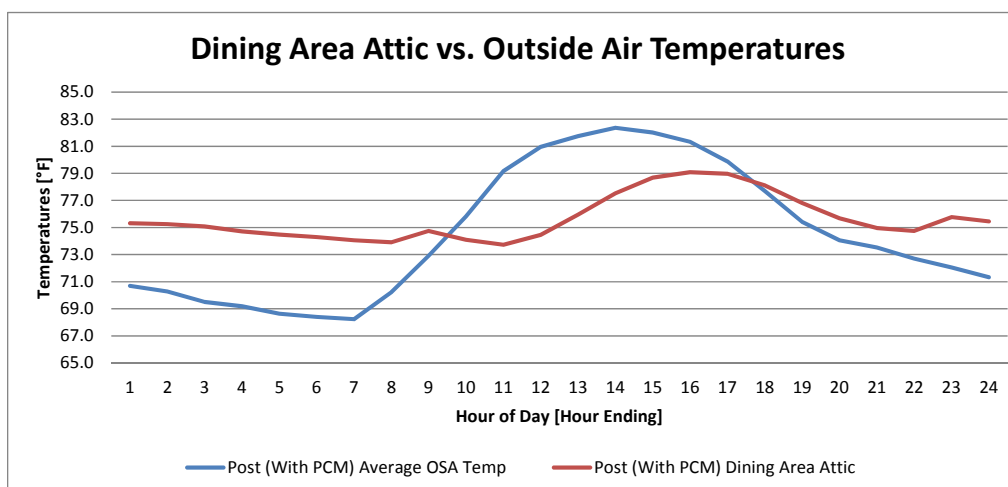


FIGURE 12. DINING ATTIC VS. OUTSIDE AIR TEMPERATURES – POST-INSTALLATION (WITH PCM)

Figure 12 shows a definite lag in the temperature rise of the attic space above the dining room with the PCM installed.

There was also an observed temperature differential above and below the PCM inside the attic space. This temperature differential is a requisite component for the energy savings from this measure. Without a temperature differential, there would be no effect from the material that the study would be able to identify. In order to capture this temperature differential, a temperature probe was inserted below the PCM and above the ceiling tiles sandwiched between the two materials. This sensor is labeled 'Below PCM'. The reading for 'Above PCM' is an additional sensor that was suspended above the PCM directly above the 'Below PCM' sensor. This pair acted as the 'Above and Below' points for the PCM. In fact, there were several points above the PCM suspended above the ceiling tiles and any will suffice for this purpose. Figure 13 is the representation of the two sensors described as Above and Below the PCM.

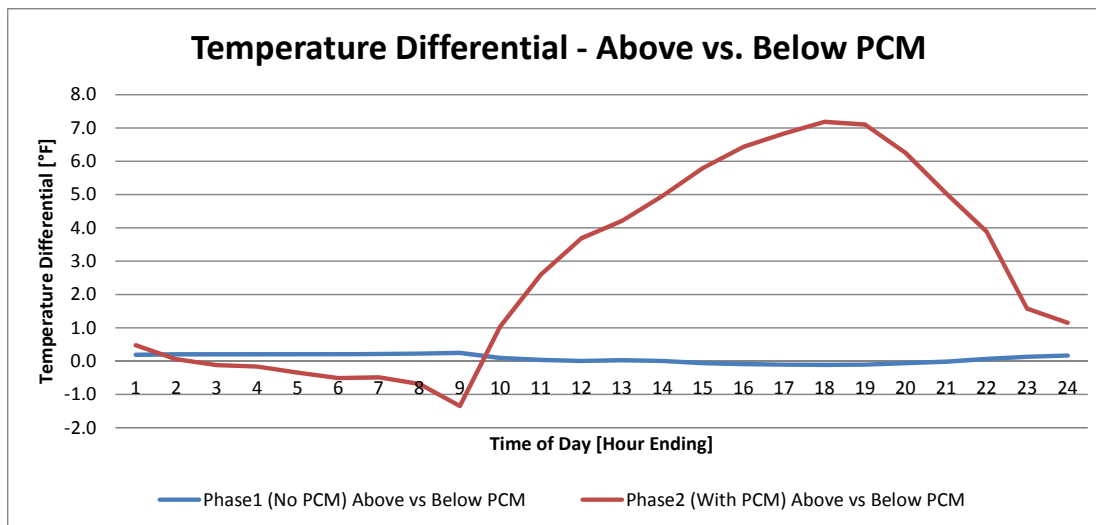


FIGURE 13. TEMPERATURE DIFFERENTIAL – ABOVE VS. BELOW THE PCM

Seeing that there was a lag created in the attic space where the temperature drift from the outside ambient conditions were delayed and that there was a temperature differential between the ceiling tiles and the attic spaces, the study turned to the energy consumption of the HVAC systems.

DEGREE DAY ANALYSIS

Cooling degree days (CDD) are a measure of how much (in degrees), and for how long (in days), outside air temperature was higher than a specific base temperature. They are used for calculations relating to the energy consumption required to cool buildings. This analysis uses hourly data to calculate CDD.

The analysis of the collected data was conducted by evaluating the energy consumption of the HVAC systems of the restaurant with respect to outside air conditions. One common method to determine energy consumption as a function of ambient conditions is to consider the facility balance point² and how far the ambient conditions vary from that balance point

² The definition of a balance point is when a space's heat output equals the heat. An example of a balance point is when space heat loss is equal to heat created in the space and no cooling is required.

during the days when the technology is being studied. As a first step, it was necessary to determine the balance point of the facility for the cooling system.

Determination of the balance point of the HVAC cooling system was conducted by looking at the cooling energy data collected by the loggers connected to the kitchen and dining room AC units. By checking the temperature when the cooling units were required to begin cooling the space, it is possible to determine the balance point for each unit respectively. Figure 14 presents the cooling amp data collected and the respective outside air temperature that corresponds to each amp reading. The analysis settled on a balance point of 60°F. In Figure 14 the sharp drop off to the left of the slope down at approximately 60°F represents the compressor balance point. The remaining amperage-use below 60°F (approx. 52°F - 60°F) is the fan-use without the compressor running. Below 52°F shows 0 Amps, which reflects when the restaurant is closed and both the fan and compressor are off.

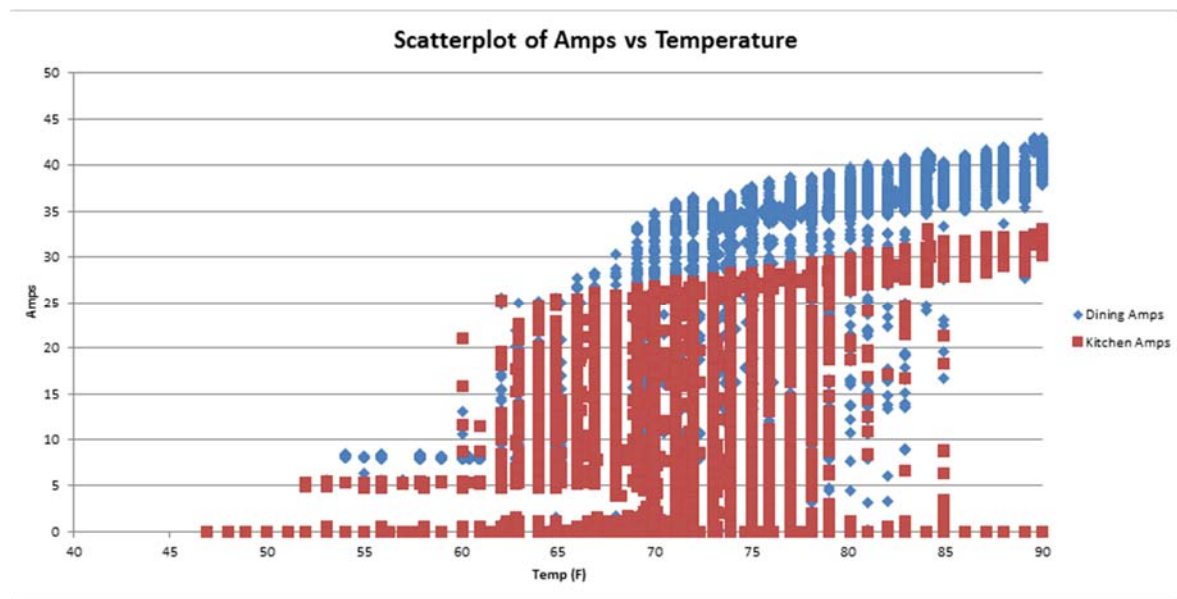


FIGURE 14. FACILITY BALANCE POINT DETERMINATION (KITCHEN AND DINING ROOM)

Next the analysis turned to heating degree days to ensure that there was no fan cycling that could be increased after the addition of the PCM. If an increase in the fan cycling could be attributed to the PCM, there might be a component of electric energy savings during the gas heating mode.

