2012

# Use of Phase Change Material in a Building Wall Assembly: A Case Study of Technical Potential in Two Climates

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## ABSTRACT

Phase change material (PCM), placed in an exterior wall, alters the temperature profile within the wall and thus influences the heat transport through the wall. This may reduce the net energy transport through the wall via interactions with diurnal temperature swings in the external environment or reduce the electricity needed to meet the net load through the wall by shifting the time of the peak load to a time when the cooling system operates more efficiently. This study covers a broad range of parameters that can influence the effectiveness of such a merged thermal storage-thermal insulation system. These parameters included climate, PCM location within the wall, amount of PCM, midpoint of the PCM melting and freezing range relative to the indoor setpoint temperature, temperature range over which phase change occurs, and the wall orientation. Two climates are investigated using finite difference and optimization analyses: Phoenix and Baltimore, with two utility rate schedules. Although potential savings for a PCM with optimized properties were greater when the PCM was concentrated near the inside wall surface, other considerations described here lead to a recommendation for a full-thickness application. An examination of the temperature distribution within the walls also revealed the potential for this system to reduce the amount of energy transported through the wall framing. Finally, economic benefits can exceed energy savings when time-of-day utility rates are in effect, reflecting the value of peak load reductions for the utility grid.

## 1. INTRODUCTION

Energy storage in buildings, and phase change material (PCM) energy storage in particular, has been studied for a number of years. The goal has typically been to buffer the indoor conditioned space against large swings in outdoor temperature, thus reducing the energy required to maintain comfort. Some of the earlier efforts focused on placing the PCM in direct contact with the conditioned space (Tomlinson and Heberle, 1990, Stovall and Tomlinson, 1995, Peippo *et al,* 1991, and Neeper, 2000). This proved effective for storing heat from incident solar energy and in reducing cooling loads for those cases where free night-time ventilation was available to freeze the PCM during unoccupied hours (Butala and Stritlh, 2009, and Eicker, 2010).

Another concept incorporates the PCM energy storage within the wall insulation itself (Khudhair and Farid, 2004, Kosny *et al,* 2007, and Kosny *et al*, 2006). This application is counter-intuitive, because the insulation retards energy transport into and out of the PCM, that is, the insulation reduces heat transfer between the PCM and both the conditioned space and the exterior environment. However, this PCM location alters the temperature profile within the wall and thus influences the heat transport through the wall. This may reduce the net energy transport through the wall via interactions with diurnal temperature swings in the external environment, or may reduce the electricity needed to meet the load by shifting the time of the peak load to a time when the cooling system operates more efficiently. Therefore, a suite of three analyses was prepared to evaluate potential applications of phase change materials (PCM) in building envelopes (Childs and Stovall, 2012, Tabares-Velasco *et al* 2012a and 2012b, Tabares-Velasco and Griffith 2012, and Kosny *et al* 2012). The first analysis is described here. The other two works focused on improved whole building modeling tools and a review of the current costs of PCMs.

## 2. ANALYSIS APPROACH

A family of detailed finite difference models were constructed using a specially modified version of the HEATING code (Childs, 1993). One-year-long transient analyses were then performed with and without the inclusion of the

PCM. Exterior boundary conditions were obtained from TMY3 weather files. The exterior boundary conditions on the wall used in this study include directional solar radiation incident on the wall surface and convective heat transfer typical of moderate wind conditions. The interior boundary condition was natural convection from the surface to the indoor air temperature. The indoor air temperature was allowed to float between the cooling setpoint (25°C) or go below the heating setpoint (20°C). The finite difference model was coupled with an optimization program, based on Press *et al* (1992), to determine the PCM melt properties (midpoint and width of melt range) that minimized the annual cooling electricity required for a given PCM location and amount.

The type of PCM being investigated is a micro-encapsulated paraffin that is distributed in a blown-in cellulose insulation within the cavity of a typical 2x6 framed wall (14 cm thick cavity), bounded by gypsum wallboard on one side and exterior sheathing board on the other, as shown in Fig 1. An idealized shape is used for the PCM melt curve as shown in Figure 2. This assumed behavior is a reasonable representation of the general shape of the melt curve for many paraffin PCMs. The melt range spans the temperature at which the PCM starts to melt to the temperature at which melting is complete. Using this generic shape, a large family of melt curves can be defined by specifying the midpoint of the melt range and the width of the melt range. For most of these analyses, it is assumed that the phase change occurs over the same temperarture range for freezing as for melting (i.e., the PCM does not exhibit hysteresis). The amount of PCM distributed in the cellulose insulation was 2.4 kg/m$^2$ of PCM of wall area, giving the wall a latent heat capacity of 408 kJ per square meter of wall surface area. Further details, including material properties, are found in Childs and Stovall (2012).

