

Phase Change Materials for Thermal Management of Kennedy Library Study Rooms

A Senior Project

presented to

the Faculty of the Materials Engineering

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Bachelor of Science

by

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1. Introduction

With little air flow, no air conditioning system, and large glass windows that face the sun in the morning, the temperature can rise quickly inside Cal Poly’s Kennedy Library on a warm day. One of the worst spots to be in the Library on the hottest days of the year are the group study rooms on the fifth floor. This is because these small spaces, approximately 24 m³ and 30 m³, respectively, are on the top floor of the building and have one exterior wall that is mostly windows facing east that allows sunlight to enter the room directly during the morning. The heat already inside the building rises throughout the day and the sun’s rays add to this heat. This results in an interior temperature much greater than the outdoor temperature (Figure 1). This is a problem that needs solving as users deserve to have a comfortable room to study in the library.

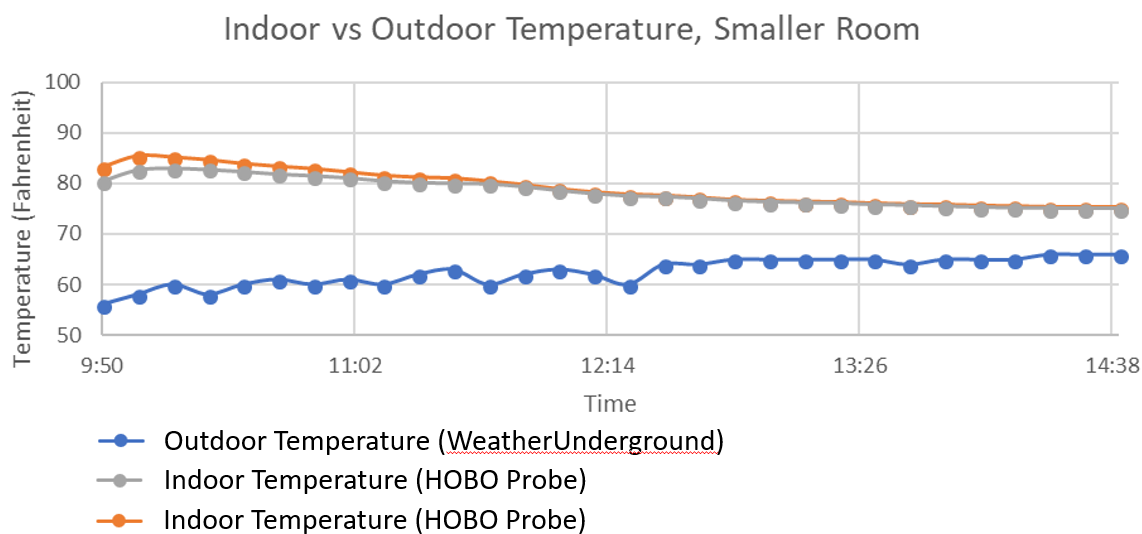


Figure 1. Temperature difference on April 19, 2018.

At their phase transition temperature, phase change materials (PCMs) release or absorb energy when solidifying or melting, respectively, in the form of heat without changing temperature. This amount of energy is called the latent heat of fusion and is a phenomenon that occurs as a thermodynamic equilibrium between the liquid and solid phases.¹ Once the material

is fully solid (after cooling) or liquid (after heating), the temperature of the material will drop or rise if cooling or heating of the material continues, respectively. All materials go through this phenomenon where the material's temperature lags the environment's changing temperature during fusion transformations.¹

PureTemp is a company that manufactures PCMs for insulation in buildings and for transportation solutions for temperature-sensitive goods using inorganic PCMs.² They use the method of macroencapsulation to hold their PCMs, where large panels, tubes, or pouches to hold the PCM.² Their products are used in many temperature-related applications, such as refrigeration, heat recovery, heat storage, and even vests for people to wear in hot work environments that will stay at 59 °F for up to two hours.² One use of their BlockVest is to line a container to maintain a constant temperature in the interior during transportation.² This is similar to the goal of reducing the internal temperature of the fifth-floor study rooms, except that the study rooms have the added factor of a wall made of mostly windows that receives direct sunlight for several hours in the morning.

An advantage of using an inorganic PCM, such as calcium chloride salt, is high latent heats of fusion. This means that less material is needed for an equivalent temperature reduction compared to an organic PCM. However, if its containment is broken, the salt is an irritant that can be harmful if ingested or inhaled. Being a health hazard is always a concern, which is why we are comparing health-friendly PCMs to the calcium chloride salt, which is not preferred for our final implementation.

From U.S. Climate Data, San Luis Obispo's average high temperature during the hottest months is about 27 °C, and the coolest months have an average high temperature of 16 °C.³ The hottest recorded temperature in San Luis Obispo is 45.56 °C.⁴ With this information in mind,

PCMs that change phase between 20 and 30 °C are targeted for use in the Library study rooms. On days where the temperature reaches 32 °C and higher, the 5th floor group study rooms can get uncomfortably hot. At 24 m³, the volume we are looking to cool by up to 20 °C requires 21.82 kJ of heat energy to change the room's temperature by one degree Celsius. Therefore, 436 kJ needs to be absorbed by the PCM to cool the room by 20 °C. PureTemp has developed several different PCMs, each of which change phase at a different temperature. At a room volume of 24 m³, 1.92 kg of PureTemp's product that absorbs 227 J/g at 23 °C is needed to keep the room 20 °C cooler than an outside temperature that is greater than or equal to 43 °C.

The organic PCM with the largest latent heat of fusion at the temperature range we are interested in is heptadecane at 167 J/g ($T_m = 21.7$ °C); paraffin waxes optimized for this use also have large ranges of melting temperatures and latent heats of fusion.⁵ For inorganic PCMs, the largest latent heat of fusion found is sodium sulfate decahydrate at 180 J/g, with $T_m = 32$ °C.⁶ Both organic and inorganic technical PCMs have high latent heats of fusion, but they have negative side effects on human health, so they will not be considered for full implementation.

Instead of hiding a room's thermal management system in its walls, floor, or ceiling, we want to make the thermal management technology visible in an aesthetically pleasing and thought-provoking way to the user. The melting and solidifying of the PCM can be visually interesting and useful for thermal management if the correct combination of PCMs and PCM packaging is implemented.

The hypothesis of this senior project is that PCMs that can provide effective, passive, and visually interesting thermal management of these study rooms in an environmentally- and health-friendly way that doesn't block a lot of sunlight from entering the rooms. The goals of this project are:

- To use a similar or lower quantity of PCMs to achieve the same thermal management effect as a commercially available PCM product.
- To use more environmentally-friendly and less toxic PCMs than a commercially available PCM product such as calcium chloride salt.
- To use visually interesting PCMs for thermal management.
- To find a vessel and method to attach this vessel to the windows of the study rooms that are non-destructive and reusable.

2. Literature Review

This literature review investigates organic and non-organic PCMs' ability to perform the task of thermal management and how to alter the PCMs' aesthetic to increase visual interest.

