# PHASESTOR LATENT ENERGY STORAGE SYSTEM
# EW201514

**Energy and Water Projects**

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**14. ABSTRACT**

This project demonstrated an advanced thermal energy storage system—Latent Energy Storage System (LESS)—that utilizes an engineered bio-based polymeric gel to store latent energy in a heat exchanger. This approach to thermal storage can deliver substantial savings for the Department of Defense (DoD) not only in energy costs but also in infrastructure, equipment, and operational maintenance costs. The technical objective was to demonstrate at the Army National Training Center (NTC) at Ft. Irwin, CA the potential for an engineered phase change material (PCM) to store thermal energy at pre-determined temperatures, providing a minimum of 20% plant peak demand energy reduction, 25% plant energy cost savings (based on time of use rates) and, when replacement is due, a 40% reduction in chiller sizing. The demonstration of the technology consisted of two phases over the 2017 and 2018 summers. The LESS' ability to store thermal energy at different preset temperatures was verified and effectiveness of LESS as a demand response measure was validated.

**15. SUBJECT TERMS**

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# Abstract

## Introduction and Objectives

This project demonstrated an advanced thermal energy storage system—Latent Energy Storage System (LESS)—that utilizes an engineered bio-based polymeric gel to store latent energy in a heat exchanger. This approach to thermal storage can deliver substantial savings for the Department of Defense (DoD) not only in energy costs but also in infrastructure, equipment, and operational maintenance costs. The technical objective was to demonstrate at the Army National Training Center (NTC) at Ft. Irwin, CA the potential for an engineered phase change material (PCM) to store thermal energy at pre-determined temperatures, providing a minimum of 20% plant peak demand energy reduction, 25% plant energy cost savings (based on time of use rates) and, when replacement is due, a 40% reduction in chiller sizing.

## Technology Description

The project expended the use of PCM into large-scale thermal energy storage systems, such as heat exchangers, for the control of electrical peak demand loads. LESS is a modular, self-contained system of thermal energy storage capable of storing and redistributing thermal energy at any predetermined temperature between -50°C to +150°C. This new technology uses the well-established principle of the latent heat of fusion when changing phase from liquid (gel) to solid. The system is based on the re-purposing of established polymer and carbon steel heat exchanger technology used extensively in the ice storage and solar thermal hot water industries. The system comprises an atmospherically vented tank, in which heat exchangers are fully immersed in a cross-linked polymeric matrix gel, specifically engineered for either high or low temperature storage. At the core of the LESS concept is an organic material derived from agricultural bi-products. The material is food grade, non-toxic, non-flammable, and developed from a renewable supply source.

## Benefits, Performance and Cost Assessment

By implementing LESS at the selected site, the project has successfully validated PCM's potential to provide in excess of 7.4% reduction in energy usage and 20% reduction in peak energy demand usage and 43% reduction in energy cost for DoD chilled water-cooling systems. The overall cooling and heating cost savings potential for DoD plants and facilities using LESS can be up to 43% depending on rate structure. The average system payback was estimated at 8 years. Furthermore, unlike traditional thermal storage systems, PCM-based storage allowed for the full integration of energy storage into existing facilities without the need to replace existing equipment or installation of new inefficient glycol-based systems. (Project Completion - 2019)

## Implementation Issues

PCM-TES technologies can face some implementation issues to market entry, these can be identified under the following categories: 1. Market readiness; 2. Containment vessel design; 3. PCM manufacturing costs in general as a thermal storage medium; 4. While PCM-TES remains an emerging technology, manufacturing cost of the PCM remains the key issue as the raw materials cannot be purchased or manufactured as a commodity product and remain a custom order. In conclusion, there is very limited data on potential opportunities for TES, therefore It's commonly accepted that the US electrical infrastructure is near it's breaking point, requiring immediate solutions to reduce peak loads.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| PCES | phase change energy solutions |
| DPW | directorate of public works |
| TES | thermal energy storage |
| HVAC | heating ventilation air conditioning |
| M&V | measurement and verification |
| TOU | time of use |
| RPE | reinforced polyethylene |
| Btu | British thermal unit |
| DoD | department of defense |
| EO | executive order |
| EPA | U.S. environmental protection agency |
| ESTCP | environmental security technology certification program |
| EW | energy and water |
| GPM | gallons per minute |
| CW | chilled water |
| CWLT | chilled water leaving temperature |
| ISO | international organization for standardization |
| ITC | investment tax credit |
| kW | kilowatt |
| kWh | kilowatt hour |
| PCM | phase change material |
| TCM | thermo-chemical material |
| UTES | underground thermal energy storage |
| NDAA 2007 | national defense authorization act of 2007 |
| O&M | operation and maintenance |
| CEC | California energy commission |
| AHRI | American heating refrigeration institute |
| ANSI | American national standards institute |

# 1.0 AKNOWLEDGEMENTS

The authors would like to thank the Environmental Security Technology Certification Program (ESTCP) project team members for their creativity, persistence, and willingness to support this project. William Schaefer at Ft. Irwin Army Training Base was instrumental in setting up the demonstration and has provided countless hours assisting with the installation of the data acquisition system (DAS) and multiyear performance testing. Emery Mechanical Consulting provided invaluable assistance with the design and installation of the DAS, as well as data analysis support and provided invaluable time designing, testing, and commissioning the PhaseStor system at Ft. Irwin. Finally, the project would not have been possible without financial support from the ESTCP, which not only provided funding but also provided valuable insights into the types of data analysis procedures and results that would be most beneficial to Department of Defense facilities and engineers.

## 2.0 EXECUTIVE SUMMARY

With nearly 300,000 sites and 2.2 Billion-ft², the DoD is the largest building owner in the US. The DoD's energy expenditure totaled over $4.1 billion FY2016, or 10% of its entire operation and maintenance budget. In FY 2016, DoD installation energy comprised approximately 21 percent of total Federal energy consumption [DoD Annual Energy Management and Resilience Report, 2017]. The Department's total energy outlay was $12.4 billion. DoD spent approximately $3.7 billion on installation energy, which included $3.5 billion to power, heat, and cool buildings and $0.15 billion to supply fuel to the fleet of NTVs. The remaining $8.7 billion outlay was for operational energy. Installation energy represented 30 percent of the Department's total energy expenditures. DoD consumed 201,410 billion British thermal units (BBtus) of installation energy, which represented 29 percent of the Department's total energy consumption. Of that, DoD consumed 198,031 BBtus in buildings (stationary combustion) and 9,241 BBtus in NTV fleet (mobile combustion). The Army is the largest consumer of installation energy, followed by the Air Force and DON (Figure 1).

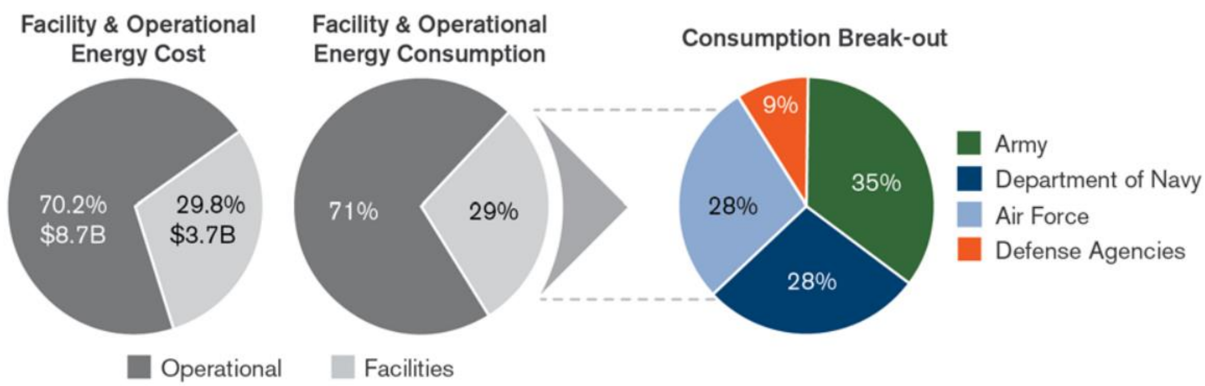


***Figure 1. DoD Installation Energy FY 2016 and U.S Commercial Sector Stationary [EIA, 2014 Monthly Commercial Sector Energy Use]***

Given the high cost of ownership combined with the DoD's commitment to reduce its carbon footprint, it is widely accepted that providing support in the development of efficient and inexpensive energy storage devices is as important as developing new sources of energy. Thermal energy storage (TES) can be defined as the temporary storage of thermal energy at a specific engineering temperature. In comparison, sensible heat is the heat that results from a temperature change and is the most common form of TES. Sensible heat storage is not a new concept, the most common example is the storage of water, which has been in practice for over a hundred years.

All forms of energy storage can reduce the time or rate mismatch between energy supply and energy demand, therefore play an important role in energy conservation. A recent study from the University of Lleida (Spain) suggests the expansion of TES technologies is expected to be significant in Europe and Asia (particularly Japan) but somewhat lower (50%) in the United States. The global potential is estimated at approximately three times the European potential. This conclusion is also supported through our own commercial experience, where over the past 2 years there has been a noticeable increase in interest for the many diverse applications suited to temperature engineered products, such as PCM's. This is becoming increasingly evident in the industrial sector, where high temperature storage shows great potential.

The following report outlines the findings of a demonstration project intended to validate the use of our organic, bio-based phase change material (PCM) to store and release thermal energy on demand. The PhaseStor-TES demonstration uses the latent energy of fusion to store energy at a prescribed temperature consistent with the HVAC chilled water leaving temperature (CWLT). PhaseStor-TES stores rejected heat from the daytime operation of the building in a non-pressurized tank filled with PCM until nighttime off peak rates, at which time it uses the refrigerant based water chiller to reject the heat to air at a time when the chiller is operating at peak efficiency due to lower ambient air temperature.

The demonstration was conducted at the Army National Training Center (NTC) at Ft. Irwin, CA. It consisted of two phases over the 2017 and 2018 summers.

- Phase 1: the installation of a small scaled demonstration tank providing approximately 40 ton-hours of storage capacity intended to validate the use of a PCM to store and release energy on demand.
- Phase 2: the installation of an enhanced scaled demonstration designed to store 100% of the heat rejected by the HVAC system during the daytime peak cooling period, reducing the use of the chiller which in turn reduces the power utility demand charge.

On completion of phase 1: the demonstration resulted in confirmation the PCM could store energy generated at night by the chiller plant and reject the heat from the building to the PCM during the peak daytime period.

On completion of phase 2: the demonstration resulted in a reduction in **energy costs by 43%** depending on rates and the reduction of **chiller energy by 7%.**

In summary, the findings on completion of phase 1 and phase 2 demonstrations are:

1. The demonstration confirmed the ability of the PhaseStor-TES to store and release energy on demand to meet the heat rejected by the chilled water HVAC system.
2. The system can provide process fluid (chilled water) at the design temperature consistent with cooling load.
3. The system was able to maintain a consistent EWT/LWT delta during the entire peak demand period.
4. The system consistently operated at an efficiency ratio with a COP greater than 3.2 during freeze and melt cycles.

***Table 1. Baseline performance comparative (numbers below are rough estimates)***

| System | Installed ton-hrs | Purchase Cost | Install Cost | Total Cost | Annual Kwh | Energy Cost | $ Saving (yr) | % Saving (yr) | Payback (yrs) w/o incentive | Payback (yrs) w/ incentive |
|---|---|---|---|---|---|---|---|---|---|---|
| No Storage Baseline | 0 | 0 | 0 | 0 | 49,700 | $ 9,391 | 0 | 0 | 0 | 0 |
| Ice-TES (Baseline)* | 128 | $ 110.00 | $ 350.00 | $ 58,788 | 59,640 | $ 5,357 | $ 4,034 | 43% | 14.6 | 7.3 |
| Phasestor-TES | 128 | $ 315.00 | $ 170.00 | $ 61,983 | 46,831 | $ 4,870 | $ 4,521 | 48% | 13.7 | 6.9 |

**comparison of the ice storage system is based on the replacement of an existing primary pumping to primary/secondary as recommended by ice-TES manufacturers. Note: it is not the general practice to install ice-TES without the replacement of the chiller plant as costs are generally prohibitive in retrofit applications.*

# 3.0 INTRODUCTION

As DoD facilities continue to age and prepare for mission-readiness, the continuance of maintenance programming and resourcing becomes inherently more complex. All facilities are experiencing rising energy and maintenance costs, these costs are often less prioritized due to mission priorities. Rising costs are largely due to increased energy use for heating and cooling. Investments in energy efficient equipment, such as HVAC, lighting and pumping systems continue, but these mature technologies offer diminishing returns.

With a federal mandate to promote resilience, energy security and a move towards net zero construction, the use of fossil fuels and other energy sources should be reduced. This includes the use of our natural gas resources, which at present play a vital role in heating dominated climates, along with heating of water for domestic, commercial and industrial applications.

As a result, DoD public works departments, facility managers and designers are now focusing on load shifting strategies to reduce energy costs. One such load shifting technology is thermal energy storage (TES). TES allows excess and/or lower cost thermal energy to be collected for later use. A Traditional TES medium, such as sensible heat storage (water) is limited by its kW/Btu capacity while current technology latent heat storage systems are limited by temperature range.

Traditional energy storage mediums consist of the following:

<u>Cold Water Storage</u>: the storage of chilled water in a tank provides additional capacity at reduced energy costs due to avoidance of peak demand charges. Unfortunately, this technology is often limited by spatial requirements due to waters low specific heat capacity. In addition, tanks often need to be oversized due to thermal stratification.

<u>Hot Water Storage</u>: the storage of hot water in an open vented or pressurized tank provides additional capacity at reduced energy costs due to avoidance of peak demand charges; hot water storage is the most common form of thermal storage in use today. Like all sensible heat storage systems, it is limited by spatial requirements due to waters low specific heat capacity.

<u>Ice Storage</u>: offers many of the same benefits that water storage provides, while using a much smaller footprint. However, can only be made at 32°F or lower, many existing chillers cannot make ice and, for those that can, the loss of chiller efficiency and chiller capacity at the low temperature required to make ice (23°F/(-5)°C to 27°F/(-3)°C), along with higher pumping costs, a need for glycol and increased system complexity, often offset the full benefit of using ice as a TES medium.

<u>Other Storage Mediums</u>: such as inorganic PCM's, paraffin wax, eutectic salts, native earth, or bedrock have only limited applications with minimal potential for use by the DoD.

Unused real estate can provide valuable space for large chilled water tanks. A major plant replacement can come via low-temperature chiller and primary glycol loop to produce ice, which shifts the energy load. This in turn allows an economical response to demand.

The problem with traditional thermal storage applications, is that they often only address energy costs without achieving real energy reductions.

Furthermore, traditional storage mediums are not "smart". While system sizes can be adjusted to shift a desired load, the mediums themselves are fixed and cannot be individually optimized for each application.

DoD facilities within the US and on foreign soils incur a multitude of differing energy supply cost structures and site limitations. In some cases, these structures don't incur peak or off-peak demand charges. To be truly applicable to DoD facilities, a TES installation must provide the following benefits:

1. Direct energy savings through increased efficiencies at the plant level.
2. Indirect energy savings at source, utility or locally owned power plants.
3. Energy cost savings through demand charge avoidance.
4. The capacity to respond quickly to demand response strategies.
5. Reduction in equipment capacity providing first cost reductions and operating/maintenance costs.
6. *Indirect benefits such as passive redundancy, reduced spatial needs and site optimization,* therefore reducing plant room and other associated operational and construction costs.

What is necessary, and missing now, is a smart technology that achieves reductions in both energy cost and use while maintaining applicability for use across of a wide range of DoD facilities and locations.

## 3.1 BACKGROUND

Over the past 15 years there has been a concentrated focus on energy storage technologies, in most cases this focus has centered on the potential for electrical energy storage, however thermal energy storage will play an important role in any future storage solutions. It is widely acknowledged that electrical energy storage technology is still very much in its infancy, and has many technical hurdles to overcome. Realistically, electrical energy storage is unlikely to become a commercially accepted technology for another 15-20 years. Contrastingly, at the other end of the spectrum we have had access to latent heat thermal storage technology for well over 30 years. Generally latent heat thermal energy storage is perceived as not providing the range of benefits for the cost, although this has much more to do with misconceptions and poor management, rather than the technology itself. Over the past 30 years latent heat thermal storage technology has progressed very little. Some of the following technologies have been applied, but so far are proving to have limited applications in the industry, due mainly to limited commercial support.

1. Underground thermal energy storage (UTES).
2. Phase change materials (PCM).
3. Thermo-chemical materials (TCM).

Sensible heat storage in the form of hot or cold-water storage tanks are a relatively inexpensive and well-established technology but are often limited by the specific heat of the medium e.g. specific heat of water is approximately 1 Btu/lb. (4.2 J/g). Temperature variability often occurs through stratification and in many cases physical constraints are the capacity limitation.

Phase Change Materials, referred to as PCMs, are substances that change between two states or phases of matter (e.g. solid to liquid) at a specific temperature. As they change phase, they absorb or release thermal energy keeping the surrounding at nearly fixed temperature. This phase change temperature can be adjusted based on eutectic mixtures of several PCMs or the use of a single PCM chemistry with the right phase change temperature. For example, unlike latent heat of water, PCMs can be utilized for higher or lower temperatures based on the applications due the flexibility in its phase change storage temperature. The comparison is shown below.
**The freeze temperature**, also known as solidification or charging temperature is the point the PCM will store "charge" latent heat or change phase from a liquid to a solid.
**The melt temperature**, also known as discharging temperature, is the point the PCM will release "discharge" latent heat and change phase from a solid to a liquid.

