2019-06

ENERGY MANAGEMENT IN NAVAL FACILITIES USING PHASE CHANGE MATERIALS

Martinez, Julian M.

Monterey, CA; Naval Postgraduate School

https://hdl.handle.net/10945/62752

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ENERGY MANAGEMENT IN NAVAL FACILITIES USING PHASE CHANGE MATERIALS

by

Julian M. Martinez

June 2019

Thesis Advisor: Muguru Chandrasekhara
Second Reader: Anthony J. Gannon

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2019	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE ENERGY MANAGEMENT IN NAVAL FACILITIES USING PHASE CHANGE MATERIALS			**5. FUNDING NUMBERS** RMMRR
6. AUTHOR(S) Julian M. Martinez			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) ONR, Arlington, VA 22217			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A
13. ABSTRACT (maximum 200 words)			
14. SUBJECT TERMS phase change material, thermal energy storage, EnergyPlus, BioPCM, passive cooling			**15. NUMBER OF PAGES** 99
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

Phase change materials (PCM) offer a great potential to passively cool buildings by using latent heat to store the room thermal energy throughout the day and releasing it at night when the ambient air is cooler. This study supports the ONR Energy, Science and Technology Evaluation Program (ESTEP) by evaluating commercial PCMs and other alternatives to traditional air conditioning methods. Flat panels of PCMs—energy panels—were installed in the ceiling and as a wall in a room. The air temperature in the room was continuously monitored for weeks by imposing varying heat loads to document the effectiveness of the PCM in achieving the desired benefits. The results showed that the PCM reacted very quickly to the applied heat load with a charge time of a few minutes, but still satisfactorily cooled the room. However, a more gradual heat loading permitted the room temperature to remain stable near the PCM melting temperature, which was the goal of the project. These conclusions also enable estimating the PCM mass required for any room if the heat loads can be quantitatively assessed. The results of this study were verified with the DoE energy management software EnergyPlus, a program that uses finite differencing methods to simulate the thermal profile of whole buildings. Reasonable qualitative agreement was obtained between the measurements and calculations.

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

ENERGY MANAGEMENT IN NAVAL FACILITIES USING PHASE CHANGE MATERIALS

Julian M. Martinez
Ensign, United States Navy
BS, U.S. Naval Academy, 2018

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2019

Approved by: Muguru Chandrasekhara
Advisor

Anthony J. Gannon
Second Reader

Garth V. Hobson
Chair, Department of Mechanical and Aerospace Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Phase change materials (PCM) offer a great potential to passively cool buildings by using latent heat to store the room thermal energy throughout the day and releasing it at night when the ambient air is cooler. This study supports the ONR Energy, Science and Technology Evaluation Program (ESTEP) by evaluating commercial PCMs and other alternatives to traditional air conditioning methods. Flat panels of PCMs—energy panels—were installed in the ceiling and as a wall in a room. The air temperature in the room was continuously monitored for weeks by imposing varying heat loads to document the effectiveness of the PCM in achieving the desired benefits. The results showed that the PCM reacted very quickly to the applied heat load with a charge time of a few minutes, but still satisfactorily cooled the room. However, a more gradual heat loading permitted the room temperature to remain stable near the PCM melting temperature, which was the goal of the project. These conclusions also enable estimating the PCM mass required for any room if the heat loads can be quantitatively assessed. The results of this study were verified with the DoE energy management software EnergyPlus, a program that uses finite differencing methods to simulate the thermal profile of whole buildings. Reasonable qualitative agreement was obtained between the measurements and calculations.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DoE	Department of Energy
DSC	Differential Scanning Calorimetry
EP	EnergyPlus
ESTEP	Energy, Science, Technology, Evaluation Program
HVAC	Heating, Ventilation, Air conditioning
NPS	Naval Postgraduate School
NREL	National Renewable Energy Lab
ONR	Office of Naval Research
PCM	Phase Change Material
PW	Public Works
TES	Thermal Energy Storage

THIS PAGE INTENTIONALLY LEFT BLANK

NOMENCLATURE

A	Area
C_p	Specific Heat Constant
g	Gravity Constant
Gr	Grashof Number
h	Convection Coefficient
k	Thermal Conductivity
L	Length
m	Mass
Nu	Nusselt Number
Pr	Prandtl Number
Q	Heat
Ra	Rayleigh Number
Re	Reynolds Number
T_∞	Freestream Temperature
T_s	Surface Temperature
V	Velocity
α	Thermal Diffusivity
β	Coefficient of Thermal Expansion
ΔT	Change in Temperature
μ	Dynamic Viscosity
ρ	Density
v	Kinematic Viscosity

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to express my deep gratitude to Professor Muguru Chandrasekhara, my thesis advisor, for his patience, guidance, valuable critiques, and for holding me to a higher standard. My grateful thanks is also extended to Mr. Dave Dausen for his assistance in obtaining the necessary equipment for data acquisition and for his programming suggestions.

I would also like to thank the three program managers from ESTEP, Ms. Marissa Brand and Ms. Stacey Curtiss from SPAWAR Pacific, and Dr. Richard Carlin from ONR, for their support throughout the project.

Finally I would like to thank my roommates, Cru Military, and the rest of my close friends and family who continue to give encouragement and support every step of the way.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Building energy service costs are a major expense for the United States Navy, which it is aiming to reduce through use of advanced engineering technologies. In this context, the Office of Naval Research (ONR) Energy, Science and Technology Evaluation Program (ESTEP) has funded research and exploration to find alternatives to the traditional heating, ventilating and air conditioning (HVAC) methods. The study being reported is one such where a Phase Change Material (PCM) was investigated to cool a room—in the Naval Postgraduate School's Mechanical Engineering Department laboratory—whose air temperature was monitored for several weeks. The PCM cooling is a self-sustaining passive method. Other than the initial cost of procurement and installation, no new costs are incurred during operation. PCM materials are environmentally friendly, biodegradable, safe materials that are said to last decades without requiring any maintenance, ever. These materials are also resilient, and will continue to perform even if grid power is lost and traditional HAVC methods are unavailable.

A PCM is primarily a chemical that changes phase at a pre-set temperature. A major advantage of PCM is that this temperature can be manipulated over a wide range by "doping" with suitable chemicals. Doping in this context means adding impurities to the PCM material, which alters the material properties such as the melting point, and conductivity. Energy management using PCM is also sometimes referred to as Thermal Energy Storage (TES) in the literature [1]. A PCM is usually packaged in the form of a gel, although other forms of the materials are also available. At the design temperature, the gel begins to melt and changes into the liquid phase. Through the liquefaction phase, the ambient heat flux is absorbed as the latent heat of fusion of the PCM and so, the ambient temperature remains nearly constant. The amount of heat absorbed depends on the thermo-physical properties of the particular PCM and its mass. Thus, it can be an effective cooling method for office spaces where the diurnal heat load changes are predictable. It increases during normal work hours in relation to outside temperature changes and varies in accordance with changes in room occupancy and usage of operating machinery, equipment, lights, incident solar radiation, etc. During evening and night hours, the heat load drops, and as the temperature drops and the environment cools, the PCM releases the absorbed latent heat of fusion and solidifies. In the process, the office space temperature increases. Thus, temperature variations in the space become nearly self-regulating unlike with standard HVAC system use.

II. BACKGROUND

In this chapter PCM in general is discussed as well as the specifics of the PCM that was used. The necessary heat transfer calculations and correlations are also presented here. Other information pertinent to this study is also included in this chapter such as the types of internal loads considered and the Monterey area weather information.

A. PCM APPLICATION

Phase change materials have a vast array of uses and applications. The most common is seen in their integration in building envelopes, more specifically the installation of PCM within low thermal inertia wallboards. Objects with a low thermal inertia have large temperature rises for small heat additions and are not considered ideal for areas with a set thermal comfort level. Building materials with low thermal inertia are commonly used because they are lightweight and relatively inexpensive. Using PCM in such situations offers potential for a better energy management of the space. Kosney et al. [2] investigated various PCM enhanced materials for a building envelope. Their most notable conclusion was that concentrated PCM does not have to be exposed directly to the interior of the building in order to provide thermal insulation and cooling.

Hawes et al. [3] indicate that a composite of PCM and concrete called thermocrete (another use of PCM in building envelopes), greatly enhances the thermos-physical properties of concrete, however it also reduces its strength considerably. Yet another building application of PCM is under floors. Floors that receive direct sunlight throughout the day store a lot of solar thermal energy. Xu et al. [4] used shape-stabilized PCM floor for passive solar heating and found that PCM in floors should not be beyond 20 mm thickness, have a heat of fusion larger than 120 KJ/kg, and a thermal conductivity larger than 0.5 W/mK.

Use of PCM in roofs [5], have not been studied well. PCM under roofs can absorb solar energy during the day and release it during the night allowing for a more regulated temperature of the interior space. Cui et al. [6] state that “windows become the main source of heat loss during the night in winter.” Hence, use of PCM in roofs can be desirable to mitigate this night time heat loss from windows. A study by Goia [7] from their testing of the thermo-physical behavior of the PCM concluded that the position and nominal melting temperature of the PCM have a major influence on the thermo-physical behavior, particularly for a PCM glazing system. Glazing is a way to insulate windows by adding another layer to a window.

Pascha [8] studied a system where PCM was placed so that it was in contact with both the inside and outside ambient temperature. The result was that for building with facades that act as heat exchangers, PCM is particularly suitable because of its thermal energy storage, and its light weight.

Salver and Sirkar [9], investigated several non-building envelope related application of PCM. Some examples are:

> Thermal protection of flight data and cockpit voice recorders, hot and cold medical therapy, transportation and storage of perishable foods, medicine, pharmaceuticals products, thermal management systems, solar power plants to store thermal energy during day time and reuse it during the latter part of the day, electronic chips to prevent operation at extreme temperatures, photovoltaic cells and solar collectors to avoid hot spots, miscellaneous use like solar-activated heat pumps, waste heat recovery, etc.

These are not considered in this study but are listed to demonstrate the scope of potential of these materials.

B. TYPES OF PCM

Phase change materials can be grouped based on the states of phase change which are solid-solid, solid-liquid, and liquid-gas. Out of these three, the solid-liquid group is the most favorable because of its thermal energy storage capacity, and its practicality for building applications [3]. The solid-liquid group have been classified into three families, namely eutectics, organics, and inorganics. Figure 1 shows further organization of the PCM categories in this group.

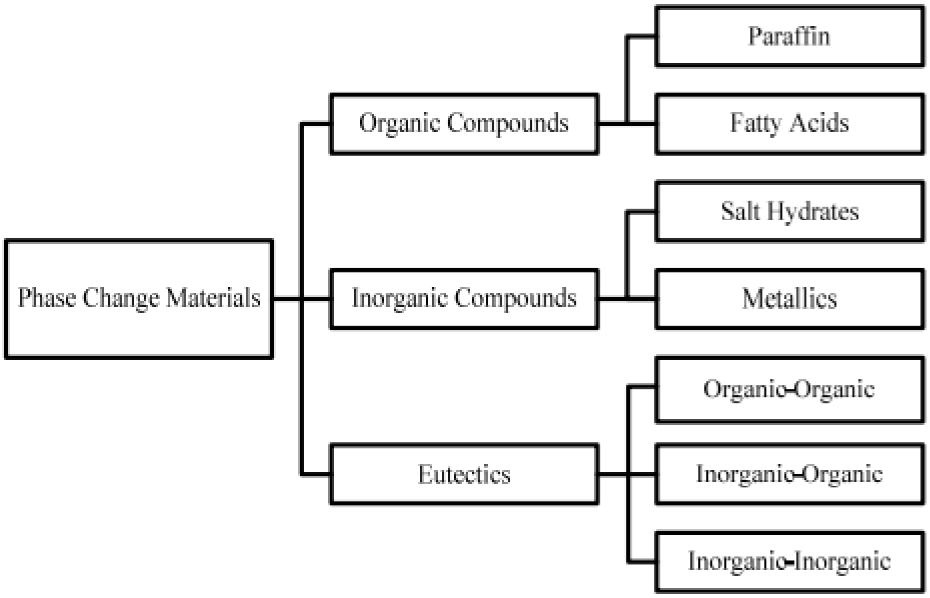

Figure 1. PCM classification. Source: [3].

Eutectics are mixtures of two or more solids that melt and freeze concurrently. Some examples are fatty alcohols, neopentyl glycol, and paraffinic hydrocarbons [10]. Sometimes, eutectics are not treated as a separate category because the eutectic mixture can be broken down into different combinations of organic and inorganic components, the difference in thermo-physical properties justify classifying them separately. It should be noted that eutectic mixtures change phase at a constant temperature while non-eutectics do so over a temperature interval [11].

Organics such as paraffin waxes, and fatty acids are chemically stable, non-corrosive, and show little to no sign of supercooling properties [12]. As will be discussed later, supercooling is not desirable. Inorganics such as salt hydrates, or metallic are generally found to have good thermal conductivity but are also known to exhibit supercooling properties. They also have a high heat of fusion, operate at high temperatures, and are corrosive to materials used in a typical building envelope [13]. They are suited to higher temperature thermal storage applications. Table 1 (reproduced below from Ref. [5]) shows a comparison of the advantages and disadvantages of all three PCM material categories.

Table 1. Overview of advantages and disadvantages of different types of PCM. Source: [5].

Organic		Inorganic		Eutectics	
Advantages	Drawbacks	Advantages	Drawbacks	Advantages	Drawbacks
-No supercooling -No phase segregation -Low vapour pressure -Large temperature range -Self-nucleating -Compatible with conventional construction materials -Chemically stable -Recyclable -High heat of fusion	-Flammable -Low thermal conductivity -Low volumetric latent heat storage capacity	-High volumetric latent heat storage capacity -Higher thermal conductivity than organic PCMs -Low cost -Non-flammable -Sharp phase change	-Corrosive to metals -Supercooling -Phase segregation -Congruent melting -High volume change	-Sharp melting points - Properties can be tailored to match specific requirements	-Limited data on thermophysical properties for many combinations - High cost

Organic PCM have the advantage of being compatible with conventional construction materials, Table 1. The most common ways of incorporating organic PCM into construction materials are direct incorporation, immersion, and macro-encapsulation. In direct incorporation, the PCM is mixed with the construction materials during fabrication. The biggest problem with this method is leakage of the PCM. Immersion is dipping the construction materials into liquid PCM and allowing the PCM to diffuse into the material and its pores. This technique also has the drawback of PCM leakage. Macro-encapsulation refers to encasing the PCM in a container such as plastic or aluminum panels [3]. The benefit of using a container is that it eliminates the leakage problem afflicting the other two methods. Such macro-encapsulated PCM panels were used in this study.

C. DETAILS OF PCM USED

The PCM used in this study is known as BioPCM, supplied by Phase Change Energy Solutions. The company literature states that BioPCM is non-toxic, renewable, biodegradable, and is made from plant based products. It includes fatty acids and their derivatives which consist of hydrocarbon chains [14]. The PCM is macro-encapsulated in a metal foil-sack which is held by a thin rod frame in an aluminum panel and sized to fit perfectly in a standard building drop ceiling tile space, so it can be easily installed. Figure 2 shows the exterior of a stack of panels and Figure 3 the typical packaging of macro-encapsulated PCM in the panels. Each panel is 0.372 sq. meters (4 sq. ft.), and weighs approximately 0.75 kg.

Figure 2. Front side of a stack of BioPCM panels

D. THERMAL PROPERTIES OF PCM USED

The thermal properties of the PCM used in this study are listed in Table 2. These values have been taken from the vendor-supplied data. The melting temperature is a “fixed” value, but a range is shown for the rest because the PCM does not maintain the same material properties through cycles of phase change. Like many materials, while the PCM is in its solid phase it has lower heat transfer qualities than when it is in the liquid phase. The significance of this is that for the same material, more heat energy is required to raise its temperature when it is in the liquid phase than when in solid phase.

Figure 3. Macro-encapsulated PCM inside aluminum, captured by thin metal rod frame

Table 2. BioPCM material properties. Source: [14].

Melting Point	23	℃
Latent Heat	210—250	J/g
Specific Heat	2.2—4.5	J/gK
Thermal Conductivity	0.15—2.5	W/mK
Relative Density	0.85—1.4	g/mL

The thermal properties mentioned previously were measured using differential scanning calorimetry (DSC) [14]. Figure 4 shows that at approximately 23 ℃ the energy storage capacity rises sharply, as this is known to be the melting temperature. This is also known as the charging phase of the PCM.

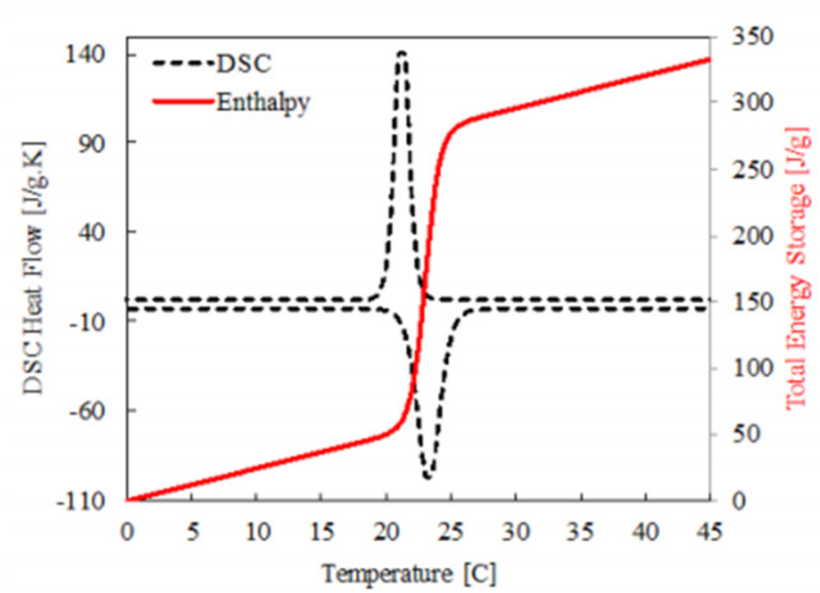

Figure 4. Results from DSC performed on PCM. Source: [14].