PCMs are already in use as temperature controls in the transportation and insulation industries as passive cooling systems. This means they are cheaper to use than conventional heating or air conditioning because apart from the energy to produce the PCM, almost no further energy is required to use it. For example, PCMs were implemented in buildings in Chile as they have extreme temperature swings in the summer and winter months between day and night time temperatures.⁷ The paraffin wax that was used was expected to absorb the daytime heat through melting, providing more comfortable conditions. Then when the temperature dropped during the night, the PCM solidified, giving off the heat energy absorbed during the day.⁷ This provided a more stable temperature throughout the day without added energy costs.⁷ Different installation methods were implemented by two different teams of engineers.⁷ Both methods involved micro-encapsulation of paraffin wax: polymer microspheres containing the wax embedded in gypsum boards.⁷ One method had water circulating between these boards to transfer heat more efficiently.⁷ The second method involved panels mounted on the inside surface of a glass façade.⁷ The panels had hollow cavities to hold the PCM, with the layer facing the outdoors made of ETFE-foil (ethylene tetrafluoroethylene) to reduce the amount of solar gain entering the building.⁷ The PCM then absorbs heat from the solar gain that does enter the building, and, since the paraffin wax has a transition from an opaque solid to a translucent liquid, the “grade of transparency” of the wax shows how much energy the PCM had absorbed.⁷ Finally, to release the heat captured by the PCM throughout the day, the panels were moved to a “central chimney,” which produced a “chimney effect” to passively move cooler outdoor air over the surface of the

panels to maximize heat transfer from the latent heat of the PCM to the cooler night air, solidifying the PCM and allowing it to absorb more heat the next day.⁷ The advantages seen by the building in Chile were cooler interior temperatures.⁷ However, the up-front costs and the added effort of moving the sheets to the chimney at the end of the day were recognized as negative aspects.

3. Method and Materials

Heptadecane and sodium sulfate decahydrate are some of the best PCMs for absorbing heat energy. However, both chemicals can be harmful if ingested or inhaled.^{8,9} To err on the side of caution, these PCMs were avoided but were used as references for other PCMs that were investigated in this project. The materials chosen for testing included heptadecane, calcium chloride salt provided by Insolcorp, coconut oil, red palm oil, white chocolate (containing palm oil, dairy products, and sugar), an assortment of honeys (Figures 2 and 3), and technical palm oil (Figure 4). These were chosen for their optical properties, their relatively low toxicity, and for having transition temperatures in the desired range.



Figure 2. Candidate PCM materials. From left to right: Heptadecane, coconut oil, red palm oil, and white chocolate.



Figure 3. The honeys that were studied as candidate PCMs.



Figure 4. Container of technical palm oil manufactured by SavEnrg. Waxy and opaque when solid; clear when liquid.

3a. Characterization of PCM Thermal Properties

Differential scanning calorimetry (DSC) was used for determining which candidate PCM(s) provide the best heat absorption. DSC measurements were completed using TA Instruments' DSC Q1000. The DSC inputs heat flow to a furnace with an empty reference pan and a pan containing the sample of interest. As both pans were heated, a thermocouple measured their relative temperature difference. At a phase transition, the temperature of the sample pan ceased rising due to the sample's latent heat of fusion. This signaled the computer to increase the heat flow to the furnace until the temperature of both pans rose again. The axes of the resulting graph were watts per gram (W/g) on the y-axis and temperature ($^{\circ}\text{C}$) on the x-axis, with a peak (endothermic reaction) or valley (exothermic reaction) occurring over the temperature range of a phase transition. This was helpful in determining the heat energy each material absorbs per gram during the phase transition or in finding that no phase transition occurred that absorbed a significant amount of heat energy.

The DSC was run at $10.00\text{ }^{\circ}\text{C}$ per minute from $10.00\text{ }^{\circ}\text{C}$ to $55.00\text{ }^{\circ}\text{C}$ and then back down to $10.00\text{ }^{\circ}\text{C}$ at $10.00\text{ }^{\circ}\text{C}$ per minute. This cycle was then repeated: the first cycle was to give the materials a consistent thermal history, giving the second cycle higher quality data. Data from the second cycle was cited in this report. The range of temperature was chosen to represent the expected temperature range of the Library study rooms ($15\text{ }^{\circ}\text{C}$ to $45\text{ }^{\circ}\text{C}$) plus an additional margin as the DSC can give faulty data when it gets within several degrees of when it was about to reverse its temperature scan. The rate of $10\text{ }^{\circ}\text{C}$ per minute was chosen on the recommendation from the lab technician, as it produced good data without being exceptionally slow. The calcium chloride was cycled through the DSC from $0\text{ }^{\circ}\text{C}$ to $65\text{ }^{\circ}\text{C}$ at $5\text{ }^{\circ}\text{C}/\text{min}$ and then back down to $0\text{ }^{\circ}\text{C}$ at $5\text{ }^{\circ}\text{C}/\text{min}$, and repeated as the first attempt of this experiment showed that it had not

recrystallized after the first cycle. This temperature range and scan rate would not work for the honey, since honey crystallizes at 12.78 °C and takes a significant amount of time to crystallize. For honey to have a phase transition, it must first crystallize. The method to crystallize honey is called “spinning.” This process was done through seeding liquid honey with small crystallites of pre-crystallized honey and whisking the mixture rapidly. Once whisked, the container holding the honey was submerged in 13 °C water until crystallized.¹⁰ The spun honey was used in the DSC to compare with the liquid honeys.

A second method of finding the best PCM candidate was finding the melting temperature of each material. The DSC can be helpful in finding a range for the melting temperature but may not find an exact melting temperature. In this method a hot plate heated up a 50 mL glass beaker of water used as a water bath for this experiment. An approximately 1.5 mL sample of each PCM in solid form was placed in its own 2 mL plastic vial that was then placed in the water bath (Figures 5, 6). A thermometer was inserted so that its bulb was in contact with the solid material. A rubber band twisted around the thermometer near the bulb was used to seal the gap between the thermometer and the sides of the vial to minimize the escape of heat energy during the experiment. The melting temperature was determined by two factors: when the thermometer paused rising and when there was an optical change in the material (e.g., coconut oil transitions from opaque to translucent when melting). The aim of this experiment is to give a more precise melting temperature than the DSC.

This experiment was run twice for two reasons. First, to give the PCM a thermal history. This was done for the same reasons explained in the DSC methodology. Second, the test was repeated to show that the transition temperature is consistent.

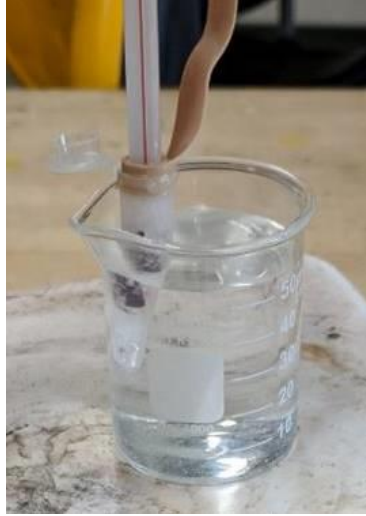


Figure 5. Setup of the transition temperature experiment.



Figure 6. Candidate PCMs prepared in 2 mL vials for the melting temperature measurement. From left to right: Heptadecane, calcium chloride salt, coconut oil, red palm oil, and white chocolate.

3b. Vessels for PCMs and their Installation

The architecture members of our team were tasked with designing a vessel to hold the PCM. Several different ideas, such as perfume bottles, scientific beakers, and 3-D printed vessels, were rejected by the team due to cost and concerns about the visibility of the PCM. The vessel design that was selected for this study was a hollow glass tile. This tile was made by using a water jet to cut 1/8-inch thick glass to make the outer walls of the vessel and 1/4-inch thick glass to be sandwiched between the outer walls of glass to form a hollow cavity to hold the PCM (Figure 7).

