Phase Change Materials for Building Cooling Applications

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EXECUTIVE SUMMARY

Phase change material (PCM) in commercial buildings save energy by actively absorbing and releasing heat. PCMs help maintain comfortable building temperatures with the potential to reduce peak sensible cooling loads and annual energy consumption in California and western climate zones with enough variation in day and night time temperatures.

Various materials have been considered for building applications, such as paraffin wax, bio-based organic materials, and eutectic salts, to take advantage of the PCM latent heat capacities and high storage densities. Like conventional thermal mass, such as concrete or adobe, PCMs can store similar amounts of heat but with significantly less mass. PCMs maintain a near-constant temperature within the conditioned space while undergoing a phase change. Melting temperatures typically range from 70 to 80°F in building cooling applications. This temperature range is varied, based on application, to minimize the heating and cooling loads for the building while maintaining the comfort of its occupants.

PCM research has been done for decades, but structural complications and flammability issues in prior PCM products have prevented adoption of the technology. Recently, some new commercial products mitigate these issues. Despite decades of research, the effect of PCM on energy consumption in buildings is not understood.

The objective of this paper is as follows:

- Analyze the performance of commercially available PCM products using the EnergyPlus software tool.
- Assess the technical potential of PCMs for reducing the cooling load in commercial buildings.
- Determine which applications optimize the energy impact of PCMs.
- Determine the California climate zones (CZs) that are the most appropriate for PCM installation.

SCE conducted simulations in five California CZs to estimate the use of PCMs to reduce peak sensible cooling demand and annual energy savings in commercial office buildings for the following applications:

- PCM in drop ceilings.
- PCM embedded in wallboard.
- PCM- embedded in wall insulation.
- PCM wall panels installed interior to wallboard.

The main benefit of PCMs is the ability to reduce the size or capacity of the building's air-conditioning system. Reduced capacity on the order of 25% was deemed possible. PCMs in buildings also reduces energy consumption when "free" cooling is accomplished when nights are cool. Annual cooling energy savings between 2 and 14% were achieved in the simulation study. When properly applied, PCM can effectively reduce installed equipment costs. The application of PCMs requires above-average design skill compared to conventional HVAC system and building design.

PCMs must go through phase transition to be useful. For this reason, care and strategic action must be taken to ensure PCMs' success in the market.

Monitored field installations are required to calibrate the simulation models developed using software tools like EnergyPlus. More importantly, these projects act as a useful tool to help persuade designers that PCM projects will succeed. Future success of PCMs depends on engaging users, designers, and PCM manufacturers in a collaborative relationship to apply and promote this technology.

ABBREVIATIONS

CEUS	Commercial End-Use Survey
CLTEESP	California Long Term Energy Efficiency Strategic Plan
CZ	Climate Zone
GWh	Gigawatt hours
HVAC	Heating, Ventilation, and Air Conditioning
kWh	Kilowatt hours
LHS	Latent Heat Storage
PCM	Phase Change Material
SCE	Southern California Edison
sf	Square Feet
SHS	Sensible Heat Storage

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INTRODUCTION

Phase change materials (PCMs) are materials that store and release latent heat. When used for building applications, the latent thermal storage capacity of PCMs can offset cooling and heating loads in a building. Typically, PCMs store heat by undergoing a solid-to-liquid phase transformation.

With energy demands forecasted to rise over the coming decades, new energy efficiency technologies are essential to minimize the need for new power generation. The California Long Term Energy Efficiency Strategic Plan (CLTEESP) further stresses the advancement of energy-efficient products by outlining the following goals:

- Zero-net energy for all new construction residential homes, and reduced energy consumption in existing residential homes by 40%, by 2020, compared to 2005 Title 24.
- Zero-net energy for all new construction commercial buildings, and 50% of existing commercial buildings, by 2030, compared to 2005 Title 24.
- New climate-appropriate (California) HVAC technologies (equipment and controls, including system diagnostics) are developed with accelerated market penetration[1].

To support these goals, Southern California Edison's (SCE) Heating, Ventilation, and Air Conditioning (HVAC) Technology and Systems Diagnostics Advocacy Program aims to develop climate appropriate HVAC strategies. Additionally, SCE's Emerging Technologies Program evaluates emerging energy-efficient technologies for adoption into utility incentive programs.

Several companies recently introduced PCMs for building applications. In some climates, adding PCMs to a structure may eliminate the requirement of mechanical air-conditioning altogether, albeit reducing the ability to control thermal comfort.

The objective of this project is as follows:

- Analyze the performance of commercially available PCM products.
- Assess the technical potential of PCMs for reducing the cooling load in commercial buildings.
- Determine which applications look most promising to optimize the energy impact of PCMs.
- Determine which California climate zones (CZs) are most appropriate for PCM installation.

BACKGROUND

Thermal energy storage in buildings comes in two forms, sensible heat storage (SHS) and latent heat storage (LHS). SHS systems charge and discharge energy or heat by using the heat capacity of the material and a corresponding change in temperature. Conversely, LHS systems charge and discharge energy by undergoing a phase change, have a higher energy density, and maintain a near-constant temperature throughout the charging and discharging process.

PCMs have been studied for decades[2]. To take advantage of the PCMs' latent heat capacities and high storage densities[3], various materials have been considered for building applications, such as paraffin wax, bio-based organic materials, and eutectic salts. Unlike conventional thermal mass, such as concrete or adobe, PCMs can store similar amounts of heat with significantly less mass, and maintain a near-constant temperature within the conditioned space while undergoing a phase change. Melting phase change temperatures typically range from 70 to 80°F in building cooling applications. This temperature range is varied based on application as to minimize the heating and cooling loads for the building while maintaining occupant comfort.

For a solid-liquid PCM product, once the temperature surrounding the PCM rises to the melting point, the PCM absorbs the heat and maintains a near-constant temperature until it fully liquefies. Most of the energy in the PCM is stored until the ambient temperature falls back to the melting point, then discharges heat, and maintains the temperature of the space until it fully solidifies. Figure 1 shows this process.[4]

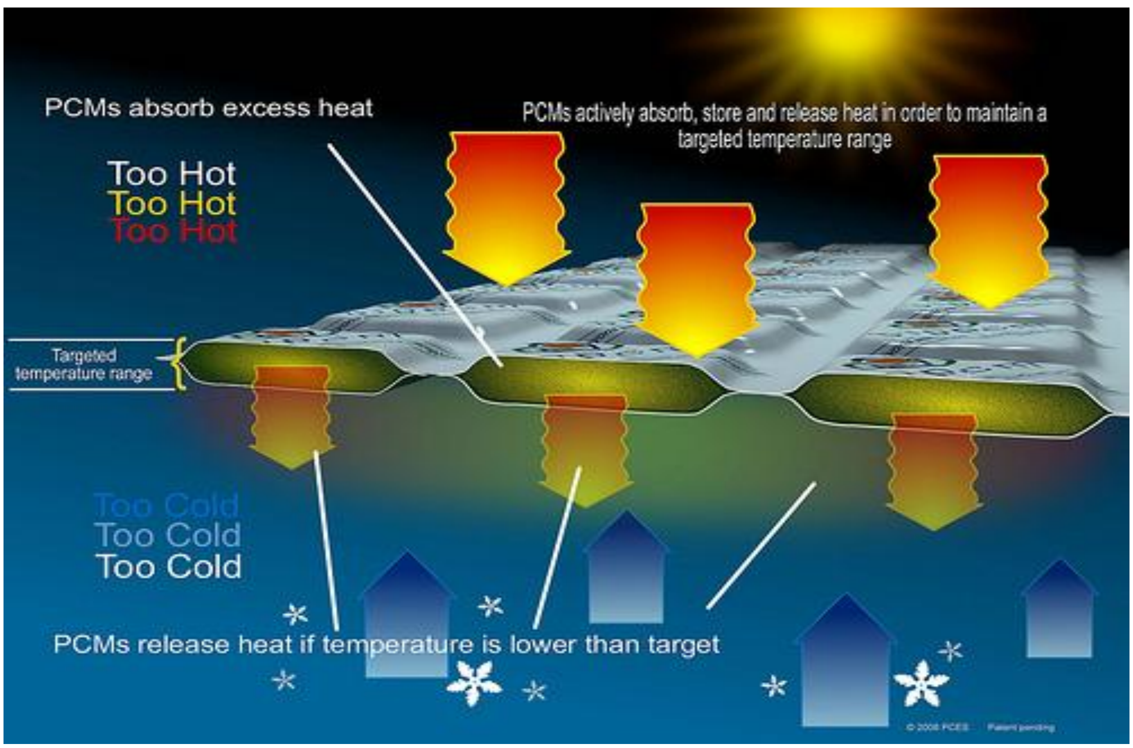

FIGURE 1. HOW PCM WORKS

PCMs can be installed as follows:

- Packaged in microencapsulated or macroencapsulated cells for application in interior wall construction (adjacent to insulation and wallboard).
- Between attic joists.
- Above ceiling panels in a drop ceiling.
- Inside the wallboard, ceiling panels, and floor tiles.

Historically, the following issues hamper the use of PCMs:

- Embedding non-encapsulated PCM directly into wallboard or concrete caused stratification.
- In wallboard, the paraffin leached to the surface creating stains and a fire hazard. Newer products mitigate this by encapsulating the PCM[5].
- Structural properties were degraded.
- Adding sufficient quantity of paraffin to concrete in compromised the strength of the material. A solid-solid phase change material, neopentyl glycol, was also explored, but it also had a negative impact on the structural properties of building materials.
- The potential for fire hazards is a problem for PCMs[6]. Fire retardants are often added to reduce flammability, but this inhibits thermal performance[7].
- PCMs experience long charging times due to low thermal conductivity. Studies have been conducted to enhance conductivity, such as adding nanoparticles or aluminum additives[8], but this raises costs.
- Issues have also been documented in the manufacturing process of PCM in wallboards[9]. The PCM tends to migrate to the outer third of wallboard when wallboard is cut due to the diffusion process.

In a 2009 study by Oak Ridge National Laboratory, EnergyPlus was used to simulate the application of PCM in a single-family ranch-style home based in Atlanta[10]. Results of the simulations showed about a 10% annual reduction in wall cooling and heating loads in the building with bio-based PCM-enhanced exterior walls. Additionally, a simulated PCM-enhanced attic floor with R-38 insulation showed a potential 14% reduction of annual loads generated by the attic, resulting in the equivalent to about R-58.

Arizona State University conducted a study measuring a reduction of 30% in annual cooling energy for a 192 square-foot (sf) shed with bio-based (organic) PCM compared to a shed without PCM[11].

Much of the analysis of the application of PCMs in buildings has not been harmonized. For example, in one study, use of PCM in roof insulation was combined with a reflective and ventilated roof. Roof reflectivity and ventilative cooling had more impact on roof heat flow than the addition of PCMs. Also, the total building energy impact (savings) is not always the metric used to characterize the efficacy of using PCMs.

Early attempts to apply materials that undergo a phase change for storing thermal energy showed mixed success. Researchers tried to use eutectic salts for storage in solar heating systems. “Melting” and “freezing” occurred repeatedly and phase change was characterized by a chemical reaction involving salt hydration. These systems were not successful primarily because the salt and water tended to separate (the salt precipitated and settled leaving the water above it), ending the contact needed for repeated reactions.

Phase change is also a mechanism used for ice storage systems where "coolth" is stored during the night and used for air-conditioning during the day. Once the heat exchanger problems are resolved, these systems performed admirably and are continuing to be applied. Since water is a pure substance, and making ice does not involve a chemical reaction, ice storage is a relatively trouble free system.

Recent product development of PCMs for heating applications in buildings, focuses on encapsulated paraffin or other organic materials with appropriate phase transition temperatures. Enclosing the paraffin allows it to melt and freeze without escaping into the surrounding material.

One significant problem is the lack of knowledge about the best way to apply PCMs in buildings. Recent studies show that this issue is complicated, and that there is little or no energy savings unless "everything is just right"[12,13]. This paper partially addresses this problem by using EnergyPlus to simulate a model commercial office building.

ASSESSMENT OBJECTIVES

The objective of this paper is as follows:

- Analyze the current market of PCM products.
- Assess the technical potential of PCMs for reducing the cooling load in commercial buildings.
- Determine which applications are the most promising for optimizing the energy impact of PCMs.
- Determine which California CZs are the most appropriate for PCM installation.

EnergyPlus simulations were conducted to determine the following:

- Determine how PCMs reduce building energy use and peak cooling requirements.
- Quantify how much PCM is "too little" and "too much".
- Conduct simulations in five CZs to determine weather-dependent performance, including sensible cooling reduction and annual energy savings.
- Perform a cost/benefit analysis.

Results from this study are used to make recommendations for the potential of PCMs to be adopted into SCE's energy-efficiency portfolio and outline future work needed to further validate the technical viability and market readiness of PCM products.

TECHNOLOGY EVALUATION

PCM products, applications, and its technical potential in SCE's service territory was determined by conducting literature research, performing EnergyPlus simulations, and reviewing existing building stock information. Additionally, SCE conducted discussions with key industry stakeholders, including PCM manufacturers, to provide focus and insight.

PCM PRODUCTS AND APPLICATIONS

There are several products and approaches used to implement PCMs in buildings, including paraffin wax, plant-based materials, and a eutectic salt mixture product. Table 1 lists examples PCM products and their applications.[14,15]

TABLE 1. LIST OF SAMPLE PCM MATERIALS AND THEIR APPLICATIONS

PCM PRODUCT	APPLICATION
Micro-encapsulated Paraffin Wax	Wallboard
	Ceiling Tile
	Wall interior adjacent to wallboard
	Embedded in wall insulation
Plant-based Materials	Wall interior adjacent to wallboard
	Attic/drop ceiling plenum floor
Eutectic Salt Mixtures	Wall interior adjacent to wallboard
	Attic/drop ceiling plenum floor

Examples of PCM building products are shown below.

Figure 2 shows an Energain® PCM Panel sandwiched between foil material with sealed edges.

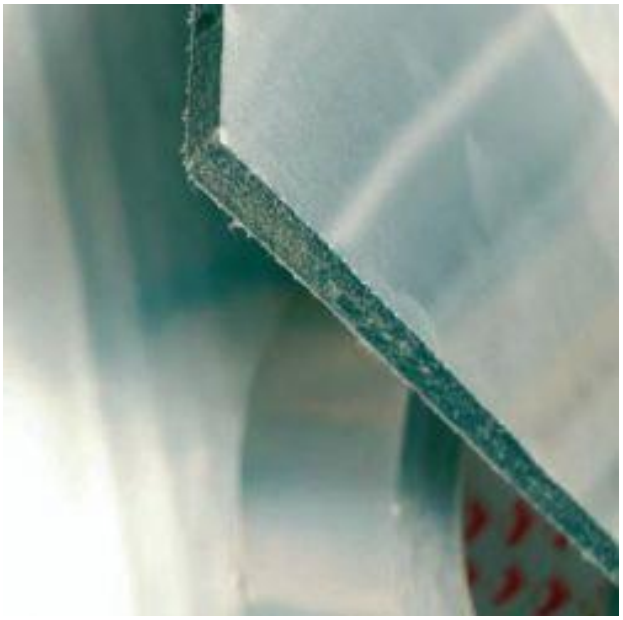

FIGURE 2. PICTURE OF ENERGAIN® PCM PANEL. THE PHASE CHANGE MATERIAL IS SANDWICHED BETWEEN FOIL MATERIAL AND EDGES ARE SEALED WITH FOIL TAPE.

Figure 3 shows Micronal® Phase Change Material in a gypsum wallboard where micro encapsulated paraffin is mixed with gypsum during the wallboard manufacturing process.

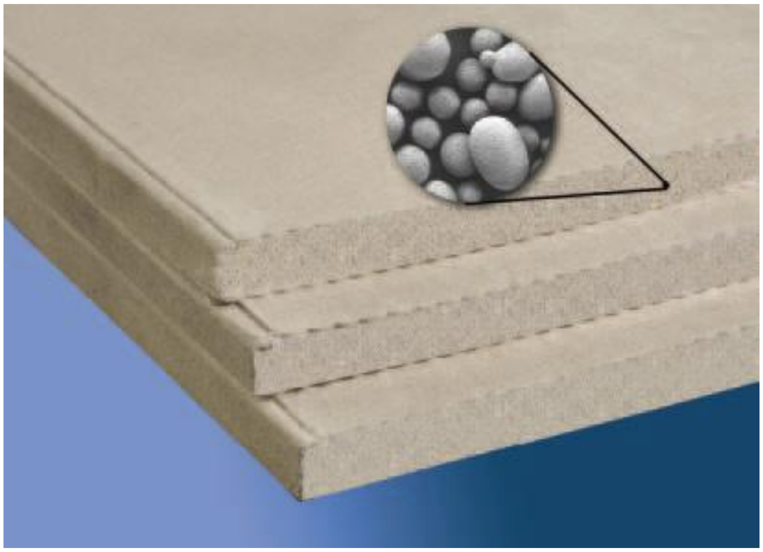

FIGURE 3. MICRONAL® PHASE CHANGE MATERIAL IN NATIONAL GYPSUM WALLBOARD. MICRO-ENCAPSULATED PARAFFIN IS MIXED WITH THE GYPSUM IN THE WALLBOARD.

Figure 4 shows a Macro-encapsulated BioPCM® Product for Placement above dropped ceilings and in the wall cavities. The phase change material is encased in plastic bubbles instead of micro-encapsulation.

FIGURE 4. MACRO-ENCAPSULATED BIOPCM® PRODUCT FOR PLACEMENT ABOVE DROPPED CEILINGS AND IN WALL CAVITIES.

Figure 5 shows Bio-PCM that is installed on Top of the Ceiling Tile in a Return Air Plenum.

FIGURE 5. BIOPCM INSTALLED ON TOP OF THE CEILING TILE IN A RETURN AIR PLENUM.

Table 2 shows the thermal properties of select PCMs. Melting temperature range and the amount of heat required for a material to undergo liquid-solid phase transition (heat of fusion) are important physical properties of PCMs. Whenever possible, these properties are based on the manufacturer's published documentation. Unfortunately, the expected useful life of PCM is not well known. The materials are engineered to withstand significant cycling without measurable hysteresis. Therefore, the useful life is predicted to be limited by the packaging/encapsulation media.

TABLE 2. PROPERTIES OF SELECT PHASE CHANGE MATERIALS

PHASE CHANGE MATERIAL	MELTING TEMPERATURE RANGE (°F)	HEAT OF FUSION (BTU/LB)
Micro-encapsulated Paraffin Wax[16,17]	73	75
Plant-based Materials[18]	73-79	71-86
Eutectic Salt Mixtures[19]	77-80	55-81

The chemical make-up of PCMs can be modified to fine-tune the desired physical properties.

Figure 6 shows the required thickness for conventional materials used in building construction to match the equivalent heat capacity of a one-inch-thick PCM with a heat of fusion of approximately 70 Btu/lb[20].

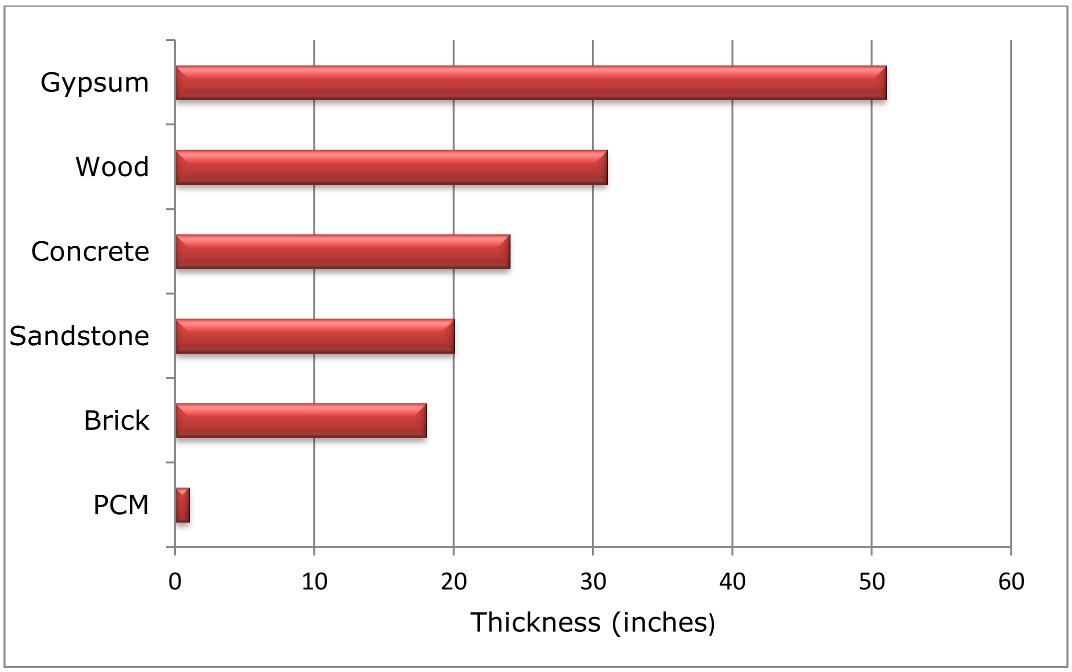

FIGURE 6. PCM THICKNESS COMPARED TO CONVENTIONAL THERMAL MASS

The high energy storage density of PCM allows the incorporation of thermal mass into wood framing and other lightweight buildings without compromising the original design. Certain PCM applications, such as placement of PCM on the plenum floor of a drop ceiling, can be implemented without major renovation.

TECHNICAL APPROACH

The initial literature review revealed that there remains a significant amount of uncertainty surrounding the performance of PCMs and its numerous applications in commercial buildings. SCE used EnergyPlus to conduct building simulations to better understand the energy savings and demand reduction potential of PCM as it pertains to the installed location, quantity of material, and CZ, while holding other building parameters and properties constant.

Five different CZs in SCE's service territory were analyzed to gain an understanding of climatic effects on PCMs. SCE performed simulations for CZ 9 (Los Angeles), CZ 10 (Riverside), CZ 14 (Edwards Air Force Base), CZ 15 (Blythe), and CZ 16 (Big Bear). To quantify the potential for demand savings, peak sensible cooling was calculated along with annual energy savings for monthly and annual cooling and heating.

Market segments were analyzed to identify the building types suitable for PCM. SCE used this analysis, along with data from the 2006 California End-Use Survey (CEUS), to project a technical market potential for PCM in its service territory.

BUILDING SIMULATIONS USING ENERGYPLUS

EnergyPlus is an energy analysis and thermal load simulation program. This program takes a user's description of the physical make-up of a building and its associated mechanical systems, and calculates the heating and cooling loads necessary to maintain thermal control set points, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would[21].