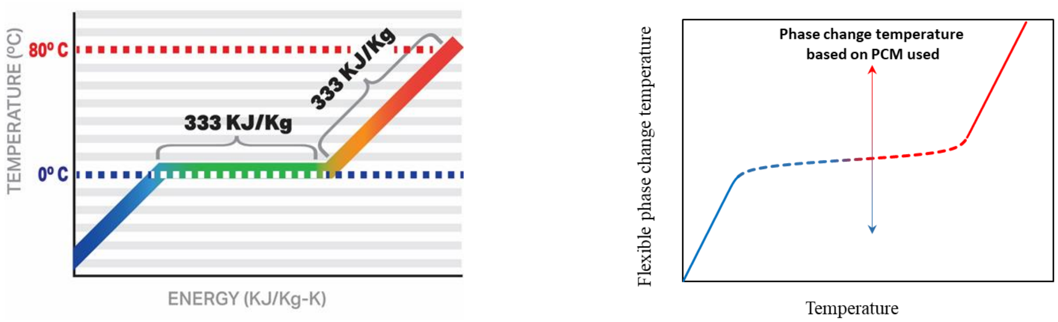


*Figure 2. A comparison between the thermal storage of ice (left) and flexible thermal storage temperature PCMs (right)*

The use of PCM based TES can overcome many of the sensible heat storage limitations. The PCM system enables higher storage capacities and can target defined discharge temperatures. The change of phase could be either a solid/liquid or a solid/solid process. Melting processes involve energy densities 100 $kWh/m^3$ (e.g. ice) compared to a typical 25 $kWh/m^3$ for sensible heat storage options. The following figure compares the achievable storage capacity at a given temperature difference for a storage medium with and without phase change.

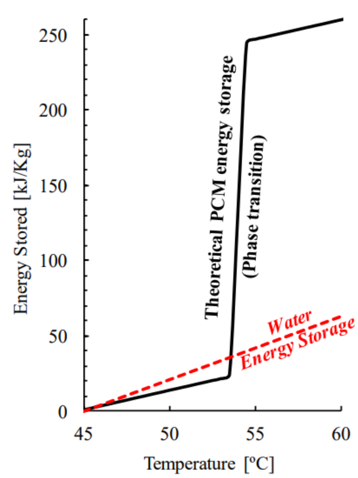


*Figure 3. Performance Comparison between PCMs latent heat and sensible heat energy systems [Saeed et al. 2018]*

Phase change materials can be used for both short-term (daily) and long-term (seasonal) energy storage, using a variety of techniques and materials. For example, the incorporation of micro-encapsulated PCMs installed into a building wall assembly can considerably increase the thermal mass and capacity of lightweight walls. The micro-encapsulated PCMs can be passively or actively charged to cool or heat the building by storing and releasing energy when the temperature range exceeds the PCM melt or freeze setpoints. This causes a reduction or avoidance in the need for mechanical heating and cooling.

Table 2 shows a comparison between chilled water sensible heat storage, Ice storage and PCM storage. Figure 3 show some of the most relevant PCMs in different temperature ranges with their melting temperature, enthalpy and density.

***Table 2. A comparison between various thermal energy storage technologies***

| | Chilled water | Ice Storage | PCM Storage |
|---|---|---|---|
| **Latent heat Storage** | 0 J/g (4.1 J/g.K sensible) | 334 J/g | 200-240 J/g |
| **Heating or cooling** | Cooling only | Cooling only | Cooling and heating (wide PCM temp range) |
| **Chiller Cost** | Lower | Higher | Lower |
| **Tank volume** | Sizable tanks | Smaller | Smaller |
| **Retrofit additional cost or complexities** | 1. Require sizable tanks<br>2. Can be integrated into existing utilities without the need to increase existing chiller capacity or glycol loop | 1. Require new chiller installation that makes ice<br>2. Require addition of glycol secondary loop system<br>3. Require addition of intermediate heat exchanger | Can be integrated into existing utilities without the need to increase existing chiller capacity or glycol loop. |
| **Charging temp** | 39-43 °F | 21-25 °F (limited by ice) | 35-43°F for cooling<br>or 30-40°F for heating<br>(due to flexible/higher PCM temp) |
| **Efficiency (COP)** | 4.0 – 6.0 | 2.4 - 4.0 | 5.0 - 6.0 |
| **Discharge temp** | 35 - 55°F "slope" | 32 - 35°F (limited by ice temp) | Flexible (varies depending on PCM) |
| **Structural stresses** | Minimal | Higher due to ice expansion | PCMs expand only upon melting "in liquid form" with mobility. |

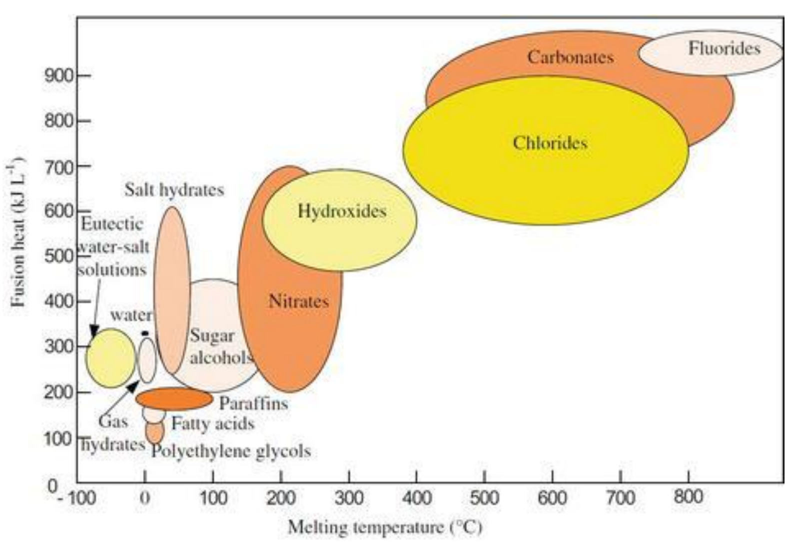


***Figure 4. Melting temperature and heat of fusion of different type of PCMs [Zhenjun et al. 2017]***

Other applications for active heating or cooling systems involve the use of macro-encapsulated PCM's tuned to melt at a pre-determined temperature. The PCM is typically encapsulated in polyethylene vessels and placed in new or existing sensible heat storage tanks thereby increasing the thermal storage capacity of the tanks by 5x to 7x the original design. This technique can often reduce or even eliminate the need to replace equipment due to increased thermal loads.

***Figure 5. Microencapsulation of PCM commonly used storage tanks or other containment vessels to increase thermal capacity; The BlockVesl developed by Puretemp is a typical example of this method.***

Other relevant technologies commercially available include both traditional and emerging products, traditional thermal storage products include

1. Hot water storage tanks – sensible heat only.
2. Chilled water storage tanks – sensible heat only.
3. Ice storage – the only commonly used latent energy storage system used for cooling.

Emerging technologies include:

1. Organic PCM encapsulated in a polyethylene membrane placed above ceiling tiles, or as a part of a wall/roof assembly.
2. Macro-encapsulated PCM capsules installed in existing or new storage tanks.
3. Paraffin wax as an integrated storage medium in gypsum or plaster wall applications.
4. Molten eutectic salt storage medium for high temperature (utility scale applications).

Current thermal energy storage technologies in the market are focused on traditional sensible heat storage, such as the conventional hot/cold tank storage [Grand View Research, 2017]. In addition, there are limited ice storage systems providing cooling to larger facilities. Compared to water-based sensible heat, there are limited installations where PCM latent heat-based products are used for large scale thermal storage.

Adoption of latent energy storage solutions provides a wide range of benefits to the DoD, including the following:

1. Energy cost reductions through:
    a. Elimination of utility demand charges.
    b. Offers a wider choice of utility rate structures.
    c. Reduced equipment sizing, for heating and cooling.
    d. Reduced equipment size supports reduced energy cost.
    e. Increases the commercial potential for renewable energy source use.
    f. Optimizes use of public and local generating plants.
    g. Offers opportunities to optimize waste heat recovery.
2. Energy security
    a. Provides HVAC system redundancy.

    b. Supports server or critical temperature-controlled equipment backup.
    c. Offers broad opportunities for portable heating or cooling systems.
    d. Supports both fossil and renewable energy sources.
    e. Reduced footprint over sensible heat storage systems.
    f. Mobility - plug and play, portable storage tanks could be charged overnight and used remote locations.
3. Energy goals
    a. Increased effectivity of energy sources, both fossil and renewable.
    b. Supports DoD energy goals through reduced cost and energy use.

## 3.2 DRIVERS

Drivers supporting wider implementation for this technology include, but not limited to:

- *Executive Order*: EO 13693.
- *Energy Independence and Security Act of 2007* mandates that federal buildings are required to consume 30% less energy than their 2005 baseline values.
- The DoD *Strategic Sustainability Performance Plan* to reduce building energy use by 30% of 2003 levels by 2015 and 37.5% by 2020.
- CEC Assembly Bill 2514.
- AHRI/ANSI Standard 900 - performance rating of equipment used for thermal cooling.

## 3.3 OBJECTIVE OF THE DEMONSTRATION

The purpose of this demonstration is to validate the performance of an engineered bio-based PCM. This allows storage of thermal energy at specified temperatures, reducing overall energy use. This agrees with energy goals set by the DoD, and is a technology that enables reduction of fossil fuels and promotion of renewable energy sources.

The primary objectives of this demonstration are to validate the following:

1. Validate performance of a bio based PCM to store and release energy at a pre-determined temperature.
2. Use of PCM based storage as a peak KW demand control strategy.
3. Control the release of energy based on building load demand over long- and short-time frames.
4. Prove the ability to control temperature discharge gradient over calculated time-period.
5. Prove the ability of a PCM to maintain consistent temperature over the trial period.

The validation of performance includes onsite data collection over the cooling season . Following a review of the output data, a comparison was drawn between chiller performance when the PhaseStor-TES is in operation, and when it is not operating. The demonstration provides comparative analysis of the system performance during three separate test conditions.

1. Chiller only (baseline).
2. Chiller/PhaseStor integrated operation.
3. PhaseStor only.

Individual test periods occurred on a weekly basis ensuring climate conditions and building load remained consistent. Use of this methodology supports generation of an accurate baseline.
In addition to the data collection activities we have constructed an eQUEST energy model of the building then calibrated the model to ensure a true baseline for comparison exists.

As our primary task is to evaluate the performance of the PhaseStor-TES, development of our building model focused on the chilled water system performance and associated loads. We have utilized industry standard ($ft^2$ based) assumptions for building plug and lighting loads, as these loads have little to no impact on the comparative analysis of the chilled water system performance. Building data was used as a cross reference to ensure the chilled water system is performing within reasonable assumptions.

To validate system performance, the following data collection devices were installed or calculated during the PhaseStor-TES site installation phase which commenced April 2017:

a. Chiller run time (minutes)
b. Chiller current (amp)
c. Chiller power (kW)
d. Chiller energy (kWh)
e. Chiller flow (gpm)
f. Pump power (kW)
g. Pump current (amp)
h. Pump energy (kWh)
i. Chilled water supply/return temperatures (°F)
j. Chilled water flow (gpm)
k. Tank leaving Btu meter (Btu)

Data acquisition occurred daily for the first week of operation to ensure correct operation. The data was reviewed for accuracy and consistency and any necessary adjustments to the system were competed.

To ensure reliable and accurate data acquisition is in place, we continued to regularly review and monitor data output for the remaining demonstration period (during summer months).
During the demonstration period, data collection was completed by our engineering staff through onsite monthly download. Data was reviewed for power (kW demand) energy (kWh) and cost ($) reduction on a regular reporting schedule.

## 3.4 TECHNOLOGY OBSTACLES

Over the past years, several industrial companies have been working to partnership with EnergyPlus software developers to enhance the predictability of phase change materials under real-life conditions via simulation tool. The goal is to enhance and optimize design parameters and performance of PCM-based system when connected to existing facilities and predict the potential for energy savings. Until now, existing simulation tools have failed to accurately predict experimental results. The obstacles and risk of not validating its energy saving potential on DoD facilities and other installations in general have increased the cost of pre-phase construction as well as number of iterations before a final and optimum system is found. For instance, there have been critical issues that impacted this demonstration. The lack of an accurate simulation tool has impacted the ability to confirm that performance of the system is consistent regardless of the different climate zones. Having said that, we believe the impact of this issue is minimal as the tanks have been tested under high temperature conditions at Ft. Irwin, CA. Although detailed discussions with several software developers, such as Big Ladder, have occurred, we have not been able to simulate the performance at the system engineering level. This is due to most efforts being focused on predicting the phase change behavior in a smaller system, such as a small room with phase change material above ceiling tiles.

# 4.0 TECHNOLOGY DESCRIPTION

## 4.1 PHASE CHANGE MATERIAL

Phase change materials (PCMs) are used for energy storage and thermal abatement in a wide range of applications in the industry. These applications cover a wide range of sizes, from applications for small portable electronics to large-scale concentrating solar plants, and a wide range of temperatures: ranging from −50°C to +175 °C depending on the type of PCM.
When it comes to PCM, the most important parameters are:

- High latent heat of fusion in the range of 200 J/g to 260 J/g
- Small density changes through the phase transition less than 2%
- Low or no supercooling tendency from 4 ºC to less than 0.1 ºC
- Chemical and thermal stability
- Non-flammability

While several types of PCMs are available by nature, there is no single material that satisfy all the points above. Thus, it's critical to choose a material based on the exact need of the applications, focusing on certain critical parameters.

### 4.1.1 Heat Transfer Enhancement

The increase of heat transfer continues to be of interest for most PCM applications. The challenge has been developing PCMs with suitable melting temperatures and high latent heats, along with a thermal conductivity, density and specific heat capacity high enough to be useful.

The optimum PCM must feature a high thermal conductivity. This is very critical for practical applications. If the thermal conductivity is low, the heat flux cannot effectively diffuse and be stored into the mass of the PCM, and only the layer of PCM closest to the heat source melts. In other words, If the thermal resistance is too high, the heat flux cannot quickly diffuse into the PCM to initiate energy storage or release. If this is the case, the PCM may act as an insulator between the heat side and energy storage side.

Carbon-based nanomaterials for instance, exhibit a higher thermal conductivity. In this project, a semi-solid matrix of PCM enhanced with Nano Graphene Platelets (NGPs) was used. Compared to conventional carbon-based nanomaterials, the nano-graphene platelets are characterized by several layers stacked horizontally creating a particle 1–15 nm in thickness [Shi et.al., 2013). Their unique morphology is shown below. Besides a high thermal conductivity, they also feature an increased flame retardancy.

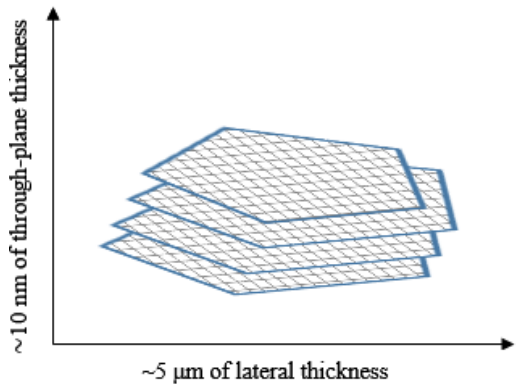


*Figure 6. Schematic diagram for a stack of Nano Graphene Platelets (NGPs).*

Another drawback of current PCMs is the possibility of leakage of its liquid phase. The used PCM in this project featured a high viscosity fluid by adding a polymeric based gelling agent in addition to the nano-graphene platelets as shown in Figure 7: (a) solid-liquid PCM mixture, (b) solid-gel PCM (c) Thermal enhanced solid-solid PCM with conductivity modulators.

*Figure 7. Digital photograph of (a) liquid PCM mixture, (b) gel PCM (c) Thermal enhanced PCM with the addition of nanomaterials*

### 4.1.2 Freezing or Charging Temperature of Phase Change Materials.

The degree of supercooling in PCMs which is the difference in melting and freezing is considered one of the most important parameters when it comes to TES applications. Carbon-based additives are commonly used as nucleating sites to reduce the effect of supercooling. This small cold region known as “cold-fingers” serve as nucleating sites which can be initiated due the presence of functionalized nanomaterials [Safari et al., 2017]. They behave like impurities that can trigger the nucleation and crystallization “freezing” process.

*Figure 8. The crystal structure of the phase change material with carbon-based additives*

*Figure 9. Crystal growth and nucleation sites in the phase change material*

## 4.2 PCM BASED PHASESTOR-TES APPLICATION

The PhaseStor-TES demonstration was based on the installation of a phase change material to store and release-controlled temperature thermal energy to meet the cooling load of B1020 (Education center) during the power utility peak demand period (weekdays, 12.00pm – 6.00pm). In phase 1, the demonstration comprised of two atmospherically vented aluminum tanks, each tank containing 960 gallons (6833 lbs.) of PCM with a total capacity of 615,000 Btu (51 ton-hours), therefore providing a combined capacity of 102 ton-hours storage. In Phase 2 when an enhanced concept system was installed, comprising 8 single modules, each tank containing ~450 gallons (3237 lbs.) of mixture with an active PCM weight of 2430 lbs. for a total capacity of 300,000 Btu (25 ton-hours), therefore providing a combined thermotical capacity of 200 ton-hours storage.

For the tanks installed in Phase 1, each tank contains 14 individual pressurized polypropylene heat exchangers fully immersed in the PCM. Each heat exchanger is factory manufactured from machine welded polypropylene, comprising 2 x 2" diameter headers welded to 196 x 3/8" diameter tubing. Each heat exchanger has a total submerged surface area of 163 $ft^2$.
The heat exchangers are connected within the top section of the tank above the headers through a common manifold and piped in parallel to maintain a pressure drop of less than 2 psi.
The process fluid, which in this demonstration was chilled water with a 5% mix of bio-based glycol, flows through the heat exchangers under a pressure of 60psi, noting, each heat exchanger has recommended maximum pressure rating of 90psi.

