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A PHASE CHANGE MATERIAL SLURRY SYSTEM TO DECREASE PEAK AIR CONDITIONING LOADS

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**ENERGY INNOVATIONS SMALL GRANT
(EISG) PROGRAM**

INDEPENDENT ASSESSMENT REPORT (IAR)

**A PHASE CHANGE MATERIAL SLURRY SYSTEM
TO DECREASE PEAK AIR CONDITIONING LOADS**

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which 5% is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts up to four solicitations a year and awards grants for promising proof-of-concept energy research.

PIER funding efforts are focused on the following seven RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:

<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049 or email

eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at

<http://www.energy.ca.gov/research/index.html>.

A Phase Change Material Slurry System To Decrease Peak Air Conditioning Loads

EISG Grant # 00-19

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Introduction

California has experienced a 17% growth in power consumption between 1988 and 2000, which was not sufficiently offset with new power generation capacity. This has resulted in a decline in the State's spinning reserve over the same period from 8.3% to 1.2% on the days with the highest peak demand. In California, air conditioning is reported to consume approximately 16,000 megawatts, which is roughly equivalent to 30% of all electricity consumed on a typical hot summer afternoon. (Ref. CEC news release in March 2002.) High peak electrical demands are a concern to utilities because of the costs associated with either buying more high priced power on the margin, or building generating and transmission facilities to handle peak loads. Furthermore, if peak demand is not decreased or shifted to off-peak times, electrical outages may occur.

If the electrical load contributed by air conditioning equipment during hot summer afternoons could be reduced by one fourth, the peak demand would be reduced by approximately 4,000 megawatts thereby reducing the likelihood of rolling blackouts that are the result of electrical demand exceeding electrical supply. It would allow the decommissioning of a number of "Peaker" plants that are inefficient and high polluters, and would permit growth of electrical consumption without the need to build new "Peaker" plants.

This project studied a phase change material (PCM) slurry system to shift a portion of summer cooling load to off-peak hours. In this system, heat is absorbed by PCM slurry during the hot part of the day and removed by the air conditioning system during off-peak hours. Unlike other systems for load shifting, the PCM slurry system does not use an additional compressor and refrigerant; it works with the existing air conditioning unit. During the hot part of the day the PCM slurry system absorbs heat. The existing air conditioner, working in conjunction with the PCM slurry system, removes heat from the building. The portion of the heat load absorbed by the PCM slurry system decreases the cooling load for the air conditioner. The combination of the two systems leads to a 30-40 percent reduction of electrical demand during the hottest part of the day. Operating costs for the PCM slurry system are relatively low compared to a compressor type system. Electricity is only used to pump the PCM slurry and to power the fan. Fluid storage volumes are relatively low because only a portion of the cooling load is absorbed.

Objectives

The goal of this project was to determine the feasibility of integrating a conventional air conditioner with a unique PCM slurry system comprised of a highly concentrated PCM slurry, a

conventional heat exchanger and a ground loop for regeneration, to achieve higher overall energy efficiency and peak load shifting. The researcher established the following project objectives:

1. Demonstrate that a stable slurry mixture with a 30% or greater PCM volume fraction can be formulated.
2. Demonstrate that a conventional shell and tube heat exchanger can be used to effectively heat the slurry mixture.
3. Demonstrate that the slurry mixture can be regenerated by pumping it through a heat exchanger cooled by conditioned air or by pumping it through a ground loop, eliminating the need for fans or chilled air in the regeneration of the slurry, as funds permit.
4. Demonstrate that the proposed PCM slurry system is capable of absorbing 30% or more of the peak A/C load.

Outcomes

1. The researcher tested a number of PCMs in slurry compositions ranging from 30 to 40 percent PCM by volume. Hexadecane was selected as the PCM for further research. Hexadecane, a relatively benign chemical, exhibits a phase change temperature of 18° C, well matched to the application. Testing revealed this PCM can super-cool before changing phase. This characteristic is common to most of PCMs investigated. However, it is not a desirable feature.
2. Because of the fact that the fluid properties of the slurry were not well known or documented, selecting a compact heat exchanger core to suit the needs required a great deal of speculation and estimation. In the end, the coil chosen was a Super Radiator Coils Dry Glycol Coil (Model No. 10x30-3R-38/96). This coil was designed for a working fluid of glycol with air temperatures of 90° F and 80° F for the inlet and outlet, respectively. Two of these coils were used; one for heating the slurry and one for cooling the slurry.
3. The PCM system developed in this project shifted a portion of the air conditioning electrical demand to off peak hours. Only a small energy consumption penalty resulted. The slurry was regenerated by use of a heat exchanger and cooled air from the air conditioner. Appendix A provides a tutorial on the basic operating issues of a ground loop applicable to this technology.
4. The project constructed a bench-scale system using a 12000 BTU (1.5 ton) air conditioner. The PCM system was sized for compatibility with the air conditioner and used about 100 gallons of PCM slurry. Initially the power consumed by the slurry pump significantly reduced the EER of the combined system. A low power pump was installed overcoming this problem. Slurry flow rate, airflow rates and temperature data was collected in order to calculate system performance. This system was capable of displacing over 30 percent of the peak air conditioner heat load.

Conclusions

1. The temperature at which the PCM actually changes phase and absorbs heat is an important design parameter of the slurry system. Supercooling of PCM slurries before phase change is a common characteristic of these materials. When a PCM supercools it does not change phase at the design temperature, thus reducing the efficiency of the system. The investigator suggested future research could seek a nucleating agent to trigger phase change at the rated temperature of the PCM.