SCE selected EnergyPlus for this project for its ability to simulate the energy transport through building elements that contain PCMs. This feature employs a finite difference technique and uses temperature/enthalpy tables for the particular PCM. These methods were developed by Pedersen and described in detail in Reference 12 and in the EnergyPlus documentation. This feature is not currently available in other simulation tools. This project used EnergyPlus versions 7.1 and 7.2.

EnergyPlus is an expansive computer program. Using it without a graphical user interface can be daunting. The DesignBuilder tool was used for this project[22]. It provides an intuitive scheme for describing buildings and systems and allows users to quickly tunnel through the mass of EnergyPlus output to extract the variables of interest. This feature was critically important to this project.

RESULTS

The simulation results highlight PCM's potential to reduce peak sensible cooling demand and annual energy savings in commercial office buildings in drop ceilings, embedded in wallboard or wall insulation, and PCM wall panels installed interior to wallboard. SCE used these results to estimate the cost benefit of installing PCMs, to examine the market potential, and to estimate the total technical potential in its service territory.

BUILDING MODEL SIMULATIONS

OPEN OFFICE WITH PCM ABOVE DROP CEILING

The first application investigated the use of PCM in return plenums above drop ceilings in commercial office buildings as shown in Figure 7.

FIGURE 7 MACRO-ENCAPSULATED BIOPCM INSTALLED IN TOP OF CEILING TILE IN A RETURN AIR PLENUM

The general airflow pattern for this drop ceiling installation is shown schematically in Figure 8.

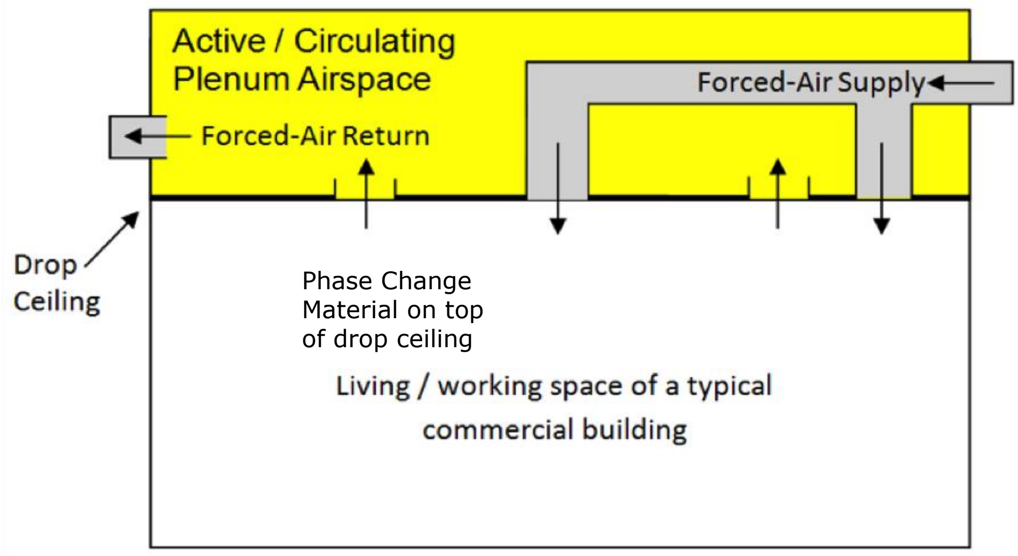

FIGURE 8 SCHEMATIC OF GENERAL AIRFLOW OF A SPACE WITH A CEILING RETURN AIR PLENUM

This is a useful application for the following reasons:

- The PCM is easily installed (see Figure 7).
- The surface area available, and therefore the amount of PCM that can be installed, is large.
- The temperature of the air in the plenum and the surface temperature of the room ceiling/plenum floor have relatively uniform variation.

To explore the efficacy of placing PCM on top of the ceiling tile in a return air plenum, researchers created an EnergyPlus model of an open plan office building with a return air plenum. Figure 9 shows model renderings.

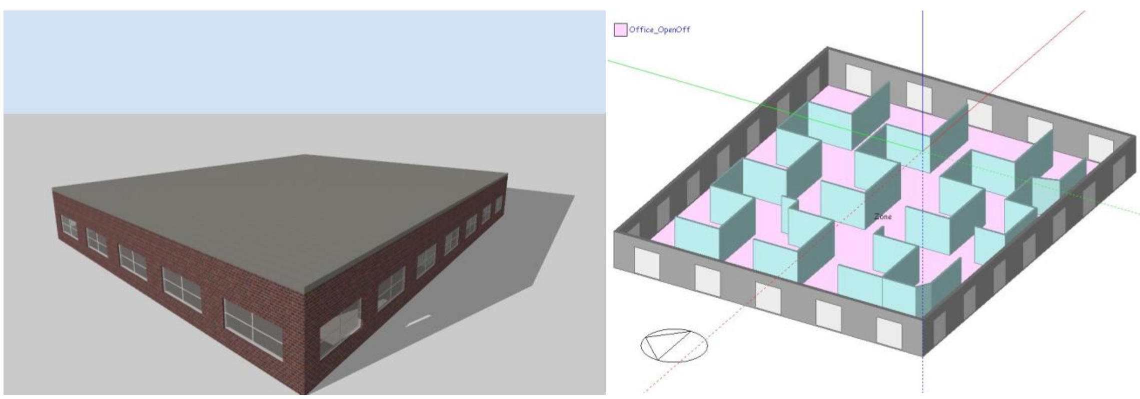

FIGURE 9 RENDERING OF OPEN OFFICE WITH PLENUM

The building is roughly 1,000 square meters in floor area (11,000 square feet). Occupancy, lighting, and equipment schedules are for a "typical" open-plan office. The heating and air conditioning system is a variable air volume with reheat system. Details of the building construction and schedules are located in Appendix A.

SUMMARY OF SIMULATION RESULTS BY CLIMATE ZONE

Researchers used an iterative approach was taken to determine the largest possible peak sensible cooling reduction in each CZ. The process began with CZ 9 (Los Angeles), and included the following steps in determining the greatest potential savings:

- Vary the PCM phase transition temperature range from 22-24°C (72-75°F) to 23-25°C (73-77°F).
- Increase PCM thickness (¼ in, ½ in, 1 in) with a constant thermostatic set point of 22°C (71.6°F).
- Alter the HVAC control strategy to pre-cool the building to 20.5°C (68.9°F) at night and maintain 22°C (71.6°F) during the day.
- Increase day and night temperature swing by pre-cooling to 20°C (68°F) at night and maintaining 24°C (75.2°F) during the day.

Similar methods were applied to CZ 10 (Riverside), CZ 14 (Edwards Air Force Base), and CZ 16 (Big Bear). These results are shown in Table 3. Refer to Appendix B for detailed results and analysis.

TABLE 3. SUMMARY OF PEAK COOLING DEMAND REDUCTION AND ANNUAL ENERGY SAVINGS FOR PCM IN DROP CEILINGS BY CLIMATE ZONE

CZ	PEAK COOLING DEMAND REDUCTION (W/FT^2)	%	ANNUAL COOLING ENERGY SAVINGS (KWH/FT^2)	%	ANNUAL HEATING ENERGY SAVINGS (KWH/FT^2)	%
9	1.21	26	1.55	14	1.47	52
10	1.18	22	1.26	13	0.35	44
14	1.18	22	0.95	10	0.42	38
15	1.20	21	1.41	8	1.28	43
16	1.04	21	0.58	13	0.59	31

SUMMARY OF PCM IN DROP CEILINGS

- PCM placed on top of a drop ceiling in the return air plenum can reduce peak cooling load on the order of 25% (more in some CZs).
- In all cases, monthly and annual heating and cooling requirements are reduced.
- For this application, diurnal room temperature variation needs to be larger than the temperature range over which the PCM changes phase. Results converged to 20-24°C (68-75°F) for a room with PCM having a 23-25°C (73-77°F) phase transition temperature range.
- Using PCM is *potentially* cost-effective depending on HVAC system costs and the cost of the PCMs. Cost benefit is achieved by the reduced capital cost of installing smaller equipment.
- A PCM with the proper phase transition temperature must be selected in coordination with the prescribed room temperature control strategy.
- For applications to succeed, additional building variables need to be measured, such as plenum air temperature and PCM temperature. Without attention and scrutiny, PCMs might not go through phase transition.

- Designing building systems that incorporate PCMs is challenging and requires advanced models and tools, such as EnergyPlus, that can calculate traditionally unimportant design variables like surface temperature and occupant comfort.

Partitioned Office with PCM in Gypsum Wallboard

In this product, micro-encapsulated PCMs are added to the drywall during manufacturing. The drywall is used as the interior surface for all the walls in each zone.

PCM wallboard is manufactured and marketed as National Gypsum BASF Micronal wallboard as shown Figure 3. Literature indicates that the phase transition occurs at 25°C, so the T-h curve phase transition occurs between 24 and 26°C[23].

Following the approach used in the previous application, the results are summarized in Table 4. Please refer to Appendix C for detailed results and analysis.

Table 4. Summary of Peak Cooling Demand Reduction and Annual Energy Savings for Partitioned Office with 1-inch PCM in Wallboard by Climate Zone

CZ	Peak Cooling Demand Reduction (W/ft^2)	%	Annual Cooling Energy Savings (kWh/ft^2)	%	Annual Heating Energy Savings (kWh/ft^2)	%
9	2.43	25	0.75	3	0.27	32
10	2.51	25	0.17	3	0.05	38
14	2.57	24	0.74	2	0.37	29
15	2.58	23	0.64	2	0.20	27
16	2.70	27	4.20	12	4.10	21

Partitioned Office with Microencapsulated PCM in Wall Insulation

Researchers simulated a nine-zone building with walls and roof containing insulation with and without PCM.

After many iterations, researchers concluded that adding PCM to batt insulation produces a nominal effect on peak building cooling loads. The reasons are as follows:

- In theory, adding PCM to the insulation moderates heat transfer *through* the walls and roof, disconnecting the PCM from heat flows *inside* the room. In practice, the heat gain through well-insulated walls and roofs is miniscule compared to other heat gains. Even if adding PCM to the insulation eliminated wall and roof heat transfer, the effect on room cooling would barely be noticeable.
- The PCM is embedded in an insulating material with poor heat transfer properties. Good heat transfer properties are necessary for effective use of PCMs.
- 40% PCM by weight in the insulation is a small amount of PCM compared to the other applications studied.

Please refer to Appendix D for detailed results and analysis.

PARTITIONED OFFICE WITH A PCM LAYER UNDER THE INTERIOR WALLBOARD

Researchers simulated a PCM named Energain immediately inside the interior wallboard. This material is shown in Figure 2. The material is used in the outside walls, in the partitions, and as the layer next to the inside layer in the roof as shown in Figure 10.

FIGURE 10. ENERGAIN PANELS ON THE INSIDE OF THE ROOF (LEFT) AND WALL (RIGHT). THE SURFACES WILL BE COVERED WITH WALLBOARD.

Results show increased benefit with a second layer of PCM before diminishing returns as shown in Figure 11.

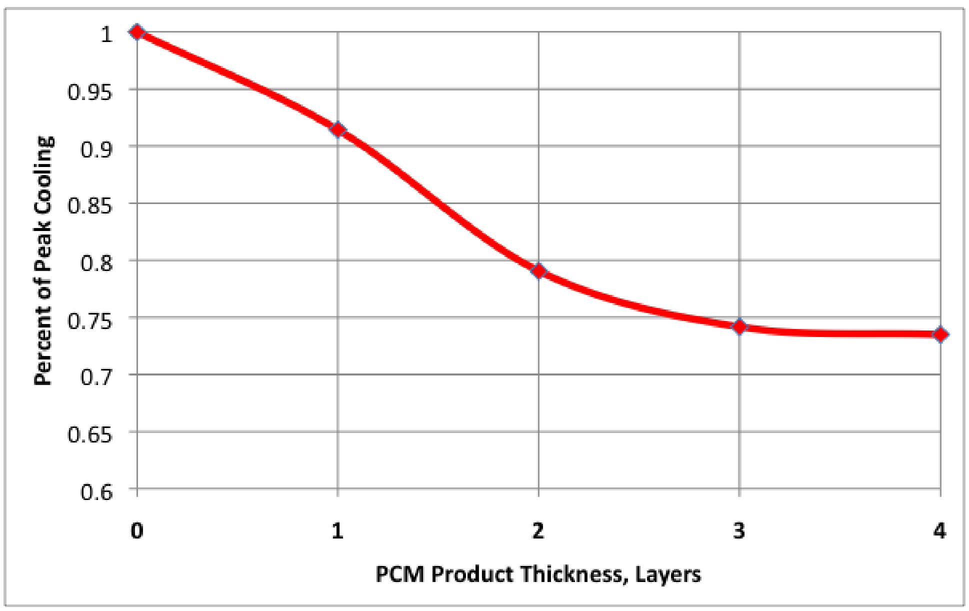

FIGURE 11. FRACTIONAL PEAK LOAD REDUCTION AS A FUNCTION OF NUMBER OF LAYERS OF PCM, CLIMATE ZONE 9.

Researchers used two layers of Energain panels to get the maximum potential, and then analyzed the savings. The results are summarized in Table 5. See Appendix E. Detailed Results for Partitioned Office with a PCM Layer Under the Interior Wallboard for detailed results and analysis.

TABLE 5. SUMMARY OF PEAK COOLING DEMAND REDUCTION AND ANNUAL ENERGY SAVINGS FOR PARTITIONED OFFICE WITH TWO PCM LAYERS UNDER INTERIOR WALLBOARD BY CLIMATE ZONE

CZ	PEAK COOLING DEMAND REDUCTION (W/FT^2)	%	ANNUAL COOLING ENERGY SAVINGS (KWH/FT^2)	%	ANNUAL HEATING ENERGY SAVINGS (KWH/FT^2)	%
9	2.88	29	0.74	2	0.28	22
10	1.95	24	1.30	4	0.84	8
14	2.04	20	1.67	5	1.21	11
15	2.32	21	0.74	2	0.28	22
16	2.60	25	1.58	7	1.30	27

COST BENEFIT ANALYSIS

Capital cost is a major factor when installing PCMs. If designers can be persuaded to reduce the capacity of the specified air conditioning system, the capital cost of the PCM, not including labor, can potentially pay for itself. From interviews and rule-of-thumb estimates, SCE assumed HVAC system costs of 22-33 $\$/ft^2$ floor area (237-355 $\$/m^2$) and a PCM cost of 2-7 $\$/ft^2$ material (21-75 $\$/m^2$). Peak sensible cooling reductions of 9 to 21% can reduce HVAC system cost enough to pay for PCM material costs. Every application and CZ simulated shows that the potential cost benefit meets or exceeds this peak sensible cooling reduction, except when installing PCMs in wall insulation.

While not as significant, annual energy savings can result in an additional reduction up to $\$0.50/ft^2$ per year[i].

[i] Based on \$0.12/kWh and annual cooling savings of 4.2 kWh/ft^2.

MARKET ANALYSIS

PCMs can be incorporated in a variety of commercial buildings. SCE used the California Commercial End-Use Survey[24] to estimate the total market for PCMs in Southern California. Table 6 shows the total estimated floor stock, by building type,[25] in SCE's service territory.

TABLE 6. BUILDING FLOOR STOCK IN SCE SERVICE TERRITORY BY BUILDING TYPE

BUILDING TYPE	FLOOR STOCK (THOUSANDS-FT^2)	COOLING ENERGY USAGE (GWH/YR)
Small Office (< 30,000 ft^2)	157,884	460
Large Office (≥ 30,000 ft^2)	227,225	899
Restaurant	61,623	483
Retail	309,601	863
Food Store	63,820	229
School	176,999	279
College	64,809	138
Refrigerated Warehouse	30,031	15
Unrefrigerated Warehouse	353,765	122
Health	106,471	454
Lodging	112,405	196
Miscellaneous	477,725	659
TOTAL	**2,142,359**	**4,939**

The commercial market sector has several buildings types suitable for PCM integration, such as small and large office buildings, restaurants, retail stores, food stores, schools, and colleges. The result is a potential market size of 1.06 billion sf of total floor stock in SCE's service territory. This corresponds to 3,351 Gigawatt-hours per year (GWh/yr) of cooling-related energy consumption.

The remaining buildings types face additional integration challenges that make the likelihood of their success minimal. For example, hospitals (health) have strict ventilation requirements that inhibit the ability to optimize the charging/discharging process, unrefrigerated warehouses are often unconditioned, and lodging buildings provide control to occupants making control strategies difficult to implement. Refrigerated warehouses and miscellaneous are also excluded from consideration.

Table 3, Table 4, and Table 5, show that the annual cooling energy reductions between 2 and 14% result in a technical potential energy savings between of 67 and 469 GWh/yr.

SUMMARY AND CONCLUSIONS

PCMs in buildings should be considered along with other energy conservation measures.

The main benefit of PCM is that the capacity of the buildings air-conditioning system can be reduced. Reduced capacity on the order of 25% is possible, which is a significant saving in capital cost and power demand. PCM in buildings will reduce energy consumption if "free" cooling is used when nights are cool. When properly applied, phase change building products can be cost effective by reducing installed equipment cost.

The application of PCM requires special training for designers and contractors. PCM will be of no benefit unless latent energy storage is achieved. PCM must go through its phase transition in order to be useful. For this reason, care and strategic action must be taken to ensure PCM's success in the market.

The following conclusions are a result of the simulation study:

- PCM can reduce peak cooling load on the order of 25% - more in some CZs.
- In most cases, monthly and annual heating and cooling requirements were reduced. This does not apply to PCM in wall insulation.
- Diurnal room temperature variation needs to be larger than the temperature range over which the PCM changes phase. Results converged to 20-24°C for a room with PCM having a 23-25°C phase transition temperature range.
- Using PCM is *potentially* cost-effective, depending on HVAC system costs and the cost of the PCM. Cost benefit is achieved by the reduced capital cost of installing smaller equipment.
- A PCM with the proper phase transition temperature must be selected in coordination with the prescribed room temperature control strategy.
- For applications to succeed, it is likely that additional building variables need to be measured, such as plenum air temperature, and PCM temperature. Without attention and scrutiny, PCM may never go through its phase transition.
- Designing building systems that incorporate PCM will be challenging and require advanced models and tools, such as EnergyPlus, that can calculate traditionally unimportant design variables like surface temperature and occupant comfort.

RECOMMENDATIONS

Despite decades of study, more work is needed to truly understand the impact PCM has on reducing cooling load in buildings. The simulation study conducted for this project helps to define the problem, but there are still many unknowns.

The recommendations are as follows:

- Investigate poorly understood parameters. For example, the heat transfer coefficient that determines energy flow between air in a plenum and PCM on top of the ceiling is not well known. Additionally, it is not clear how air moves in the plenum of a drop ceiling.
- Verify rooms and buildings perform like the modeling software predicts. EnergyPlus is based on fundamental first principles, but when designing a building to use PCMs, it is important to know the correct model parameters, for example, the need for temperature/enthalpy data for PCM products. Test standards are being developed by standards development organizations to more accurately measure PCM properties.
- Use demonstration projects to calibrate the simulation models that are developed using software tools like EnergyPlus. These demonstration projects must persuade designers that PCM projects can succeed. These projects need to be carefully crafted and managed by trained personnel.
- Engage and educate users, designers, and PCM manufacturers in a collaborative relationship so that PCM technology is beneficial.
- Investigate improvements in the thermal comfort of building occupants. The surface temperature of wall and ceiling elements is more uniform when PCMs are used. Improved comfort leads to improved productivity. EnergyPlus and DesignBuilder have extensive comfort analysis features. This potential benefit needs to be explored quantitatively.

APPENDIX A. SIMULATION MODEL INPUT DETAILS

Appendix A provides details of the simulation model input.

Figure 12 shows the Scheduled Heat Gains for Interior Lighting, Equipment, and Occupants.

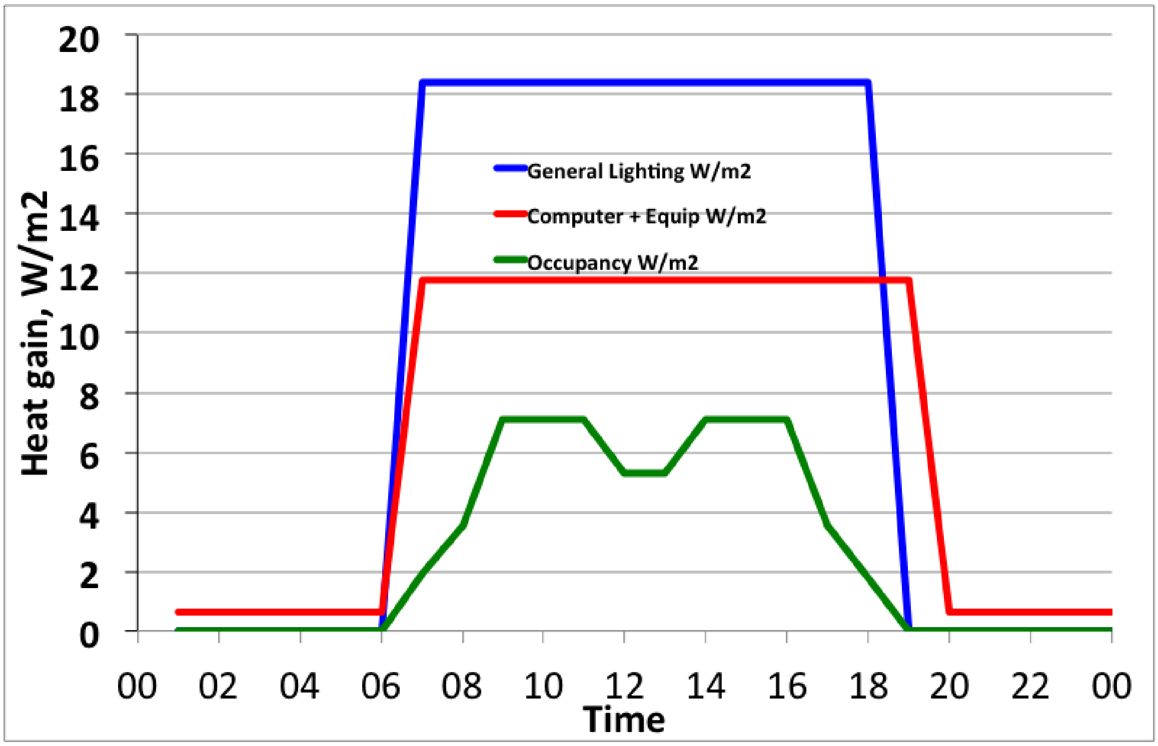

FIGURE 12 SIMULATION MODEL SCHEDULED HEAT GAINS FOR INTERIOR LIGHTING, EQUIPMENT, AND OCCUPANTS

Table 7 shows peak internal heat gains for the simulation model.

