ESTCP
Cost and Performance Report

(EW-201138)

Innovative Phase Change Approach for Significant Energy Savings

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ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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COST & PERFORMANCE REPORT
Project: EW-201138

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

AAD	Automatic Airflow Damper
AFB	Air Force Base
ARA	Applied Research Associates
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BLCC	Building Life Cycle Cost
BP	Balance Point
CA	California
CBP	Cooling Balance Point
CDD	Cooling Degree Days
CFM	Cubic Feet per Minute
CO^2	Carbon Dioxide
cRIO	Compact RIO
DoD	Department of Defense
ECU	Environmental Control Unit
FL	Florida
FPI	Fins per Inch
HECU	Hybrid Environmental Control Unit
HBP	Heating Balance Point
HDD	Heating Degree Days
H_r	Humidity Ratio
HVAC	Heating, ventilation, air conditioning
H_z	Hertz
kg	kilogram
kJ	kilojoule
kW	kilowatt
kWh	kilowatt hour
lbs.	Pound
LVM	Logical Volume Manager
MSDS	Material Safety Data Sheet
NPT	National Pipe Thread
PCA	Principal Component Analysis
PCM	Phase Change Material

PCS	Phase change slurry
PLS	Peak Load Shaving
PT18	PureTemp18, commercial phase change material
Q18	QuarTek 18, commercial phase change material
RH	Relative Humidity
SIR	Savings-to-Investment Ratio
UHMWPE	Ultra High Molecular Weight Polyethylene
VI	Virtual Instrument

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The novel technology developed during this effort is a hybrid Environmental Control Unit (ECU). The Hybrid ECU (HECU) integrates a heat exchanger filled with Phase Change Material (PCM) into a facility's air conditioning system. When installed, the PCM acts as a thermal battery, storing cold energy to supplement the facility's ECU operations and reducing operational energy use and cost.

OBJECTIVES OF THE DEMONSTRATION

The overarching objective was to demonstrate that PCM in a heat exchanger design and integrated into a building ventilation system can result in significant energy savings on Department of Defense Installations while maintaining cooled spaces within a comfortable temperature and humidity range, (71-73^{o}F, ≤ 65% Relative Humidity [RH]), and shave peak cooling electric demands.

The HECU technology yielded energy savings and energy cost savings, but not to levels stated in the project objectives. Specific numeric success criteria—and the results—are summarized below under Demonstration Results.

TECHNOLOGY DESCRIPTION

PCM absorbs and releases a large amount of heat within a narrow temperature range as it undergoes phase change. As the temperature increases above the melting point, PCM melts and absorbs heat. Similarly, as the temperature drops below the solidification point, heat is released as the PCM solidifies.

The novel technology developed during this effort is an HECU. The HECU integrates a PCM-filled heat exchanger into a facility's air conditioning system. When installed, the PCM acts as a thermal battery storing cold energy to supplement the facility's ECU operations reducing operational energy use and cost.

DEMONSTRATION RESULTS

After extensive pre-demonstration testing, two methods of integrating the PCM modules into a facility's air conditioning system emerged: (1) PCM-filled coils suspended under ceiling air registers. A simple retrofit, this method targets continuous PCM use by ensuring the coils are always in the path of airflow. (2) Peak Load Shaving (PLS) using a large PCM-filled coil. This method uses a PCM module with large thermal storage capacity to absorb heat and maintain the room temperature during the peak demand period of the day.

When demonstrating the PLS technology, the unit could only carry 1/3 of the peak heat load due to manufacturing and cost limitations. To evaluate this technology against the objectives, the performance results for the demonstrated unit were extrapolated, assuming 3 times the mass of the demonstrated PCM was required to manage the full peak heat load. The results of the extrapolated analysis are presented in Section 6.4.

The success and savings of the two applications described above were evaluated using six quantitative performance objectives and the seventh is a qualitative performance objective.

1. **Reduce Air Conditioning Electric Consumption:** Success criteria – ≥ 30% reduction in cooling energy consumption compared with baseline energy consumption.

    - **Result for PCM Ceiling Coils:** The demonstration showed a 19% reduction in air conditioning energy use compared to the baseline. Achieving <30% reduction in energy consumption requires three changes in the application of the PCM: 1) Redesign the PCM ceiling coils to regenerate in less time to save the energy used in regeneration; 2) Use different medium for regeneration than air; and 3) Change the role of PCM ceiling coils from a subservient to the air conditioning unit to be the main source of cooling and the air conditioning unit regenerate the PCM as needed.
    - Result for Peak Load Shaving PCM Coil: The demonstration of the PLS coil showed 1.47% energy savings, based on Tyndall Air Force Base (AFB) electricity pricing, this reduced the air conditioning energy cost by 6.2%. The demonstration did not show significant energy savings since the PCM in the PLS coil has to be regenerated using the same air conditioning unit and air as the heat transfer medium. If PCM can be regenerated at night using ambient low temperature air or ground source cooler water, this application will significantly reduce energy consumption.

2. **Reducing Peak Electrical Demand:** Success criteria – Demonstrate 2 hours of peak demand reduction.

    - **Result for Peak Load Shaving PCM Coil:** During the demonstration, the PLS coil covered the two hours it was designed for.

3. **Provide Comfort Zone Conditions:** Success criteria – Room temperature in the range of 71–73F and relative humidity ≤ 65%.

    - **Result for PCM Ceiling Coils:** During the demonstration, the PCM-filled coils maintained the room temperature and humidity within these criteria.
    - **Result for Peak Load Shaving PCM Coil:** The demonstration displayed the PCM can maintain room temperature in the range of 71-73°F during the peak hours. The relative humidity. However, increased from 63% to 78% during the operation. Two factors contributed to this increase: (1) the building is located in a high humidity climate where the building average humidity had been in the range of 55-75% even without the PCM unit, and (2) the PCM had a higher melting point temperature, 64.4°F, than the dew point for the room conditions. At 72°F and 60% relative humidity the air dew point is 52.18°F. To reduce the relative humidity to proper levels, alternative PCM can be chosen with a lower melting temperature than the air dew point to condense the water from the humid air.

4. **Measure Maintenance Frequency:** Success criteria – Maintain maintenance requirement as current system

    - **Result for PCM Ceiling Coils:** After the initial installation, the PCM ceiling coils operated passively and did not require additional maintenance.

- **Result for Large PCM Coil for Peak Load Shaving:** After the initial installation, the PCM PLS coil operated passively and did not require additional maintenance.

5. **Minimize System Air Pressure Drop:** Success criteria – Maximum of 2% increase in Air Handler Fan energy consumption

   - **Result for PCM Ceiling Coils:** The demonstration exposed that after installation of the PCM module, fan energy consumption did not increase and air flow rate did not decrease.
   - **Result for Peak Load Shaving PCM Coil:** The demonstration disclosed that after installation of the PCM module, fan energy consumption did not increase, and airflow rate only decreased by about 100 CFM (from original air flow rate of 1600 CFM). This did not affect the operation of the air conditioning unit and there is no need to change air handler fan. It should be noted that the drop in the airflow rate due to the installation of the PCM module can be attributed to two factors: (1) pressure drop across the PCM module, and (2) pressure drop due to the installation of the additional duct system. The second factor can be avoided because the PCM is designed to be a drop-in unit to the existing duct system. Because of the physical space constrains of the demonstration site, an extended length of new duct system had to be installed to route the air flow for the demonstration; therefore, the pressure drop of overall system was increased. Without the installation of the new duct system, the air flow rate drop, due to the PCM module, should be > 100 Cubic Feet per minute (CFM) , 6.25% of the original air flow rate, and have even less impact to the existing air handler system. With the installation of the new duct system, if the original flow rate of 1600 CFM is to be maintained, the fan power would increase by approximately 16% to maintain the static pressure at 0.4 inch of water.

6. **Economic Benefits:** Success criteria – < 6 years discounted pay-back period, Saving-to-Investment Ratio (SIR).

   - **Result for PCM Ceiling Coils:** The current design of the PCM ceiling coils could not meet the 6-year payback period. A redesign focusing on higher energy density storage, quicker PCM regeneration, and reduced manufacturing cost is necessary to approach this target.

   - **Result for Peak Load Shaving PCM Coil:** The demonstration showed that the current design for the PLS coil could not meet the target 6-year payback period. In regions with high fluctuation in peak price and large daily ambient temperature changes, such as Sacramento, California, the current design could achieve a 22-year pay-back period with a product lifespan of 30 years. If night-time air recharging was used, the pay-back period could occur in 14 years. Improvements that will help approach the target payback period include obtaining PCM with higher specific thermal storage, which will reduce the unit footprint and cost.

7. **Ease of Use and Maintenance:** Success criteria – A single field technician able to effectively use and maintain the unit with minimal training

- **Result for PCM Ceiling Coils:** Field technicians with proper training can install the PCM ceiling coils. After the installation, the ceiling coils operated passively and did not require additional adjustments or maintenances.
- **Result for Peak Load Shaving PCM Coil:** Field technicians with proper training can install the PCM PLS coil. The PLS coil operated passively and did not require additional adjustments or maintenances. Therefore, no additional work by field technician was needed for the PLS coil. A single field technician with Environmental Control Unit (ECU) training only requires minimal additional training to check and handle the operation of the PLS coil.

IMPLEMENTATION ISSUES

Space limitation in the test facility was the primary factor which prohibited the installation of a PLS unit large enough to cool the room for the entire 6-hour peak period. Figure 3 shows the PLS unit installed in the building. Tripling the footprint was impractical in an existing facility of this size (1,200 square feet) but could be factored into the building design for full-scale implementation. Secondly, considerations of cost and time also affected the decision to build a prototype capable of carrying 2 hours of the peak period.

The PLS energy cost savings could be much higher; again using Tyndall AFB electricity pricing, the building can save 5.33% in energy use and 20.88% in energy cost if the entire peak period is managed by the PCM unit. Further, the demonstration shows that the energy cost savings could be higher in regions with larger fluctuations in peak prices. Using Pacific Gas and Electric pricing for Sacramento California, a 30% air conditioning energy cost saving is possible.

Inability to meet energy savings and comfort objectives can be addressed through a change in the operation mode of the integrated PCM heat exchanger. In the current mode of operation, the air conditioner is the heart of the system, and the PCM unit supplements its operation. A better approach is to make the PCM heat exchanger the main system component, where the air conditioner supplements the PCM unit. In this manner, when the room needs cooling, the thermostat then triggers the air handler fan only, allowing the PCM coils to absorb heat from the room. Once the PCM is fully melted, as indicated by PCM temperature, the compressor is activated until the PCM is fully regenerated. Therefore, the PCM provides cooling to the room, and the air conditioner is only used when regeneration is needed. This mode of operation keeps the PCM temperature close to the phase change temperature, allowing the high latent heat capacity of PCM to be better used.

1.0 INTRODUCTION

The sharp rise in the use of energy has had a debilitating effect on the environment due to Carbon dioxide (CO_2) emissions and on the economy due to the high cost of energy. In fact, residential and commercial buildings' energy use credited to up to 50% of CO_2 emissions from electric power plants. Heating, air conditioning, lighting, and information technologies have made our buildings increasingly hungry for energy. Under the Kyoto Protocol, industrialized countries have agreed to curb their CO_2 emissions 75% by 2050. To accomplish this goal, energy consumption has to be reduced by developing energy efficient technologies to maintain the level of activities we currently have. It is estimated that reducing our energy consumption in the United States 30% by 2020 would eliminate the need for 1,000 new power plants, a significant reduction in CO_2 emissions and energy cost rates.

