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Thermal Storage with Phase Change Materials— Shifts Loads, Saves Energy, Costs Less*

Jeffrey L. Ihnen, P.E.

ABSTRACT

Energy storage has been around since shortly after man harnessed fire. A pile or stack of wood is stored energy waiting to be used. More recently, for hundreds of years, ice was harvested from ponds and lakes for preserving foods through the summer and shoulder seasons. Electricity and refrigeration eliminated the need for ice harvesting and storage.

Coming full circle, a nascent industry is emerging to store the benefits of electricity, consuming electricity to "charge" storage materials when electricity prices are low, and discharging the storage materials when electricity prices are high. The storage materials of choice are phase change materials (PCMs). Phase change materials have a great capacity to release and absorb heat at a wide range of temperatures, from frozen food warehouses at minus 20°F to occupied room temperatures. These wide-ranging phase change materials offer an enormous opportunity to shift electrical loads in "grid-interactive, efficient buildings" (GEBs) in which PCMs do the same thing as batteries or other storage technologies, but at a small fraction of the cost. These technologies are in the pre-emerging-technology phase of market adoption. Still the author/presenter believes they will become widely accepted due to their flexibility, cost-effectiveness, simplicity, zero moving parts, longevity, and non-invasiveness.

CONCEPTS

Thermal energy storage using ice produced by mechanical refrigeration (chillers) has been in use for decades. More recently, innovative

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*Based on a paper presented at the 2020 Virtual AEE World Energy Conference.

companies are developing a wide range of PCMs to store energy for both heating and cooling applications.

The Beginnings—Ice Storage

Initially, thermal energy storage was used to shift electric loads from peak periods, typically middle to late afternoon, weekdays, when energy and electrical demand charges are high, to off-peak periods at night when prices are low. The primary driver was dollar-cost savings. In most cases, energy consumption increases as chiller efficiencies decrease because of the greater temperature lift required during ice-making. Other energy impactors included additional pumping energy because of a more viscous solution of chilled water and antifreeze and less favorable heat transfer characteristics of the antifreeze.

Cooling loads with ice systems can be shifted entirely off peak, using larger storage systems, or systems can be designed to augment mechanical cooling during peak periods. This latter design concept helps to minimize cost by using the ice-storage system to downsize chilled water plants that would operate at a more level load around the clock, enabling peak loads to be met during the day with both ice and the chiller.

Newer Developments

A variety of materials and solutions that change phase over a range of temperatures introduces a new series of benefits versus pumped storage systems.

First, PCMs can be used in passive ways that require no additional system energy, including minimal added temperature lift described above. This is made possible because PCMs with melting points very close to load temperatures can be used, and therefore, cooling systems see a negligible difference in operating parameters. In many, if not most cases, efficiency increases because the PCM can be charged overnight when cooling conditions are more favorable or even “free” with economizer cooling. Second, there is no added pumping energy or degradation of fluid heat transfer with the use of passive PCMs used in the conditioned space.

Because PCMs are typically situated in conditioned spaces and absorb and release energy at constant temperatures, they are in many instances likely to maintain space conditions at a more constant temperature than spaces that are mechanically cooled only.

Phase change materials are often used for reserve cooling in case of power interruption or refrigeration system malfunction. Like batteries for emergency lighting and computer system uninterruptible power supplies, PCMs will help maintain temperatures during outages for spaces such as marine vessels to cold storage, data centers and telecom shelters.

PCM INTRODUCTION

Phase change materials are available for temperatures ranging from -150°F to 2,200°F. This article features PCMs suitable for conditioning commercial and industrial facilities, and therefore, temperature ranges of –20°F for freezers to the mid 70°F range for occupied-space conditioning.

The following is a brief review of important characteristics of PCMs as well as performance metrics for three types of PCMs: salts, organics, and vegetable-derived materials.

PCM Characteristics [1]

There are several important characteristics of PCM development and performance to consider for each application.

Latent heat of fusion is the heat available for space heating (freezing the PCM) or space cooling (melting). High latent heat is desired.

Sharpness of latent heat is the temperature band over which the material freezes and thaws. A narrow range is desired.

Melting and freezing proximity is the temperature difference, if any, between the freezing point and melting point. The same freezing and melting temperatures are desired.

Stability is the material's ability to maintain its freezing and melting points and latent heat capacity over many freeze-thaw cycles.

Containment systems should have good heat transfer characteristics, be appropriate for the temperature, and resist corrosion. Metals have good thermal conductivity but may be expensive or prone to corrosion. Plastics have limited temperature ranges and have lower thermal conductivity. Plastics can also react unfavorably with certain hydrocarbon PCMs.

Environmentally friendly such that the material is non-combustible, inert, or biodegradable.

PCM TYPES

This article focuses on the application of PCMs to buildings – occupied spaces, and commercial and industrial frozen food storage.