TABLE 7 SIMULATION MODEL PEAK INTERNAL HEAT GAINS

LOAD	SI UNITS	TYPICAL US AE UNITS
Lighting	18.75 W/m^2	4601.74 W/ft^2
Equipment	11.77 W/m^2	1.09 W/ft^2
People	0.111 $people/m^2$	97 ft^2/person

Figure 13 shows the wall construction inputs for the simulation model.

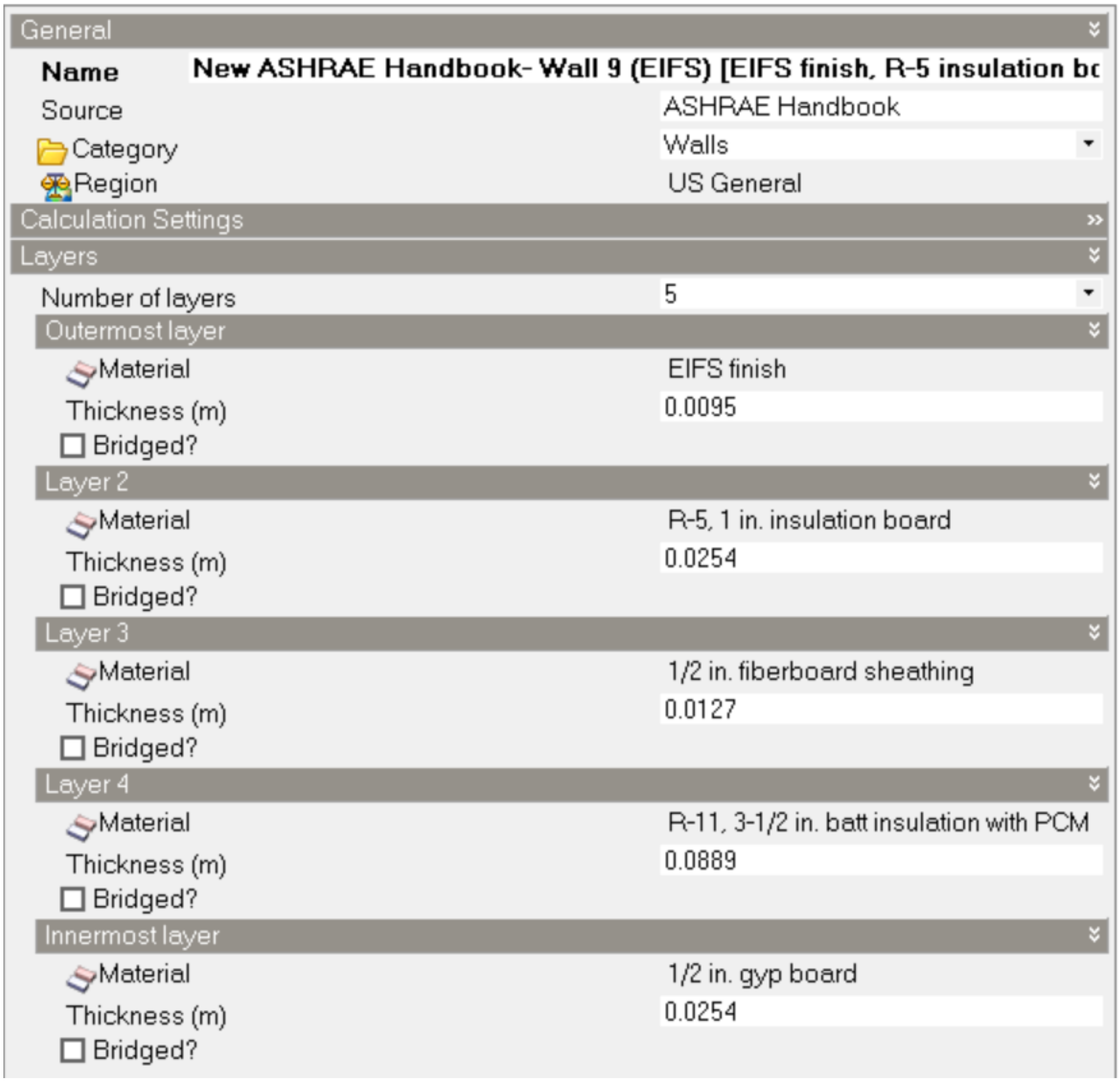

FIGURE 13 SIMULATION MODEL WALL CONSTRUCTION INPUTS

Figure 14 shows the partition construction input for the simulation model.

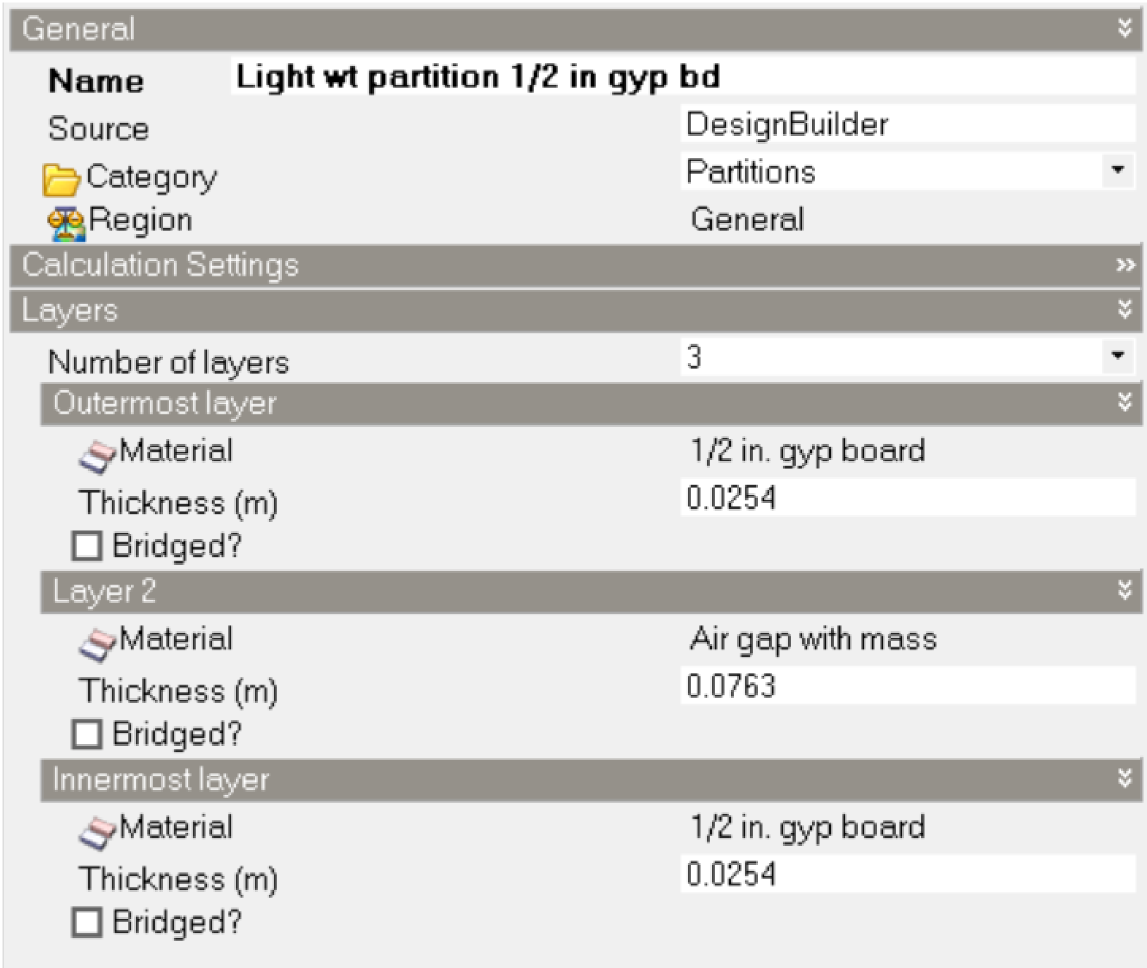

FIGURE 14 SIMULATION MODEL PARTITION CONSTRUCTION INPUT

Figure 15 shows the roof construction input for the simulation model.

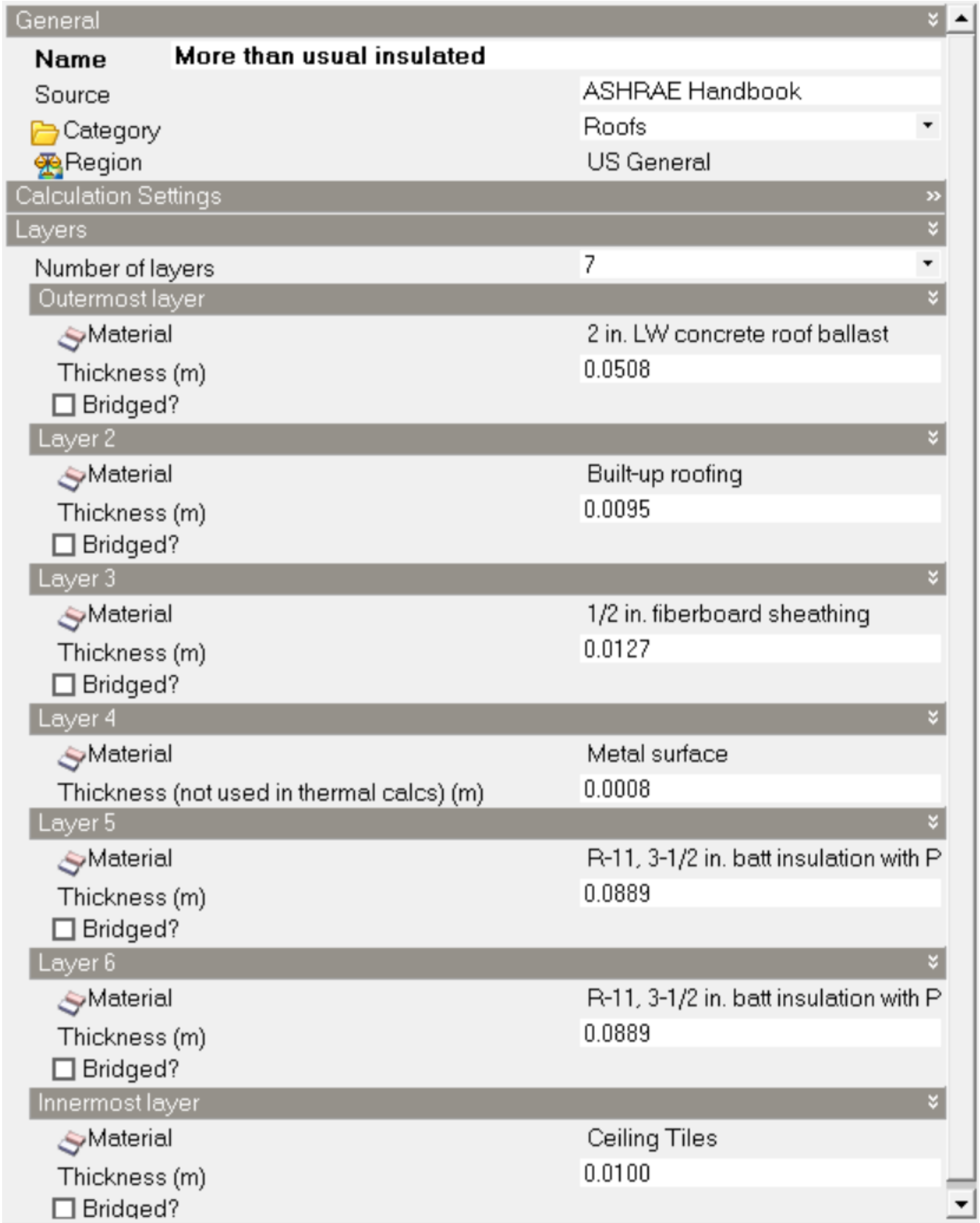

FIGURE 15 SIMULATION MODEL ROOF CONSTRUCTION INPUT

APPENDIX B. DETAILED RESULTS OF AN OPEN OFFICE WITH PCM ABOVE A DROP CEILING

Researchers investigated the use of PCM in return plenums above drop ceilings in commercial office buildings. An example of this installation is shown in Figure 16. The general airflow pattern for this installation is shown schematically in Figure 17.

FIGURE 16 MACRO-ENCAPSULATED BIOPCM INSTALLED IN TOP OF CEILING TILE IN A RETURN AIR PLENUM

The general airflow pattern for the Macro-encapsulated BioPCM installation is shown schematically in Figure 17.

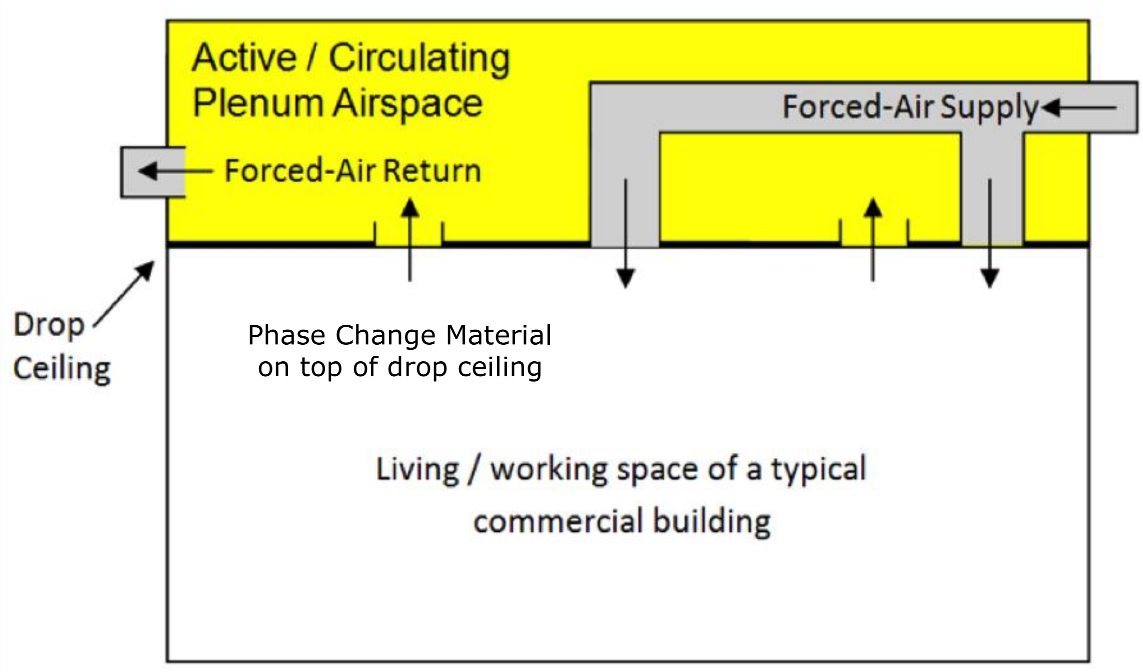

FIGURE 17 SCHEMATIC OF GENERAL AIRFLOW OF A SPACE WITH A CEILING RETURN AIR PLENUM

This is a desirable application for the following reasons:

- The PCM is easily installed (see Figure 16).
- The surface area available, and therefore the amount of PCM that can be installed, is large.
- The temperature of the air in the plenum and the surface temperature of the room ceiling/plenum floor have relatively uniform variation.

To explore the efficacy of placing PCM on top of the ceiling tile in a return air plenum, researchers created an EnergyPlus model of an open plan office building with a return air plenum. Renderings of the model are shown in Figure 18.

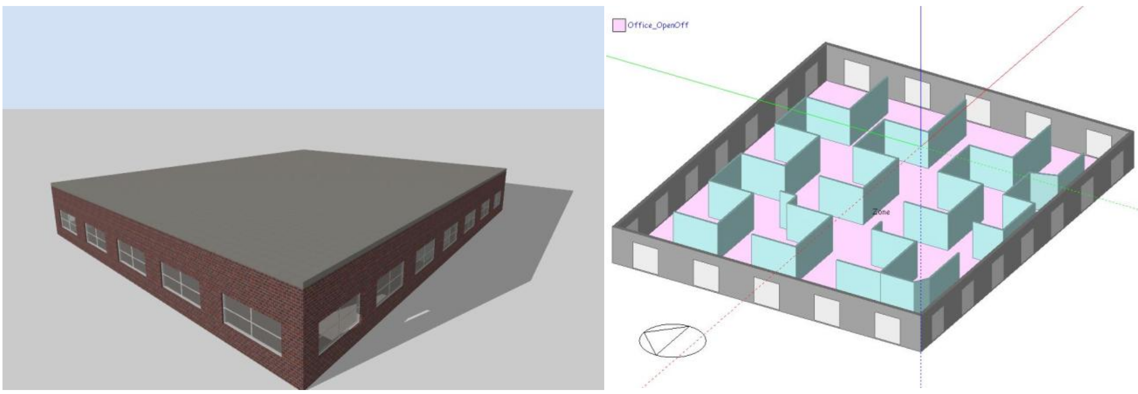

FIGURE 18 RENDERING OF OPEN OFFICE WITH PLENUM

The building is roughly 1,000 square meters in floor area (11,000 square feet). Occupancy, lighting and equipment schedules are for a "typical" open-plan office. The heating and air conditioning system is of the variable air volume with reheat type.

To highlight the impact of phase change material in the envelope the HVAC system is adjusted as follows:

- Fan energy was neglected.
- Variable air volume boxes (valves) were allowed to module to zero for the summer design day study.
- Required ventilation was set to zero.
- The system uses an economy cycle that uses outdoor air for cooling whenever its temperature was below room temperature.

CALIFORNIA CLIMATE ZONE 9, LOS ANGELES

The first location studied was Los Angeles, CA. The annual weather data was for California CZ 9, and the baseline has the building controlled to a constant temperature of 22^{o}C (71.6^{o}F).

The most important reason for considering the application of PCM in building is that the peak air-conditioning load can be reduced, which reduces the installed cost of new HVAC systems and reduces peak electrical demand charges. Researchers examined the peak load for the design day for the baseline, the temperature of the plenum air, and the top surface of the ceiling (the PCM layer surface temperature). Figure 17 shows that the plenum air temperature is also the return air temperature and, given a constant cold air supply temperature, is proportional to the sensible cooling accomplished by the cooling coil in the air handler.

The top surface of the plenum gives us an idea of the temperature of the phase change layer. The difference between the plenum air temperature and the temperature of the top surface of the plenum defines the temperature difference that is the forcing function for heat transfer between the plenum air (also the return air) and the PCM surface. If the plenum air is warmer than the surface heat, it is transferring heat to the PCM and vice versa. If the temperature difference is large, more heat is transferred by convection than if the difference is small.

Figure 19 shows the temperature of the plenum and the PCM surface. The top blue line is the plenum air temperature and the red dashed line is the PCM surface temperature with no PCM. In this case, "no PCM" is a layer with the same properties as the PCM, such as conductivity, density, and specific heat.

Notice that the surface and air temperatures are nearly equal. Also notice that both the air and surface temperatures range between about 22°C and 24.5°C, which means that the PCM should have a phase transition between these temperatures. The data for the bubble pack PCM shows that the phase transition occurs over approximately a 2°C range. We are left to choose 22-24 or 23-25°C. To make the choice we will simulate both ranges and use enough PCM to make the difference clear.

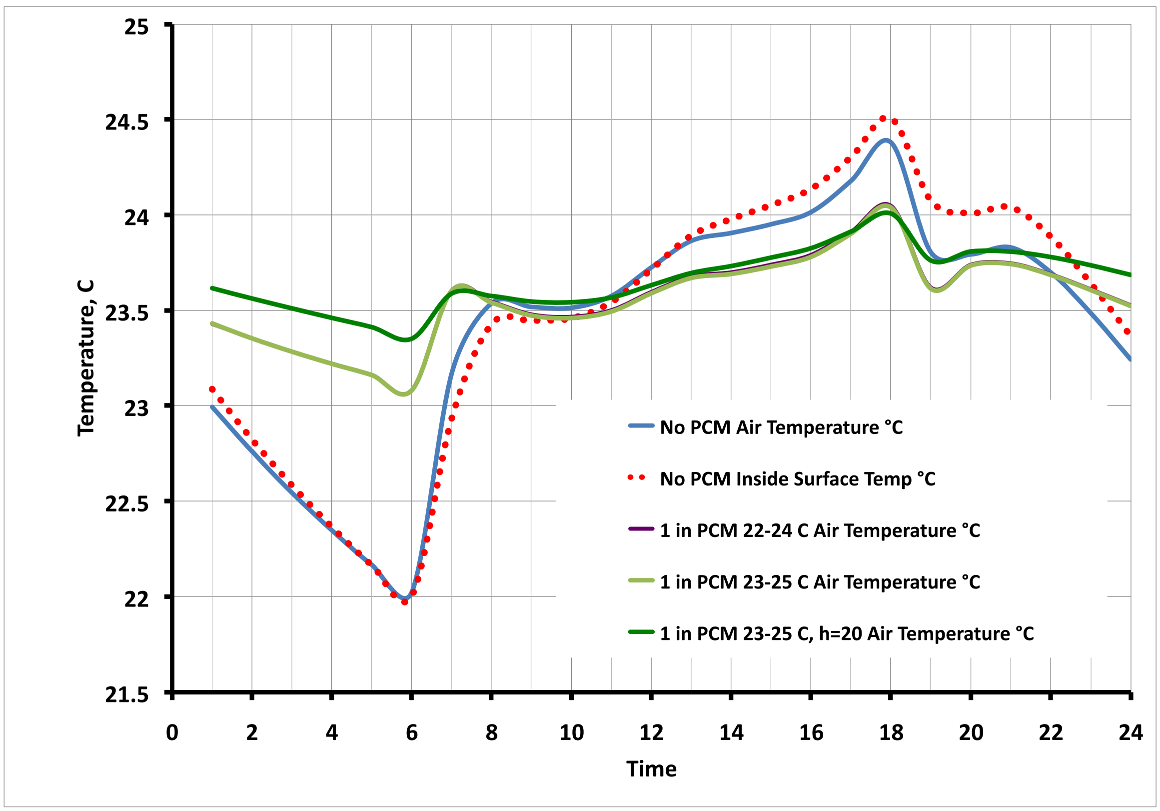

FIGURE 19. PLENUM AIR AND SURFACE TEMPERATURES, WITH AND WITHOUT PCM, CLIMATE ZONE 9.

In this instance, it does not matter whether the PCM melts between 22-24 or 23-25°C.

Researchers reviewed the EnergyPlus results and observed that the convection heat transfer coefficient between the plenum air and the PCM surface varies from about 4 to about 6 W/m^2-K. This is low since it is based largely on the assumption of natural convection. In the ceiling plenum, the convection heat transfer is forced or a mix of forced and natural. The bubble pack PCM product has "bumps" of encapsulated PCM above its flat surface lying on the ceiling and it presents about 1.8 square meters of surface area for heat transfer per square meter of ceiling.

Equation 1 shows the governing heat transfer equation between the bubble pack and the plenum.