For the tanks installed in Phase 2, the same type of heat exchangers were used, however the size of individual tanks was smaller to give more flexibility in the parallel and series connections as modular tanks, comprising 8 single modules. Each tank contains 6 heat exchangers with 10% increase in surface contact area. The tanks are blow form/welded internal polyethylene tank with Internal lightweight tubular steel framing. A comparison between the two tank concepts, phase 1 tanks (PS-1) and phase 2 tanks (PS-2) is provided below.

*Table 3. A summary table for Phase 1 (PS-1) and Phase 2 (PS-2) tanks*

| Tank | Size (inch) | Heat Exchangers | HX Length (inch) | Manifold | Construction | Ton-hrs |
|---|---|---|---|---|---|---|
| PS-1 | 86 x 66 x 86 | 14 | 136 | PVC | Aluminum | 40 |
| PS-2 | 52 x 45 x 94 | 6 | 166 | Polypropylene | Polyethylene | 25 |

The system comprises of the following commercially available components:

1. Bio-based PCM – manufactured by Phase Change Energy Solutions.
2. Polypropylene tubing heat exchangers - manufactured by Fafco Industries.
3. Internal polyethylene film liner – generic manufacture.
4. Close celled polyisocyanurate insulation -generic manufacture.
5. Storage tank – generic manufacture.
    a. Aluminum internal skin.
    b. Aluminum structural frame.
    c. Aluminum exterior skin.


Exterior view of the 50 ton-hour tank with cut away showing multiple vertical heat exchanger mounting

***Figure 10. Exterior view of PhaseStor tank and cutaway showing heat-exchange array***

View from top of tank, prior to lid being fixed into place. Photo shows top of heat exchangers headers (black piping) interconnected by manifold (white piping).

***Figure 11. Top sectional view of heat-exchange header and manifold***

## 4.3 SITE-RELATED PERMITS AND REGULATIONS

Permitting requests were consistent with city/county building authority requirements encountered when installing plumbing or HVAC related installations for commercial buildings.

A complete design drawing set was submitted for review. The review process was completed within 2 weeks consistent with our expectations. There were several concerns raised by authorities prior to approval:

1. Fire marshal review: the storage tank and operating components are constructed from nationally approved plumbing products commonly used in plumbing installations and pose no fire hazard. The PCM is approved for installation in all areas of the building, the PCM formula includes a fire-retardant component and has a class A fire rating. We have submitted appropriate documentation as required by all fire authorities and received approval.
2. Environmental Inspector: A safety data sheet is provided in the appendix. Concerns were raised prior to installation regarding the potential for leakage causing contamination to the site. We discussed the potential for leakage to the surrounding environment due to manufacturing or installation faults, or in the case of a tank rupture due to an accident or natural event. The PCM is a vegetable oil base product and therefore bio-degradable like other vegetable-based products. For the TES application the PCM is formulated to remain in solid form up to 120°F and that above this temperature it will remain in a thick gel like the consistency of toothpaste.
3. Plumbing: as there were no sewer or storm drains within the zone of installation and given the PCM remains in solid form, the plumbing inspector had no concerns.
4. Digging and welding permits were required to complete the installation.
5. There were no other related regulations applicable to this installation.

## 4.4 TECHNOLOGY OVERVIEW

The two primary applications of a PCM based thermal storage system could be installed as part of a new HVAC chilled water-cooling installation or as an addition to an existing installation. In both applications the tank is installed as a component of the chilled water piping system and depending on the application could be either upstream or downstream of the electric chiller or heat pump.

The TES is intended to provide added storage capacity through the latent heat of fusion to charge (freeze) the PCM contained in the tank by passing a lower temperature process fluid through the heat exchangers at a temperature differential lower than the PCM freeze point. Then discharge (melt) the PCM and release the stored energy (Btu/KW) within the PCM at a temperature differential, higher than the PCM melt point.

The timing of freezing and melting of the PCM is determined by the utility rate structure, which is calculated based on the cost of power at different times of the day depending on the seasonal peak demand rate structure. This practice is commonly known as Time of Use (TOU).

## 4.5 TECHNOLOGY DEVELOPMENT

The use of PCM for energy storage is still considered an emerging technology, however it is starting to gain commercial traction in Europe and Australia. The viability of the PhaseStor system using a bio based PCM was first demonstrated in 2012 using a small ice storage tank and heat exchangers provided by Calmac Industries, the industry leader in ice storage technology.

After completion of the initial technology demonstration Phase Change Energy Solutions (PCES) commenced design of their own tanks and heat exchangers specifically engineered to optimize the particular-characteristics inherent to the bio-based PCM formula.

Following several years of development PCES are moving towards commercializing the product and at the time of writing have secured the rights to manufacture their own heat exchangers and tanks. PCES have commenced their 1st manufacturing plant dedicated to the manufacture of the PhaseStor-TES and was in full production by the 3rd quarter of 2018.

## 4.6 TECHNOLOGY POTENTIAL

Power Utility demand charges based on TOU rates often exceed 50% of the cost of power purchased at many facilities. For example, the kWh cost at Ft. Irwin is 800% ($0.46) higher during the peak period when compared to the off-peak period ($0.054). Studies (Brattle Group 2016) indicate TOU rate and dynamic pricing are expected to increase across most Utilities in the coming years, with Southern California Edison (SCE) being the first to introduce TOU rate for residential customers in 2019. The regulatory bodies and Utilities understand the need to decrease peak power use and to level the daily and seasonal power curve.

The urgent need to change our current energy use patterns provides consumers with access to considerable incentives to install technologies aimed at reducing peak power use. Currently, some CA Power Utilities support the installations of demand reduction strategies like the PCM based TES with an incentive of $875 kW to a maximum of $1.5 million per project [Yin, R et. Al, 2015]

The introduction of a new technology like PCM-TES provides an opportunity not previously available to many facilities due to its potential to address retrofit applications. In many cases a

PCM-TES will have minimal impact on the existing chilled water system due to its ability to melt/freeze at engineered temperatures to suit each installation.

The widespread use of TES technology offers the opportunity to eliminate demand charges associated with chilled water HVAC systems. Introduction of this technology will not only change the way we operate existing buildings but will force a paradigm shift in the design of new buildings through reduction in chiller/heat pump sizing, impacting not only the HVAC system but will also have a considerable impact on the design/sizing of the electrical systems, as the HVAC system is often the primary driver of electrical system design.

## 4.7 Advantages and Limitations of The Technology

The installation of a TES system in commercial building applications is generally intended to support a cost reduction strategy. However, installations offer many notable benefits.

The primary drivers for installing TES:

- Cost saving.
- Resiliency.
- Redundancy.
- Additional capacity.

Cost Saving: is one of the four primary drivers for installing a TES unit. Cost savings are generally associated with a reduction in power utility demand charges. Demand charges are based on time of use (TOU) rate structures, where utilities charge an added rate per kW during peak periods of use.

Resiliency: TES systems are commonly used to provide backup support to server rooms or other facilities where thermal control is critical to the facilities operations.

Redundancy: TES can also be used where redundant equipment would normally be considered in the design. The installation of storage provides the opportunity to change the typical operation of the HVAC from a load-based response, operating on peaks and troughs to a system that operates closer to a constant flat line.

Additional capacity: facilities are continually changing their missions often resulting in expansion or contraction of HVAC services. TES offers the potential to increase or decrease cooling capacity without the need to replace existing equipment. A TES can be installed remotely from the chiller plant or the building and be centrally located to service multiple facilities if needed.

Maintenance: the PCM-TES could be considered in many ways similar to an atmospheric vented (non-pressurized) sensible heat storage tank. It is a passive technology generally requiring annual inspection and limited maintenance.

PCM: the bio-based PCM is a solid gel-based product and remains solid in either it's frozen or melted state. With an expansion rate of between 3%-5% it does not exert differing stresses on the storage vessel. There is no evaporation therefore does not require regular filling or level indicators. Bactericides or algaecides are not required.

Piping: the internal components comprise of welded polypropylene or polyethylene piping with no mechanical joints. There are no internal controls or valves.

Glycol: in many cases the PCM-TES will not require glycol, however this is dependent on the chiller manufacturer recommendations and the freeze/melt temperature required by the chilled water supply temperature. Generally, chiller manufacturers recommend glycol where the leaving water temperature (LWT) is below 38°F.

Seasonal shut down: some installations may require being shut down during the winter period. This would require a reduction of some of process fluid in the heat exchanger to reduce the chance of fluid freezing in the piping.

Maintenance recommendations:

1. Annual visual inspection for tank integrity.
2. Winter shut down, partially drain-down of process fluid in heat exchanger to reduce chance of a pressure increase in the event of fluid freezing.

Performance Limitations: PCM-TES is a passive technology with no moving parts or containing fluids. In the event of any type of mechanical failure the system can be easily be isolated from the primary chilled water loop through the control valves required to operate the freeze and melt cycles.

PCM long term performance: the PCM has continued to be tested under laboratory conditions using a thermal cycling accelerator to perform accelerated performance testing. As of release of this report the PCM has been continuously cycled through a complete freeze/melt cycle for the equivalent operational use of 85 years. Publicly available laboratory tests results indicate there is less than a 1% thermal capacity degradation over the specified operational use period.

Tank leakage: the most likely risk associated with a PCM-TES is the potential for internal leakage to the chilled water piping configuration. This is considered low rick, given the piping is fully welded polypropylene with no mechanical joints. Polypropylene piping products have a long-established quality record and are totally contained inside the tank. If a leak were to occur, the result would be loss of process fluid (treated water), leading to a shut-down of the chiller. Due to the piping configuration the TES could easily be isolated from the primary chilled water system allowing continued operation without the TES.

Once identified if the leak is above the PCM level, then a fusion welded repair coupling could be used, or if the leak is below the PCM level, the single heat exchanger could be isolated using a fusion welded cap. Isolating a single heat exchanger would have little noticeable impact to the performance of the system.

Cost Limitations: there is considerable historical data related to the installation of traditional TES systems such as chilled water and ice storage systems. As to be expected there is limited historical data available for the PCM based TES, however the installations are very similar to ice storage, (given ice is a PCM). The only discernable difference is the manufacturing costs associated with the PCM itself. Currently the manufacturing cost for a bio-based PCM range from $0.87 - $1.52 per lb.

There is historical DoD cost analysis for TES available to researchers dating back to 1991. Generally, industry published costs range from $90 ton-hr. to $350 ton-hr.

Costs vary considerably based on the specifics of the installation. Noting: when the TES is included in a new design, there is little to no noticeable cost increase per ton, however where TES is to be installed into an existing system the cost is dependent on the conditions and existing system limitations, therefore costs could range from 2x to 3x higher when installing into existing system than a new system.

## 4.8 POTENTIAL BARRIERS TO ACCEPTANCE

PCM-TES technologies face several primary barriers to market entry, these can be identified under the following categories:

1. Market readiness.
2. Containment vessel design.
3. PCM manufacturing costs in general as a thermal storage medium
4. While PCM-TES remains an emerging technology, manufacturing cost of the PCM remains the key issue as the raw materials cannot be purchased or manufactured as a commodity product and remain a custom order.

Additional barriers relate to material properties and stability, currently each storage application uses a specific TES design to fit specific boundary conditions and requirements. R&D activities focus on all TES technologies. Most of such R&D efforts deal with materials (i.e. storage media for different temperature ranges), heat exchange, containment vessels and thermal insulation development.

PCM-TES market development and penetration varies considerably, depending on the application and geographic region. Given the many applications not only in commercial HVAC but also high/low temperature, industrial, agricultural, transport and storage, it is very difficult to determine the actual market opportunities.

Penetration into the building sector is comparably slow where the construction of new buildings is around 1.3% per year and the renovation rate is around 1.5%.

Given the slower acceptance of PCM based technologies in the US, there is very limited data on potential opportunities. It’s commonly accepted that the US electrical infrastructure is near it’s breaking point, requiring immediate solutions to reduce peak loads.

In Europe where interest in PCM technologies is far greater there are studies suggesting the potential of 5% implementation rate of TES systems in buildings. Penetration could be much higher in emerging economies with their high rates of new building construction and slow expansion of the electrical infrastructure. TES potential for co-generation and district heating in Europe is also associated with the building stock. The implementation rate of co-generation is 10.2%, while the implementation of TES in these systems is assumed to be 15%.

The industrial sector also features in many of the European studies, suggesting about 5% of the final energy consumption could be provided by TES installations.

In particular, the use of industrial waste heat is expected to grow since the price of fossil fuels will rise and energy efficiency incentives will increase. Based on the University of Lleida study, the expansion of TES technologies is expected to be significant in Europe and Asia (particularly Japan) and somewhat lower (50%) in the United States. The global potential is estimated at approximately three times the European potential.

## 5.0 FACILITY/SITE DESCRIPTION

The demonstration of a bio based PCM thermal energy storage system is being conducted at the Ft. Irwin, U.S. Army, National Training Center, located approximately 37 miles northeast of Barstow, California midway between Las Vegas, Nevada and Los Angeles, California. The base is located adjacent the high Mojave Desert's hills and mountains.

The demonstration is being conducted in two phases with both phases taking place at the same location, Building 1020 3rd Ave. Ft. Irwin Village.

Building 1020 is an 12,500 ft² education center including an entry lobby, administration offices, general learning and computer classrooms. B1020 is located in the central area of the base, surrounded by base recreation facilities.

### 5.1 GENERAL FACILITY/SITE SELECTION CRITERIA

Site selection was based on the following criteria:

Geographic location: to maximize the potential savings of a cooling-based TES, a cooling dominated location was preferable. A review of the cooling degree days (CDD) for Ft. Irwin which has been based on the recommended ASHRAE HDD/CDD transition temperature of 65°F confirms a five-yearly average of 3228 CDD per year.

***Table 4. 1-year average CDD data for Ft. Irwin CA. http://www.degreedays.net/#***

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22 | 87 | 137 | 269 | 611 | 735 | 678 | 456 | 194 | 36 | 2 | 3228 |

Facility Description: The building was constructed in the mid-1990's, and represents the typical base construction comprising a single story, slab on grade with double walled blockwork and insulated metal deck roof. The building type and construction is very typical of Base construction throughout the west coast and inland regions. Mechanical and electrical systems are also typical of the region.

The hours of operation are 7.30am – 5.00pm 5 days a week, this is consistent with the operating hours of many facilities over the base.

Total building area is 12,500 ft², however this includes 2000 ft² of non-conditioned zones.
Comfort control for the building is provided by a single air handler (AHU-1) located in the mechanical room supplying pre-conditioned air to multiple zoned variable air volume units with hot water heating coils located throughout the facility. AHU-1 is provided with a water coil connected to the central chilled water system for cooling, and hot water boiler for heating. The cooling equipment is located in a plant room within the main building. A 70-ton air cooled chiller is located in a rear service yard. The chiller was replaced in 2016 however pumps and controls remain as original. The service yard is fully fenced and has adequate space to install the PhaseStor TES without having to seek additional base architectural approvals. The service yard is readily accessible at all times providing ease of installation and providing the opportunity for ongoing demonstration activities over the course of the summer test period. As such, our planned interruptions to the cooling system has minimal impact to the facilities daily operations. The location of the TES did not impact the building occupants as it is located in the rear service yard away from the main entry and occupied zones.

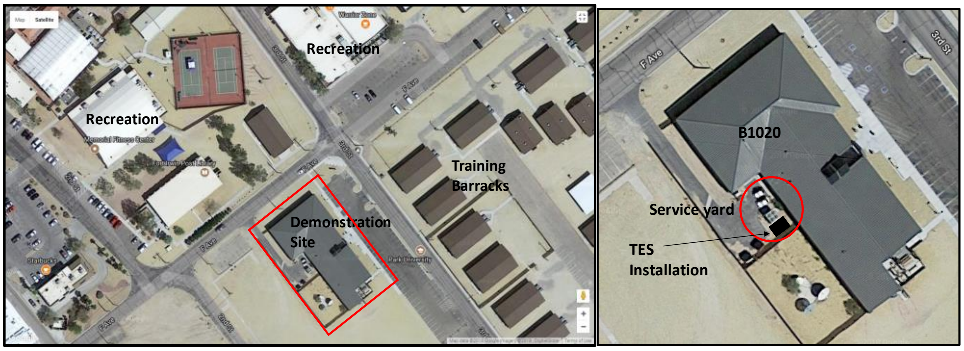


*Figure 12. Aerial images of building street location and TES installation in rear service yard*

## 5.2 PROPERTY TRANSFER OR DECOMMISSIONING

The demonstration comprised of two individual phased installations. The phase 1 installation was partially removed on completion in November 2017. The tanks were drained and removed from site. Remaining TES dedicated pipework and controls were sealed and secured but remain in place as part of the phase 2 installation.

The phase 2 installation required replacing both the phase 1 tanks with the newly designed modular system, comprising 8 single modules. Since these types of tanks are modular, meaning that the installation had more tanks, Phase 2 required more piping modifications, added control valves and expansion of the control-panel. The Phase 2 TES system was partially removed on completion in May 2019. Tanks were drained and removed but the pipework and controls remain in place so that they can be used in future for a new TES if needed.

## 5.3 PERFORMANCE OBJECTIVES

Name and Definition: The performance objective of the PhaseStor -TES demonstration project is to validate the performance characteristics of a solid to solid bio-based phase change material to store and discharge thermal energy on demand, consistent with the existing chilled water supply temperature.

