Phase Change Materials in Refrigeration

EFFICIENCY VERMONT RESEARCH & DEVELOPMENT REPORT

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Introduction

In this 2020 Efficiency Vermont R&D paper, phase change materials in multiple refrigeration applications will be discussed. It is important considering the nascent nature of this technology that efficiency programs remain curious about how current and future forms of PCM may be applicable to Vermont. For this reason, Efficiency Vermont took the opportunity to explore a few applications during the 2020 R&D calendar year to determine PCM potential viability in Vermont. This paper will follow a natural chronology of Efficiency Vermont's research in the field of PCMs. First, definitions and scoping of PCMs will be presented. Then, a small-scale Vermont prototype will be designed, tested, and discussed. Finally, the paper will dive into an identified future opportunity and break down the potential for PCMs in cold chain in Vermont.

Background

How PCMS Work
Phase Change Materials (PCMs) store latent heat by virtue of their chemical makeup. PCMs are substances that change from solid, liquid, or gas phases to another phase. PCMs typically contain salt hydrates, paraffin, or some other bio-material capable of storing heat. When the PCM changes from a solid to a liquid, it absorbs and stores heat energy from the surrounding space. When it changes from a liquid to a solid, it releases that energy back into the air. A laboratory can program a PCM to a specific temperature, making it conducive to being customized for different market applications.

Benefits
The primary objective of applying PCMs to commercial refrigeration is to reduce or shift the cooling load, while maintaining a stable temperature for the commercial end use—that is, keeping refrigerator contents consistently cold. PCMs can provide energy cost savings to the customer, improve the efficiency of the refrigeration system, extend equipment life, and reduce maintenance costs. In the case of refrigeration, reducing the number and volatility of temperature fluctuations has positive impacts on the quality of food, vaccine integrity, and other refrigerated products using PCM.[1]

From a utility and grid perspective, one of PCMs' most consistent and obvious benefits is how well they enable flexible load management. Pre-cooling a refrigeration system with PCMs ahead of a peak event or power outage allows building operators to enable flexible management of the energy load, because PCMs offer stored cooling energy. This attribute of PCMs means that the system not only is less likely to add load during a peak event, but also significantly reduces the need for inefficient or more carbon-intensive backup fuels. Further, PCMs' benefits to flexible load management have associated reductions in greenhouse gas (GHG) emissions in areas that are sourcing energy generation from non-renewable sources.

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[1] Tulapurkar, Chetan, Pradip Radhakrishnan Subramaniam, G. Thagamani, and Ramasamy Thiyagarajan, 2010. "Phase Change Materials for Domestic Refrigerators to Improve Food Quality and Prolong Compressor Off Time." Presented at the International Refrigeration and Air Conditioning Conference, Purdue University. https://pdfs.semanticscholar.org/2fa8/2879f3a83d2a55dbfed13a22fd55ec2600ec.pdf.

Because PCMs offer non-mechanical cooling during peaks or power outages, they offer resilience and redundancy benefits to a refrigeration system. An example of this is loading a system during Vermont's cool summer nights, outside peak events. The energy savings from the PCMs come from the reduction in the number of incidents of cycling on and off and/or shorter durations of the run-time on refrigeration systems and subsequent reduced wear on compressors.

The Role of Phase Change Materials in Efficiency Programming for the Commercial and Industrial Market

Phase change materials—substances that store latent heat for heating and cooling—have classically been an under-investigated topic for building decarbonization. To explore the variety of their uses in efficiency programming, and quantify their value to its program portfolio, Efficiency Vermont embarked on a research and development (R&D) project that investigated building envelope and refrigeration applications for these substances. The resulting project data and analyses show that, when installed appropriately, they could offer four significant benefits:

- Noticeable energy cost savings to the customer
- Improvements to a refrigeration system's efficiency
- Extension of equipment life
- Reduction in maintenance costs

This report contains the project's background, scope, and results, in the context of incorporating phase change materials (PCMs) into efficiency programs that address commercial and industrial (C&I) markets. It also offers an anatomical view of how the resulting basis for a program began with a hunch, encountered setbacks, and eventually succeeded in providing the information necessary for launching a productive program in the C&I market.