1.1 BACKGROUND

The Department of Defense (DoD) spends about $4 billion per year on facility energy consumption, with air conditioning equipment being the largest energy consumer. Executive Order (EO) 13423 called for a 30% reduction in energy use by the end of fiscal year 2015 relative to the baseline of fiscal year 2003. In an attempt to meet EO 13423, the Air Force opted to set thermostats to 78°F (25.6°C) in the cooling season and 68°F (20°C) in the heating season; however, these temperatures are outside normal comfort zone limits for most people. To achieve comfort and energy savings, room temperatures need to be maintained around 72°F (22°C) with minimal air conditioning equipment energy use.

Prior to this project, limited work had been done using Phase Change Materials (PCM) to stabilize building temperatures and reduce energy demand. These technology approaches apply PCM to building walls or in slurries for water chillers. The application of PCM in walls, future applications in floor tiles, or office furniture is a passive approach which adds higher R-values to walls and floors. One study that used PCM in wall panels, Kośny et al [1], found that microencapsulated paraffinic PCM reduced peak-hour heat flux by at least 30% compared with conventional construction, and the peak-hour load was shifted about 2 hr in the PCM wall. Analysis of the temperature profiles showed that the PCM was going through full charging and discharging processes during the 24-h time period, and the PCM heat storage capacity PCM thermally stabilized the core of the wall.

Phase change slurry (PCS) made from either an emulsified PCM in a fluid or micro-encapsulated PCM, in a fluid is an attractive alternative to chilled water for comfort cooling applications. A PCS containing 30weight% paraffin has double the heat capacity of water in the 5 to 11°C (41.0 to 51.8°F) temperature range.

The HECU technology uses a PCM with a heat capacity of 207 kilojoules per kilogram (kJ/kg); it is designed to absorb room thermal loads to minimize air conditioning use and to level load demands for air conditioning.

1.2 OBJECTIVE OF THE DEMONSTRATION

The technical objectives of the project consist of five goals:

1. Determine demonstration site baseline energy consumption;
2. Develop the air-to-PCM unit;
3. Determine demonstration site performance while retrofitted with the PCM technology; analyze performance data and calculate actual savings;
4. Determine implementation parameters
5. Prepare a technology transition plan for DoD-wide implementation.

The overarching objective is to demonstrate that PCM in a heat exchanger design and integrated into building ventilation system can result in significant energy savings on DoD installations while:

a) Maintaining cooled spaces within a comfortable temperature and humidity ranges (71-73°F, ≤ 65%RH), and
b) Shaving peak cooling electric demands

1.3 REGULATORY DRIVERS

The drivers that the HECU technology addresses are listed below, with a brief description of the sections dealing with the energy demands, efficiency issues, and commercialization of American technologies. These are addressed in greater detail in the Final Technical Report.

Executive Order 13693 "Planning for Federal Sustainability in the Next Decade" set goals (paraphrased) to "*…reduce energy use in Federal buildings by 2.5 percent per year between 2015 and 2025…*" and to "*…identify opportunities to transition test-bed technologies to achieve the goals…*"

The Energy Policy Act of 2005 Section 902 Goals: Objectives included "…reducing the cost of energy and making the economy more efficient and competitive…" and "…improving the energy security of the United States."

The Energy Independence and Security Act of 2007: "…support policies and programs…to promote the use of American-made clean and efficient energy technologies, products, and energy and environmental management services."

The American Clean Energy Act of 2009: "…promote clean energy technology development, enhanced energy efficiency, improved energy security, and energy innovation and workforce development…"

The 2006 Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (MOU) states some goals and objectives are to "reduce the total ownership cost of facilities" and to "improve energy efficiency and water conservation."

The DoD Strategic Sustainability Performance Plan of 2010: "DoD embraces sustainability as a means of improving mission accomplishment…" and "…reducing the energy demands of our operational forces is a major focus of the Department's efforts to cut energy consumption…"

The 2010 MOU between the U.S. DoE and the U.S. DoD Concerning Cooperation in a Strategic Partnership to Enhance Energy Security states that, “The DoD aims to speed innovative energy and conservation technologies from laboratories to military end users,” and “solving military challenges through innovation has the potential to yield spin-off technologies that benefit the civilian community as well.”

The Air Force Energy Plan of 2010: One of the Air Force 2030 Energy End State Goals is that “Research, Development, Test, and Evaluation (RD&TE) has delivered the new cost-effective energy technologies necessary to substantially reduce demand and increase supply”.

The Army Energy Security Implementation Strategy (AESIS) of 2009: Mission is to “…make energy a consideration for all Army activities to reduce demand, increase efficiency, seek alternative sources, and create a culture of energy accountability while sustaining or enhancing operational capabilities.”

The Naval Energy Strategy of 2009: “The expeditionary community will work toward lightening the load and reducing the fuel consumption of vehicles, generators, and other equipment.”

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

Two PCM applications emerged with the potential to reduce air conditioning energy consumption and cost: (1) Peak load shaving (PLS) using a large PCM-filled coil to reduce/eliminate energy use during the hottest time of the day, and (2) PCM-filled coils suspended under ceiling air registers for continuous use. The PLS approach transferred ECU operation from the daily peak use period to the off- peak early morning period. This approach solidifies the PCM in the large coil in the early morning, and in the afternoon. The PCM melts to cool the room for several hours while the ECU condenser unit stays off. PLS reduces the cost of energy, as the electricity is more expensive during peak demand hours. The theory behind PCM-filled ceiling coils was to reduce operation of the ECU condenser unit by conditioning the room while the condenser unit was off—allowing it to stay off longer than it normally would each cycle.

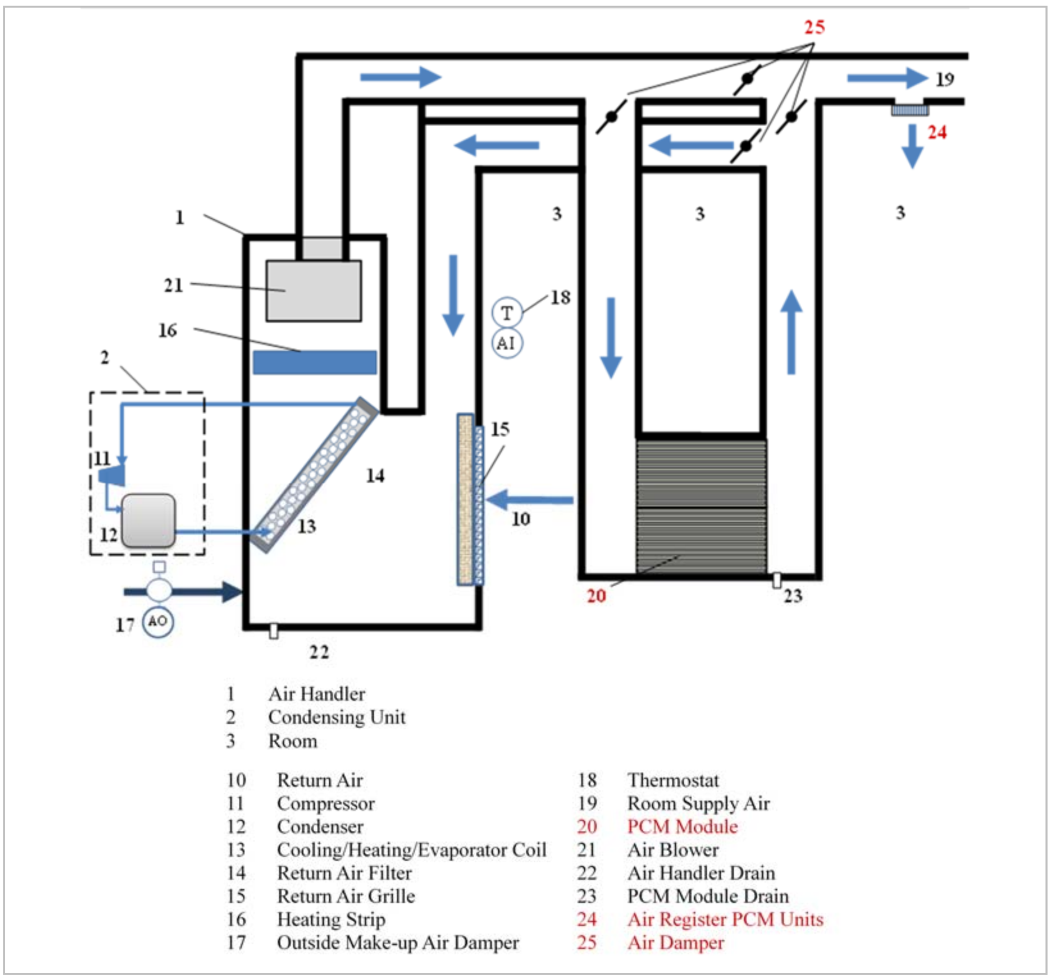


Figure 1. Schematic of Technology as Applied

The HECU technology consisted of an air-to-PCM heat exchanger integrated with the air handler of the ECU. A PCM with optimum latent heat and melting /solidification temperatures was used to store and release thermal energy.

Figure 1 shows the schematics of the integrated system. In this configuration, the air conditioning unit was used to achieve room relative humidity below 65% and to regenerate the PCM unit.

The two approaches used in the demonstration of the HECU technology are as follows: (1) used a large PCM module, 20, for air conditioning PLS; and (2) used smaller PCM modules, 24, installed below each ceiling air register. The PLS PCM module is located downstream of the air handler with a bypass loop to allow the building to operate in normal mode if required, while smaller PCM units are installed on the air outlet registers. Each PCM unit was a tube-fin heat exchanger made of copper tubes filled with PCM and equipped with fins to maximize heat transfer rate. The individual tube works under no internal pressure caused by thermal expansion during melting. These tubes are filled to a level to accommodate the degree of thermal expansion, making leakage potential low. The room thermostat, 18, controls the system operation while the data acquisition system controls the Automatic Air Dampers (AAD). And air handler fan will allow for intermittent or continuous fan operation. The HECU has three modes of operations: normal operation, operation with PCM, and regeneration of PCM:

PLS – Applied Research Associates (ARA) designed and tested several iterations of the PCM module in our lab facilities. A flat tube configuration (Figure 2) designed to minimize the size and weight of the module was tested and reconfigured to achieve high heat transfer rate between air and the PCM. To improve the heat transfer rate for the flat tube prototype, two methods were investigated: (1) addition of carbon graphite additive to improve the thermal conductivity of the PCM, and (2) the addition of fins to improve the convective heat transfer of the prototype. The carbon graphite additive showed little improvement from the pure PCM prototype. The results from this experiment suggest that the limiting heat transfer component for the flat plate design was heat convection from the air rather than conduction through the PCM. This conclusion precipitated the addition of 0.006" thick waffle pattern aluminum sheets to improve the convective heat transfer of the flat tube prototype, which, provided only a slight improvement in heat transfer rate—most likely due to less than perfect contact between the fins and the flat tubes—as the fins were not heat bonded to the tubes after insertion.

Figure 2. Flat Plate Design

When these experiments with the flat plate design displayed low heat transfer rate, a commercially available tube-fin design (Figure 3) was used to maximize heat transfer surface. Several generations of the tube and fin design were attempted, but for the sake of brevity, only the final design is shown in Figure 3.

Figure 3. Large PCM-Filled Coil Unit

PCM-Filled Coils Under Ceiling Registers – In the demonstration building (9732 Tyndall Air Force Base [AFB]), the 4 ton ECU's condenser unit operates for 5-20 minutes each cycle on a warm day, depending on the building's thermal load. Since the PCM is dependent on the ECU for regeneration, it must solidify within the condenser run time to change phase every cycle. Off- the-shelf water coils and evaporator coils presented an excellent opportunity to test PCM in a high heat transfer rate design without investing heavily in custom prototypes. Two variations were tested: (1) placing PCM-filled coils inside the duct, and (2) mounting the coils inside the room directly under the ceiling registers (Figure 4). Only the option used in the demonstration—coils under the registers—is discussed in this summary report.