As seen in Table 2, the thermal conductivity of the PCM used changes from 0.15 to 2.5 W/mK. Typically, the solid phase of a material has a higher thermal conductivity that goes down while transitioning to the liquid phase. A thermal conductivity of 0.15 W/mK is low compared to that of water which is 0.56 W/mK. A lower thermal conductivity translates to a lower rate of heat conduction through a material, and a longer charging phase. This makes using a PCM unattractive for applications where there are rapid temperature changes, because the PCM cannot absorb and distribute energy fast enough for there to be a significant effect [15]. There are some studies performed to enhance the thermal conductivity of PCM, but these have not resulted in in sufficiently altering the properties of the PCM [16]. The PCM used in this study held in an aluminum panel, which is actually beneficial due to the large thermal conductivity of pure aluminum (237 W/m K), which is significantly greater than that of the PCM, and less than 1 cm thick.

E. SUPERCOOLING

Supercooling is a phenomenon where a liquid remains a liquid at temperature below its freezing point. When a liquid freezes to a solid phase its molecular structure has to be rearranged from a disordered to an ordered structure. Rapid cooling of liquid does not allow it enough time for this to occur. This causes a decrease in the ability of the PCM to recover heat. This effect is most commonly seen in inorganic PCM material such as salt hydrates, but is also exhibited in microencapsulated PCM. Some studies have shown that adding a nucleating agent reduces the amount of supercooling, but it makes the material more expensive and its thermal properties inferior [15]. The PCM selected for this study did not have these issues.

F. HEAT TRANSFER CALCULATIONS

Two modes of heat transfer are relevant to this study. The first is heat transfer by conduction. Conduction is governed by Fourier's law eqn. (1). Conduction in this study will only be used for heat transfer through a surface with a particular thickness, thermal conductivity, area, and known temperatures on both sides of it. Conduction will only be considered for the material surrounding the PCM and not through the PCM itself.

$$Q = k * A * \frac{\partial T}{\partial n} \qquad (1)$$

The dominant mode of heat transfer in this experiment is convective heat transfer. Newton's law of cooling—eqn. (2)—can be used to calculate heat transfer rates from a fluid flowing over a solid surface, in this case convection consisted of the room air flowing over the various surfaces of the room. No other fluids besides the room air were considered. In this study there was mixed convection comprised of forced and natural convection over the surfaces. This assumption was used to calculate the convective heat transfer coefficient *h*. Another assumption made is that all the heat transfer occurs over either vertical or horizontal surfaces. By assuming convection over a flat plate, we can use already established correlations, and well known heat transfer solutions.

$$Q = h * A * \Delta T \qquad (2)$$

The convection coefficient h, in eqn. (2) can be solved for a horizontal flat plate if the Nusselt number can be determined. The Nusselt number is defined in eqn. (3). Which also involves the convection coefficient. Several Nusselt number correlations are found in the literature depending on the details of the flow process involved and using the appropriate one for the flow regime allows one to arrive at h. eqn. (4) and eqn. (5) show the Nusselt correlations for laminar and turbulent flow. [17]

$$Nu = \frac{h * L}{k} \tag{3}$$

$$\begin{aligned} &Laminar\ Flow: Re\ <\ 500{,}000 \\ &Nu\ =\ 0.664\ Re^{0.5}\ Pr^{0.33} \end{aligned} \tag{4}$$

$$\begin{aligned} &For\ Turbulent\ Flow:\ Re\ >\ 500{,}000 \\ &Nu\ =\ Pr^{0.33}\ (\ 0.037\ Re^{0.8} - 871) \end{aligned} \tag{5}$$

The Reynolds number and Prandtl number used in eqn. (4) and eqn. (5) are defined mathematically in eqn. (6) and eqn. (7) respectively. In this study, a Reynolds number below 500,000 will be considered laminar, and a Reynolds number above 500,000 turbulent. The correlations shown in this section are valid for fluids with Prandtl numbers between 0.6 and 50. [17]

$$\mathrm{Re} = \frac{\rho * V * L}{\mu} \tag{6}$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{7}$$

The correlation for Nusselt number in eqn. (4) and eqn. (5) are for a horizontal flat plate while eqn. (8) and eqn. (9) are for a vertical flat plate. The major difference is the non-dimensional number used to quantify the flow. A vertical flat plate is dominated by buoyant forces compared to a horizontal plate and so the Rayleigh number is used in place of the Reynolds number. [17]

$$For\ Laminar\ Flow\ -\ Ra < 10^9$$

$$Nu = 0.68 + \left(0.670 Ra^{1/4}\right) / \left[1 + \left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{4/9} \tag{8}$$

$$For\ Turbulent\ Flow\ -\ Ra > 10^9$$

$$Nu = \left\{0.825 + \left(0.387 Ra^{1/6}\right) / \left[1 + \left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{8/27}\right\}^2 \tag{9}$$

The Rayleigh number eqn. (10) is the Grashof number eqn. (11) multiplied by the Prandtl number eqn. (7). Equation 11 shows that the Grashof number is the ratio of buoyancy force to viscous force, which can be mathematically represented as shown with the variables having the usual meaning. [17]

$$Ra = Gr * \Pr \tag{10}$$

$$Gr = \frac{\text{Buoyant Force}}{\text{Viscous Force}} = \frac{g\beta\left(T_s - T_\infty\right)L^3}{\nu^2} \tag{11}$$

In what follows, it is assumed that the modes of heat transfer described previously are instantaneously synchronous with the heat load start and end cycles. The amount of heat transferred to a material while not changing phase, the sensible heat, can be measured by measuring the temperature of the material. The sensible heat rate can be calculated using eqn. (12) as the product of the mass of the material, its specific heat, and the change in temperature.

$$Q = m * C_P * dT \tag{12}$$

G. WEATHER DATA – MONTEREY

This study was performed at the Naval Postgraduate School in Monterey, California. EnergyPlus offers weather files free for download online. These files are specific to each region around the world, and major cities within that region. The weather files contain average temperature, wind, and atmospheric conditions for each day based on historic data. They also include the position, direction, and intensity of the sun for the entire year. However, for this study, the actual atmospheric temperature was measured using a thermocouple throughout the experiment. These measurements were validated with meteorological data [18]. For calculations with EnergyPlus, the downloaded weather data file was used.

H. INTERNAL LOADS

Internal loads are heat sources that arise from within a zone. The term zone is identical to its usage in the EnergyPlus program, and in this thesis refers to the room the experiment took place. For this study, internal loads are divided into three major categories: people (occupancy), lights, and equipment. This study will simulate conditions such that the internal loads are present during a normal work day from 0800 to 1700. Within each category of internal loads there is latent and sensible heat transfer taking place. Latency of occupancy internal loads comes from water vapor and radiation that people produce. In other types of loads, it could be just the thermal inertia of the units. This latency causes a time delay in the sensible heat generated, which is expressed as a cooling load factor (CLF) associated with each internal load. The CLF is based on the total time the heat load was generated by the source and the time at which it was introduced into the zone. [19]

The internal load attributable to people can be found listed (per person) in Table 3. Based on the appropriate activity the corresponding load needs to be simulated. The resulting number can then be multiplied by the CLF in Table 4 to estimate the amount of cooling energy needed per hour per zone. Tables 3, 4, and 5 are included below from source [19] for completeness.

Table 3. Sensible and latent heat gain for typical applications (Btu/Hr) [19]. 1 BTUh is 0.293071 W.

Level of Activity	Typical	Heat Gain / Person BTUh	
	Application	SHG (qs)	LHG (ql)
Seated at rest	Theater	245	105
Seated, light work	Office	245	155
Moderate office work	Office	250	200
Standing, walking slowly	Retail Sales	250	250
Light bench work	Factory	275	475
Dancing	Nightclub	305	545
Heavy work	Factory	580	870

Table 4. Cooling load factors for people. Source: [19].

People ZONE Type = C Hours: 8:00 AM to 6:00 PM (10 Hours Total)

Total	Time of Day										
Hours	8	9	10	11	12	13	14	15	16	17	18	19
Space	Number of hours after entry into space											
↓	0	1	2	3	4	5	6	7	8	9	10	0
2		0.60	0.68	0.14	0.11	0.09	0.07	0.06	0.05	0.04	0.03	
4		0.60	0.68	0.74	0.79	0.23	0.18	0.14	0.12	0.10	0.08	
6		0.61	0.69	0.74	0.79	0.83	0.86	0.28	0.22	0.18	0.15	
8		0.61	0.69	0.75	0.79	0.83	0.86	0.89	0.91	0.32	0.26	
10		0.62	0.70	0.75	0.80	0.83	0.86	0.89	0.91	0.92	0.94	
12		0.63	0.71	0.76	0.81	0.84	0.87	0.89	0.91	0.93	0.94	
14		0.65	0.72	0.77	0.82	0.85	0.88	0.90	0.92	0.93	0.94	
16		0.68	0.74	0.79	0.83	0.86	0.89	0.91	0.92	0.94	0.95	
18		0.72	0.78	0.82	0.85	0.88	0.90	0.92	0.93	0.94	0.95	

The internal load resulting from lights depends on the wattage of the light bulbs and the percentage of lights that are on. Table 5 below gives the CLF for lights. The total heat produced from lights in watts is the product of the power of the light bulb and the CLF.

Table 5. CLF for lights. Source: [19].

Lights ZONE Type = D Hours: 8:00 AM to 6:00 PM (10 Hours Total)

Total	Time of Day											
Hours	8	9	10	11	12	13	14	15	16	17	18	19
Space	Number of hours after entry into space											
↓	0	1	2	3	4	5	6	7	8	9	10	0
8		0.66	0.72	0.76	0.79	0.81	0.83	0.85	0.86	0.25	0.20	
10		0.68	0.74	0.77	0.80	0.82	0.84	0.86	0.87	0.88	0.90	
12		0.70	0.75	0.79	0.81	0.83	0.85	0.87	0.88	0.89	0.90	
14		0.72	0.77	0.81	0.83	0.85	0.86	0.88	0.89	0.90	0.91	
16		0.75	0.80	0.83	0.85	0.87	0.88	0.89	0.90	0.91	0.92	

THIS PAGE INTENTIONALLY LEFT BLANK

III. DESCRIPTION OF THE STUDY

This chapter describes the experimental setup, including the office/lab space whose temperature was managed, the instrumentation used, data acquisition and processing methods used. The test conditions and process of verification of the results are also explained. Following these, the study was expanded to analyze the particular laboratory space thermal loads and analysis using the DoE/NREL provided EnergyPlus 9.0.1 through simulations with and without the use of PCM.

A. DETAILS OF LABORATORY SPACE

The laboratory for this study was a single room—zone—on the second floor of the Mechanical Engineering building of the Naval Postgraduate School, Monterey, CA. The floor area measures 2.87 meters by 2.79 meters and the room height is 2.85 meters. There are two single-pane windows side by side with each measuring 1 meter wide and 1.6 meters high. There is an air supply and return vent connected to the HVAC to manage the room temperature throughout the year. Both vents were sealed off during the study to prevent potential heat transfer from the room to the outside through them. The entrance to the laboratory was controlled through a locked door that was only opened for entry and exit of the operators. A door weather strip minimized air leakage into the room. This led to controlled thermal conditions in the room, with incident thermal radiation through the windows as the only uncontrollable heating parameter.

B. INSTRUMENTATION

Two different varieties of thermocouples were used in the study. The first was the type-K thermocouple probe. These thermocouples measured the room air temperature, the outside air temperature, the heater outlet, and the drop ceiling temperature. An arrangement of 16 thermocouples each 0.61 meters apart was placed at a height of 2.74 meters in order to measure the air temperature. There was one additional thermocouple to measure each of the other parameters described previously. The other thermocouple used was also of the type–K family, but was equipped with a self-adhesive tape for mounting where desired.

These allowed measurement of the temperature at the interface of the PCM and its aluminum drop ceiling panel shell and the outside of the pane as shown in Figure 5

Figure 5. Self-adhesive thermocouple at interface of PCM and aluminum shell

All thermocouple measurements were acquired using a LabVIEW driven data acquisition system. A series of National Instruments NI-9212 modules were used. The thermocouples plugged directly into the modules (see Figure 3) and allowed for the information to be recorded into a dedicated DAQ computer. An infrared laser thermometer was used periodically to verify the measurements registered by the data acquisition system.

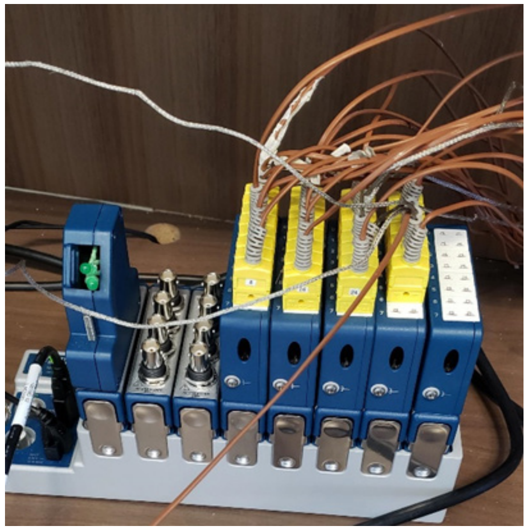

Figure 6. Thermocouples plugged into NI-9212 modules for data acquisition

A normal space heater was used to simulate and impose a controlled heat load into the room. The heater has an overload thermal protection feature and a rocker switch which made it compliant with safety standards. The heater has two power level setting set at 1500 W and 1300 W. The heater was connected to an energy and power meter to measure the energy consumed and assumed input into the room as thermal load. Additionally, a timer switch in it permitted controlling heater load cycling as desired. Another smaller capacity unit later in the study was substituted for the larger one in an attempt to simulate just the heat loads of the room occupants.

C. THERMOCOUPLE GRID

A skeletal grid was created to rigidly mount thermocouples at desired locations in the room. It was constructed out of standard “8020” extruded aluminum components. The frame consisted of a trapezoidal strut structure with five baseplates that could be rigidly attached to the ground and five “3030” columns that supported the top frame. Due to the pre-existing columns in the room, five columns were necessary. As shown in Figure 7, 2.44 m long “1515” slotted beams carried by these columns created a grid pattern that supported the thermocouples, at 0.6 m spacing. The thermocouples were rigidly attached to the slotted beams through corner brackets and screws.

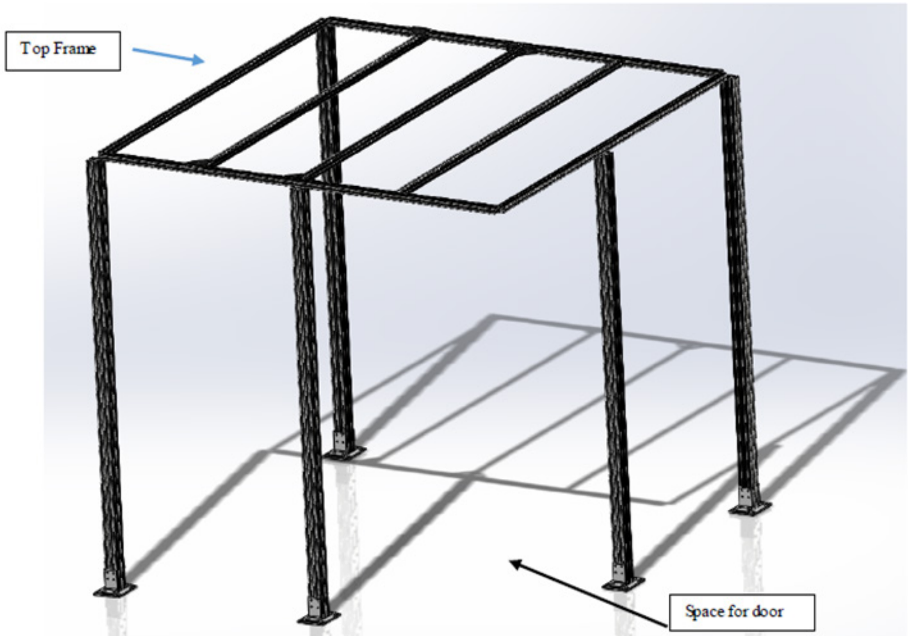

Figure 7. Model of aluminum 8020 frame. Made in Solid Works.

D. PCM PANEL MOUNTING

As stated earlier, the PCM was contained in easy to use panels. Differing numbers of these were used as replacement panels for the drop ceiling to document the effects of the PCM mass on cooling, Figure 8. Additionally, another PCM mounting structure was built using 8020 components which served as a parallel makeshift wall. Figure 9 shows an array of eight PCM panels that were placed in the wall. The most PCM panels installed were 12 panels, 4 in the ceiling and 8 in the wall.