Figure 15 shows several different days of hourly amp data, from Midnight to Midnight for the dining room. Multiple days were graphed to show behavior for a variety of different temperatures. As can be seen in every day, there is a plateau at approximately 8 amps; this 8-amp plateau is related to the fan. This constant operation shows that the fan operates continuously while the dining room is open, and then shuts off based on a timeclock. Because the fan operation is set and not related to heating or cooling, there will be no electrical savings associated with a reduction in gas heating. Therefore, heating degree days do not result in any electrical savings at the dining room unit, and only cooling degree days are relevant.

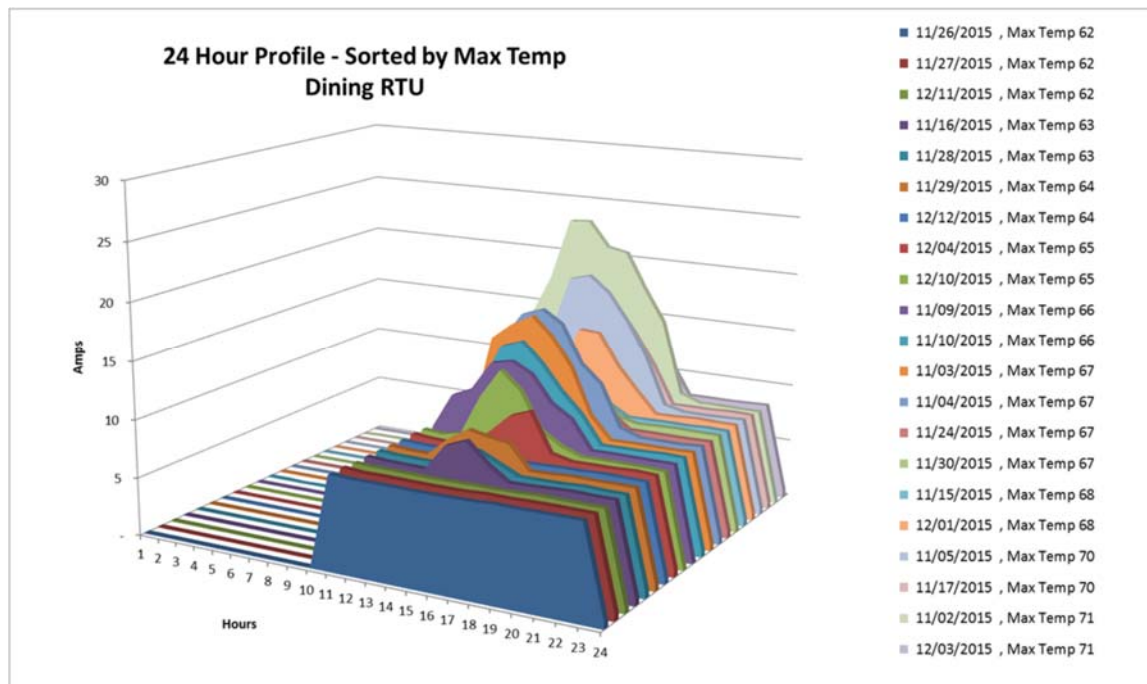


FIGURE 15. 24-HOUR TEMPERATURE PROFILES – DINING ROOM (FAN AND COMPRESSOR)

The same chart is shown in Figure 16 for the Kitchen AC Unit. The operation is similar, but the fan runs slightly longer hours on this unit while the crew is cleaning up and prepping for the next day³.

³ The 1 AM hour on 11/02 is missing data and not a data point when the fan was not operational.

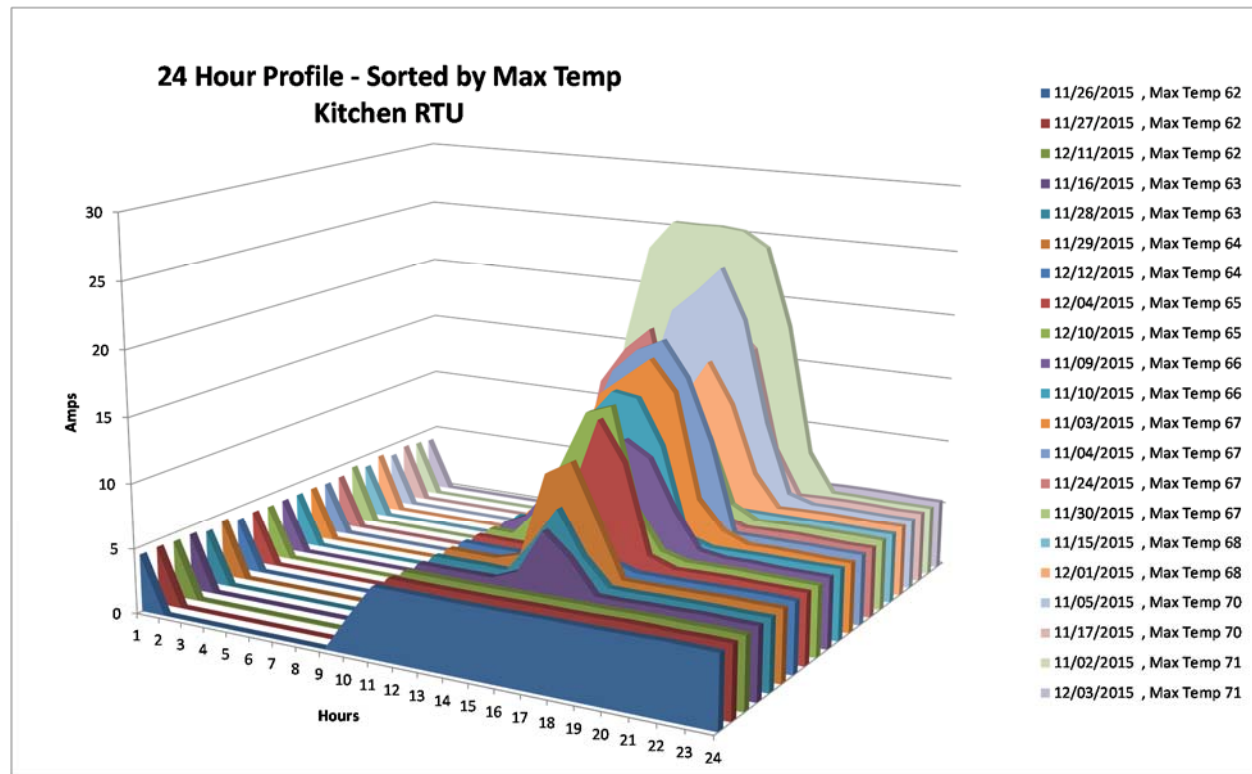


FIGURE 16. 24-HOUR TEMPERATURE PROFILES – KITCHEN (FAN AND COMPRESSOR)

Since the fan runs continuously during the facility operational hours, only cooling electrical energy savings potential is associated with the installation of the PCM at this facility.

This study evaluates the magnitude of those cooling energy savings related to the hours of operation of this facility and those CDD that occur during those operating hours (CDDO = CDD Open). Cooling degree days that occur outside the normal operating hours for this facility are excluded from this analysis as they are not impacting the energy consumption of the HVAC systems that provide cooling to the spaces.

The measured kW was used to convert the monitored amps to kW for all of the monitored data points during the baseline and post-implementation monitoring periods. Each HVAC unit, the kitchen and dining room unit, had their own respective conversion factors measured during field visits where loggers were installed and true root-mean-square (RMS) power was simultaneously measured and recorded in conjunction with AMPs in order to correlate amps to power. By converting the amp logger data to power and subsequently energy over time, the daily energy profile is developed for each unit relative to ambient conditions.

When plotting the electric energy consumed by the HVAC system each day with respect to the CDDO it can be seen in Figure 17 that there is an increasing amount of energy consumed by the HVAC units that corresponds to the increasing daily CDDO. Because of some unusual trending gaps in the data, it was necessary to analyze the data as three separate groups. Group 1 was analyzed from zero (0) to 6 CDDO; this group represents the lower end of the cooling spectrum where there was more cycling of the compressor and potentially some heating in the morning hours when the restaurant was open. Group 2 was analyzed from 6 to 13 for the baseline condition and from 6 to 14 for the PCM condition. The

difference is due to the influence of the PCM in the space conditioning. The addition of the PCM caused the electric energy consumption to reach the daily peak slower in response to increasing CDDO than it did in the baseline condition. Above 252 kWh/day, in Group 3, each case was capped as that was the predicted maximum for both conditions.