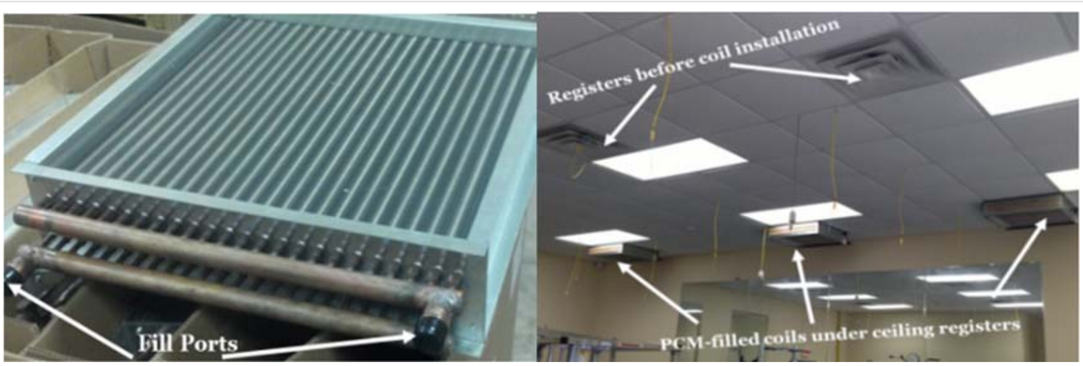


Figure 4. PCM-Filled Ceiling Coils

Tube diameter affects the rate of phase change and is an important parameter in selecting a PCM coil. Coils with 1/2" and 3/8" outer diameter tubing were tested in closed loop and open loop configurations. Preliminary closed loop tests demonstrated that 3/8" diameter coils—which is the smallest standard tubing size available—had shorter phase change time and was, therefore, more likely to solidify within the shorter condenser cycles.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

ARA's HECU technology integrates PCM into a building's air conditioning ventilation system. This active approach provides forced convection to optimize PCM module performance. In addition, buildings can remain usable while being retrofitted with the technology. With the PCM modules installed, the ECU will regenerate the PCM as needed while cooling the building. For the PLS approach, the total energy use was reduced by 1.47%, resulting in energy cost savings of 6.2%. During the demonstration, the module was sized to manage 2 hours out of the 6-hour peak period. Space limitation in the test facility was the primary factor which prohibited the installation of a PLS unit large enough to cool the room for the entire 6-hour peak period. Figure 3 shows the PLS unit installed in the building. Tripling the footprint was impractical in an existing facility of this size (1,200 square feet) but could be factored into the building design for full-scale implementation. Secondary considerations of cost and time also affected the decision to build a prototype capable of carrying 2 hours of the peak period. In an ideal case, with a PCM unit sized to support the entire peak period, it could produce a cost savings of 20.88% and energy savings of 5.33%. Further, in regions with higher peak electrical rates and higher ambient temperature fluctuations during the day, cost savings upwards of 30% should be realized. In the all-day approach, where the PCM modules were installed on the ceiling air registers, the hybrid air conditioning system resulted in energy use reduction of 19%.

To increase the energy savings, the time taken to regenerate the PCM modules needs to be shorter than the current time while making sure that the PCM in the modules has completely changed phase during cooling cycles to benefit from the high latent heat of the PCM.

3.0 PERFORMANCE OBJECTIVES

To quantify the energy savings from the proposed PCM technology and achieve the projected goals, a set of performance objectives were developed. This effort demonstrated two PCM technologies: PCM-filled coils placed under ceiling registers and a large PCM coil for peak load shaving. These performance objectives and results for both technologies are divided into five quantitative performance objectives and one qualitative performance objective, which are summarized in Table 1.

Table 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results (Ceiling Coils)	Results (Peak Load Shaving)
Quantitative Performance Objectives					
Reduce Facility Air Conditioning Electric Consumption.	Facility's electric usage profile Kilowatt hour (kWh).	Total energy consumed (kWh), energy consumed in compressor and fans; room temperature and humidity, ambient temperature, and solar incidence profiles.	≥30% reduction in cooling energy consumption compared with baseline cooling energy consumption.	Up to 19% cooling Energy Savings.	Up to 6.2% energy cost saving and 1.47% energy savings.
Reducing Peak Electric Demand.	Facility's electric usage profile (kWh) during peak demand period.	Total energy consumed (kWh), energy consumed in compressor and fans; room temperature and humidity, ambient temperature, and solar incidence profiles during peak periods.	Show 2 hours coverage of the peak demand period with condenser unit off.	N/A	Demonstrated 2 hours of peak demand reduction. To cover the entire 6 hours, three times of the PCM is needed.
Provide Comfort Zone Conditions	Maintain room temperature and relative humidity steady and comfortable.	Room relative humidity and temperature measurements profile, Feedback from Occupants.	Room temperature in the range of 71-73°F and relative humidity ≤ 65% ASHRAE[1] Standards 62.1-2013.	Maintain both temperature and humidity in the range of 70-73F. Relative humidity also stayed ≤ 65%	Maintained room temperature in the range of 70-73F. Relative humidity increased markedly (from 55% to 75%) due to high PCM melting point
Measure Maintenance Frequency	Number of maintenance visits required.	Maintenance data from log in folder.	Maintain maintenance requirement as current system	No additional maintenance requirements	No additional maintenance requirements
Minimize System Air Pressure Drop	Pressure drop measurements in each system component (psi) and Air Handler fan power consumption (kWh).	Air Flow Rate and Pressures, Air Handler Fan Power.	Maximum of 2% increase in Air Handler Fan energy consumption	No increase in fan energy. Airflow rate drop slightly (100 CFM) 6% no additional fan power needed.	No increase in fan energy. Airflow rate drop 6% (100 CFM) no additional fan power needed.

[1] American Society of Heating, Refrigeration, and Air-Conditioning Engineers

Table 1. Performance Objectives (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria	Results (Ceiling Coils)	Results (Peak Load Shaving)
Quantitative Performance Objectives					
Economic Benefits	Discounted Simple Payback, Savings-to-Investment ratio.	Unit cost, labor cost, maintenance costs, energy savings.	< 6 years payback period.	19.4% Energy Savings, Savings-to-Investment (SIR)=0.12	20% energy cost saving, SIR=0.2 (Demonstration Site – Tyndall AFB, FL) SIR=1.81 (Sacramento, CA Case)
Qualitative Performance Objectives					
Ease of use and Maintenance	Ability of a technician-level individual to use and maintain the technology.	Feedback from technician on usability and maintainability and time required to use.	A field technician with minimal training able to effectively use and maintain the unit.	Passive operation and required no additional operation, maintenance or technicians.	Passive operation and required no additional operation, maintenance or technicians.

4.0 FACILITY/SITE DESCRIPTION

Figure 5 shows the relative location of the demonstration site at Tyndall AFB, in the panhandle of Florida. The demonstration building is a relatively new exercise gym, Building 9732, located on Tyndall AFB, Florida.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

Figure 5. Tyndall AFB Demonstration Site

The site was identified for several reasons: (1) the great interest and support from the Tyndall AFB Civil Engineering Squadron, and the Energy Group Manager at the Air Force Civil Engineer Center (AFCEC); (2) the building is only utilized during lunch hours and after hours providing better control on facility usage; and (3) the building is relatively new, so it was constructed to latest building codes.

The 1,200 square feet, one story building (Figure 6) has an exercise room, male and female locker rooms, and a mechanical room. The main entrance and all windows are on the South-facing wall. With no surrounding buildings or trees, the facility is directly exposed to daytime sun. Two 3-ton condensing units with a combined 2,100 CFM air handler originally conditioned the building. However, due to the baseline testing and analysis, the local power company performed a Manual N Load calculation and re-sized the building for a 4 ton split air conditioning system. There are two 200 CFM exhaust louvers on the West wall and a 400 CFM makeup louver on the North wall. Inside the building, there are 11 supply grills, 9 of which are in the exercise room, where the return grill is also located.

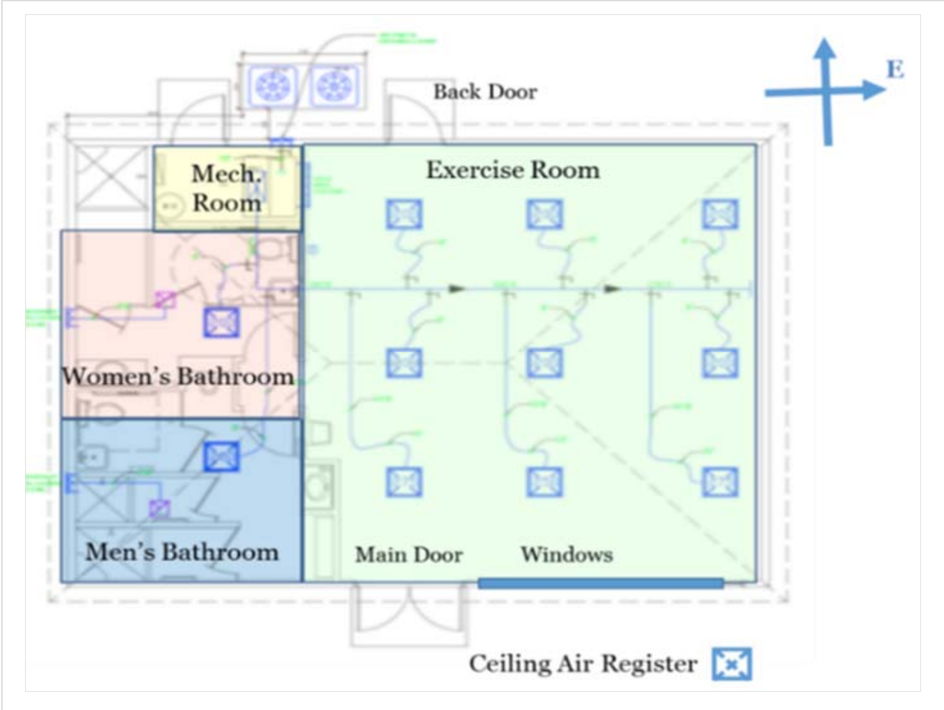


Figure 6. Facility Floor Plan

4.2 FACILITY/SITE CONDITIONS

Tyndall AFB is located in a hot and humid climate region. During the hot season (May to October), ambient temperature lows may range from the mid to high 70s°F, requiring an air conditioning unit to provide cool air for the solidification phase. The PCM system is designed according to the gym's building requirements and the need to cool the building during working hours (7:00-16:00). Tyndall AFB Civil Engineering Squadron supported/approved this demonstration effort.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

Testing was designed to determine the impact of two PCM technologies on the performance of the existing ECU system in building 9732 at Tyndall AFB. A 12-month baseline performance test was conducted to measure the energy consumption of the existing ECU system as a function of weather conditions. Baseline testing was followed by demonstration test runs for the two PCM technologies and performance was evaluated against the baseline data using the performance objectives outlined in Table 1. Performance Objectives. As weather conditions can vary significantly from year to year, a weather normalization approach was used to accurately compare the performance of the PCM technologies to the baseline.

Room temperature, humidity distribution, ECU, total building power consumption, and weather station data were collected during the baseline and demonstration periods. Additional sensors inside the PCM modules provided data on PCM conditions. Test runs were conducted under two controlled variables that were kept the same for all tests; these are the room thermostat temperature setting of 72^{o}F and the use of the same air conditioning equipment.

Testing consisted of nine phases: (1) Demonstration Site Preparation; (2) Instrumentation and Data Acquisition; (3) Baseline Performance Test; (4) Design of the PCM System; (5) Fabrication and Testing of the PCM System; (6) Field Demonstration; (7) Data Analyses; (8) Economic Benefit Analysis; and (9) Technology Transition Plans Development.