Purpose: The purpose of the demonstration is to validate a reduction in chiller plant energy and cost savings by the installation of a temperature-controlled Btu storage system in parallel to an existing conventional non-storage chilled water generation system. A baseline for the non-storage (existing system) will be developed to validate chiller energy use reduction. The baseline is then used to compare the demonstration option of the two latent thermal storage systems PhaseStor (proposed demonstration) and ice storage (traditional comparative technology)

Technology description: the technology demonstration proposed under this award demonstrated the energy savings potential of a bio-based latent energy storage system – PhaseStor-TES (thermal energy storage).

The bio-based phase change material (PCM) is fully contained within a structural storage tank. The tank is internally lined with rigid insulation surrounding a flexible RPE (reinforced polyethylene liner). The RPE liner forms secondary containment for a bio-based phase change material manufactured from organic non-food grade fatty acids. The Bio-PCM is formulated specifically for large scale thermal storage applications and is unique, in that it remains in solid form regardless of charge state (phase change).

By utilizing a solid to solid transition many potential environmental concerns related to leakage or spills have been minimized.

DoD use and relevance: The cooling of many DoD facilities is accomplished through the installation of a chilled water-cooling system. A chilled water system generates chilled water by rejecting heat to a refrigerant by use of an electrically powered chiller. The chiller is responsible for generating chilled water, which is then distributed throughout the building to remove excess heat created by external temperature variations, internal loads produced by equipment heat rejection or heat generated by increased occupant loads.

The basis of the current design strategy is to meet increased loads by ramping up the chiller to maintain the desired space temperature. This strategy results in the following operational characteristics:

a. Chillers are sized to meet the peak load. This design characteristic results in equipment that is oversized for normal operation, as the peak load typically occurs for less than 10% of the equipment's operating life.
b. Highest energy use when power is at its highest cost.
c. Chiller is under-utilized when building cooling loads are low, and electricity costs are low.
d. Increased load on the power grid when power demand is at its peak and generation is at its least efficient.
e. Limited system resiliency for critical load periods.

Contribution toward a DoD goal: the DoD goal towards zero net energy designs, energy independence and energy resilience inherently promote greater integration of renewable energy into existing facilities.

- DoD facilities are increasing their reliance on renewable resources. However, to ensure reliable energy supply, renewable resources require the integration of energy storage to offset periods of low or no generation.
- Consistent energy flow is the primary hurdle faced by the integration of renewable generation into mainstream power supplies. Integration of energy storage is now an important consideration for any existing or new facility.
- The need for energy resiliency across DoD facilities requires alternate energy resources to be generated and stored. Thermal storage is a primary resource available to eliminate the need for instantaneous response, particularly in the case of critical climate control.

Metric: the following measured units are proposed for the demonstration:

- Tons of refrigeration (ton)
- Tons of refrigeration per given time period (ton-hrs.)
- Kilowatt hours (kWh)
- Kilowatt (kW)
- British thermal unit (Btu)
- Gallons per minute (gpm)
- Temperature (°F)

Metric (units) used to measure performance: the primary units of measurement used for performance of the PhaseStor-TES is saved kWh, KW (demand) and cost avoidance $.

*Table 5. Building information*

| Table 2: Building Data / Operating Hours – Ft. Irwin, Building 1020 | | | | | |
|---|---|---|---|---|---|
| **Type** | **Building Area** | **Typical Operating Hours** | **Occupants** | **Annual Hours** | **Average Monthly kWh*** |
| Education Center, Administration, Lecture Theater, Classrooms | 18,500 $ft^2$ | M-F 0730-1630 | 120 | 2500 | N/A |

*Figure 13. Front and rear view of demonstration site, Building 1020*

The demonstration was completed in two phases:

Phase 1: small scaled demonstration (50-80 ton-hrs.) to validate technology performance.

Phase 2: Enhanced larger scale demonstration (180-220 ton-hrs.) to validate the tangible economic value of utilizing a PCM based thermal storage system.

The B1020 is the preferred site location for the following demonstration:

- Chiller performance and specifications are well known.
- Building performance is understood. There are performance concerns with the building due to un-insulated roof areas. These are to be repaired prior to phase 2 demonstration.
- The building manager and maintenance staff are familiar with the operation of the PhaseStor system and support future demonstrations.
- There remain partial installation of controls and plumbing at B1020 to support further demonstrations.
- B1020 is not a critical facility and impacts due to the demonstration have minimal impact to the base operations.

Data. To measure the PhaseStor-TES performance we will collect and review chiller performance in kWh and kW demand. Both metrices will be collected as a direct digital output.

Analytical Methodology: Methodology will be based on a post and pre-installation comparative analysis, including the following:

- Phase 1 installation commenced mid-April 2017 at Building 1020. Collection of baseline test data has been ongoing since early May 2017. Data collection occurs at 5-minute intervals, where it is locally stored. Then transmitted every hour through a dedicated cell connection to a web-based interface. The data can then be accessed whenever required.

Following the completion of the installation data will be collected daily for the 1st week of operation to ensure calibration and data collection devices are operating correctly. Following confirmation of operation, weekly downloads will occur for the following 4 weeks. After our initial review data will be downloaded monthly. The demonstration period ended in the summer months of 2017.

- Pre-installation: the PhaseStor-TES was configured as a side stream flow, this allows for continuous uninterrupted flow from the existing system. The design of the PhaseStor-TES includes a bypass to divert flow at any time during the demonstration period through integrated automated controls. Although we have been actively collecting baseline data over the past month, there is no need to monitor the chiller performance prior to the installation as real-time performance data will be available during the demonstration.
- Baseline development: a baseline for the existing chilled water installation was developed during the demonstration period through alternating operation of the chilled water system to bypass the PhaseStor-TES (pre-existing condition) allowing weekly/bi-weekly cycling. This process ensures the climatic conditions are similar for pre and post operating conditions.
- Power and energy analysis of the chilled water system including primary and auxiliary equipment was monitored by the following equipment to be installed during the construction phase:

***Table 6. Data Monitoring equipment***

| **Item** | **Description** | **Cost** | **Link** |
|---|---|---|---|
| E50B2 Power & Energy Meter - T-VER-E50B2 | The E50B2 Power & Energy Meter measures current and amperage and computes energy and power that are then transmitted as a pulse to provide the most accurate energy and power measurements available |  | http://www.onsetcomp.com/products/sensors/t-ver-e50b2 |
| UX120-017M 4-channel pulse data logger | The T-VER-E50B2 Energy and Power Meter outputs (3) sets of pulses which are logged by the UX120-017. These pulses represent Watt-hours, Amp-hours, and VAR-hours. HOBOware software uses these pulse values to calculate AC Current, AC Voltage, kW, Power Factor, VARs, and VA. |  | http://www.onsetcomp.com/products/data-loggers/ux120-017m |
| Split-Core Current TransformerAccu-CT. | The Accu-CT revenue grade, split-core current transformer offers outstanding linearity and phase angle accuracy over full temperature range and down to 1% of rated current.<br>Exceptionally low phase angle error: essential for accurate power and energy measurements. |  | http://www.onsetcomp.com/products/sensors/t-act-0750-050 |
| 12-Bit Temp Smart Sensor | The 12-bit Temperature Smart Sensor provides < ± 0.2° C total accuracy (< ±0.36° F) and resolution of < ± 0.03° C (< ±0.054° F) over the range of from 0° to 50° C (32° to 122° F). A selectable measurement-averaging feature further improves accuracy. |  | http://www.onsetcomp.com/products/sensors/s-tmb-m017 |
| Btu Meter Onicon | System-40 BTU Measurement System provides highly accurate and reliable thermal energy measurement in heating and cooling systems. |  | http://www.onicon.com/ONICON_Whats_New.html |

Success Criteria: Demonstration success was determined by the following criteria:

- Annual chiller energy saving determined in kWh from baseline. The demonstration will target 5% kWh reduction based on the existing non-storage installation.
- Annual energy cost reduction of 20-40% "depending on utility rates and structure" determined by kWh cost reduction + kW demand savings ($) based on the existing non-storage installation
- Validation of bio based PCM to store energy over time measured in loss of Btu/hr./°F.
- Validation of bio based PCM to maintain constant output measured in gpm (flow) and °F (temperature).

## 5.4 SUMMARY OF PERFORMANCE OBJECTIVES

***Table 7. performance quantitative objectives***

| Performance Objective | Metric | Data Requirements | Success Criteria | Results |
|---|---|---|---|---|
| **Quantitative Performance Objectives** | | | | |
| Energy Usage | kWh | kWh usage from chiller | **5% reduction compared to baseline** | **Achieved 7.4% reduction compared to baseline** |
| Peak demand energy usage | kW | kW demand from chiller | **20% reduction to measured baseline** | **20% reduction in peak demand usage. 14.2 vs 17.7 kWh maximum energy usage) during on peak-hrs (table 16)** |
| System Economics | $ | Dollar costs and chiller replacement | **25% reduction in energy cost and use of existing chiller** | **43% reduction in energy cost** |

***Table 8. performance qualitative objectives***

| Performance Objective | Metric | Data Requirements | Success Criteria | Results |
|---|---|---|---|---|
| **Qualitative Performance Objectives** | | | | |
| System Resilience | Ton-hrs. | Measured and calculated energy storage capacity | **Validate % of usable energy capacity in the system** | **verified 24/25 ton.hr (96%) of claimed energy storage per tank to be available in the tanks "figure 26"** |
| User Satisfaction | Comfort temperature | Survey | **Negligible effect on space comfort level over baseline** | **Satisfied cooling needs during discharge periods** |

## 5.5 PERFORMANCE OBJECTIVES DESCRIPTIONS.

**Quantitative performance objectives**: The primary goal of the performance objective is to validate that PhaseStor-TES performs equal to or better than traditional non-storage and established latent energy storage systems, such as ice.

1. **Energy use:** Savings are to be achieved by generating chilled water at times when chiller efficiency is optimized due to lower ambient air temperature, and when electrical costs are at their lowest. Energy use reduction is achieved through the following actions:
    - The chiller plant was operated during night-time off peak hours when ambient air temperature is lower than the chiller design specification based on operating conditions in compliance with AHRI Efficiency Rating Standards 550-590, 2015. This will provide increased chiller efficiency - providing energy savings.
    - Operating the chiller at full capacity (night-time tank charge cycle) for longer periods reduces cycling time and reduction of starting load amps - reducing energy use.
    - By operating the chiller in lower ambient air conditions, and under a programmed schedule rather than conventional instantaneous load response provides opportunities to reduce chiller cycling times, hence savings energy
    - **Metrics**: comparing HVAC energy consumption before and after the installation of the TES system using a baseline of similar ambient conditions
2. **Peak demand energy use:** Energy savings are achieved by reducing energy consumption during peak demand hours through the following actions:
    - Utilizing the chiller in off-peak periods avoids peak hour demand charges.
    - Operating the chiller at increased efficiencies and avoiding operating the chiller at peak demand periods reduces kW demand and kWh consumption at source generation – supporting a reduction in source energy greenhouse gas emissions.
3. **System Economics:** Energy cost savings are achieved by reducing cost of energy consuming during peak demand hours through the following actions:
    - **Energy cost:**
        - Charging the system in off-peak hours when cost of electricity is less
        - Allowing the TES to engage during on-peak hours when cost of energy per kWh is higher, so that the TES is producing chiller water keeping the chiller partially or complete off, hence avoid paying for kWh when the rates are higher.
        - **Metrics**: Calculations compared the cost savings associated with shifting kWh load from on-peak hours to the off-peak hours.
    - **Cost Avoidance**:
        - Thermal storage, regardless of the medium used is a proven technology in providing resilience for facilities, particularly with critical thermal load requirements. PCM technology expands the opportunities to add energy resilience into existing cooling or heating systems without the need for replacement of existing infrastructure, while using considerably less $ft^2$/Btu storage area than traditional sensible heat storage systems. Integrating thermal storage as a component of the design provides the opportunity to reduce the chiller size through use of passive storage. This practice is

commonplace when designing traditional TES solutions such as ice and chilled water. The use of storage is particularly common in hot water system design.

**Qualitative performance objectives**

1. **System Resilience.** Validation of the available energy storage capacity in the system was achieved through the following actions
    - Meaning the total energy storage capacity that can be experimental stored in the tank
    - **Metrics**: Energy storage capacity was calculated using the temperature variation across the tanks and running a one-time test with a known GPM and EWT via the equation storage capacity = 500xGPMxdT and integrating it while increasing the temperature of the tank from a temperature that equals that typical night time charging temperature to a temperature that equals that return water supply temperature
2. **User Satisfaction**: Integration of thermal storage into existing facilities provides benefits to the users by the following **qualitative metrics**:
    1. Provides the ability for the user to maintain cooling of critical facilities in event of power grid disruptions by use of the chilled water pump only. This reduces or eliminates the need for the chiller to operate during short time period disruptions, hence no need to use a huge electricity generators or batteries as a backup.
    2. Supports the use of renewable resources by optimizing the use of the resource when natural resources are available. PhaseStor-TESS will store energy for later use when renewable generation is limited due to variations in climatic conditions.

## 6.0 TEST DESIGN

The following provides a detailed description of the system design and testing conducted during the demonstration.

Fundamental problem: many DoD facilities, particularly those facilities over 10,000 $ft^2$ utilize electric water chillers and centralized water distribution systems to provide comfort and process cooling throughout the building. Generally, these systems are inherently oversized to meet a peak load that very often only occurs for less than 10% of the equipment's life. Including thermal storage into the system provides cost savings, and system redundancy.
The proposed PhaseStor latent energy storage system may be an improved approach to conventional instantaneous response systems.

Demonstration question: can PCM-based latent energy storage systems provide an economic alternative to the traditional non-storage installation and compete with established thermal storage systems such as chilled water and ice storage.

How much energy and cost savings can be achieved by implementing the PhaseStor system into an existing chilled water system.

## 6.1 CONCEPTUAL TEST DESIGN

| | |
|---|---|
| Independent Variable | Absence of thermal storage in existing chilled water system |
| Dependent Variable | • Total electricity consumed by the selected chilled water plant<br>• Total cost of electricity for the selected chilled water plant<br>• Runtime of the chilled water equipment |
| Controlled Variables | • Chilled water plant (cooling) equipment<br>• Building operations being served by the chilled water plant |
| Hypothesis | The hypothesis tested that the installation of the PhaseStor thermal energy storage system reduces energy consumption and energy costs by utilizing the plant during off peak, low cost, higher efficiency periods (nighttime) to charge the pcm. The stored energy is then used during the peak period. (shifting plant load profile). |
| Test Design | The baseline period was developed over a two-week period prior to installation and two weeks post installation. The demonstration period was conducted over weekends and during normal periods of operation. (M-F, 7.30 – 16.30)<br><br>**Phase I: Baseline assessment and data collection**<br>This phase consisted of surveying the plant to assess the existing operation, control sequence and collect equipment and building specifications. This effort was intended to support the PhaseStor pipework design, installation, and for future modeling tasks.<br><br>**Phase II: Installation and commissioning**<br>The PhaseStor tanks were installed onsite and connected into the chiller plant pipework. A dedicated Allerton control panel was integrated into the existing Siemen based controls. Commissioning tests were performed, and system brought online.<br><br>**Data collection and analysis**<br>After commissioning, the PhaseStor tanks operate continuously using a 5-day time schedule program, consistent with building operations. |

## 6.2 BASELINE CHARACTERIZATION

The only direct impacts on the building performance are associated with the operation of the electric chiller, water pumps and associated controller. There may be an indirect impact on control of internal building temperatures due to variation in supply water temperature which will be monitored during the test procedure.

The PhaseStor tanks are installed and controlled as a side stream to the main chiller pipework, this configuration enables a baseline characterization period that is concurrent with the demonstration period by allowing bypass of the PhaseStor system at any time. Data logging equipment was installed one-month prior to the PhaseStor installation to ensure data collection devices were operating correctly, and to provide additional baseline data in the event of loss of data during the test period.

The change between PhaseStor chiller operation and existing chiller operation is accomplished with installation of 3-way bypass valves controlled using the newly installed Allerton controller.

The data for the baseline characterization was collected independently from the Allerton controller using a dedicated Onset (Hobo) data acquisition module with web based (remote) access through a cellular connection. Data was collected and used in an Excel based calculator analysis. Data will be used from May 2017, to October 2017, along with data indicating original equipment and control operation.

The individual equipment power consumption data is summed at each period (5 minute) to arrive at the total power consumed at the plant. The individual equipment included the chiller and chilled water pumps. Other data used included: outdoor air temperature and humidity, indoor air temperature at representative rooms within building 1020, type of day (weekday or weekend).

After analysis of the data, irregular, anomalous spikes will be removed before using the data for modeling the baseline operation.