EQUATION 1. HEAT TRANSFER EQUATION BETWEEN THE BUBBLE PACK AND THE PLENUM AIR

$$Q = 1.8hA\ \Delta T$$

Where Q is the heat transfer in watts, h is the convection coefficient in W/m^2-K, A is the ceiling surface area in m^2, the number 1.8 is the ratio of heat transfer surface to ceiling area, and ΔT is the temperature difference between the PCM surface and the plenum air, °C.

Figure 20 shows a curve where 1.8h has been assumed to be 20 W/m^2-K. There is no specific experimental justification for this number except that a lower bound for forced convection over a flat surface is about 10 and if the number is increased beyond 20, the results change very little. The heat transfer process in the plenum is a topic for future analytical and experimental study. 20 W/m^2-K is used for the remainder of the study.

Researchers simulated various thicknesses of the phase change layer above the ceiling as shown in Figure 20. It is clear that the plenum temperature is reduced by approximately the same amount for any thickness over ½ inch[ii].

[ii] We comingle SI and inch-pound units in the report because products are marketed in terms familiar to the construction industry, i.e. "half-inch wallboard," or "one-inch BioPCM."

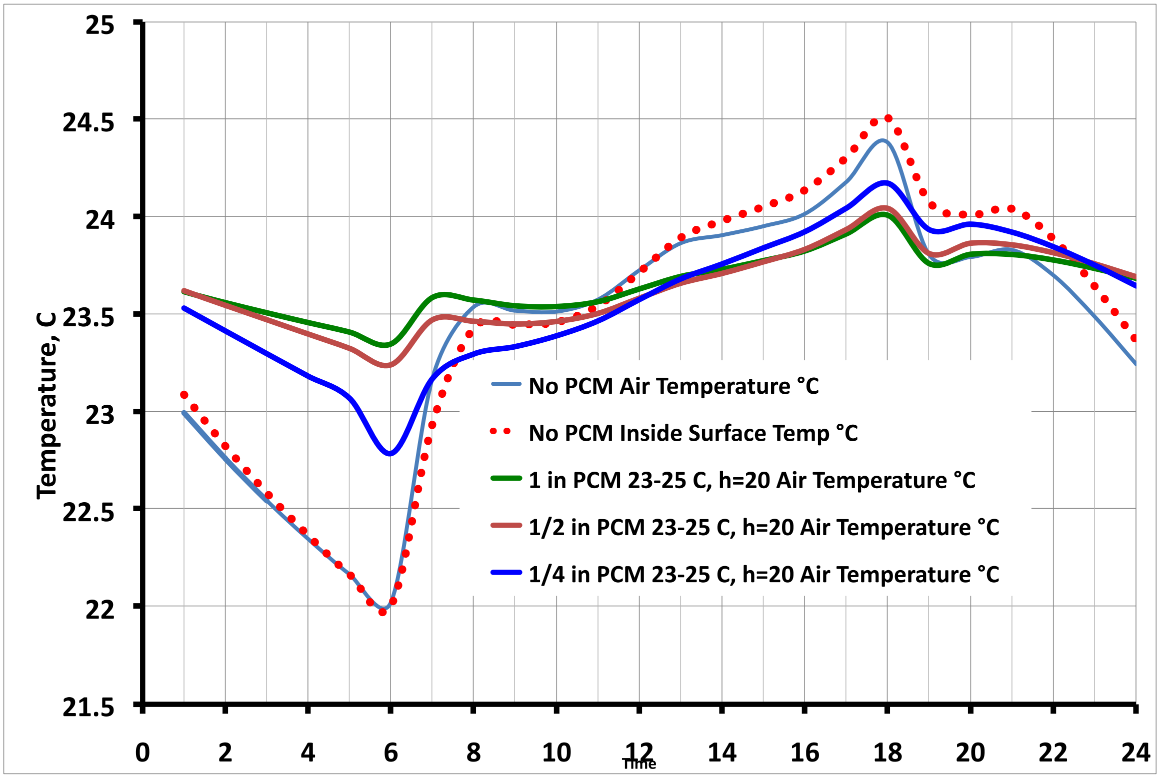

FIGURE 20. PLENUM TEMPERATURES FOR VARIOUS THICKNESSES OF PCM MATERIAL, CLIMATE ZONE 9.

Figure 21 shows the impact of PCM on the design day sensible cooling profiles. Adding PCM reduces the peak sensible cooling load from 65.3 W/m^2 to approximately 60.6 W/m^2, approximately a 7% reduction.

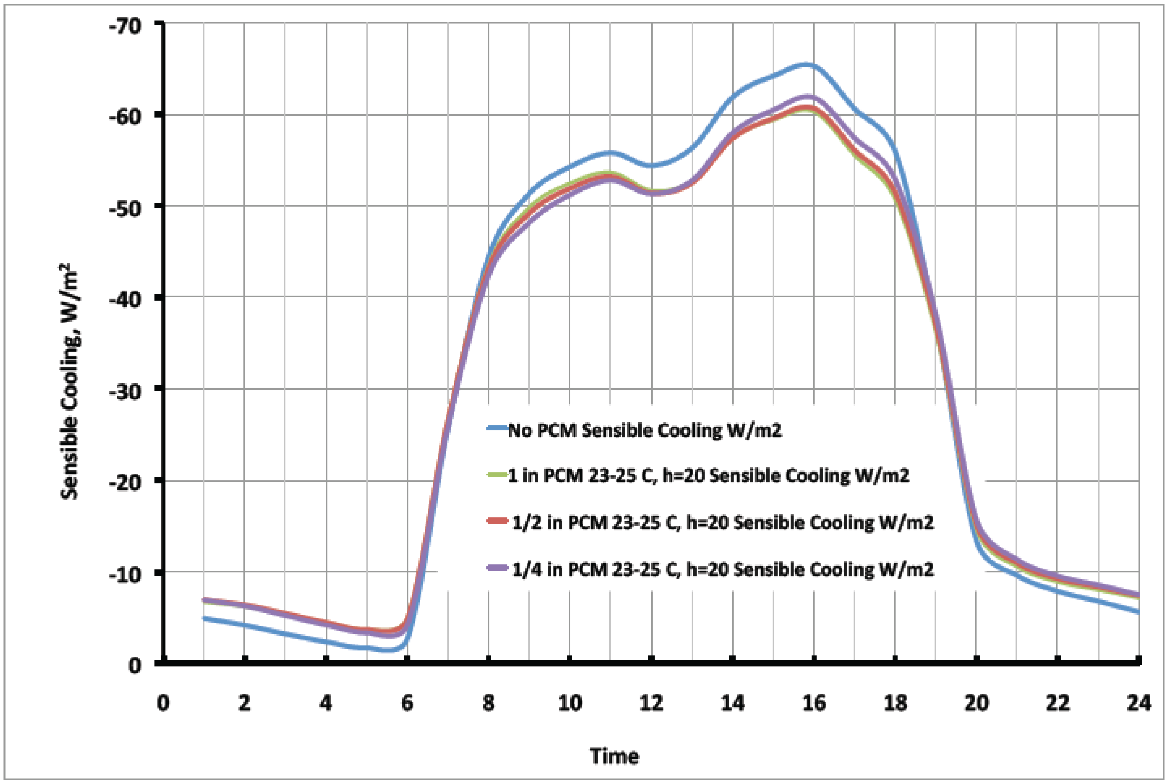

FIGURE 21. SENSIBLE COOLING FOR DIFFERING AMOUNTS OF 23-25 °C PCM ABOVE THE CEILING, CLIMATE ZONE 9.

It is clear that using PMC material more than 1/2–inch thick is excessive and provides very little additional reduction in peak load. Figure 22 shows where the percentage of peak load is plotted against PCM thickness.

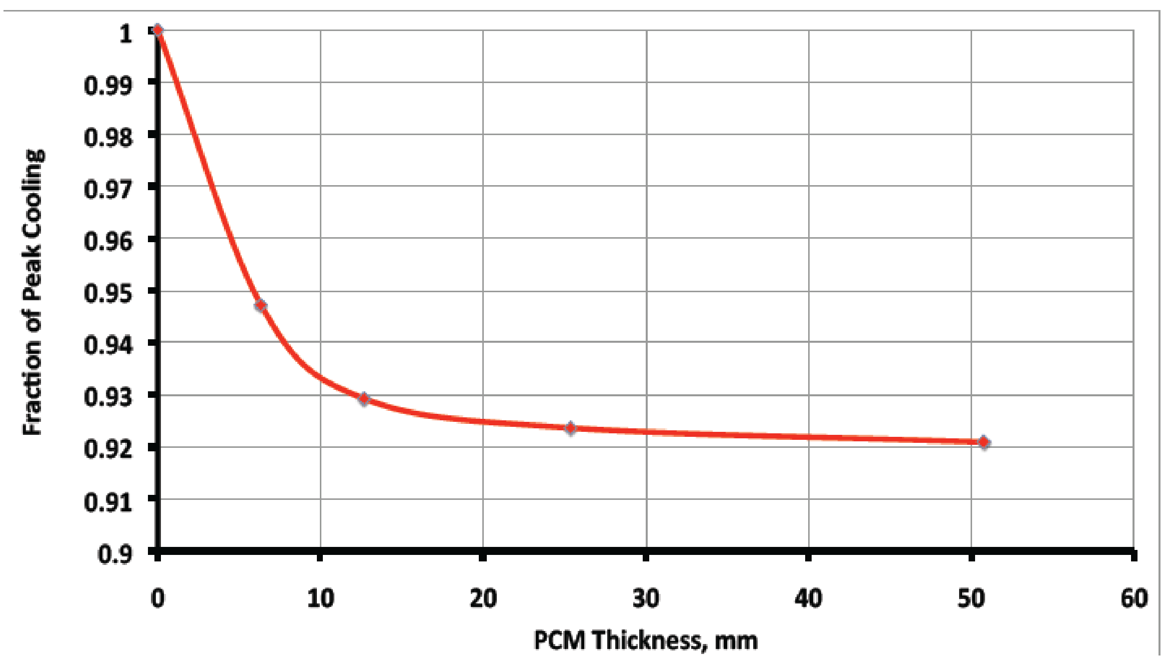

FIGURE 22. PEAK LOAD FRACTION VERSUS THICKNESS OF PCM, CLIMATE ZONE 9.

Figure 23 shows the plenum and surface temperatures for no PCM and ½-inch of PCM. For the ½-inch PCM, the solid and dotted lines cross at about 6:00 and again at about 19:00 hours. During this interval, the plenum air is warmer than the PCM surface and the air is losing heat to the PCM. Figure 9 shows the difference between the blue and red lines (no PCM and ½-inch PCM), summed over the above interval (6 to 19 hours), to determine how much "coolth"[iii] is provided by the PCM. The result is 34 kJ/m^2, and the latent heat of fusion of the PCM is about 170 kJ/kg. For a ½-in layer, the capacity to store heat is 550 kJ/m^2, which is larger than the 34 kJ/m^2 exchanged on the design day. If ¼-inch is used, the peak temperatures and loads are not reduced by as much as the ½-inch layer. This is in spite of the fact that even ¼-inch, with 275 kJ/m^2, is overkill. PCM material does not cycle completely through the phase transition and the PCM surface temperature varies by approximately 0.5°C, which gives the appearance of poor performance. This issue is addressed later in this report.

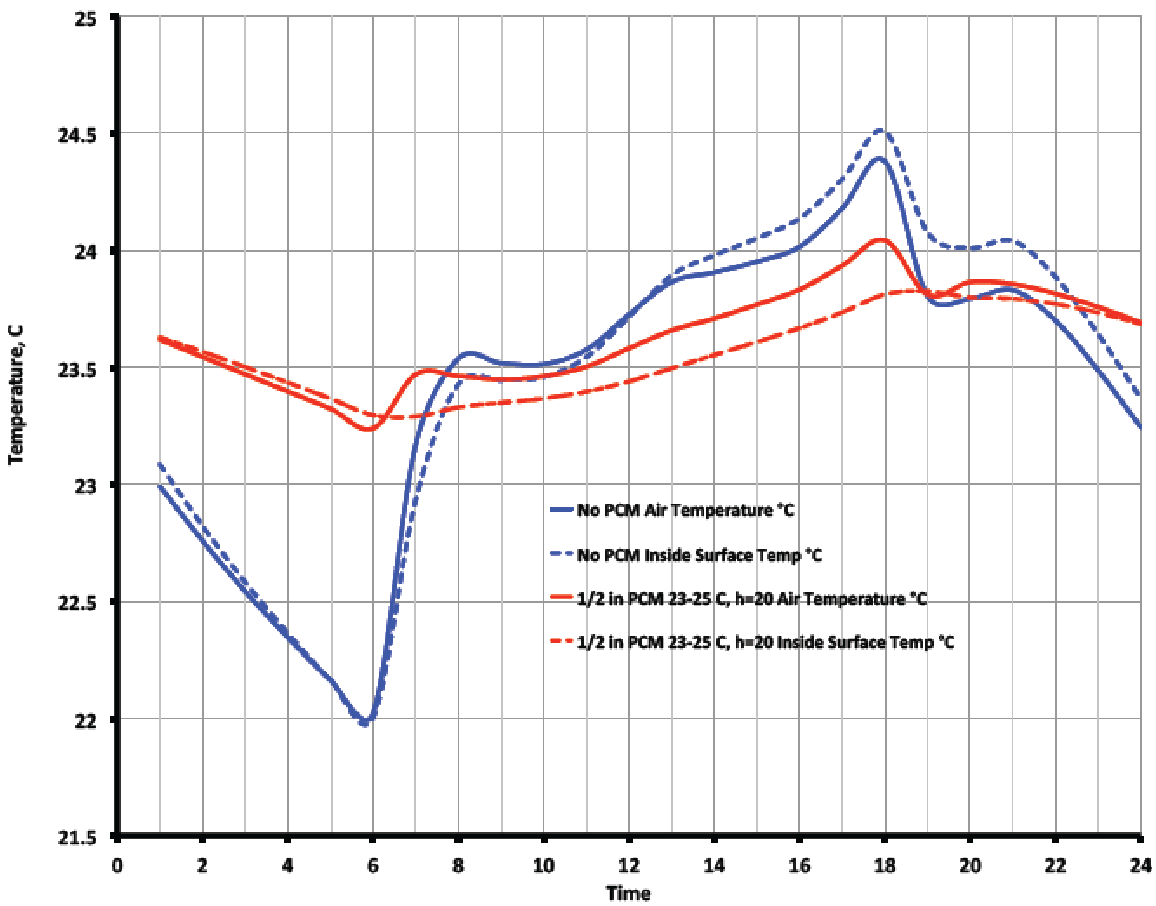

FIGURE 23. PLENUM AND SURFACE TEMPERATURES FOR NO PCM AND 1/2 INCH PCM, CLIMATE ZONE 9. NOTICE THAT THE PLENUM AIR IS WARMER THAN THE SURFACE FROM ABOUT 6:00 TO ABOUT 19:00.

[iii] "Coolth" refers to the ability of PCM to transfer coolness to (remove heat from) the space

The monthly and annual results for no PCM and ½-inch 23-25°C are shown Figure 24 and Figure 25. The monthly totals with PCM are always less than without PCM. The annual total with PCM is about 5% less for cooling and about 10% less for heating than without PCM. The annual energy savings are not large with PCM because a greater fraction of the cooling load occurs during evening/night time hours when economy cycle cooling can be used to reduce or eliminate cooling coil demand.

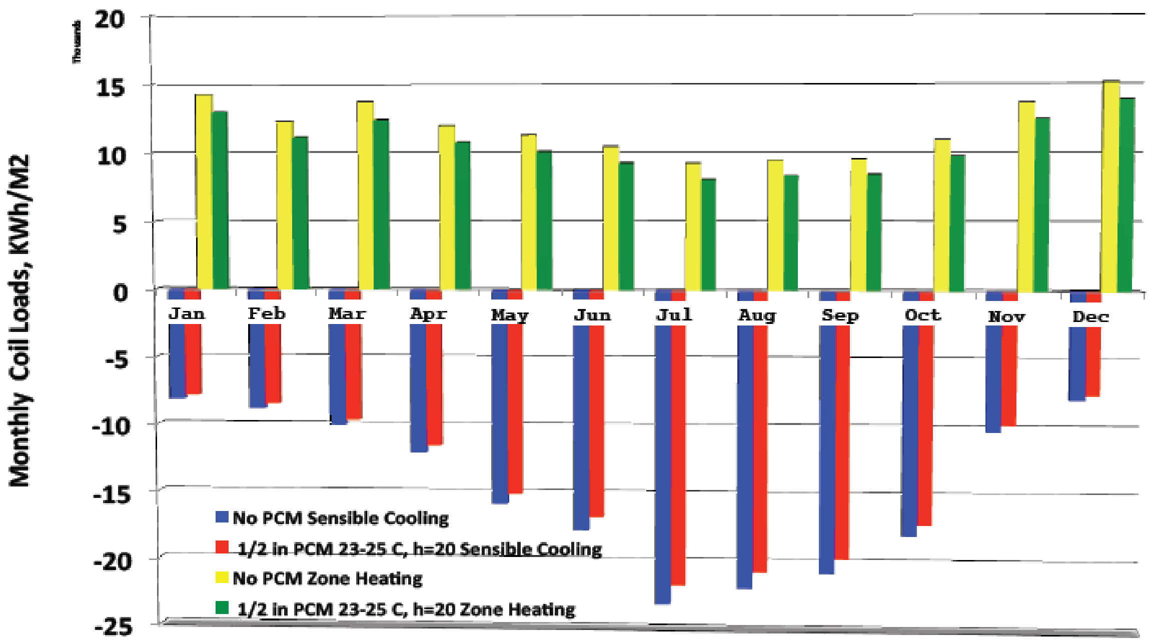

FIGURE 24. MONTHLY HEATING AND COOLING REQUIREMENTS WITH AND WITHOUT PCM, CLIMATE ZONE 9.

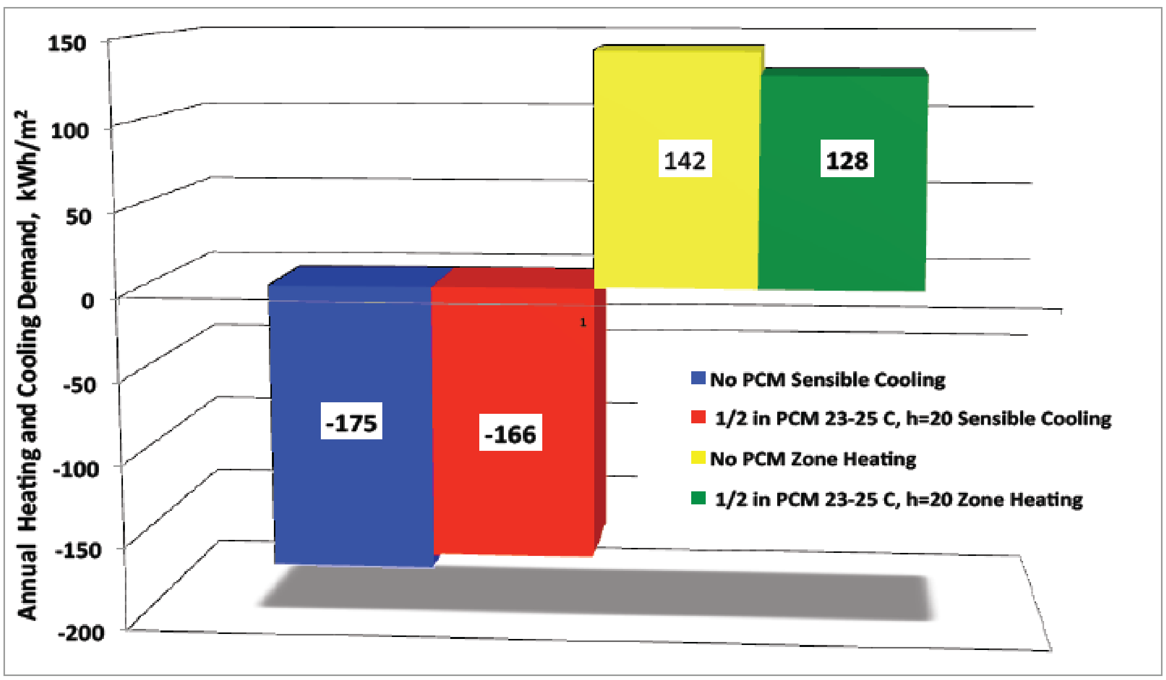

FIGURE 25. ANNUAL HEATING AND COOLING DEMAND, WITH AND WITHOUT PCM, CLIMATE ZONE 9.

For peak sensible cooling requirements, the change is from 65.3 W/m^2 without PCM to 60.6 W/m^2 with 1/2 inch of PCM, approximately 7%. If designers can be persuaded to reduce the capacity of the specified air conditioning system, the first cost savings would be between 9 $\$/m^2$ and 13 $\$/m^2$ and the cost of the PCM product would be 21 $\$/m^2$ to 75 $\$/m^2$[iv]. The cost of PCM is not justified based solely on first cost savings.

For existing buildings, most cost savings are likely to result from lower electricity demand charges.

Proponents of putting PCM above the ceiling argue that the room should be cooled below the phase transition temperature at night and allowed to go above this temperature during the day. Researchers simulated a building with a temperature control profile that is set to 20.5°C at night and 22°C during the day. Starting with a new baseline, researchers looked at the plenum air and surface temperatures to establish a desired phase transition temperature. If we look at the blue line and blue dashed line shown in Figure 26, we see that the temperatures for the plenum and plenum floor vary from about 20.5°C to 24.5°C.