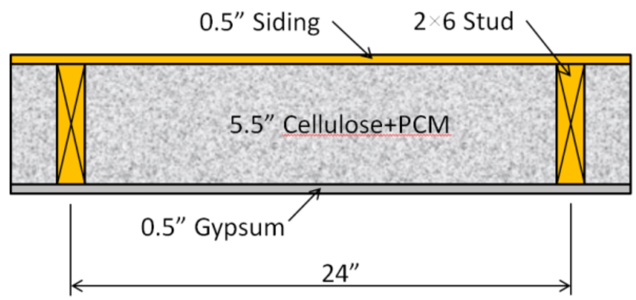


**Figure 1** Wall cross section

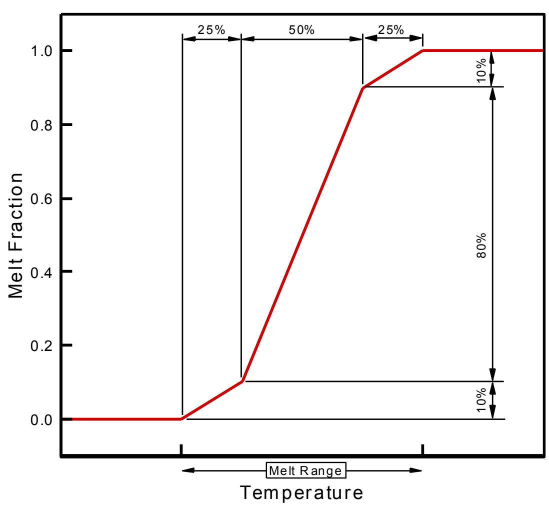


**Figure 2** Idealized PCM melt curve

The annual cooling electricity use is determined by the cooling load through the wall and the efficiency of the cooling system. The energy efficiency ratio varied linearly with temperature from above 14 to below 8 Btu/kWh as the ambient temperature varied from 24 to 46°C (75 to 115°F).

The parameters varied in this study are summarized in Table 1. Two climates are investigated: Phoenix and Baltimore. Two utility rate schedules were evaluated for Phoenix. The goal is to reduce the total electricity required for annual cooling needs by identifying optimal PCM characteristics for specific applications.

**Table 1** Analysis Structure Applied to Phoenix and Baltimore Climates

| Analysis Stage | PCM Melt Range (°C) | | Amount of PCM ($kg/m^2$) | Location within Wall | Wall Orientation | Time Period | Rate Structure | Setpoint Temp. (°C) |
|---|---|---|---|---|---|---|---|---|
| | Midpoint | Width | | | | | | |
| Single Parameter Evaluation | ***Varied*** | 4 | 2.4 | Full Thickness | South | Annual | Fixed | 25 |
| | ***Varied*** | 4 | 2.4 | Full Thickness | All four | Annual | Fixed | 25 |
| | 27 Phoenix, 25 Baltimore | 4 | 2.4 | Full Thickness | ***Varied*** | Annual | Fixed | 25 |
| | 27 Phoenix, 25 Baltimore | 4 | 2.4 | Full Thickness | West | ***Monthly*** | Fixed | 25 |
| | 27 Phoenix, 25 Baltimore | 4 | ***Varied*** | Full Thickness | All four | Annual | Fixed | 25 |
| | 27 Phoenix | 4 | 2.4 | Full Thickness | All four | Annual | ***Time of Day*** | 25 |
| Property Optimization | ***Varied*** | ***Varied*** | 2.4 | ***Varied*** | All four | Annual | Fixed | 25 |
| Setpoint temperature | Optimal* | Optimal* | 2.4 | ***Varied*** | All four | Annual | Fixed | ***Varied*** |
| Thermal Bridging | Optimal* | Optimal* | 2.4 | ***Varied*** | All four | Annual | Fixed | 25 |
| Selected Real PCM | Figure 19 | Figure 19 | 2.4 | ***Varied*** | All four | Annual | Fixed | 25 |
| Hysteresis | Figure 22 | Figure 22 | 2.4 | Full Thickness | West | Annual | Fixed | 25 |
| * For assumed 25°C setpoint temperature | | | | | | | | |

# 3. RESULTS

## 3.1 Single Parameter Variations

The optimal midpoint of the melt range depended on whether the goal was to reduce the annual cooling load, cooling electricity peak, or cooling electricity consumption, as shown in Fig. 3. (The effects on heating load and peaks are also shown, but this investigation focused on cooling.) In Phoenix, the cooling electricity savings are much greater than the cooling load savings, because the air conditioner efficiency is significantly greater during the cooler night time hours. However, the cooling load and cooling electricity savings are nearly equal in Baltimore, where the greater humidity reduces the difference between day and night time temperatures. For both locations, the maximum reduction in annual peak cooling load occurs at a melt midpoint temperature well above the cooling setpoint.

Figure 4 shows how the reduction in cooling electricity varies as a function of the midpoint of the melt range for four wall orientations. For all four orientations, the peak reduction in annual cooling electricity use occurs at a melt midpoint of approximately 27°C in Phoenix, which is 2°C above the assumed cooling setpoint temperature. In Baltimore, the best reduction occurred when the melt midpoint was approximately equal to the assumed cooling setpoint of 25°C. The savings potential for the south and west walls is about twice that of the north and east walls. Figure 5 shows the impact of the PCM relative to the annual cooling electricity use for Phoenix and Baltimore. The savings represent a greater proportion of the total in Baltimore, but the magnitude of the savings is far greater in Phoenix.

The cooling season is much longer in Phoenix, with significant savings occuring over seven months, versus four months in Baltimore. The maximum monthly savings is about the same in both climates, almost 0.06 $kWh/m^2$ in June for a west-facing wall.