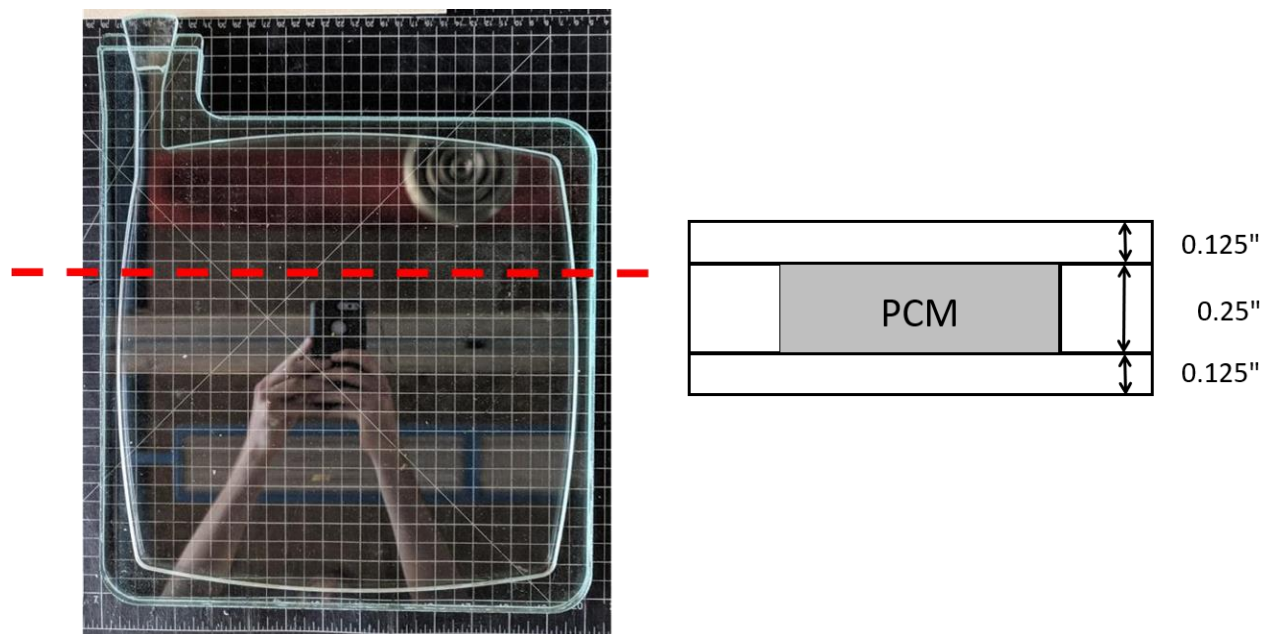


Figure 7. Plan view of assembled hollow tile on left. The diagram on the right shows a cross section view of the hollow tile through the dotted red line.

The tiles were filled with PCM by heating the PCMs to their liquid state in a glass beaker on a hot plate, then pouring the PCM through a plastic funnel inserted into the neck of the hollow cavity. For most of the PCMs, this method worked acceptably. However, the white chocolate had to have about 1 gram of coconut oil added to every 15 grams of white chocolate in order to achieve a suitable viscosity, and the tile was submerged in warm water during filling to make the white chocolate flow and fill the hollow cavity thoroughly. Even with these measures, it took approximately 5 hours to fill the tile with white chocolate. Also, the calcium chloride salt turned into more of a viscous slurry than a liquid when heated, and it was unable to flow into the tile. Hence the technical palm oil was substituted for it in the subsequent proof-of-concept experiment.

Instead of hanging or permanently attaching a PCM vessel to windows or walls, an easily detachable, non-destructive, and reusable method was preferred. A company called GeckSkinTM manufactures the GripHangerTM, a high surface area, soft polymer pad attached to a hook via a

strong and flexible clear polymer strap called a tendon (Figure 8). The company named themselves GeckSkin™ to draw parallels between their high surface area pad plus tendon and how gecko feet work in adhering to vertical surfaces. Gecko feet are not sticky in the same way a fly trap is sticky. Instead, they utilize folds and follicles in their feet to increase the contact surface area between their foot and a surface, and tendons in their feet hold the load by transferring the load over the large surface area of their feet. Similarly, the high surface area pad on GeckSkin™'s products allows for maximum contact onto a vertical glass or wall, and the strong polymer transfers nearly all the weight attached to the hook to the glass.

Several GripHanger™ straps were purchased and tested for this project. In a paper written by the professors who started this company, a description of how to make homemade GeckSkin™ was given.¹¹ Latex, muslin (a cotton fabric), tape, and a clean, flat surface are required to make homemade GeckSkin™. The clean, flat surface used was a pane of glass to maximize the surface area contact of the GeckSkin™. The tape was used to build up a rectangular mold into which a thin layer of latex was painted (Figure 9). A strip of muslin was laid on top of the first layer of latex, and another layer of latex was then painted on top of the muslin to fully wet it so that the muslin can transfer the load to the latex. The muslin extended past the edge of the latex mold, so objects could hang from the muslin strip. Once the latex had dried, the finished product was peeled from the tape mold. To mimic the professionally made GeckSkin™, a clothes hanger was attached to the muslin strip by wrapping the excess muslin around the hanger and using latex to adhere the muslin to itself (Figure 10).

Before the commercial GripHanger™ arrived, a homemade version was made with pad dimensions of 5 inches by 3.5 inches to see how much load a homemade version could hold. The

rest of the homemade GripHangers™ had the same pad dimensions as the commercial product so that they could be compared.



Figure 8. Commercial GripHanger™. One-inch by 2-inch surface-area polymer pad on right, attached to packaging to preserve surface to be stuck to glass and placed on top of an index card for visibility.

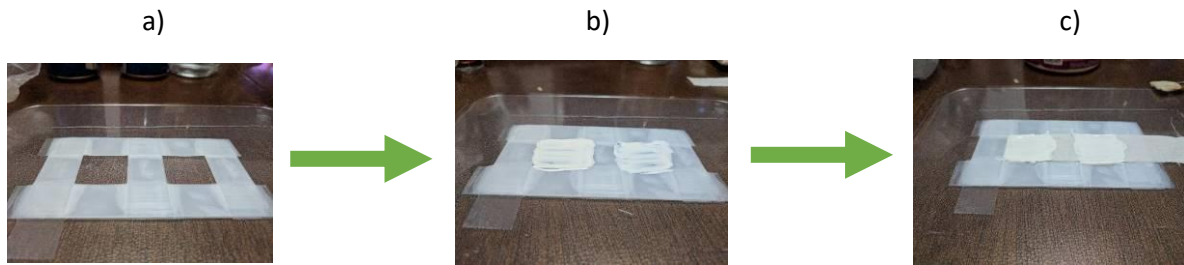


Figure 9. Process of making homemade GripHanger™. Tape mold is built up (a), then the bottom layer of latex is painted into the mold (b), and then the muslin is laid on top with a second layer of latex painted on top of it to fully wet it (c).



Figure 10. Homemade GripHanger™ attached to clothes hanger.

To see if the homemade GripHanger™ was comparable to the commercial GripHanger™, roughness measurements were performed on the GeckSkin™s and the pane of glass used to make the homemade version. This test was conducted using a Mitutoyo SJ 201 P/M surface tester. The Mitutoyo SJ 201 P/M works by running a stylus head over a surface and measuring the flexion the head induces on the stylus arm. This makes it precise and accurate for hard surfaces, but less so for flexible, rubbery surfaces like the GeckSkin™. The pane of glass, the commercial GeckSkin™, and three generations of homemade GeckSkin™ were tested using this instrument. The machine took five 2.5 mm-long scans over the pad material and averaged the roughness measured by the stylus head over the five scans. The roughness of the pane of glass was averaged over five 0.25 mm-long scans, since the surface tester was more consistent with harder surfaces. This experiment was run three times on each sample, and the results of the three runs were averaged to obtain an average roughness.