During the demonstration, the ECU system's operation was controlled by a National Instruments LabVIEW program, which allowed the thermostat or LabVIEW to control the air conditioning system's compressor and evaporator fan functions according to the needs of the PCM technologies. The LabVIEW program also controlled automated airflow dampers to direct airflow through the ducts.

5.2 BASELINE CHARACTERIZATION

Baseline testing established reference conditions for building temperatures, humidity, and the equipment's electricity usage. Sensors were installed to examine building conditions and predict baseline performance as a function of weather conditions. Details of the sensor, data acquisition, and wireless data transmission systems are provided in the Final Report.

Baseline characterization was done using the weather normalization statistical approach to develop a relationship between the energy use and weather conditions.

5.2.1 Sampling Protocol

Baseline tests established reference conditions for building temperatures, humidity, and equipment's electricity usage. Sensors which include 42 thermocouples, 9 relative humidity sensors, 3 power transducers, 2 door sensors, and 2 air pressure sensors – were installed at the demonstration building to establish baseline performance weather dependence and examine building behavior. Figure 7 show sensor locations.

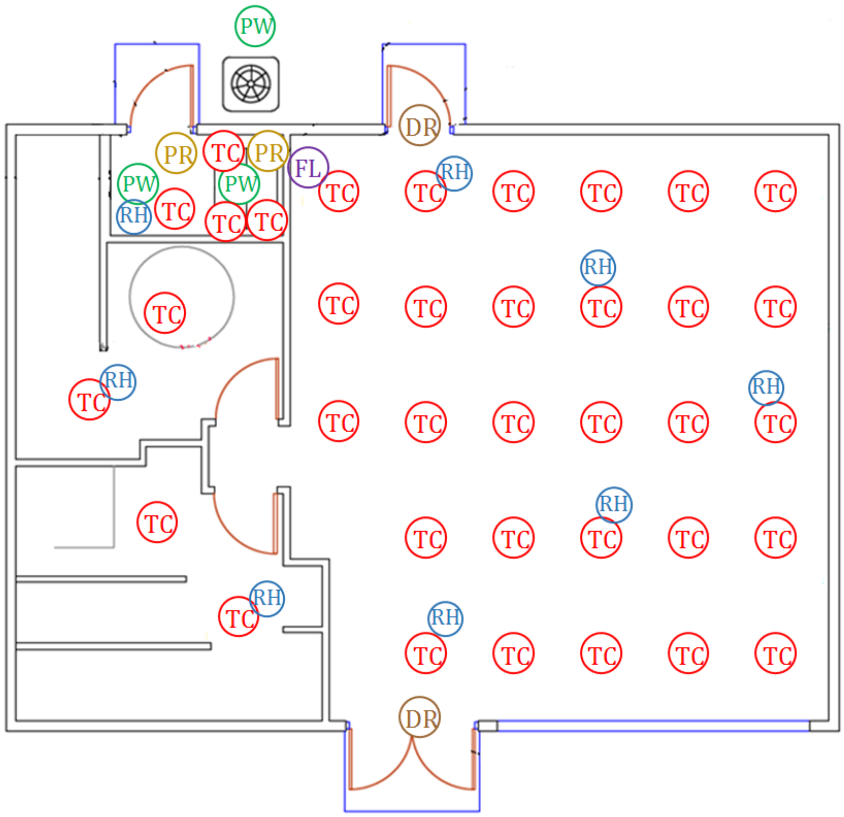


Figure 7: Demonstration Building Sensor Locations. Sensors Key – TC: Thermocouple; RH: Relative Humidity; DR: Door Open/Close; PW: Power; PR: Pressure; and FL: Flow

Red, blue, green, yellow, purple, and brown circles in Figure 7 indicate thermocouple, relative humidity and power transducer, pressure transducer, flow meter, and door sensor locations respectively. Twenty-nine thermocouples were installed in the main exercise room, two in the men's restroom, two in the women's restroom, one in the mechanical room, three in the air handler inside the mechanical room, and five in the attic space above the main exercise room. Attic space thermocouples were positioned above the exercise room's center and four corners. There were five relative humidity sensors in the main exercise room, one in each restroom, one in the mechanical room, and one in the air handler. Three power transducers measured air handler, condenser unit, and total gym power. Pressure transducers measured air handler pressure drop to get total system pressure drop for redundant flow rate calculations and to ensure that the technology did not cause adversely high pressure drops. Door sensors were used to track occupancy. The volumetric airflow rate was measured using a Nelson & Company duct mount station, which was installed in the duct directly above the air handler in the mechanical room ceiling.

Weather data was also collected at a location in close proximity to the building using a NovaLynx weather station. The weather station measured solar radiation, ambient temperature, and ambient relative humidity (Table 2).

Table 2. Weather Data Recorded By NovaLynx Station

Measurement Type	Quantity
Temperature	1
Relative Humidity	1
Wind Speed	1
Wind Direction	1
Barometric Pressure	1
Rain Gauge	1
Solar Radiation	1

The sensors and weather station were connected to a National Instruments Compact RIO (cRIO) 9014 industrial controller along with a cRIO 9116 eight-slot chassis. The chassis had three NI 9213 thermocouple input modules, four NI 9203 current analogue input modules for power, humidity, weather station connections, and one NI 9201 voltage input module for door sensors.

Ethernet connected the cRIO controller to a Dell OptiPlex 960 desktop computer that runs National Instrument's LabVIEW Developer Suite 2011 software with Real Time option. During demonstration, data collected at a sampling frequency of 1Herts (Hz) and digitally written to Logical Volume Manager (LVM) files by LabVIEW. Retrieving files and monitoring the system remotely was accomplished using a Raven XE modem, Verizon Mobile Broadband service, and Window's Remote Desktop.

5.2.2 Key Baseline Results

In addition to requiring baseline data for determining energy savings, this data was also necessary for designing the technology. In particular, the building heat loads and radiation patterns were needed for sizing and placing heat exchangers.

Daily building heat loads may be determined by summing heat removed by the ECU system, Q. This in turn may be determined from the evaporator coil temperature drop and the air mass flow rate as:

$$Q = \dot{m}C_p(T_{in} - T_{out})$$ **Equation 1**

Temperatures before and after the evaporator coil (T_{in}, T_{out}) were measured using thermocouples inside the air handler. $\dot{m}$ was determined using the total volumetric flow rate and assuming constant air density. Air specific heat, C_p, was taken to be constant.

Figure 8 shows Q (blue) and ambient temperature (yellow) for a typical day. Heat infiltration rate (red) was estimated by hourly averaging Q and inverting its sign. The area under this curve represents energy added to the building during that time in kJ. For the day examined, the largest amount of energy added to the building while the condenser unit was off, was 3,233 kJ.

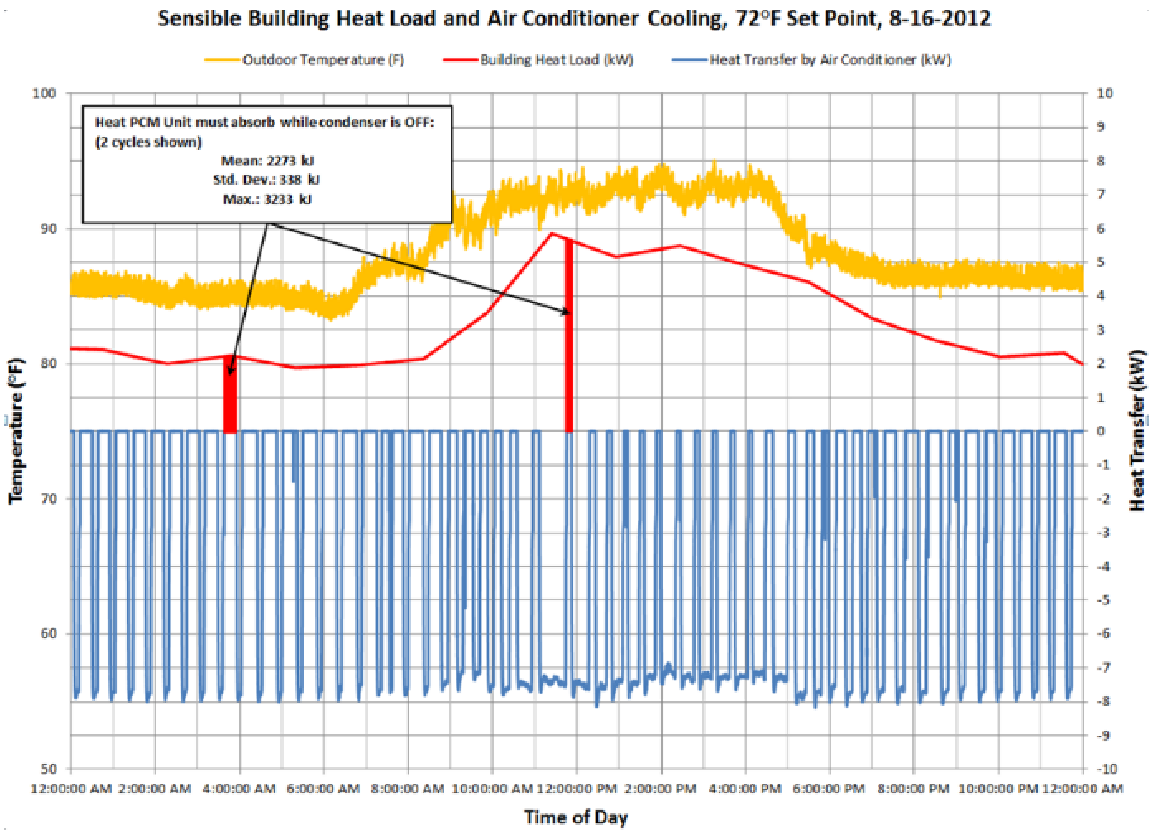


Figure 8: Heat Transfer In and Out of the Building, 8-16-2012

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 PCM-filled Ceiling Coils Installation

PCM-filled coils were selected for the continuous operation and installed under the ceiling air registers. The high heat transfer design of the coils was proven in pre-demonstration testing to allow the PCM to change phase with each air conditioning cycle. The ECU's evaporator fan consumed too much energy to allow it to run continuously. For this reason, the coils were suspended directly beneath the 11 air registers in the drop ceiling, allowing for natural convection cooling when the air handler's fan was off.

The 24" x 24" coils (Figure 9) was designed to fully cover the ceiling registers. Each coil holds approximately 2.9kg of PCM, for a heat storage capacity of 550kJ per coil, sufficient to absorb the building load between air conditioning cycles (the period where the ECU is disengaged).

Figure 9: Ceiling Coil before Installation

The coils were mounted flush with the existing drop ceiling and sealed with a gasket to ensure that all air exiting the ceiling registers passed through the coils. The 40-pound (when filled) coils were suspended from ceiling joists in the attic to support the weight. No changes were made to the building's existing duct system to accommodate the ceiling coils. However, operational changes (described later) were made to the air conditioning unit's control system.

5.3.2 Large PCM-filled Coil for Peak Load Shaving

The other promising technology that emerged from pre-demonstration testing was PLS using a large PCM-filled coil (Figure 10). The large coil is a thermal storage module capable of maintaining the demonstration building at the desired set temperature for several hours. The custom coil, manufactured by Diversified Heat Transfer, had a 48" x 48" face area. PCM was pumped into the 32 rows of 5/8" copper tubing to attain a fill volume of 180 liters, which equates to 28,500 kJ of latent heat storage capacity. Fin spacing was 8 fins per inch.

Figure 10. Large PCM-Filled Coil Prior to Installation at the Demonstration Site

The large PCM coil was designed to be solidified by the ECU during off-peak hours so that it could be used to maintain the desired room set temperature for several hours during the peak period. This mode of operation avoids peak hour cost of electricity by transferring compressor activity to off-peak hours.