Small-Scale DIY PCM Installation in Vermont

Trying the Untried, on a Vermont Scale —How the PCM Project Began

Efficiency Vermont's investigation of phase change materials began in summer 2019. PCMs at the time were a topic that was bubbling up from many internal and external sources: staff knowledge of innovative thermal storage options, the utility consortiums Efficiency Vermont belongs to that address emerging technologies, and conference agendas. Efficiency Vermont's Emerging Technologies and Services (ETS) team summer intern, Kayla Freischlag conducted a market research and feasibility project on PCMs. Kayla uncovered several possible market opportunities, from which Efficiency Vermont staff chose two for further investigation: PCM applications for building envelopes and commercial refrigeration. Efficiency Vermont learned of other utilities' interest in the topic, as well—and, two energy efficiency utilities that were piloting one manufacturer's PCM product in large freezer applications.

Efficiency Vermont employees attended the International Congress on Refrigeration in Montreal in August 2019, which offered 18 papers on PCMs' role in refrigeration. With Efficiency Vermont's preliminary research on the topic, and with the knowledge gained from this international research, the Emerging Technologies and Services team designed a pilot project for Vermont.

Scoping
By the time Efficiency Vermont scoped this PCM project, the staff had already tested emerging technologies for ice storage; however, those technologies failed to meet an acceptable threshold of energy savings. In addition, ice storage *per se* has its own constraints in terms of innovation, compared to the more effective PCMs such as salt hydrates and paraffin. Therefore, Efficiency Vermont considered ice storage out of scope as a possible comparison material for PCMs but chose other PCMs for both their easily testable effectiveness and their relatively innovative attributes in non-mechanical load management applications.

Attempted Applications
Since Efficiency Vermont began its PCM research in 2019, the topic has skyrocketed in popularity at webinars, conferences, and market player conversations in Vermont. Worldwide, researchers and innovators have been experimenting with other applications for PCMs, too. Because each PCM is optimized for a specific temperature set point, there are thousands of needs for different set temperatures that could find PCMs beneficial. Globally, the most common PCM refrigeration applications appear to be for the food cold chain and vaccine markets.[2] *Cold chain* refers to the transportation of refrigerated or frozen products, from source point to end use.[3]

From the perspective of conducting local experiments with an objective of quantifying energy savings and flexible load management performance from PCMs, Efficiency Vermont sought opportunities for PCM refrigeration methods in Vermont. That search led the team to Viking Cold Solutions (VCS), which has installed PCMs in large freezer warehouse applications in several locations across the United States. Efficiency programs at utilities like Xcel and San Diego Gas & Electric, and at Efficiency Maine, have used VCS to install PCM products and controls atop freezer racks. This commercial application has demonstrated the following benefits:

- Essential interior freezer space is not taken up by PCM installation.
- The combination of PCM + controls, as an efficiency measure, delivers energy savings.
- The combination of PCM + controls allows for flexible load management during peaks, and resilience in the case of a power outage.

Despite the promising search for effective applications and PCMs' equally promising results to date, the lack of consumer-ready solutions is a barrier to widespread use of PCMs in this nascent market. Viking Cold Solutions appeared to be an appropriate partner for Efficiency Vermont in exploring the PCM market and perhaps finding additional applications. **Figure 1** shows a typical VCS installation in a frozen warehouse.

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[2] See, for example, Oró, E., L. Miró, M. M. Farid, and L. F. Cabeza, 2012. "Improving thermal performance of freezers using phase change materials," *International Journal of Refrigeration 35* (4) June: 984-91. https://www.sciencedirect.com/science/article/abs/pii/S0140700712000059.
Liu, Guanghai., Junzhang Wu, Ruhe Xie, Judith Evans, and Allen Foster, 2019. "Design and application of a novel cold chain pallet using a phase change material." *Proceedings of the 25th IIR International Congress of Refrigeration,* Montreal, August. https://openresearch.lsbu.ac.uk/item/8853x.
World Health Organization and PATH, 2013. "Innovative passive cooling options for vaccines," *Optimize.* Evidence Brief Series. August.
https://www.who.int/immunization/programmes_systems/supply_chain/optimize/evidence_brief_passive_cooling.pdf.
[3] In its research, the Efficiency Vermont team learned of an unusual experiment in the cold chain market: making shipping pallets out of PCMs, to safely transport high-priced Japanese fish across the seas.