A load-bearing test was done to compare the commercial GripHanger™ to the homemade GripHanger™. This was accomplished by attaching a 5 pound weight to the hook of each GripHanger™. The GripHanger™ that adhered to the window for a longer period was deemed the better choice for implementation in the Library.

3c. Tailoring the Aesthetics of an Inorganic PCM

If the calcium chloride proved to be the most useful PCM, changing the color to improve its aesthetic would be ideal. The calcium chloride naturally occurs in a dull beige color (Figure 11). It was hypothesized that the color of the calcium chloride could be altered by introducing F-centers into the salt. This was done by irradiating the calcium chloride with X-rays. The Bruker Tracer III-SD X-ray fluorescence (XRF) handheld device and the Siemens Kristalloflex

Diffraktometer D5000 X-ray diffractometer (XRD) were used to try to produce F-centers in the calcium chloride crystals, which are point defects (vacancies) in the structure that can be filled by electrons to effectively introduce a band gap defect state, thus changing the color of the material.

The XRF instrument used an accelerating voltage of 20 kV with a rhodium target to emit X-rays.¹² The setup had the XRF device facing upwards with its protective cap seated over the sample. The sample was a line of the salt aligned with the emitter, so that the device could sense a sample and emit X-rays. The salt was wrapped in plastic wrap to hold it in place. The XRD was run at 30 mA, 40 kV accelerating voltage, and at 0.1 degree increment per second. It uses a scanning X-ray emitter to irradiate a sample of the PCM sitting on a glass slide (Figure 11).



Figure 11. Dull beige inorganic PCM (calcium chloride salt).

3d. Proof-of-Concept Experiment

The team thought it prudent to save resources and do a small scale, proof-of-concept experiment before applying many glass tiles to the fifth-floor study rooms, as on campus water jet cutting capability is very limited and takes a lot of time to use. This made it difficult to produce the hollow glass tiles in large quantities.

Six boxes each having a one cubic foot interior were made from 2-inch closed cell polyurethane foam, with one wall of each box being the glass tile filled with a candidate PCM. The edges on the inside of the box were filled using Great Stuff[®] spray insulating foam (Figure 12). Unfortunately, the calcium chloride salt was unable to enter the through the fill hole of the PCM vessel, so PureTemp's technical palm oil replaced the salt to represent a commercial PCM for the proof-of-concept experiment. The top foam wall of each box had a hole punched through the center so that a HOBO temperature probe could be inserted to measure the interior temperature of the box (Figure 12). The six boxes were arranged on the roof of Building 5 on the Cal Poly campus to face the same direction as the fifth-floor study rooms (Figure 13). The HOBO dataloggers captured temperature data over 48 hours so that the interior temperature of each box could be compared. The outdoor temperature was found by WeatherUnderground to compare to the internal temperature of the boxes. The goal was to find the PCM that reduced the box's interior temperature the most in this proof-of-concept experiment. A PocketLab Voyager with a temperature probe was used to periodically measure the outside temperature at the location of the experiment. (The PocketLab Voyager requires a Bluetooth capable device to be linked to it at all times to record data, which was not feasible for continuous outside temperature measurement over a 48 hour experiment.) It was found that the actual midday temperature was about 9 °C warmer and the actual nighttime temperature was about 3 °C warmer than the reported WeatherUnderground temperature.



Figure 12. Interior of proof-of-concept experiment box, showing insulating foam and HOBO temperature probe at top.



Figure 13. Proof of concept experiment setup. From left to right: Tiles filled with honey, coconut oil, red palm oil, heptadecane, PureTemp's palm oil, and white chocolate.

4. Results

4a. Thermal Properties of PCMs

Analysis using the TA Universal Analysis software provided important thermal properties (Table 1) for the success of the candidate PCMs, such as heat capacity and latent heat of fusion. Table 1 also has the density of the PCMs at 25 °C.

Table 1. PCM Properties

PCM	Heat Capacity [J/(g*°C)]	Latent Heat of Fusion [J/kg]	Density @25 °C [kg/m ³]
Heptadecane	24.226	125400	777 ⁸
Calcium Chloride Salt	2.089	19540	860 ¹³
Coconut Oil	0.835	1263	903 ¹⁴
Red Palm Oil	0.493	2102	887 ¹⁵
White Chocolate	4.869	24000	947 ¹⁶
Average Honey	0.269	19.969	1420 ¹⁷
Water	4.127 ¹⁸	334000 ¹⁸	997 ¹⁸
Technical Palm Oil	1.990 ¹⁹	227000 ¹⁹	830 ¹⁹

The DSC results in Table 2 were also produced using TA Instruments' Universal Analysis. Some important features of the DSC curves are the peak height, the area under the peak, the transition temperature range, and the post-transition energy absorption (Figure 14). The peak height was defined as the difference between the maximum value of W/g of the peak and the W/g value immediately to the right of the second inflection point (Figure 14). The positions of the endothermic peak and the beginning and the end of the phase transition were found, and the area under the peak was found using the "Integrate Peak" function of the software. The area

under this peak correlates with the latent heat of fusion and was taken from the first inflection point to the second inflection point (Figure 14). The transition temperature range was measured from the first to the second inflection point. Finally, the post-transition energy absorption was the steady state W/g value just after the second inflection point, since some of the PCMs do not have a stable W/g value before the peak.

Table 2. DSC data for candidate PCMs

Sample	Transition Temps (°C)	Peak Height (W/g)	Energy Absorbed (J/g)
Heptadecane	21.02 to 33.57	2.6439	125.4
Calcium Chloride Salt	15.59 to 27.76	0.22585	19.54
Coconut Oil	24.23 to 30.42	0.0828	1.263
Red Palm Oil	22.20 to 29.18	0.0405	2.102
White Chocolate	19.88 to 36.83	0.2796	24
Average Honey	N/A	N/A	0.020

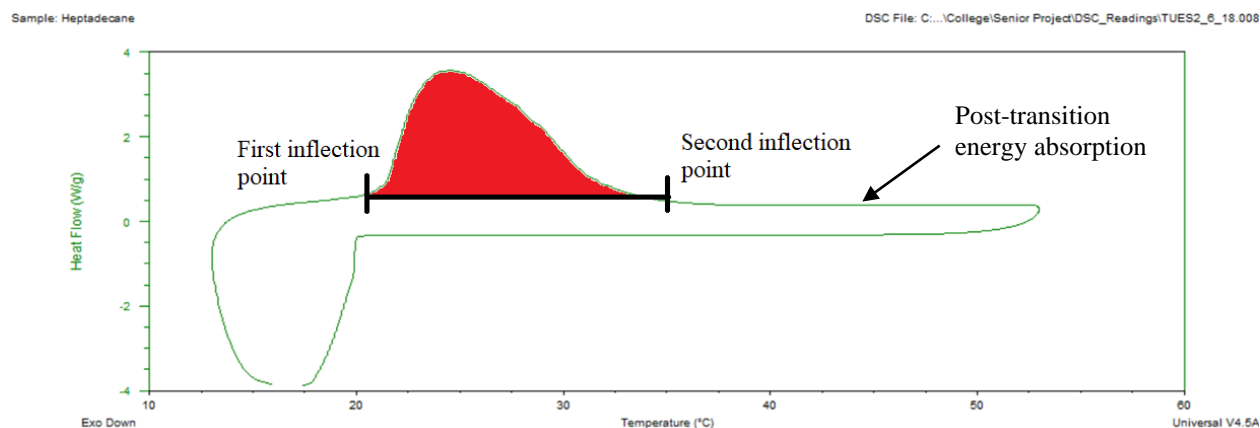


Figure 14. Diagram of DSC curve. Area under the endothermic peak (red) is correlated with latent heat of fusion.