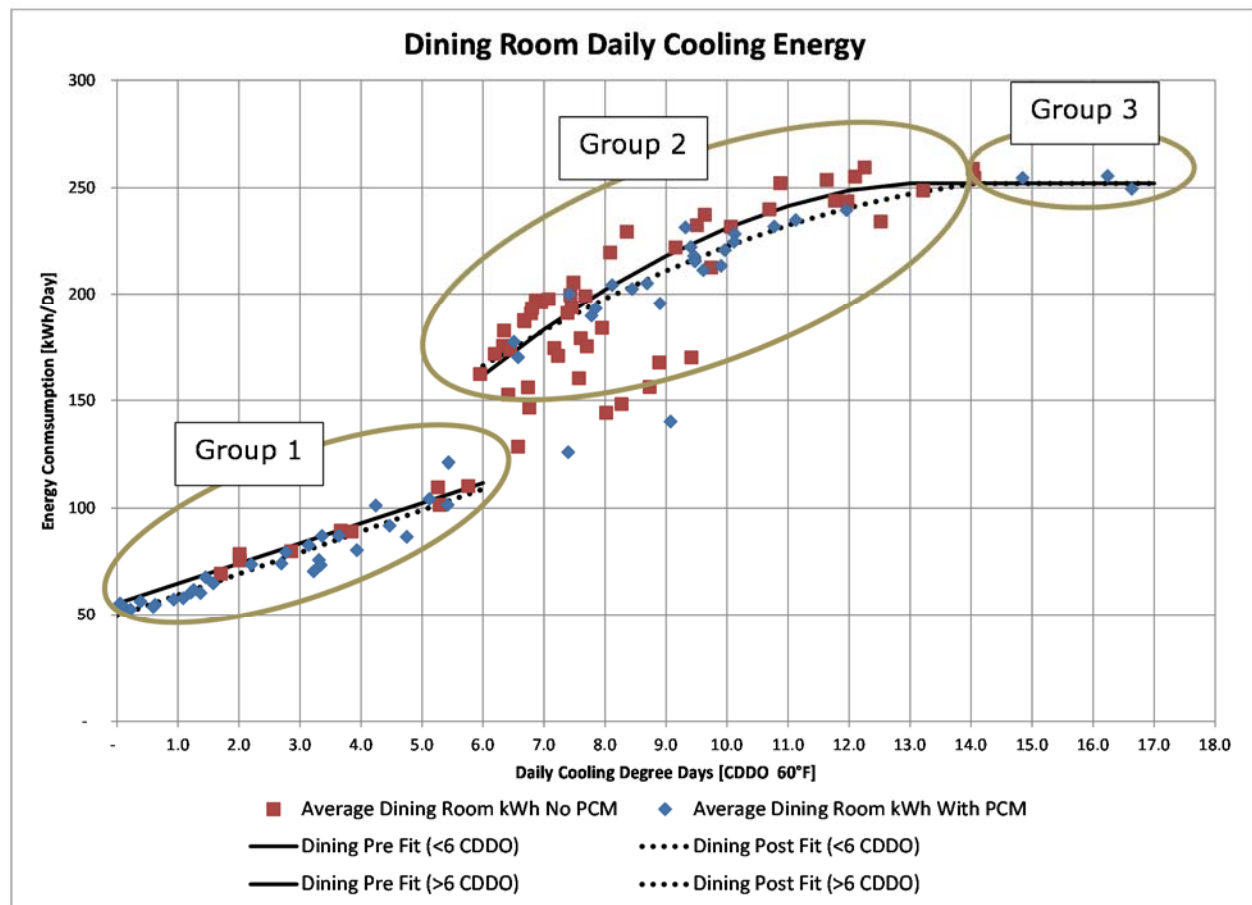


FIGURE 17. DINING ROOM DAILY COOLING ENERGY

A similar analysis was conducted for the kitchen and similar groupings were made for the kitchen data set as there were similar characteristics found in the kitchen HVAC unit energy patterns. Figure 18 shows the data and fits developed for the kitchen. As with the dining room unit, there is a lag in the kitchen unit to reach the peak after the installation of the PCM, but there is little or no apparent change in the lower ranges, or Group 1 data sets. These data sets peak at a lower kWh/day due to this kitchen unit being a slightly smaller size with a smaller supply air fan unit.

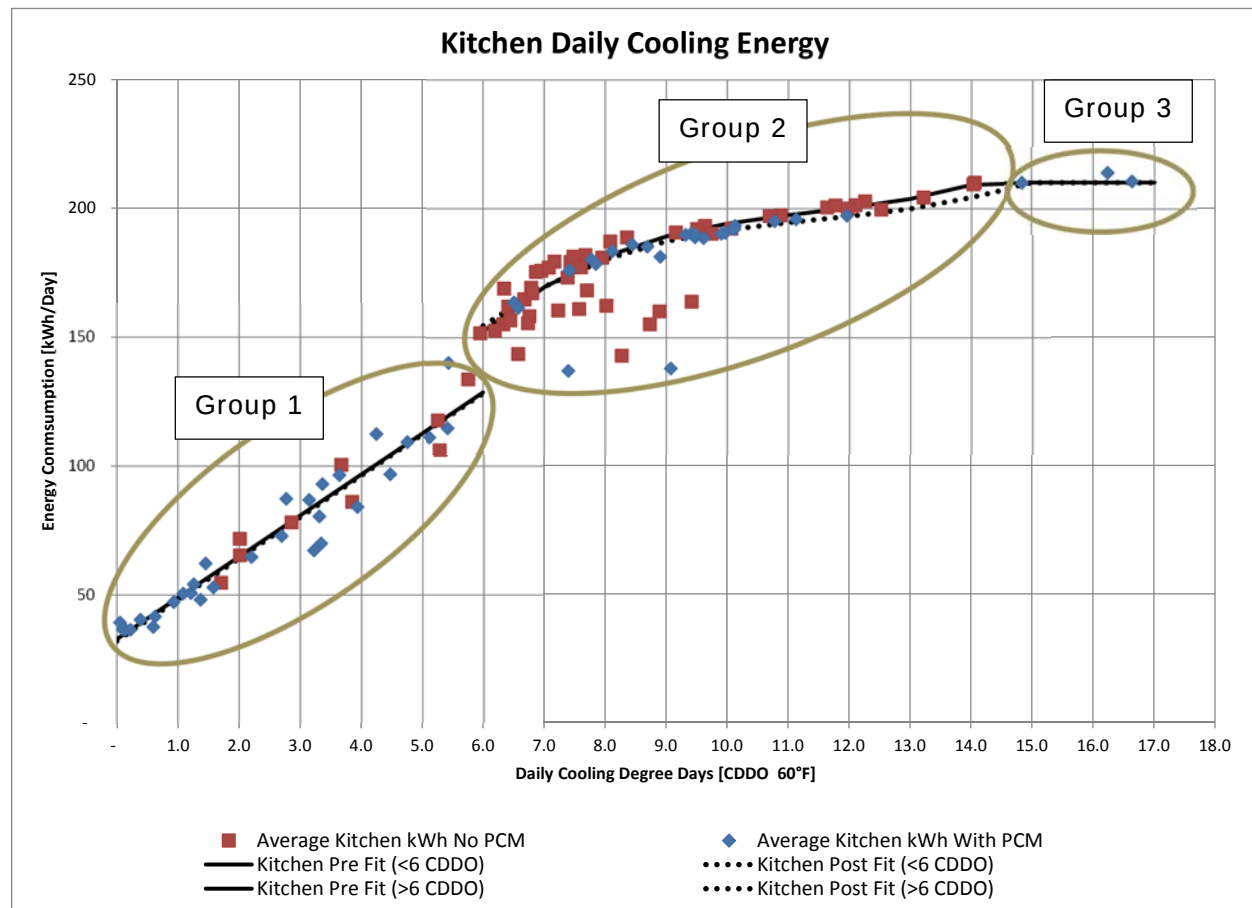


FIGURE 18. KITCHEN DAILY COOLING ENERGY

ANNUAL ENERGY SAVINGS ANALYSIS

In order to estimate the annual energy savings from the installation of the PCM at the test facility, there needed to be a correlation from the developed energy usage profiles that were based on CDDO (when the facility was open) to standard daily CDD (CDD generated for all hours of each day of the energy study). This was necessary because annual CDD are only available for full days and it would be difficult to generate a three-year annual CDDO profile from available sources on the internet. This study uses three years of historical data for CDD3Y to analyze the energy efficiency potential of this technology. By averaging the last three years of data, a three-year average profile is created as the basis for the analysis period.