Figure 1. Viking Cold Solutions system installed in a warehouse for frozen goods.[4] Source: Viking Cold Solutions.

The opportunities in Vermont for wider testing of PCMs in other applications are limited by the size of the market. Distribution networks are, in fact, limited by Vermont's topographical geography and the absence of a major east-west corridor to other markets. The Efficiency Vermont team scoped a project for one of the state's largest freezers, a 2,860 square-foot space. But the building had recently been fit up with a new rack refrigeration system using low global warming potential (GWP) carbon dioxide (CO_2) natural refrigerant. VCS was reluctant to apply PCM technology to a CO_2 system, given their desire to apply it to existing systems reliant on either hydrofluorocarbon (HFC)-containing freon or ammonia.[5]

Efficiency Vermont staff subsequently approached VCS with a smaller freezer application for military customers. For this market, resiliency and redundancy of a cooling method are critical reasons for exploring PCM. Some branches of the military need several days of supplies on hand at all times, if they are to effectively respond to a disaster or other event characterized by unpredictability—especially if electricity is not available. PCM could allow military or other essential applications keep important goods frozen or refrigerated in an emergency or in the event of equipment failure, and still meet the military's resiliency requirements.

[4] VCS claims its PCM + controls solutions can achieve a reduction in energy costs of up to 35 percent. https://www.vikingcold.com/.

[5] For an overview of refrigerants, their respective GWP, and the role of natural refrigerants in commercial refrigeration, see White, Ali, and Ethan Bellavance, 2019. "Refrigerant Management." Presentation by Efficiency Vermont (beginning on Slide 16) at Vermont Best Practices Exchange conference. https://www.efficiencyvermont.com/Media/Default/docs/bpx/bpx-2019-refrigeration-double-session.pdf.

Viking Cold Solutions felt that the proposed military project in Vermont was too small to be of interest, especially against the backdrop of increasing numbers of large PCM projects and evolving incentives nationwide. VCS did, however, offer to sell the customer the controls package that usually comes with the PCM installation, to optimize the refrigeration controls and thus deliver additional energy savings. Efficiency Vermont declined, citing small benefits from such an approach when it can help customers pursue savings with refrigeration contractors who already help customers with their refrigeration controls.

With these findings, Efficiency Vermont spoke with other energy efficiency utilities about their experience with PCM installations. On a call with the Consortium for Energy Efficiency's Emerging Technology Collaborative on June 17, 2020, it became apparent that the only successful utility-involved energy-saving installations of PCMs were in large freezer warehouses with Viking Cold Solutions. Therefore, the barriers that Efficiency Vermont was facing—finding commercially available product, replacing appropriate baseline equipment, and accommodating the scale of Vermont's small buildings—could not be overcome with deeper knowledge of the PCM market. Some utilities said they had made their own proposals to VCS, and when the company declined, they would re-propose projects with different customer types. Understandably, VCS's criteria for moving forward with projects are tied to their business model, which primarily favors large-scale applications, which are more cost-effective for VCS.

Chest Freezer PCM Experiment

The Efficiency Vermont team subsequently designed an experiment to test the energy efficiency effects of using PCM on a chest freezer that operates in a basement. Between September 2 and September 17, 2020, the team monitored the freezer that was nearly full of phase change materials in a 10 percent sodium chloride solution. From September 19 to October 1 of the same year, the team monitored the freezer while it stood completely empty[6]. During both periods, the freezer was operating at the same setpoint and the freezer was not opened or closed. Data intervals were 1 minute.

The team performed a regression analysis to estimate the effect of the PCMs on the total daily energy consumption of the freezer. The team found that the presence of PCM had a statistically significant effect on daily energy use. PCM increased the average daily energy use of the freezer by 113.6 Wh, when controlling for outdoor air temperature. With 95 percent confidence, the average daily energy use increases between 78.6 to 148.6 Wh when adding PCM to the freezer.[7]

Figure 2 shows the daily predicted baseline energy use when the freezer is completely empty with a 95 percent confidence interval, compared to daily observed energy use during the period when PCM was installed and uninstalled. There were no observed savings accrued between September 2 and September 17, and in fact, energy use increased by 1.8 kWh.