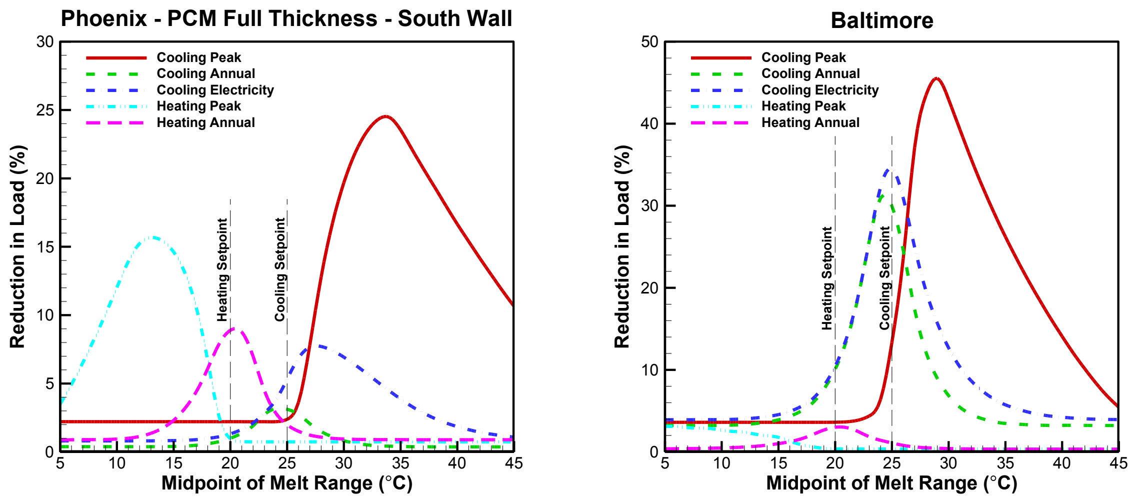


**Figure 3** Impact of Melt Midpoint on Heating/Cooling Loads – South Wall, PCM Full Thickness, 2.4 kg/m$^2$, 4°C Melt Range