Figure 8. PCM panel placed in the ceiling

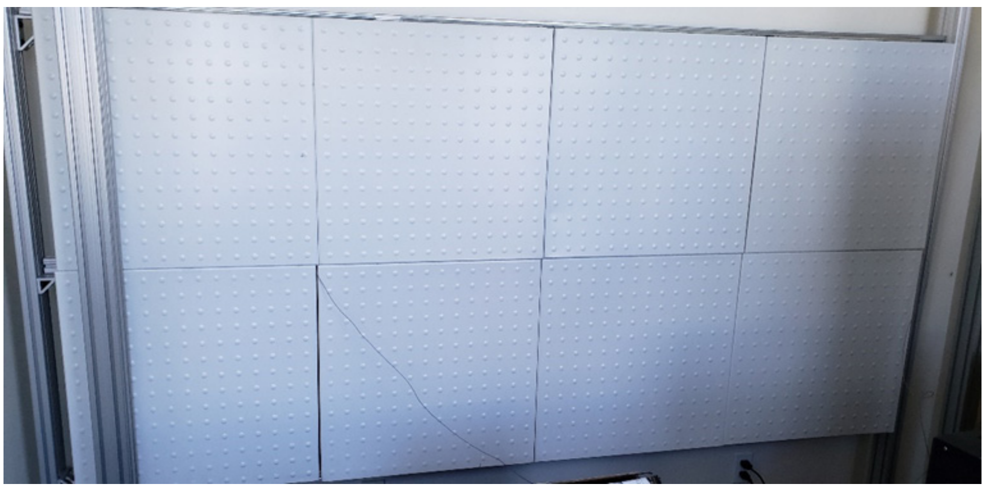

Figure 9. PCM panels placed in to wall

E. DETAILS OF THE EXPERIMENT

The study began with recording the temperature of the room throughout a 24-hr day. This revealed that the HVAC schedule used by the NPS Public Works (PW), Figure 10 plotted for January 6. In the results figures, each test day is plotted from 0600 HRS that day to 0600 HRS the next day. The results clearly showed that with HVAC system turned on as per pre-programmed schedule, producing a sharp rise in room air temperature to an uncomfortable 35º C (308 K) around 0600 HRS. It was explained that this sharp temperature spike was necessary to raise the room temperature to a comfortable value for occupants when the work day begins. The HVAC system turned on periodically throughout the day based on the room temperature of the room, occupancy motion sensors, and time of day. Such a large temperature, which was significantly above the PCM melting temperature of 23.4° C (295.4 K) and could cause the entire PCM to melt leaving it with little capacity available when needed through the day, and interfered with the study conditions. Also, as can be seen from Figure 10, the PW heating schedule included numerous uncontrolled oscillations which affected the study. Consequently, it was turned off and a space heater was set up to introduce prescribed heating cycles and loads.

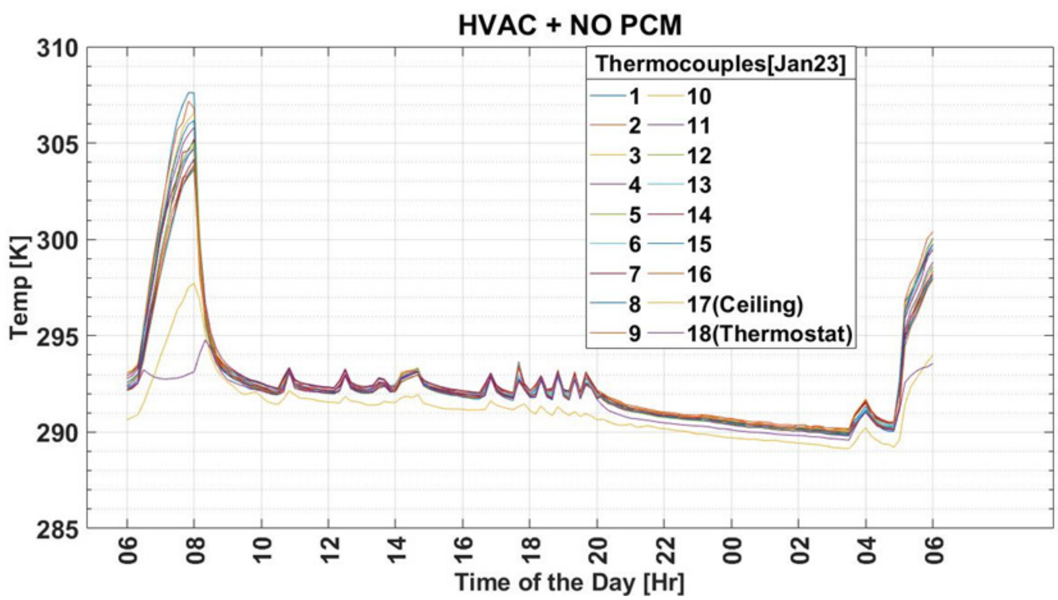

Figure 10. Room air temperature variations with building HVAC system use

With the HVAC system turned off and no other heat sources present, the air temperature was monitored to serve as a baseline for the study. Subsequently, specific heat load cycles were introduced using the space heater. Primarily, these were estimated using ASHRAE recommendations for building internal heat gains that routinely occur through occupancy, utilities, lights and equipment. Several different heating cycles were tested between 0800 HRS and 1600 HRS to reflect building occupancy and the concomitant load variations. Once the recorded room temperature variations demonstrated a repeatable pattern with the same heating cycle, two PCM panels were introduced and their number was slowly increased until noticeable cooling was observed. With 12 panels in place, other cycles were introduced. The details of the various test conditions are summarized in Table 6.

Table 6. Summary of test conditions

Test #	Heat Source	Heat Cycle	Cooling
1	HVAC	Preset	None
2	None	None	None
3	Heater—1500 W	1 hour on—1 hour off	None
4	Heater—1500 W	2 hours on—1.5 hours off	None
5	Heater—1500 W	2 hours on—1.5 hours off	2 Panels
6	Heater—1500 W	2 hours on—1.5 hours off	4 Panels
7	Heater—1500 W	2 hours on—1.5 hours off	12 Panels
8	None	None	12 Panels
9	Heater—1500 W	10 min on at 0900 & 1400	12 Panels
10	Heater—1500 W	20 min on at 0900 & 1400	12 Panels
11	Heater—1500 W	30 min on at 0900 & 1400	12 Panels
12	Heater—1500 W	5 min on—10 min off	12 Panels
13	Heater—1500 W	5 min on—55 min off	12 Panels
14	Heater—500 W	45 min on—15 min off	12 Panels

F. DATA PROCESSING

The data from the data acquisition software described earlier was first sorted and exported as a text file for further sorting and analysis using MATLAB. Data was collected every second, but only the temperatures at every minute were used for this study. All plots and calculations in this thesis were made with MATLAB.

G. VERIFICATION OF RESULTS

It is important to have an independent method of verifying results of any study. To that extent, the DoE/NREL supplied EnergyPlus software was used to compute the temperature variations in the room for several conditions for a model of the room. The model consist of four walls, a roof, floor and two windows, Figure 11. All dimensions of the model match the dimensions of the room described in Sec. 3.A. Standard material and construction details recommended by EnergyPlus were used for the walls. Thus, the walls were constructed with two layers of gypsum and an air gap in-between. These interior surfaces were treated as adiabatic walls since the outside of the wall was inside a larger lab space and thus, its temperature was close to that inside the room. The wall with windows facing outdoors was not adiabatic. This wall experienced heat transfer from the ambient to the room air, which effectively introduced the effects of the ambient temperature difference changes, wind effects, etc., on the room thermal energy equilibrium. No solar exposure was included since there is a tree and building that provide shading for the room throughout the day. The PCM wall (see Figure 9) was modeled by adding another layer to the interior walls. This layer used material properties of the PCM and given enough thickness to match the mass of the total PCM used. Conduction Finite Differencing (CondFD) and a larger number of time steps were specified when using the PCM so that EnergyPlus can calculate the various quantities using the temperature differential within each layer of the material. Otherwise the entire material volume would be treated as isothermal, which leads to erroneous computational values.

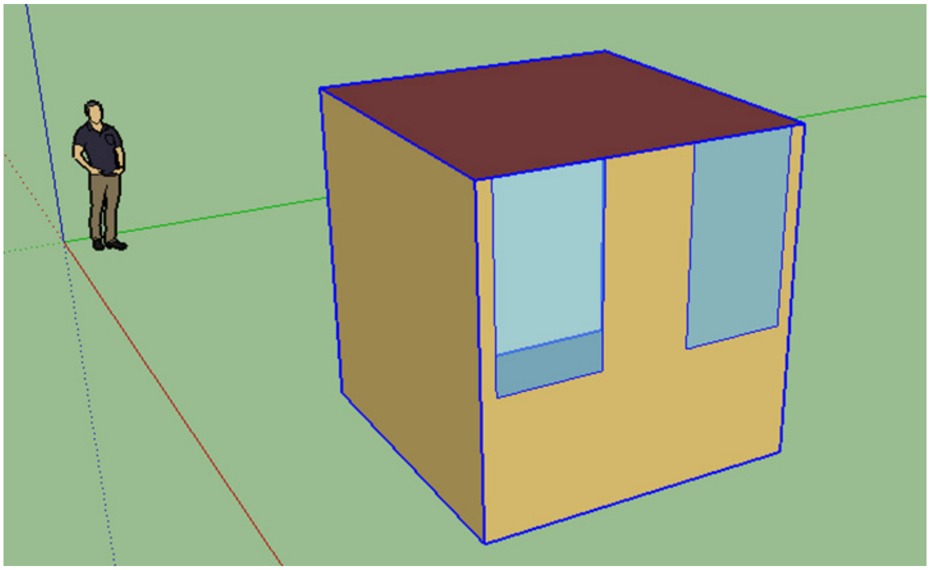

Figure 11. EnergyPlus model of thermo-controlled room created using SketchUp2017

Various heating schedules matching the actual heating cycles were run for several of the cases described in Table 6. These cases were run for two design days, one in January and one in June. This allowed the ambient temperature to have an appreciable effect on the temperature of the room, as seen in the results. The variables changed for each case were the heat loads, the heat load schedule, and the amount of PCM present. All objects changed within the EnergyPlus input file can be found in the EnergyPlus Input Output Reference [20].

EnergyPlus also allows calculation of the total energy bills for the test space using specific location energy rates. In an attempt to estimate potential cost savings of using PCM in this study, calculations were also run for the first working day of every week of the year and the results were compared with and without the PCM in use.

H. EXPERIMENTAL UNCERTAINTY

The most variable parameter that contributed to the uncertainty of this study was the Monterey area weather. The varying amounts of solar loads and ambient air temperatures can only be sufficiently quantified on a case by case basis. As tests progressed, the weather continuously changed with seasons. However, as shown in the experimental results, the weather affected the temperature of the room by a maximum of two degrees. The next source of uncertainty was from the thermocouples. The manufacturer suggests +/- 2.2 C or +/-.75% limits of error. Thus the measurements captured by the data acquisition system and the temperature measured with the infrared laser thermometer on average measured to within +/- 2 C.

IV. RESULTS

This chapter is composed of two sections. The experimental results are discussed in the first section. The measured room air temperature averaged over all the 18 thermocouple values, the ambient outdoor temperature, and a reference line for the PCM melting temperature are presented on all data plots. The second section is comprised of the analytical results from EnergyPlus. The data is represented in two types of plots. Each plot shows the zone temperature of the experimental room model.

A. EXPERIMENT RESULTS

The first set of experimental conditions were no internal heat gains and no PCM in the room, the results are shown in Figure 12. The room air temperature stayed low and within the generally accepted comfort zone with a maximum of about 21ºC. Clearly, without internal heat gains this meant there was no need for cooling. Figure 12 also shows that during the day time, the room temperature difference with the outdoor air was about 7 K with the exception between the hours of 11:30 AM and 12:30 PM. The room air temperature changed gradually through the day.

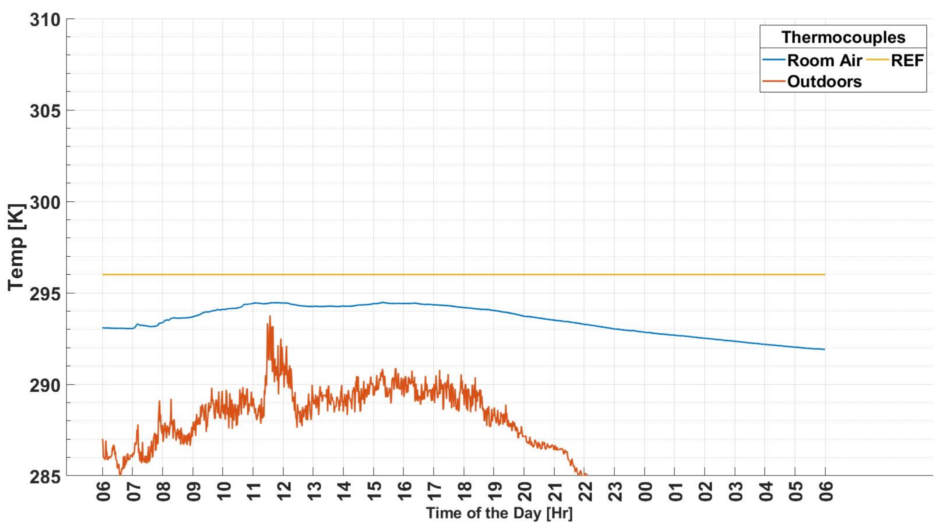

Figure 12. Room air and ambient temperatures: No PCM, no heating

The outdoor temperature was slightly noisy due to atmospheric factors like wind, rain and so on. Even so, this is considered a good and accurate measure of the local air temperature outside of the window. A comparison of the measured outside air temperature with the meteorological data for the Monterey area for April 28, Figure 13 confirmed the measured range of value and trend observed with varying hours of the day.

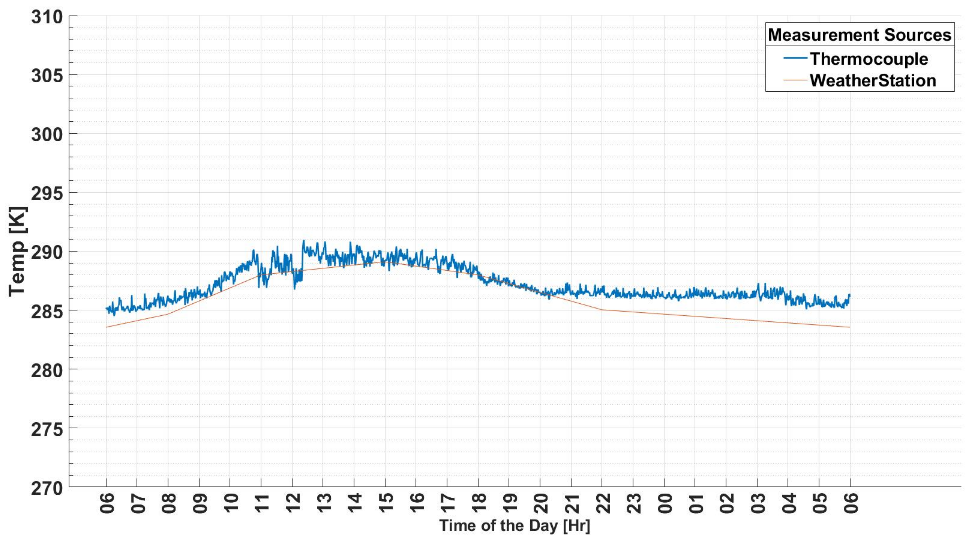

Figure 13. Weather data comparison of thermocouple measurement to the meteorological data

The results in Figure 14 show the addition of PCM into the experimental environment with no internal heat gains added. The only source of heat gain throughout the day was the outside ambient environment. The reason for this step was to document the effect of adding PCM panels when no internal heat gains were present so that a reference basis could be established for later parts of the study. As described earlier, the use of 12 PCM panels was arrived at by experimental trials in which the number of PCM panels was gradually increased in the room until a measurable effect was seen.

The temperature of the room, once again, stayed below the melting temperature of the PCM. This is important because PCM use is intended to exploit its latent heat to produce cooling effects. It is then clear that without any internal heat gains, there was no need to cool the room on the day this experimental data was acquired. As can be expected, Figure 14 shows a similar relationship between the average room temperature and the outside ambient. Any differences seen in temperature was because of variations in the overall outdoor ambient conditions. To determine the effectiveness of PCM the temperature of the room must be raised above the PCM melting temperature.