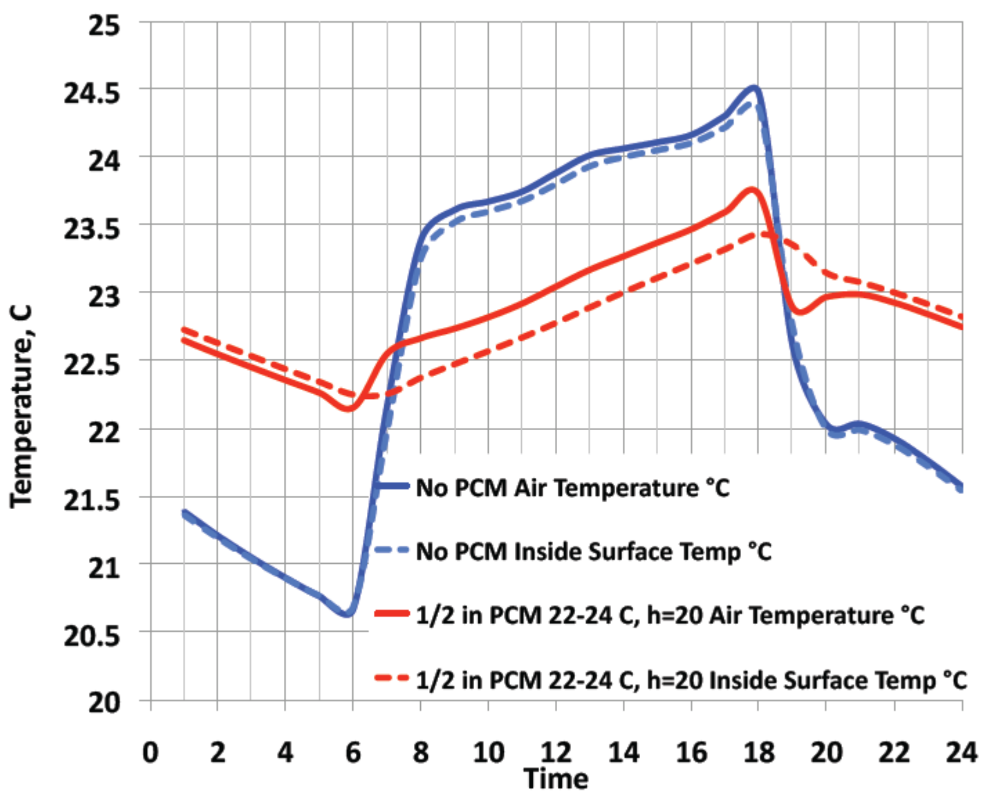

FIGURE 26. PLENUM AND SURFACES TEMPERATURES, NO PCM AND 1/2 INCH PCM, CLIMATE ZONE 9.

[iv] Cost data comes from rules of thumb, private communications. AC cost $22-$33/ft2 ($237-$355/m2), PCM cost $2-$7/ft2 ($21-$75/m2)

A phase transition temperature of 22-24°C is a good choice. Simulating ½-in of PCM with this range, the red solid and dashed lines show that this is acceptable. Both the plenum air and the PCM surface temperature remain within the phase transition temperature range.

It is clear how much PCM is needed and by how much the peak cooling load can be reduced. Figure 27 shows that we need ½ inch of PCM to get the highest peak temperature reduction possible since increasing from ½ inch to 1 inch produces no significant change.

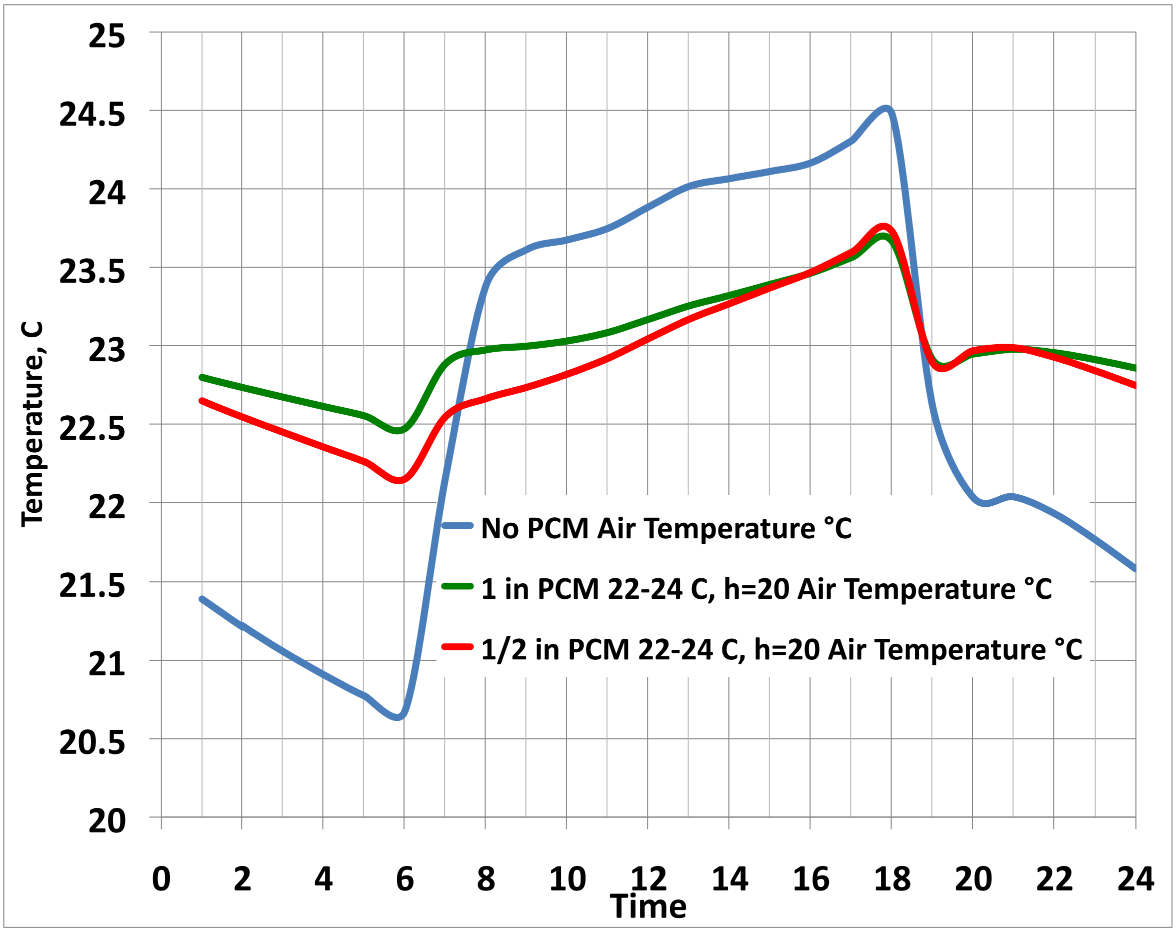

FIGURE 27.PLENUM TEMPERATURE FOR VARIOUS THICKNESS OF PCM MATERIAL, CLIMATE ZONE 9.

Figure 28 shows the daily cooling load profile for varying PCM thickness. Caution is required when cooling a space at night. If the thermostat set point suddenly changes from 22 to 20.5°C, a peak cooling load results. By gradually cooling the space, this peak is eliminated as shown by the red curve.

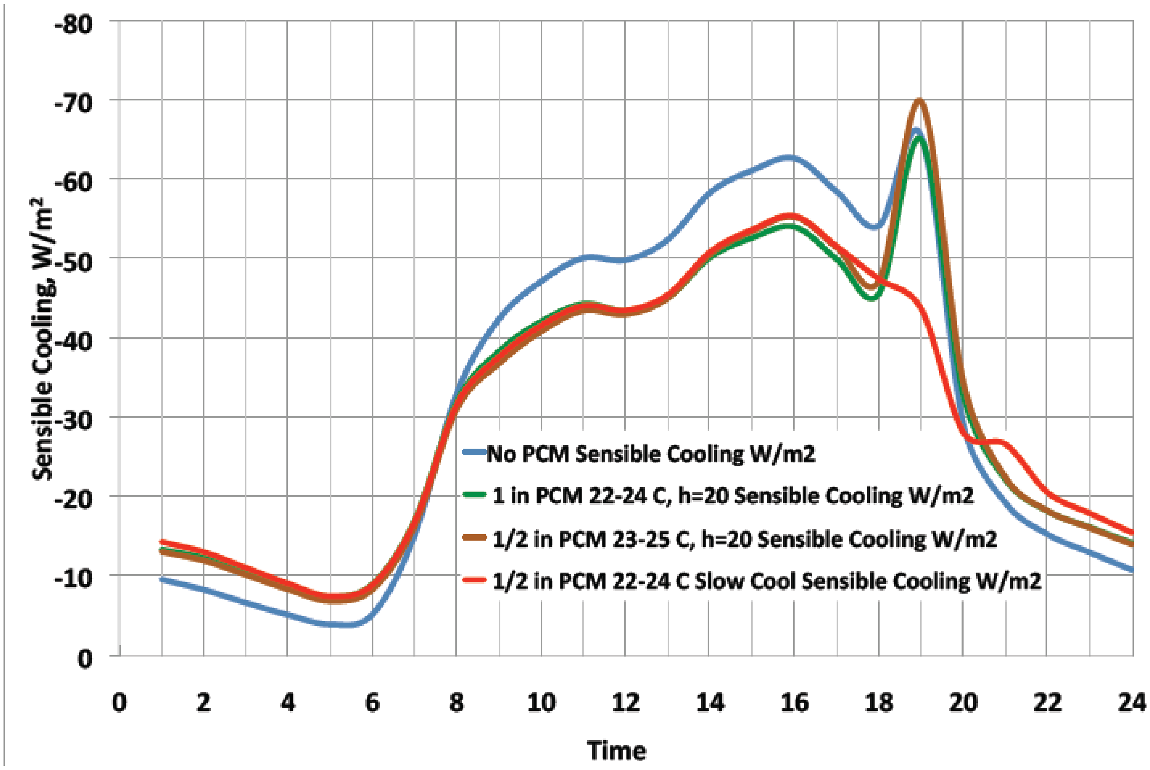

FIGURE 28. SENSIBLE COOLING FOR VARIOUS PCM THICKNESSES, COOL NIGHTS, CLIMATE ZONE 9.

Figure 29 shows how the peak cooling is reduced with increasing PCM.

With the cool nights/warm days control strategy and ½-inch of PCM, the peak sensible cooling load is reduced 11.6% from 62.7 W/m^2 to 55.4 W/m^2. This means that the potential first cost savings using smaller HVAC equipment is in the range of 14.5 to 21.8 $\$/m^2$. In this case, the first cost savings in equipment may cover the cost of the PCM product.

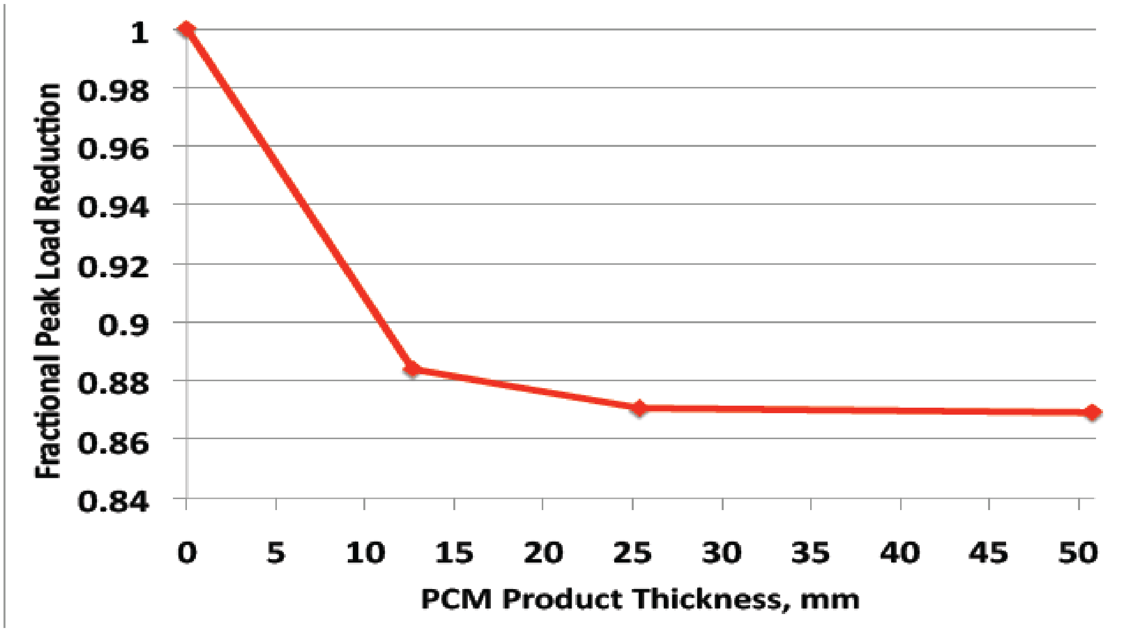

FIGURE 29. PERCENT OF PEAK LOAD VERSUS PCM THICKNESS, CLIMATE ZONE 9.

Figure 30 and Figure 31 show the monthly and annual results from simulations with and without PCM. The monthly and annual heating and cooling energy requirements are lower when PCM is added.

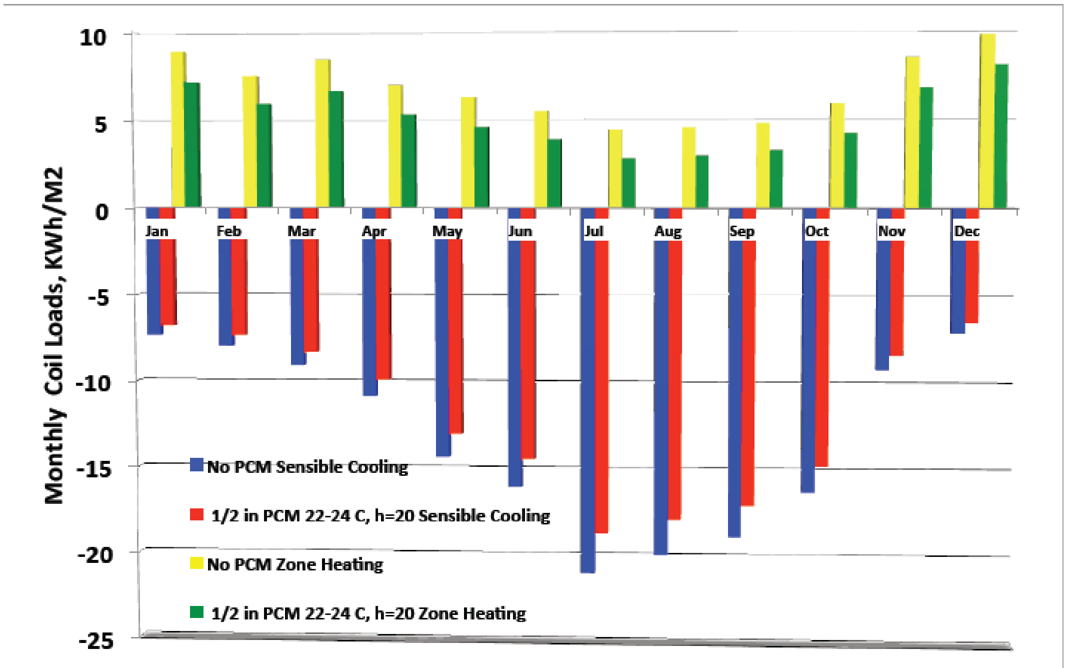

FIGURE 30. MONTHLY HEATING AND COOLING REQUIREMENTS WITH AND WITHOUT PCM, CLIMATE ZONE 9.

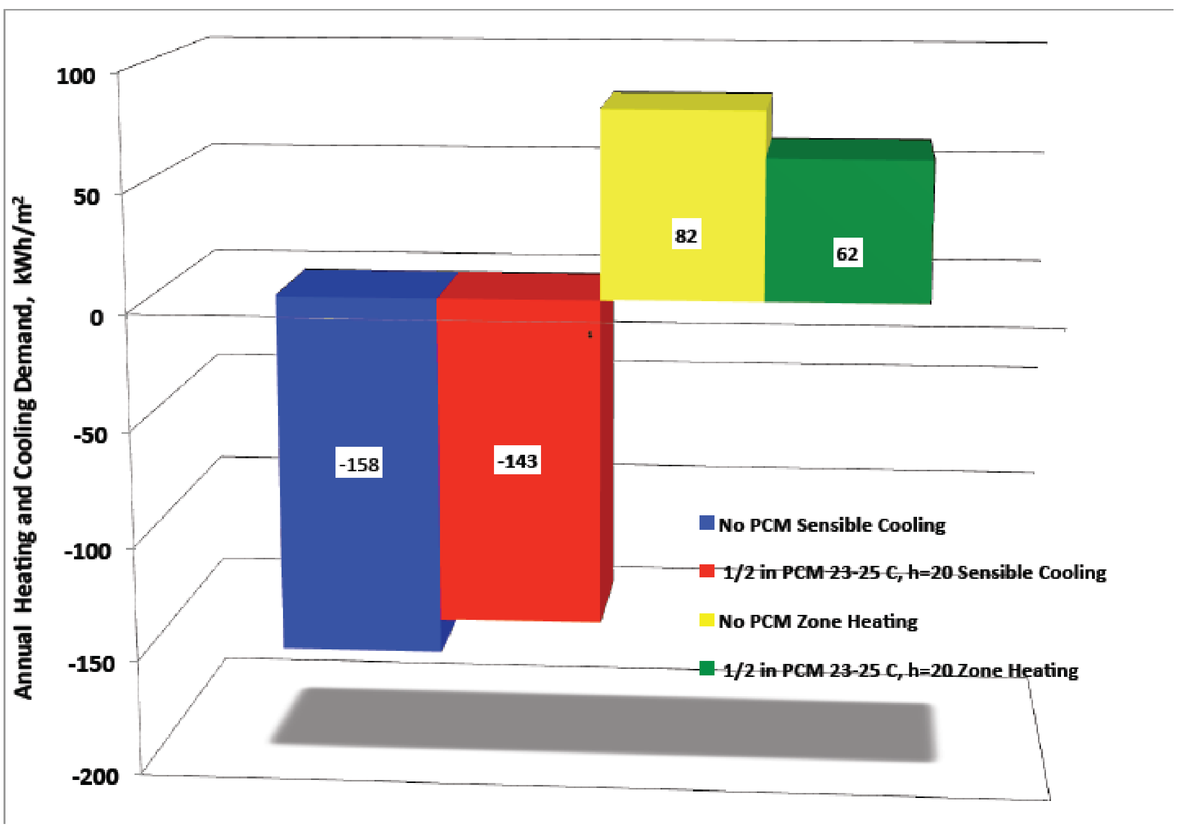

FIGURE 31. ANNUAL HEATING AND COOLING DEMAND, WITH AND WITHOUT PCM, CLIMATE ZONE 9.

On an annual basis, using PCMs result in a 10% reduction in sensible cooling required, and approximately 24% reduction in heating required. This is not the desired reduction in peak loads and energy consumption.

Researchers performed additional testing and the results are shown in Figure 32. The green line represents the conductivity of the PCM at 100 times its nominal value, and the convection coefficient above the plenum floor is set to the maximum allowed in EnergyPlus (999 W/m2-K). The plenum temperature and the plenum floor temperature (PCM surface temperature) are both plotted. The lines appear to fall on top of each other because, with a near infinite convection coefficient (relatively speaking), the temperature difference between the PCM surface and the plenum air is miniscule. Given the high conductivity of the PCM layer, nearly all of the PCMs are at the same temperature as the green line, using the equivalent of an infinitely long, counter-flow heat exchanger.

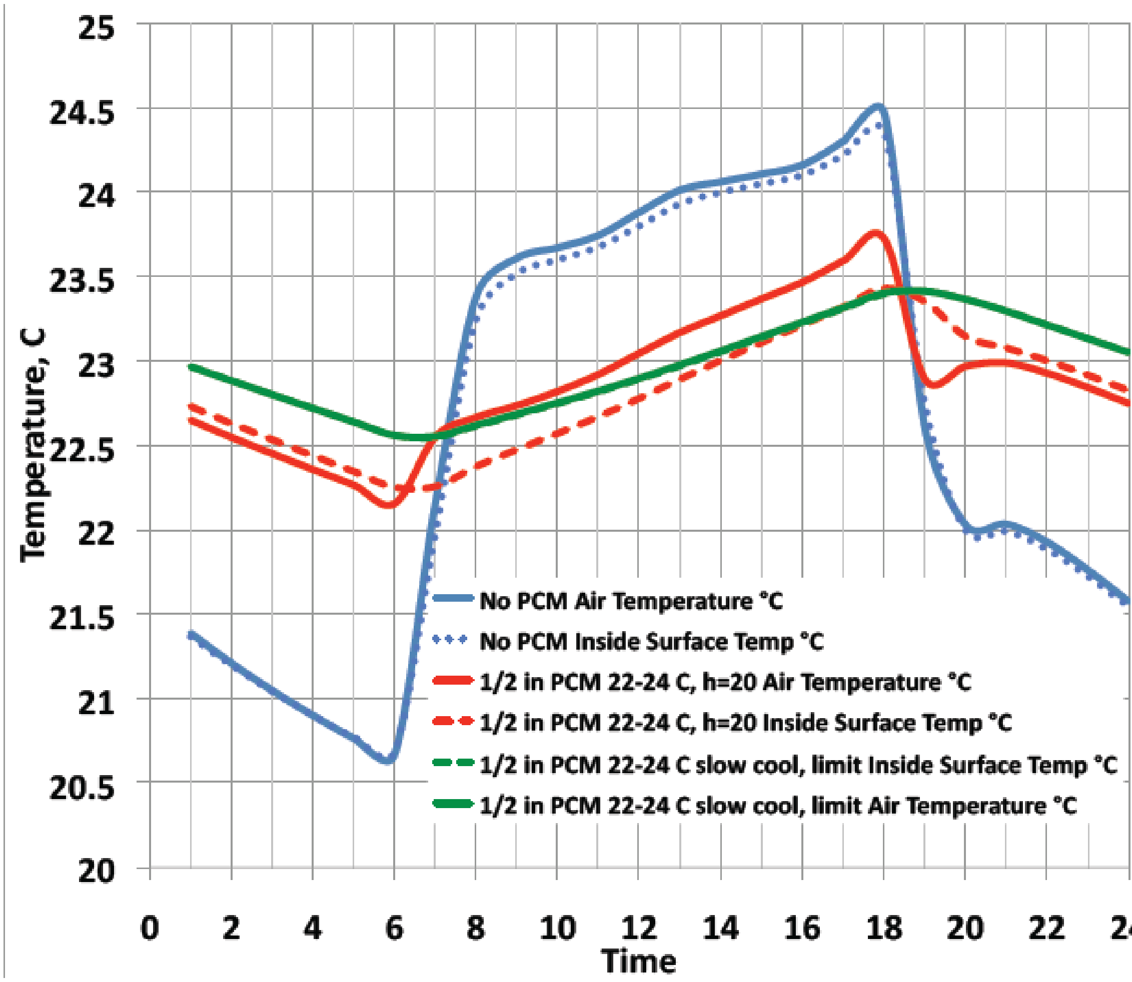

FIGURE 32. ADDING THE GREEN LINE TO SHOW THE LIMITING CASE FOR PCM BENEFIT WITHOUT A BIGGER ROOM TEMPERATURE SWING.

The green line in Figure 32 varies by approximately 0.9°C. This is less than half of the 2°C phase transition range. Fixing everything else, the only way to improve this situation and make better use of the PCM is to increase the room temperature during the day and decrease the room temperature at night.

This is achieved by changing the room temperature control profile from 20.5°C at night and 22°C during the day to 20°C and 24°C.

Researchers defined the limitations of the PCM in reducing peak cooling. The green line in Figure 33 shows the best results.