Figure 1 shows the melting range of PCMs researched for this article, including the temperature range of interest in the shaded area. [2][3]

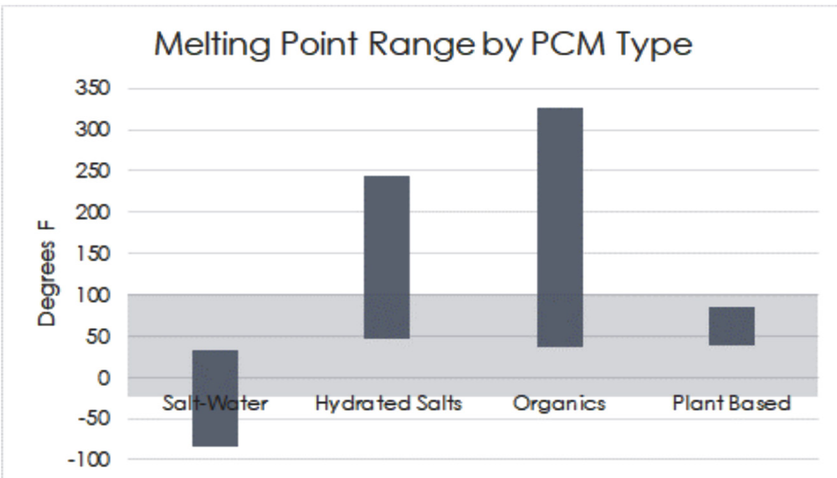

Figure 1. Melting Ranges by PCM Type

Salts in Water

Adding salts to water depresses the freezing point. Salt-water PCMs use blends of salts to achieve various freezing points. The blend of salts and water is fine-tuned such that the entire blend freezes (changes phase) at one precise temperature known as the eutectic point. At lower concentrations, water alone will change phase, leaving a more concentrated salt-water solution as liquid [4]. In this case, freezing would occur over a range of temperatures until the eutectic concentration is reached. Phase change over a range of temperatures is undesirable to precisely serve a load at a given temperature.

Figure 2 shows latent heat capacity of a range of eutectic freeze points of salt-water solutions. The latent heat capacity declines with higher concentrations of salt and corresponding lower freezing temperatures. While the lower latent heat capacity is less desirable, it simply requires more material for a given amount of phase change heat transfer.

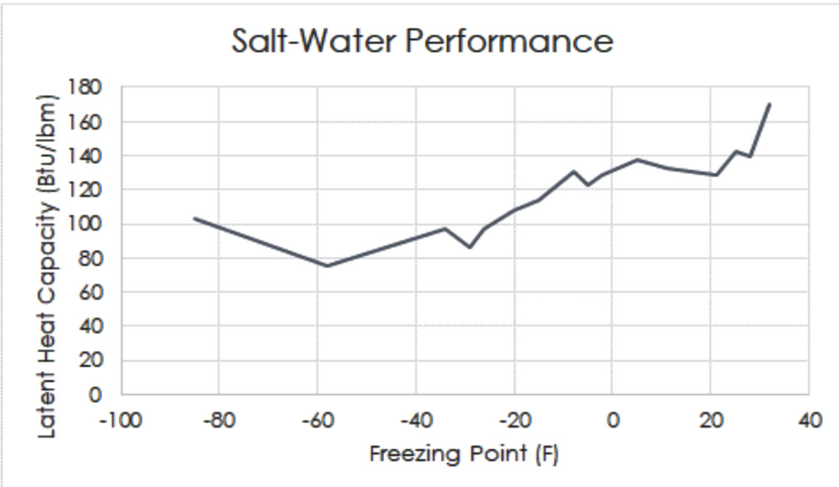

Figure 2. Salt-water PCM Characteristics

Hydrated Salts

Hydrated salts are a different family of salt-water-solution PCMs that freeze above the freezing point of pure water. These PCMs can be trickier to manage because not all of them have a eutectic freeze point. Solutions with eutectic freeze points are said to be congruent. Some solutions are incongruent, which means the salts will crystalize, precipitate, and settle out of solution. Some incongruent solutions may be treated with additives to avoid this. Gels are added to other incongruent solutions such that the salt crystals that form do not settle out of solution and permanently change the PCM's characteristics.

Figure 3 shows latent heat capacity for a range of freezing points for hydrated salt solutions. The latent heat capacity for these solutions is significantly lower than the latent heat capacities of sub-32°F salt-water PCMs.