By creating this correlation between CDDO and CDD, the relationship between kWh and CDDO can be used to build a bridge from kWh to CDD. Initially, the correlation between CDDO and CDD is created by calculating the CDDO value from the CDD for the exact same days used in the energy data analysis. Having both CDDO and CDD for this timeframe provides the opportunity to build a relationship that generates a formula that can be applied to the annual CDD to generate annual CDDO. In other words, a formula is derived for CDDO as a function of CDD or $CDDO = f(CDD)$ is developed. Figure 19 presents the relationship between CDDO and CDD for the timeframe of the data collection and analysis period. The equation on the figure provides the formula for CDDO in terms of CDD.

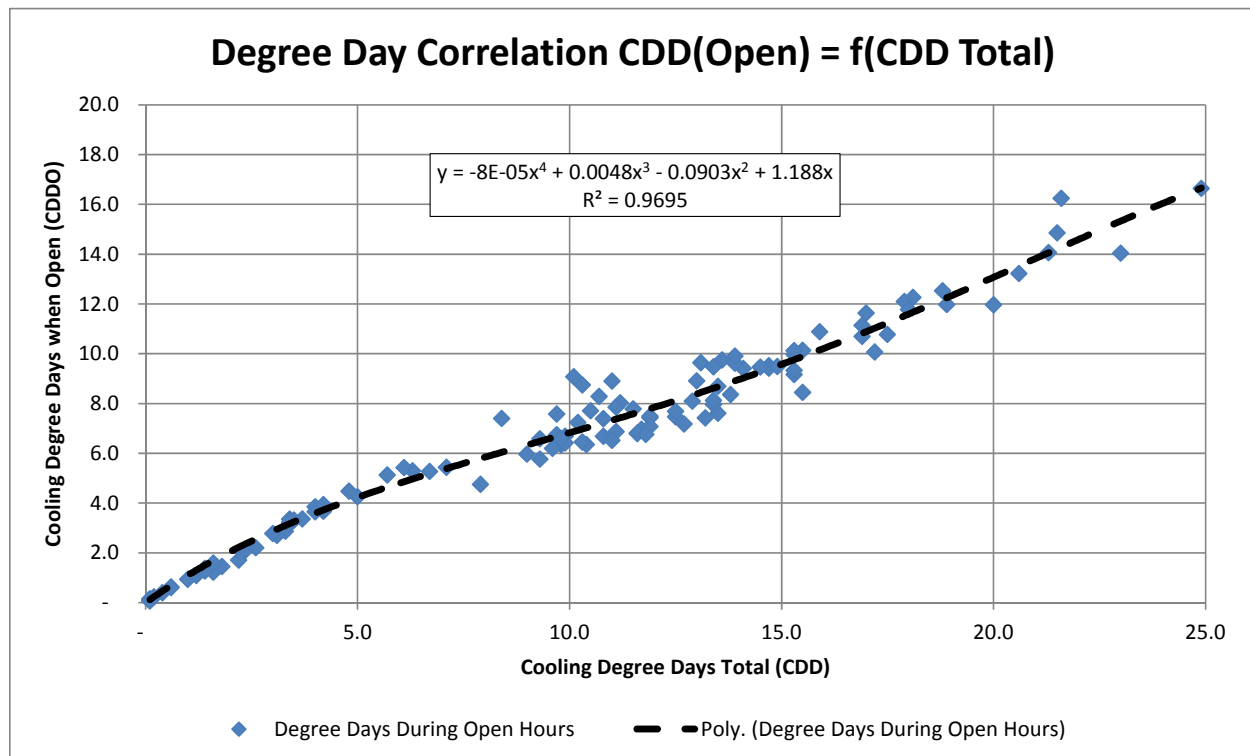


FIGURE 19. DEGREE DAY CORRELATION CDDO=F(CDD)

First, the three-year average CDD for all days in a calendar year was calculated. Next, the formula from Figure 19 was applied to the CDD generated for the three year average CDDO profile. This generated profile represents the CDDO in daily increments for 365 days in a year. Finally, the formulas for the energy consumption (see Equation 1 through Equation 13, Appendix A) applied to the three-year average CDDO values to generate the daily energy consumption for each condition, baseline and retrofit. This process was repeated for the dining room and the kitchen to generate annual energy consumption for the dining room and kitchen both before and after the installation of the PCM.

Table 7 shows the final results of the analysis for the dining room and the kitchen. It should be noted that there were no peak demand savings associated with the PCM technology, as the HVAC unit ran at full capacity during both the baseline and post implementation periods when needed.

TABLE 7. ANNUAL ENERGY AND DEMAND SAVINGS

	HVAC ENERGY BASELINE [kWh]	HVAC ENERGY POST [kWh]	ANNUAL HVAC ENERGY SAVINGS [kWh]	NORMALIZED ANNUAL SAVINGS [kWh/SF]	HVAC ENERGY SAVINGS [%]
Dining Room	48,421	46,981	1,440	1.61	3.0
Kitchen	45,164	44,896	268	0.21	0.6
Totals	93,585	91,877	1,708	0.78	1.8

PCM EFFICIENCY

The PCM was installed over approximately 60% of the attic space above the ceiling tiles in both the dining room and the kitchen. In order to determine the efficiency of the PCM with respect to the heat load reduction, the PCM properties are referenced and used to calculate the quantity of energy that the PCM is designed to remove from the attic through the phase change process. It can be seen from Figure 20 that the PCM delivers approximately 80 Btu/lb when changing phase from its frozen to its thawed state.

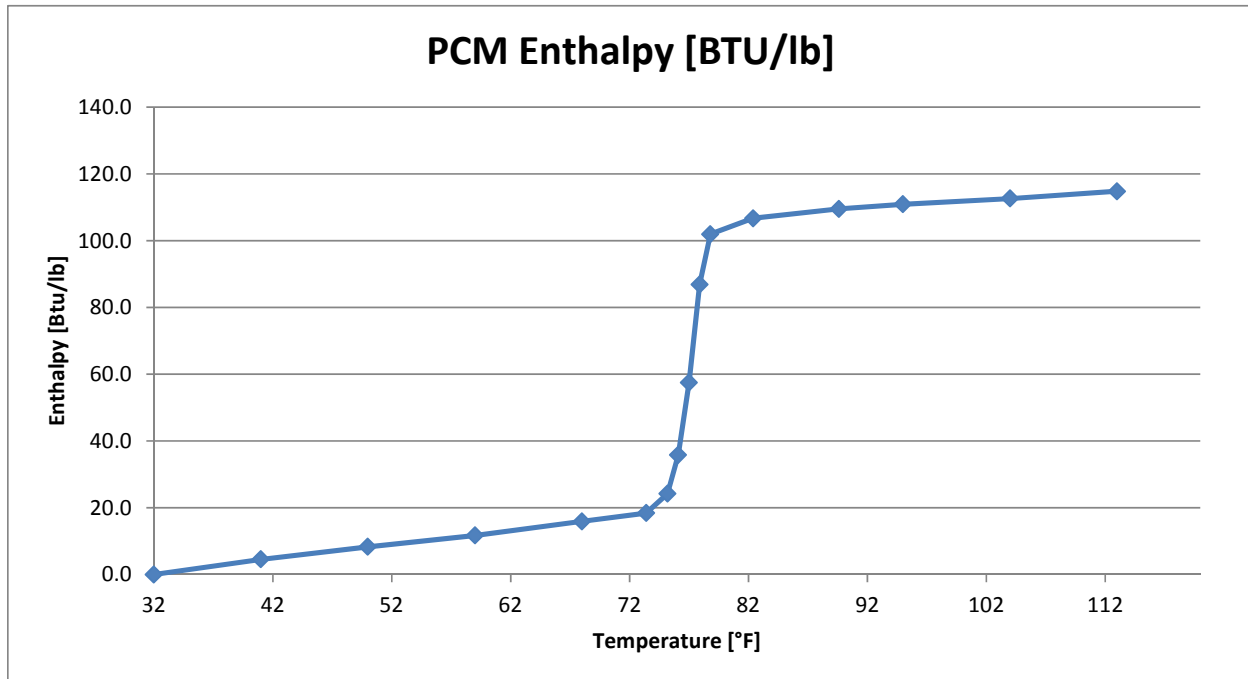


FIGURE 20. PCM ENTHALPY CHART

When the square footage for each treated space is multiplied by the PCM packaged material density (1.61 Kg/M^2 , 0.33 lb/SF), the result is the pounds of PCM installed. This value is then adjusted for the percentage of the space that was treated (in this case, 60%). The material weight is then multiplied by the 80 British Thermal Units per pound (Btu/lb) to determine the Btu delivered each day by the PCM from the transitional effects. Since this effect occurs every day of the year, the material maximum effect is the product of the calculated value for a single day multiplied by 365 days in a year. These calculations are presented in Table 8.