***Table 9. Sample of data collection***

| Date | Pump (gpm) | AHU CHWS | CHWR | Chiller OA | AHU Leaving Coil | AHU CHWS | Upper Tank | Tank-1 CEWT-DLWT | Tank-1 CLWT DEWT | Tank-2 CEWT-DLWT | Tank-2 CLWT DEWT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/20/2017 0:00 | 96.43 | 54.69 | 56.99 | 94.61 | 56.64 | 54.69 | 57.07 | 54.95 | 55.73 | 57.63 | 55.73 |
| 6/20/2017 0:05 | 95.81 | 54.95 | 57.85 | 94.61 | 57.46 | 54.95 | 57.38 | 54.99 | 59.62 | 57.63 | 59.87 |
| 6/20/2017 0:10 | 96.1 | 55.39 | 57.51 | 94.23 | 57.12 | 55.39 | 57.12 | 54.99 | 55.47 | 57.63 | 55.47 |
| 6/20/2017 0:15 | 95.79 | 54.65 | 57.46 | 93.94 | 57.03 | 54.65 | 57.33 | 55.04 | 59.1 | 57.59 | 59.36 |
| 6/20/2017 0:20 | 96.98 | 55.99 | 58.32 | 92.86 | 57.85 | 55.99 | 57.2 | 55.04 | 55.17 | 57.55 | 55.17 |
| 6/20/2017 0:25 | 95.59 | 54.17 | 56.9 | 92.81 | 56.56 | 54.17 | 57.29 | 55.04 | 58.58 | 57.55 | 58.76 |
| 6/20/2017 0:30 | 96.53 | 57.12 | 59.36 | 92.48 | 58.84 | 57.12 | 57.25 | 55.08 | 55.3 | 57.59 | 55.3 |
| 6/20/2017 0:35 | 96.53 | 53.47 | 56.12 | 92.39 | 55.82 | 53.47 | 57.2 | 55.04 | 57.72 | 57.59 | 57.81 |
| 6/20/2017 0:40 | 96.31 | 56.56 | 59.44 | 92.34 | 58.76 | 56.56 | 57.33 | 55.13 | 56.77 | 57.63 | 56.94 |
| 6/20/2017 0:45 | 95.26 | 53.56 | 55.52 | 92.29 | 55.21 | 53.56 | 57.12 | 55.13 | 56.77 | 57.63 | 56.86 |
| 6/20/2017 0:50 | 97.84 | 55.69 | 58.71 | 92.15 | 58.15 | 55.69 | 57.38 | 55.17 | 58.37 | 57.63 | 58.58 |
| 6/20/2017 0:55 | 97.19 | 54.6 | 56.86 | 92.2 | 56.47 | 54.6 | 57.07 | 55.17 | 55.95 | 57.63 | 55.95 |

***Table 10. Sample of data collection for previous table***

| |
|---|
| Pump (gpm) - chilled water pump flow |
| CHWS - chilled water supply |
| CHWR - chilled water return |
| OA - outside air temperature |
| AHU Leaving Coil - air handling unit (coil) leaving chilled water temperature |
| AHU CHWS - air handling unit chilled water supply temperature |
| Upper Tank - air temperature in Phasestor tank above pcm |
| CEWT - charge cycle entering water temperature |
| DLWT - discharge cycle leaving water temperature |

## 6.3 INSTALLATION IMAGES

The following images show completed installation details:

Installation of bypass valves

Onset web based monitoring devices


Allerton BMS controller

Installation of VFD's to CHW pumps

Installation of tank

***Figure 14. INSTALLATION IMAGES for Phase 1***

***Figure 15. INSTALLATION IMAGES for Phase 2***

## 6.4 PROCEDURE AND TEST PLAN

**Procedure**:

1. Investigate building operations, chiller design and installation options
2. Install data acquisition devices for kW, kWh, gpm, multiple inlet and outlet temperatures and pressure transducers to the chiller plant equipment, test and commission for operation
3. Install PhaseStor tank and controls, test for tank integrity, test control sequences and commission
4. Test and manually operate the system for one week to determine final temperature control and develop operational schedule
5. Monitor operation remotely for 30 days and develop preliminary data analysis.
6. Visit site to make any system or control corrections.
7. Install and commission VFD's to provide additional control options and evaluate effect on chiller performance and building operation.
8. Test and manually operate the system for one week to determine final temperature control and develop operational schedule
9. Monitor operation remotely for 30 days and develop final data analysis.

## 6.5 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

System Design: Cooling for the HVAC system at B1020 comprises a piped chilled water system supplying chilled water (CHW) to a single air handling unit (AHU-1). The chilled water is supplied by a Trane model CGAM 070A air cooled electric chiller. The PhaseStor-TES was integrated into the existing chilled water generation system by the modification of the CHWS and CHWR piping to include valve connections allowing the TES to operate in sequence with electric water chiller.

The schematic below shows the new piping (black/solid) required to connect the tanks into the existing piping (grey/dashed).

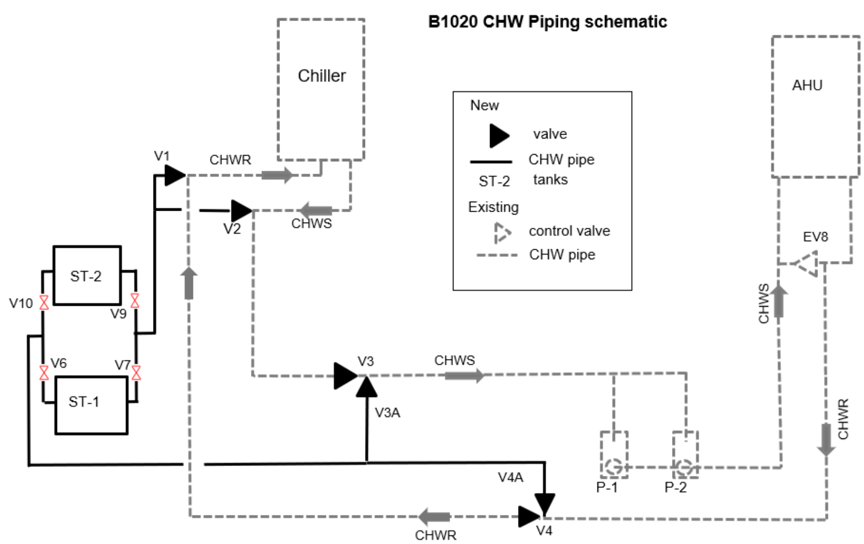


*Figure 16. Revised piping schematic*

Phase 1 installation components included the following:

1. 2x (40-50) ton-hr. capacity PhaseStor storage tanks. (ST-1, ST-2). The exact ton.hr capacity depends on the operating conditions such as EWT, hence, a range of 40-50 ton.hr is provided. Otherwise, a conservative capacity of 40 ton.hr can be considered.
2. 1xAllerton VLCA 1688 control module
3. 3” insulated schedule 40 PVC piping (80 lf)
4. Belimo automatic control valves (detailed below)

***Table 11. Installed control valves***

| Tag | Supplier | Manufacture | Size | Model |
|---|---|---|---|---|
| V1 | Kele | Belimo | 3" | F680HD GRX24-MFT-T-N4 |
| V2 | Kele | Belimo | 3" | F680HD GRX24-MFT-T-N4 |
| V3 | Kele | Belimo | 3" | F780HDM2xGMX24-MFT-X1 |
| V4 | Kele | Belimo | 3" | F780HDM2xGMX24-MFT-X1 |

<u>System Integration</u>:

Cooling for the HVAC system at B1020 is comprised of a piped chilled water system supplying chilled water (CHW) to a single air handling unit (AHU-1). The chilled water is supplied by a Trane model CGAM-070A air cooled electric chiller. The PhaseStor-TES was integrated into the existing chilled water generation system by the modification of the CHWS and CHWR piping to include valve connections allowing the TES to operate in sequence with electric water chiller. The PhaseStor system does not change or replace the existing original components of the system, it was simply added to the as seen in the schematic (below). This shows the addition of storage tanks (inside the red circle) and associated automatic control valving used to divert flow from the existing piping configuration through the PhaseStor tanks to freeze and melt the PCM. In phase 2, each of the two thermal storage tanks below was simply replaced by 4 tanks (2x2 matrix) yielding 8 tanks (2 tanks in series) in a matrix of 4x2 as seen in the subsequent figure.

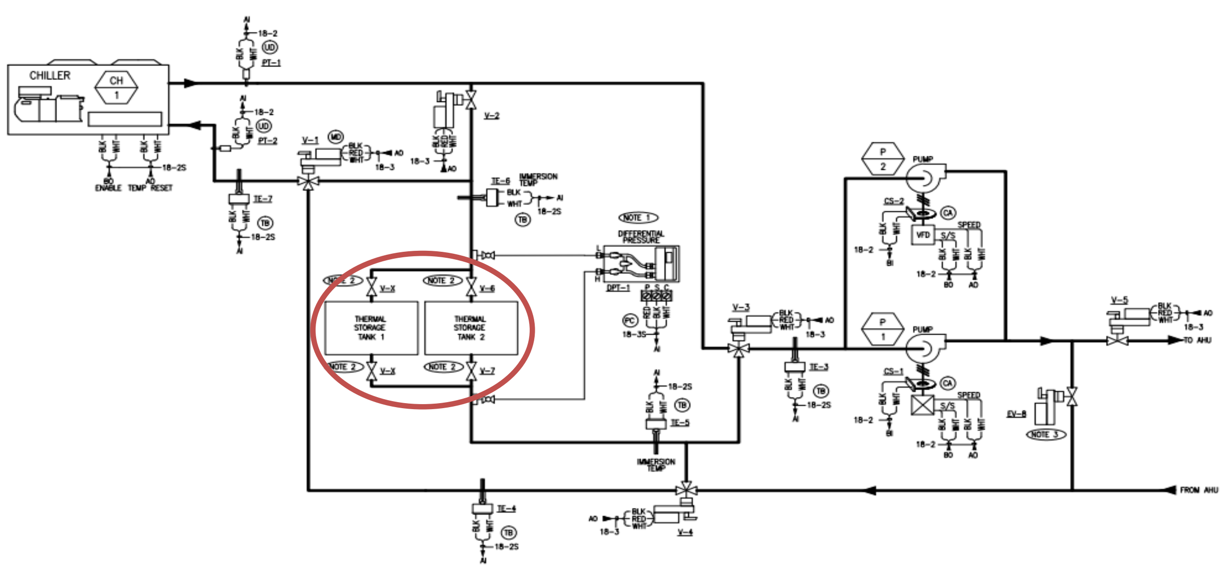


***Figure 17. Schematic diagram for the integration of thermal storage tanks.***

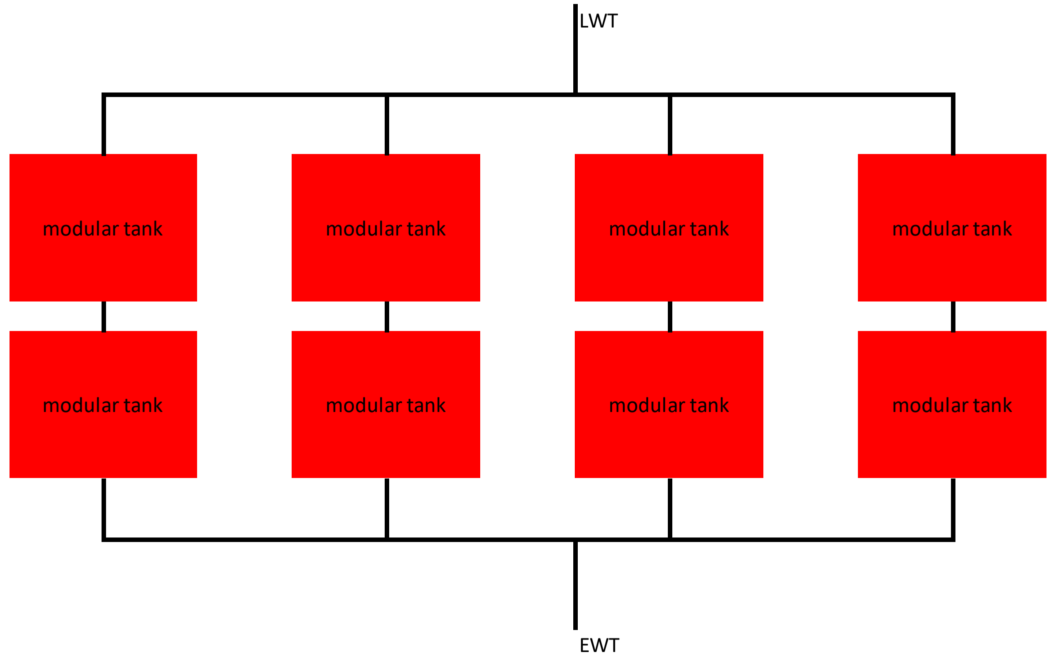


***Figure 18. Schematic diagram for the circuit of the tanks for Phase 2.***

System Controls: at the commencement of Phase 1 in 2017 the existing CHW system was still under warranty for an ESP contract with Siemens Energy. The contract terms restricted the demonstration to communicate or to reprogram the sequence of operations with the existing Siemens controller. To overcome this concern, we installed an Allerton VLCA-1688 standalone controller. The VLCA 1688 has full expansion and interface capabilities to the Siemens panel. Interface with the Siemens controller will be part of the Phase 2 demonstration.

The Allerton VLCA-1688 module controls three primary sequence of operations as follows:

1. Normal (off-peak) - the chiller remains in the normal operating sequence, at all times other than noted in freeze and melt cycles. Vales to the tanks remain in the closed position (bypassing the tanks). Normal operation is set as the default in the event of loss of signal.
2. Night-time charge (freeze) cycle – Between 1.00am – 6.00am controls valves open to allow CHWR from the building to pass through then return to the chiller. The chiller LWT =40°F.
3. Peak demand (melt) cycle – Between 11.45am – 5.00pm the CHWR flows through the tanks, upstream of the chiller. Chiller remains off until EWT =54°F.

**Legend**
V and ▶: Manual 3-way valve connection point for the HVAC chilled water return/supply loop
V and ▷: Manual 3-way valve connection point for the thermal storage loop
V and ⋈: Manual one-way valve
EV: Electric valve
P: Pump
ST: Storage tanks
AHU: Air handling unit

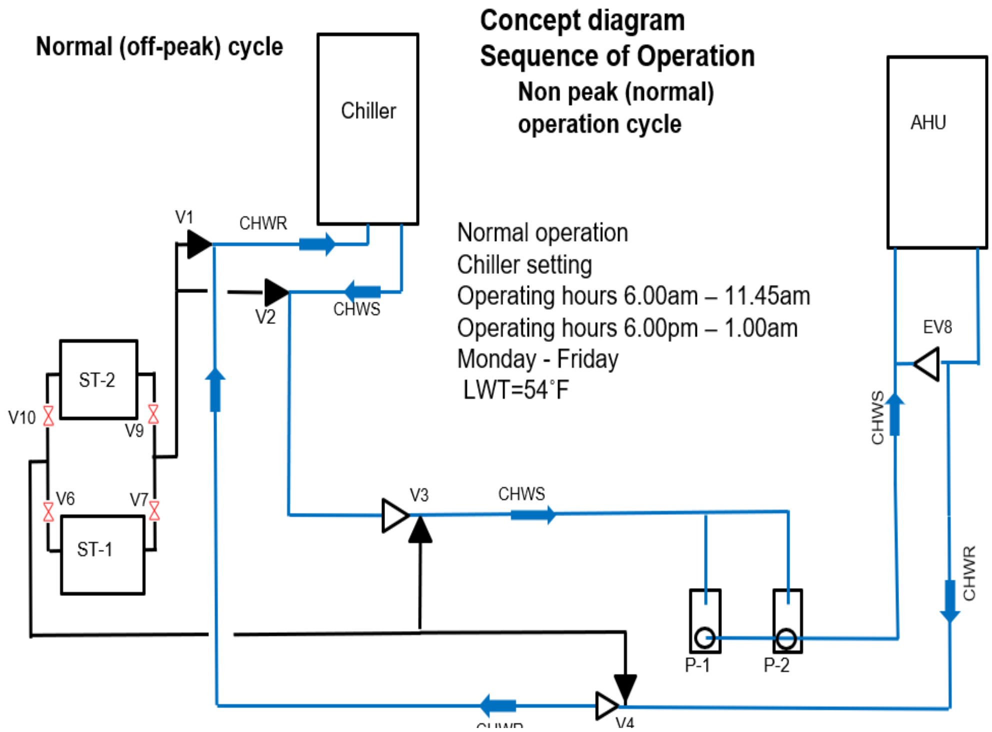


*Figure 19. Diagrams show the off-peak sequence of operations and valve control strategy*

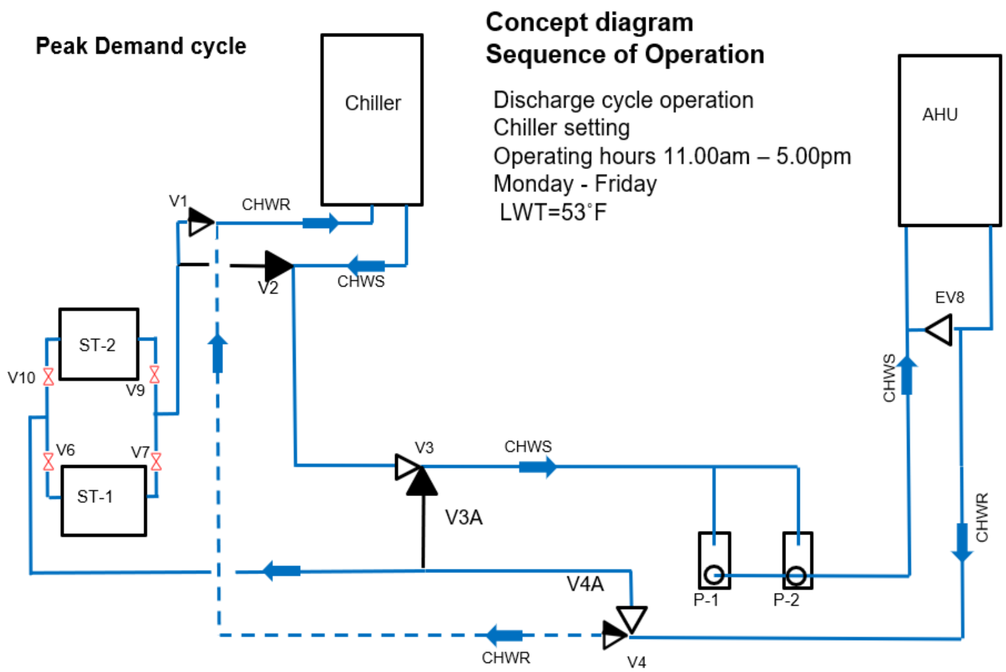


*Figure 20. Diagrams show the on-peak sequence of operations and valve control strategy*