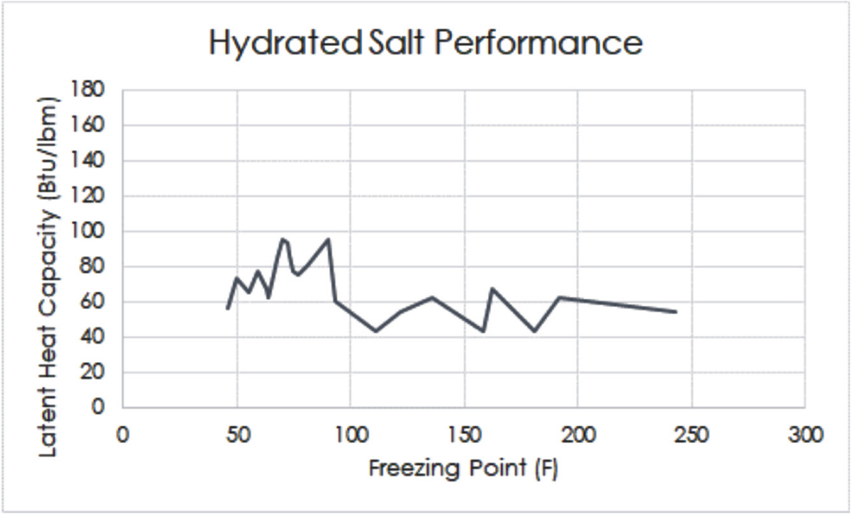

Figure 3. Hydrated Salt PCM Characteristics

Organic

Organic PCMs, by definition, include hydrocarbon chains. PCMs with longer carbon chains have higher melting points which are all above the atmospheric freezing point of water, 32°F. This family of PCMs includes petroleum, animal fats, and vegetable oils.

Challenges with this family of PCMs include a range of melting points because their composition is rarely pure, meaning they have carbon chains of varying length and carbon content. For example, animal and vegetable fats include four or more types of fatty acids, each of which have varying hydrocarbon chain lengths and therefore, melting points [5]. For example, common consumable fats have melting points that vary by 5 to 20°F [6]. While 100% purification is prohibitively expensive, some level of separation is available to shrink the range of melting temperatures.

Figure 4 shows latent heat capacity for 52 organic PCMs. Their latent heat performance is better than hydrated salts but not quite as good as salt-water solutions.

Data from Figure 2 through Figure 4 were taken from PCM Products, a United Kingdom company. Not shown in Figure 4 are data from Phase Change Solutions, a bio PCM provider based in Asheboro, NC. Their PCM products are all plant-based with quoted latent heat capacities of 90-110 Btu/lbm over 12 temperature melting points from 39°F to 84°F.

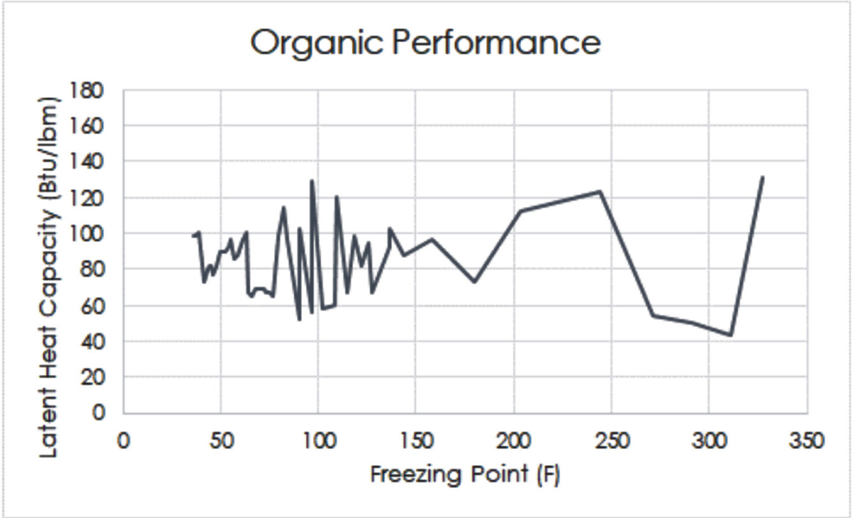

Figure 4. Organic PCM Characteristics

APPLICATIONS

A thorough secondary review of online resources indicates very little research into PCM applications, other than conventional ice storage, has been completed to date. There are many studies of PCM materials, but not many studies concerning their performance in actual applications. Much of the PCM material research has spanned the last 10 or more years indicating there isn't much momentum behind these technologies, particularly in occupied spaces like offices, schools, and hospitals.

There has been greater application of PCMs in refrigerated or frozen storage spaces, transportation of temperature-sensitive products, and serving as a backup to maintain temperatures in case of power outages.

Because field demonstrations and case studies of room-temperature PCMs are scarce with minimal documented design considerations, the author considers and suggests design considerations that have yet to be extensively tested.

Occupied-space Conditioning with Ice Storage

The predominant top-of-mind application of thermal energy storage is likely space cooling to shift cooling energy and electrical demand to off-peak nighttime hours. The conventional PCM is pure water and the conventional means of storing the thermal energy is ice. A simple depiction of this system is shown in Figure 5. The primary loop includes a water-glycol solution for sub-freezing temperatures. The plate-and-frame heat exchanger is used to transfer heat from the building loop (loads) to the chiller primary loop. Note that design configurations are limitless.