Since the honeys did not have a phase transition peak, an estimate of the energy absorbed per gram was found by using the “Integrate Peak” function from 30 °C to 40 °C as most phase transitions of the other PCMs occurred over about 10 °C near this range and the slope of the DSC

curve over this temperature range is consistent throughout the entire DSC cycle for the honeys. After finding that the honeys (including the spun honey) had approximately the same thermal properties, thermal characteristics of an “average honey” were found by averaging each of the phase transition temperature range, the peak height, and the energy absorbed over all the honeys that were tested.

DSC results (Figures 15a – 15e and Table 2) showed that three of the PCMs absorbed significantly more energy per unit mass than the other PCMs (highlighted in green in Table 2). Heptadecane and the calcium chloride salt are, as expected, two of the top three PCMs at absorbing energy. Interestingly, the white chocolate performed exceptionally well, even absorbing more energy per gram than the calcium chloride salt. A magnitude lower in energy absorption than the calcium chloride salt were coconut oil and red palm oil, which performed approximately the same. These two candidate PCMs performed moderately well (indicated in yellow in Table 2) relative to the other PCMs. Finally, the honeys did not absorb energy well, which is why the “Average Honey” is highlighted in red in Table 2.

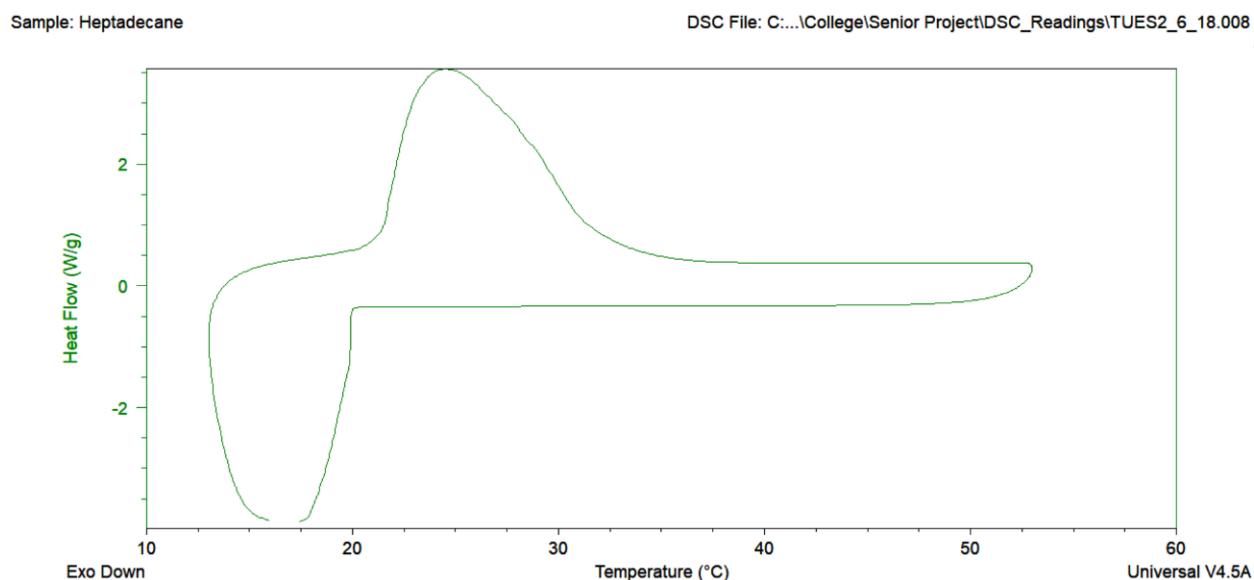


Figure 15a. Heptadecane DSC curve.

Sample: Anhydrous Salt

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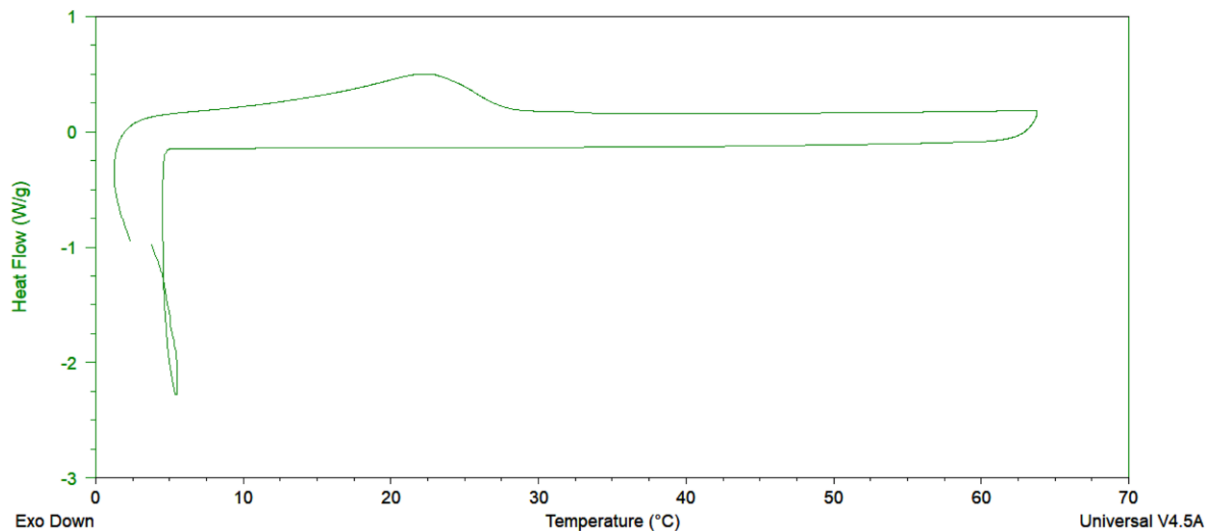


Figure 15b. Calcium chloride salt DSC curve.

Sample: Coconut Oil

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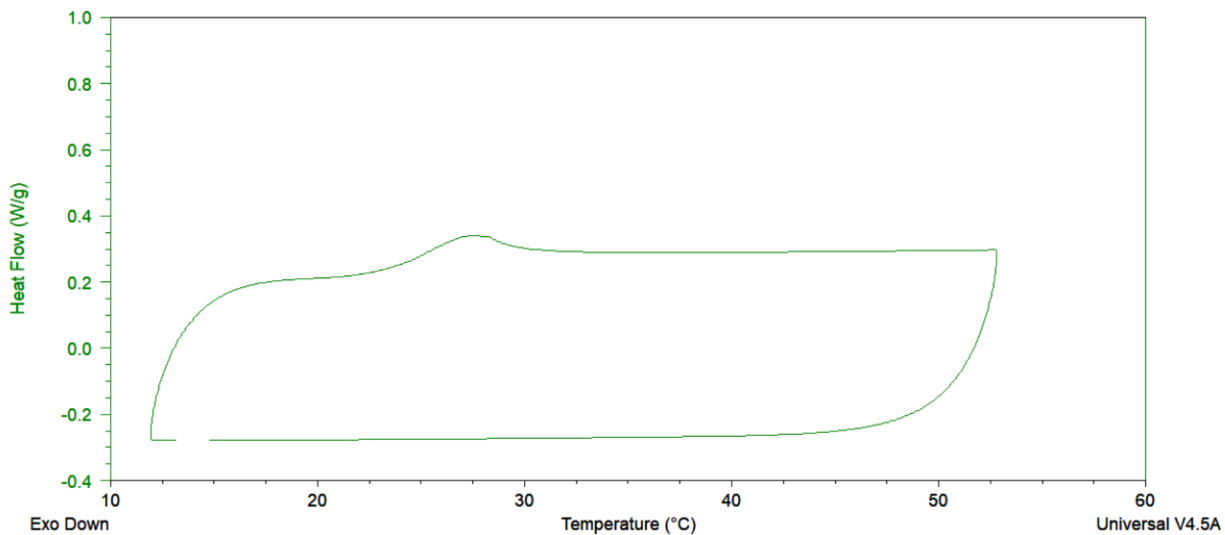


Figure 15c. Coconut oil DSC curve.