To simplify installation, the coil was placed on the floor in the exercise room along the north wall, positioned to avoid blocking exits in accordance with fire codes. A new branch of duct was constructed to integrate the large coil into the existing ECU system. Another branch to allow air to return to the air handler for closed loop regeneration. Four automatic airflow dampers controlled by a National Instruments LabView program were located in the new duct to control the use of the large coil.

Figure 11 is the three dimensional drawing of the demonstration building duct with the new branches added. AAD1 to AAD4 are the four automatic airflow dampers that dictated the pathway of air flow.

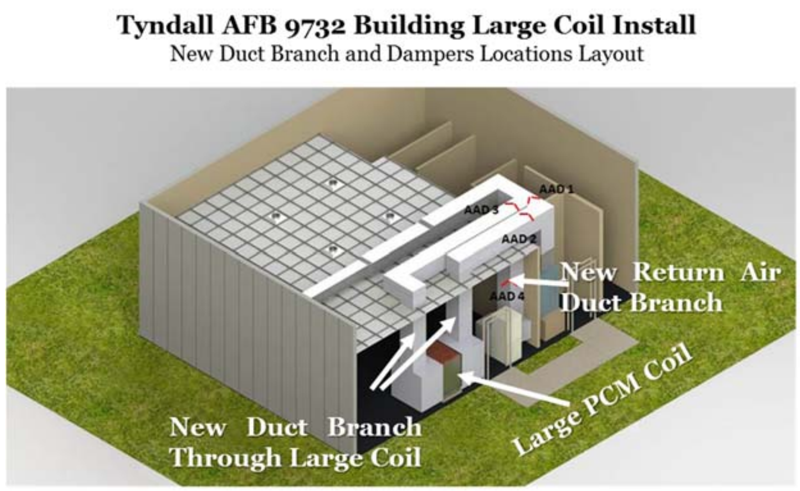


Figure 11. New Duct System after Integrating the Large PCM-Filled Coil

The existing duct in Building 9732 was modified to integrate the large PCM-filled coil. The added duct branch started above the mechanical room where the existing duct made its first 90° bend. From there, the duct went down into the exercise room through the drop ceiling and fed through the large coil before going back up through drop ceiling and reattaching to the existing duct.

5.3.3 Instrumentation and Controls

A National Instruments LabVIEW program was used to control the existing ECU's condenser unit and air handler fan; dampers routing air through the ductwork via control relays were, in turn, connected to these components.

5.4 SAMPLING PROTOCOL

5.4.1 Additional Sampling for Tech Demonstration

Building and weather related sensors used during demonstration were the same as those described in Section 5.2.1. Additional sensors were located inside PCM modules to gain insight on the behavior of the PCM. These additional sensor readings were recorded by LabView in a separate LVM file at a sampling frequency of 1Hz.

Three ceiling coils in the exercise room were instrumented, Figure 12. In these ceiling coils, inlet and exit air temperatures and PCM temperatures inside the first and last tube rows were measured using thermocouples, Figure 13.

Figure 12. Instrumented Ceiling Coil Locations in the Demonstration Building

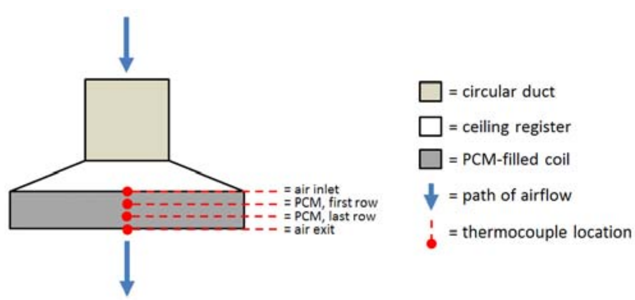


Figure 13. PCM-filled Ceiling Coil Thermocouple Locations

Thermocouples in the PLS coil measured air temperatures at the coil's inlet and exit, and PCM temperatures at three locations in the first and last row tube rows (Figure 14). PCM probes were inserted into copper tubes to a depth that measured PCM temperature at the airflow's center. Table 3 summarizes the additional sensors that were installed for the demonstration.

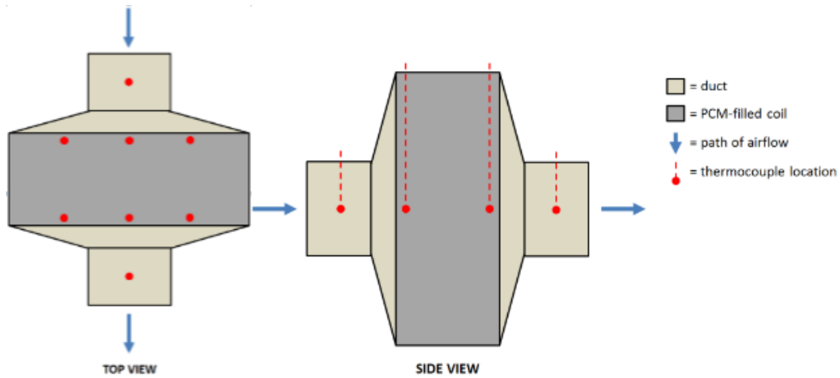


Figure 14. Peak Load Shaving Coil Thermocouple Locations

Table 3. Sensors Added For the Demonstration

Location	Type K Thermocouple	Air flow
Peak Load Shaving Coil	8	0
Ceiling Coils	12	0
Duct	0	1

5.4.2 Quality Assurance

Quality assurance during sampling was provided in several ways. For physical measurements, the dense sensor layout ensured that if a sensor failed, there was another measurement in close proximity. For data, LabVIEW recorded two files each day for redundancy. To improve the quality of collected data and eliminate noise, ARA used LabVIEW's moving average function to smooth them.

5.5 OPERATIONAL TESTING

5.5.1 LabVIEW Controls

Testing the PCM technologies required control over the ECU's condenser unit, air handler fan, and automatic airflow dampers. Control was achieved using a LabVIEW program that operated relays connected to these components. This program identified when each technology was used and their operational schemes, which are discussed in more detail in the following two subsections.

Figure 15 shows a screenshot of the LabVIEW Virtual Instrument (VI) user interface for the program that monitored and controlled the two PCM technologies in the demonstration. Ceiling coil and PLS coil temperatures are shown on left and right respectively. ECU operation and damper positions are shown in the center; green lights indicate when LabVIEW is engaging components. Gauges on the bottom show air handler and condenser unit power usage Airflow measured by a duct mount station, and current room temperature measured next to the thermostat. The VI includes several user specified parameters to make small adjustments to the PCM technology's operation.

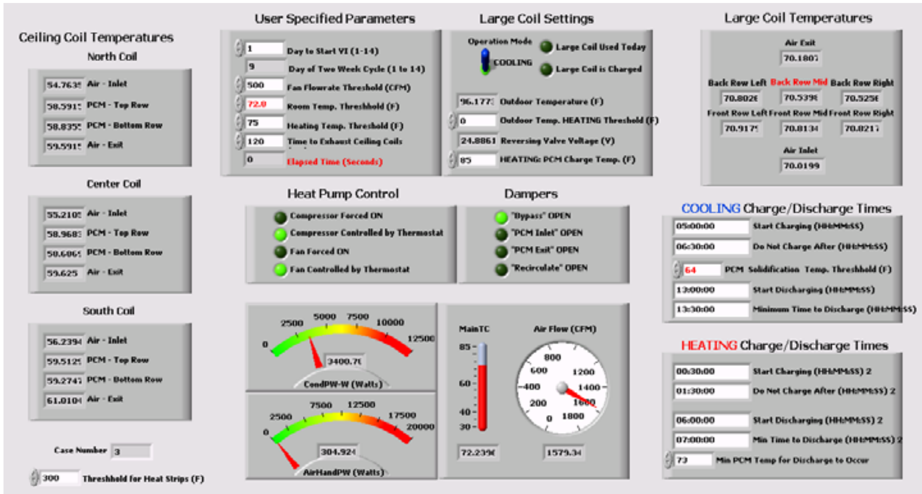


Figure 15. Screenshot of LabVIEW Virtual Instrument (VI)

5.5.2 PCM-filled Ceiling Coils Testing

Normally, the fan and condenser unit run simultaneously to cool the room. When the room temperature reaches the thermostat set point, the condenser unit is turned off and the air handler fan runs for an additional 90 seconds to take advantage of the still-cold evaporator coil.

Normal air conditioning operation was slightly modified to optimize ceiling coils use. Originally, the plan was to run the air handler fan continuously so PCM could benefit from forced convection during both freezing and melting. Forced convection greatly enhances heat transfer to and from PCM and expedites phase change. However, pre-demonstration testing exhibited continuous fan usage consumed significantly over the entire day. Therefore, the air conditioning system operated as normal, but the fan was forced to run for 2 minutes each cycle prior to the condenser unit engaging. This operation allows PCM to benefit from forced convection while absorbing heat from the room but uses significantly less energy than if the fan ran continuously. Additionally, ceiling coils can still cool the room by natural convection while the fan is off.

To implement this operation, communication between the thermostat and condenser unit was routed through the LabVIEW controller. This controller then adjusted normal air conditioning operation resulting in the following pattern each cycle:

1. Room temperature exceeds thermostat cooling set temperature. Thermostat turns fan on (Relay 1, Figure 16, closed) and attempts to turn on condenser unit. Condenser unit power is blocked by LabVIEW controlled relay (Relay 2, Figure 16, open).
2. Measured fan is on when measured power exceeds 150Watt. LabVIEW takes fan to be on and starts a two-minute timer.
3. Two-minutes elapse and LabVIEW controller closes relay (Relay 2, Figure 16) allowing thermostat to power condenser unit.

4. LabVIEW waits for condenser unit to turn off at the end of a cooling cycle and then opens the relay (Relay 2, Figure 16). The thermostat cannot turn it on in the next cycle. LabVIEW determines condenser unit is off when measured condenser unit power < 500W.

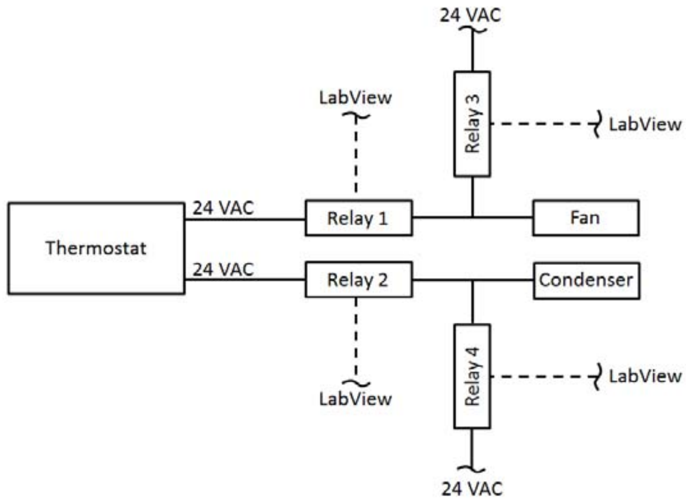


Figure 16. Schematic of LabVIEW/Thermostat Connections

While ceiling coils installation was completed on September 9, 2013, testing using the above 4-step sequence began on November 1, 2013, following PLS coil installation. From this point forward during the demonstration, 'normal air conditioning operation' refers to the 4-step sequence listed above. Ceiling coil testing took place every day the PLS coil was not used. Testing was completed on November 30, 2014.