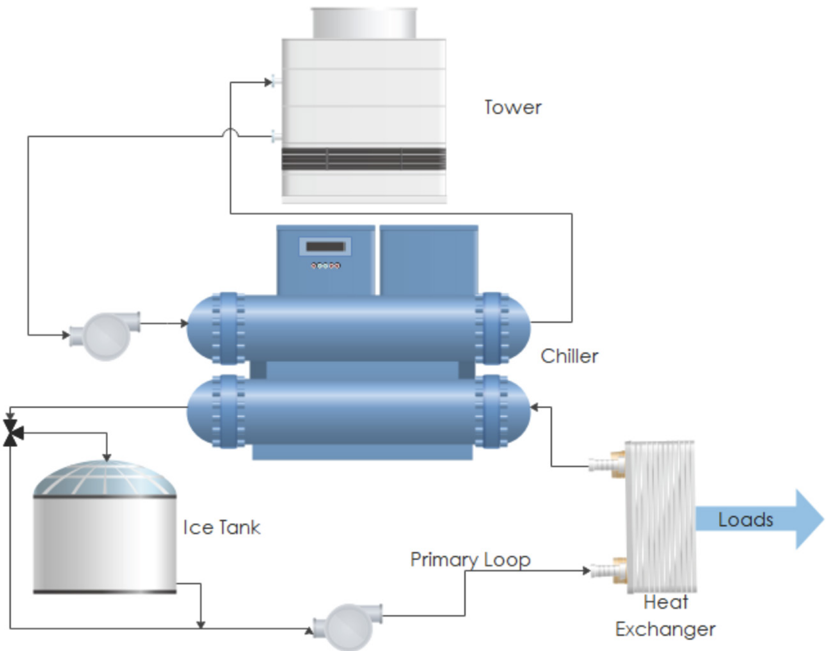

Figure 5. Ice Storage

Ice storage systems represented in Figure 5 have been deployed for several decades. Technical barriers are minimal.

The financial driver for ice storage systems is to shift electricity consumption from more-expensive daytime/peak pricing periods to less expensive off-peak periods. It is also used to reduce peak demand charges for the energy user.

Even though energy consumption is shifted off-peak, net energy consumption is likely to increase compared to storage-less systems. First, it takes more chiller power to produce a 25°F water-glycol solution used to charge the storage tanks with ice, compared to conventional chiller supply temperatures of 40 to 45°F. Second, the glycol solution is more viscous and has poorer heat transfer properties. This requires more pumping power and a greater temperature difference between the evaporating refrigerant and the water-glycol solution.

As noted, design considerations are limitless. Systems can be designed such that the chillers run nearly fully loaded around the clock on design days. This helps minimize system capital cost by using the storage system to offset chiller capacity. Another option is to design the system such that the chillers are not needed during peak periods, maximizing savings at the expense of a chiller plant with greater chilling capacity and an ice storage system that is oversized for days in which design conditions are not met. This latter option is not likely to be the most cost effective because the author's experience has shown that the most cost-effective option is one where all equipment is used closer to its maximum capacity at all times.

In the case of hybrid systems where chillers are needed during design days, one or more chillers can be dedicated to ice making off-peak. If required on design days, that chiller can provide chilled water to the loads along with the ice and other chillers.

Another consideration for ice storage systems is to operate chillers in series rather than in parallel. Chillers operating with less chilled-water temperature lift in each of two chillers piped in series operate more efficiently overall, even though the total temperature drop is the same.

Cold Storage with Salt-water PCMs

Plastic containers, resembling reusable freezer packs common for consumer use in insulated coolers, are used with salt-water PCM energy storage applications. These PCMs incorporate a combination of salts to achieve specific freezing points for various applications, from 32°F down to −85°F.

Salt-water PCM applications include freezer warehouses and walk-in freezers. These are passive applications where the PCM is located in the warehouse or storage unit, but outside the occupied space, typically above the racks in a warehouse. This position not only keeps the PCM out of the way, it also provides free convectional cooling if the power goes out.

Figure 6 shows an application of salt-water PCMs in a walk-in freezer. In this application, the structure is bolted to the ceiling to support the PCM containers.

Figure 6. Salt-water PCM Application
(Source: Viking Cold Solutions)

This technology is promising with proven results. It typically saves energy in addition to shifting load to off-peak periods.

A salt-water PCM typically saves energy by charging the material overnight when outdoor air conditions are cooler, requiring less refrigeration compressor lift. Second, it allows systems to run closer to full capacity, which is almost always more efficient than part load efficiency, whether partial loads are met with rotary-compressor rotor shortening, unloading reciprocating-compressor cylinders, or using variable frequency drives. Third, unlike making ice for space conditioning as described above, this PCM can be charged at near-normal temperatures. Therefore, there is very little compressor lift penalty.

In areas with high penetration rates of solar electricity production, the PCMs can be charged during daytime hours to take advantage of an abundance of solar generation.