TABLE 8. ANNUAL ENERGY AND DEMAND SAVINGS

	SPACE SF	SPACE KWH	SPACE KWH/SF	60% SF-PCM	CONVERTED TO LB/SF
Dining Room	896	1,440	1.61	538	0.33
Kitchen	1,280	268	0.21	768	0.33
Totals	2,176	1,708	0.78	1,306	0.33

	BTU/LB (PHASE CHANGE, NON- SENSIBLE RANGE)	DAILY PCM-BTU	INSTALLED ANNUAL PCM-BTU	ANNUAL ENERGY SAVED [BTU]	PCM EFFICIENCY
Dining Room	80	14,193	5,180,314	4,914,720	95%
Kitchen	80	20,275	7,400,448	914,684	12%
Totals	80	34,468	12,580,762	5,829,404	46%

As seen in Table 8, the dining room installation delivered the expected energy reduction to the space. The kitchen ventilation system may have also limited PCM efficiency in the kitchen. More understanding is needed on how infiltration, internal heat gains and exhaust hoods impact PCM efficiency.

This site studied utilized natural gas for its heating system and not electricity. Based on the available weather data, both heating and cooling, were required for this site during this test period and any energy savings from heating was not considered in this report.

DISCUSSION

The technology did reduce the cooling loads of the test facility in the dining room as expected. There was a definite shift within the attic space after the installation of the PCM that caused that space to remain significantly cooler on hot days longer than it did without the PCM installed. Even though this translated to minimal energy savings at the HVAC units, the level of energy savings that occurred in the dining room aligns with the expectations for the installed material (95% PCM efficiency).

There are several factors that contribute to the 'lower than expected' energy savings from the kitchen. Primarily, the internal heat loads were a major barrier to achieving energy savings associated with the technology in the kitchen space. Additionally, the infiltration into the kitchen space from the make-up air unit serving the vent hoods plays a role. Finally, the ceiling tiles in the kitchen space are made from one half-inch gypsum. This makes heat transmission from the attic space minimal and significantly delayed.

The location may not have been the optimal testing facility for this technology, as the return was discovered to be ducted rather than plenum return. The PCM has a much better opportunity to show HVAC savings if it is able to directly cool the return air, but because the area above the ceiling tiles is an attic and not a plenum, the PCM serves as more of an additional layer of insulation added to the ceiling tiles. In addition to the ducted return and thick kitchen ceiling tiles, a significant portion of the ceiling is hard lid rather than drop down, which minimizes the attic area where the PCM can be installed.

CONCLUSIONS

The PCM performed to reduce the heat gain from the attic space for several hours each day and delivered energy savings to this project. The magnitude of energy savings aligned with expectations for the dining room. There was little alignment for the kitchen. There is potential for an alternative installation to demonstrate more cooling energy savings where the attic heat loads could be offset using more PCM or an alternative site where the internal gains are less significant.

There is also potential for energy savings with respect to heating energy consumption. However, the site studied utilized natural gas for its heating system and not electricity and any energy savings from heating was not considered in this report. The fans on the HVAC units operated continuously leaving no opportunity for the HVAC system to develop electric energy savings relative to the PCM installation.

RECOMMENDATIONS

It is recommended that the PCM be tested in an alternative building type where the internal heat loads and infiltration are less impactful to the cooling system. Additionally, testing should be done on plenum return systems as opposed to ducted return systems in order to increase convective heat transfer across the PCM.

Based on the results of this assessment, the product can be recommended for adoption in customized energy efficiency programs. The PCM demonstrated that it was able to affect the overall space temperature of the attic area and reduce energy consumption for the dining room. Since there was no significant reduction in the kitchen area, future installations are cautioned to consider their applications as well as their internal gains and how those internal gains will work in conjunction with PCM.

The results of this assessment conclude that the technology is able to produce energy savings, and there are applications where the technology can be effectively applied. Customers considering PCM should conduct a cost-benefit analysis to ensure PCM is viable on a site by site basis.

Additional study of alternative materials (wall coverings, decorative items, etc.) can enhance the impact of the PCM by adding it directly to spaces and not limiting it to attic and plenum spaces.

APPENDICES

APPENDIX A, ENERGY SAVINGS ANALYSIS DETAILS

DINING ROOM ANALYSIS

One pair of formulas calculated the dining room kWh for CDDO below 6 each day. The dining room formulas for CDDO below 6 are determined to be daily kWh = $9.3908 \times \text{CDDO} + 55.36$ for the baseline and daily kWh = $9.9159 \times \text{CDDO} + 49.433$ for the post-installation period. Figure 21 shows the development of the regression for the CDDO below 6 CDDO for the dining room. This represents the group 1 data analysis for the dining room.

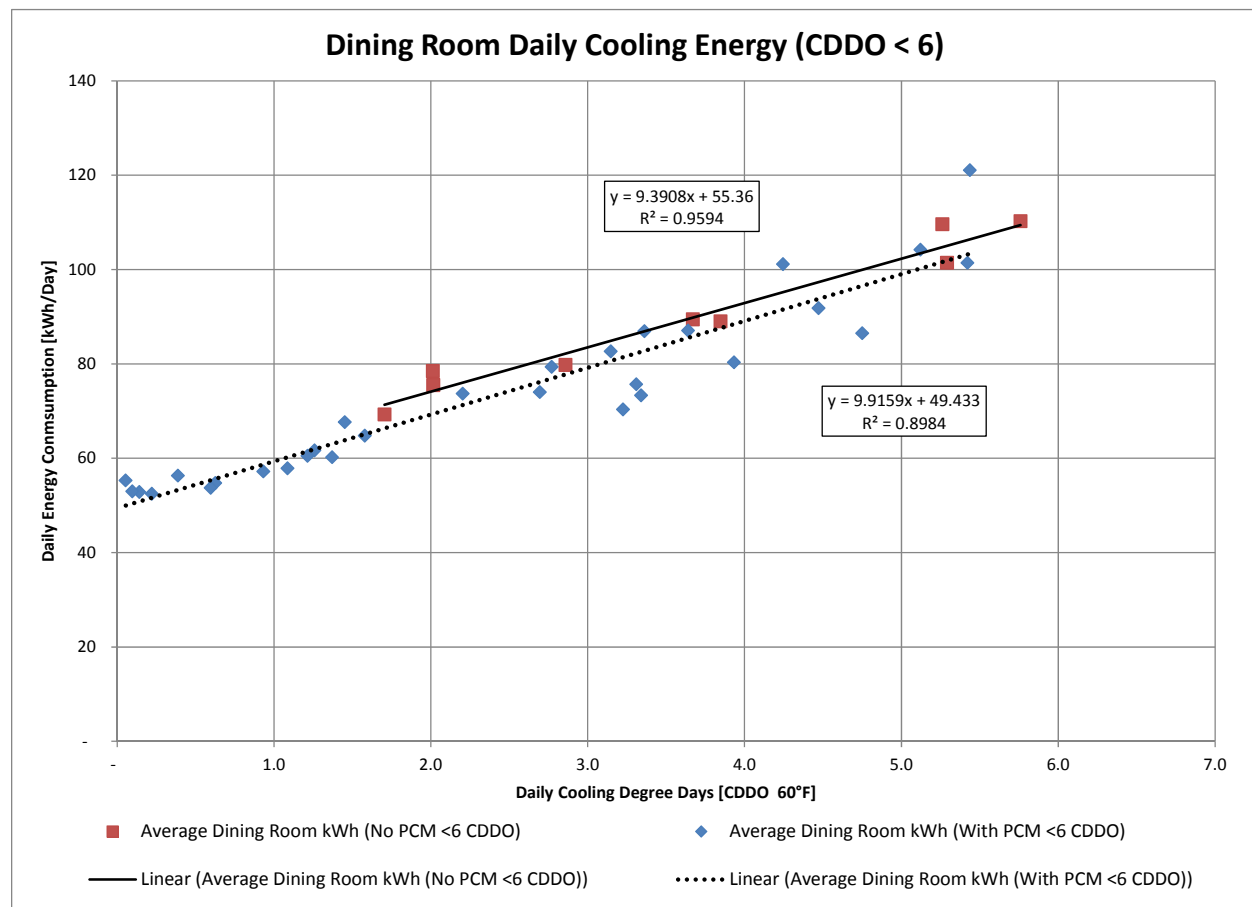


FIGURE 21. DINING ROOM DAILY ENERGY CONSUMPTION VS. CDDO (GROUP 1)

It is apparent from the regression in Figure 20 that the energy consumption of the baseline cooling configuration, No PCM, is always using more cooling energy than the post-installation configuration. Since the post-installation regression always calculates lower energy consumption than the baseline, the analysis predicts that there will be energy savings from the PCM installation whenever the CDDO is less than 6.