[6] The team removed data at the beginning and end of the two periods, to avoid adjustment period bias from adding and removing PCM.

[7] The energy use of the freezer is weather dependent, and thus it would not be appropriate to extrapolate annual data from these results. The collected data would not have a representative relationship with weather.

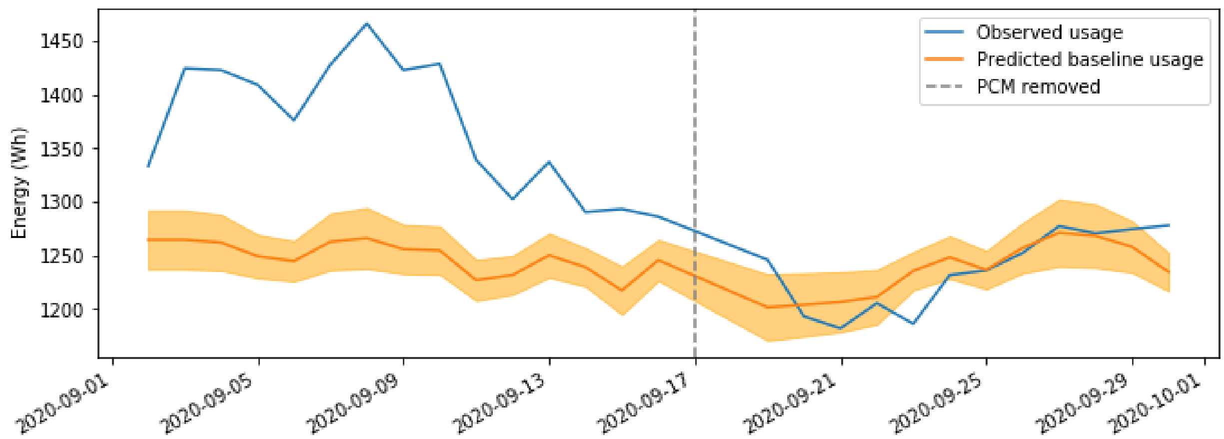

Figure 2. Chest freezer observed energy use with and without PCM, compared to baseline model prediction of an empty freezer with a 95% confidence interval.

When controlling for outdoor air temperature, PCM increased the duty cycle duration by 4.3 percent per day. **Figure 3** shows an example of the difference in cycle between the freezer running with PCM and without PCM. The compressor turns on less frequently and for longer duration when PCM is installed. This reduction in cycling helps extend equipment life but does not necessarily result in energy savings.

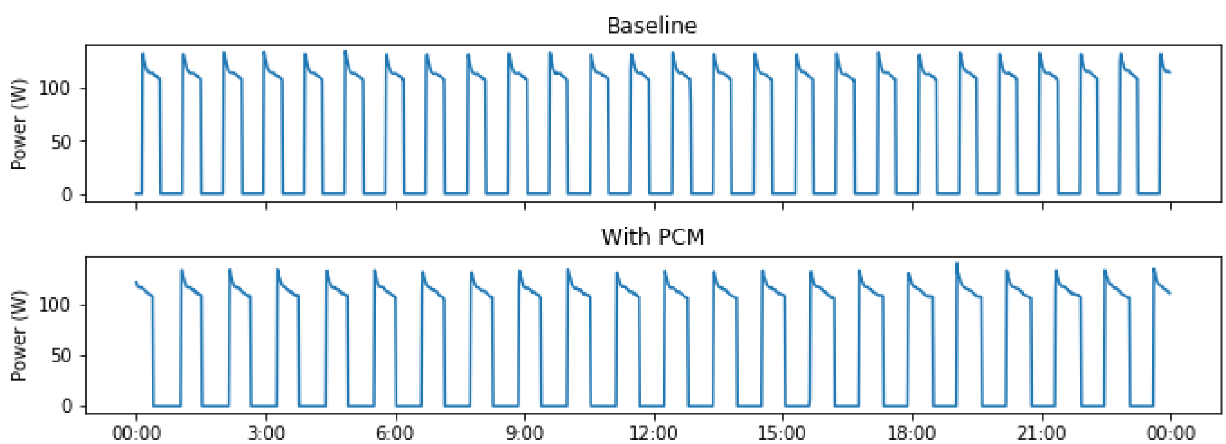

Figure 3. Comparison of chest freezer compressor cycles without PCM (Baseline) and with PCM, across a 24-hour period.