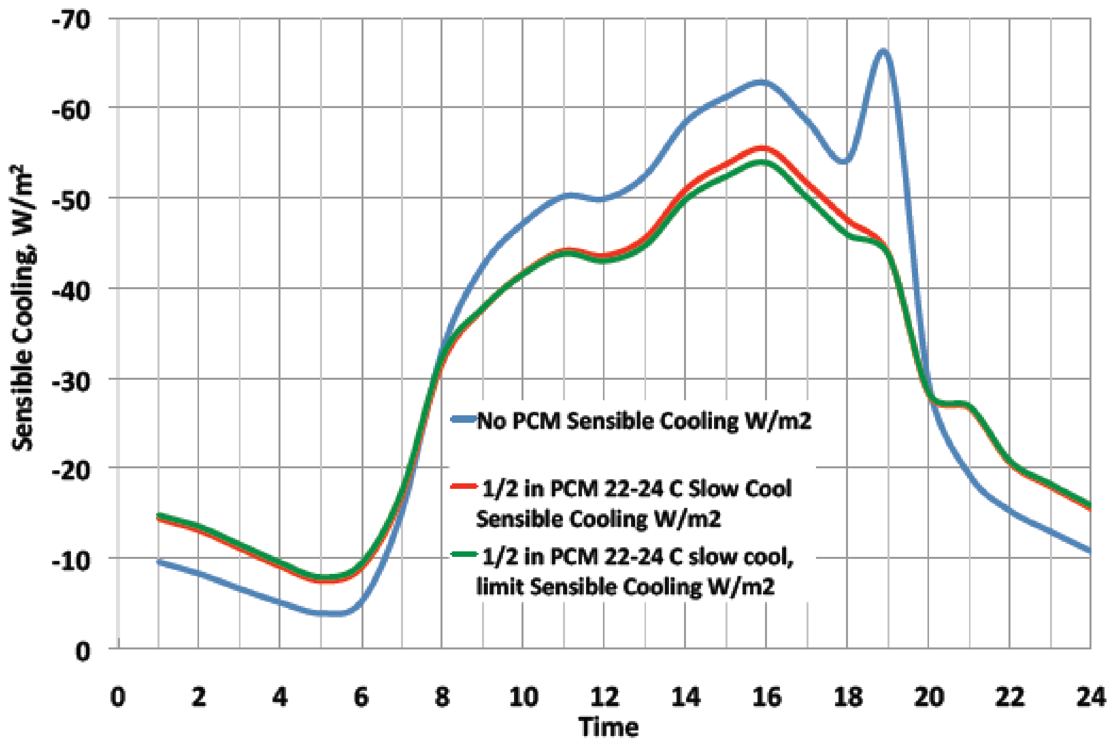

FIGURE 33. SENSIBLE COOLING LOAD PROFILE FOR NO PCM, PCM WITH REASONABLE HEAT TRANSFER, AND PCM IN THE LIMITING CASE, CLIMATE ZONE 9.

The blue solid and dashed lines are the new baseline. The red lines are for ½-inch of PCM above the ceiling. It is clear that PCM is "running out" at 2 PM. This is at the point where the dotted surface temperature line reaches 24°C, the upper limit of the phase transition. To try to achieve a better peak load reduction, the choice is to either use more PCM or change the PCM phase transition range.

Researchers add more PCM by simulating a 1.5-inch layer above the ceiling with a 22-24°C phase transition. This result is the black line in Figure 34. The plenum air temperature drops toward 23°C early in the morning, moves up toward 25°C, and then changes slope to continue upward. This suggests that the PCM is melting before the end of the day.

Researchers then change the phase transition temperature. Based on the previous simulation (black line) 23-25°C is the new range. The green line in Figure 34 shows that the plenum air temperature stays within the range of 23-25°C. This means that the PCM is always in the phase transition temperature band.

Figure 34 shows the plenum air temperature and surface temperature for various PCM options.

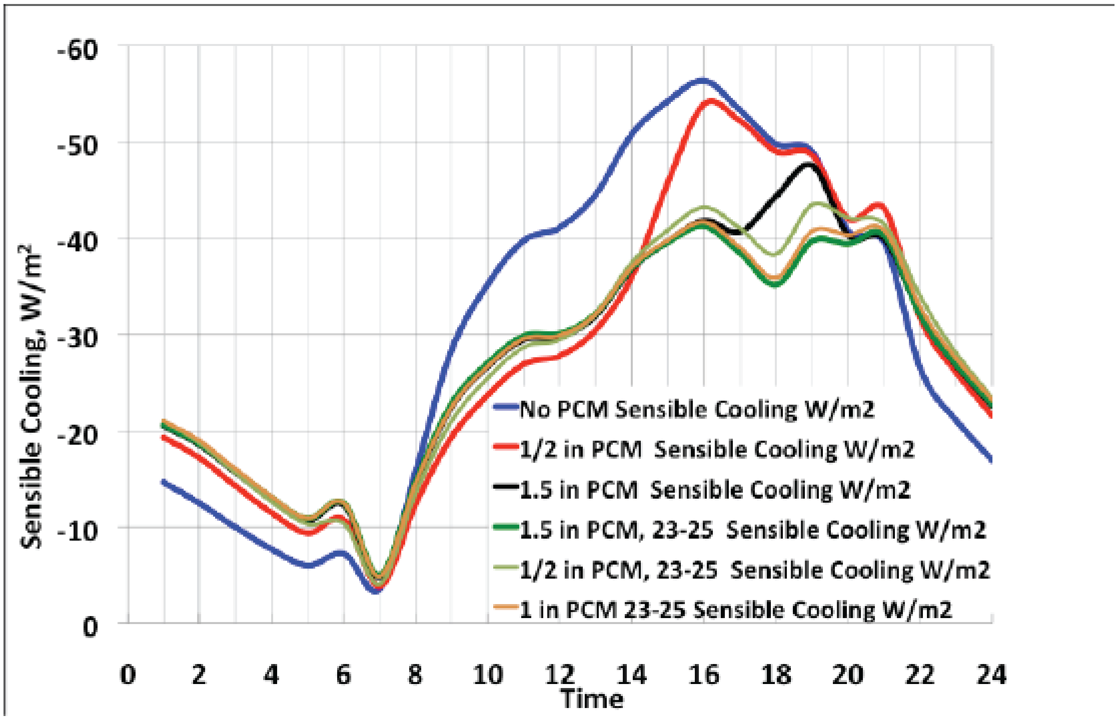

FIGURE 34. PLENUM TEMPERATURE AND PCM SURFACE TEMPERATURE FOR THE OFFICE WITH BROADER TEMPERATURE SWING, CLIMATE ZONE 9.

This represents a potential first-cost savings by reducing equipment size of $62-$92/m^2 compared to $21-$75/m^2 for PCM. PCM may be cost-effective based on first cost depending on HVAC system costs and a favorable price from the PCM vendor.

Figure 35 shows the sensible cooling required for a simulated summer day. (The bumpy behavior of the curves to the right of 4 PM can be ignored. This variation is due to the particular cool down schedule specified.) 1-inch of PCM with phase transition between 23-25^{o}C is enough to reduce the peak sensible cooling load to the full extent. The peak is reduced from 54.6 W/m2 to 41.6 W/m2, a reduction of 26%.

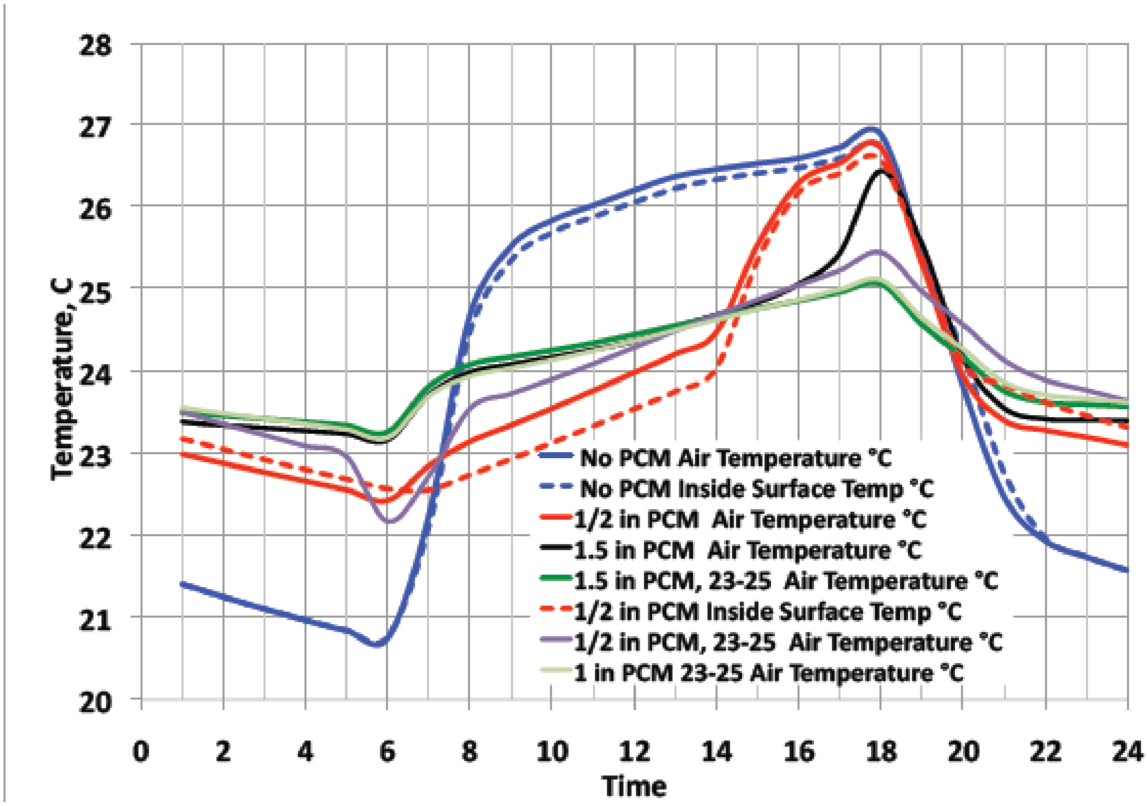

FIGURE 35. SENSIBLE COOLING FOR VARIOUS PHASE TRANSITION TEMPERATURES AND VARIOUS AMOUNTS OF PHASE CHANGE MATERIAL, CLIMATE ZONE 9.

Figure 36 and Figure 37 show the annual simulation results. These results show reductions for each month in both heating and cooling. On an annual basis, the cooling required is reduced by 14% and the heating by 52%. (Note that the heating reduction is a large percent of a relatively small number.)

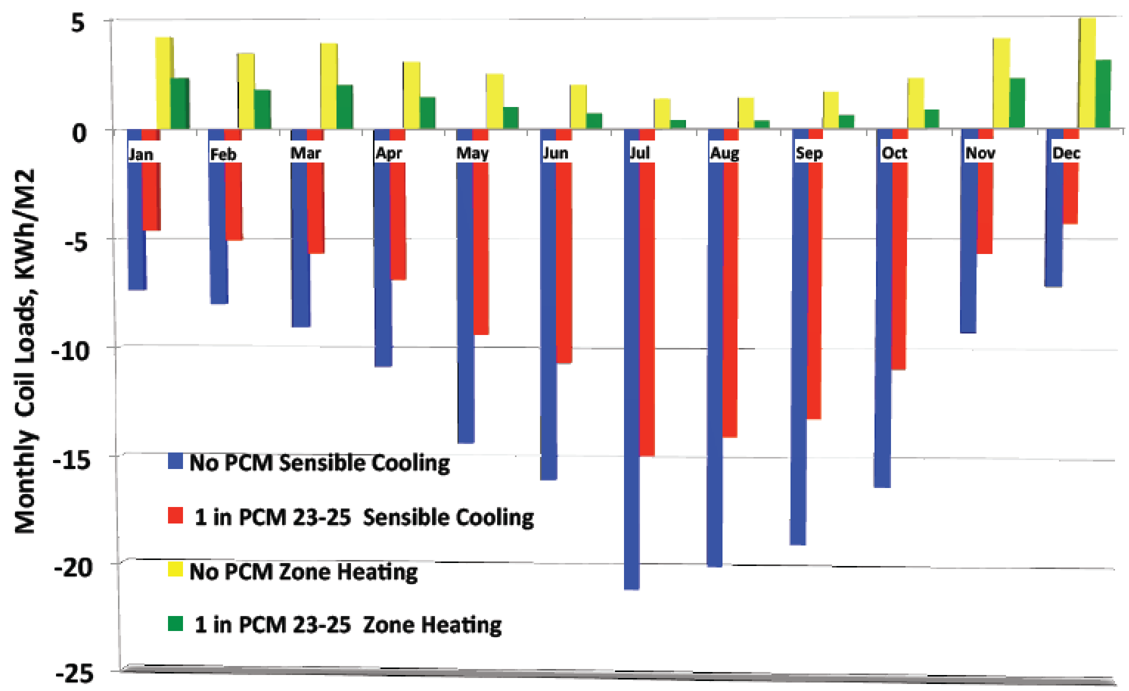

FIGURE 36. MONTHLY HEATING AND COOLING WITH AND WITHOUT PCM, CLIMATE ZONE 9.

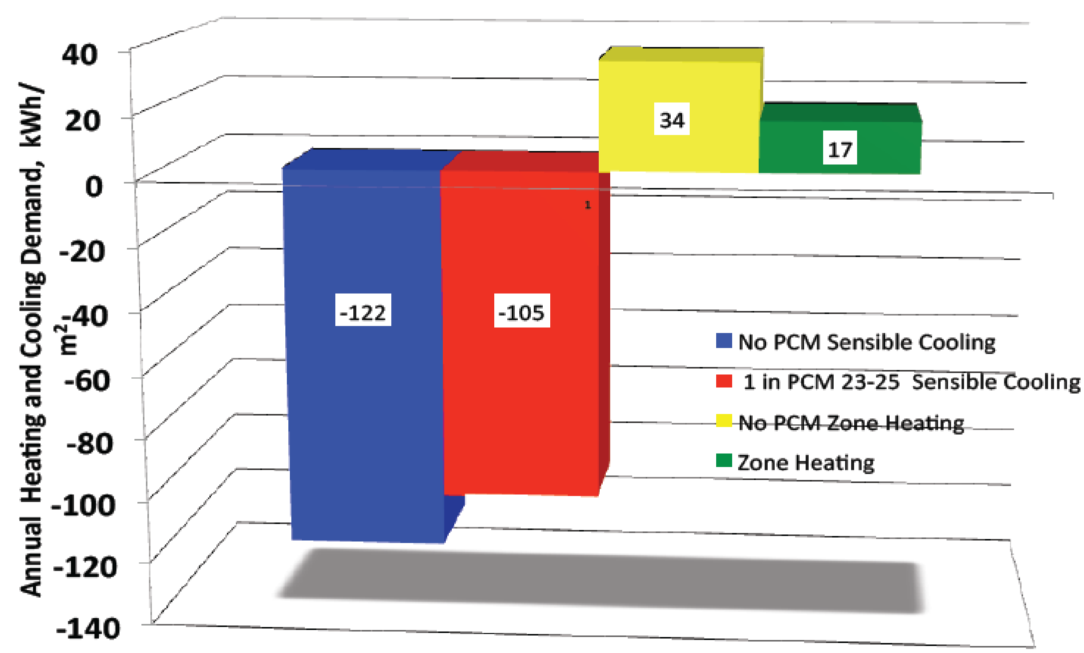

FIGURE 37. ANNUAL HEATING AND COOLING WITH AND WITHOUT PCM, CLIMATE ZONE 9.

APPENDIX C. DETAILED RESULTS OF A PARTITIONED OFFICE WITH PCM IN WALLBOARD

This section discusses the use of phase change materials in gypsum wallboard. In this product, microencapsulated phase change material becomes part of the drywall during manufacturing. The drywall is used as the interior surface for all the walls in each zone. To carry out the simulations, researchers developed a prototypical 9-zone building with 8 exterior zones and one core zone. The interior partitions and the exterior walls have interior layers that consist of 1/2-inch gypsum board with and without phase change material. Renderings of this 9-zone office are shown in Figure 38. This new model is used because the previous open-office model had a lot of ceiling area, but not much wall area. Compared to the open office, where the ceiling was almost half the of the heat transfer surface, this model provides partitions and walls to apply dry wall. These walls represent about 2/3 of the heat transfer surface inside the zones.

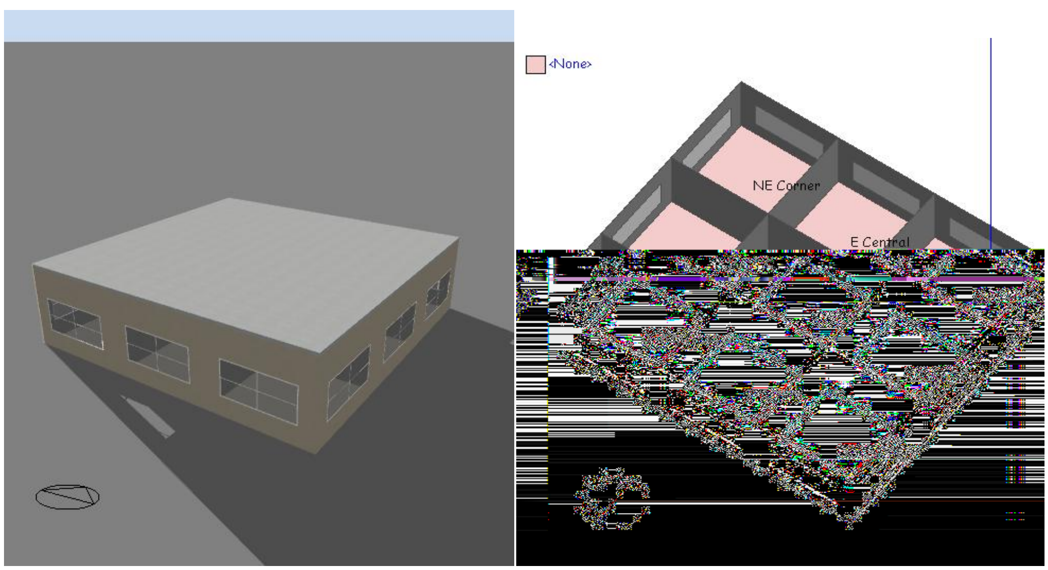

FIGURE 38. RENDERING OF NINE-ZONE OFFICE MODEL USED TO EVALUATE PCM IN WALLBOARD.

PCM wallboard is manufactured and marketed as National Gypsum BASF Micronal wallboard (see Figure 3). Its temperature/enthalpy (T-h) curve is shown in Figure 39. The literature indicates that the phase transition occurs at 25°C so the T-h curve has the phase transition occurring between 24 and 26°C.

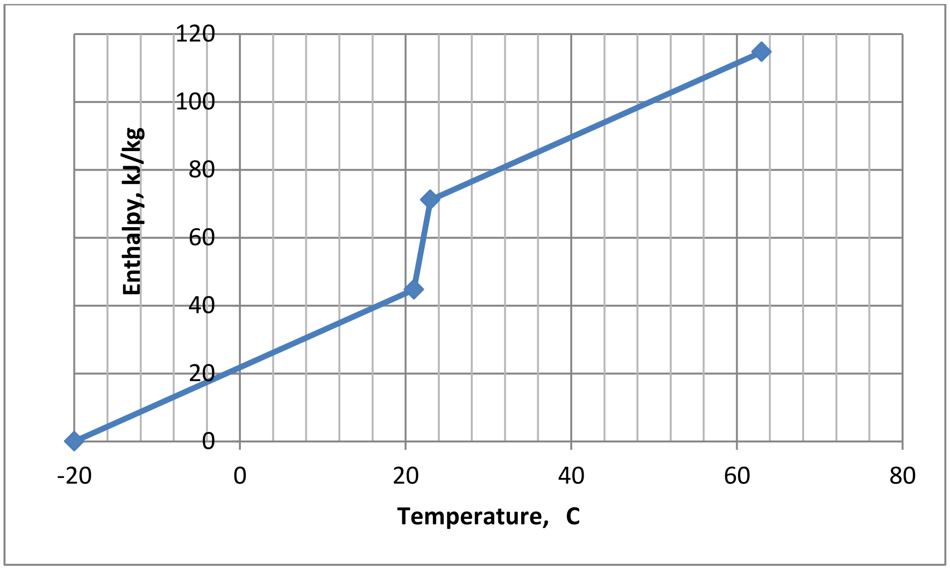

FIGURE 39. TEMPERATURE/ENTHALPY CURVE FOR MICRONAL WALLBOARD.

CALIFORNIA CLIMATE ZONE 9, LOS ANGELES

In CZ 9, Los Angeles, California, researchers started with a baseline simulation with no PCM in the building. The spaces are controlled to 22°C (71.6°F).

Figure 40 shows the inside surface temperatures of a typical partition in the south central zone of the building and the air temperatures in the zone. The surface temperature is the temperature of one side of the wallboard that contains PCM. Because of radiant energy absorption by the wall, its surface temperature rises above the room temperature. The lower set of lines in light blue are for the case where the room thermostat is set to 22°C.

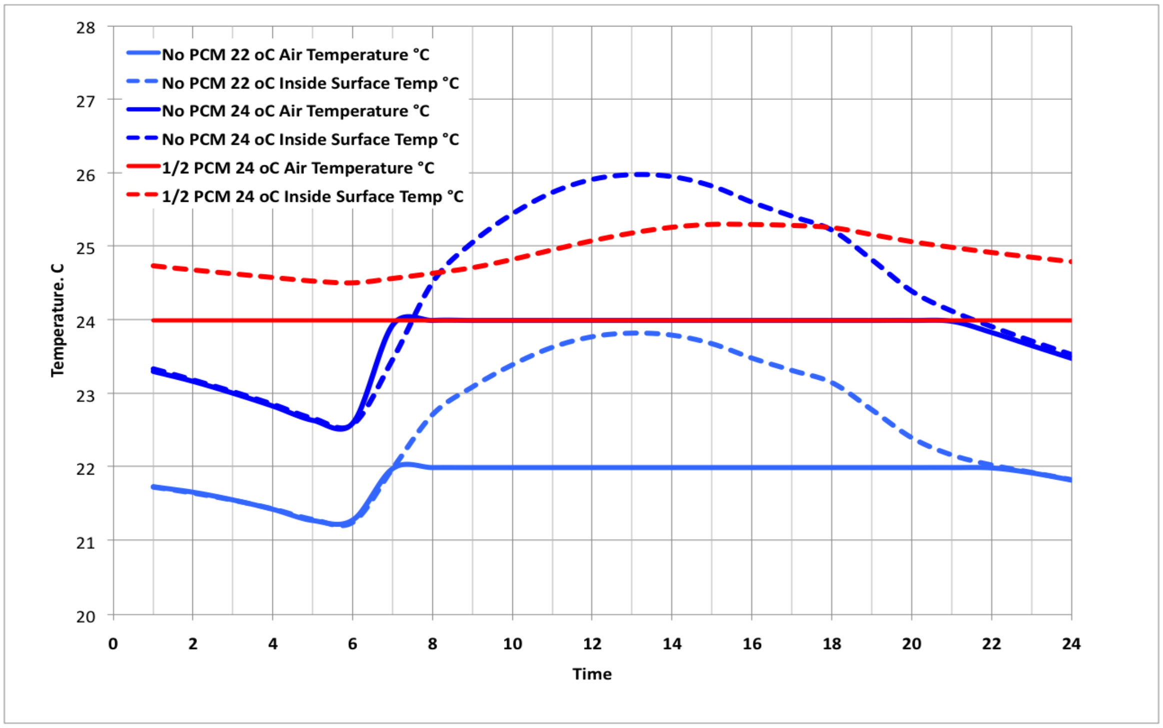

FIGURE 40. ROOM TEMPERATURE AND DRYWALL SURFACE TEMPERATURE, 9 ZONES, WITH AND WITHOUT NO PCM, CLIMATE ZONE 9.