5.5.3 PLS Testing

Closed Loop Freezing

To ensure PCM was fully frozen throughout the PLS coil, a dedicated freezing period in the morning was added, where the ECU supplied cold air to the PCM coil in a closed loop. The control scheme for this test consisted of three operation modes as follows:

1. *Normal Operation* from 12:00 AM until 5:00 AM
2. *Closed Loop Regeneration* from 5:00 AM until the PCM is fully frozen. Fan and condenser unit are forced on (Relays 3 and 4 closed, relays 1 and 2 open Figure 16) LabVIEW's criteria for complete freezing was measured PCM temperature in last tube row ≤ 63.5°F (determined experimentally).
3. *Normal Operation* from the end of step 2) until 1:00 PM
4. *PLS* coil continuously absorbs room heat until it is depleted or unable to keep the room cool. LabVIEW forces air handler fan on (Relay 3 closed, Relays 1 and 4 open Figure 16). This phase ends when the room thermostat calls for cooling (Relay 2 closed, condenser unit power monitored). This means that even if there was unused PCM capacity, the PLS coil was not absorbing room heat load quickly enough to maintain the room at set temperature. At this point, even if the large PCM coil had unused capacity, use of the PLS coil was discontinued until the next test day.

5. *Normal Operation* for the remainder of the day.

Switching between these modes of operation was accomplished through damper changes and dictated use of air conditioning components governed by the LabVIEW program. Figure 17 shows damper configurations and airflow paths for the three modes.

Closed loop freezing has several benefits that increase the heat transfer rate from the PCM module to the air and reduce solidification time. These factors are discussed as they pertain to the heat transfer rate, Equation 2:

$$\dot{q} = \dot{m} * C_p * (T_{INLET} - T_{EXIT}) \quad \textbf{Equation 2}$$

Where:

$\dot{q}$ = heat transfer rate (kW) at which heat is transferred to the air as it passes through the PCM module. If the heat transfer rate is increased, the solidification time will decrease.

C_p = specific heat of air (kJ/kg°K),

$\dot{m}$ = mass flow rate of air (kg/s),

$(T_{INLET} - T_{EXIT})$ = The temperature difference (°K) between the air at the inlet and exit of the PCM module. The closed loop configuration increases $(T_{INLET} - T_{EXIT})$, increasing $\dot{q}$ and decreasing solidification time.

The PLS coil was installed on November 1, 2013. Since it was designed for cooling with PLS, limited testing was done in winter. Most PLS coil testing was from March 2014 to July 2014.

Open Loop Regeneration

Open loop regeneration was tested in an attempt to reduce system complexity. In this mode of operation, the air path was constant (Figure 17, bottom). LabVIEW's control scheme for this test was:

1. Normal air conditioning operation from 12:00 AM until 1:00 PM. Air is routed through PLS coil
2. Condenser unit is prevented from engaging (Relay 2 and 4, Figure 16, open), fan is forced on (Relay 3, Figure 16, closed). PLS coil absorbs heat from the room until it is depleted or unable to keep the room cool (Relay 2, Figure 16, closed and condenser unit power monitored)
3. Normal air conditioning operation for the remainder of the day

In this 3-step control scheme, PCM regenerated throughout the day. When the ECU cools the room, cold air flows through the PLS coil and the PCM partially freezes. Once the room cools, the fan runs for 2 minutes after the condenser unit is off. Thus, PCM experiences significantly more forced convection during freezing than melting. At 1:00 PM, the fan is turned on and PCM absorbs room heat while it melts. The condenser unit stays off until the PCM capacity is depleted or until the thermostat calls for air conditioning. Normal air conditioning operation is then resumed and PCM begins to gradually freeze again until it is used again at 1:00 PM the following day.

The only control necessary for this control is forcing the fan to run while the PLS coil is used to condition the room during peak hours.

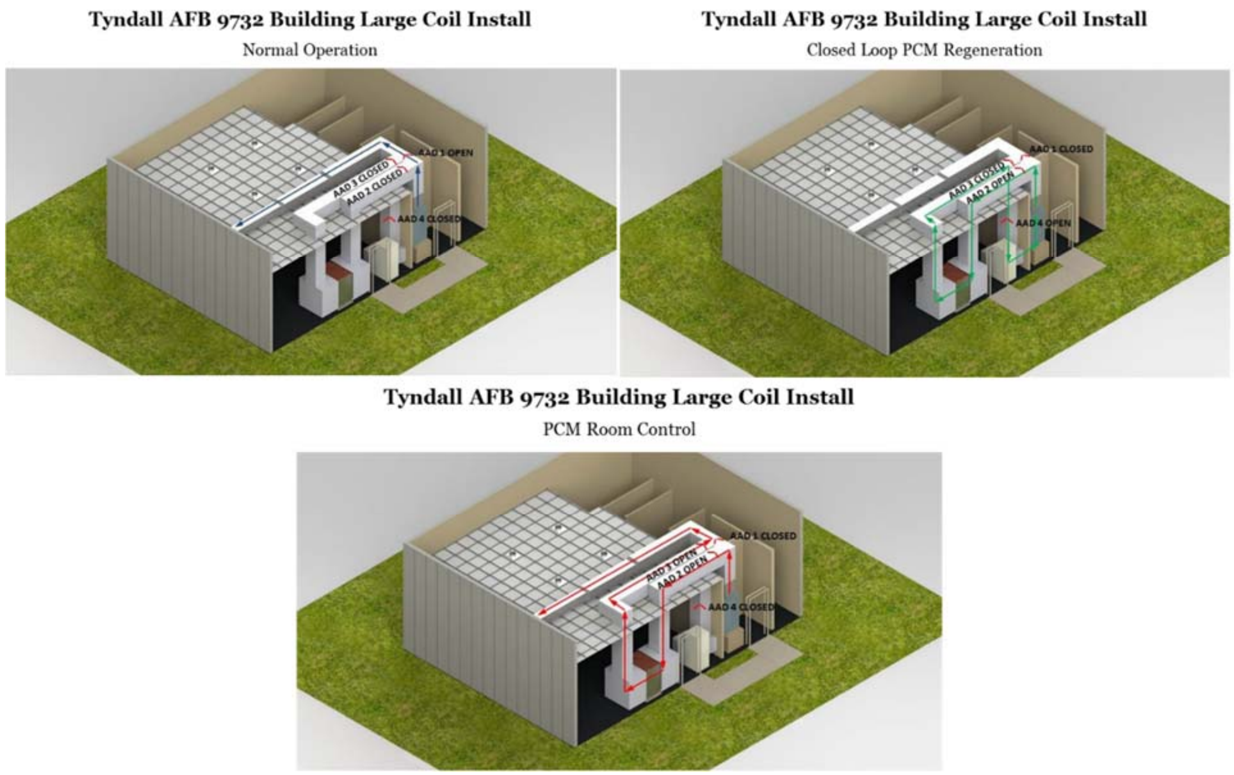


Figure 17. Diagram Showing the Three Modes of Operation Using the Large PCM-Filled Coil for PLS.

6.0 PERFORMANCE ASSESSMENT

6.1 WEATHER NORMALIZATION

6.1.1 Weather Normalization Model

The statistical method outlined by Avina [2] is designed to calculate actual energy savings for a retrofit and taking into account the changes in outdoor temperatures before and after the retrofit. For example, the year selected for baseline data could have been cooler or warmer than the year selected for the technology demonstration. Direct comparison of energy consumption between the two years will yield false conclusions. Therefore, the weather normalization method compares how much energy would have been consumed without the retrofit to how much energy was consumed with the retrofit in place; therefore, savings are given as:

Savings = Energy would be consumed without PCM – Energy consumed with PCM

The weather normalization approach described by Avina [2] uses one independent variable, the Cooling Degree Days (CDD). To calculate CDD, a reference temperature, called building Balance Point (BP), is needed. The CDD is the difference between a BP and the outdoor average temperature. Since each building has its own (BP) of cooling, using baseline data, the cooling BP can be calculated and used to determine the CDD. Performing multiple regression analysis, using collected baseline data for ECU energy consumption as a dependent variable. The cooling-degree days per day as the independent variable and the demonstration building energy consumption behavior can be expressed as:

$$E_{Hd} = a + b \times CDD_d \qquad \textbf{Equation 3}$$

Where E_{Hd} is the energy consumption, a and b are regression coefficients, and CDD_d is cooling degree day, which is found for each day as:

$$CDD_d = \frac{1}{N}\sum_{i=1}^{N}\left\{\left(\frac{(T_{hi} - T_{lo})}{2}\right)_i - T_{BP}\right\} \; ; \quad \frac{(T_{hi} - T_{lo})}{2} - T_{BP} > 0 \qquad \textbf{Equation 4}$$

Where:

CDD_d = Cooling Degree Days per day

T_{hi} = Daily high temperature

T_{lo} = Daily low temperature

T_{BP} = Cooling Balance Point temperature

N = Number of averaging days

6.2 PCM-FILLED CEILING COILS RESULTS

6.2.1 Model Parameters

The coefficients in equation 3 are given in Table 4 for baseline and demonstration data.

Table 4. Baseline and Demonstration Model Parameters

	a	b	R^2
Baseline	4.5032	1.4966	0.90
Demonstration	2.5583	1.272	0.88

6.2.2 PCM-filled Ceiling Coils Energy Savings

To compare the energy consumption of the retrofit ECU system to the original system, the baseline models were evaluated at the same weather conditions for the demo case data. The change in energy consumption is then calculated as:

$$\Delta E = (E_B - E_D) / E_B$$

Equation 5

Table 5. Retrofit System Percentage Energy Savings

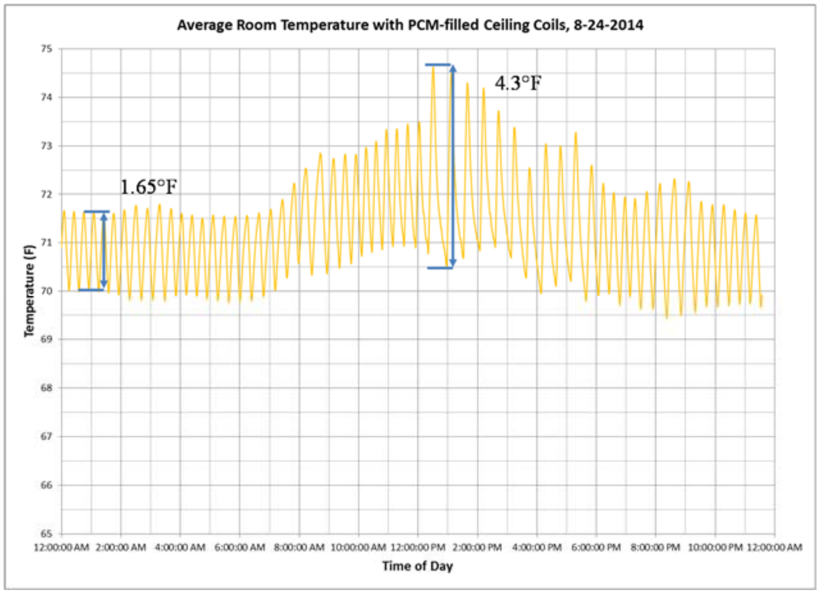
T_{BP} (°F)	1 Day	4 Days	7 Days	Average Energy Savings
64	18.7519	18.7118	19.3557	18.9398 ± 0.7448

Where E_D is the demo case total energy consumption and E_B is the predicted baseline energy consumption over the same time period and weather conditions. Table 5 summarizes the percentage PCM retrofit energy savings for the linear and nonlinear models at 64°F T_{BP}. The average energy savings for each model are reported within the 90% confidence interval.