Key Takeaways

Do-it-yourself (DIY) PCM installation

- A fully closed, undisturbed chest freezer was not an ideal test case for measuring the effectiveness of installed PCMs. Having product in the freezer and testing on a unit with temperature fluctuations like when the door is opened and closed very often would provide additional insights into PCM performance in application.
- PCMs can be made easily with products at home—for example, the salt water used in this test case.

DIY PCM energy

- PCM increased the average daily energy use of the freezer by 113.6 Wh. This freezer and its setpoints were not designed or optimized for operation with PCM.

DIY PCM cycling

- Duty cycle duration increased by 4.3 percent per day. In this case, the compressor turns on less frequently and for longer duration when PCM is installed in order to maintain the freezer's desired setpoints.
- Cycle counts were lower when using PCM. Less cycling on and off reduces the wear and tear on a compressor.

General PCM takeaways

- It is necessary to identify and calibrate the correct PCM for an application.
- PCM can increase energy use if not designed and controlled appropriately. Applications that benefit from PCM include projects requiring resilience in power outage, projects with frequent door openings where maintaining low-product temperatures during those times is critical, and locations where time of day load management is important.
- If Vermont is to increase the use of PCMs in commercial and / or residential applications, more research is needed to identify specific applications and their optimal conditions for installation and operation, and other types of PCM that can lend themselves to DIY projects or which are commercially available.
- More market-ready applications for smaller scale refrigeration systems are needed to make PCM in refrigeration more relevant to the Vermont market.

Investigation of PCM for Future Potential

National & International Interest
The initial PCM research and DIY project uncovered valuable information about the current state of PCMs and suggested specific areas for next steps. The Efficiency Vermont team is mindful of the significant investments worldwide in PCM development and will continue to seek opportunities for innovative uses of PCMs for application in the Vermont market. The international market sees great potential in cold chain applications for PCM, so Efficiency Vermont also investigated PCM cold chain applications as described in the following section of the paper.

From a national perspective, The U.S. Department of Energy and its national laboratories are investing millions of dollars in the development of PCMs. In fact, Oak Ridge National Laboratory (ORNL) recently demonstrated the many different types of PCMs that are chemically possible and addressed emerging applications for PCMs on a DOE webinar in 2020 called "Thermal Energy Storage Webinar: Novel Materials in Thermal Energy." Common inorganic PCMs were identified like salt hydrates, ice, salt, and metals, as well as organic PCMs like paraffin waxes, fatty acids, and alcohols.[8] Salt hydrates are considered the PCM with the most potential according to ORNL. Salt

[8] Oak Ridge National Laboratory, 2020. "Novel materials in thermal energy storage for buildings." Thermal Energy Storage Webinar Series. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/buildings/thermal-energy-storage-webinar-series-novel-materials-thermal-energy-storage.

hydrates have the following benefits: include low cost, high volumetric energy storage capacity, non-flammable, and non-toxic. These benefits are displayed in Figure 5, as compared to other PCMs categorized by ORNL.