If the room temperature is at 22°C, there is no benefit to adding the PCM wallboard product, which has a transition temperature centered at 25°C. The wall temperature never enters the phase transition temperature range. Researchers added PCM to the 22°C case as a test and, as expected, the lines overlapped.

To make use of the available product researchers raised the room set point temperature to approximately 2°C. These results are represented by the dark blue line Figure 40.

Researchers then used ½ inch of PCM wallboard. Results show that the wallboard surface temperature stays well inside the 24-26°C phase transition regions. This is good news and bad news. The graph indicates that the PCM wallboard is melting and thawing throughout the day. Since the wall temperature does not drop below 24°C or rise above 26°C, adding more PCM is not likely to reduce peak loads. The energy flow into and out of the wall is limited by other factors, such as the energy transfer rate between the wall and the room air. This is confirmed by examining the sensible cooling required for various thickness of PCM drywall shown in Figure 41.

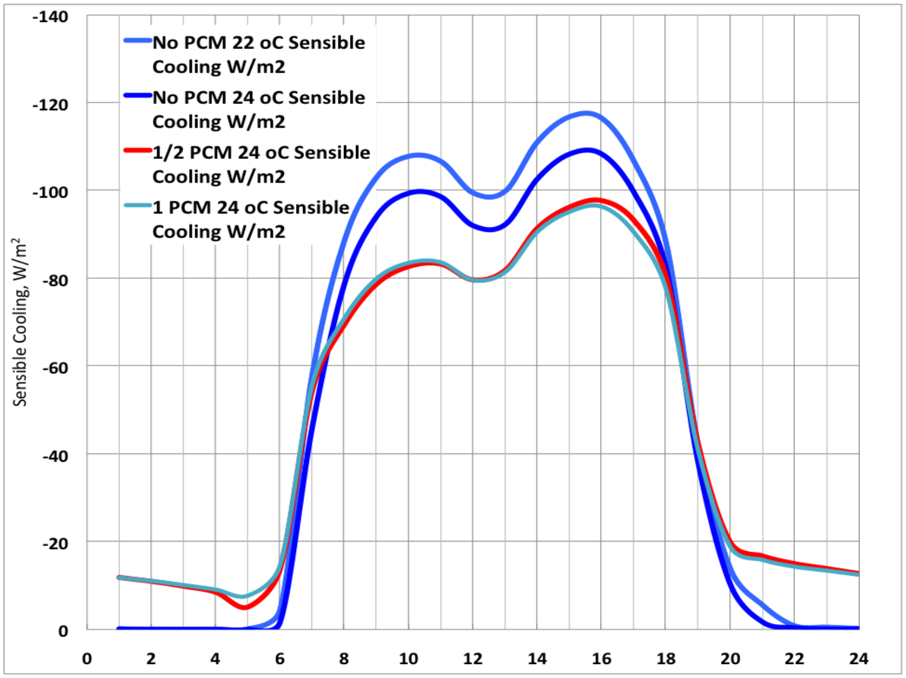

FIGURE 41. SENSIBLE COOLING LOADS WITH AND WITHOUT PCM, CLIMATE ZONE 9.

Adding a wallboard layer to provide 1 inch of PCM instead of ½ does not provide any significant additional peak load reduction. The best choice is ½ inch of the PCM drywall with the room temperature set at 24°C. The peak load is reduced from 115.6 W/m2 to 104.3 W/m2, or 9.8%.

Sub-cooling the building at night to a temperature below the phase transition range produces more peak load reduction. Raising the room thermostat setting above 25°C during the day is outside the comfort region, so the settings are 21°C at night and 25°C during the day.

Figure 42 shows room air and surface temperatures for various options. Note that the surface of the wallboard stays within the phase transition range for both ½ inch and 1 inch of PCM wallboard.

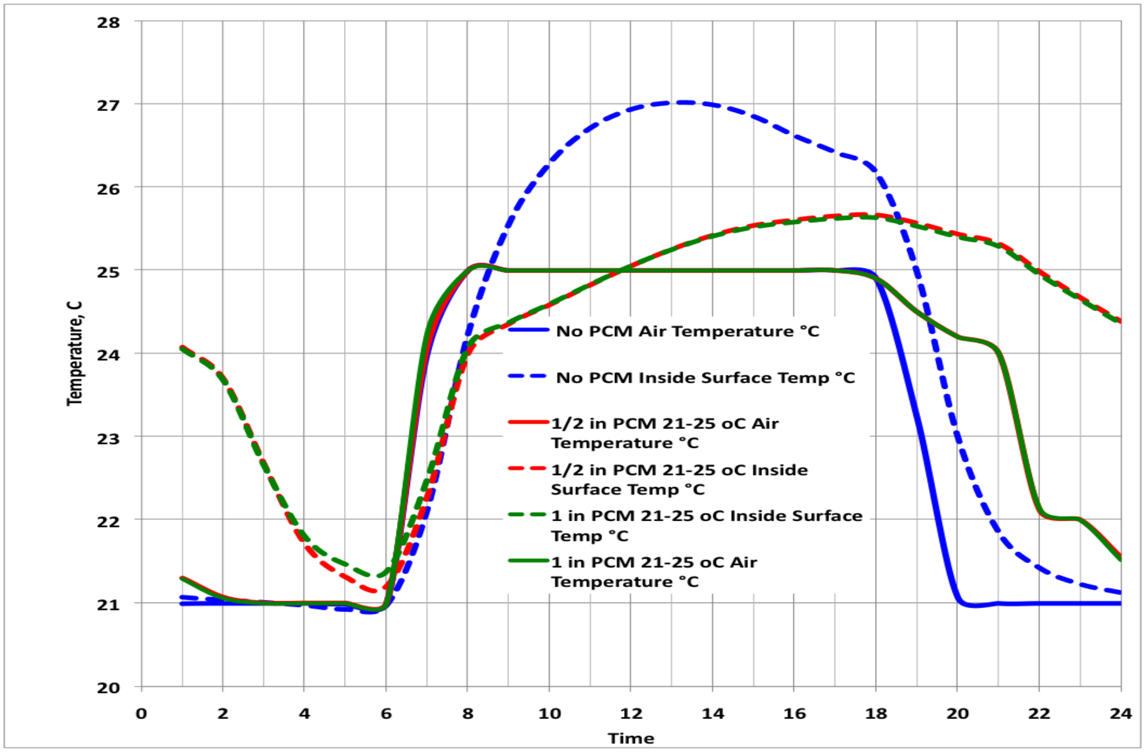

FIGURE 42. ROOM TEMPERATURE AND WALL SURFACE TEMPERATURES WITH NIGHT SETBACK, WITH AND WITHOUT PCM, CLIMATE ZONE 9.

Even though the surface temperatures are not very different from the ½ to the 1 inch cases, the peak is further reduced by using 1 inch of PCM drywall as shown in See Figure 43.

The peak air-conditioning sensible cooling is reduced from 103.1 W/m2 to 84.8 W/m2 for ½ inch PCM and 76.9 W/m2 for 1 inch PCM wallboard. This is an 18% and 25% reduction, respectively.

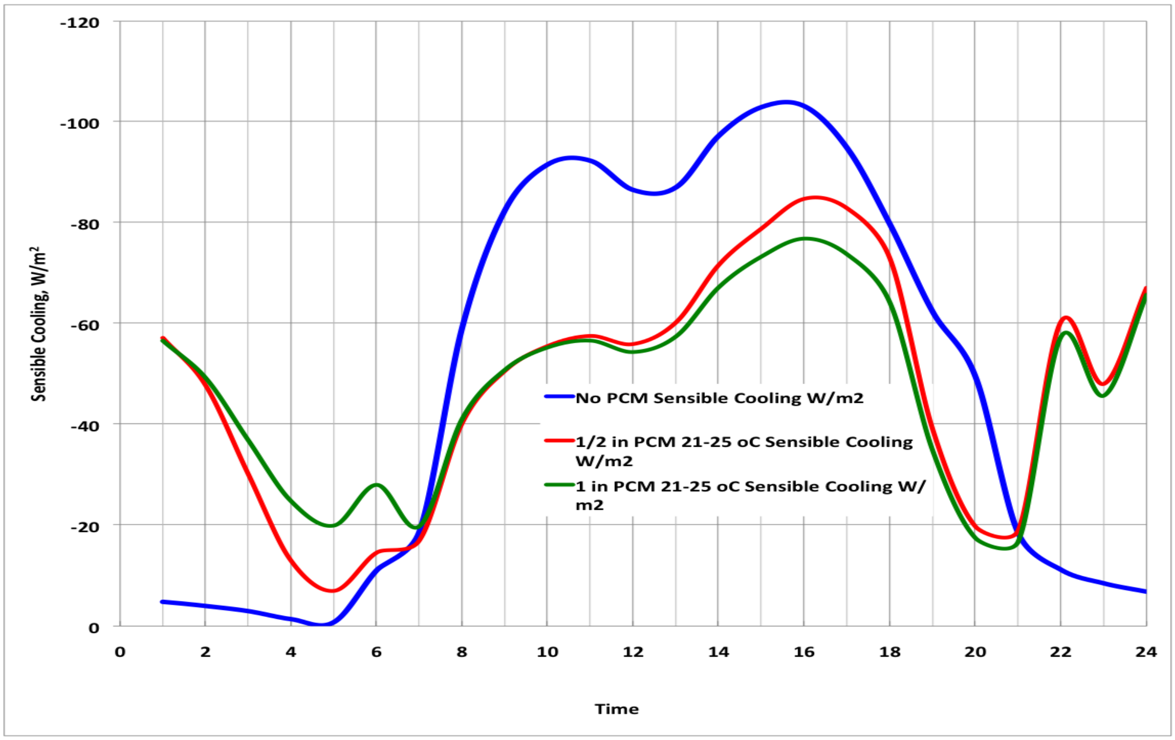

FIGURE 43. SENSIBLE COOLING FOR THE NINE-ZONE BUILDING WITH PCM WALLBOARD, CLIMATE ZONE 9.

Figure 44 and Figure 45 show that the monthly and annual demands for heating and cooling are slightly reduced.

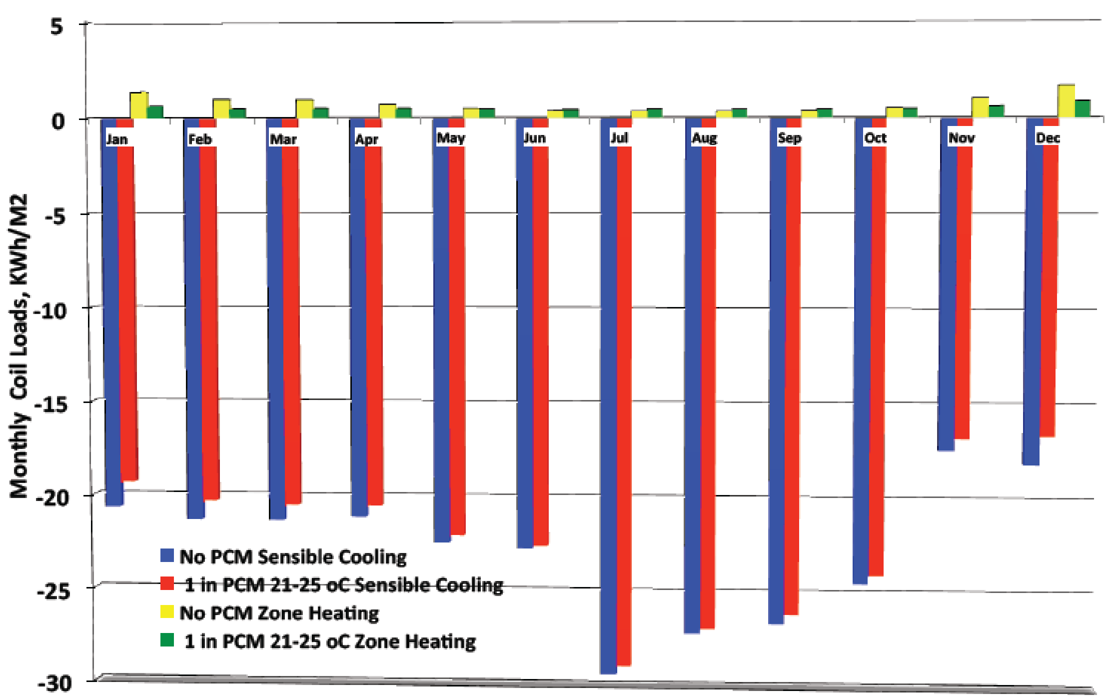

FIGURE 44. MONTHLY COOLING AND HEATING DEMAND WITH AND WITHOUT PCM, CLIMATE ZONE 9.

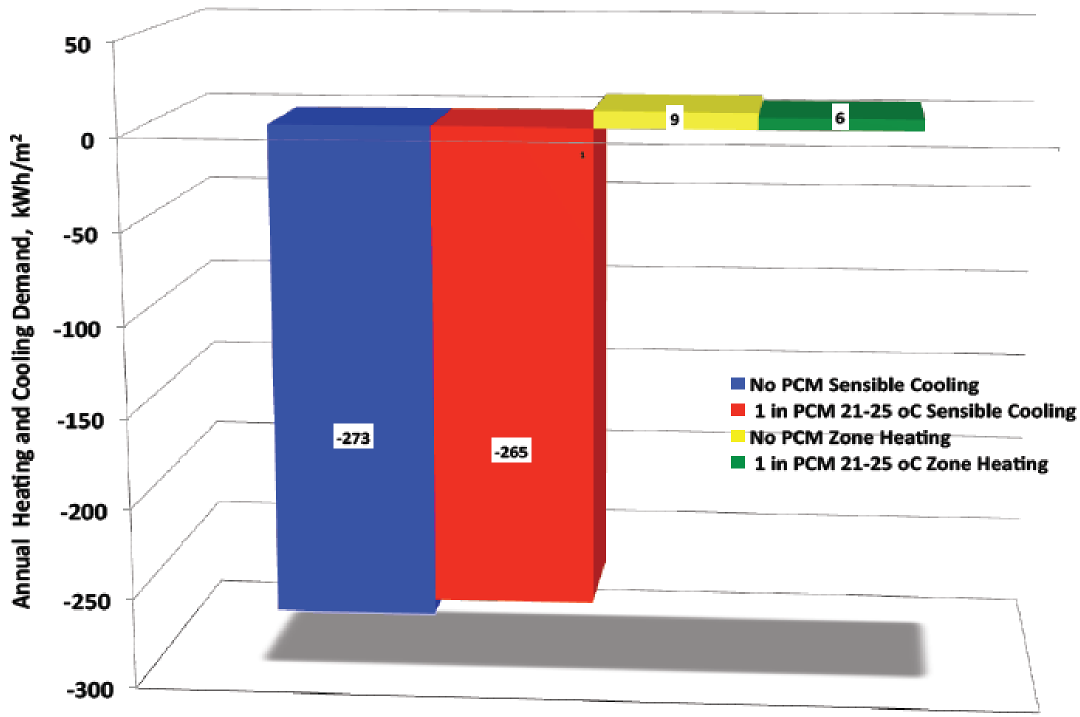

FIGURE 45. ANNUAL HEATING AND COOLING DEMAND WITH AND WITHOUT PCM, CLIMATE ZONE 9.

APPENDIX D. DETAILED RESULTS OF A PARTITIONED OFFICE WITH PCM IN WALL INSULATION

Another proposed PCM product consists of microencapsulated PCMs interspersed in fiberglass insulation. For this study, a nine-zone building was simulated with walls and roof containing insulation with and without PCM. Figure 46 shows the details for the wall and roof section. The roof is 252 mm thick, and the wall is 145 mm. The figure is not to scale.

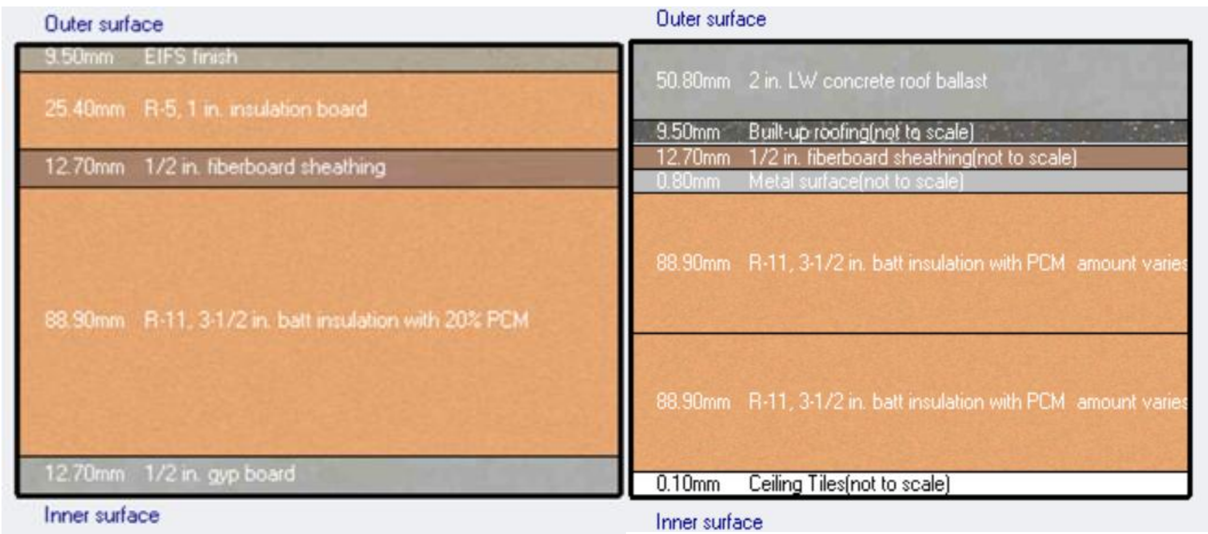

FIGURE 46. WALL (LEFT) AND ROOF (RIGHT) SECTIONS FOR BUILDING MODEL INCORPORATING PCM IN WALL INSULATION.

Researchers simulated a baseline building without PCM and then added the PCM to the insulation. Current test products with PCM contain about 20%-%40 PCM by weight. Table 8 lists the properties used in this study.

TABLE 8. MATERIAL PROPERTIES FOR PCM INSULATION.

MATERIAL PROPERTIES	VALUE
Equivalent latent heat, J/kg	68,000 (40% PCM by weight)
Melting Temperature, °C	26
Thermal Conductivity, W/m K	.003365
Specific Heat, J/kg K	960
Density, kg/m3	29

CALIFORNIA CLIMATE ZONE 9, LOS ANGELES

Researchers simulated the building using California CZ 9 weather data. Figure 47 shows the room air temperature and the inside temperature of the exterior wall for a typical zone, with and without PCM in the exterior wall insulation. We simulated phase change material with two different phase transition temperatures. It is clear that the inside surface temperature of the wall board adjacent to the PCM insulation does not change.

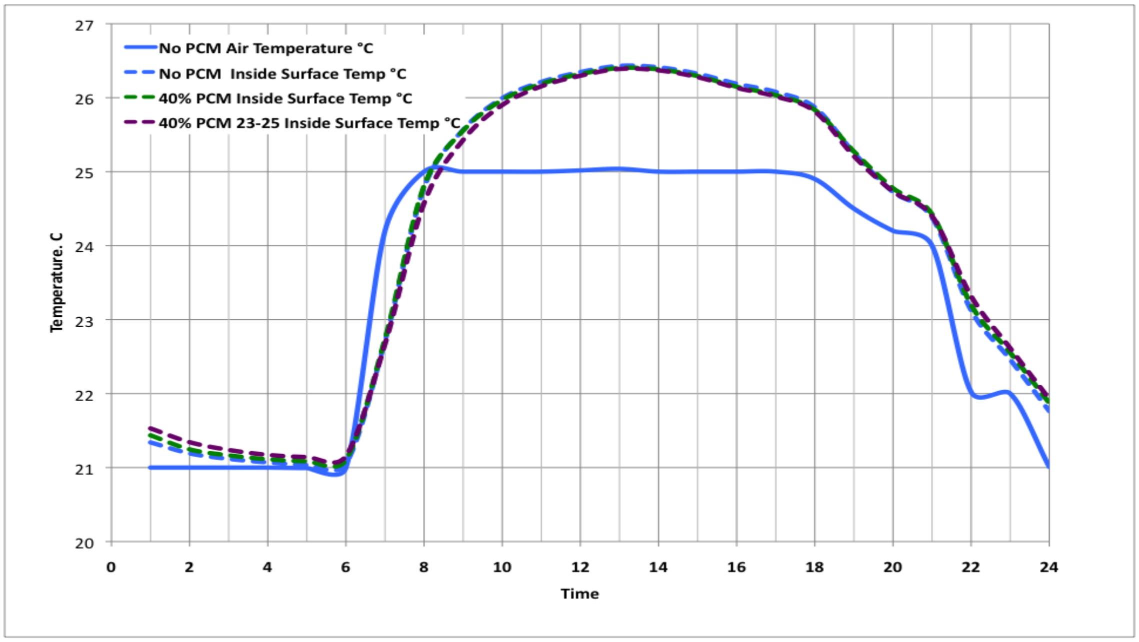

FIGURE 47. HOURLY ROOM TEMPERATURES AND SURFACE TEMPERATURES WITH AND WITHOUT PCM IN THE WALL AND ROOF INSULATION.

Since the wall and ceiling surface temperature is part of the computed surface-by-surface energy balance calculated by EnergyPlus, if the surface temperature does not change, the cooling load will not change. This is confirmed in Figure 48 which shows the sensible cooling load with and without PCM.