The next range of data for regression is the range above 6 CDD and below the point where there is nearly continuous operation of the cooling system. At some point along the CDDO

scale there exists a point where the energy consumption of the cooling units was relatively constant, varying little from day-to-day and not impacted significantly by the CDDO any longer. This can be demonstrated by looking at the daily profiles of days as the ambient temperatures increase. As ambient conditions increase, so do the number of CDD and CDDO. With increasing ambient temperatures, the cooling system operations can be seen to operate more during the day and reach a critical point where they do not stop running throughout the day. Figure 22 shows the progression of days leading from cooler days where the cooling system cycles to hotter days where the cooling system runs continuously throughout the day. Current measurements greater than 35 amps on the hotter days are caused by outdoor ambient conditions elevating the condensing temperatures. The increased energy consumption associated with these elevated ambient temperatures does not translate into increased cooling capacity; instead, the increased energy consumption translates to less efficient operation.

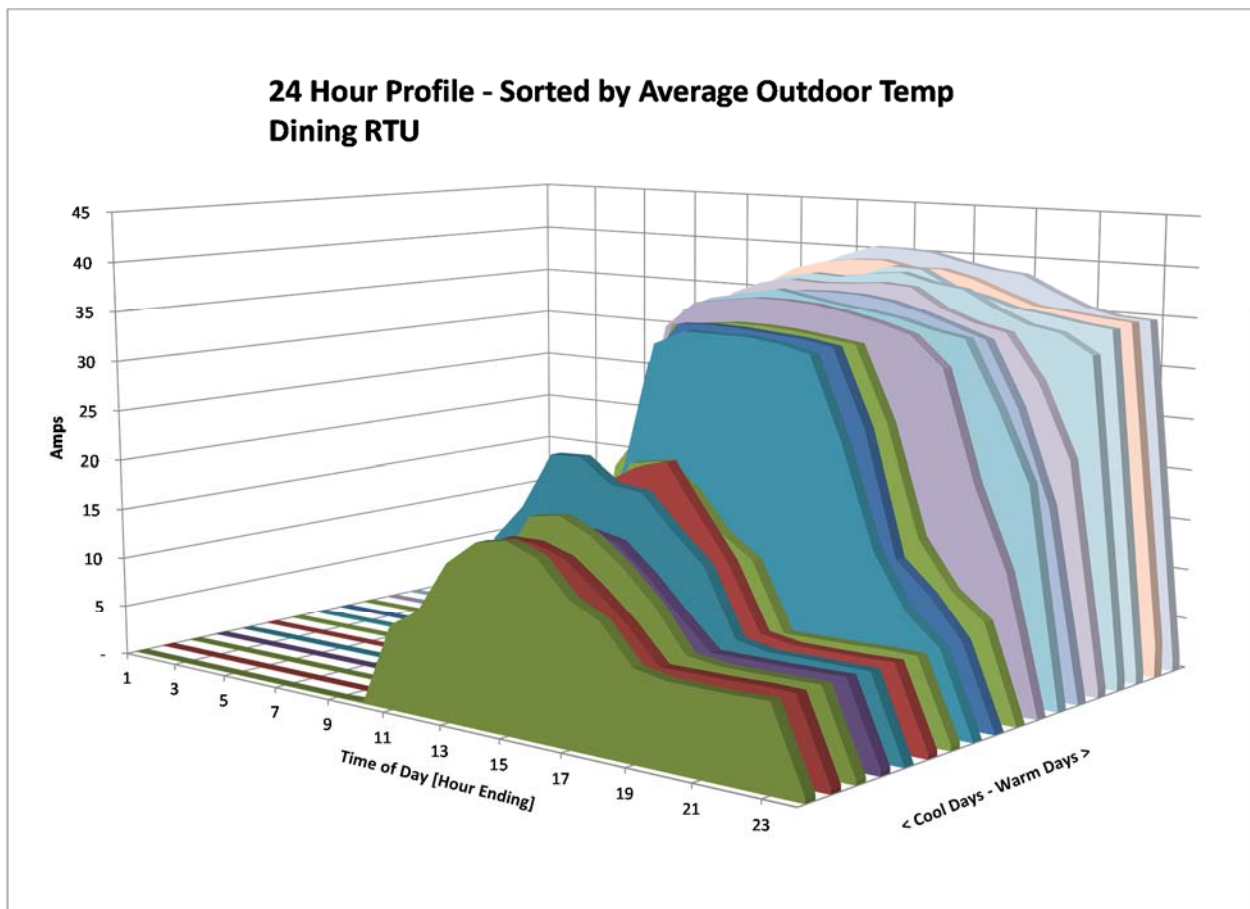


FIGURE 22. DINING ROOM DAILY COOLING ENERGY PROFILES

Further analysis was required to determine the point where the cooling unit's energy consumption leveled off with respect to increasing ambient conditions. This determination was made during the intermediate portion of the temperature profile analysis. The temperature range of CDDO above 6 and below the plateau was examined to develop a regression that will represent this stage of the cooling unit operation. Some data reduction was required to isolate those data points that were most representative of the trends that represented the operational characteristics that were applicable to this range of operation. Figure 23 presents the final data set and the associated regression formulas that resulted from the analysis of the Group 2 data analysis for the dining room data.