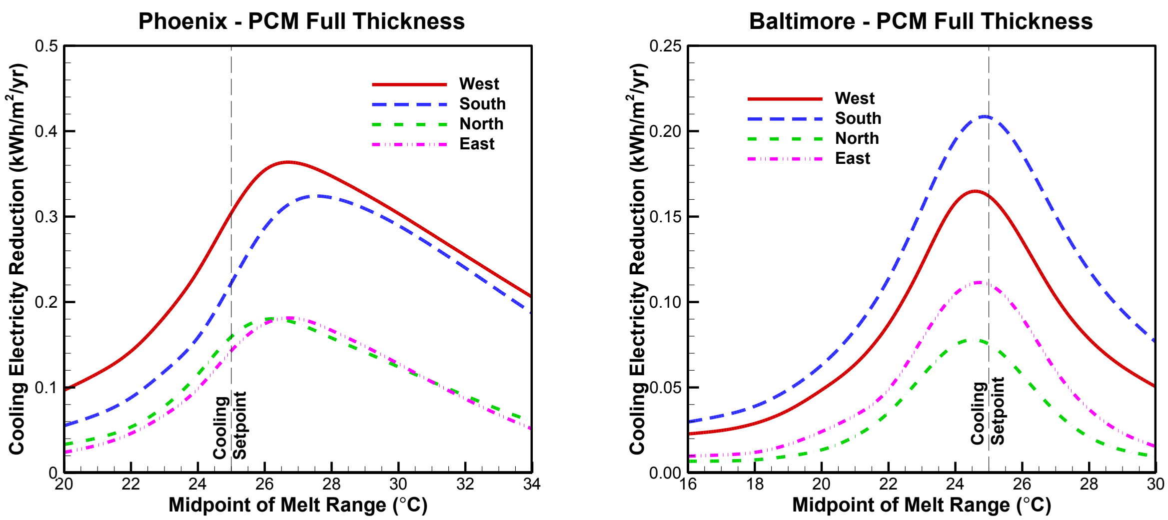


**Figure 4** Impact of Wall Orientation – PCM Full Thickness, 2.4 kg/m$^2$, 4°C Melt Range

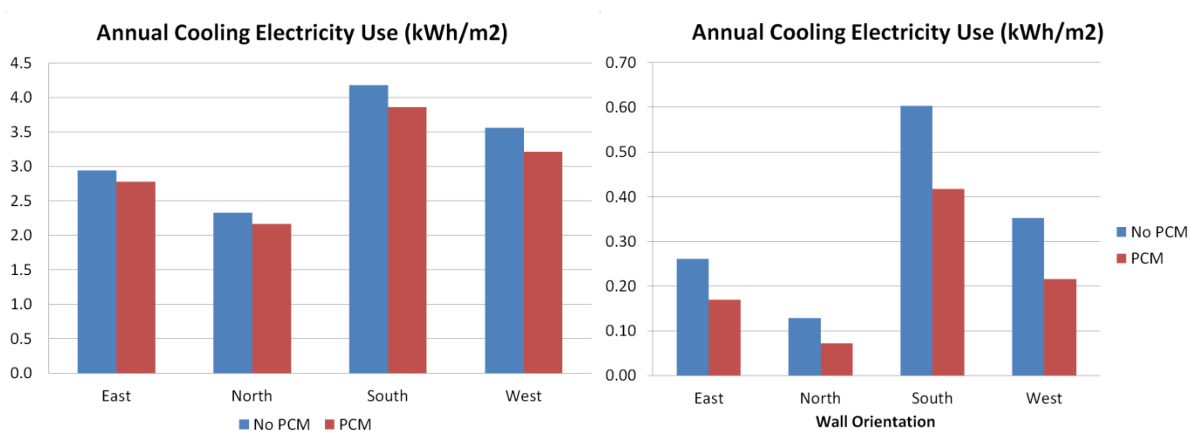


**Figure 5** Annual Cooling Electricity Use – PCM Full Thickness, 2.4 kg/m$^2$, 4°C Melt Range, Phoenix (L, 27°C Melt Midpoint) and Baltimore (R, 25°C Melt Midpoint)

The results just presented all used 2.4 kg of PCM per square meter of wall surface area. Figure 6 shows the reduction in cooling electricity use as a function of the mass of PCM. For small amounts of PCM the reduction in cooling electricity use changes approximately linearly with the mass of PCM, but there are diminishing savings for incremental increases in PCM beyond some point. The use of 2.4 kg/m$^2$ appears to be reasonable for Phoenix, but the optimal amount might be slightly smaller amount since the curves have begun to flatten out. This issue needs to be revisited when mature manufacturing costs are known for the PCM system.

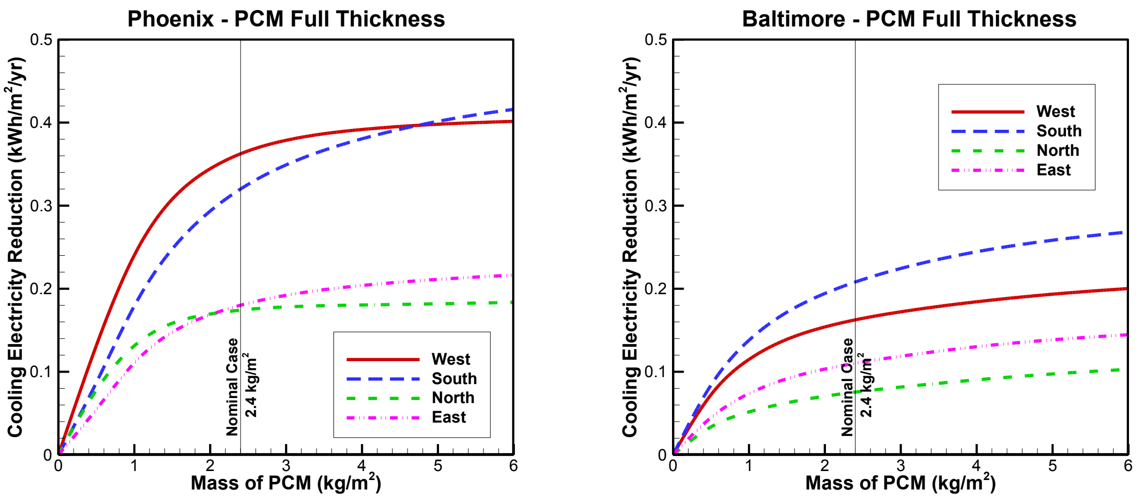


**Figure 6 Impact of mass of PCM – PCM full thickness, 4°C melt range, Phoenix (L, 27°C Melt Midpoint) and Baltimore (R, 25°C Melt Midpoint)**

When time-of-day electricity pricing is available, PCM applications can produce electricity cost savings that are greater than would be indicated by the reduction in electricity use. Phoenix offers such a rate option; because of the significant shift of electricity use from day to evening, the annual cooling electricity savings of 8% translated to annual cooling electricity cost savings of 30%.

## 3.2 Optimal PCM Properties

The results presented up until now have all assumed that the PCM is uniformly distributed through the entire thickness of the cellulose and that the melt range is 4°C. To determine the maximum benefit of PCM, the interactions between the location of PCM in the wall and the optimized melt curve (i.e., the combined selection of the midpoint and width of the melt range) need to be considered. To do this the HEATING model was coupled with an optimization program for three scenarios based on the location of the PCM: (1) an inner layer of cellulose containing PCM and an outer layer of only cellulose, (2) an inner layer of only cellulose and an outer layer of cellulose containing PCM and (3) a layer of cellulose containing PCM sandwiched between two layers of only cellulose. The width of the layer containing the PCM was varied for all three scenarios, while the total amount of PCM in the wall is held constant at 2.4 kg/m$^2$. Note that the three scenarios converge for the case where the width of the PCM layer is equal to the width of the cavity.

To better understand the optimization procedure, consider figure 7 which shows annual energy *use* as a function of both melt midpoint and melt range for two possible PCM distributions within the wall thickness for Phoenix and Baltimore. In this figure, the variation in energy *use* varies significantly from side to side as the midpoint temperature changes, but very little from top to bottom as the width of the melting range changes. The optimum combination would be located in the darkest blue region where the cooling electricity use is about 3.2 kWh/m$^2$ per year in Phoenix and about 0.18 kWh/m$^2$ per year in Baltimore. In Phoenix, the minimal energy use occurs for a relatively broad range of melt midpoint temperatures, while in Baltimore the optimal melt midpoint is focused more narrowly around the setpoint temperature of 25°C. In both Phoenix and Baltimore, locating the PCM within the inner quarter of the wall thickness increases the sensitivity of the electricity use to the melt midpoint temperature relative to the full thickness PCM distribution.