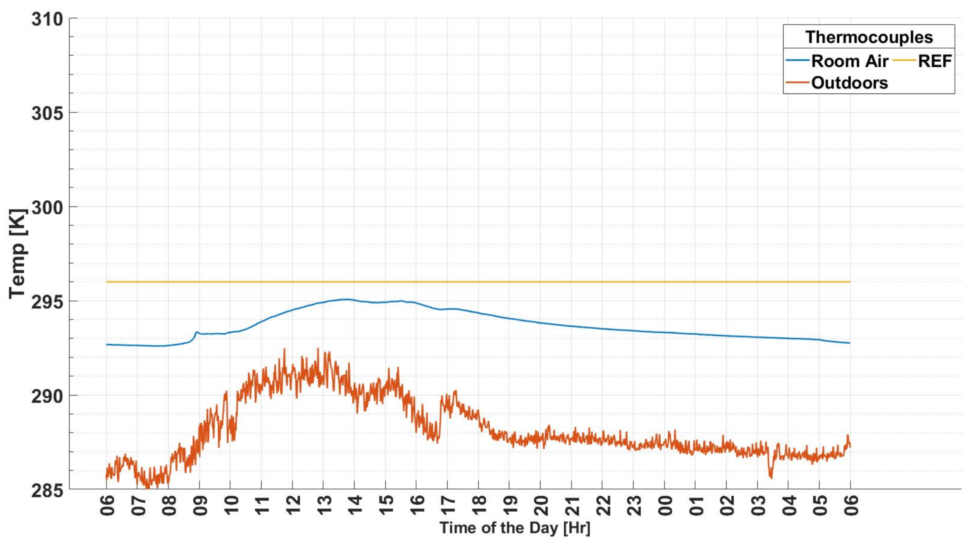

Figure 14. Room air and ambient temperatures: 12 PCM panels, no heating

Consequently, heat loads were introduced into the room using a space heater as described earlier. The initial heating schedule implemented was aimed to introduce all the energy from the internal gains, discussed earlier, into the room in just two cycles. The hypothesis was that once the energy was introduced, the PCM would absorb it as its latent heat, and cooling could be observed. As can be seen from Figure 15, the schedule resulted in peak heater exhaust temperature of over 40 K above the PCM design temp of 294 K. But the temperature of the PCM panel itself remained close to its melting temperature, with only a small increase above it during the afternoon hours. However, the extreme and rapidly imposed temperature change seemed to increase the room air temp to only about 3–5 K above the PCM melting temp. The overall air temperature varied by 6–8 K. Whereas, this can be acceptable for the short periods of time seen in the figure, the ultimate goal of the study was to establish the feasibility of maintaining the room air temperature close to the PCM design temperature. The rapid fall of the PCM temperature indicates that it had not melted fully and so, in the absence of additional imposed heat loads, would remain low. It was deduced that because of the low thermal conductivity of the PCM material, a longer charging time would be useful. Despite these deductions, it became clear that a potential benefit of PCM is that the room air temperature is not as affected by the outside air temperature when internal heat gains are added (see the spike in outside temperature between 1100 HRS and 1230 HRS in Figure 15). This result appeared to hold until the room air temperature dropped below the PCM melting temperature (at around 2000 HRS) at which point the room air temperature fell synchronously with the outdoor temperature.

When the ambient environment does not have drastic spikes in temperature, as is usually not the case, the results in Figure 15 and Figure 16 appear similar. The same heating cycle was implemented for Figure 15 and 16, however, the ambient temperature did not exceed the room air temperature or the PCM melting temperature.

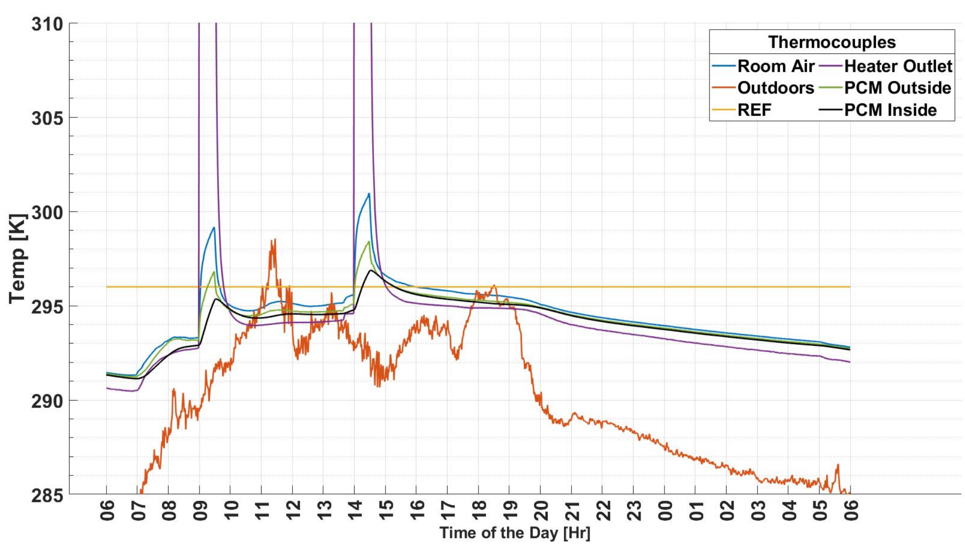

Figure 15. Room air and other measured temperatures Rapidly introduced heat load; 12 PCM panels with heating

While the general trend is the same for both sets of results, Figure 16 has a lower average temperature than Figure 15. The outside air temperature rises quickly in Figure 15 around 0800 HRS, before the room air temperature got close to the PCM melting temperature. If the PCM in Figure 16 had melted, it would have solidified close to its melting point. Since the temperature fell immediately once the heat turned off it can be assumed there was little to no melting meaning no latent heat transfer.

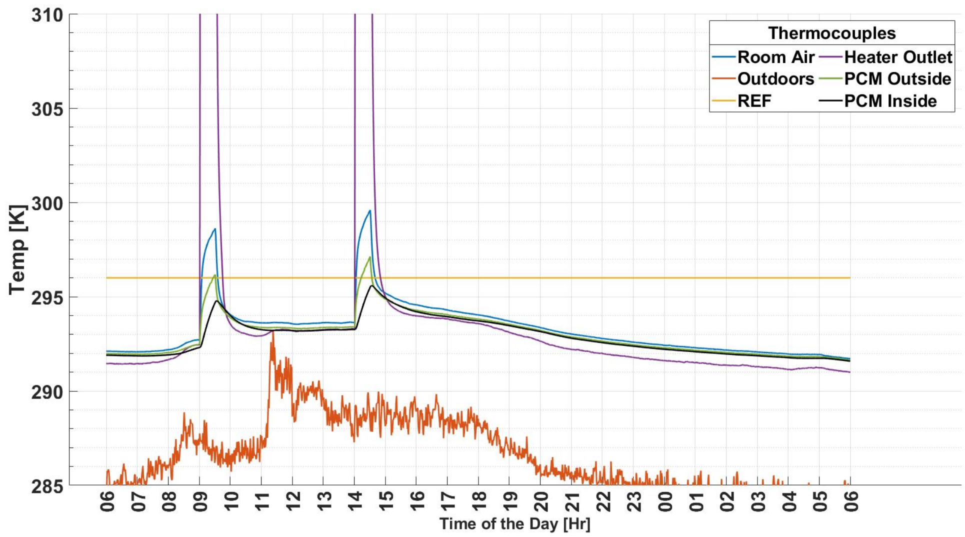

Figure 16. Room air and other measured temperatures Rapidly introduced heat load; Typical Monterey area day; 12 PCM panels with heating

An interesting observation in Figure 15 is that between 1000 to 1200 HRS, the outside air temperature was noticeably higher than the PCM melting temperature of 296K. This caused the PCM temperature to show a very slight upswing, but was still about 5K below the air temperature at its peak. The proper heating cycle due to occupancy is generally a steady heat load. As stated earlier, the room can safely house two people. The heater could not introduce the exact heat load in a steady manner due to its design features. Also, to incorporate the fact that people take breaks and leave the room meant that an intermittent schedule with long on-times and short off-times was needed for a better representation of the conditions for which the PCM cooling method is to be proven. Such a heating cycle was introduced and can be seen in Figure 17. This heating cycle incorporates the total energy from the internal gains, which was calculated earlier, for the full work day. Due to the design constraints of the heater it was turned off for 15 minutes after being on for about 90 minutes, yet the total energy input matched the intended amount.

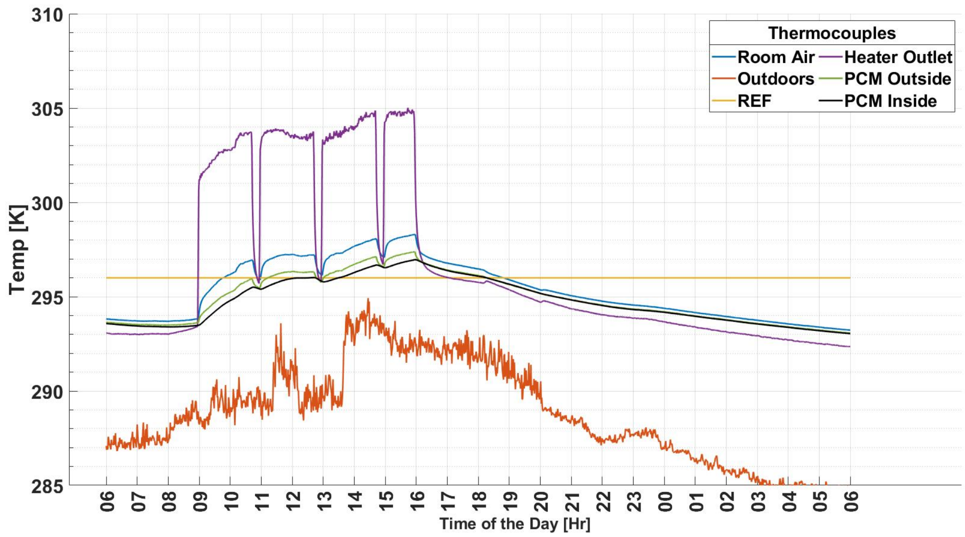

Figure 17. Room air and other measured temperatures: Gradually introduced heat load; Typical Monterey area spring day; 12 PCM panels with heating

The results in Figure 17 show that from 1100 HRS to 1400 HRS (can be deemed peak afternoon hours) the room air temperature stays reasonably steady. Even after that, the air temperature rises by only a degree until 1630 HRS (near the end of work day). This increase also corresponds to an increase in the PCM temperature which is now in its liquid phase. It can be seen that the average room air temperature hovers within a degree of the PCM melting temp, and almost near that value between 1100 HRS to 1400 HRS. Thus, it appears that the goal of the project was met. This data set was acquired during the mid-spring season and the diurnal temperature varied (the red line) by over 10 K, but the temperature inside the room was within 5 K.

The discharge phase for the results shown in Figure 17 started when the heat turned off at 1600. At that point there is a gradual decline in the temperature of the room and the PCM temperature drops gradually as it loses its sensible heat. Only after 1800 HRS did the latent heat feed back into the room air as the PCM cooled further. These results can be better seen by examining Figure 18. After about 0900 HRS, the room air is at the PCM temperature, both are below the PCM fusion temperature, a trend that is maintained the rest of the data cycle (i.e., until the next day).

When reading Figure 16 with Figure 17, it can be seen that there is an immediate 0.8 K drop in Figure 17 and a 4.4 K drop in Figure 16. While both sets of conditions involved 12 PCM panels within the room, data in Figure 17 correspond to a longer charge phase. A longer charge phase is important since the panels have low thermal conductivity which implies the PCM takes a longer time to melt and thus, can maintain the temperature closer to its melting temperature. Similarly, the PCM becomes a better source of heat (thermal storage system) when all of the material is undergoing a full phase transition from gel back to solid.

Figure 18 also helps highlight the increase in the nighttime temperature with PCM, and with a long discharge phase. The room air temperature remained within a degree of the PCM melting temperature five hours after the discharge phase started. It can naturally be expected to follow the ambient outdoor temperature, but the difference between the ambient outdoor temperature and the room air temperature constantly increased as the night progressed. This affirms the deduction that the PCM is able to maintain an environment close to its melting temperature. Figure 19 compares the temperature difference between the room air and the PCM melting temperature for the data from Figure 16 and Figure 17. Again, this illustrates the initial drop in temperature proceeding the end of each heating cycle. It also helps highlight that with a longer charge phase there is more potential for latent heat absorption. Despite the room air of the more intense heating cycle reaching higher peak temperatures, it loses most of the energy and drops below the PCM melting temperature almost instantly. The room air with lower intensity, but longer duration heating drops to the PCM melting temperature 3 hours after the heating stops. An energy balance performed on the results in Figure 17 helps shed some light on the various sources of loss and gain involved in this experiment.

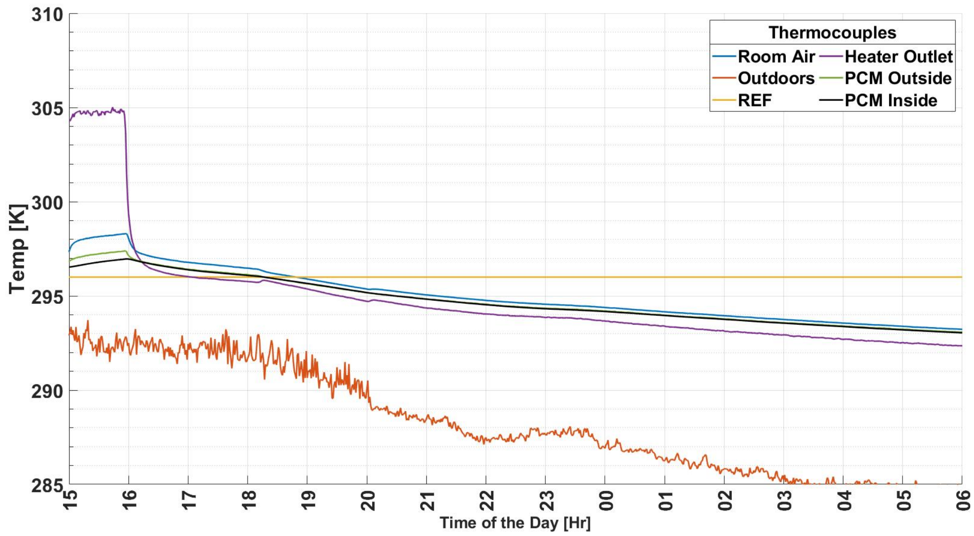

Figure 18. Detailed view of the nighttime hours from Figure 17

The energy balance takes into account heat transfer from the heat source to the air, PCM, window, and walls of the room using experimental temperature data, known material properties, and the correlations discussed earlier in the background chapter. The results are displayed in Figure 20. The percentages of Figure 20 are the values from Table 7, which were normalized using the total heat energy input by the heater using the energy meter reading. It is clear that the single pane glass window accounts for a large portion of the energy loss from the room. The effects of this are seen in the experimental results whenever the heat is turned off and there is a sudden drop in temperature. The next major energy loss is to the PCM latent heat. The walls because of their high thermal mass absorb heat similar to the PCM, but without changing phase, and to a lesser degree. The latent heat absorbed by the PCM and the walls, aside from the window, are the main sources of heat absorption that help decrease the peak temperature. These walls and PCM together are the causes as to why the temperature was maintained throughout the night.

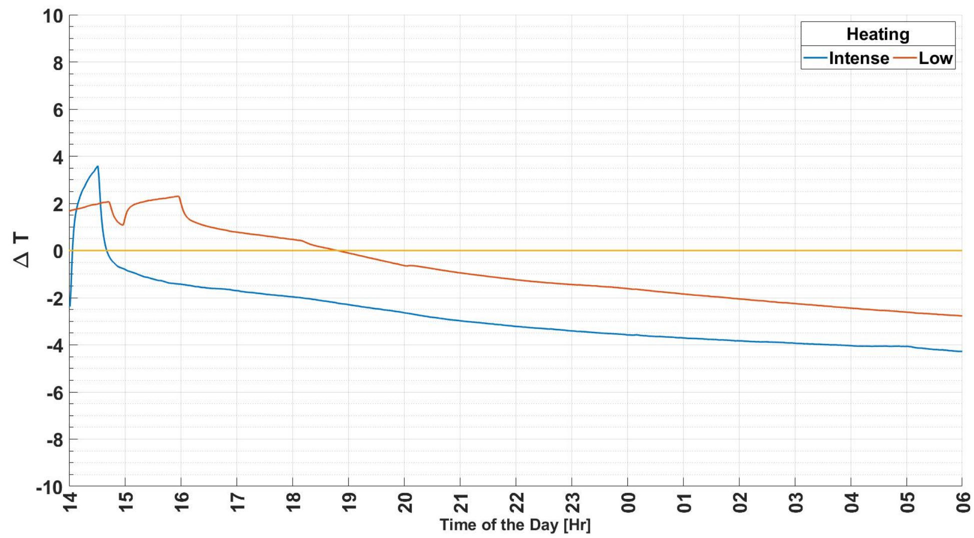

Figure 19. Temperature difference between the room air and the PCM melting Temperature for Figure 16 (rapid heat load input, and Figure 17 gradual heat load input)

Table 7. Energy balance quantities

SOURCE	ENERGY (KJ)	EQN
Input Heat Load	10828.8	N/A
Air	81.1	12
PCM(Sensible)	54.2	2
PCM(Latent)	2250	12
Window	7101.7	2
Walls	1007.3	2