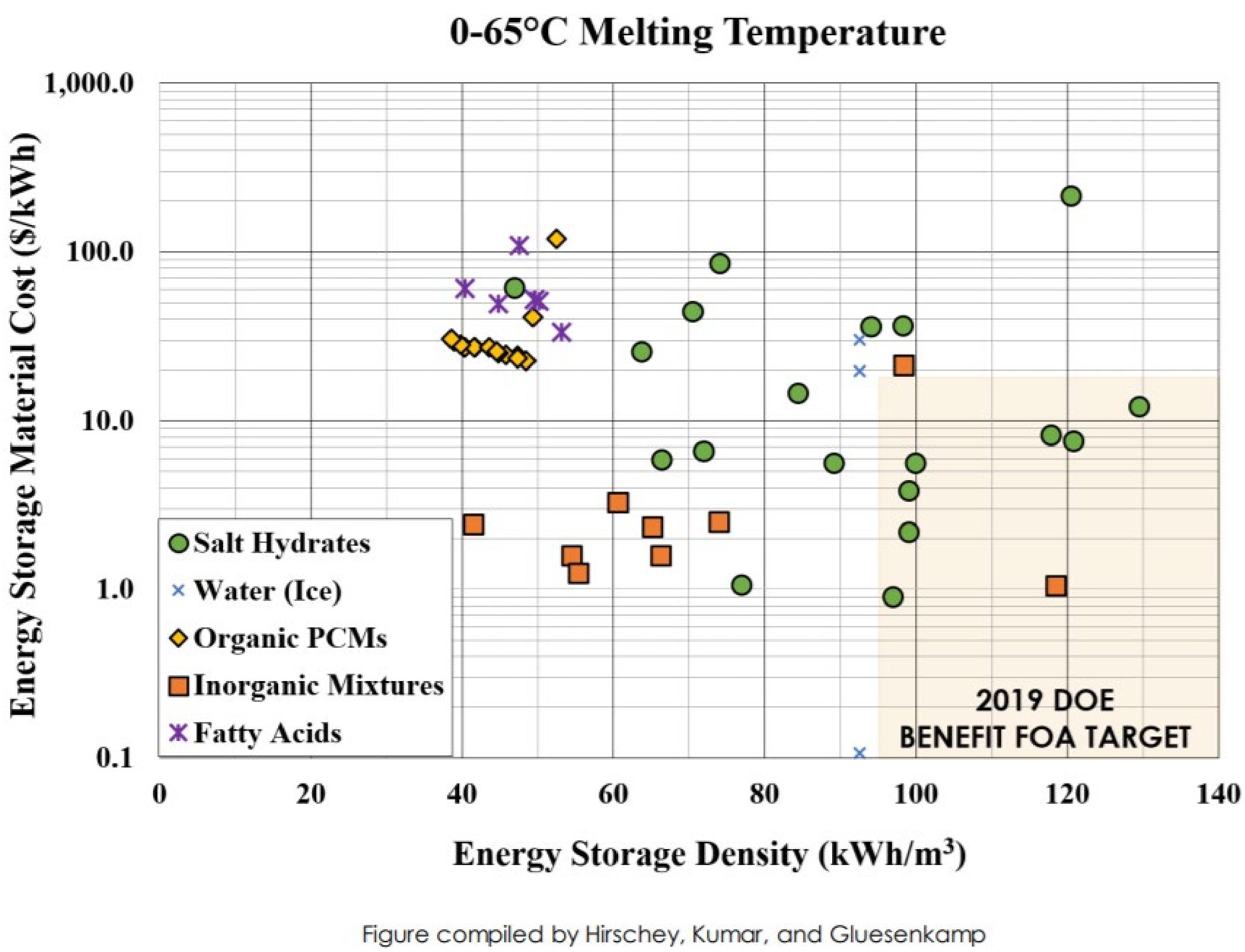

Figure 5. Slide showing salt hydrate use for PCM, relative to other materials, and their melting temperatures.[9]

Investigation of Cold Chain for Future Potential

The development and expansion of the cold chain[10] is becoming increasingly important for markets across the globe. PCM effectiveness depends on many factors:

- Size of the transporting vehicle
- Desired product temperature
- Product siting on the vehicle
- Air distribution / circulation patterns

[9] Oak Ridge National Laboratory, 2020. "Novel materials."

[10] The term *cold chain* refers to the supply chain of temperature-controlled products. Unbroken cold chains involve series and sequences of refrigerated production, storage, and distribution, with associated equipment and logistics. When distributed, these elements must maintain their quality through a desired low-temperature range.