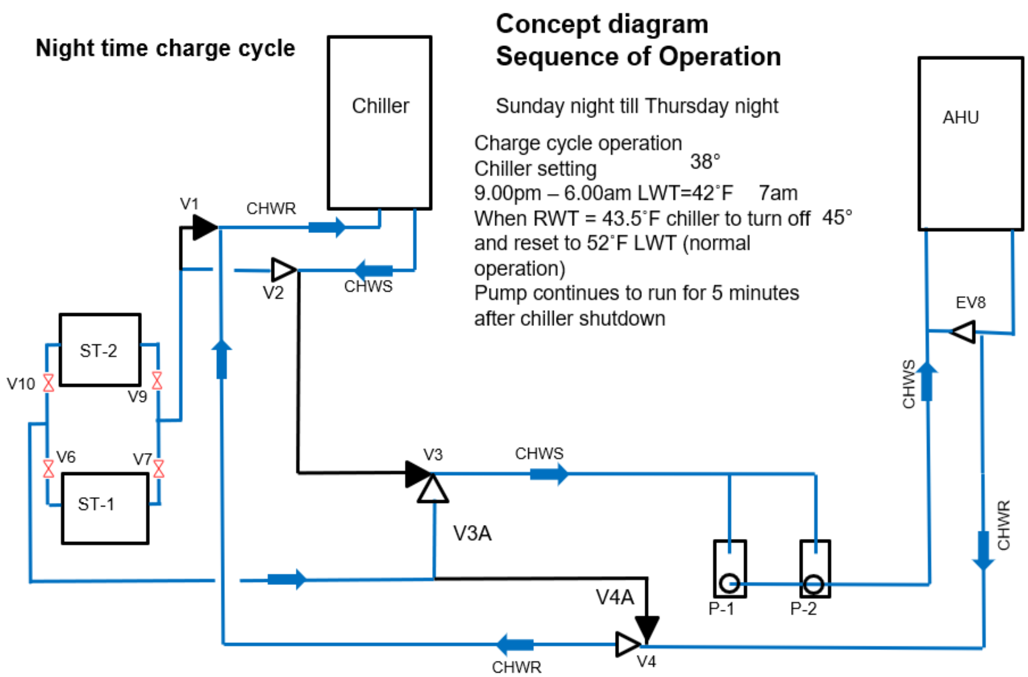


*Figure 21. Diagrams show the charging sequence of operations and valve control strategy*

*Figure 22. The Allerton control module and installation images*

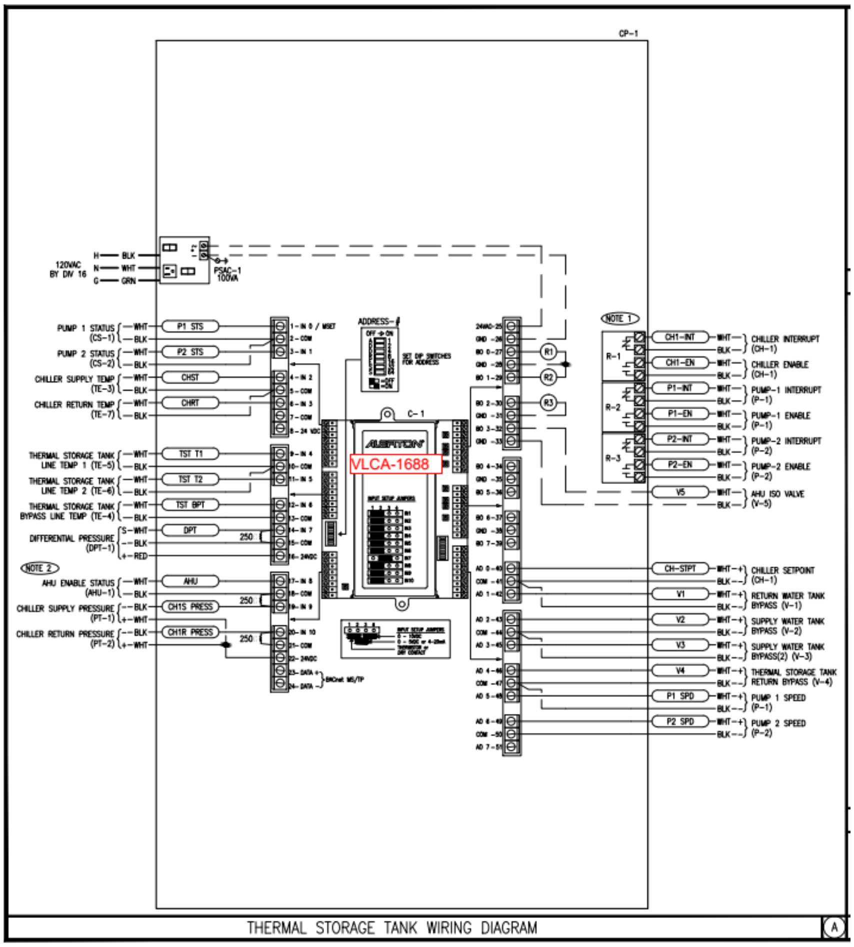


*Figure 23. Built diagram of Allerton control module and installation images*

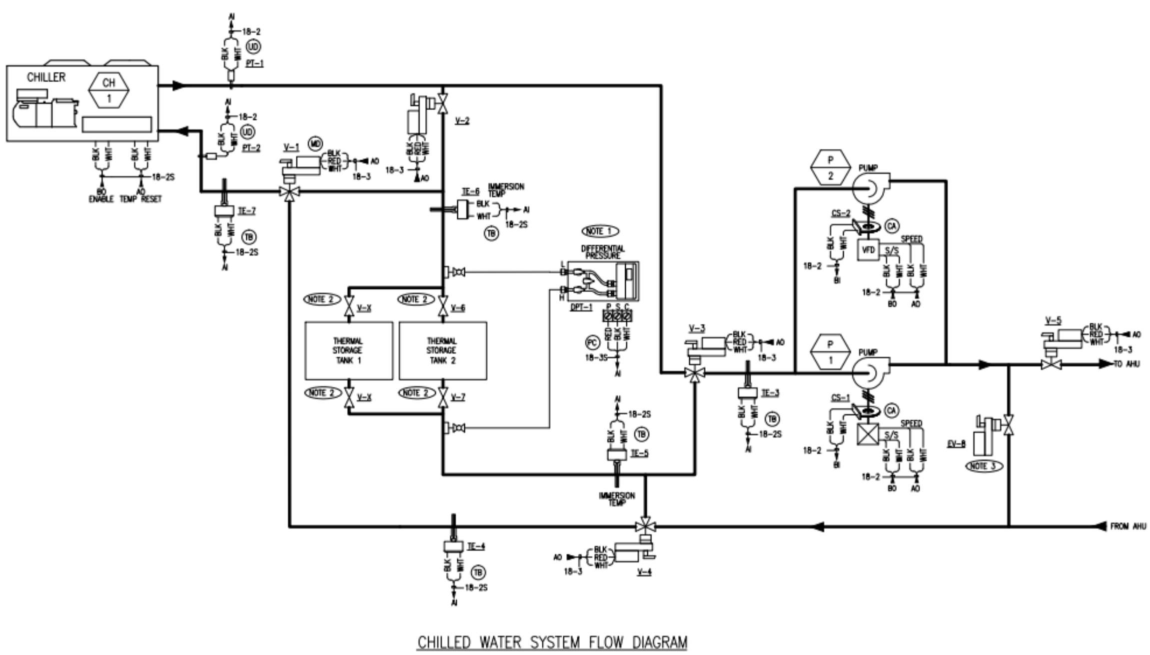


*Figure 24. Chilled water piping and control schematic*

## 6.6 OPERATIONAL TESTING

Operational Testing of Cost and Performance: The operational aspects of the technology include a melt cycle which occurs over a 5-hour period from 12.00pm – 5.00pm -This aligns with the power utilities peak demand period – and a freeze "charge cycle" over a 5 hour period from 12.00am – 5.00am "at night" during off-peak hours when electricity charges are lower.

The chiller operates on a 24/7 schedule. During occupied hours the space temperatures are maintained at 76°F. To melt the PCM the return water is directed through the storage tanks, the return water varies in temperature depending on the amount of heat being rejected from the building. The return water typically returns between 56-60°F. The engineered melt temperature of the PCM is 45.5°F.

In normal operation the tank inlet (return water) is blended with tank bypass to maintain a constant 54°F leaving water temperature. Under this control strategy the chiller remains off until water temperature increases above the chiller setpoint temperature (54°F)

During the freeze cycle, which occurs over a 5-hour period from 12.00am – 5.00am, the chiller operates on a 24/7 schedule. During unoccupied hours the space temperatures are maintained at 78°F. To freeze the PCM the chiller ramps down from the normal operating setpoint of 54°F to 38°F. The 38°F is 5.5°F lower than the engineered freeze temperature of the PCM (freeze temperature 43.5°F), supplying water at 38°F provides the driving power needed to mechanically change phase, and to avoid super-cooling of the PCM.

The freeze temperature is the point the PCM will store latent heat or change phase from a liquid to a solid. The chiller provides water to the PhaseStor tanks.

Modeling and Simulation: models were developed using eQuest and EnergyPlus plus simulation tools. The models were used to confirm that building performance aligned with typical expectations for similar use and construction. Models were developed to provide a comparative study of the performance of ice storage baseline to assist in determining the benefits PCM-based storage provides over ice storage.

Timeline: monitoring of the building indicates the chiller operates during the winter and summer seasons, however winter use is limited and sporadic, with very little use during January. The operation of the chiller aligns to outside air temperature and appears to cycle whenever temperature exceeds 65°F. this occurs regularly during all months other than January. Although the building calls for cooling the intent of our demonstration is to evaluate the cost benefit, however there is no winter peak demand charge, therefore only limited opportunities to offset costs other than the peak summer period June-September. Therefore, the test period coincides with this period. To ensure accurate data collection the demonstration was conducted over an extended summer period from April – November (2017) as phase 1 then expanded for phase 2 for April – September (2018).

## 6.7 SAMPLING PROTOCOL

The data collection process for this demonstration comprises the Onset RX3000 series web-based logger. The demonstration collects 5-minute interval data which is downloaded every hour. The data is stored as CSV files on a central cloud-based server. The data is accessible to the team with the password to download in multiple formats. Our engineering team download data at regular intervals to review and analyze it.

### 6.8 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

The equipment calibration process for this demonstration such as for the temperature sensors and flow meters is part of the Hobolink system and Onset RX3000 series. The Hobolink platform allows the user to calibrate the sensors at any time by defining a scaled unit, multiplier factor and offset factor to calibrate the readings of sensors and ensure accuracy. The sensor configuration window is accessible to anyone. The engineering team can check data at regular intervals to review and analyze any discrepancies or changes in the accuracy if readings or calibration setting. Incorrect readings or faulty measurement equipment can be detected quickly by the user when a spike or outlier reading appears in the graph, or when unexpected values appears on the Hobolink platform, in example, a spike, temperature difference between the measured values and chiller setpoint, or unusual GPM fluctuation between two sensors in the same closed loop.

## 7.0 RESULTS AND PERFORMANCE ASSESSMENT

As stated in previous sections, the primary goal of the performance objective is to validate that the PhaseStor-TES performs equal to or better than traditional non-storage and established latent energy storage systems, such as ice.

Savings are achieved by generating chilled water during off-peak hours (12:00AM – 5:00AM), when chiller efficiency is optimized due to lower ambient air temperature, and when electrical costs are at their lowest. This process is called the **charge or freeze cycle**. During this process, the chiller ramps down from the normal operating setpoint of 54°F to 38°F, which 5.5°F lower than the engineered freeze temperature of the PCM (freeze temperature 43.5°F), supplying water at 38°F provides the driving power needed to mechanically storage thermal energy and initiate the change phase in the tanks.

<u>Charge cycle:</u> During the charge “freeze” cycle, the chiller ramps down to 38°F to achieve a 5.5°F temperature difference between the PCM freeze/charge (43-45°F) point and the water loop that runs through the system so that the mechanical energy is stored in the form of thermal energy. This process and the temperature profile can be seen in the table below. When the temperature difference between the EWT and LWT is less than 1.5°F the tanks can be assumed to fully charged with thermal energy.

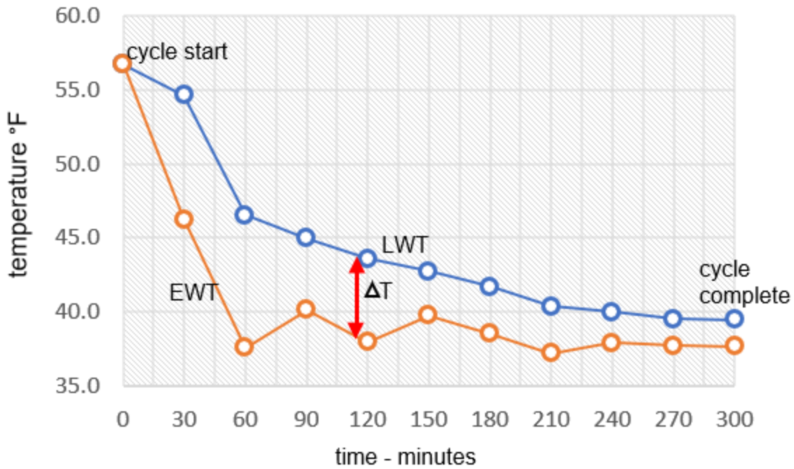

*Figure 25. Daily Peak Period Melt (Discharge) Cycle*

Discharge cycle: This mechanical energy is stored in the form of thermal energy, so it can be utilized later during the on-peak hours when electrical costs are at their lowest. This process is called the **Discharge or melt cycle**. Because the energy is already stored in the tanks, the chilled water can be generated during on-peak hours by simply directing the return water through the storage tanks, allowing the chiller to be turned-off during on peak hours.

Controlled-temperature discharge strategy: In general, the return water typically returns between 56-60°F, while the chiller (or PhaseStor tanks in this case) needs to generate a minimum of 54-55°F chiller water temperature prior to returning to the AHU.
During the first few hours of the discharge cycle, the tanks typically run at their peak performance level. Which means, in some cases, it is possible that the return water may be chilled to even lower temperature that what's needed. To remedy this, a controlled-temperature profile strategy was adopted. The example shown below shows an example of uncontrolled and controlled-temperature profile. The uncontrolled profile shows the variable temperature when leaving the tank, the controlled temperature is maintained at 54°F through a modulating valve, which blends the return water and tank leaving water prior to returning to the AHU.

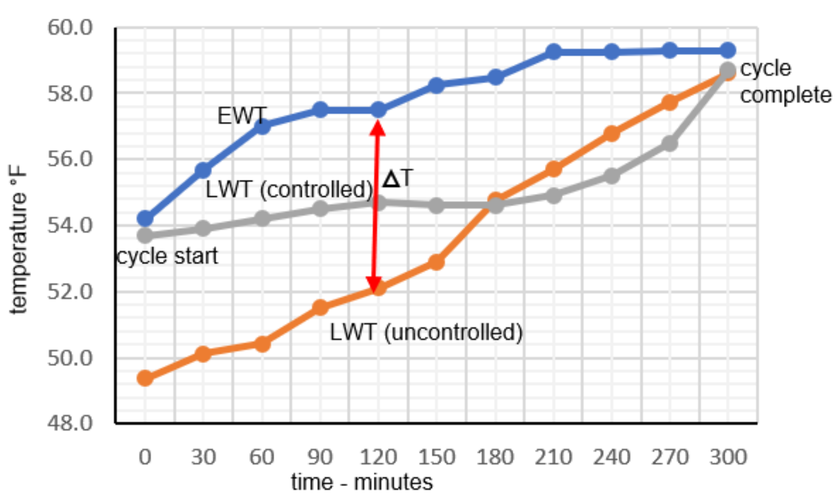

*Figure 26. Daily Peak Period Melt (Discharge) Cycle*

Statistical Methodologies for the verifications of Thermal Energy Storage Capacity: The total energy capacity that can be stored in one tank can be checked at any time by considering the temperature variation across the tanks and running a one-time test with a known GPM and EWT. These two parameters could be varying as long as they are recorded as a function of time, so they can be entered in the integration below:

$$Q = \int_0^t q'(t).dt = m^o * C_p \int_0^t \left(T_i - T_o(t)\right).dt$$

Where $m^o$ is the mass flow rate of the loop through one tank, $T_i$ is the inlet water temperature (EWT), $T_o$ is the leaving water temperature LWT, $C_p$ is the specific heat of water in the loop which is 4.17 J/gK, and $t$ is the time. The figure below shows the results for the total energy storage verification of the tanks.

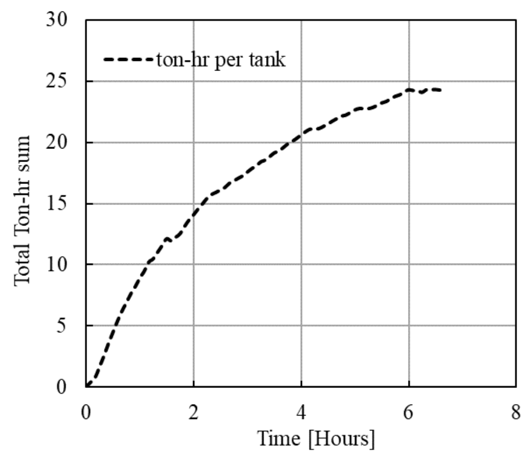


***Figure 27. Verification of the total energy capacity that can be stored in one tank***

Results for the shifted energy profile. The daily energy profile shows the kWh shows both the baseline energy profile and the installed PhaseStor energy profile in kWh.