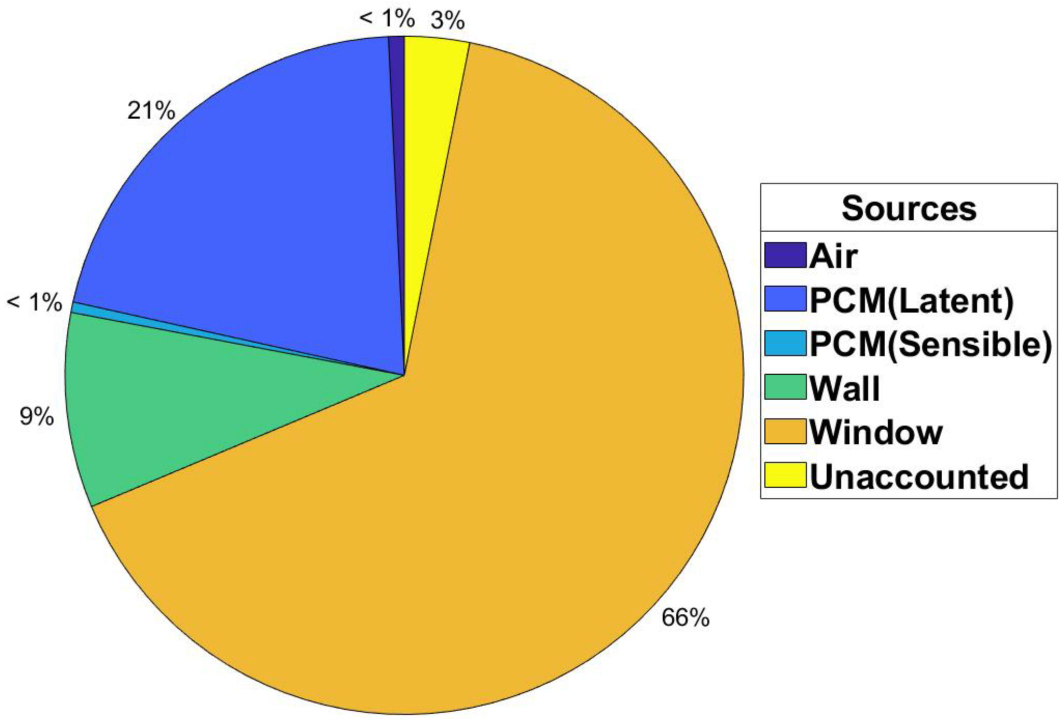

Figure 20. Energy balance

The results in Figure 21 had the same experimental conditions as those in Figure 17, but the PCM mass was doubled. An extra layer of macroencapsulated PCM was added to the back of each panel. The varying ambient temperature makes it difficult to compare the temperatures of Figure 21 and 17 directly, but the response of the PCM is shown to be unique for each set of experimental conditions. Figure 21 shows that simply stacking layers of PCM does not add much benefit for set internal heat gains. However, the response of the PCM inside temperature in Figure 21 follows room air temperature response to heating much less than it does in Figure 17. This suggests that there may still be some unused latent heat to cool. The amount of heat transferred through the PCM is limited to how much energy the surface can transfer by convection, and then the subsequent conduction through the material. Since the thermal conductivity of the PCM and its encapsulation is very low, along with the fact that the gel like material shifts it cannot be ascertained if the material fully melted and if so, at which stack level. If the material had been spread out to increase surface area, and the mode of heat transfer changed to predominantly convection, then perhaps there may have been a pronounced effect as the one seen in Figure 17.

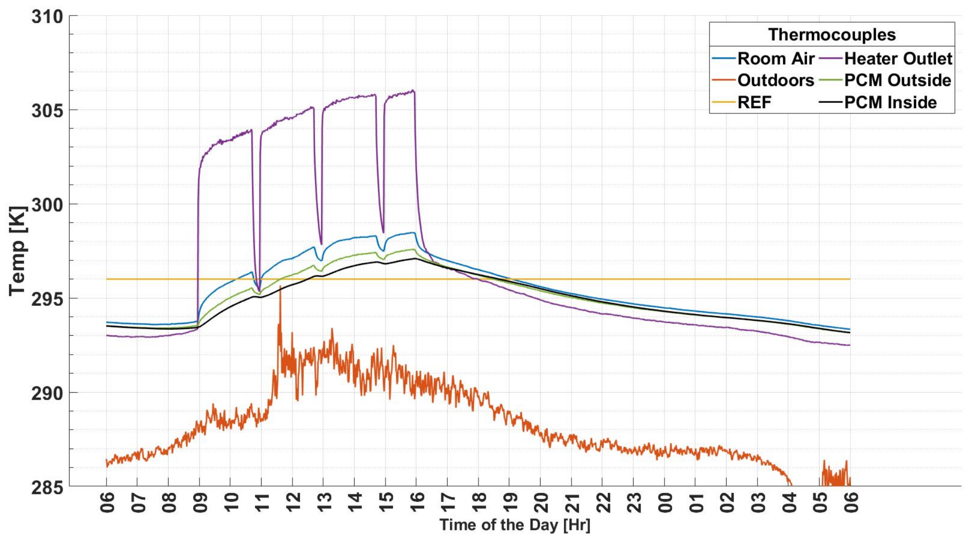

Figure 21. Room air and other measured temperatures; Gradually introduced heat load; Typical Monterey area spring day; 12 PCM panels with double PCM mass and heating

B. ANALYTICAL RESULTS

The results of energy and temperature calculations obtained through EnergyPlus were comparable to the experiments. Figure 22 is a plot of the average zone temperature from a winter design day in January. For these calculations, the average weather data for ambient outdoor conditions January was used while the heat load imposed was the same as the internal heat gains established earlier. The only difference was internal heat gain was present in the room for the duration of the work day with no breaks. For the winter design day in Figure 22 the overall trend of the curves is similar to that seen for the room air in Figure 17. Figure 22 confirms that the average nighttime temperature is warmer with PCM present. With the PCM, the room air temperature is nearly steady at 27ºC compared to the PCM design temperature of 23ºC. However, the calculations did not account for the heat loss through the windows and so, this result is accepted as consistent. Without the PCM, the room air temp rises gradually through the work day by about 7ºC, which is normally considered to be a large change and adds to the occupants' discomfort. Without the internal heat gains the overall temperature of the room is higher with PCM, and so, it seems to be a better situation.

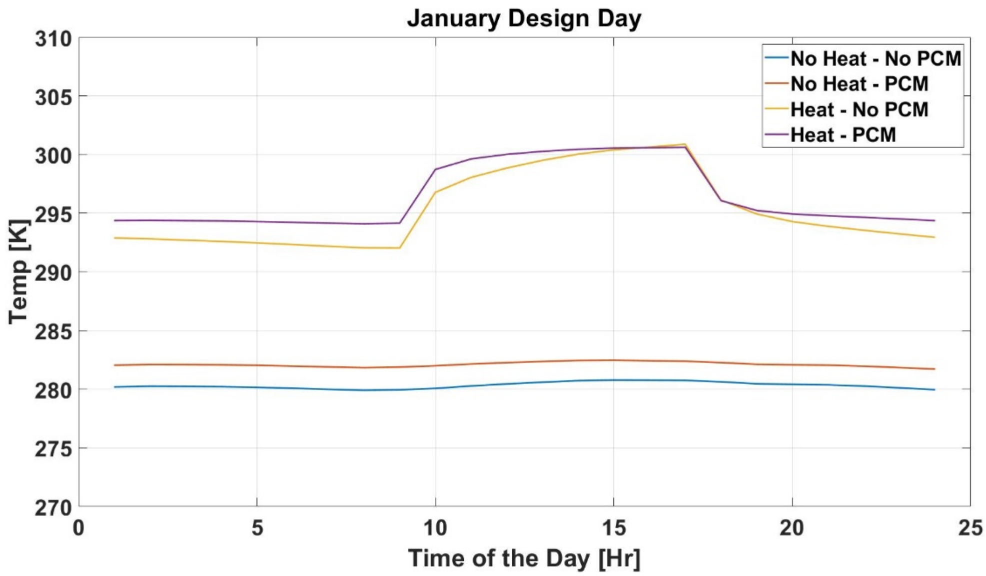

Figure 22. EnergyPlus results for a winter design day with/without heat and with/without PCM

A similar analysis for a summer day is presented in Figure 23. Due to the warmer ambient, the outdoor heat load causes the peak room air temperature without PCM to be higher than a summer design day with PCM by 2.5 K. Corresponding experimental data for summer temperatures is not yet available at this time and hope to be generated in the near future. Regardless, the EnergyPlus analysis shows that with PCM installed, the room air can be *passively* cooled even for this conditions by an average of 1.5ºC to 2ºC over the course of the work day.

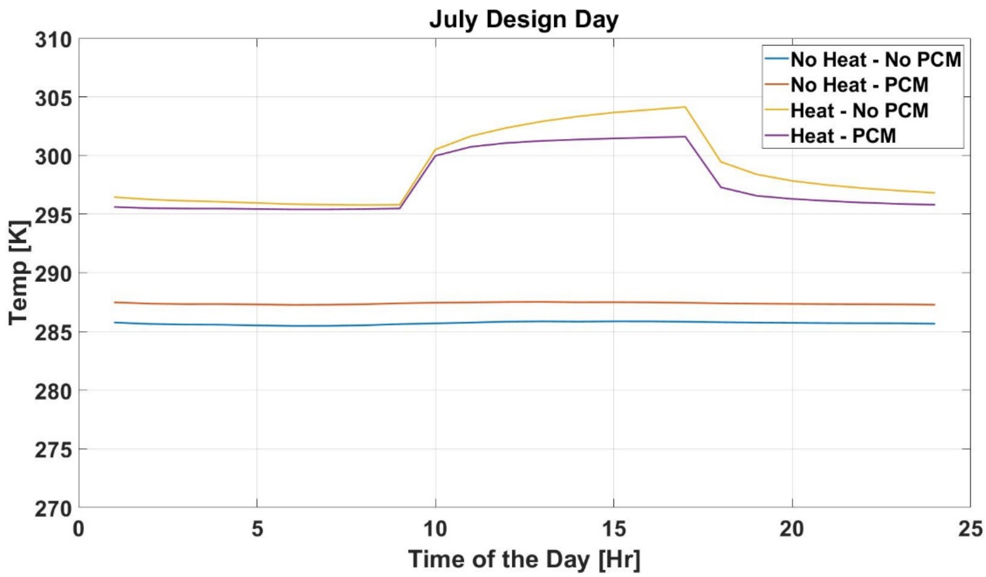

Figure 23. EnergyPlus results for a summer design day with/without heat and with/without PCM

A major advantage of the simulation software is that a variety of practical situations can be simply realized to quantify the benefits of the use of PCM over extended periods. Similar experimental studies are more difficult to perform due to the many variables that (including the length of the tests measured in weeks) which can affect the results.

Here, EnergyPlus was used to derive an estimate of the temperature variations over the course of a year. Figures 24–27 show these results; more specifically they present results spanning 52 weeks, with a single day from each week. Fours specific cases were run, one with No PCM and No Internal Heat Gains (Heat), PCM, but with No Heat, No PCM, but with Heat and PCM with Heat. The corresponding room air temperature plots are shown in Figures 24–27.

For the first two cases with no internal heat gains the average temperature for the room with no PCM, Figure 24, was less than the room with PCM, Figure 25. The peak temperature for the room without PCM was 290.4 K and for the room with PCM it was 292.1 K. Both of these happened week 39, (around the end of the summer), and both are still under the melting temperature of the PCM.

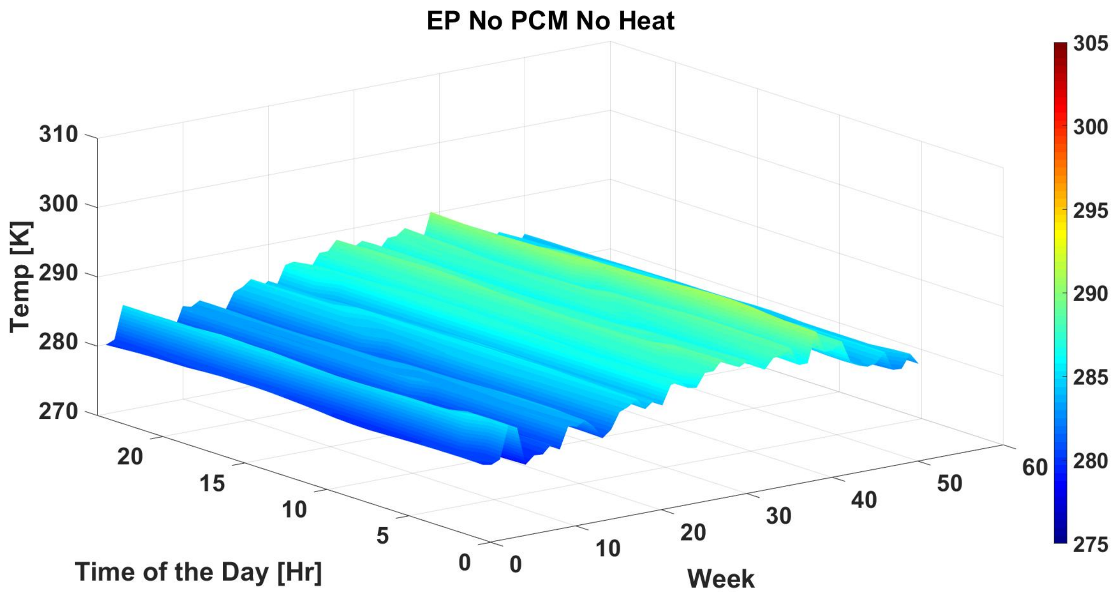

Figure 24. Temperature throughout the day for one day a week for 52 weeks with no PCM present and no internal heat gains

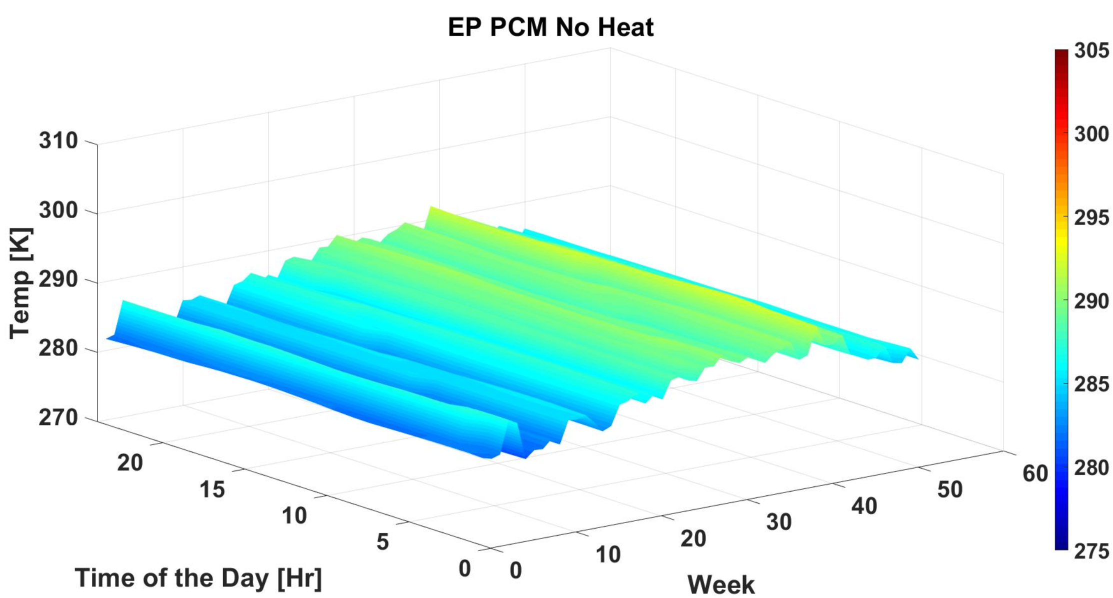

Figure 25. Temperature throughout the day for one day a week for 52 weeks with PCM present but no internal heat gains

The next two cases have internal heat gains. It should be noted that the plots, Figure 26 and Figure 27, show the zone temperature for the year. There is a peak temperature within the zone that shifts in time and slightly in temperature each week. The peak is towards the end of the summer around week 40.

For the case of the room with PCM, Figure 27 shows that temperature is higher during the winter months and that temperature is lower during the summer months (no black color) compared with the room with no PCM, Figure 26. The peak temperature out of the year for the room with no PCM was 302.9 K while the peak temperature out of the year for the room with PCM was 300.1 K. This is a 2.8 K peak temperature difference for the year. If this model is accurate to within a degree then the advantage of PCM use is evident here in maintaining the room around the melting temperature of the PCM and for reducing the peak temperature. This will reduce heating costs in winter months and cooling costs in summer months.