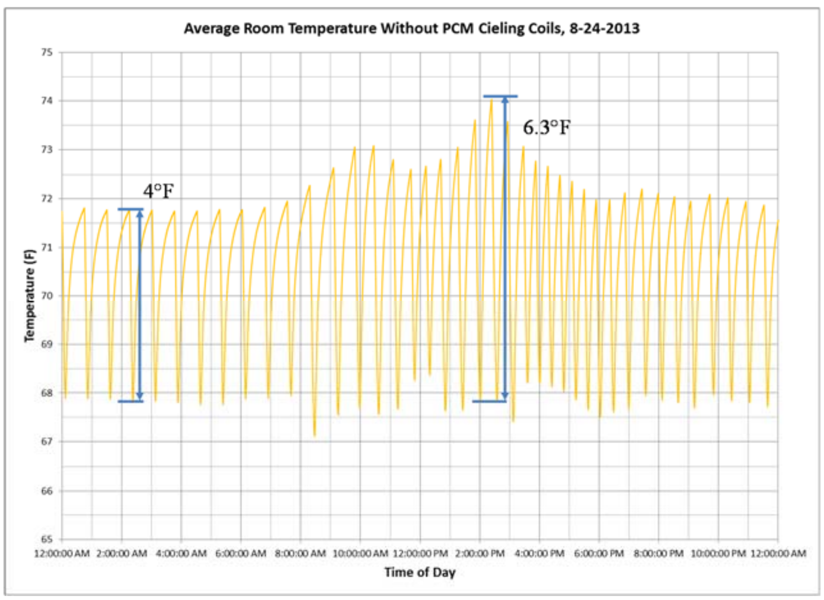
6.2.3 Room Temperature Regulation

Because latent heat is absorbed and released by PCM, the average room temperature fluctuated in a tapered band when compared to the building configuration without the HECU system. Figure 33a and Figure 33b show the average room temperature with and without the PCM ceiling coils in place. The average was taken for 25 thermocouples hung 9 feet above floor (3 feet below ceiling). The maximum room average temperature difference was 4.3°F for the PCM ceiling coils in place while it was 6.3°F for the baseline case. Also the minimum room average temperature difference was 1.65°F for the PCM ceiling coils in place while it was 4°F for the baseline case.

Narrow changes in temperature makes the room more comfortable than large temperature swings. Reducing the presence of low room temperatures points lead to the reduction of heat gained from the environment to the building interior. Figure 18 shows the lower room temperature ranged between 69.8°F and 70.5°F, about 2 degrees higher than the baseline case.



(a)



(b)

Figure 18. Air Temperature Supplied to the Room During Demonstration (a) and During Baseline Testing (b).

Air flow rate varies between the 11 registers, as the original ducts were designed to supply more air to the south side of the building, which has windows. The highest flow rates are delivered to registers 3, 6, and 9 near the south wall. All other registers in the exercise room experience slightly lower flow rates, and the registers in the restrooms experience the lowest flow rates. Registers 6, 5, and 4 in the exercise room were instrumented with thermocouples to analyze PCM behavior in the ceiling coils at low, medium, and high air flow rates on both hot and mild days.

6.3 LARGE PCM-FILLED COIL FOR PLS

As stated before, the PLS coil was selected to cover only 2 hours of the 6 hours period due to the size of the PLS coil and the space availability in the demonstration site.

6.3.1 Closed Loop Regeneration

Figure 19 shows room temperature, average indoor relative humidity on the left vertical axis, electrical power usage of the condenser unit, and air handler on the right vertical axis. Based on the data in Figure 19, the PLS coil was able to maintain room temperature for about two hours from a one-hour charge. Specifically, the unit was regenerated from 5:00–6:00 AM (period of constant condenser unit and fan operation) while the condenser unit remained unused from 1:00–3:00 PM (condenser unit power is zero) while the room temperature was maintained at its set point. Since the condenser unit power usage is highly correlated with outdoor temperatures, this shift in condenser unit usage time resulted in energy savings. Further, higher electrical rates during peak hours are avoided. Continuously running the fan during PLS coil melting lead to an increase in indoor average relative humidity.

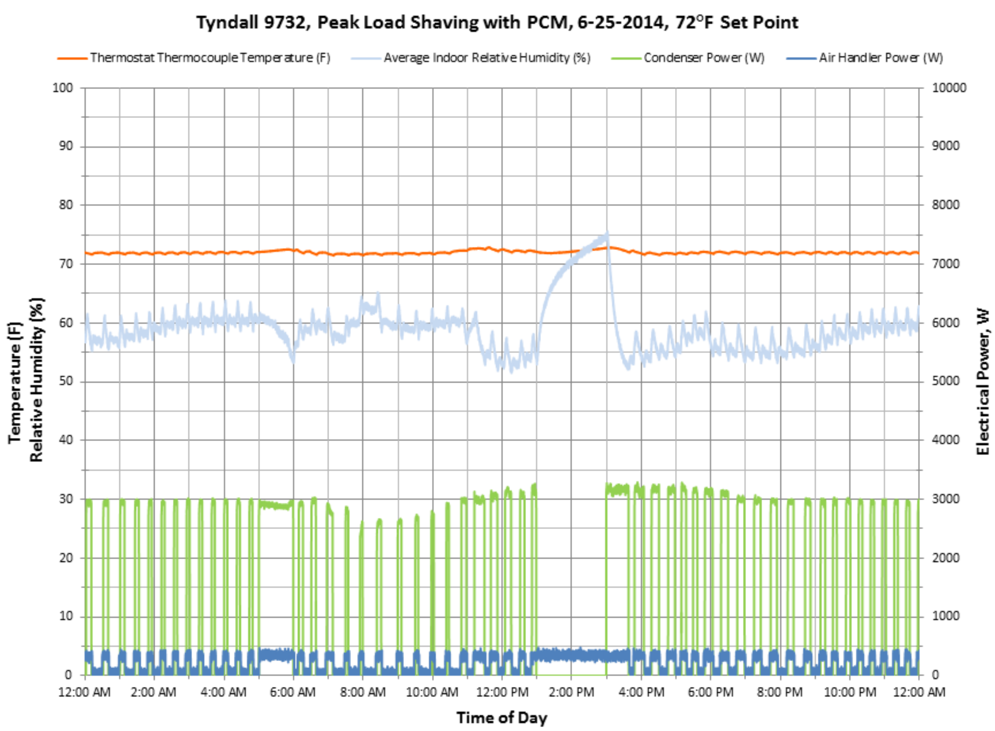


Figure 19. Peak Load Shaving Using Closed Loop Regeneration

6.3.2 Open Loop Regeneration

Closed loop regeneration was used as a tool to expedite PCM solidification. Details on the benefits of this operation as they pertain to heat transfer are discussed in the Final Report.

6.4 PERFORMANCE BASED CONCLUSIONS AND RECOMMENDATIONS

6.4.1 PCM-filled Ceiling Coils Recommendations

A limitation of the PCM-filled ceiling coil application is the low flow rate at the registers. Ideally, the PCM would change phase completely in each cycle, melting to absorb heat from the room, and regenerated by the condenser unit. There are two possibilities for improving the flow rate to registers. First, is to replace the air handler fan with one that provides a higher flow rate. This approach has its own limitation, since the increase in flow rate adversely affects the energy use by the HECU. Secondly is to redesign the PCM module for a better heat transfer rate.

6.4.2 PLS Recommendations

In an ideal case, PCM would have melted in six hours, eliminating condenser unit activity for the entire peak period. However, three times the PCM mass would be required to achieve this. To adjust for the additional PCM mass, the closed loop's freezing period should also be increased to 1.5 hours. Using these changes, an ideal day can be constructed from existing demonstration data using the following modifications:

1. The charging period should be extended to 1.5 hours, where the air handler and condenser unit loads are modified.
2. The 6-hour peak-load period should be modified so that the fan runs continuously and the condenser unit does not run at all.
3. The hour immediately following the PCM melting period should be modified as a catch-up hour, where the ECU returns the relative humidity in the room to normal levels. During this hour, the fan and condenser unit run continuously. This is a conservative adjustment since the relative humidity in the room was returned to normal in 30 minutes during the demonstration.
4. The hour immediately following the regeneration period should be conservatively modified as a catch-up hour for room temperature, since the gym is not conditioned during closed loop regeneration. This adjustment can be made by adding the energy to the ECU unit which would have used to condition the building during the regeneration (according to the baseline) to the hour immediately after charging.

6.4.3 Recommendations for Both Technologies

As test data show, both technologies have shown a level of success in reducing energy consumption and increased energy cost savings as applied to the demonstration site. Several factors, if applied, can maximize the energy savings, energy cost savings, and reduce the PCM modules size and weight. Applying these factors to the design and mode of operation of the HECU can result in efficient and compact commercialized technologies. These factors include:

1. **PCM Selection –** PCMs with higher thermal storage capacity can significantly reduce the size and weight of the PCM module. For this application and temperature range, salt hydrate PCMs and organic PCMs both have advantages and disadvantages.

The former has higher heat storage but can be corrosive; and the latter has lower heat storage, but better compatibility with metals. As PCM technology improves, there are candidates in both categories that offer improved performance beyond the PCM used in this study.

- For this application, it is useful to compare PCMs based on energy density (MJ/m^3), a metric that accounts for both the latent heat (kJ/kg) and PCM density (kg/m^3). The organic PCM used in this study has an energy density of approximately 169 MJ/m^3. Higher energy density organic PCMs have been developed, such as Rubitherm's RT18HC, which has approximately 193 MJ/m^3, potentially reducing the PCM heat exchanger size and weight by 14%.
- Salt hydrate PCMs, such as PlusIce® S15 have energy densities up to 250 MJ/m^3, allowing for almost a *40% reduction* in heat exchanger size and weight. While salt hydrates are generally less compatible with metals than organic PCMs, methods exist to minimize corrosion. Heat exchangers can be manufactured using more corrosion resistant alloys. For example, AL 3005LL is a "long life" aluminum alloy with improved corrosion resistance. In addition, protective coatings can be used such as Heresite P413, a coating used by heat exchanger manufacturers to protect ECU equipment from salt corrosion.
- Using a PCM with higher thermal storage capacity, with latent heat higher than 207kJ/kg, the one used in this study. Several candidates have recently been identified. Hexadecane, has a density of 0.773 kg/L at 20°C and latent heat of 236 kJ/kg. Hydrophilic Organic PCM has a density of 0.896 kg/L at 15°C and latent heat of 320 kJ/kg. The impact of using Hydrophilic Organic PCM in place of the PT18 or the Q18 PCMs, the size and weight of the PCM module can be reduced by 45%.

2. **PCM Module Design –** Using a bar-and-plate heat exchangers design will reduce the PCM module volume by 20% if six inches wide and half inch thick is used instead of the half inch tube. With fins on the inside of the tube and in between tubes. This approach will make the PCM module smaller in size, lighter in weight, and with high heat transfer coefficient.
3. **Mode of Operation –** Applying a different mode of operation to take advantage of PCM high thermal storage capacity. In this approach the PCM modules are the main system component, where the ECU supplements the PCM modules and the thermostat would trigger the air handler fan only, allowing the PCM coils to absorb heat from the room. Once the PCM is fully melted as indicated by PCM temperature, the condenser unit is activated until the PCM is fully regenerated. In this mode of operation, PCM temperature is always close to the phase change temperature, and the high latent heat capacity of PCM is better used.

In applications where peak load period electric cost is different from the rest of the day and the facilities are used 24/7, both HECU technologies can be combined into one system to take advantage of the PLS cost savings and rest of the day energy savings. This approach will maximize the benefits of HECU technology.

7.0 COST ASSESSMENT

7.1 COST MODEL

The field demonstration performance data was used in estimating the life cycle operation costs of the full scale commercial PCM ECU. The technology demonstration cost models for the two configurations are discussed below.

7.1.1 PCM-filled Ceiling Coils

The primary differences between the ceiling coils used during the demonstration and those proposed for mass-production is the cost of the coils themselves and the cost of the PCM. The upper section of Table 6 contains "as-demonstrated" costs for the coils used during the demonstration, while the lower section details anticipated costs for mass-produced modules. The reason for presenting the costs for both is to more accurately represent costs and benefits of future applications of this technology. The Final Technical Report includes discussion of each cost element, but this summary report is limited to the tables.