A typical chiller profile during June is displayed in the figure below showing the baseline for a daily load profile of the 70-ton chiller at B1020. The peak use coincides with demand charge period 11.00am-6.00pm

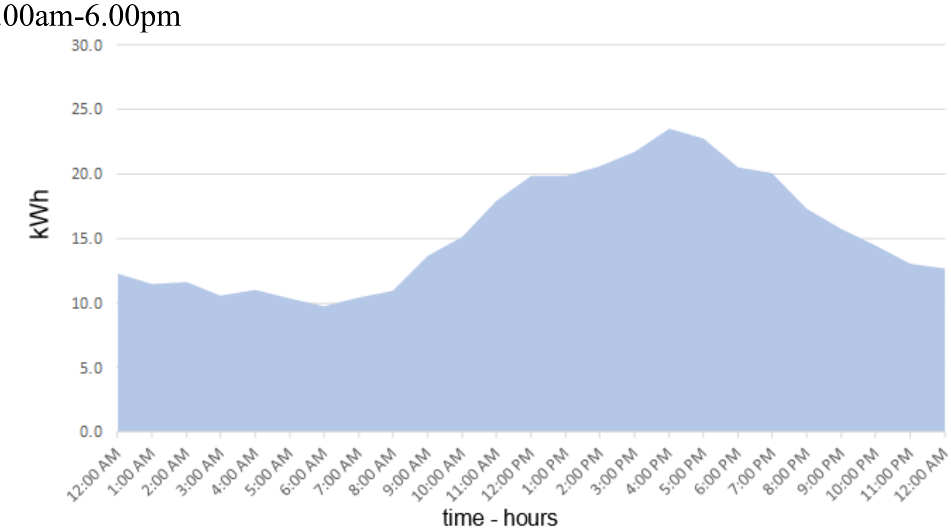


***Figure 28. Typical chiller daily (June) load profile for B1020***

The figure below shows the chiller load profile following installation of small demonstration scale TES. Data shows an increase in energy use to charge (freeze) from 1.00 – 6.00am. while showing the chiller requires no compressor power while the tank is discharging (melting) 11.00am-1.00pm.

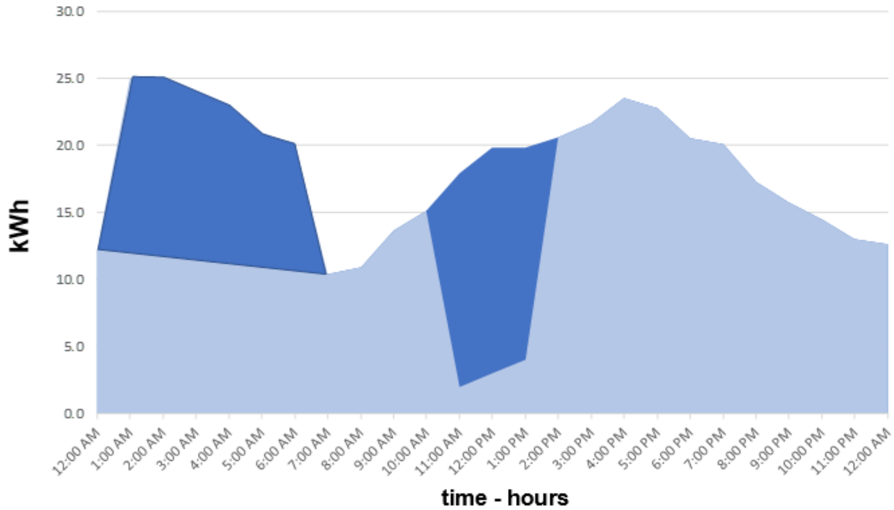


*Figure 29. Daily (June) load profile for B1020 with TES*

Another set of data for September and December of 2018 is displayed in the figure below where the baseline is shown as the blue cross hatched area. This is the existing 70-ton chiller and associated loads with no thermal storage. The baseline is the averaged energy use over the summer period and represents the normal operating conditions of the existing chilled water system.
The time at which the TES system is engaged was changed to 1PM to cover as much energy as possible within the on-peak hours shown in table 15. The PhaseStor energy use is shown as the transparent gray area over the baseline. This is the averaged energy use over the summer period (4 months) and represents the new operating conditions of the existing chilled water system using storage.
The graph below shows the increased energy use the over the non-peak during the freeze cycle, and the resulting reduced energy use during the peak demand cycle.

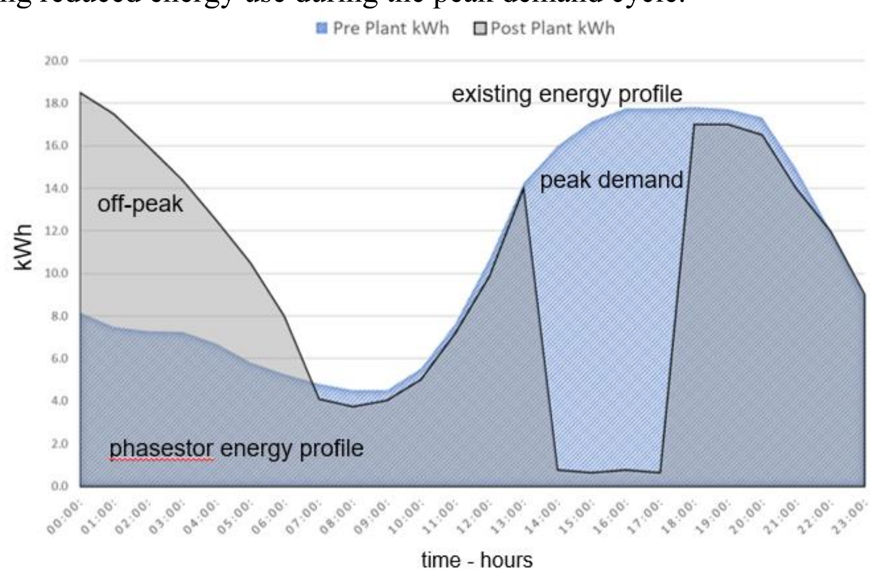


*Figure 30 Reduced energy use during the peak demand cycle.*

Energy Savings Assessment. Phase -1 Installed in the summer of 2017 was a small installation of 40 ton-hours. The intent of the installation was to prove the Bio-PCM had the ability to store and release thermal energy as demanded by the HVAC system. That was a proof of concept test and provided enough confidence in the data to enable moving onto phase 2. On completion of Phase 1, the results confirmed the engineered Bio-PCM was capable of storing and releasing thermal energy at design flow rates, and is capable of maintaining a constant temperature for the inlet and outlet temperature profile. Phase 2, installed in the summer of 2018, is a larger scaled installation sized to provide a higher ratio of the daily average peak demand load. Following 3 months of testing, as shown in the data in the previous sections and next table, the following performance metrics were achieved:

- Annual chiller energy savings of 7.4%
- Chiller energy cost savings of 43% (as shown in the next subsection)

***Table 12. kWh Data for the Pre and Post consumption of for the existing 70-ton chiller***

| PRE | | | Post (PhaseStor TES) | | |
|---|---|---|---|---|---|
| Date | Ambient °F | Plant kWh | Date | Ambient °F | Plant kWh |
| 09/10/2018 0:00 | 80.7 | 8.2 | 12/10/2018 0:00 | 79.1 | 17.5 |
| 09/10/2018 1:00 | 78.5 | 7.5 | 12/10/2018 1:00 | 77.9 | 17.0 |
| 09/10/2018 2:00 | 80.2 | 7.3 | 12/10/2018 2:00 | 77.8 | 16.0 |
| 09/10/2018 3:00 | 78.2 | 7.2 | 12/10/2018 3:00 | 76.8 | 14.4 |
| 09/10/2018 4:00 | 76.4 | 6.7 | 12/10/2018 4:00 | 76.3 | 13.0 |
| 09/10/2018 5:00 | 75.1 | 5.8 | 12/10/2018 5:00 | 75.9 | 11.5 |
| 09/10/2018 6:00 | 72.7 | 5.3 | 12/10/2018 6:00 | 75.2 | 9.0 |
| 09/10/2018 7:00 | 69.7 | 4.8 | 12/10/2018 7:00 | 72.9 | 4.5 |
| 09/10/2018 8:00 | 69.6 | 4.5 | 12/10/2018 8:00 | 71.6 | 4.1 |
| 09/10/2018 9:00 | 70.8 | 4.5 | 12/10/2018 9:00 | 72.9 | 4.5 |
| 09/10/2018 10:00 | 76.4 | 5.5 | 12/10/2018 10:00 | 76.6 | 5.5 |
| 09/10/2018 11:00 | 81.7 | 7.6 | 12/10/2018 11:00 | 82.2 | 7.6 |
| 09/10/2018 12:00 | 87.9 | 10.7 | 12/10/2018 12:00 | 86.5 | 10.7 |
| 09/10/2018 13:00 | 91.6 | 14.2 | 12/10/2018 13:00 | 90.6 | 14.2 |
| 09/10/2018 14:00 | 95.3 | 16.0 | 12/10/2018 14:00 | 94.8 | 0.8 |
| 09/10/2018 15:00 | 98.2 | 17.1 | 12/10/2018 15:00 | 99.0 | 0.7 |
| 09/10/2018 16:00 | 102.7 | 17.7 | 12/10/2018 16:00 | 104.4 | 0.8 |
| 09/10/2018 17:00 | 107.2 | 17.7 | 12/10/2018 17:00 | 105.4 | 0.7 |
| 09/10/2018 18:00 | 103.3 | 17.8 | 12/10/2018 18:00 | 100.2 | 17.0 |
| 09/10/2018 19:00 | 102.3 | 17.7 | 12/10/2018 19:00 | 98.6 | 17.0 |
| 09/10/2018 20:00 | 97.4 | 17.3 | 12/10/2018 20:00 | 93.3 | 16.5 |
| 09/10/2018 21:00 | 91.0 | 14.9 | 12/10/2018 21:00 | 87.8 | 14.0 |
| 09/10/2018 22:00 | 86.9 | 12.0 | 12/10/2018 22:00 | 84.6 | 12.0 |
| 09/10/2018 23:00 | 83.1 | 8.9 | 12/10/2018 23:00 | 81.5 | 9.0 |

*Table 13. Data comparison and energy savings*

| Data type | Date of baseline | Average ambient temperature | plant kWh sum | Annual Energy Savings |
|---|---|---|---|---|
| Pre (Baseline) | September 2018 | 85.7°F | 257.05 | |
| Post (PhaseStor) | December 2018 | 85.1°F | 237.94 | 7.4% |

On completion of phase 2: the demonstration resulted in a reduction in energy costs by 43% (as shown in next subsection); and the reduction of chiller energy by 7.4% during running the chiller at night when temperature is lower, and chillers are running more efficiently.

Other finding:

1. The demonstration confirmed the ability of the PhaseStor-TES to store and release energy on demand to meet the heat rejected by the building chilled water HVAC system as shown in the daily load profiles.
2. The system can provide process fluid (chilled water) at the design temperature consistent with building cooling load as shown in the controlled-temperature discharge figure.
3. The system was able to maintain a consistent EWT/LWT delta during the entire peak demand period as shown in the controlled-temperature discharge figure.
4. The system consistently operated at an efficiency ratio with a COP greater than 3.2 during freeze and melt cycles.

Peak Load Shifting and Cost Savings Assessment

This section shows that the above load shifting savings **resulted in a 43% energy cost saving** due to demand charge avoidance, noting we have used the specific service schedule and rates for Ft. Irwin during 2018 which is one of the lowest utility cost structures in the country at only $0.0582 per kWh. In addition to reducing existing chiller plant operating costs and energy use, implementation of this strategy makes it possible to achieve a reduction in the new or replacement chiller plant capacity to a chiller

The below the rate structure for large users above 500kW demand per month. Note that the rates provided are one of the lowest in the country and could represent a saving of 30% below the national average. Also, the energy cost savings was maintained between 42%-44% even when using the 200kW-500kW rate schedule.

*Table 14. Service rate schedules at Ft. Irwin*

| Schedule | Hours | Energy Charges / kWh |
|---|---|---|
| On-peak | 12:00PM – 6:00 PM | $0.33443 |
| Mid-peak | 8:00AM – 12:00PM<br>+ 6:00PM – 11:00PM | $0.10561 |
| Off-peak | 11:00PM - 8:00AM | $0.05534 |

*Table 15. Energy charges for the Pre and Post baseline*

| Date | Plant (PRE) kWh | Plant (POST) kWh | Difference kWh | Rate schedule | Rate $/kWh | Charges, $ (PRE) | Charges, $ (POST) | Rate Difference ($) |
|---|---|---|---|---|---|---|---|---|
| 12/10/2018 0:00 | 8.2 | 17.5 | 9.3 | Off-peak | 0.05534 | 0.453788 | 0.96845 | 0.514662 |
| 12/10/2018 1:00 | 7.5 | 17 | 9.5 | Off-peak | 0.05534 | 0.41505 | 0.94078 | 0.52573 |
| 12/10/2018 2:00 | 7.3 | 16 | 8.7 | Off-peak | 0.05534 | 0.403982 | 0.88544 | 0.481458 |
| 12/10/2018 3:00 | 7.2 | 14.4 | 7.2 | Off-peak | 0.05534 | 0.398448 | 0.796896 | 0.398448 |
| 12/10/2018 4:00 | 6.7 | 13 | 6.3 | Off-peak | 0.05534 | 0.370778 | 0.71942 | 0.348642 |
| 12/10/2018 5:00 | 5.8 | 11.5 | 5.7 | Off-peak | 0.05534 | 0.320972 | 0.63641 | 0.315438 |
| 12/10/2018 6:00 | 5.3 | 9 | 3.7 | Off-peak | 0.05534 | 0.293302 | 0.49806 | 0.204758 |
| 12/10/2018 7:00 | 4.8 | 4.5 | -0.3 | Off-peak | 0.05534 | 0.265632 | 0.24903 | -0.016602 |
| 12/10/2018 8:00 | 4.5 | 4.1 | -0.4 | Mid-peak | 0.10561 | 0.475245 | 0.433001 | -0.042244 |
| 12/10/2018 9:00 | 4.5 | 4.5 | 0 | Mid-peak | 0.10561 | 0.475245 | 0.475245 | 0 |
| 12/10/2018 10:00 | 5.5 | 5.5 | 0 | Mid-peak | 0.10561 | 0.580855 | 0.580855 | 0 |
| 12/10/2018 11:00 | 7.6 | 7.6 | 0 | Mid-peak | 0.10561 | 0.802636 | 0.802636 | 0 |
| 12/10/2018 12:00 | 10.7 | 10.7 | 0 | On-peak | 0.33443 | 3.578401 | 3.578401 | 0 |
| 12/10/2018 13:00 | 14.2 | 14.2 | 0 | On-peak | 0.33443 | 4.748906 | 4.748906 | 0 |
| 12/10/2018 14:00 | 16 | 0.8 | -15.2 | On-peak | 0.33443 | 5.35088 | 0.267544 | -5.083336 |
| 12/10/2018 15:00 | 17.1 | 0.7 | -16.4 | On-peak | 0.33443 | 5.718753 | 0.234101 | -5.484652 |
| 12/10/2018 16:00 | 17.7 | 0.8 | -16.9 | On-peak | 0.33443 | 5.919411 | 0.267544 | -5.651867 |
| 12/10/2018 17:00 | 17.7 | 0.7 | -17 | On-peak | 0.33443 | 5.919411 | 0.234101 | -5.68531 |
| 12/10/2018 18:00 | 17.8 | 17 | -0.8 | Mid-peak | 0.10561 | 1.879858 | 1.79537 | -0.084488 |
| 12/10/2018 19:00 | 17.7 | 17 | -0.7 | Mid-peak | 0.10561 | 1.869297 | 1.79537 | -0.073927 |
| 12/10/2018 20:00 | 17.3 | 16.5 | -0.8 | Mid-peak | 0.10561 | 1.827053 | 1.742565 | -0.084488 |
| 12/10/2018 21:00 | 14.9 | 14 | -0.9 | Mid-peak | 0.10561 | 1.573589 | 1.47854 | -0.095049 |
| 12/10/2018 22:00 | 12 | 12 | 0 | Mid-peak | 0.10561 | 1.26732 | 1.26732 | 0 |
| 12/10/2018 23:00 | 8.9 | 9 | 0.1 | Off-peak | 0.05534 | 0.492526 | 0.49806 | 0.005534 |

*Table 16. Data comparison and energy cost savings*

| Data type | Date of baseline | Average ambient temperature | plant charges (kWh sum) | Energy Cost Savings ($) % |
|---|---|---|---|---|
| Pre (Baseline) | Sep-18 | 85.7°F | 45.4 | |
| Post (PhaseStor) | Dec-18 | 85.1°F | 25.9 | 42.97% |

# 8.0 COST ASSESSMENT

Given the pace of development of new PCM products a cost model continues to evolve. During phase 1 of our demonstration we used a PCM formula initially developed for passive thermal control of buildings with thermal properties similar to the needs of large-scale thermal storage. The manufacturing cost of $1.52lb can be reduced in future when larger quantities of the materials are synthesized for larger installations. Over the year of the demonstration (2017) further investigation of a product specifically designed for large scale storage has been developed, this new formula not only provides 30% more thermal capacity per lb., but also manufacturing costs have decreased by 45%.