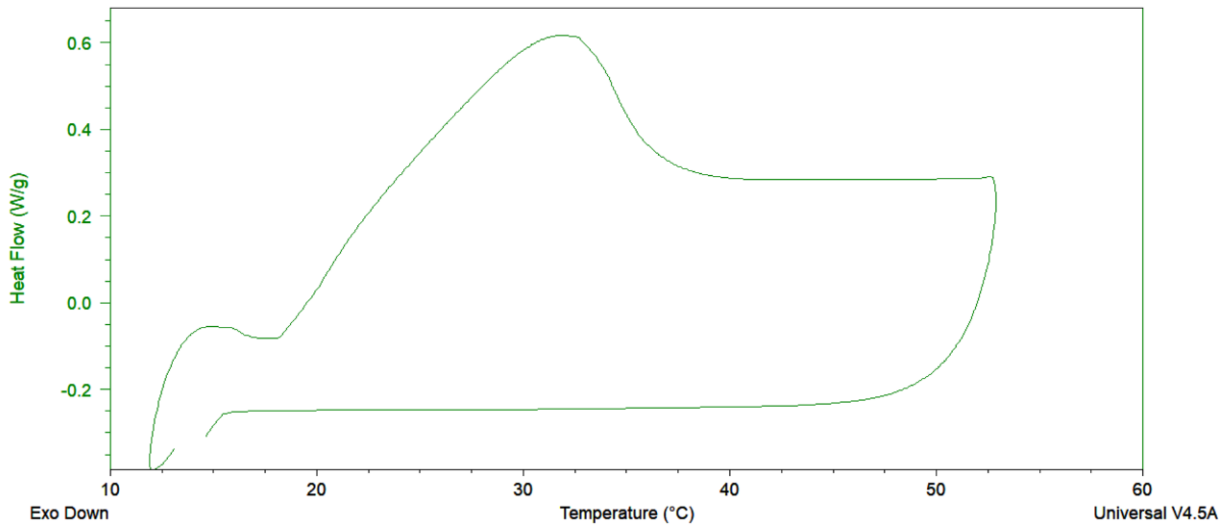


Figure 15d. White chocolate DSC curve.

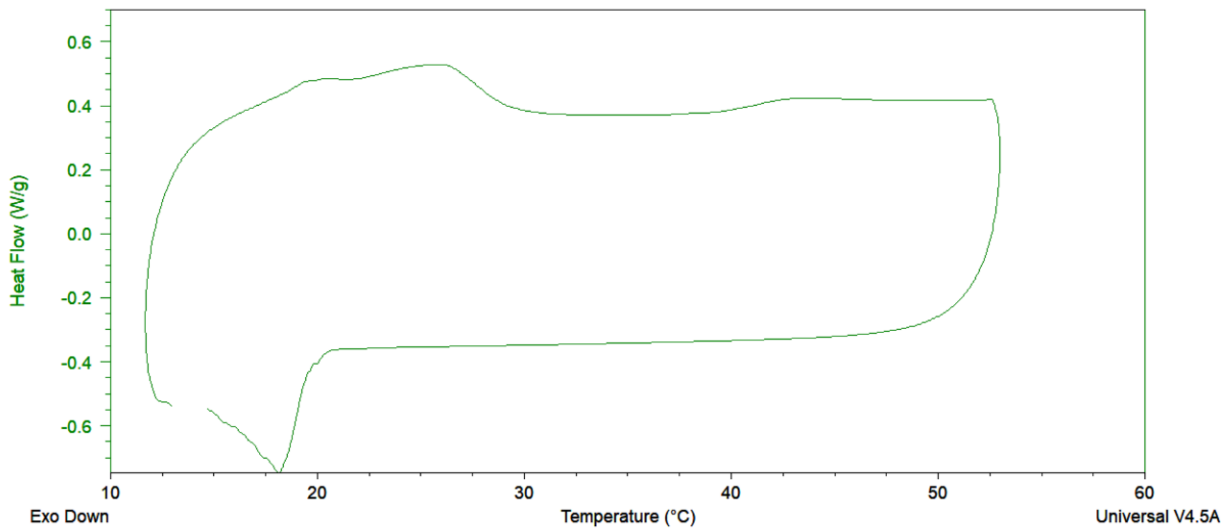


Figure 15e. Red palm oil DSC curve.

The results of the melting temperature experiment are shown in Table 3. The solid to liquid transition of some materials were easy to see by a visual cue. For example, both the heptadecane and the coconut oil transitioned from an opaque solid to a translucent liquid.

However, the solid to liquid transition of other materials were more difficult to see visually, so the thermometer reading when the temperature stopped rising was relied upon more than visual cues. Examples of this were the calcium chloride and the red palm oil, both of which do not have a strong visual cue that the solid to liquid transition was completed.

The “Average Transition Temperature” column is highlighted green in Table 3 for each PCM for two reasons. First, the transition temperature range for each PCM overlapped between the two runs. Second, the average transition temperature of each PCM was in the desired range for the study rooms.

Table 3. Melting temperature results of candidate PCM

Sample	Cycle	Hot Water Bath Temperature (°C)	Transition Temperature(s) (°C)	Average Transition Temperature (°C)
Heptadecane	1	32	23-26	25.25
	2	45	24-28	
Calcium Chloride	1	30	25-27	26.75
	2	45	27-28	
Coconut Oil	1	28.5	24-26	23.75
	2	45	21-24	
Red Palm Oil	1	33	23-26	24.75
	2	45	23-27	
White Chocolate	1	32	26-27	27
	2	40	27-28	

4b. Results: PCM Vessel and Installation

The surface roughness results for the GeckSkin™s are shown in Table 4. Predictably, the glass has the most consistent surface roughness. The GeckSkin™s have rougher surfaces, especially the homemade ones. The surface roughnesses that are highlighted in green in Table 4 indicate smooth and consistent surfaces, relative to the commercial GeckSkin™. However, the most recent homemade version could hold a load for a longer time than the other homemade versions, indicating that surface roughness may not be the only factor determining how well a GripHanger™ performs.

The results of the load-bearing experiment for the different GeckSkin™s found that the homemade version was unable to bear a five pound load, whereas the commercial version held a five pound load for over six hours. Since the hollow glass tile weighs two pounds and approximately one pound of each PCM can fit inside each tile, the GripHanger™ should be able to hold a vessel filled with PCM for many hours.