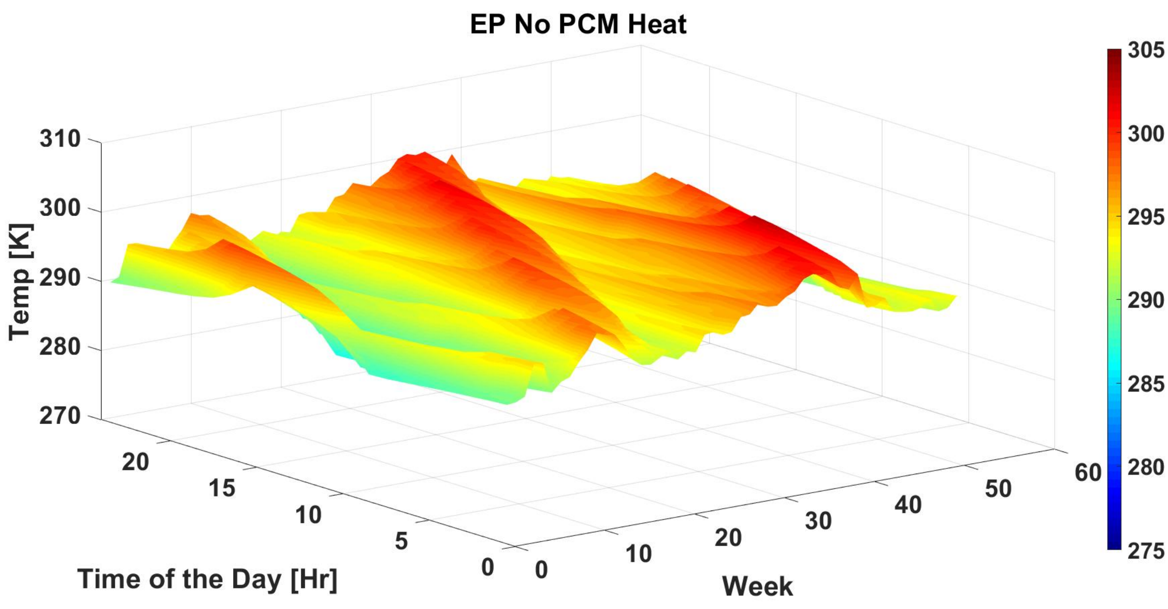

Figure 26. Temperature throughout the day for one day a week for 52 weeks with no PCM present but internal heat gains

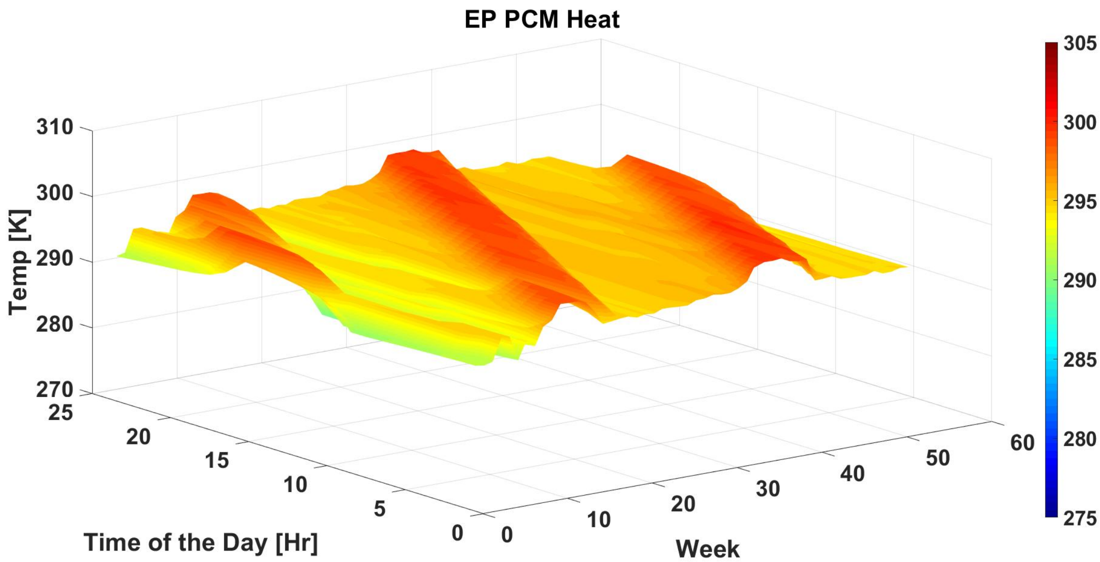

Figure 27. Temperature throughout the day for one day a week for 52 weeks with PCM present and internal heat gains

Overall, the dynamics of the temperature profile for the EnergyPlus results were comparable to the experimental results, even though the experimental temperatures were off by a few degrees. This is most likely due to the variability of the weather and the modeling of the room, especially the exterior wall and window. There were more losses for the experiment all together than there were for the EnergyPlus model. This is what ultimately led to the increased nighttime temperature for winter analytical cases with PCM, and the decrease in peak temperature for summer analytical cases with PCM.

C. COST ANALYSIS

Using the results shown in Figure 17 and the energy balance it should be noted that the PCM cooled the room by 1.1 K. This was found by taking the latent energy stored in the PCM Table 7 and using eqn. (12) to calculate how much temperature change this is for the room air. Taken from multiple sources and averaged, the national average cost for electricity is \$0.132 per kWh. Using all this information, the cost to cool or heat the room as appropriate by 1.1 K for a year is \$87. Twelve panels were deduced to be the minimal amount to produce these results, with each panel costing \$40 each. This results in a \$480 initial cost and a payback time of 5.5 years.

V. CONCLUSIONS

In this thesis, organic macroencapsulated PCM inside aluminum panels were implemented directly into a controlled environment. Various temperatures were recorded over a 24-hour period in order to observe the effect PCM had in keeping the room air temperature within a desired range. The goal was to see if PCM could help maintain the room air temperature within a particular comfort zone throughout the day. The key conclusions from a portion of this study are listed.

The experiment:

- The goal was achieved, and the room air temperature was properly maintained within 2 degrees of the PCM melting temperature for most of the day.
- A PCM-controlled environment minimizes the fluctuations of the temperature due to the ambient environment.
- Utilizing a gradual heating scheme allows for a more effective use of the PCM latent thermal energy storage.

The energy balance and heat transfer calculations:

- PCM accounted for 21% of the total cooling.

The analytical results from EnergyPlus:

- Peak temperatures over the year with PCM were lower.
- Winter time temperatures were higher and Summer time temperatures were lower with PCM.

The conclusions stated in this thesis are unique to the type of PCM used, where it was implemented, room setup, and environmental ambient conditions. While they are not easily comparable to the conclusions found by others, they are inherently cohesive to the nature of PCM as reported by others.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A: MATLAB CODE FOR SORTING RAW DATA

```
%% Reading in Thermocouple Data from Text File (Cleaning and Cutting)
%%By Julian Martinez
%%With help from Professor Dausen

%Pressure Data Columns
%1.  Time (sec)
%2.  Pressure1 (psig)
%3.  Pressure2 (psig) ...

%Temperature Data Columns
%1.  Time (sec)
%2.  Temperature1 (F)
%2.  Temperature1 (F) ...

clc
clear all
close all

%% Inputs
% Format for input DD/MM/YYYY,HH:MM
StartDate = '04/17/2019,15:01';
EndDate = '04/18/2019,06:00';

% File name for upload
FileName = 'OfficeTemperatureOneDataApr17Run01.txt';
FileName2 = 'OfficeTemperatureTwoDataApr17Run01.txt';

% # of thermocouples used for this file +1 for time column
% 2 text files being read in
tc = 24+1;
tc2 = 16+1;

%% I
% The Low Speed data is imported and cleaned.  The timestamp is
modified to
% read only seconds and the spaces through the run
%  are ommited (sorted to the end).
%  The resultant variable LowSpeedData contains all of the raw data for
%further analysis.
LowSpeedOrig = importdata(FileName);  %Original for testing

LowSpeedRawData = LowSpeedOrig.data;
LowSpeedTime = LowSpeedOrig.rowheaders;

DataPoints = length(LowSpeedRawData);

TimeNum = zeros(DataPoints,1);
TimeStamp = char(LowSpeedTime(1:DataPoints));
```

```
% Put the date column vector in proper notation(no spaces only ,:/)
Time = strings(DataPoints,1);
for K = 1:DataPoints
    if TimeStamp(K,9) == ' '
Time(K,1) = horzcat(TimeStamp(K,1:8),',',TimeStamp(K,11:16));
    else
Time(K,1) = horzcat(TimeStamp(K,1:9),',',TimeStamp(K,12:17));
    end
end

formatin = 'mm/dd/yyyy,HH:MM';
for K = 1:2:DataPoints
    TimeNum(K,1) = datenum(Time(K,1),formatin);
end

LowSpeedData = horzcat(TimeNum, LowSpeedRawData);

% May need to change tc if thermocouple # changes
temp = zeros(round((length(LowSpeedData)/2)),tc);
for j=1:tc
k=1;
for h=1:2:length(LowSpeedData)
    temp(k,j) = LowSpeedData(h,j);
    k=k+1;
end
end
LowSpeedData = temp;

%%
% Create for loop to decrease the size of the data from a data point
every
% second to a data point every minuteby taking the matrix and equating
it
% to a new matrix with only index multiples of 60
row = length(LowSpeedData); %cuts zeros out of data
Temp = zeros(round((row/60)),tc); % creates a matrix to...
                                  %store every 60th or every minute
for j = 1:tc % tc columns time --> temp1 -->temp2...
    k = 1; % counter for the row number must reset every column
for i = 1:60:row  %actual method for cutting down the data
    Temp(k,j) = LowSpeedData(i,j); %puts values into temp matrix
    k = k+1; %actual row counter
end
end

StartI = find(Temp(:,1)==datenum(StartDate));
EndI = find(Temp(:,1)==datenum(EndDate));

PartI = Temp(StartI:EndI,:);

%% II
% Text file 2
% The Low Speed data is imported and cleaned.  The timestamp is
modified
```

```
% to read only seconds and the spaces through the run
%  are ommited (sorted to the end).
%  The resultant variable LowSpeedData contains all of the raw data
for...
                                                        % further
analysis.
LowSpeedOrig2 = importdata(FileName2);  %Original for testing

LowSpeedRawData2 = LowSpeedOrig2.data;
LowSpeedTime2 = LowSpeedOrig2.rowheaders;

DataPoints2 = length(LowSpeedRawData2);

TimeNum2 = zeros(DataPoints2,1);
TimeStamp2 = char(LowSpeedTime2(1:DataPoints2));

% Put the date column vector in proper notation(no spaces only ,:/)
Time2 = strings(DataPoints2,1);
for K = 1:DataPoints2
    if TimeStamp2(K,9) == ' '
Time2(K,1) = horzcat(TimeStamp2(K,1:8),',',TimeStamp2(K,11:16));
    else
Time2(K,1) = horzcat(TimeStamp2(K,1:9),',',TimeStamp2(K,12:17));
    end
end

formatin = 'mm/dd/yyyy,HH:MM';
for K = 1:2:DataPoints2
    TimeNum2(K,1) = datenum(Time2(K,1),formatin);
    %TimeNum(K,1) = str2double(TimeStamp(K,18:26))';
end

LowSpeedData2 = horzcat(TimeNum2, LowSpeedRawData2);

% For 19 thermocouples (may need to change if # thermocouples changes)
temp2 = zeros(round((length(LowSpeedData2)/2)),tc);
for j=1:tc2
k=1;
for h=1:2:length(LowSpeedData2)
    temp2(k,j) = LowSpeedData2(h,j);
    k=k+1;
end
end
LowSpeedData2 = temp2;

% below line is wrong
% LowSpeedData = sort(isnan(LowSpeedData),1);  %Sort is completed by
time and eliminates the NaN by placing at end

%%
% Create for loop to decrease the size of the data from a data point
every
% second to a data point every minuteby taking the matrix and equating
it
```

```
% to a new matrix with only index multiples of 60
row2 = length(LowSpeedData2); %cuts zeros out of data
Temp2 = zeros(round((row2/60)),tc2); % creates a matrix to store every
60th or every minute
for j = 1:tc2 %25 columns time --> temp1 -->temp2
    k = 1; %counter for the row number must reset every column
for i = 1:60:row2  %actual method for sorting the data
    Temp2(k,j) = LowSpeedData2(i,j); %puts values into temp matrix
    k = k+1; %actual row counter
end
end

StartII = find(Temp2(:,1)==datenum(StartDate));
EndII = find(Temp2(:,1)==datenum(EndDate));

PartII = Temp2(StartII:EndII,:); %equates temp matrix with desired one

% Format for variable name MMMDD = ...
Apr17 = [PartI, PartII(:,2:17)];

%%
% Saves variable as a matlab file
save ('Apr17','Apr17')
```

APPENDIX B: MATLAB CODE FOR PLOTTING WITH DATENUM

```
%% Plotting Sorted Thermocouple Data
clc;
clear all;
close all;

% Import Sorted Datenum Data File from folder which this scipt is in
% Must be .mat
TempFile = importdata('Apr28.mat');

% Fcn to go from Farenheit to Kelvin
K = @(F) ((F-32)*(5/9))+273;

% Only the temperatures not times should be tranformed with K()
% This preserves the time column
file = [TempFile(:,1),K(TempFile(:,2:41))];

%%
% Points is the interval so :15 is every 15 min.
Points = 1:1:length(file);%
time = file(Points);%
%%
%Room air average
T_Air_Avg = sum(file(Points,2:17)')./16;
%Average PCM Outside surface temp
T_PCM_OUT = sum(file(Points,21:2:27)')./4;
%Average PCM Inside surface temp
T_PCM_IN = sum([file(Points,22:2:28)';file(Points,30:31)'])./6;

% Corresponding Column numbers
% TC (room air): 1 - 16
% Outside: 20
% PCM 1: Outside - 21, Inside - 22
% PCM 2: Outside - 23, Inside - 24
% PCM 3: Outside - 25, Inside - 26
% PCM 4: Outside - 27, Inside - 28
% Heater outlet: 29
% PCM R: 30
% PCM L: 31
%%
figure(1);clf
hold on

h = plot(time,T_Air_Avg,'linewidth',2);
h = plot(time,file(Points,20),'linewidth',2);
h = plot(time,(K(73.4)*ones(1,length(Points))),'linewidth',2);
h = plot(time,file(Points,29),'linewidth',2);
h = plot(time,T_PCM_OUT,time,T_PCM_IN,'black','linewidth',2);
set(gca,'xtick',time(1:60:length(time)))
% need to format x-axis (time)
dateformat = 'HH';
```

```
datetick('x',dateformat,'keeplimits','keepticks')
xtickangle(90)
grid on
set(gca, 'YMinorTick','on', 'YMinorGrid','on')
ylim([270,310]) %Weather data

%% Detailed Temperature Range
% Use this to get a smaller Temperature Range
% StartTime = '05/10/2019,15:00';                  %%%%%    Stop
% EndTime = '05/11/2019,06:00';                    %%%%%    Here
% StartI = find(file(:,1)==datenum(StartTime));
% EndI = find(file(:,1)==datenum(EndTime));
% a= file(StartI,1);
% b= file(EndI,1);
% xlim([a,b])
%%
set(gca,'FontSize',24,'fontweight','bold');
title('OUTDOOR AMBIENT TEMPERATURE')
xlabel('Time of the Day [Hr]','FontSize',20,'fontweight','bold')
ylabel('Temp [K]')
lgd = legend('Room Air','Outdoors','REF','Heater Outlet','PCM
Outside','PCM Inside');
lgd.NumColumns = 2;
title(lgd,'Measurement Sources')
```