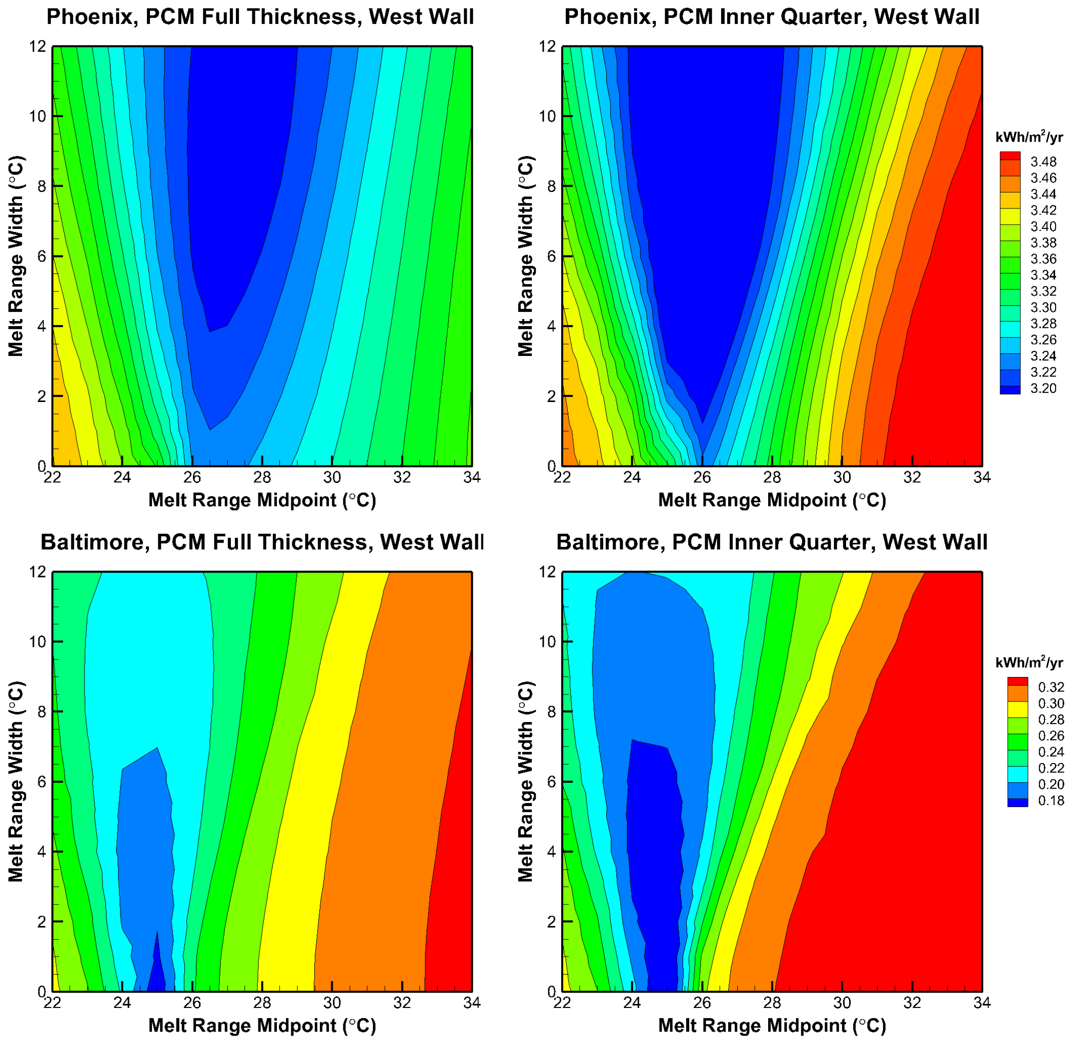


**Figure 7** Cooling electricity use sensitivity to melt range midpoint and width, 2.4 kg/m$^2$

That optimum melt range combination of midpoint and width was calculated for each of the three cellulose location scenarios considered here. Figure 8 shows clearly that concentrating the PCM near the outside of the wall is a poor strategy for both Phoenix and Baltimore, even when the PCM properties are optimized for that location. The analysis also showed that there is a small advantage to concentrating the PCM near the inside surface for both climates. The savings are relatively insensitive to the width of the cellulose region for the inner and sandwich layer PCM placement options. The melt range midpoint approaches the indoor setpoint for the inside PCM distribution in Phoenix, while the optimal melt range wide shrinks to about 3°C. In Baltimore, the optimal melt midpoint was constant at 25°C and the optimal melt range width was constant at 0°C for both the inside and sandwich PCM distributions. A melt range width of 0°C would be close to the behavior of an ideal PCM, not a real PCM. However, the relatively minor sensitivity of the reduction in cooling electricity use to the melt range, shown in Figure 7, indicates that significant savings are still possible at melt ranges in the 2 to 4°C ballpark.