***Table 17. Cost analysis for B1020 installation – Phase 1***

| System | Installed ton-hrs | Purchase Cost | Install Cost | Total Cost | Annual Kwh | Energy Cost | $ Saving (yr) | % Saving (yr) | Payback (yrs) w/o incentive | Payback (yrs) w/ incentive |
|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | 0 | 0 | 0 | 0 | 49,700 | $ 9,391 | 0 | 0 | 0 | 0 |
| TES | 102 | $ 450 | $ 870 | $ 134,640 | 49,859 | $ 6,135 | $ 3,256 | 35% | 41.4 | 20.7 |

The cost control was proved to be difficult during the phase 1 installation due to the following reasons:

1. Cost increase related to both the tank and PCM manufacturing process associated with a tank construction and manufacture of the PCM.
2. Demonstration site being only 10,000 ft² was not sufficiently serviced with the type of system infrastructure a typical application would likely have.
3. The TES installation occurs in buildings over 70 ft². Therefore, most installations would have a certain minimum level of system support, e.g. control panel.
4. Contractors were not familiar with the technology leading to additional costs related to the installation.

***Table 18. Detailed cost breakdown for B1020 installation – Phase 1***

| DESCRIPTION | QTY. | UNIT | COST | LABOR COST | TOTAL | HANDLING | SELL |
|---|---|---|---|---|---|---|---|
| ***CHW System*** | | | | | | | $ 78,198 |
| Tank Manufacture & Delivery | 102 | t-hr | $315.00 | $ - | $ - | $ 5,000 | $ 37,130 |
| Concrete Support base | 1 | ea | $3,600.00 | $ 480 | $ 4,359 | $ 436 | $ 5,318 |
| Pipework Installation | 48 | lf | $19.50 | $ 20,117 | $ 21,125 | $ 2,113 | $ 25,773 |
| Motorized control valves | 3 | ea | $1,500.00 | $ 210 | $ 5,058 | $ 506 | $ 6,171 |
| Insulation & Jacketing | 45 | lf | $12.00 | $ 377 | $ 964 | $ 96 | $ 1,177 |
| Miscellanous Fixtures | 50 | ea | $25.00 | $ 419 | $ 1,778 | $ 178 | $ 2,170 |
| Water Treatment Chemicals | 1 | ea | $350.00 | $ - | $ 377 | $ 38 | $ 460 |
| ***Electrical + Controls*** | | | | | | | $ 36,071 |
| Control Circuits/Breakers | 6 | ea | $254 | $ 80 | $ 1,726 | $ 173 | $ 2,105 |
| Conduit + Cabling | 45 | lf | $12 | $ 2,858 | $ 3,441 | $ 344 | $ 4,198 |
| Controller | 1 | ea | $15,000 | $ 8,200 | $ 24,400 | $ 2,440 | $ 29,768 |
| ***Miscellaneous*** | | | | | | | $ 20,207 |
| Consumables Allowance | 20 | ea | $25 | $ 294 | $ 833 | $ 83 | $ 1,016 |
| Clean-up | 1 | ea | $350 | $ 424 | $ 801 | $ 80 | $ 977 |
| Equipment Rental | 1 | ea | $1,500 | $ 424 | $ 2,040 | $ 204 | $ 2,488 |
| Commissioning | 1 | ea | $50 | $ 2,640 | $ 2,694 | $ 269 | $ 3,287 |
| General Superintendent | 1 | ea | $145 | $ 8,520 | $ 8,676 | $ 868 | $ 10,585 |
| Project Management | 1 | ea | $155 | $ 7,200 | $ 7,367 | $ 737 | $ 8,988 |
| Administration | 1 | ea | $65 | $ 450 | $ 520 | $ 52 | $ 634 |
| ***Total*** | | | | | | | $ 134,477 |

In addition to the development of a superior PCM formula as described above, we have also redesigned the tank and heat exchanger in Phase 2 configuration to achieve a further reduction in manufacturing cost of 35%.

***Table 19. Cost analysis for B1020 installation – Phase 2***

| System | Installed ton-hrs | Purchase Cost | Install Cost | Total Cost | Annual Kwh | Energy Cost | $ Saving (yr) | % Saving (yr) | Payback (yrs) w/o incentive | Payback (yrs) w/ incentive |
|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | 0 | 0 | 0 | 0 | 49,700 | $ 9,391 | 0 | 0 | 0 | 0 |
| TES | 139 | $ 315 | $ 200 | $ 71,667 | 51,373 | $ 5,131 | $ 4,260 | 45% | 16.8 | 8.4 |

***Table 20. Detailed cost breakdown for B1020 installation – Phase 2***

| DESCRIPTION | QTY. | UNIT | COST | LABOR COST | TOTAL | HANDLING | SELL |
|---|---|---|---|---|---|---|---|
| ***CHW System*** | | | | | | | $ 60,182 |
| Tank Manufacture & Delivery | 139 | t-hr | $315.00 | $ - | $ - | $ 5,000 | $ 48,785 |
| Pipework Installation | 15 | lf | $19.50 | $ 6,287 | $ 6,602 | $ 660 | $ 8,054 |
| Motorized control valves | 1 | ea | $1,500.00 | $ 70 | $ 1,686 | $ 169 | $ 2,057 |
| Insulation & Jacketing | 15 | lf | $12.00 | $ 126 | $ 321 | $ 32 | $ 392 |
| Miscellanous Fixtures | 10 | ea | $25.00 | $ 84 | $ 356 | $ 36 | $ 434 |
| Water Treatment Chemicals | 1 | ea | $350.00 | $ - | $ 377 | $ 38 | $ 460 |
| ***Electrical + Controls*** | | | | | | | $ 933 |
| Control Circuits/Breakers | 0 | ea | $254 | $ - | $ - | $ - | $ - |
| Conduit + Cabling | 10 | lf | $12 | $ 635 | $ 765 | $ 76 | $ 933 |
| Controller | 0 | ea | $15,000 | $ - | $ - | $ - | $ - |
| ***Miscellaneous*** | | | | | | | $ 10,344 |
| Consumables Allowance | 10 | ea | $25 | $ 147 | $ 417 | $ 42 | $ 508 |
| Clean-up | 1 | ea | $350 | $ 424 | $ 801 | $ 80 | $ 977 |
| Equipment Rental | 1 | ea | $1,500 | $ 424 | $ 2,040 | $ 204 | $ 2,488 |
| Commissioning | 1 | ea | $50 | $ 1,200 | $ 1,254 | $ 125 | $ 1,530 |
| General Superintendent | 1 | ea | $145 | $ 4,260 | $ 4,416 | $ 442 | $ 5,388 |
| Project Management | 1 | ea | $155 | $ 3,600 | $ 3,767 | $ 377 | $ 4,596 |
| Administration | 1 | ea | $65 | $ 225 | $ 295 | $ 30 | $ 360 |
| ***Total*** | | | | | | | $ 71,459 |

Maintenance: the PCM-TES could be considered in many ways similar to an atmospheric vented (non-pressurized) sensible heat storage tank.

PCM: the bio-based PCM is a solid gel-based product and remains solid in either it's frozen or melted states. With an expansion rate of between 3%-5% it does not exert differing stresses on the vessel which reduced any potential structural failure. There is no evaporation therefore does not require regular filling or level indicators. Bactericides or algaecides are not required due to the chemistry of the Bio-based PCM used which is derived from plant based, non-toxic, non-edible and sustainable resources.

# 9.0 TECHNOLOGY TRANSFER

The work presented in this document provides valuable information for integrating this technology in HVAC systems which requires systems with PCM temperature range of 2-8°C as in the case if this study. However, the technology can also be applied in other applications with PCM in temperatures below 0°C and above 15°C, for example:

- Cold storage with integrated chiller packages

- Whole Foods demonstration project
- Randall County CC high temperature demonstration
- Modular heat storage in NY
- Considerable interest from Canadian firms for partnerships

***Table 21. A summary of target audience for the technology transfer***

| Target Audience | Planned Tech Transfer Tool/Action | Status of Implementation |
| --- | --- | --- |
| DoD End-User | System Sizing Calculator | Big Ladder (consultant) is developing PCM module for EnergyPlus. |
| Commercial | System Sizing Calculator | Demonstration projects with Axiom Exergy and Randolph Community College (RCC). |
| Industrial | Industry specific conference presentations | PhaseStor is being active marketed at trade shows as an emerging technology. |

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## Appendix A: Points of Contact

List all the important points of contact involved in the demonstration, such as co-investigators, sponsors, industry partners, regulators, etc. The list should include the following information: (1) full name, (2) organization, (3) telephone number and e-mail address, and (4) the role of the individual in the project.

Use the tabular format below:

| **Point of Contact** | **Organization** | **Phone & E-mail** | **Role in Project** |
|---|---|---|---|
| Dr. Rami Saeed | Phase Change Energy Solutions | +1.573-201-0889<br>rsaeed@phasechange.com<br>ramirs91@gmail.com | PI |
| Shayne Rolfe | Phase Change Energy Solutions | +1-336.629.3000<br>srolfe@phasechange.com | PI |
| | | | |
| | | | |
| | | | |
| | | | |

## Appendix A: PCM Safety Data Sheet

| | |
|---|---|
| PRODUCT NAME | PCM Q8 – Melting: 8°C |
| REVISION DATE | Nov 02, 2018 |
| MANUFACTURER | Phase Change Energy Solutions<br>120 East Pritchard Street<br>Asheboro, NC |
| TELEPHONE | 336-629-3000 |
| FAX | 336-629-3100 |
| WEB | www.phasechange.com |

| **1. EMERGENCY TELEPHONE NUMBER** | |
|---|---|
| Emergency | For questions regarding this product, first call 1-800-283-7887<br>If it is an emergency and there is no response, please contact the following:<br>**For emergencies in the US and Canada**, call CHEMTREC day or night at 800-424-9300<br>**For emergencies outside US and Canada**, call CHEMTREC day or night at +1-703-527-3887. |

| **2. COMPOSITION/INFORMATION** | |
|---|---|
| CAS # | Proprietary blend of plant-based ingredients |
| COMPONENTS | Proprietary blend of plant based, Kosher ingredients derived from vegetable oils such as Fatty Acids, Fatty Alcohols, Fatty Esters and their derivatives and any combination of the previously mentioned products, also listed on the GRAS list (Generally Recognize As Safe by the FDA), and contain no petroleum or animal fat products. This product is composed of 100% biobased content. Third-party verification for a product's biobased content is administered through the USDA BioPreferred program. Visit: "https://www.biopreferred.gov/BioPreferred/faces/catalog/Catalog.xhtml" and search BioPCM |

| **3. PHYSICAL & CHEMICAL PROPERTIES** | | | |
|---|---|---|---|
| APPEARANCE | Colorless liquid (above melting point) | VAPOR DENSITY (Air = 1) | Not available |
| ODOR | Mild odor | RELATIVE DENSITY | 0.85-0.9 g/mL @ 25°C (77 °F) |
| pH | Not applicable | UPPER FLAMABILITY LIMIT (UFL) | Not available |
| MELTING POINT | 8 °C | LOWER FLAMMABILITY LIMIT (LFL) | Not available |
| BIOLING POINT | >250 °C (482 °F) | SOLUBILITY IN WATER | Insoluble |
| FLASH POINT | >110°C (230 °F) - Pensky-Marten Closed Cup | AUTO-IGNITION TEMPERATURE | Does not ignite |
| EVAPORATION RATE | Not available | VISCOSITY | 4CP @ 25 °C (77 °F) |
| VAPOR PRESSURE | <1 mmHg @ 25 °C (77 °F) | EXPLOSION LIMITS | Does not contain explosives |
| OXIDATION PROPERTIES | | Does not contain oxidizing properties | |

## 4. HAZARDS IDENTIFICATION

GHS label elements, including precautionary statements

| | | |
|---|---|---|
| PICTOGRAM |  | |
| SIGNAL WORD | Warning | |
| CLASSIFICATION | Classified as non-hazardous to humans and environment | |
| HAZARDOUS MATERIALS IDENTIFICATION SYSTEM (HMIS) | | |
| HEALTH: 0 | FLAMMABILITY: 0 | REACTIVITY: 0 |

## 5. FIRST AID

| | |
|---|---|
| EYE CONTACT | No significant eye irritation can be expected from normal contact. Rinse with plenty of water for 15 minutes. If eye irritation persists, seek medical advice/attention. |
| INHALATION | No irritation can be expected from short and medium-term exposure. If breathing is difficult, move to fresh air, or provide oxygen if breathing issues persist. |
| INGESTION | Rinse mouth with water and do not induce vomiting. If vomiting occurs, keep head lower than hips to help prevent aspiration. |

## 6. FIRE FIGHTING

| | | | |
|---|---|---|---|
| HAZARDOUS COMBUSTION PRODUCTS | Carbon dioxide and/or low molecular weight hydrocarbons. | | |
| EXTINGUISHING MEDIA | Water, foam, dry chemicals, or carbon dioxide. | | |
| FIRE FIGHTING INSTRUCTIONS | **As in any other fire accidents**, firefighters should wear protective clothing, including a self-contained breathing apparatus. | | |
| NATIONAL FIRE PROTECTION ASSOCIATION (NFPA) RATING | | | |
| HEALTH: 0 | FLAMMABILITY: 1 | REACTIVITY: 0 | PERSONAL PROTECTION: D |

## 7. ACCIDENTAL RELEASE MEASURES

| | |
|---|---|
| PERSONAL PRECAUTIONS | Avoid ingestion or eye contact. If a mist or vapor is generated, move to fresh air. |
| ENVIRONMENTAL PRECAUTIONS | Minimize contamination surface water, ground water, and drains. |
| METHODS FOR CLEANING UP SPILLS | Absorb with inert material, such as sand or dry earth, and place mixture into appropriate containers for disposal. |

## 8. HANDLING & STORAGE

| | |
|---|---|
| HANDLING | No special personal protection is required under normal handling conditions. However, gloves and goggles are recommended. |
| STORAGE | Keep away from heat, sparks, or open flames. |
| SAFE STORAGE/ TRANSPORT PRESSURE | Ambient. |

| 9. CHEMICAL STABILITY & REACTIVITY INFORMATION | |
|---|---|
| REACTIVITY | Not a self-reactive substance. |
| CHEMICAL STABILITY | Stable under normal temperatures and pressure. |
| CONDITIONS TO AVOID | Heat, flames, sparks and other sources of ignition. |
| MATERIALS TO AVOID | Incompatible materials/oxidizing agents and strong bases |
| HAZARDOUS REACTIONS | Will not polymerize |
| HAZARDOUS DECOMPOSITION PRODUCTS | Thermal decomposition will evolve carbon dioxide and/or low molecular weight hydrocarbons which may include irritant vapors |
| THERMAL DECOMPOSITION PRODUCTS | Oxides of carbon and water |

| 10. EXPOSURE CONTROLS/PERSONAL PROTECTION | |
|---|---|
| EXPOSURE LIMITS | No exposure limits have been established for this product. |
| EXPOSURE GUIDELINES | Wash the exposed area(s) with warm water and soap. |
| VENTILATION | No respiratory protection is required under normal handling conditions. |
| PERSONAL PROTECTIVE EQUIPMENT | No special personal protection is required under normal handling conditions. However, gloves and goggles are recommended. |
| SKIN/BODY PROTECTION | No special personal protection is required under normal handling conditions. However, gloves and goggles are recommended. |
| EYE PROTECTION | No eye protection is required under normal handling conditions. |
| ENGINEERING MEASURES | No special engineering measures are needed. |

| 11. TOXOLOGICAL INFORMATION | |
|---|---|
| EYE EFFECTS | No significant eye irritation can be expected from contact with this product. |
| SKIN EFFECTS | No skin irritation can be expected from short-term exposure to this product.<br>Skin – rabbit; Result: No skin irritation |
| SUBCHRONIC EFFECTS | No known effects. |
| CHRONIC EFFECTS | No known effects. |
| MUTAGENICITY | No data available for this product. |
| TERATOLOGY | No data available for this product. |
| CARCINOGENICITY | Not listed by ACGIH, IARC, NTP, DFG, OR OSHA |
| CHEMICAL NAME DATA AGENCY | No limits established for this product |

| 12. DISPOSAL CONSIDERATIONS |
|---|
| Disposal methods should be in accordance with local, state, and national environmental laws and regulations. |

| 13. TRANSPORT INFORMATION | |
|---|---|
| DOT SHIPPING INFORMATION | Not classified |
| PROPER SHIPPING NAME | Non-hazardous material |
| PACKING GROUP | Not applicable |
| LAND TRANSPORT ADR/RID/ADN | Not classified |
| U.S. DOT INFORMATION | Not classified |

<table>
<tr><th colspan="4">14. REGULATORY INFORMATION</th></tr>
<tr><td colspan="2">GHS CLASSIFICATION</td><td colspan="2">Not classified as a hazardous material to humans or the environment</td></tr>
<tr><td colspan="2">U.S. FEDERAL REGULATIONS</td><td colspan="2">No product components are listed under: CERCLA (40 CFR 302.4) and SARA Sections: 302 (40 CFR 355), 311/312 (40 CFR 370.21), 313 (40 CFR 372.65)</td></tr>
<tr><td colspan="4">CHEMICAL INVENTORY LISTING</td></tr>
<tr><td>Europe (EINECS): Compliant</td><td>USA (TSCA): Compliant</td><td>Canada (DSL): Compliant</td><td>Australia (AICS): Compliant</td></tr>
<tr><td>Japan (ENCS): Compliant</td><td>China (IECSC): Compliant</td><td>Korea (ECL): Compliant</td><td>Philippines (PICCS): Compliant</td></tr>
</table>