APPENDIX C: EXAMPLE ENERGYPLUS INPUT FILE

```
!-Generator IDFEditor 1.50
!-Option OriginalOrderBottom

!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-      Use '!' comments if they need to be retained when using the IDFEditor.

Version,
    9.0;                     !- Version Identifier

Building,
    Untitled,                !- Name
    0.0,                     !- North Axis {deg}
    City,                    !- Terrain
    0.04,                    !- Loads Convergence Tolerance Value
    0.4,                     !- Temperature Convergence Tolerance Value {deltaC}
    FullInteriorAndExterior, !- Solar Distribution
    25,                      !- Maximum Number of Warmup Days
    ;                        !- Minimum Number of Warmup Days

Timestep,
    20;                      !- Number of Timesteps per Hour

SurfaceConvectionAlgorithm:Inside,
    TARP;                    !- Algorithm

SurfaceConvectionAlgorithm:Outside,
    DOE-2;                   !- Algorithm

HeatBalanceAlgorithm,
    ConductionFiniteDifference;  !- Algorithm

HeatBalanceSettings:ConductionFiniteDifference,
    FullyImplicitFirstOrder, !- Difference Scheme
    3.0,                     !- Space Discretization Constant
    1.0,                     !- Relaxation Factor
    0.002;                   !- Inside Face Surface Temperature Convergence Criteria

SimulationControl,
    No,                      !- Do Zone Sizing Calculation
    No,                      !- Do System Sizing Calculation
    No,                      !- Do Plant Sizing Calculation
```

```
    Yes,                    !- Run Simulation for Sizing Periods
    Yes;                    !- Run Simulation for Weather File Run Periods

RunPeriod,
    Week 1,        !- Name
    1,                !- Begin Month
    1,                !- Begin Day of Month
    ,                 !- Begin Year
    1,                !- End Month
    1,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 2,        !- Name
    1,                !- Begin Month
    8,                !- Begin Day of Month
    ,                 !- Begin Year
    1,                !- End Month
    8,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 3,        !- Name
    1,                !- Begin Month
    15,                !- Begin Day of Month
    ,                 !- Begin Year
    1,                !- End Month
    15,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 4,        !- Name
    1,                !- Begin Month
    22,                !- Begin Day of Month
    ,                 !- Begin Year
    1,                !- End Month
    22,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 5,        !- Name
    1,                !- Begin Month
    29,                !- Begin Day of Month
    ,                 !- Begin Year
    1,                !- End Month
```

```
    29,                   !- End Day of Month
    ;                     !- End Year

RunPeriod,
    Week 6,          !- Name
    2,                  !- Begin Month
    5,                  !- Begin Day of Month
    ,                   !- Begin Year
    2,                  !- End Month
    5,                  !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 7,          !- Name
    2,                  !- Begin Month
    12,                   !- Begin Day of Month
    ,                   !- Begin Year
    2,                  !- End Month
    12,                   !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 8,          !- Name
    2,                  !- Begin Month
    19,                   !- Begin Day of Month
    ,                   !- Begin Year
    2,                  !- End Month
    19,                   !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 9,          !- Name
    2,                  !- Begin Month
    26,                   !- Begin Day of Month
    ,                   !- Begin Year
    2,                  !- End Month
    26,                   !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 10,          !- Name
    3,                  !- Begin Month
    5,                  !- Begin Day of Month
    ,                   !- Begin Year
    3,                  !- End Month
```

```
    5,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 11,          !- Name
    3,                !- Begin Month
    12,               !- Begin Day of Month
    ,                 !- Begin Year
    3,                !- End Month
    12,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 12,          !- Name
    3,                !- Begin Month
    19,               !- Begin Day of Month
    ,                 !- Begin Year
    3,                !- End Month
    19,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 13,          !- Name
    3,                !- Begin Month
    26,               !- Begin Day of Month
    ,                 !- Begin Year
    3,                !- End Month
    26,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 14,          !- Name
    4,                !- Begin Month
    4,                !- Begin Day of Month
    ,                 !- Begin Year
    4,                !- End Month
    4,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 15,          !- Name
    4,                !- Begin Month
    11,               !- Begin Day of Month
    ,                 !- Begin Year
    4,                !- End Month
```

```
  11,                  !- End Day of Month
  ;                    !- End Year

RunPeriod,
  Week 16,             !- Name
  4,                   !- Begin Month
  18,                  !- Begin Day of Month
  ,                    !- Begin Year
  4,                   !- End Month
  18,                  !- End Day of Month
  ;                    !- End Year

RunPeriod,
  Week 17,             !- Name
  4,                   !- Begin Month
  25,                  !- Begin Day of Month
  ,                    !- Begin Year
  4,                   !- End Month
  25,                  !- End Day of Month
  ;                    !- End Year

RunPeriod,
  Week 18,             !- Name
  5,                   !- Begin Month
  1,                   !- Begin Day of Month
  ,                    !- Begin Year
  5,                   !- End Month
  1
  ,                    !- End Day of Month
  ;                    !- End Year

RunPeriod,
  Week 19,             !- Name
  5,                   !- Begin Month
  8,                   !- Begin Day of Month
  ,                    !- Begin Year
  5,                   !- End Month
  8,                   !- End Day of Month
  ;                    !- End Year

RunPeriod,
  Week 20,             !- Name
  5,                   !- Begin Month
  15,                  !- Begin Day of Month
  ,                    !- Begin Year
```

```
    5,                 !- End Month
    15,                  !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 21,         !- Name
    5,                 !- Begin Month
    22,                  !- Begin Day of Month
    ,                  !- Begin Year
    5,                 !- End Month
    22,                  !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 22,         !- Name
    5,                 !- Begin Month
    29,                  !- Begin Day of Month
    ,                  !- Begin Year
    5,                 !- End Month
    29,                  !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 23,         !- Name
    6,                 !- Begin Month
    5,                 !- Begin Day of Month
    ,                  !- Begin Year
    6,                 !- End Month
    5,                 !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 24,         !- Name
    6,                 !- Begin Month
    12,                  !- Begin Day of Month
    ,                  !- Begin Year
    6,                 !- End Month
    12,                  !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 25,         !- Name
    6,                 !- Begin Month
    19,                  !- Begin Day of Month
    ,                  !- Begin Year
```

```
    6,                !- End Month
    19,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 26,          !- Name
    6,                !- Begin Month
    26,               !- Begin Day of Month
    ,                 !- Begin Year
    6,                !- End Month
    26,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 27,          !- Name
    7,                !- Begin Month
    3,                !- Begin Day of Month
    ,                 !- Begin Year
    7,                !- End Month
    3,                !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 28,          !- Name
    7,                !- Begin Month
    10,               !- Begin Day of Month
    ,                 !- Begin Year
    7,                !- End Month
    10,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 29,          !- Name
    7,                !- Begin Month
    17,               !- Begin Day of Month
    ,                 !- Begin Year
    7,                !- End Month
    17,               !- End Day of Month
    ;                 !- End Year

RunPeriod,
    Week 30,          !- Name
    7,                !- Begin Month
    24,               !- Begin Day of Month
    ,                 !- Begin Year
```

```
    7,                  !- End Month
    24,                 !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 31,            !- Name
    7,                  !- Begin Month
    31,                 !- Begin Day of Month
    ,                   !- Begin Year
    7,                  !- End Month
    31,                 !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 32,            !- Name
    8,                  !- Begin Month
    7,                  !- Begin Day of Month
    ,                   !- Begin Year
    8,                  !- End Month
    7,                  !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 33,            !- Name
    8,                  !- Begin Month
    14,                 !- Begin Day of Month
    ,                   !- Begin Year
    8,                  !- End Month
    14,                 !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 34,            !- Name
    8,                  !- Begin Month
    21,                 !- Begin Day of Month
    ,                   !- Begin Year
    8,                  !- End Month
    21,                 !- End Day of Month
    ;                   !- End Year

RunPeriod,
    Week 35,            !- Name
    8,                  !- Begin Month
    28,                 !- Begin Day of Month
    ,                   !- Begin Year
```

```
    8,                 !- End Month
    28,                !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 36,           !- Name
    9,                 !- Begin Month
    4,                 !- Begin Day of Month
    ,                  !- Begin Year
    9,                 !- End Month
    4,                 !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 37,           !- Name
    9,                 !- Begin Month
    11,                !- Begin Day of Month
    ,                  !- Begin Year
    9,                 !- End Month
    11,                !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 38,           !- Name
    9,                 !- Begin Month
    18,                !- Begin Day of Month
    ,                  !- Begin Year
    9,                 !- End Month
    18,                !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 39,           !- Name
    9,                 !- Begin Month
    25,                !- Begin Day of Month
    ,                  !- Begin Year
    9,                 !- End Month
    25,                !- End Day of Month
    ;                  !- End Year

RunPeriod,
    Week 40,           !- Name
    10,                !- Begin Month
    2,                 !- Begin Day of Month
    ,                  !- Begin Year
```

```
    10,                    !- End Month
    2,                     !- End Day of Month
    ;                      !- End Year

RunPeriod,
    Week 41,               !- Name
    10,                    !- Begin Month
    9,                     !- Begin Day of Month
    ,                      !- Begin Year
    10,                    !- End Month
    9,                     !- End Day of Month
    ;                      !- End Year

RunPeriod,
    Week 42,               !- Name
    10,                    !- Begin Month
    16,                    !- Begin Day of Month
    ,                      !- Begin Year
    10,                    !- End Month
    16,                    !- End Day of Month
    ;                      !- End Year

RunPeriod,
    Week 43,               !- Name
    10,                    !- Begin Month
    23,                    !- Begin Day of Month
    ,                      !- Begin Year
    10,                    !- End Month
    23,                    !- End Day of Month
    ;                      !- End Year

RunPeriod,
    Week 44,               !- Name
    10,                    !- Begin Month
    30,                    !- Begin Day of Month
    ,                      !- Begin Year
    10,                    !- End Month
    30,                    !- End Day of Month
    ;                      !- End Year

RunPeriod,
    Week 45,               !- Name
    11,                    !- Begin Month
    6,                     !- Begin Day of Month
    ,                      !- Begin Year
```

```
    11,                  !- End Month
    6,                   !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 46,             !- Name
    11,                  !- Begin Month
    13,                  !- Begin Day of Month
    ,                    !- Begin Year
    11,                  !- End Month
    13,                  !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 47,             !- Name
    11,                  !- Begin Month
    20,                  !- Begin Day of Month
    ,                    !- Begin Year
    11,                  !- End Month
    20,                  !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 48,             !- Name
    11,                  !- Begin Month
    27,                  !- Begin Day of Month
    ,                    !- Begin Year
    11,                  !- End Month
    27,                  !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 49,             !- Name
    12,                  !- Begin Month
    4,                   !- Begin Day of Month
    ,                    !- Begin Year
    12,                  !- End Month
    4,                   !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 50,             !- Name
    12,                  !- Begin Month
    11,                  !- Begin Day of Month
    ,                    !- Begin Year
```

```
    12,                    !- End Month
    11,                    !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 51,         !- Name
    12,                    !- Begin Month
    18,                    !- Begin Day of Month
    ,                    !- Begin Year
    12,                    !- End Month
    18,                    !- End Day of Month
    ;                    !- End Year

RunPeriod,
    Week 52,         !- Name
    12,                    !- Begin Month
    25,                    !- Begin Day of Month
    ,                    !- Begin Year
    12,                    !- End Month
    25,                    !- End Day of Month
    ;                    !- End Year

Site:Location,
    Monterey CA,            !- Name
    36.6,                  !- Latitude {deg}
    -121.87,                !- Longitude {deg}
    -8.0,                  !- Time Zone {hr}
    50.0;                  !- Elevation {m}

GlobalGeometryRules,
    UpperLeftCorner,        !- Starting Vertex Position
    Counterclockwise,       !- Vertex Entry Direction
    Relative;               !- Coordinate System

Material,
    F08 Metal surface,      !- Name
    Smooth,                 !- Roughness
    0.0008,                 !- Thickness {m}
    45.28,                  !- Conductivity {W/m-K}
    7824,                   !- Density {kg/m3}
    500;                    !- Specific Heat {J/kg-K}

Material,
    I01 25mm insulation board,  !- Name
    MediumRough,            !- Roughness
```

```
    0.0254,                  !- Thickness {m}
    0.03,                    !- Conductivity {W/m-K}
    43,                      !- Density {kg/m3}
    1210;                    !- Specific Heat {J/kg-K}

Material,
    I02 50mm insulation board,  !- Name
    MediumRough,             !- Roughness
    0.0508,                  !- Thickness {m}
    0.03,                    !- Conductivity {W/m-K}
    43,                      !- Density {kg/m3}
    1210;                    !- Specific Heat {J/kg-K}

Material,
    G01a 19mm gypsum board,  !- Name
    MediumSmooth,            !- Roughness
    0.019,                   !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    1090;                    !- Specific Heat {J/kg-K}

Material,
    M11 100mm lightweight concrete,  !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    0.53,                    !- Conductivity {W/m-K}
    1280,                    !- Density {kg/m3}
    840;                     !- Specific Heat {J/kg-K}

Material,
    F16 Acoustic tile,       !- Name
    MediumSmooth,            !- Roughness
    0.0191,                  !- Thickness {m}
    0.06,                    !- Conductivity {W/m-K}
    368,                     !- Density {kg/m3}
    590;                     !- Specific Heat {J/kg-K}

Material,
    M01 100mm brick,         !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    0.89,                    !- Conductivity {W/m-K}
    1920,                    !- Density {kg/m3}
    790;                     !- Specific Heat {J/kg-K}
```

```
Material,
    M15 200mm heavyweight concrete,  !- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    1.95,                    !- Conductivity {W/m-K}
    2240,                    !- Density {kg/m3}
    900;                     !- Specific Heat {J/kg-K}

Material,
    M05 200mm concrete block,!- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    1.11,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    920;                     !- Specific Heat {J/kg-K}

Material,
    G05 25mm wood,           !- Name
    MediumSmooth,            !- Roughness
    0.0254,                  !- Thickness {m}
    0.15,                    !- Conductivity {W/m-K}
    608,                     !- Density {kg/m3}
    1630;                    !- Specific Heat {J/kg-K}

Material,
    PCM,                     !- Name
    Smooth,                  !- Roughness
    1e-2,                    !- Thickness {m}
    2.5,                     !- Conductivity {W/m-K}
    1400,                    !- Density {kg/m3}
    4500,                    !- Specific Heat {J/kg-K}
    0.9000000,               !- Thermal Absorptance
    0.9200000,               !- Solar Absorptance
    0.9200000;               !- Visible Absorptance

MaterialProperty:PhaseChange,
    PCM,                     !- Name
    0,                       !- Temperature Coefficient for Thermal Conductivity {W/m-K2}
    0,                       !- Temperature 1 {C}
    0,                       !- Enthalpy 1 {J/kg}
    22.5,                    !- Temperature 2 {C}
    50000,                   !- Enthalpy 2 {J/kg}
    23.5,                    !- Temperature 3 {C}
    300000,                  !- Enthalpy 3 {J/kg}
    45,                      !- Temperature 4 {C}
```

```
    340000;                  !- Enthalpy 4 {J/kg}

  Material:AirGap,
    F04 Wall air space resistance,  !- Name
    0.15;                    !- Thermal Resistance {m2-K/W}

  Material:AirGap,
    F05 Ceiling air space resistance,  !- Name
    0.18;                    !- Thermal Resistance {m2-K/W}

  WindowMaterial:Glazing,
    Clear 3mm,               !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.003,                   !- Thickness {m}
    0.837,                   !- Solar Transmittance at Normal Incidence
    0.075,                   !- Front Side Solar Reflectance at Normal Incidence
    0.075,                   !- Back Side Solar Reflectance at Normal Incidence
    0.898,                   !- Visible Transmittance at Normal Incidence
    0.081,                   !- Front Side Visible Reflectance at Normal Incidence
    0.081,                   !- Back Side Visible Reflectance at Normal Incidence
    0,                       !- Infrared Transmittance at Normal Incidence
    0.84,                    !- Front Side Infrared Hemispherical Emissivity
    0.84,                    !- Back Side Infrared Hemispherical Emissivity
    0.9;                     !- Conductivity {W/m-K}

  WindowMaterial:Gas,
    Air 13mm,                !- Name
    Air,                     !- Gas Type
    0.0127;                  !- Thickness {m}

  Construction,
    Exterior Floor,          !- Name
    I02 50mm insulation board,  !- Outside Layer
    M15 200mm heavyweight concrete;  !- Layer 2

  Construction,
    Interior Floor,          !- Name
    F16 Acoustic tile,       !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    M11 100mm lightweight concrete;  !- Layer 3

  Construction,
    Exterior Wall,           !- Name
    M01 100mm brick,         !- Outside Layer
```

```
    M15 200mm heavyweight concrete,  !- Layer 2
    I02 50mm insulation board,  !- Layer 3
    F04 Wall air space resistance,  !- Layer 4
    G01a 19mm gypsum board;  !- Layer 5

Construction,
    Interior Wall,           !- Name
    G01a 19mm gypsum board,  !- Outside Layer
    F04 Wall air space resistance,  !- Layer 2
    G01a 19mm gypsum board;  !- Layer 3

Construction,
    PCM Wall,                !- Name
    M01 100mm brick,         !- Outside Layer
    M15 200mm heavyweight concrete,  !- Layer 2
    I02 50mm insulation board,  !- Layer 3
    F04 Wall air space resistance,  !- Layer 4
    G01a 19mm gypsum board,  !- Layer 5
    PCM;                     !- Layer 6

Construction,
    Exterior Roof,           !- Name
    M11 100mm lightweight concrete,  !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    F16 Acoustic tile;       !- Layer 3

Construction,
    Interior Ceiling,        !- Name
    M11 100mm lightweight concrete,  !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    F16 Acoustic tile;       !- Layer 3

Construction,
    Exterior Window,         !- Name
    Clear 3mm,               !- Outside Layer
    Air 13mm,                !- Layer 2
    Clear 3mm;               !- Layer 3

Construction,
    Interior Window,         !- Name
    Clear 3mm;               !- Outside Layer

Construction,
    Interior Door,           !- Name
    G05 25mm wood;           !- Outside Layer
```

```
ScheduleTypeLimits,
    Any Number;              !- Name

ScheduleTypeLimits,
    Fraction,                !- Name
    0.0,                     !- Lower Limit Value
    1.0,                     !- Upper Limit Value
    CONTINUOUS;              !- Numeric Type

ScheduleTypeLimits,
    Temperature,             !- Name
    -60,                     !- Lower Limit Value
    200,                     !- Upper Limit Value
    CONTINUOUS;              !- Numeric Type

ScheduleTypeLimits,
    On/Off,                  !- Name
    0,                       !- Lower Limit Value
    1,                       !- Upper Limit Value
    DISCRETE;                !- Numeric Type

ScheduleTypeLimits,
    Control Type,            !- Name
    0,                       !- Lower Limit Value
    4,                       !- Upper Limit Value
    DISCRETE;                !- Numeric Type

ScheduleTypeLimits,
    Humidity,                !- Name
    10,                      !- Lower Limit Value
    90,                      !- Upper Limit Value
    CONTINUOUS;              !- Numeric Type

ScheduleTypeLimits,
    Number;                  !- Name

Schedule:Compact,
    Office Lights Schedule,  !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 05:00,            !- Field 3
    0.05,                    !- Field 4
    Until: 07:00,            !- Field 5
```

```
    0.1,                     !- Field 6
    Until: 08:00,            !- Field 7
    0.3,                     !- Field 8
    Until: 17:00,            !- Field 9
    0.9,                     !- Field 10
    Until: 18:00,            !- Field 11
    0.5,                     !- Field 12
    Until: 20:00,            !- Field 13
    0.3,                     !- Field 14
    Until: 22:00,            !- Field 15
    0.2,                     !- Field 16
    Until: 23:00,            !- Field 17
    0.1,                     !- Field 18
    Until: 24:00,            !- Field 19
    0.05,                    !- Field 20
    For: SummerDesignDay,    !- Field 21
    Until: 24:00,            !- Field 22
    1.0,                     !- Field 23
    For: Saturday,           !- Field 24
    Until: 06:00,            !- Field 25
    0.05,                    !- Field 26
    Until: 08:00,            !- Field 27
    0.1,                     !- Field 28
    Until: 12:00,            !- Field 29
    0.3,                     !- Field 30
    Until: 17:00,            !- Field 31
    0.15,                    !- Field 32
    Until: 24:00,            !- Field 33
    0.05,                    !- Field 34
    For: WinterDesignDay,    !- Field 35
    Until: 24:00,            !- Field 36
    0.0,                     !- Field 37
    For: Sunday Holidays AllOtherDays,  !- Field 38
    Until: 24:00,            !- Field 39
    0.05;                    !- Field 40

Output:VariableDictionary,
    IDF;                     !- Key Field

Zone,
    Zone A,                  !- Name
    0.0,                     !- Direction of Relative North {deg}
    3.296691,                !- X Origin {m}
    2.669943,                !- Y Origin {m}
    0.0,                     !- Z Origin {m}
```

```
    ,                    !- Type
    1;                   !- Multiplier

BuildingSurface:Detailed,
    CDCD81,              !- Name
    Floor,               !- Surface Type
    Exterior Floor,      !- Construction Name
    Zone A,              !- Zone Name
    Adiabatic,           !- Outside Boundary Condition
    ,                    !- Outside Boundary Condition Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    0.0,                 !- View Factor to Ground
    4,                   !- Number of Vertices
    2.052755970724,      !- Vertex 1 X-coordinate {m}
    -1.265328256509,     !- Vertex 1 Y-coordinate {m}
    0.000000000000,      !- Vertex 1 Z-coordinate {m}
    2.052755970724,      !- Vertex 2 X-coordinate {m}
    1.528671743491,      !- Vertex 2 Y-coordinate {m}
    0.000000000000,      !- Vertex 2 Z-coordinate {m}
    4.922955970724,      !- Vertex 3 X-coordinate {m}
    1.528671743491,      !- Vertex 3 Y-coordinate {m}
    0.000000000000,      !- Vertex 3 Z-coordinate {m}
    4.922955970724,      !- Vertex 4 X-coordinate {m}
    -1.265328256509,     !- Vertex 4 Y-coordinate {m}
    0.000000000000;      !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    Door Wall,           !- Name
    Wall,                !- Surface Type
    Exterior Wall,       !- Construction Name
    Zone A,              !- Zone Name
    Adiabatic,           !- Outside Boundary Condition
    ,                    !- Outside Boundary Condition Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    0.0,                 !- View Factor to Ground
    4,                   !- Number of Vertices
    2.052755970724,      !- Vertex 1 X-coordinate {m}
    -1.265328256509,     !- Vertex 1 Y-coordinate {m}
    2.844800000000,      !- Vertex 1 Z-coordinate {m}
    2.052755970724,      !- Vertex 2 X-coordinate {m}
    -1.265328256509,     !- Vertex 2 Y-coordinate {m}
    0.000000000000,      !- Vertex 2 Z-coordinate {m}
    4.922955970724,      !- Vertex 3 X-coordinate {m}
```

```
    -1.265328256509,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,         !- Vertex 3 Z-coordinate {m}
    4.922955970724,         !- Vertex 4 X-coordinate {m}
    -1.265328256509,        !- Vertex 4 Y-coordinate {m}
    2.844800000000;         !- Vertex 4 Z-coordinate {m}

  BuildingSurface:Detailed,
    2CF3A5,                 !- Name
    Roof,                   !- Surface Type
    Exterior Roof,          !- Construction Name
    Zone A,                 !- Zone Name
    Adiabatic,              !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    NoSun,                  !- Sun Exposure
    NoWind,                 !- Wind Exposure
    0.0,                    !- View Factor to Ground
    4,                      !- Number of Vertices
    4.922955970724,         !- Vertex 1 X-coordinate {m}
    -1.265328256509,        !- Vertex 1 Y-coordinate {m}
    2.844800000000,         !- Vertex 1 Z-coordinate {m}
    4.922955970724,         !- Vertex 2 X-coordinate {m}
    1.528671743491,         !- Vertex 2 Y-coordinate {m}
    2.844800000000,         !- Vertex 2 Z-coordinate {m}
    2.052755970724,         !- Vertex 3 X-coordinate {m}
    1.528671743491,         !- Vertex 3 Y-coordinate {m}
    2.844800000000,         !- Vertex 3 Z-coordinate {m}
    2.052755970724,         !- Vertex 4 X-coordinate {m}
    -1.265328256509,        !- Vertex 4 Y-coordinate {m}
    2.844800000000;         !- Vertex 4 Z-coordinate {m}

  BuildingSurface:Detailed,
    PCM Wall,               !- Name
    Wall,                   !- Surface Type
    PCM Wall,               !- Construction Name
    Zone A,                 !- Zone Name
    Adiabatic,              !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    NoSun,                  !- Sun Exposure
    NoWind,                 !- Wind Exposure
    0.0,                    !- View Factor to Ground
    4,                      !- Number of Vertices
    2.052755970724,         !- Vertex 1 X-coordinate {m}
    1.528671743491,         !- Vertex 1 Y-coordinate {m}
    2.844800000000,         !- Vertex 1 Z-coordinate {m}
    2.052755970724,         !- Vertex 2 X-coordinate {m}
```

```
    1.528671743491,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    2.052755970724,          !- Vertex 3 X-coordinate {m}
    -1.265328256509,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    2.052755970724,          !- Vertex 4 X-coordinate {m}
    -1.265328256509,         !- Vertex 4 Y-coordinate {m}
    2.844800000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    FF9BDA,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    Zone A,                  !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    0.0,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    4.922955970724,          !- Vertex 1 X-coordinate {m}
    1.528671743491,          !- Vertex 1 Y-coordinate {m}
    2.844800000000,          !- Vertex 1 Z-coordinate {m}
    4.922955970724,          !- Vertex 2 X-coordinate {m}
    1.528671743491,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    2.052755970724,          !- Vertex 3 X-coordinate {m}
    1.528671743491,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    2.052755970724,          !- Vertex 4 X-coordinate {m}
    1.528671743491,          !- Vertex 4 Y-coordinate {m}
    2.844800000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    Window Wall,             !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    Zone A,                  !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    WindExposed,             !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    4.922955970724,          !- Vertex 1 X-coordinate {m}
```

```
    -1.265328256509,        !- Vertex 1 Y-coordinate {m}
    2.844800000000,         !- Vertex 1 Z-coordinate {m}
    4.922955970724,         !- Vertex 2 X-coordinate {m}
    -1.265328256509,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,         !- Vertex 2 Z-coordinate {m}
    4.922955970724,         !- Vertex 3 X-coordinate {m}
    1.528671743491,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,         !- Vertex 3 Z-coordinate {m}
    4.922955970724,         !- Vertex 4 X-coordinate {m}
    1.528671743491,         !- Vertex 4 Y-coordinate {m}
    2.844800000000;         !- Vertex 4 Z-coordinate {m}

FenestrationSurface:Detailed,
    FF9405,                 !- Name
    Window,                 !- Surface Type
    Exterior Window,        !- Construction Name
    Window Wall,            !- Building Surface Name
    ,                       !- Outside Boundary Condition Object
    ,                       !- View Factor to Ground
    ,                       !- Frame and Divider Name
    ,                       !- Multiplier
    4,                      !- Number of Vertices
    4.922955970724,         !- Vertex 1 X-coordinate {m}
    0.512671743491,         !- Vertex 1 Y-coordinate {m}
    2.844800000000,         !- Vertex 1 Z-coordinate {m}
    4.922955970724,         !- Vertex 2 X-coordinate {m}
    0.512671743491,         !- Vertex 2 Y-coordinate {m}
    1.193800000000,         !- Vertex 2 Z-coordinate {m}
    4.922955970724,         !- Vertex 3 X-coordinate {m}
    1.401671743491,         !- Vertex 3 Y-coordinate {m}
    1.193800000000,         !- Vertex 3 Z-coordinate {m}
    4.922955970724,         !- Vertex 4 X-coordinate {m}
    1.401671743491,         !- Vertex 4 Y-coordinate {m}
    2.844800000000;         !- Vertex 4 Z-coordinate {m}

FenestrationSurface:Detailed,
    C6FF71,                 !- Name
    Window,                 !- Surface Type
    Exterior Window,        !- Construction Name
    Window Wall,            !- Building Surface Name
    ,                       !- Outside Boundary Condition Object
    ,                       !- View Factor to Ground
    ,                       !- Frame and Divider Name
    ,                       !- Multiplier
    4,                      !- Number of Vertices
```

```
    4.922955970724,          !- Vertex 1 X-coordinate {m}
    -1.138328256509,         !- Vertex 1 Y-coordinate {m}
    2.844800000000,          !- Vertex 1 Z-coordinate {m}
    4.922955970724,          !- Vertex 2 X-coordinate {m}
    -1.138328256509,         !- Vertex 2 Y-coordinate {m}
    1.193800000000,          !- Vertex 2 Z-coordinate {m}
    4.922955970724,          !- Vertex 3 X-coordinate {m}
    -0.249328256509,         !- Vertex 3 Y-coordinate {m}
    1.193800000000,          !- Vertex 3 Z-coordinate {m}
    4.922955970724,          !- Vertex 4 X-coordinate {m}
    -0.249328256509,         !- Vertex 4 Y-coordinate {m}
    2.844800000000;          !- Vertex 4 Z-coordinate {m}

Output:Table:SummaryReports,
    AnnualBuildingUtilityPerformanceSummary,  !- Report 1 Name
    InputVerificationandResultsSummary,  !- Report 2 Name
    SourceEnergyEndUseComponentsSummary,  !- Report 3 Name
    EnvelopeSummary,         !- Report 4 Name
    EquipmentSummary;        !- Report 5 Name

OutputControl:Table:Style,
    HTML,                    !- Column Separator
    None;                    !- Unit Conversion

Schedule:Compact,
    Occupancy Schedule,      !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 09:00,            !- Field 3
    0,                       !- Field 4
    Until: 16:00,            !- Field 5
    1,                       !- Field 6
    Until: 24:00,            !- Field 7
    0;                       !- Field 8

Schedule:Compact,
    Lighting Schedule,       !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 09:00,            !- Field 3
    0,                       !- Field 4
    Until: 16:00,            !- Field 5
    1,                       !- Field 6
```

```
    Until: 24:00,           !- Field 7
    0;                      !- Field 8

Schedule:Compact,
    Computer Schedule,      !- Name
    Fraction,               !- Schedule Type Limits Name
    Through: 12/31,         !- Field 1
    For: AllDays,           !- Field 2
    Until: 09:00,           !- Field 3
    0,                      !- Field 4
    Until: 16:00,           !- Field 5
    1,                      !- Field 6
    Until: 24:00,           !- Field 7
    0;                      !- Field 8

Schedule:Compact,
    Activity Schedule,      !- Name
    Any Number,             !- Schedule Type Limits Name
    Through: 12/31,         !- Field 1
    For: AllDays,           !- Field 2
    Until: 09:00,           !- Field 3
    0,                      !- Field 4
    Until: 16:00,           !- Field 5
    67,                     !- Field 6
    Until: 24:00,           !- Field 7
    0;                      !- Field 8

People,
    Office Employees,       !- Name
    Zone A,                 !- Zone or ZoneList Name
    Occupancy Schedule,     !- Number of People Schedule Name
    People,                 !- Number of People Calculation Method
    2,                      !- Number of People
    ,                       !- People per Zone Floor Area {person/m2}
    ,                       !- Zone Floor Area per Person {m2/person}
    0.3,                    !- Fraction Radiant
    autocalculate,          !- Sensible Heat Fraction
    Activity Schedule;      !- Activity Level Schedule Name

!Activity level should be 250btu/hr*2 people*0.92(CLF) = 460 btu/hr
!460 btu/hr = 134.8126922 W
Lights,
    Zone A Lights,          !- Name
    Zone A,                 !- Zone or ZoneList Name
    Lighting Schedule,      !- Schedule Name
```

```
    LightingLevel,          !- Design Level Calculation Method
    80,                     !- Lighting Level {W}
    ,                       !- Watts per Zone Floor Area {W/m2}
    ,                       !- Watts per Person {W/person}
    0,                      !- Return Air Fraction
    0.7,                    !- Fraction Radiant
    0.1,                    !- Fraction Visible
    1.0;                    !- Fraction Replaceable

ElectricEquipment,
    Computer,               !- Name
    Zone A,                 !- Zone or ZoneList Name
    Computer Schedule,      !- Schedule Name
    EquipmentLevel,         !- Design Level Calculation Method
    100,                    !- Design Level {W}
    ,                       !- Watts per Zone Floor Area {W/m2}
    ,                       !- Watts per Person {W/person}
    0,                      !- Fraction Latent
    0,                      !- Fraction Radiant
    0;                      !- Fraction Lost

Output:Variable,
    *,                      !- Key Value
    Zone Mean Air Temperature,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                      !- Key Value
    People Total Heating Energy,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                      !- Key Value
    People Occupant Count,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                      !- Key Value
    People Total Heating Rate,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                      !- Key Value
    Lights Electric Power,  !- Variable Name
    hourly;                 !- Reporting Frequency
```

```
Output:Variable,
    *,                    !- Key Value
    Lights Total Heating Energy,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                    !- Key Value
    Lights Total Heating Rate,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                    !- Key Value
    Electric Equipment Electric Power,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                    !- Key Value
    Electric Equipment Electric Energy,  !- Variable Name
    hourly;                 !- Reporting Frequency

Output:Variable,
    *,                    !- Key Value
    Zone Windows Total Transmitted Solar Radiation Rate,  !- Variable Name
    hourly;                 !- Reporting Frequency
Output:Variable,*,Site Outdoor Air Drybulb Temperature,hourly; !- Zone Average [C]
```