Salt-water PCM technology has significant non-energy benefits. First, it helps maintain a more constant freezer temperature, especially compared to thermal storage, by simply driving product temperatures lower and coasting through portions of the peak period. This allows for superior load shifting and demand response. Second, it provides substantial backup in case of power outages or equipment failure. Third, there are no moving parts and maintenance is almost non-existent. Forth, it is non-invasive to the refrigeration system and can be installed with minimal disruption to operations.

Introduction to Biological PCMs

Biologically based PCMs are a subset of organic PCMs that use plant or animal-based fats as the PCM. The analysis in this article is based on the Phase Change Energy Solutions products, which are all plant-based.

These plant-based PCMs are offered in several products to be applied for space conditioning. They include blankets that can be added to wall structures, roof decks, or above suspended ceilings. They are also offered in architectural panels that may be easily retrofitted by attaching them to walls or ceilings. Bulk thermal storage is available similar to ice storage except the PCM is the plant-based type rather than water.

Bulk Storage with Biologically Based PCMs

Bulk storage using biological PCMs work like conventional ice storage, but rather than water they employ temperature-tuned PCM material that more closely matches normal chilled water temperatures. Phase-change points include a range of temperatures that are ideal for chillers: four temperature choices from 39°F to 46°F. Therefore, the chiller-lift penalty associated with making 25°F chilled water and antifreeze solution is mostly avoided.

Like conventional ice storage, bio-based PCM storage allows cooling to occur overnight when compressors can run at lower head pressure in cooler conditions for condensing refrigerant. Because there is plenty of time for recharging the PCM, cooling sources can be operated at their most-efficient point. For instance, unlike positive displacement compressors used for cold food storage, centrifugal chillers typically operate most efficiently in the 60 to 70% loading range. Chillers can spend more time operating in their sweet spot rather than what the building demands at all times. Cooling energy consumption and power demand are also shifted to less-expensive off-peak periods.

Occupied-space Conditioning with Biologically Based PCMs—Blankets

Blankets with packets of PCM sandwiched between multi-layered films resembling a down jacket can be used in a variety of interior space-conditioning applications.

First, it warrants mentioning that occupied buildings are not like cold storage facilities. Occupied buildings have heating AND cooling loads rather than cooling only. Having both heating and cooling loads is a factor because there is dead band temperature between heating and cooling setpoints (e.g., 72°F and 75°F). It may not be economical or feasible to use one PCM material for both heating and cooling, considering that phase change is necessary to maximize energy impacts. Designers also need to consider the heating fuel. If the heating fuel is natural gas, there are rarely demand or time-of-use rates. Buildings heated by electricity, whether electric resistance or heat pump, are often subject to similar demand and time of use tariffs experienced during the cooling season.

Designers need to consider that heating and cooling loads are typically greatest along exterior walls rather than interior partitions. In spaces with exterior exposure, it is beneficial for comfort and phase-change leverage to locate the PCM on or near the exterior surface.

Blankets can be deployed in many ways, but this analysis includes deployment as part of the wall structure, laid above suspended ceiling tiles, or as part of a wall-mounted panel.

With PCM blankets installed behind gypsum board in walls, the material is most likely only suitable for heating or cooling (pick one) as the load penetrates the wall, typically from the outside on its way to the occupied space. This becomes a very complex heat transfer problem and most likely requires testing. It may also be a challenge to freeze the PCM behind the gypsum board. This would require sub-cooling the space to a degree that the PCM can reject heat through the gypsum board or other finishing material to the conditioned space. The gypsum board's insulating value will impede heat transfer (conduction) and temperature difference that drives free convection. The need to charge the PCM by sub-cooling the space may result in a call for heat first thing in the morning for occupancy. This needs to be considered and avoided to achieve optimal cost effectiveness. Furthermore, melting the PCM would largely require heat transfer through the wall assembly. Does this require more heat gain than necessary for cost effective insulation? Insulation costs versus PCM costs must be evaluated.

Another option for the PCM blankets is to install them on partitions on the building's interior, as shown in Figure 7. [7]