Table 6. PCM-filled Ceiling Coil Cost Model

Ceiling Coils		
Cost Element	**Data Tracked During the Demonstration**	**Estimated Costs**
1. Hardware Capital Costs		
1a. Heat Exchanger Units	Prototype cost 11 @ $692.68 per	$ 7,619
1b. Hardware to Build	No additional hardware to build	$ -
1c. Labor to Build	Assembly of prototypes (filling with PCM)	$ 720
1d. Phase Change Material	Quartek Q18: 6.37 lbs per coil X 11 Coils @ $3.50 per lb	$ 245
2. Installation Costs		
2a. Hardware to Install	Tubing, eye bolts, wire cable, etc.	$ 1,093
2b. Labor to Install	Labor required to install (2 people, 2 Days)	$ 2,880
3. Operating Costs		
3a. Facility Operational Costs	Annual estimated reduction in energy required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$ (79)
3b. Maintenance	Frequency of required maintenance	None During Demo
	Labor and material per maintenance action	$ -
3c. Hardware Lifetime	Virtually indefinite. There are no moving parts and no degradation of PCM	30 Years
3d. Operator Training	None required. Function is transparent to building occupants	$ -
3e. Residual Value	No residual value was estimated for the proptotypes	$ -
Cost Element	**Projected Costs for Mass-Produced Units**	**Estimated Costs**
1. Hardware Capital Costs		
1a. Heat Exchanger Units	Mass-produced units 11 @ $245 per	$ 2,695
1b. Hardware to Build	(included in cost of mass-produced units)	$ -
1c. Labor to Build	(included in cost of mass-produced units)	$ -
1d. Phase Change Material	PCM 11, PCM-Expert.com 6.37 lbs per coil X 11 Coils @ $0.50 per lb	$ 35
2. Installation Costs		
2a. Hardware to Install	(included in cost of mass-produced units)	$ -
2b. Labor to Install	Labor required to install (2 people, 1 Day)	$ 1,440
3. Operating Costs		
3a. Facility Operational Costs	Annual energy cost reduction required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$ (79)
3b. Maintenance	Frequency of required maintenance	5-Year (Cleaning)
	Labor and material per maintenance action	$ 225
3c. Hardware Lifetime	Virtually indefinite. There are no moving parts and no degradation of PCM	30 Years
3d. Operator Training	None required. Function is transparent to building occupants	$ -
3e. Residual Value	Estimated scrap value of aluminum @ ~$0.90 per pound (11 coils at 30 lbs per)	$ 297

7.1.2 PLS

As cited in the executive summary, the PLS unit could only carry 2 hours of the 6-hour peak heat load, which was not sufficient to achieve the project's objectives. Extrapolated data for a unit sized to carry the entire peak load period is included in the Final Report.

Since the PLS unit installed for the demonstration only had enough capacity to cool the building for two hours of the six-hour peak load period (12:00–18:00), the upper section of the cost model (Table 7) details costs incurred during the technology demonstration, and the lower half of the table addresses estimated costs for a mass-produced PLS system appropriately sized to cool the building for the entire six-hour peak load period. The Final Technical Report includes discussion of each cost element, but this summary report is limited to the tables.

Table 7. Peak Load Shaving Unit Cost Model

Large Peak-Load Shaving Unit		
Cost Element	**Data Tracked During the Demonstration**	**Estimated Costs**
1. Hardware Capital Costs		
1a. Heat Exchanger	Prototype cost	$ 9,000
1b. Hardware to Build	Screws, duct board, controller, tape, etc.	$ 670
1c. Labor to Build	Assembly of prototype	$ 10,080
1d. Phase Change Materials	Quartek Q18: 298 lbs @ $3.50 per	$ 1,043
2. Installation Costs		
2a. Hardware to Install	Duct board, dampers, actuators, tape	$ 1,203
2b. Labor to Install	Labor required to install	$ 2,520
3. Operating Costs		
3a. Facility Operational Costs	Annual estimated reduction in energy required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$ (24)
3b. Maintenance	Frequency of required maintenance	None During Demo
	Labor and material per maintenance action	$ -
3c. Hardware Lifetime	Virtually indefinite, except for damper actuators	30 Years
3d. Operator Training	None required. Function is transparent to building occupants	$ -
3e. Residual Value	No residual value was estimated for the prototype	$ -
Cost Element	**Projected Costs for Mass-Produced Units**	**Estimated Costs**
1. Hardware Capital Costs		
1a. Heat Exchanger	Mass-produced unit (complete assembly)	$,352
1b. Hardware to Build	(included in cost of mass-produced unit)	$ -
1c. Labor to Build	(included in cost of mass-produced unit)	$ -
1d. Phase Change Material	PCM 11, PCM-Expert.com 896 lbs @ $0.50 per	$ 448
2. Installation Costs		
2a. Hardware to Install	(included in cost of mass-produced unit)	$ -
2b. Labor to Install	Labor required to install (2 people, 1 Day)	$ 1,440
3. Operating Costs		
3a. Facility Operational Costs	Annual energy cost reduction required vs. baseline data (based on estimated 165 days of beneficial PCM cooling days per year)	$ (71)
3b. Maintenance	Frequency of required maintenance	5-Year (Cleaning)
	Labor and material per maintenance action	$ 225
3c. Hardware Lifetime	Virtually indefinite, except for damper actuators	30 Years
3d. Operator Training	None required-function is transparent to building occupants	$ -
3e. Residual Value	Estimated scrap value of 1,000 -1,200 lbs of aluminum @ ~$0.90 per pound	$ 1,000

7.2 COST DRIVERS

7.2.1 PCM-filled Ceiling Coils

Low operating cost is an important cost driver for this PCM technology. The unit, after installation, operates passively with the ECU, does not need modifications to the existing air handler, and does not increase fan energy consumption. A single field technician with ECU training only requires minimal additional training to check and handle the operation of the PCM module.

7.2.2 PLS

The major cost driver for the implementation of the HECU technology will be the reduction of the peak energy consumption while reducing energy cost. Energy demand is not uniformly distributed and buildings' need for electricity to be concentrated in certain places at certain times. In the United States, the annual peak demand for electricity occurs on hot summer afternoons when air conditioning is needed to maintain comfort zone conditions. Generating the electricity to meet such spikes is extremely costly. By transferring peak load to off-peak hours, a building manager can avoid peak hour surcharges and reduce building energy cost without impacting building operation.

Table 8 provides an example of energy cost savings for the demonstration building located at Tyndall AFB from shifting Heating, Ventilation and air conditioning (HVAC) loads to off-peak hours. A Real Time Pricing system provided by Gulf Power Company is applied to the 26 June 2016 PLS demonstration day energy usage data to provide a one-day snapshot of PLS energy cost savings. The values in the "HVAC Energy Usage (kWh)" column of are the sums of peak and off-peak hours from 26 June 2014. Similarly, the "HVAC Energy Cost" column represents the sums of hourly time-of-use costs per kWh" for peak and off-peak periods of the same day. This data demonstrates that, although the PCM unit only managed two hours from the peak period, the PCM module can shave air conditioning energy cost by 6.20%.

Table 8. Peak Load Shaving Energy Cost Savings

	HVAC Energy Usage (kWh)	HVAC Energy Cost
Demonstration Data for 2 Hours Peak Load Shaving Using PCM (Values Extracted from Upper Half of Table 16)		
Peak Hours (12:00-18:00)	8.602	$1.116
Off-Peak hours	23.402	$1.759
Total	32.004	$2.88
Baseline Energy Prediction (Values Extracted from Lower Half of Table 17)		
Peak Hours (12:00-18:00)	11.094	$1.451
Off-Peak hours	21.386	$1.614
Total	32.481	$3.06
Cost Savings		
Actual Energy Cost Saving for 2-Hour Peak Shaving		6.20%

[Note: References to Tables 16 and 17 within Table 8 refer to tables in the Final Report]

Discussion included in Appendix B of the Final Report references extrapolated data for a system sized to manage an entire 6-hour peak period.

7.3 COST ANALYSIS AND COMPARISON

The Building Life-Cycle Cost (BLCC) analysis of the ceiling coils yielded a savings-to-investment ratio of 0.12 and -4.03% adjusted internal rate of return indicating the PCM-filled ceiling coils are not cost effective at this time in this specific application. However, data analysis in the Final Report demonstrated a 19.74% reduction in ECU energy usage—which, even if only for 165 days of the year—provides insight into the future viability of this technology.

The BLCC analysis of the PLS System confirmed that the PLS alternative is not cost effective at this time due to a SIR of 0.2 and Adjusted Internal Rate of Return of -2.36%. Data analysis found in Appendix B of the Final Report showed reductions of 4.78% in ECU energy consumption and 17.83% in the cost of energy used for ECU cooling at the Tyndall AFB demonstration site. While still not economically feasible at this time, ARA engineers believe the "tipping point" to making PLS technology more cost-effective is achievable through further design enhancements. Improved heat transfer efficiency, intelligent control systems to optimize time, duration of charging and discharging cycles. Scaling the technology to larger systems where these percentage reductions in ECU energy consumption and costs will have a greater impact and shorter payback periods.

Advances in PCM technology and manufacturing methods will enable smaller, lighter, and less expensive PLS units. Future performance enhancements through selection of PCM with higher energy density than the Quartek Q18, viability of the technology in locales with larger fluctuations in hourly electricity rates, and ambient temperature are included in Appendix B of the Final Report.

8.0 IMPLEMENTATION ISSUES

8.1 CEILING COILS

There are fewer options for ceiling coil installation, as installation location is dictated by the ceiling register locations in the facility. Building codes and ASHRAE standards should still be followed, but an additional safety concern with this technology is ensuring that the coils are properly supported since they are overhead. PCM-filled ceiling coils that cover a 2'x2' register, such as the ones used in the demonstration, weigh approximately 40 Pounds (lbs.) and are too heavy to be supported by a drop ceiling. Therefore, the support system should be installed in the attic space using ceiling joists. During installation, the support system should be inspected to make sure it is safe during severe weather, such as earthquakes, to avoid injury caused by the overhead coils.

8.2 PLS

The PLS PCM module can be installed using a process similar to installing an air handler. Installing the PCM module into new buildings is quite straightforward, as the building can be designed to allow sufficient space for the PCM module to sit next to the air handler in the mechanical room. For retrofits, however, the installation must be determined based on the specific facility. If there is not sufficient space in the mechanical room, the PCM module can be located in the attic space, outside on a concrete slab, on a rooftop, or on the floor in an unused room of the facility. Of these options, the attic space is the most convenient, since the duct is typically already in the attic space, which reduces the length of duct required for the PCM module, and minimizes pressure drop. In other locations, such as outside or on the roof, holes must be cut through walls to allow the duct to run to the PCM module and back inside.

Building codes and ASHRAE standards will serve as the main guidelines during the install and should be followed to ensure that the unit is properly supported while maintaining fire codes and airflow requirements. For the demonstration building, the ideally sized PCM module contains 980 lbs. of PCM in addition to the weight of the heat exchanger, bringing the total weight of the PCM module to approximately 1 ton. The footprint would be approximately 10 square feet, so the load per square foot is 220 lbs. Depending on the install location, the unit might require additional support. If the unit cannot be adequately supported using the existing structure, a stand can be constructed to support the unit.

The end-user wanted to make sure the unit was well supported and that installation did not interfere with any fire codes pertaining to building access. During the demonstration, ARA installed the unit on the floor in the exercise room, while adhering to fire codes. The unit was installed without blocking any doors or impeding exit in case of an emergency. The only other end-user concern was floor space. This is a valid concern, which is why the ideal location for the unit was determined to be in the attic space.

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9.0 REFERENCES

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APPENDIX A POINTS OF CONTACT

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