LIST OF REFERENCES

[1] D Zhou, CY Zhao, and Y Tian. “Review on thermal energy storage with phase change materials (PCMs) in building applications.” *Applied Energy* (2012).

[2] J. Kośny, D. Yarbrough, W. Miller, T. Petrie, P. Childs, and A.M. Syed. “PCM-Enhanced building envelopes in current ORNL research projects.” Oak Ridge National Laboratory, Oak Ridge, TN. n. d.

[3] DW Hawes, D Feldman, and D Banu. “Latent heat storage in building materials.” *Energy and Buildings*, vol. 20 (1993): pp. 77–86.

[4] X. Xu, Y. Zhang, K. Ling, H. Di and R. Yang, “Modeling and simulation on thermal performance of shape-stabilized phase change material floor used in passive solar buildings,” *Energy and Buildings*, vol. 37 (2005): pp. 1084–1091.

[5] S.E. Kalnæsa, and B.P. Jelleab. “Phase change materials for building applications: A state-of-the-art review and future research opportunities.” *Energy and Buildings*, vol. 94 (2015): pp. 150–176.

[6] Y. Cui, J. Xie, J. Liu, J. Wang, and S. Chen. “A review on phase change material application in building.” *Advances in Mechanical Engineering*, vol. 9, no. 6 (2017): pp. 1–15.

[7] F. Goia. “Thermo-physical behavior and energy performance assessment of PCM glazing system configurations: a numerical analysis.” *Front Architec Res*, vol. 1 (2012): pp. 341–347.

[8] K. S. Pascha. “The use of phase-change-material as cooling-strategy for buildings in the Chilean climate.” *International Journal of Low-Carbon Technologies*, vol. 3, no. 2, (April 2008): pp. 101–109

[9] I. O. Salyer, and A. K. Sircar, “A review of phase change materials research for thermal energy storage in heating and cooling applications at the University of Dayton from 1982 to 1996,” *International Journal of Global Energy Issues*, vol. 9, no. 3, (1997): pp. 183–198.

[10] J. Kosny, and David W. Yarbrough. “Use of PCM-enhanced insulations in the building envelope.” *Journal of Building Enclosure Design* (Summer/Fall 2008).

[11] M. Labat, J. Virgone, D. David, and F. Kuznik. “Experimental assessment of a PCM to air heat exchanger storage system for building ventilation application.” *Applied Thermal Engineering*, Elsevier, 2014, 66, pp.375-382.

[12] Z. Bakó- Biró. “Analytical and experimental modelling of energy storage in phase change materials for natural cooling of buildings.” n.d.

[13] P. R. Ingole, T. R. Mohod, and S. S. Gaddamwar. “Use of phase change materials in construction of buildings: A review.” *International Journal of Engineering Research and General Science*, vol. 2, no. 4, (June-July, 2014).

[14] “From URL” https://phasechange.com/wp-content/uploads/2018/02/BioPCM-Data-Sheet-Q23.pdf

[15] A. Bland, M. Khzouz, T. Statheros, and E. I. Gkanas. “PCMs for residential building applications: A short review focused on disadvantages and proposals for future development.” *Buildings*, vol. 7, no. 78 (2017).

[16] “Phase change materials for building cooling applications.” *ET11SCE1260/HT.11.SCE.022 Report. Design & Engineering Services Customer Service Organization Southern California Edison*. (2012)

[17] W. Kays, M. Crawford, and B. Weigand. “Convective heat and mass transfer.” The McGraw-Hill Company, New York. (2005).

[18] “From URL” https://weatherspark.com/y/1042/Average-Weather-in-Monterey-California-United-States-Year-Round#Sections-BestTime

[19] V. C. Thomas. “Internal heat gains (IHG).” URL http://energy-models.com/internal-heat-gains-ihg

[20] U.S. Department of Energy. Input Output Reference, 27 March 2019.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California