Table 4. Average surface roughness R_a of Geckskin™s

Sample	Ra (micrometers)	Average Ra (micrometers)	Length of Measure (mm x number of scans taken)
Glass Surface	0.3	0.30	0.25 x 5
	0.3		
	0.3		
6" x 3.5", old, homemade Geckskin™	3.28	2.66	2.5 x 5
	2.03		
	2.68		
1" x 2", new, homemade Geckskin™	2.78	6.62	2.5 x 5
	6		
	11.09		
1" x 2", old, homemade Geckskin™	1.78	3.11	2.5 x 5
	4.61		
	2.93		
1" x 2", Commercial Geckskin™	2.51	2.07	2.5 x 5
	2.62		
	1.07		

4c. Results: Aesthetics of an Inorganic PCM

The XRF experiment to introduce F-center defects into the calcium chloride PCM did not appear to change the color of the PCM. The Bruker device is only able to run continuously for a period of 15 seconds, and after 25 irradiations the color of the salt was unchanged. Additionally, after two cycles of irradiation of approximately 30 minutes each through the XRD, the color of the same salt sample was unchanged (Figure 16).



Figure 16. Photos of calcium chloride salt before and after X-ray irradiation. No significant color change was observed.

4d. Results: Proof-of-Concept Experiment

Recording of temperature data inside the proof-of-concept boxes was done using HOBO H21-USB Micro Station dataloggers and probes. The amount of data that was captured crashed the Excel software, so temperature data is shown on two separate temperature plots (instead of a single plot) from the HOBO software (Figures 17a and b). The outdoor temperature was found using WeatherUnderground from the Bond Street station (Figure 18).

White chocolate performed notably better than the rest of the PCMs, including the commercial palm oil and the heptadecane. This phenomenon could be due to the shading that the white chocolate produced. All of the PCMs turned somewhat translucent after their phase change except for the white chocolate, which stayed opaque. This shading kept the internal temperature of the white chocolate's box much lower than the other boxes as direct sunlight contributes significantly to an increase in temperature in the boxes. Direct sunlight can be correlated to increased temperature in the boxes as the outdoor temperature does not reach its maximum until mid-afternoon, whereas the boxes' temperatures peak before noon and decrease once the sunlight no longer hits the PCM vessel (Figures 17a, 17b, and 18).

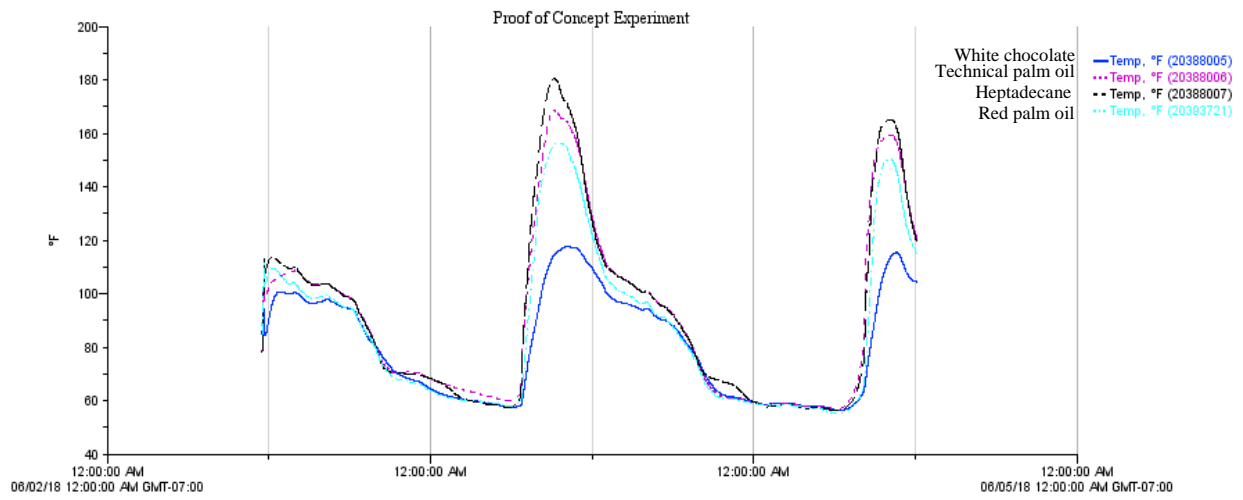


Figure 17a. White chocolate, technical palm oil, heptadecane, and red palm oil internal box temperatures.

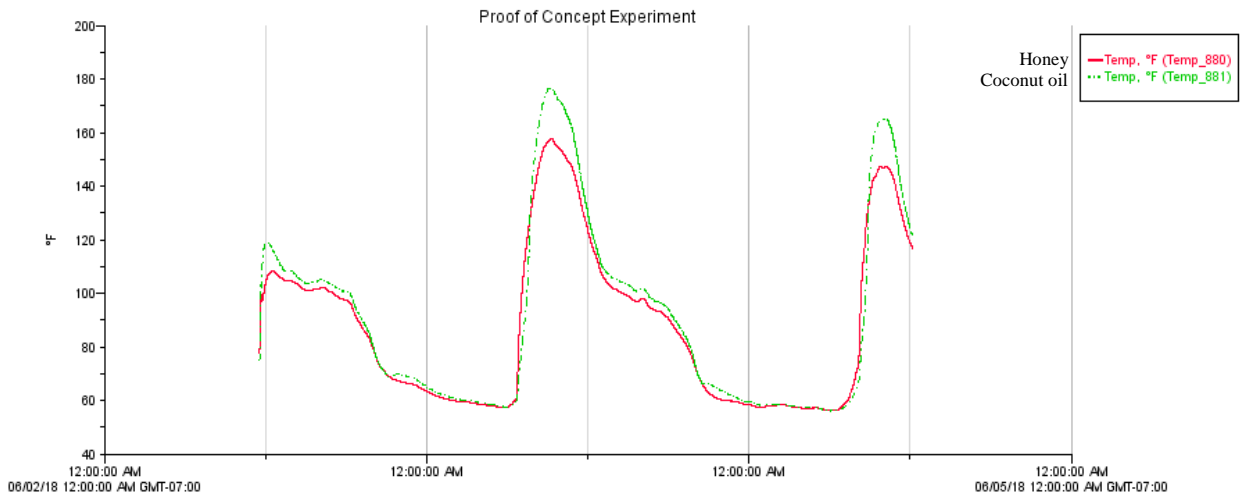


Figure 17b. Honey and coconut oil internal box temperatures.

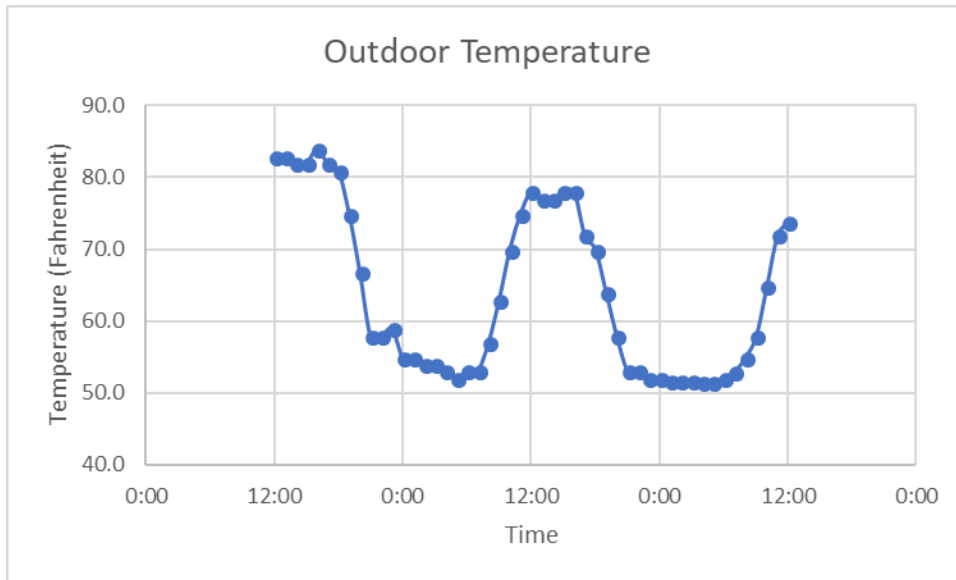


Figure 18. Outdoor temperature over the course of the 48-hour proof-of-concept experiment.