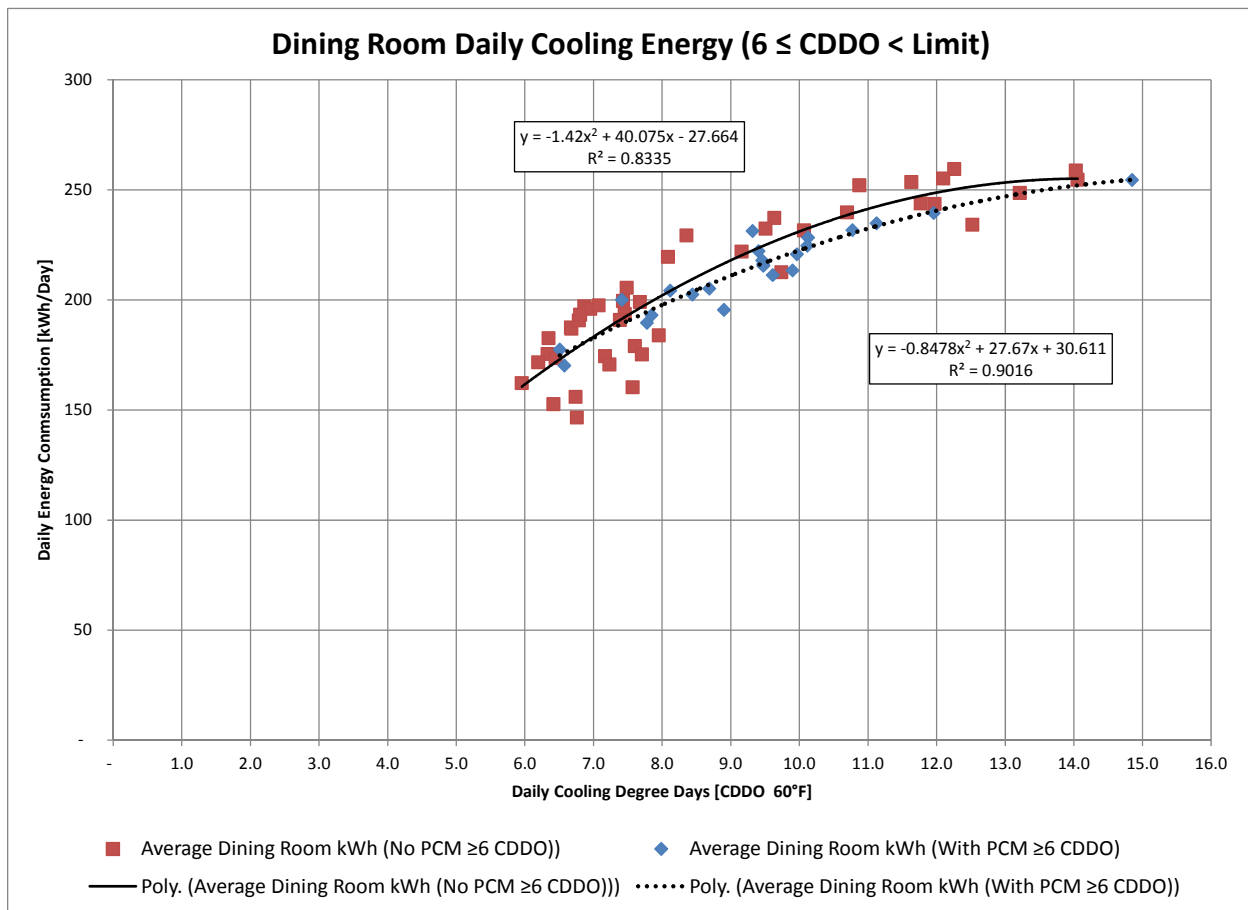


FIGURE 23. DINING ROOM DAILY ENERGY CONSUMPTION VS. CDDO (GROUP 2)

It can be seen in Figure 23 that the limit for cooling energy consumption for both units is the same and the analysis calculated the limit as 252 kWh/day. The difference between the two operations, baseline vs. post-installation, is that the baseline operation reaches this limit at 13 CDDO/day while the post-installation case reaches the same kWh/day limit at 14 CDDO/day. This delay in reaching the fully-operational cooling unit profile is one source of the calculated energy savings for the dining room.

Any CDDO above 13 for the baseline case and 14 CDDO for the PCM case were set to a constant 252 kWh for the final analysis of annual energy consumption for the dining room unit (Group 3).

In the final analysis of annual energy consumption for the baseline case, the annual energy consumption was calculated using a three-year average CDD for the John Wayne Airport (KSNA). The balance point used to generate the CDD was set to 60°F based on examination of cooling unit runtime data in conjunction with ambient temperature data. (See Figure 14.) The Three-year average CDD data was converted to annual kWh using the following series of formulas developed throughout the analysis.

EQUATION 1. CDD TO kWh CONVERSION

$$\text{CDDO} = -8\text{E-}05 \times \text{CDD}^4 + 0.0048 \times \text{CDD}^3 - 0.0903 \times \text{CDD}^2 + 1.188 \times \text{CDD}$$

After the conversion from CDD to CDDO, there were conditions applied to determine which of three formulas to apply to the derived value of CDDO for the daily kWh.

EQUATION 2. DINING BASELINE DAILY kWh FOR CDDO LESS THAN 6

$$\text{Dining}_{\text{Baseline}}(\text{Daily kWh}) = 9.3908 \times \text{CDDO} + 55.36$$

If the value of CDDO was greater than 6 and less than 13 (the limit for the baseline in the dining room), then Equation 3 was used as follows:

EQUATION 3. DINING BASELINE DAILY kWh FOR CDDO GREATER THAN OR EQUAL TO 6 AND LESS THAN 13

$$\text{Dining}_{\text{Baseline}}(\text{Daily kWh}) = -1.42 \times \text{CDDO}^2 + 40.075 \times \text{CDDO} - 27.664$$

And finally, any values for CDDO greater than 13 were set to 252 kWh/day.

EQUATION 4. DINING BASELINE DAILY kWh FOR CDDO ABOVE 13

$$\text{Dining}_{\text{Baseline}}(\text{Daily kWh}) = 252$$

Equation 5 presents the post-installation (PCM) dining room for the daily energy consumption for days when the CDDO was calculated to be less than 6.

EQUATION 5. DINING PCM DAILY kWh FOR CDDO LESS THAN 6

$$\text{Dining}_{\text{PCM}}(\text{Daily kWh}) = 9.9.9159 \times \text{CDDO} + 49.433$$

If the value of CDDO was greater than or equal to 6 and less than 14 (the limit for the PCM in the dining room), then Equation 6 was used as follows:

EQUATION 6. DINING PCM DAILY kWh FOR CDDO GREATER THAN OR EQUAL TO 6 AND LESS THAN 14

$$\text{Dining}_{\text{PCM}}(\text{Daily kWh}) = -0.8478 \times \text{CDDO}^2 + 27.67 \times \text{CDDO} - 30.611$$

And finally, any values for CDDO greater than 14 were set to 252 kWh/day.

EQUATION 7. DINING PCM DAILY kWh FOR CDDO ABOVE 14

$$\text{Dining}_{\text{PCM}}(\text{Daily kWh}) = 252$$

KITCHEN ANALYSIS

One pair of formulas calculated the kitchen kWh for CDDO below 6 each day. The kitchen formulas for CDDO below 6 were determined to be daily kWh = $15.954 \times \text{CDDO} + 33.016$ for the baseline and daily kWh = $16.023 \times \text{CDDO} + 32.24$ for the post-installation period.

Figure 24 shows the development of the regression for the CDDO below 6 CDDO for the kitchen. This represents the Group 1 data analysis for the dining room.

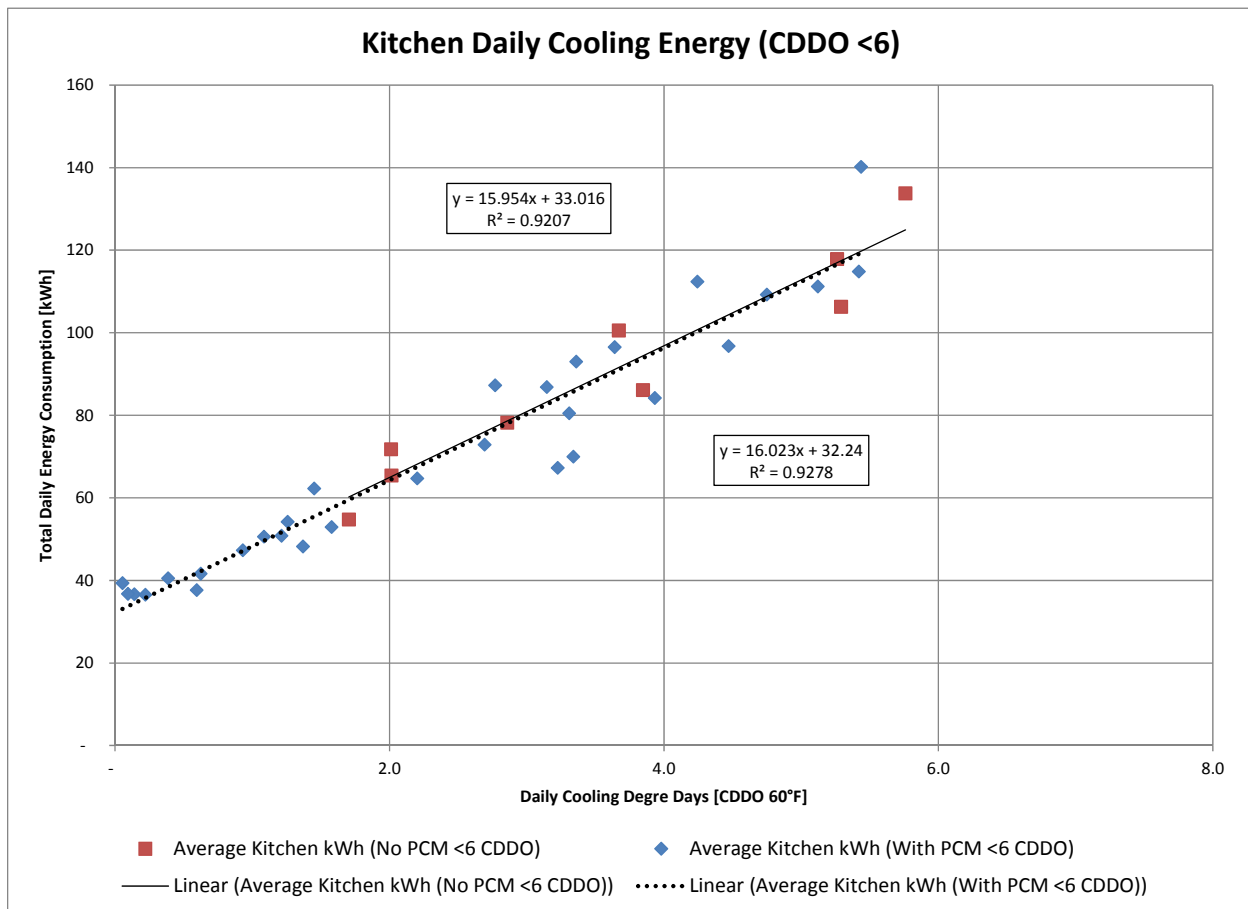


FIGURE 24. KITCHEN DAILY ENERGY CONSUMPTION VS. CDDO (GROUP 1)

Unlike in the dining room data under 6 CDDO, the baseline and post-implementation data for the kitchen under 6 CDDO are fairly similar. In this figure, it is not apparent that the PCM made a significant impact in the kitchen for this regression group.