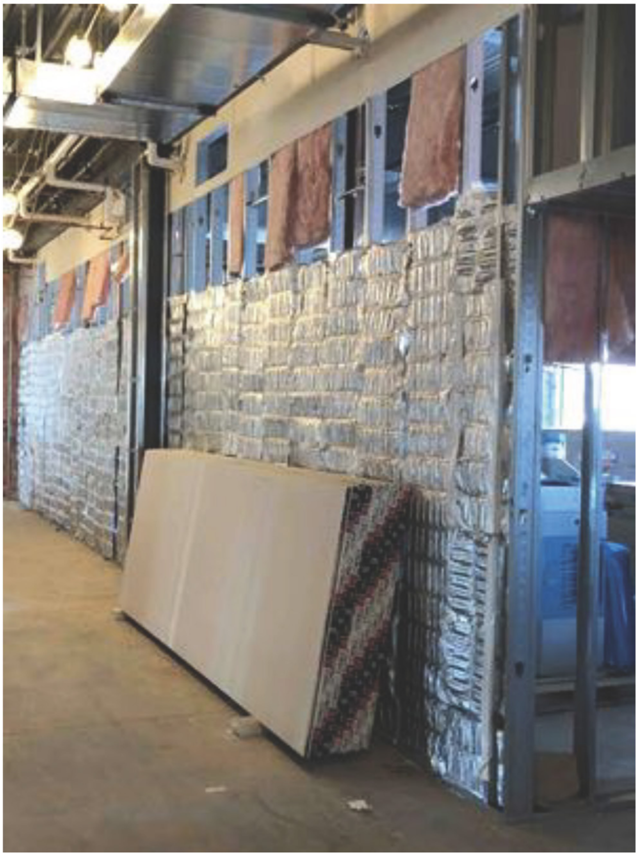

Figure 7. PCM Partition Application

A challenge installing PCM blankets on interior partitions would be the lack of cooling load on these structures. Their only heat gain is ambient indoor air. There is no conduction or radiation like an external wall or ceiling experiences. This may require an unacceptable temperature swing to get the PCM to cycle from solid to liquid.

Another application of the PCM blanket is to install them above suspended ceiling tiles. This is an easy retrofit application. However, the space above the ceiling tile must be considered. In many cases, these spaces are used as return and/or exhaust air plenums. In these cases, some of the cooling provided by the absorbed heat may be rejected outdoors. Like the wall application, this is a very complex heat transfer situation. Ceiling panels have R-values of about 1 to 1.5 ft^2-F-hr/Btu [8], which is not insignificant. Like the wall application, the space may need to be subcooled excessively to recharge the blanket overnight. Most of the temperature-moderating "benefit" could be in the unoccupied space above the ceiling panels.

Architectural panels containing PCM blankets may be the best application for space conditioning in nearly any commercial building. These panels act like water-based panels used for heating or cooling. This application, shown in Figure 8, avoids many of the challenges and uncertainties of the hidden-blanket installations as part of wall structures or above ceiling tiles noted above. It allows heat transfer with the conditioned space with only a minimal amount of thermal resistance caused by the panel material, making it much more like the proven-successful salt-water PCM storage systems used in freezer applications.

Figure 8. PCM Wall Panels
(Source: Phase Change Solutions)

TEST RESULTS

Case studies for PCM applications are scarce, and therefore, the author is relying on his knowledge of energy, heating, cooling, and comfort issues, along with information provided in available documentation.

Most documented test results of room-temperature (about 70-75°F) cover the ability of the PCM to absorb and release heat, and to moderate temperature. However, people do not readily accept a wide band of temperature fluctuations. This is one challenge for these technologies. The only test results found that included metered energy savings were for cold storage and telecommunication. Can PCMs save energy and keep occupied spaces comfortable? The author was not able to find energy-saving impacts for applications of PCMs to commercially or institutionally occupied spaces.

First, this article reviews two case studies showing energy impacts; one for salt-water PCMs in frozen food storage facilities, and a second for a bio-PCM application in telecommunication equipment facilities. Second, this article breaks down two A-B tests showing results for PCMs' ability to moderate temperature and absorb heat in would-be occupied spaces.

Salt-water PCM Test Including Energy Analysis

San Diego Gas and Electric sponsored two studies in one report for using salt-water PCMs in frozen food storage applications [9]. The first is for a walk-in freezer for a mess hall facility at Camp Pendleton. The second is for a frozen food warehouse for the San Diego Food Bank. This PCM technology is conducive to retrofitting in facilities as they are non-invasive and can be located out of the way high in the space above racks and shelves.

The mess hall refrigeration system was controlled to shift load from day and peak periods to nighttime off-peak periods. The food bank system was controlled to use abundant site-generated solar energy to charge during the day.

The mess hall application saved 30% energy and 3% peak demand for the affected equipment. The food bank application saved 39% energy and 11% peak demand. Peak demand, as reported, is the maximum demand regardless of time of day when it occurs. Billed peak demand and especially peak demand reduction during grid-coincident peak demand could be substantially greater, especially for the mess hall.

The financial performance of these applications included an estimated simple payback of about 6 years for the mess hall project and 3 years for the food bank project.

Bio PCM Test Including Energy Analysis

The Society of Cable Telecommunications Engineers and International Society of Broadband Experts sponsored an energy and simple financial analysis for the application of a bio PCM in two telecommunication shelters located near Davis, CA. [10] This application includes PCM wall and ceiling panels shown in Figure 9. This is an ideal application for superior heat transfer performance and available temperature swing to freeze and melt the PCM around a target control temperature of 78°F in these unmanned facilities.

Savings are reported to be the result of longer cooling system cycles. While this is certainly the case in humid climates where moisture is condensed on coils and then re-evaporated into the space on every cycle, it may have less effect in dry climates like California's. However, as with the freezer application, shifting more of the cooling load to overnight hours can also improve efficiency, depending on cooling system characteristics.