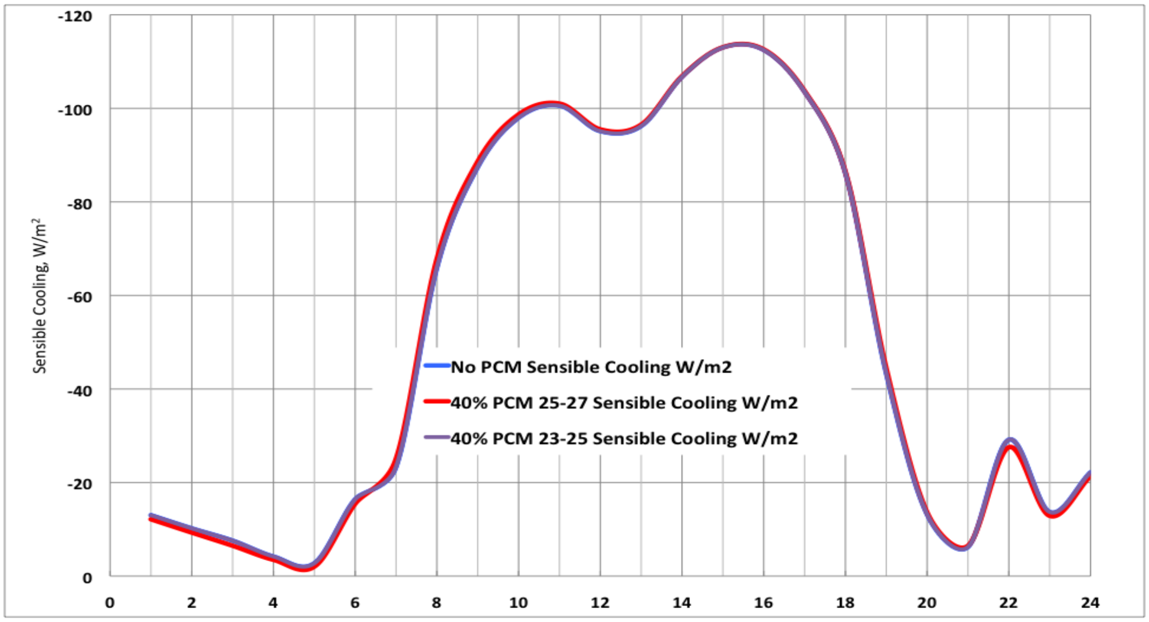

FIGURE 48. SENSIBLE COOLING FOR THE BUILDING WITH AND WITHOUT PCM IN THE WALL AND ROOF INSULATION.

Researchers ran annual simulations to determine if PCM in the wall and roof insulation benefits annual energy consumption, and it did not. Figure 49 shows that insulation with PCM is not beneficial for this office building in other California locations.

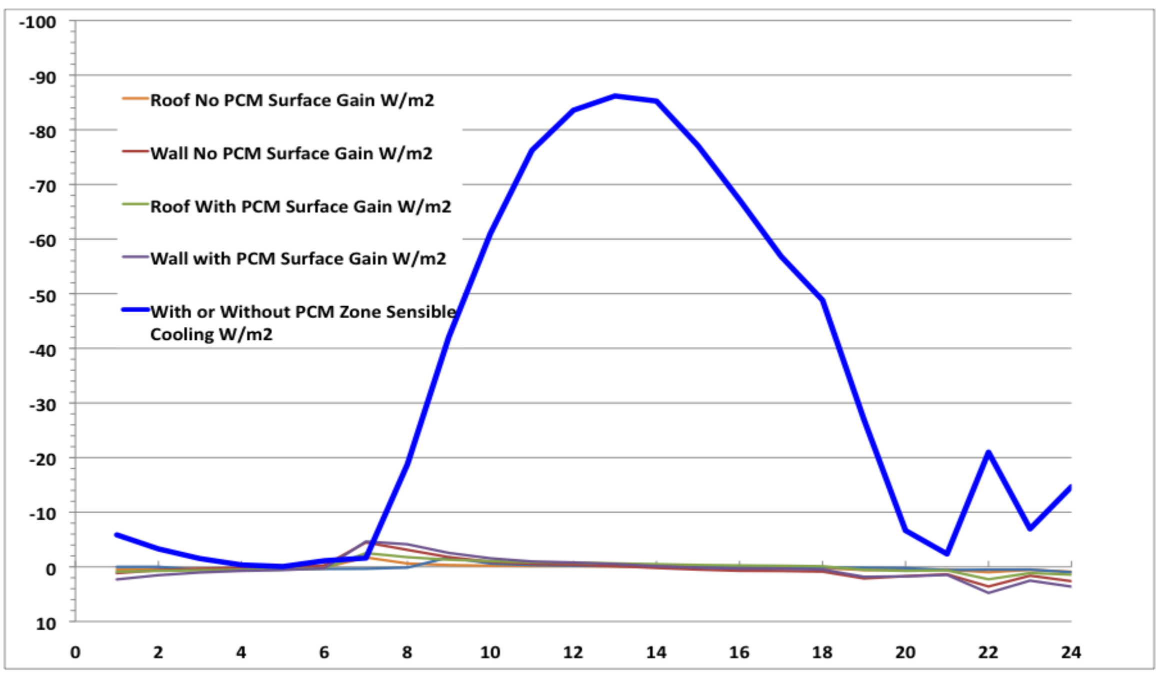

FIGURE 49. WALL AND ROOF HEAT GAIN, WITH AND WITHOUT PCM IN THE INSULATION, COMPARED TO THE SENSIBLE COOLING IN THE ZONE.

APPENDIX E. DETAILED RESULTS FOR PARTITIONED OFFICE WITH A PCM LAYER UNDER THE INTERIOR WALLBOARD

To test this option, researchers placed a layer of phase change material named Energain immediately inside the interior wallboard. This material is shown in Figure 2 near the beginning of the report. The material is used in both the outside walls, the partitions, and as the layer next to the inside layer in the roof as shown below in Figure 50.

FIGURE 50. ENERGAIN PANELS ON THE INSIDE OF THE ROOF AND WALL. THE SURFACES WILL BE COVERED WITH DRYWALL.

Energain's manufacturer, DuPont, supplied the temperature-enthalpy data that is shown in Figure 51[26]. A four-point approximation is used to describe the phase change material in EnergyPlus.

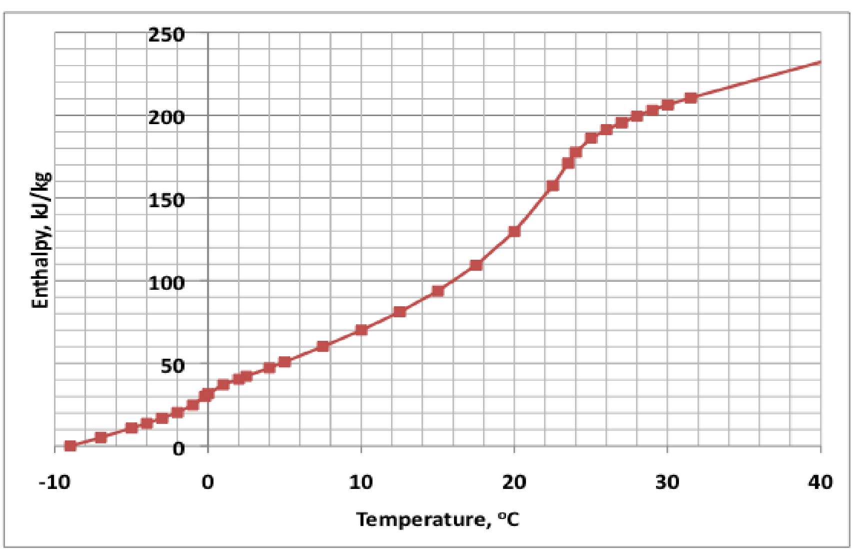

FIGURE 51. TEMPERATURE-ENTHALPY CURVE FOR ENERGAIN (FROM DUPONT).

CALIFORNIA CLIMATE ZONE 9, LOS ANGELES

Researchers used the weather data from CZ 9 to simulate a room where the temperature is maintained between 21 and 25°C. This section provides results for a summer design day.

Figure 52 shows the sensible cooling with and without PCM under the drywall. 1x, 2x, and 3x represent one, two and three layers of the PCM respectively. Although the product is marketed as a one-layer application, there is some benefit to using more PCM. For one layer, the peak sensible cooling is reduced from 108.1 W/m^2 to 91.4 W/m^2 or 15.0%. With two layers, the peak is reduced to 77.2 W/m^2 or 28.6%, which is nearly twice that of one layer. Three and four layers produce only nominal additional peak reduction.

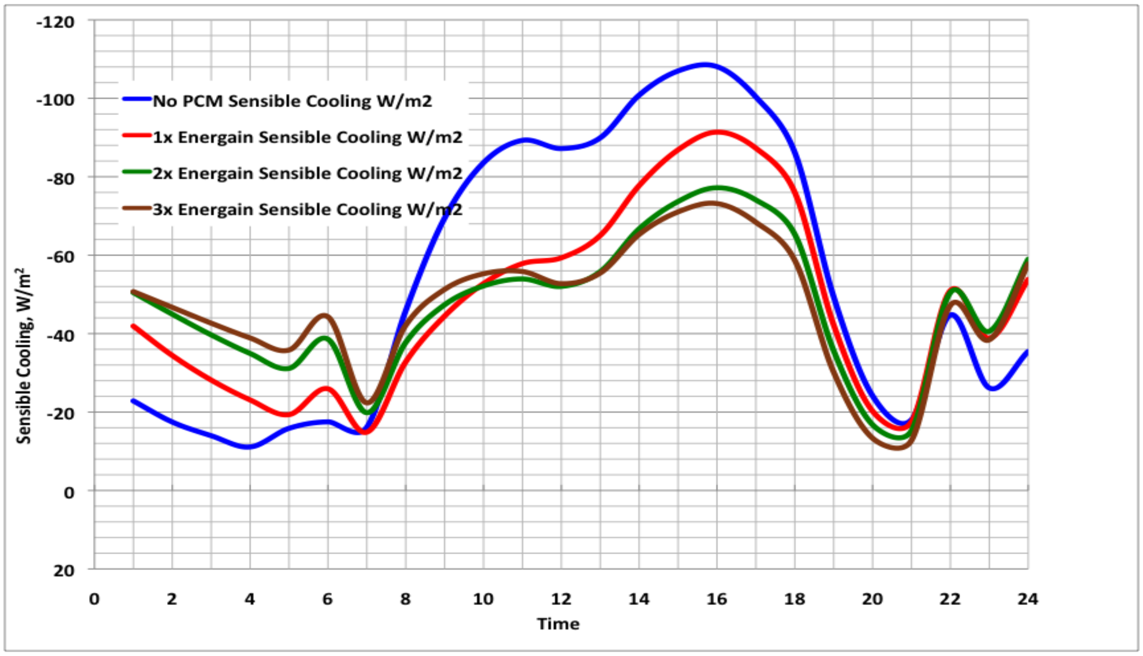

FIGURE 52. SUMMER DESIGN DAY SENSIBLE COOLING FOR THE BUILDING WITH AND WITHOUT ENERGAIN IN THE WALL, ROOF AND PARTITIONS, CLIMATE ZONE 9.

Figure 53 illustrates the diminishing returns with more layers of PCM.

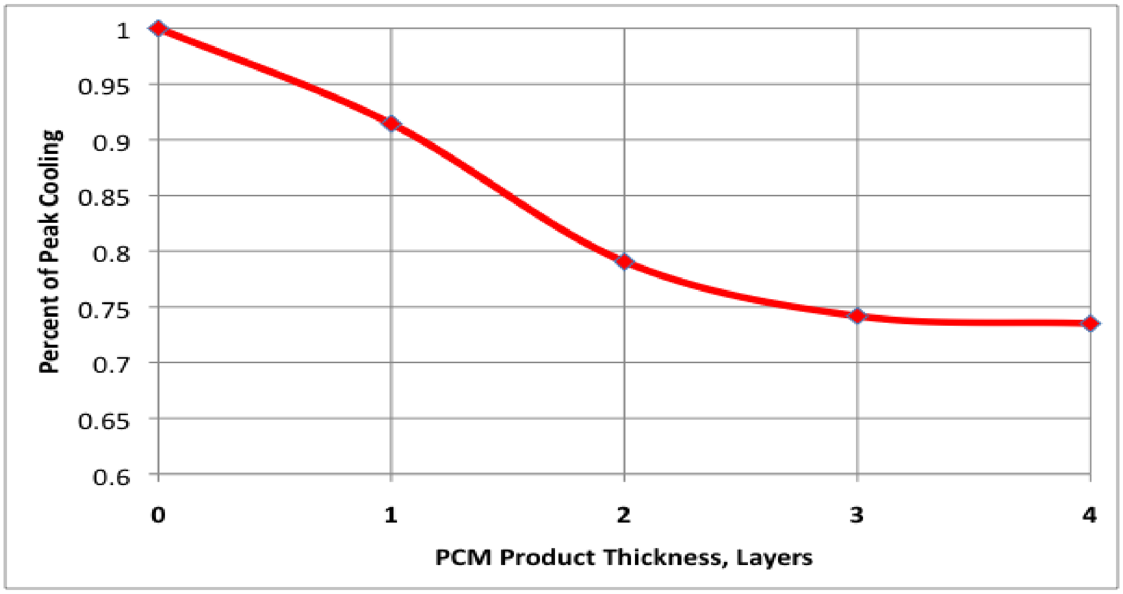

FIGURE 53. FRACTIONAL PEAK LOAD REDUCTION AS A FUNCTION OF NUMBER OF LAYERS OF PCM, CLIMATE ZONE 9.

Figure 54 shows the inside surface temperature of the exterior wall of the south central office. This plot shows that the PCM can improve the comfort of building occupants. The surface temperature with PCM peaks at just over 1°C less than the same room surface without PCM. This is probably true for all the surfaces in the room except the floor. Note that when PCM is present, the temperature peaks at a later time.

One comfort index is the so-called "comfort temperature" witch is the average of the room air temperature and the mean radiant temperature of the room. If most of the surfaces in the room surrounding the occupants are cooler, the mean radiant and comfort temperature will be lower for the same room air temperature. The impact of PCM on comfort is a subject for further study.

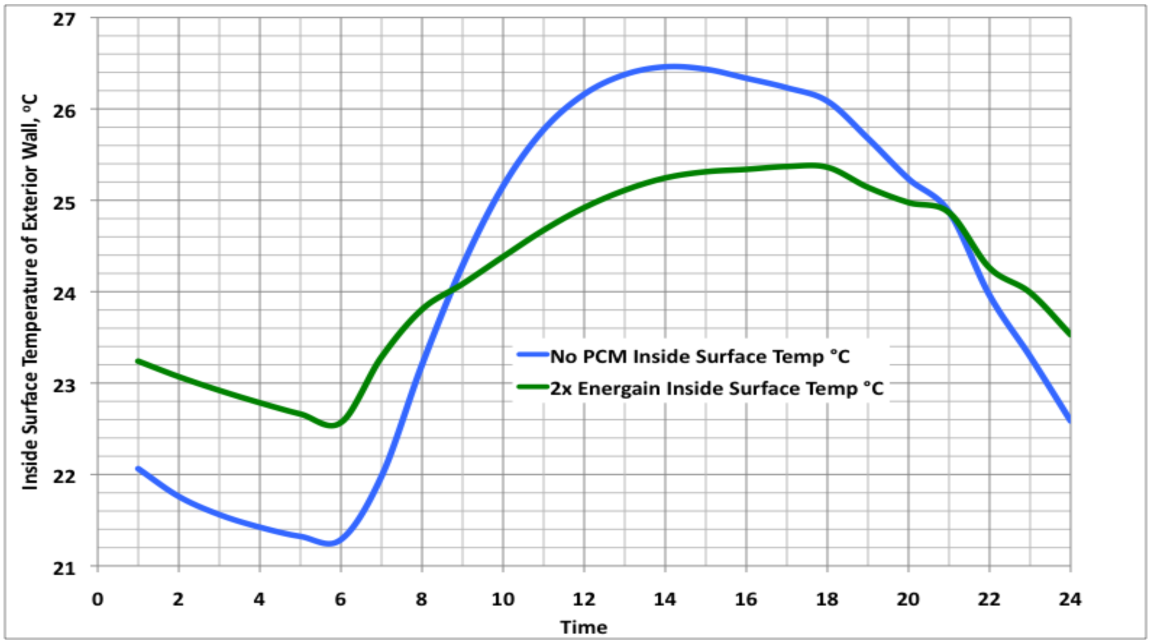

FIGURE 54. INSIDE SURFACE TEMPERATURE OF THE EXTERIOR WALL, WITH AND WITHOUT PCM, CLIMATE ZONE 9.

The peak load reduction for this application is significant, but is it cost effective? One layer of PCM can save from \$35 to \$53 $/m^2 of floor space by reducing initial equipment costs. Two layers can save from \$61 to \$101 $/m^2 of floor space. The cost goals for the price of the PCM product are \$25 $/m^2 of product. If one layer is used on each wall and the ceiling and/or roof, that corresponds to roughly 5 times the floor area, which .makes the cost about \$125 $/m^2 of floor area. At this price, the first cost savings for equipment may not offset the cost of PCM. For two layers or for a product with twice as much PCM, the cost may be less than double \$125 $/m^2 but it will be much too high to recoup with equipment first cost savings.

Figure 55 and Figure 56 show the annual results. Reductions in annual heating and cooling are modest and contribute little to making PCM cost effective.

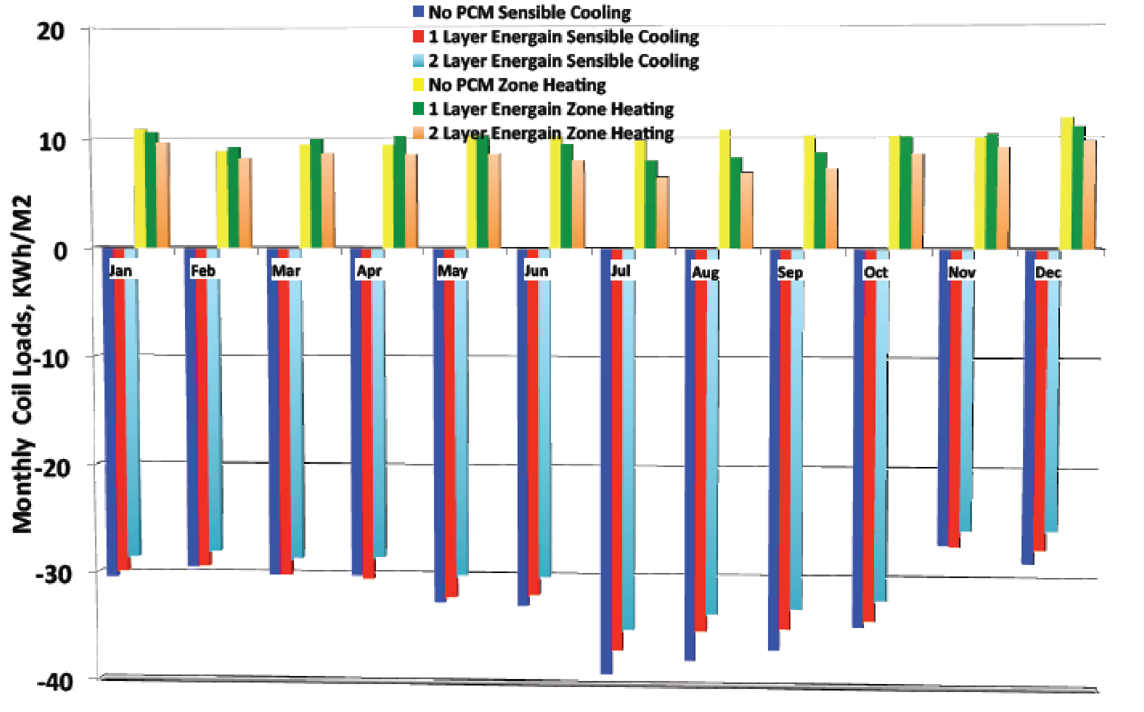

FIGURE 55. MONTHLY HEATING AND COOLING DEMAND WITHOUT PCM AND WITH TWO AND THREE LAYERS OF PCM, CLIMATE ZONE 9.

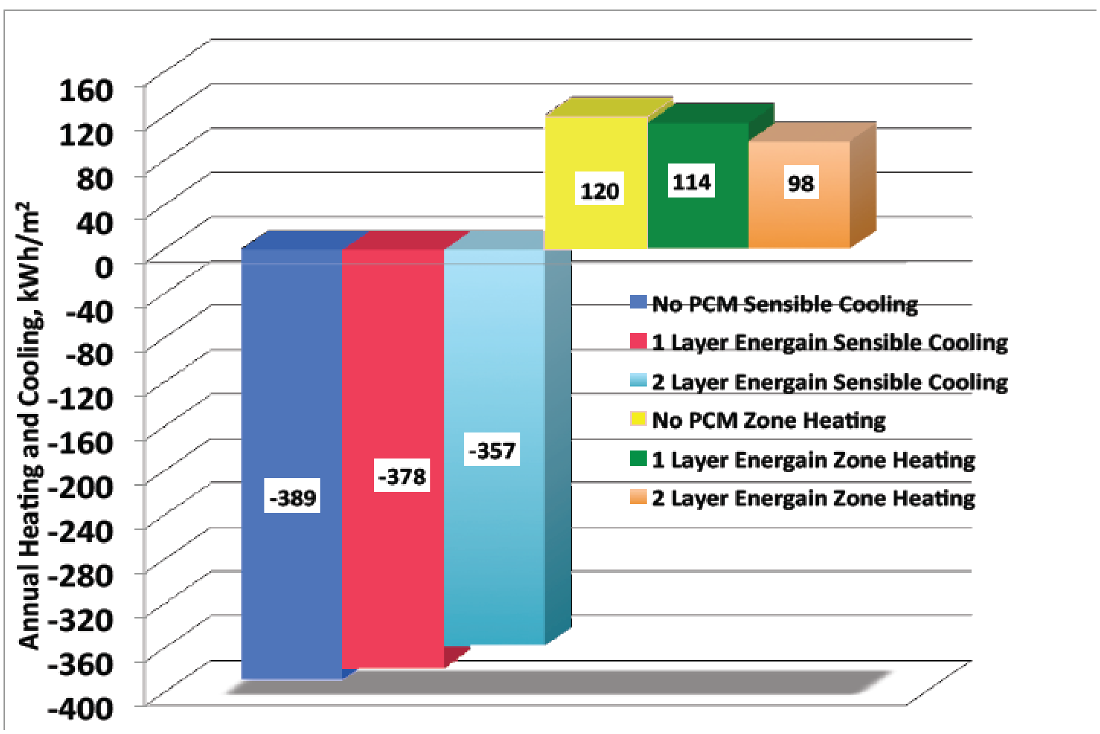

FIGURE 56. ANNUAL HEATING AND COOLING DEMAND WITH NO PCM, AND WITH TWO AND THREE LAYERS OF PCM.

The qualitative results for all the other simulated climate zones are the same as for Los Angeles.

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