The optimal PCM melt midpoints described previously are for a specific set of assumptions. If the wall is shaded rather than in full sun, if the wall exterior surface solar absorptivity is different, or if other factors are varied, the optimal melt midpoint could be different. As the PCM is concentrated nearer to the inside surface, the optimal melt midpoint approaches the cooling setpoint temperature. The setpoint temperature selection, with or without PCM in the wall, determines how many hours per year the building will need to be actively heated and cooled. The impact of such changes will vary by climate, according to the local environmental temperature distribution relative to the

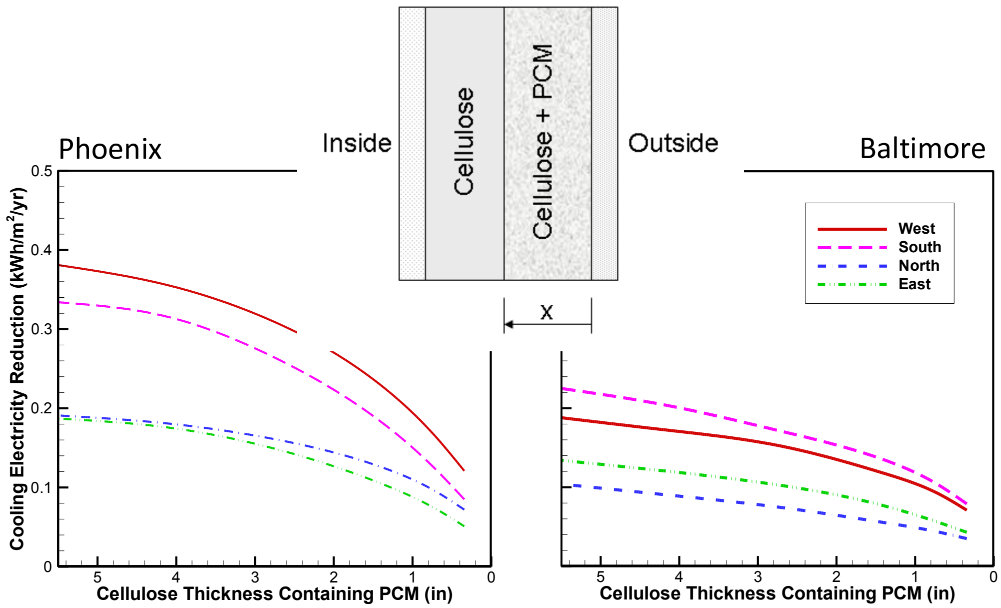


**Figure 8** Electricity savings for optimal PCM properties, PCM concentrated toward outside, 2.4 kg/m$^2$

selected setpoint temperature. For full thickness PCM, and using the optimal melting curve identified based on the assumed 25°C setpoint, changing the cooling setpoint a couple of degrees has very little impact on the cooling electricity savings in Phoenix, but as the PCM is concentrated in thinner layers near the inside, the cooling setpoint selection has a much more pronounced impact, as shown in Figure 9.

The savings in Baltimore are about five times more sensitive to changes in the setpoint, even for the full thickness application, than they were in Phoenix. However, similar to Phoenix, the full thickness application is less sensitive to changes in the setpoint than cases with the PCM concentrated nearer the interior surface. Therefore, the full thickness application is a more conservative choice even though the inner quarter application offers slightly greater savings potential.