Figure 9. Bio PCM Telecommunication Application

Savings are estimated to be about 15% using retrofit isolation, metering on the cooling equipment, and 20% using whole-building energy analysis using utility meter data. The paper states the latter whole-building approach was normalized to weather conditions to extrapolate savings for an entire year. However, the results show that the metered savings were simply extrapolated by dividing the savings over the metered period to obtain monthly savings and multiplying that by 12 for annual savings. Also, the discussion for weather normalization uses cooling degree days and a balance point of 65°F, meaning that the facility needs no cooling when it is 65°F or colder outdoors. That is a good balance point for homes and light commercial facilities with low internal gains. These telecommunication shelters are likely to have a much lower balance point temperature. Determining the balance point can be straightforward by comparing energy consumption to outdoor temperature.

The estimated simple payback for these tests is less than two years.

Bio PCM A-B Thermal Test

An A-B test was conducted on a Phoenix-area high school using two similar buildings, each with two floors above grade. Room temperatures were monitored before HVAC systems were active in this A-B test, as shown in Figure 10. [11]

Areas F and B are very similar two-story sections of the building. Area F is the control (baseline) section and Area B is the test section. Room numbers beginning with 1 or 2 indicate first or second floor, respectively.

PCMs should dampen the temperature fluctuation from cool nights to hot days, but comparing second-floor data in the yellow (control) and gray (test) curves, the temperature swings for the test area are greater much of the time. Periods near the beginning, middle, and end of the test period from April through May show the temperatures in these second floor test and control spaces are nearly the same.

Test and control spaces for the first floor track more closely, but again, during many periods the temperature swings in the test area are greater than the control area. There also appears to be some forcing of temperatures in these areas because the temperature curves are not smooth.

The PCM in this case is installed on interior partitions (see Figure 7). Its melting point is 73°F. There is minimal discernable temperature fluctuation at any particular room temperature range (blue v orange or yellow v gray).

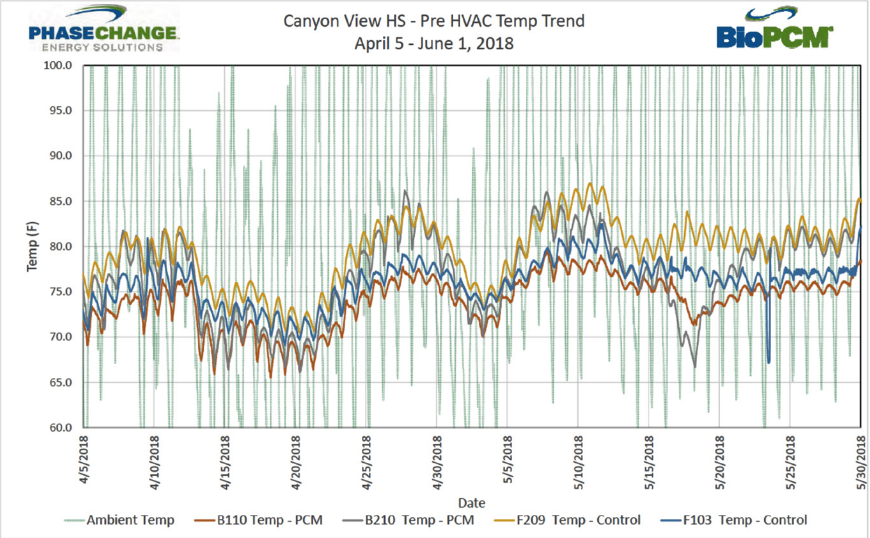

Figure 10. Bio PCM Temperature Test Results (Source: Pure Temp, LLC.)

Salt Hydrate PCM A-B Thermal Test

A second A-B test was conducted recently in Germany [12] to study computational models and demonstrate the dampening effects of PCMs on space conditioning. This case used a salt hydrate PCM in plastic containers resembling the common freezer pack used for food coolers. The melting point of this PCM is 21 to 22°C (70 to 72°F).

The test building and PCM packs are shown in Figure 11 and Figure 12, respectively. The results are shown in Figure 13.

There are two notable findings from these test results. First, the PCM acts as thermal mass and provides an insulating effect even when phase change is not occurring. The insulating effect would be due to blocking radiation from the exterior sheathing and the impedance to natural convective air flow in the wall cavity. The result is less temperature swing in the test space, even when the material remains in one phase, solid (below 20°C [68°F]) or liquid (above 23°C [73°F]).

The second finding is that the PCM has its greatest impact when it is changing phase in the temperature range of 20 to 23°C (68 to 73°F).