- Composition of PCM
- Concentration of PCM per unit of space it serves
- Layout of the PCM inside the transporting vehicle
- Whether the refrigeration system is on board and charged by diesel, or charged ahead of time by electricity

Efficiency Vermont defined and categorized advantages and disadvantages of a conventional refrigeration system contained in PCM-transporting vehicles, and four PCM options.[11]

- **Conventional system.** Vapor compression system in which an on-board refrigeration system comprises a compressor, condenser, and evaporator.
  - Advantages
    - Proven technology
    - Market share adoption is significant
    - It is easy to control / adjust temperature setpoints
  - Disadvantages
    - Most systems do not use low-GWP refrigerants
    - High GHG emissions occur when systems are powered by diesel engines
    - On-board system takes up space within the truck's box
    - High noise level when in operation
    - Frequent opening of the box and unloading of goods causes refrigeration unit to start and stop frequently, resulting in large temperature fluctuations inside the box
    - Requires frequent system maintenance

- **PCM pallet.**[12] This is a flat structure containing PCM, on which products are stored when they are being transported. The pallet is charged at an external facility, when the pallet is empty and / or when products are being stored at a warehouse, port, or distribution center. The pallet can be used in refrigerated or non-refrigerated vehicles or containers, with or without traditional refrigeration systems' being used in conjunction with the pallet. The system configuration depends on the transport time and distance and is designed to maintain a consistent product temperature. Construction reflects a typical pallet design with an additional built-up layer containing the PCM.
  - Advantages
    - Easy and inexpensive to manufacture, install, service, and replace
    - Easily transferrable; pallet stays with products, so there is no additional loading / unloading at regional distribution sites
    - Can be charged with or without product on the pallet
    - Pallet can be charged with traditional refrigeration system or a dedicated independent system
    - Tracking service is optional

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[11] For this categorization and definition, Efficiency Vermont relied primarily on information from Zhao, Yi, Zulia Zhang, and Ziaofeng Xu, 2020. "Application and research progress of cold storage technology in cold chain transportation and distribution." *Journal of Thermal Analysis and Colorimetry 139:* 1419-34. file:///C:/Users/fhuessy/Downloads/Application%20and%20research%20progress%20of%20cold%20storage%20technology%20in%20cold%20chain%20transportation%20and%20distribution%20_%20SpringerLink.html.

[12] Liu, Guanghai, et al., 2019. "Design and application."

    - Disadvantages
        - Cooling effect comes from beneath the product, which creates a larger temperature gradation from the topmost products to the lower products; this problem can be avoided by stacking multiple pallets on top of each other
        - Products need to be unloaded from the pallet at the distribution site, so that the pallet can stay with the transport vehicle / container, which is otherwise picked up later when products have been removed

- PCM cold plates.[13] A metal plate containing PCMs, affixed to the inside of the transport vehicle or container. Plates can be attached to the top, sides, internal partitions, front, or back of the refrigerated space—essentially for the purpose of avoiding damage to the plates. The plates are charged at an external facility, typically by a mechanical connection that is made to the transporting vehicle. The cooling is generated by a traditional vapor compression refrigeration system; the inside of the transport vehicle is typically sub-cooled to recharge the plates. The plates take up additional space inside the transport vehicle or container, so it is best to use this PCM system in place of a traditional system, but it could also be added as a retrofit option to an existing vehicle or container.
    - Advantages
        - The method is easy and inexpensive to manufacture, install, service, and replace.
        - It can be retrofitted into existing vehicles.
        - Cooling can be provided from all sides (except bottom) of the transporting vehicle for even temperature distribution.
        - Cold plates have better heat retention capacity than air, so they keep the internal temperature of the vehicle more stable when doors are frequently opened and closed.
    - Disadvantages
        - The method requires special charging equipment.
        - The layout of the panels / plates and the cargo contained within the transport vehicle makes a big difference in the temperature distribution within the vehicle. Because of this, extra care must be taken to make the layout optimal for refrigeration performance.
        - Cooling capacity and temperature dependent on type/composition of PCM used in plate
        - The panels / plates take up additional space within the transport vehicle which reduces product storage

- PCM insulated thermal shell.[14] PCM can be built into the structural insulation of the thermal shell of a refrigerated vehicle or a container. The PCM insulation is permanently installed in the vehicle or container, so this method would be best for new transportation vehicles/containers. It helps prevent heat loss through the body of the vehicle. PCMs would

[13] Zhao, Yi, et al., 2020. "Application and research."
[14] Zhao, Yi, et al., 2020. "Application and research."

be externally charged via a mechanical connection to the vehicle / container at a distribution site.