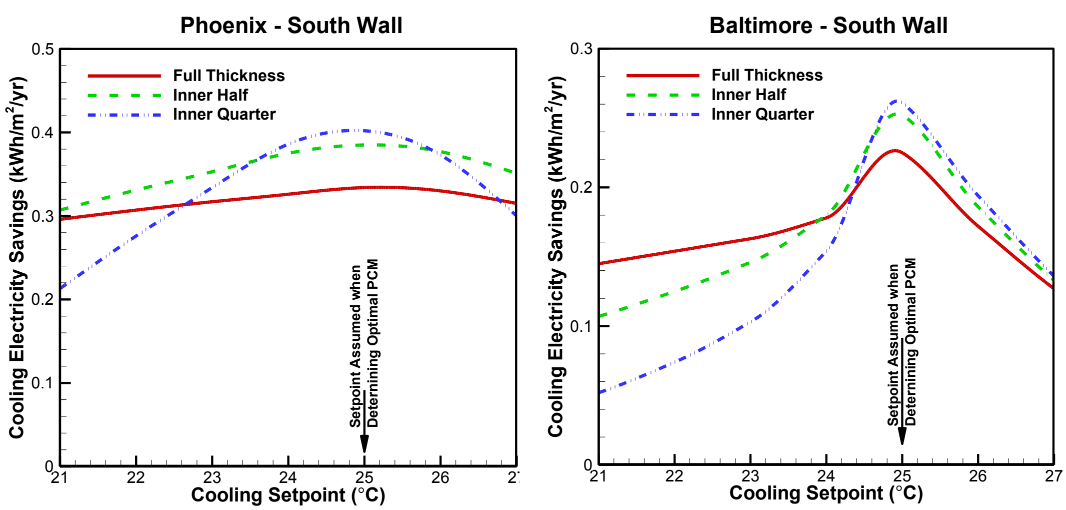


**Figure 9** Sensitivity to altered cooling setpoint

### 3.3 Impact of PCM on Wall Framing Heat Transfer

The results presented to this point have only looked at the performance of a wall without thermal bridging, that is, at the clear wall section between studs. The actual wall of interest has 2×6 studs placed 24 inches on center as shown previously in Figure 1. A two-dimensional model of the wall is utilized to determine how the presence of thermal bridges affects the performance of the PCM in reducing cooling electricity use. If the stud area and the clear-wall area behaved as independent parallel paths, then the reduction in cooling electricity use produced by the PCM would be expected to be less in the wall with bridges than in the wall without bridges. However, the temperature contours in the wall without PCM (top) and with PCM (bottom) at mid-afternoon in early July (see Figure 10) show that the presence of PCM in the cellulose has altered the temperature contours, and consequently the heat flow, through the stud. This new temperature profile shows that the temperature gradient, and thus the heat flow, near the interior wall has been reduced, which reduces the heat flow through the thermal bridge and into the interior space. The reduction in cooling electricity use, which is actually greater in the wall with bridges, is shown in Figure 11. A metal stud wall was also analyzed and showed results similar to those for the wood frame wall.

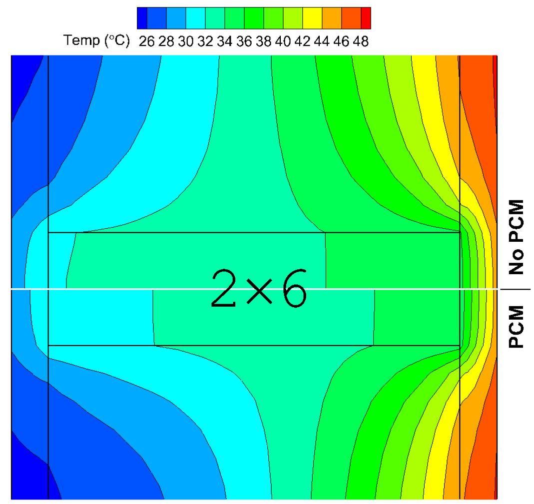


**Figure 10** Temperature contours without PCM (top) and with PCM (bottom) - west wall, PCM full thickness, early July, mid-afternoon, indoor face on left, Phoenix

### 3.4 Performance of One Commercial PCM

The previous analyses reported here indicate that for a given location of the PCM in the wall, a specific midpoint and width of the melt range will produce the maximum benefit from the PCM. While there is some flexibility in formulating a PCM to obtain desired melt characteristics, it is not possible to exactly match the optimal characteristics. Using the melt curve for one particular commercially available, micro-encapsulated PCM and the same analysis tools, the optimal placement of this PCM in a wall and the resulting performance were determined. The optimal location for this PCM within the wall is a layer of cellulose with PCM in the middle portion of the cellulose insulation for all four wall orientations, although this location performs only slightly better than having the PCM uniformly distributed through the entire cellulose thickness. Therefore, from a practical standpoint, the incremental savings would not justify the added complexity of installing the insulation in three layers (cellulose, cellulose with PCM, cellulose.) For full thickness PCM in Phoenix, the commercially available PCM performs 13-

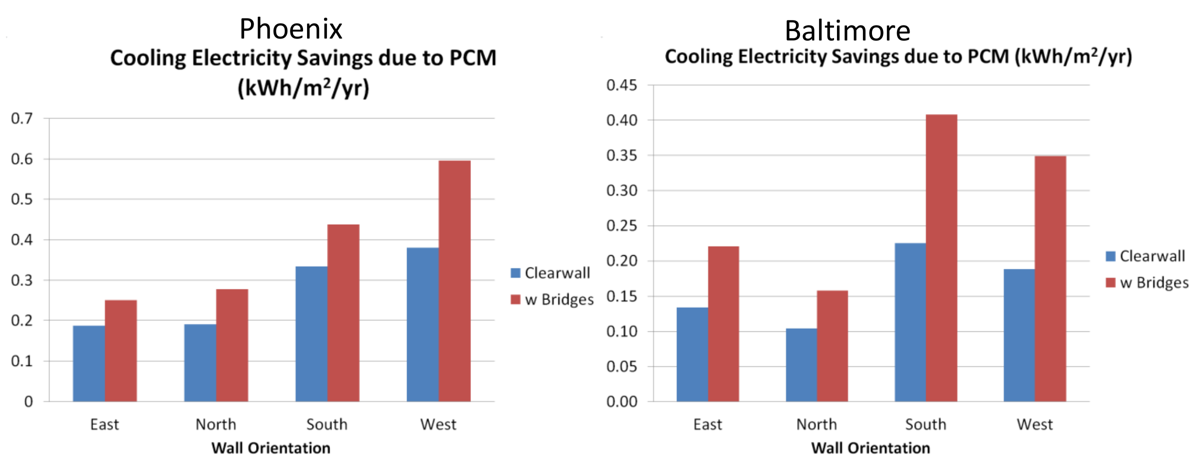


**Figure 11** PCM full thickness with and without thermal bridging, 2.4 kg PCM/$m^2$ wall area

28% worse than the optimal PCM depending on wall orientation. In Baltimore, this particular PCM only produces savings of about half that of the optimal PCM. This demonstrates the need to select a PCM with the optimal properties in mind for each location.