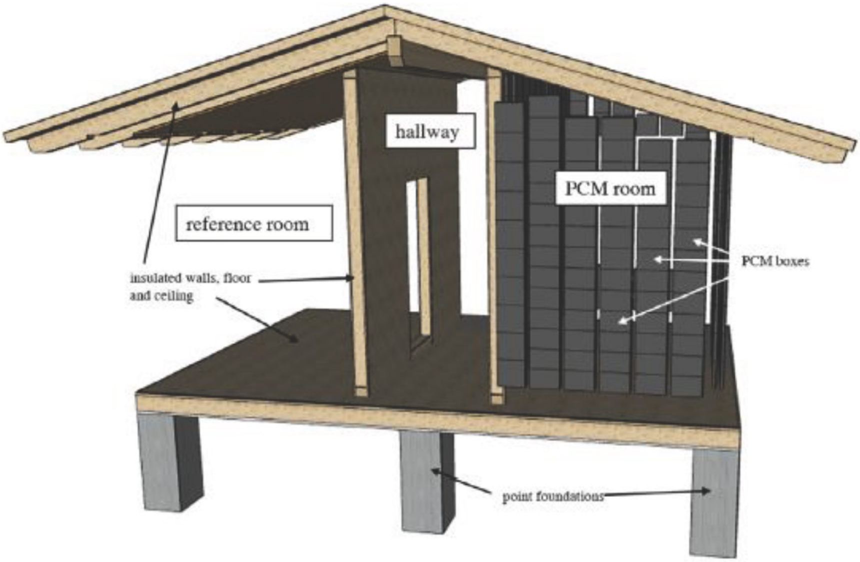

Figure 11. Salt Hydrate Test Facility

Figure 12. PCM Installation

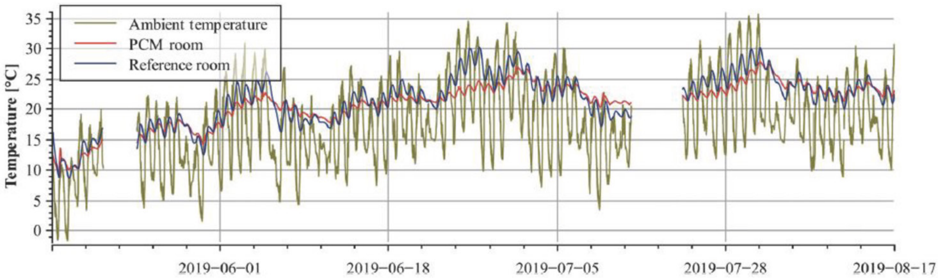

Figure 13. Salt Hydrate Temperature Test Results

CONCLUSIONS

Phase change material deployment is still in the pre-emerging-market phase of adoption. Adoption of PCMs for commercial and industrial refrigeration and other applications where thermal comfort is not a primary factor is far ahead of adoption for occupied commercial space conditioning.

Commercial and industrial refrigeration applications are mostly confined to frozen food warehouses and walk-in freezers. Performance of these PCM applications has proven to be very successful for both shifting cooling loads to periods of lower demand and energy charges, and in most cases, saving energy by charging the PCM (freezing it) during more favorable, cooler nighttime conditions. These applications work well because the PCM is in direct contact with the conditioned space air and out of the way of occupants and equipment used in these spaces.

Facilities that are conditioned to protect equipment or products and are not sensitive to people's thermal comfort issues are also great opportunities for PCMs.

Phase change materials used for occupied space conditioning is largely still in the testing and validation phase of product development. Theory and metered results indicate that PCMs have the desired effect of adding thermal mass to buildings, but their energy-saving and load shifting potential have not been widely proven.

Most test applications have placed the PCM outside the occupied space, in walls behind gypsum board, sandwiched between insulation layers, or blanketed above ceiling panels. PCM incorporation into building design is far more challenging than deploying it in direct contact with the conditioned space. Deployment within the building structure or above ceiling panels would require a lot of testing to get it right because the material needs to cycle from liquid to solid to be effective and this is not a straightforward analysis. More predictable outcomes seem to be available by deploying the same strategies that have been successfully proven in frozen food facilities. The PCMs can be used in architectural wall or ceiling panels, or decorative ceiling hung panels. Any PCM type, including organic, biological or salt-hydrates could be used for these applications. However, the challenge for thermal comfort is to freeze the PCM overnight while avoiding the need for heat in the morning to keep spaces in their comfort zones.

Phase change materials could also be used in refrigerated warehouses and walk-in coolers using organic, biological, or salt-hydrate PCMs.

Overall, energy savings and load shifting potential for PCMs in direct contact with conditioned spaces is vast and possibly cost effective in most applications.

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AUTHOR BIOGRAPHY

Jeffrey L. Ihnen, P.E., is the Chief Executive Officer at Michaels Energy. His responsibilities as CEO include program evaluation, proposal and sales strategy, as well as discovering the next big thing. Jeff started on the ground floor with Michaels Energy in January 1996 doing energy audits and feasibility studies. He worked his way into managing the energy efficiency practices and, for the last several years, the entire company. Jeff earned a Bachelor of Science degree in mechanical engineering from South Dakota State University. He spent four and a half years in the Naval nuclear propulsion program earning a master's degree in nuclear engineering (classified). Before joining Michaels Energy, Jeff earned a Master of Science degree in mechanical engineering from the University of Wisconsin-Madison. Mr. Ihnen may be contacted via email at JLI@MichaelsEnergy.com.