- Advantages
  - This method does not take up additional storage space within the vehicle.
  - PCM on all sides of the vehicle allows for even temperature distribution.
- Disadvantages
  - PCM is not easily replaced, serviced, or maintained.
  - PCMs can be recharged only a certain number of times before losing effectiveness, thus compromising long-term integrity of their properties.
  - This method requires special charge equipment.
  - The structural components of the thermal shell act as insulation, thus reducing the effectiveness of the PCM at directly cooling the products being transported

- PCM insulated box.[15] PCMs can be used to construct an insulated cold storage box in which products are stored. This insulated box is then loaded into a refrigerated or non-refrigerated vehicle or container. Essentially, the insulated cold-storage box is an enclosed pallet cube with six insulated sides that contain PCM. The box can be designed for multiple uses or a single use.
  - Advantages
    - PCMs can be charged during off-peak hours.
    - This method replaces fossil fuels and results in reduced GHG emissions and other air pollutants.
    - This method reduces heat island effects in cities by removing combustion of trucks cooling products compared to electricity being used to cool.
    - PCM has higher heat (cool) retention capacity than air, so it results in more consistent product temperatures when doors are opened and closed.
    - The insulated box reduces or eliminates refrigerant charge, thereby reducing GHG emissions.
    - This method contributes to resiliency during power outages and fuel shortages, since insulated boxes can hold the cold for relatively long periods of time.
  - Disadvantages
    - PCMs can be recharged only a certain number of times before losing effectiveness, thus compromising long-term integrity of their properties.
    - This method results in low controllability of system temperatures.
    - The discharge time and duration depend on ambient temperatures and environmental conditions.
    - Many products are still in the development phase, thus making commercially available product an issue.
    - Some technologies require charge equipment to be located at pick-up / drop-off locations, thus limiting options for charging.
    - Pre-cooling time is longer than mechanical cooling time

[15] Zhao, Yi, et al., 2020. "Application and research."

- **Combination system.** This mixes a traditional vapor compressor system with a PCM thermal energy storage system.
    - Advantages
        - This method reduces GHG emissions, but not by as much as full PCM systems do.
        - A combination system adds resilience to the refrigeration task.
        - The method can substantially withstand extended transportation times / distances
    - Disadvantages
        - The method requires more complicated systems and controls
        - It is more expensive than the other methods to purchase, operate, and maintain

Cold Chain Conclusions for Vermont

How do these cold-chain options pertain to Vermont? The market for refrigerated or frozen PCM products is still small, compared to the worldwide need for cold chain. Driving distances in the state do not inhibit PCMs' ability to stay cold. Much of the merchandise transported in Vermont does not need to be refrigerated. That is, local beer, berries, vegetables, and milk coming from farmers are not refrigerated until they reach their refineries or retail destinations. None of these goods is typically transported frozen. PCM has niche applications that might be useful, but given the low amounts of commercially available product, it is not likely PCM will take hold in Vermont's cold chain for the foreseeable future. Thus, as PCM cold chain technologies continue to evolve, the Vermont market for them will likely expand slowly to adopt them. Until then, most Vermont companies are unlikely to invest in PCMs until the technology and applications are better understood for commercial temperature needs.

Final Conclusions

PCMs are being investigated at a national level and are being developed rapidly by private companies. PCM in refrigeration seems to have enough benefits and efficiency examples to be a good candidate for promotion in the marketplace once more products become available that align with Vermont's market.

Efficiency Vermont will further categorize the market and specific potential for Vermont. The existing success with PCM in energy-saving applications worldwide gives Efficiency Vermont confidence in future Vermont application.

Efficiency Vermont has planned a 2021 R&D project for pairing PCMs with building space conditioning. The team hopes to identify cost-acceptable applications for PCMs considering comfort, energy efficiency, GHG reduction and resilience.