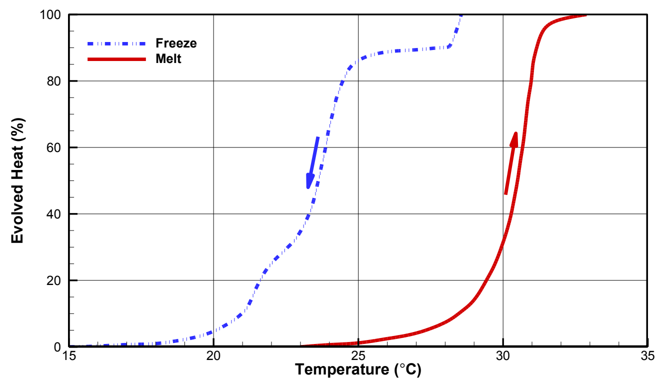


**Figure 12** Freeze and melt curves demonstrating hysteresis

In the previous analysis it was assumed that the commercial PCM examined does not exhibit hysteresis, but testing indicates that this commercial PCM can exhibit hysteresis. The melt and freeze curves are shown in Figure 12. The finite element model has been modified to represent a PCM with separate melt and freeze curves. In this implementation any melt transient follows the melt curve, and any freeze transient follows the freeze curve. This means that a PCM that has undergone a partial melt which then experiences a drop in temperature will maintain the constant melt fraction until the temperature has dropped sufficiently to intersect the freeze curve. Only after the freeze curve is intersected can the melt fraction decrease. A similar scenario occurs for a partial freeze followed by an increase in temperature. In Phoenix, the hysteresis reduced the effectiveness of the PCM in reducing cooling electricity use from 37% to 60% depending on the wall orientation, but in Baltimore the hysteresis had only a small impact on the savings.

However evidence suggests that this simple hysteresis model does not accurately represent the actual PCM behavior. Laboratory measurements show that when this particular PCM experiences a partial melt followed by a refreezing, the freezing process actually goes back down the melt curve rather than switching to the freeze curve. It appears that the PCM must experience a complete melt, and possibly even exceed the melt range upper bound, before the freezing process will follow the freeze curve rather than the melt curve. It is not clear what occurs when there is a partial freezing followed by remelting. The actual performance of the PCM in reducing cooling electricity use will fall somewhere between the two models presented. Further investigation into the phase change behavior of the PCM is needed.

## 4. CONCLUSIONS

The addition of PCM to a well-insulated wall appears to have a **minor impact on the overall cooling electricity** needed to meet the annual cooling needs. In south- and west-facing walls, the PCM can save ~0.33 kWh/m$^2$-year in Phoenix and ~0.17 kWh/m$^2$-year in Baltimore. However, PCM savings are greater **in walls with thermal bridges** than in idealized walls without bridges used for most of this analysis. (Phoenix: 62% Increased savings west wall, 30% increased savings south wall)(Baltimore: 80% south, 84% west). In all cases, the PCM wall system is **effective at shifting peak loads** and should be considered as a tool for utility demand reduction. Any cost benefit analysis should include savings for **time-of-day rates** where available. For example, in Phoenix, the system can save about 8% of the wall-related cooling electricity use, but about 30% of the wall-related cooling electricity cost when time of day rates are available.

**The most effective location for the PCM-cellulose layer is throughout the full thickness of the wall cavity.** Concentrating the PCM near the inner surface of the wall reduces cooling electricity use slightly as compared to PCM uniformly distributed through the entire thickness of the wall cavity. However, the performance of PCM placed closer to the interior is more sensitive to any variation in the indoor temperature setpoint, so the full thickness location is a more conservative choice. The full thickness application will also avoid the complexity and cost associated with with the installation of a layer of insulation/PCM and a then second layer of insulation only. The optimal amount of PCM within the wall will vary with the PCM properties, application type, and climate. In one case examined, about 50% of the PCM assumed here provided about 75% of the savings. Examining this issue will be important in any cost benefit analysis.
The midpoint of the melt range for a PCM must be chosen to target the specific load of interest, that is, an installation with a goal of reducing the peak demand will have a higher melting midpoint than an installation with a

goal of reducing annual electricity use. A PCM with a wider melt range, typical of 'real' PCMs, is more effective in Phoenix, while one with a narrow melt range is more effective in Baltimore.

Further work is needed in several areas. The impact of a PCM's melt/freeze characteristics, including hysteresis, were explored, and could cause significant changes in the PCM savings. However, experimental results show such behavior may vary, especially for partial melt-freeze cycles, so further experimental investigations are needed. Other locations within a building, in particular an attic location, will experience a different temperature variation, and may be a more effective location for a PCM system. The PCM properties that would optimize the savings for alternate configurations are likely to be different from those that optimize the savings for the wall application. Also, the potential impact on heating loads was small for these two climates, but should be investigated in cooler climates.

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## ACKNOWLEDGEMENTS

This work was supported by the Building Technologies Program within the U.S. Department of Energy under the direction of Marc LaFrance. Craig Christensen and Chuck Booten of the National Renewable Energy Laboratory worked to coordinate the three-study effort.