The boxes with PCMs having the two next lowest internal temperatures were the red palm oil and the honey. These two performed moderately well, again likely due to having better shading ability compared to the PCMs that are substantially translucent (coconut oil, heptadecane, and technical palm oil).

5. Analysis

5a. Analysis: Thermal Properties

The DSC results indicated a promising selection of PCMs that are not dangerous to humans or for the environment. The honeys did not absorb as much heat as coconut oil, red palm oil, or white chocolate. Palm oil, however, has a large impact on habitat destruction.²⁰ To lower the lifetime environmental impact of the PCMs, palm oil is not recommended for the final implementation in the study rooms. Coconut oil has the smallest temperature range over which its solid to liquid transition occurs while having comparable energy absorption to red palm oil. White chocolate performs surprisingly well, with similar energy absorbed as the calcium chloride salt. This is likely due to the relatively large range over which its transition occurs. With an estimated 800 kJ needed to be absorbed to cool the room by 20 °C on an exceptionally hot day and using the data from Table 1, 33.3 kg of white chocolate would be needed, compared to 6.4 kg of heptadecane, 380 kg of red palm oil, and 633 kg of coconut oil. This is assuming that the DSC data is representative of the bulk material, and that the vessel containing the PCM perfectly transfers the heat to the PCM. These amounts of PCM are incompatible with the team's goal of maintaining visibility from the study rooms' windows, as this much of the candidate materials would cover the entire window.

The melting temperature experiment matches the DSC curves with the average melting temperature falling within each PCM's DSC endothermic peak. This indicates that a phase change is being seen at the endothermic peaks of the DSC curves. The DSC and the transition temperature tests have overlapping transition temperature ranges, showing consistency of the phase transition temperature, although the transition temperature experiment has a narrower range.

5b. Analysis: PCM Vessel and Installation

The method for installing the PCMs to a window using commercial GeckSkin™ appeared promising. The homemade GeckSkin™ appeared to have too rough or inconsistent of a surface to hold a vessel containing a PCM for an extended period (i.e., hours to days). This could be attributed to the Mitutoyo SJ 201 P/M surface tester not being ideal for softer surfaces and possibly dragging the latex in the sample over itself and reading that as exceptionally uneven. However, the commercial GeckSkin™ was less rough and had more consistent readings. Also, the results indicate that the smoothness of the surface does not seem to correlate with an increased ability to bear a load. Correlation between smoothness and load-bearing ability had been expected, but was not observed. The older homemade versions of GeckSkin™ had smoother surfaces yet lesser ability to stay attached to a window pane than the newer but rougher version. This signifies that the smoothness of the GeckSkin™ is not the only variable that affects its load-bearing ability.

The vessel performed moderately well at containing the PCMs. There were several problems with the hollow tile vessel design that became apparent. Filling the vessels with PCM was difficult and time consuming, especially when the PCM in question was very viscous. One way this could be solved is by filling the hollow cavity of the vessel before the vessel is epoxied. This could be done by affixing the middle layer of glass to one of the outer walls of glass, filling the cavity with PCM, then affixing the second outer wall to seal the PCM. Moreover, for a full implementation, there needs to be a way to attach the GripHanger™ hook to the vessel. This would involve a redesign of the vessel.

Another factor that must be addressed is the longevity of the PCMs. White chocolate, red palm oil, and coconut oil all have shelf lives of about 5 months, so rancidity may be an issue if

these PCMs are used for a period of longer than several months. PCM candidates with better longevity are preferred.

The vessel used in this project had trouble staying sealed. The plug that was to act as a cap to the fill hole of the vessel had to be cut using the water jet. Because the plugs would fall through if cut out of the glass, they had to be cut only partially and then popped out. This method left a small nub of glass on each tab, making them unusable (Figure 19). Instead, duct tape was used to seal the fill hole of the vessel. If the nubs on the caps could be eliminated in the production of the vessel, this would likely seal the fill hole better than the duct tape.

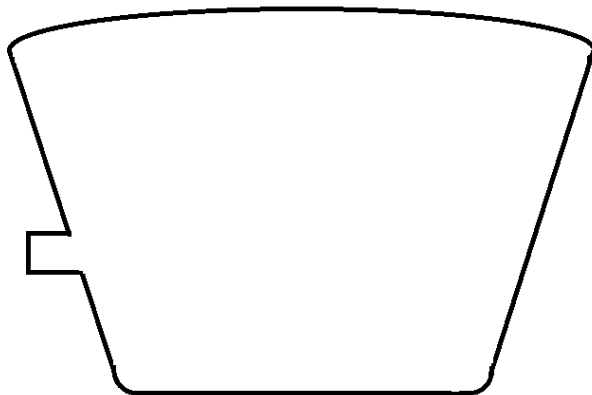


Figure 19. Plan view schematic of the shape of the glass plugs for the hollow tile PCM vessels. The small nub on the left side of the plug made them effectively unusable.

5c. Analysis: Aesthetic of an Inorganic PCM

The results of XRF irradiation of the calcium chloride salt were inconclusive. Perhaps F-center defects were occurring but there were not enough to visibly change the color of the calcium chloride, or perhaps a more intense X-ray source was needed to change the color of the calcium chloride sample. Regardless, due to calcium chloride's detrimental human health effects, its use is not recommended.¹³

5d. Analysis: Proof-of-Concept Experiment

White chocolate appears to be a promising PCM, as it was the most effective at maintaining lower temperatures in the interior of the proof-of-concept box during the day time when the outside temperature was at its maximum. Honey and red palm oil also performed well. The PCMs whose liquid phase were highly translucent performed the worst, despite heptadecane absorbing the most energy per gram according to DSC results.

The fact that the maximum temperature in the boxes peaked before the maximum outdoor temperature is indicative of two things: (1) direct sunlight is the main cause of increased internal box temperature, and (2) the more sunlight that is blocked by the PCM leads to a smaller increase in internal box temperature. These two factors lead to the conclusion that the amount of sunlight that is blocked is important in selecting a PCM to lower the internal temperature of a room.

6. Conclusions

It is recommended that white chocolate be used as a window treatment to help with the Library study rooms' thermal management. However, given the difficulty of filling the hollow tiles with white chocolate, a re-design of a vessel to hold the white chocolate is recommended. This re-design should include some means of attaching the commercial GripHanger™. Also, further testing should be conducted into the homemade GeckSkin™ to see if there is a better way to produce higher quality GeckSkin™, such as pouring the latex into the mold rather than using a paint brush to spread the latex in the mold. Also, the commercial GeckSkin™ does not visually look like the homemade version, indicating a different material. Switching to a silicone or another moldable rubber could result in a better homemade version of the GeckSkin™.

Further testing should also be done on combinations of PCMs to see if a further decrease in internal temperature in the proof-of-concept experiment boxes and an increase in longevity can be achieved. Additionally, testing should be done on the effect of shading on internal room temperature.

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