The next range of data for regression was the range above 6 CDD and below the point where there was nearly continuous operation of the cooling system. Similar to the dining room, at some point along the CDDO scale there exists a point for the kitchen where the energy consumption of the cooling units was constant, varying little from day-to-day and not impacted significantly by the CDDO any longer. The kitchen provides a similar load profile shape to that of the one in Figure 22 for the dining room.

Further analysis was required to determine the point where the cooling unit's energy consumption leveled off with respect to increasing ambient conditions. This determination was made during the intermediate portion of the temperature profile analysis. The temperature range of CDDO above 6 and below the plateau was examined to develop a regression that will represent this stage of the cooling unit operation. Some data reduction was required to isolate the data points that were most representative of the trends that represented the operational characteristics that were applicable to this range of operation. Figure 25 presents the final data set and the associated regression formulas that resulted from the analysis of the Group 2 data analysis for the dining room data.

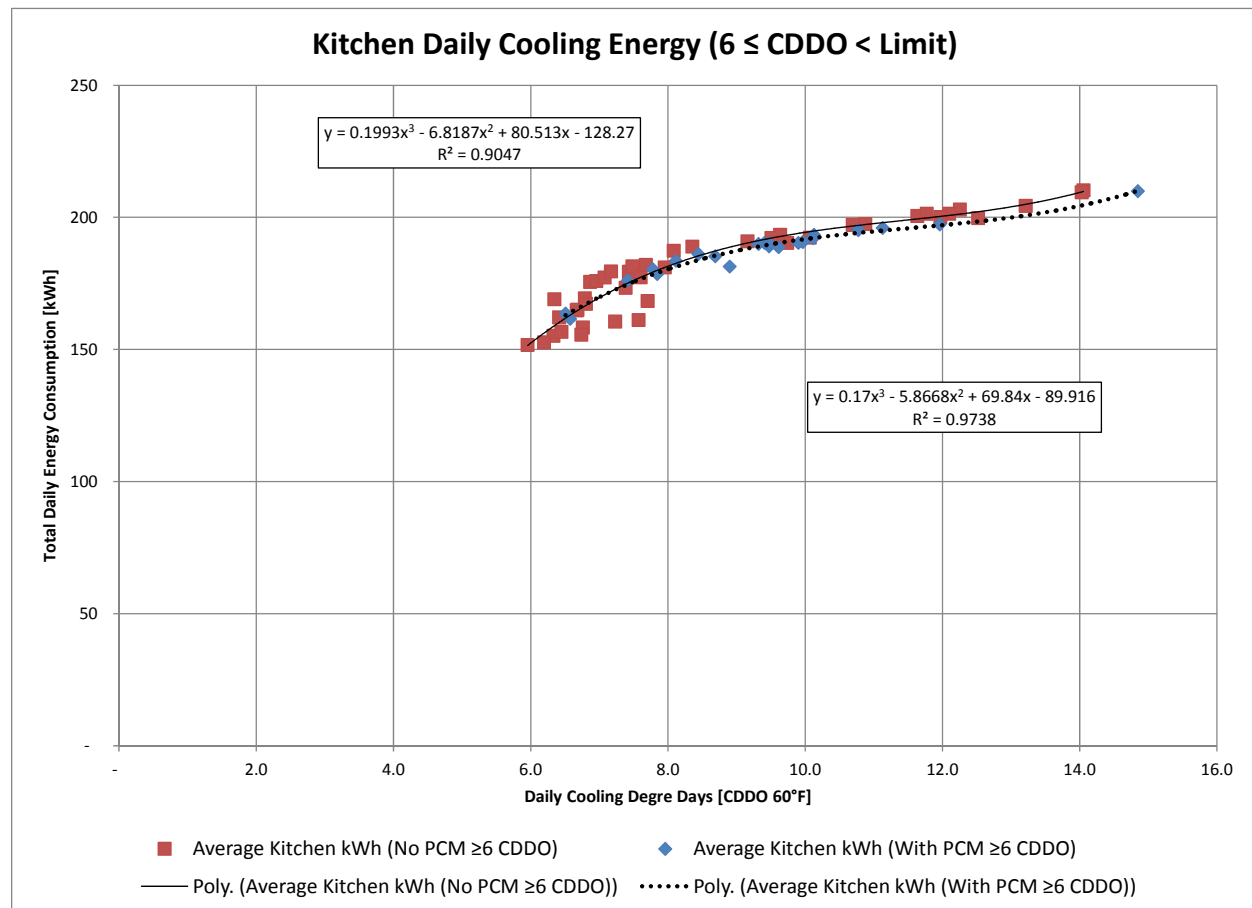


FIGURE 25. KITCHEN DAILY ENERGY CONSUMPTION VS. CDDO (GROUP 2)

It can be seen in Figure 25 that the limit for cooling energy consumption for both units is the same and the analysis calculated the limit as 210 kWh/day. The difference between the two operations, baseline vs. post-installation, is that the baseline operation reaches this limit at 14 CDDO/day while the post-installation case reaches the same kWh/day limit at 15 CDDO/day. This delay in reaching the fully-operational cooling unit profile is one source of the calculated energy savings for the dining room.

Any CDDO greater than 14 for the baseline case and 15 CDDO for the PCM case were set to a constant 210 kWh for the final analysis of annual energy consumption for the dining room unit (Group 3).

The three-year average CDD data was converted to annual kWh using Equation 1 in the Dining section of this Appendix. After the conversion from CDD to CDDO, there were conditions applied to determine which of three formulas to apply to the derived value of CDDO for the daily kWh.

If the value of CDDO was less than 6, then Equation 8 was used as follows:

EQUATION 8. KITCHEN BASELINE DAILY kWh FOR CDDO LESS THAN 6

$$\text{Kitchen}_{\text{Baseline}}(\text{Daily kWh}) = 15.954 \times \text{CDDO} + 33.016$$

If the value of CDDO was greater than or equal to 6 and less than 14 (the limit for the baseline in the dining room), then Equation 9 was used as follows:

EQUATION 9. KITCHEN BASELINE DAILY kWh FOR CDDO GREATER THAN OR EQUAL TO 6 AND BELOW 14

$$\text{Kitchen}_{\text{Baseline}}(\text{Daily kWh}) = 0.1993 \times \text{CDDO}^3 - 6.8187 \times \text{CDDO}^2 + 80.513 \times \text{CDDO} - 128.27$$

And finally, any values for CDDO greater than 14 were set to 210 kWh/day as shown in Equation 10.

EQUATION 10. KITCHEN BASELINE DAILY kWh FOR CDDO GREATER THAN 14

$$\text{Kitchen}_{\text{Baseline}}(\text{Daily kWh}) = 210$$

Equation 11 presents the post-installation (PCM) kitchen for the daily energy consumption for days when the CDDO was calculated to be less than 6.

EQUATION 11. KITCHEN PCM DAILY kWh FOR CDDO LESS THAN 6

$$\text{Kitchen}_{\text{PCM}}(\text{Daily kWh}) = 16.023 \times \text{CDDO} + 32.24$$

If the value of CDDO was greater than or equal to 6 and less than 15 (the limit for the PCM in the kitchen), then Equation 12 was used as follows:

EQUATION 12. KITCHEN PCM DAILY kWh FOR CDDO GREATER THAN OR EQUAL TO 6 AND LESS THAN 15

$$\text{Kitchen}_{\text{PCM}}(\text{Daily kWh}) = 0.17 \times \text{CDDO}^3 - 5.8668 \times \text{CDDO}^2 + 69.84 \times \text{CDDO} - 89.916$$

And finally, any values for CDDO greater than 15 were set to 210 kWh/day.

EQUATION 13. KITCHEN PCM DAILY kWh FOR CDDO GREATER THAN 15

$$\text{Kitchen}_{\text{PCM}}(\text{Daily kWh}) = 210$$