2. The slurry system is relatively simple to fabricate. Materials compatibility may be an issue for products containing PCMs.
3. The bench-scale slurry system was very sensitive to the energy used by the slurry pump. Parasitic losses of pumps and fans in this system should be addressed during future design work. The slurry must be redesigned before this system can operate with a ground loop, due to the supercooling. Supercooling brings the regeneration temperature to below ground temperature.
4. Feasibility of this technology has been demonstrated. It has the potential to shift a portion of residential air conditioning loads from peak to off peak periods. This technology could reduce the growing peak electrical demand in California.

Recommendations

The PA recommends the researcher undertake further laboratory study either to find a PCM material that does not exhibit supercooling or to develop a method to induce phase change at the design temperature. After successful completion of that work he should conduct long-term field tests to prove the PCM system, gather performance data, and study materials compatibility. Concurrently, the researcher should seek a commercialization partner who will aid in system specification and provide a marketing strategy.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. Deployment of systems that can shift the electricity demand of air conditioners from peak to off-peak hours could reduce the load on generating and transmission facilities in California. Phase change material systems incorporated into air conditioners have the potential to shift electrical demand. The financial impacts of blackouts, brownouts, or reduced power quality are significant to the California economy. Electric utilities benefit from the reduced need to purchase expensive peak electricity or to construct new peaking plants.

If the technology in this project were commercially developed and widely implemented, significant amounts of residential and commercial air conditioning electrical loads could be shifted to off-peak times. Shifting load at period of peak demand reduces the need for utilities to start and run less efficient generators. Those generators are typically costly to operate and produce higher levels of air emissions than base load generators. Shifting load also reduces peak demand on California's electricity transmission system, resulting in lower cost, more reliable electricity. All ratepayers would benefit.

Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

A product based on this technology would be highly valued by consumers if, and only if, time-of-use electricity rates were in effect. Time-of-use rates would provide a strong economic incentive to individuals to consider load-shifting technology when they install or replace their air conditioning equipment. Without time-of-use pricing California agencies and utilities would have to provide economic incentives to purchasers of air-conditioners to install an unproven technology that may be priced higher than standard technology. Unless the utility provided significant incentives, the product would not find wide acceptance.

The researcher has not yet contacted utility companies. He plans to contact them to elicit their views and to seek participation in full-scale prototype testing. Utility participation during field-testing is critical in order to facilitate acceptance of the technology.

Engineering/Technical

A bench-scale system has been developed and tested. The researcher demonstrated the feasibility of the concept. At least one significant scientific challenge remains before commencing full-scale testing. The researcher must identify a low-cost PCM that does not exhibit supercooling. Considerable effort in materials development and testing may be necessary to identify a material with those characteristics.

Legal/Contractual

Leading Technology Designs, Inc. filed for a provisional patent with the U.S. Patent and Trademark Office (Application No. 60/369,168 – Filed March 29, 2002). The patent focuses on the system fluid.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental. The researcher has begun work on a risk assessment of the system. He is evaluating the environmental and safety aspects of the potential working fluids.

Production Readiness/Commercialization

The researcher has postponed the development of a production readiness and commercialization plan pending the receipt of additional development funding. He is developing a business plan prior to offering the technology to private investors.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

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(EISG) PROGRAM**

EISG FINAL REPORT

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Allen “Lindy” Linda has to also be thanked for his knowledge of HVAC systems and for the loan of the air-conditioning unit used for the bench-scale tests. Lindy was a good sounding board for the practical aspects of air-conditioning systems as an instructor of HVAC at Northwest Technical College.

Most importantly, I would like to thank the EISG Program for their support and for the patience of Steve Russell during the completion of the final report.

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Abstract

A Phase Change Material (PCM) Slurry system was developed and tested. The system was designed to absorb portions of peak air-conditioning loads and to shift the electrical demand for these loads to an off-peak time. PCM slurry compositions ranging from 30-50 percent PCM were successfully developed, found to be stable, and tested in a small flow apparatus. The slurry mixtures consisted of an emulsifier, a hydrocarbon PCM, and water. The slurries did exhibit supercooling during the cooling/solidification process. Other PCMs could be evaluated to minimize the impact of the supercooling. Slurry mixtures were stored for periods of up to 8 months in duration and were still an emulsion. The particles did coalesce slightly, but mild agitation of the mixture broke the particles into smaller particles once again. Design calculations were conducted to design a bench-scale apparatus. The bench-scale system was sized for a 1.5-ton air-conditioning unit. Tests were undertaken with this system to evaluate the potential of the system for shifting peak air-conditioning loads. Test results indicated that 40 percent of the peak air-conditioning load can be absorbed and stored for later cooling. The system was also shown to be very efficient by operating at an average Energy Efficiency Rating (EER) of 154 during heat absorption (time of peak electrical demand). Typical air-conditioning systems operate at an EER of 12 to 16. The system operated efficiently during times of peak demand, demonstrating the ability of the system to shift peak demand by 40 percent or more.

Key Words: phase change, thermal energy storage, air conditioning, PCM, slurry, peak shifting

Executive Summary

Peak electrical demand is growing at a rate faster than new generating capacity is being built. This situation results in the potential for brownouts or blackouts. During the summer of 2000, California experienced such a situation. A major factor in these power shortages was the increased demand for air-conditioning. If electrical loads were constant all day long, there would be no concern over increases in electrical demand. But, demand fluctuates during the day due to changes in electrical needs. A major factor in demand increases is the electrical demand associated with air-conditioning loads. In addition, outdoor temperatures directly affect the peaks associated with air-conditioning. Hence, hot summers can lead to regular power shortages.

The peaks in the demand can be reduced by shutting off the air-conditioning systems, developing more efficient methods of air-conditioning, giving incentives to residential and industrial users to decrease their air-conditioning loads, or shifting a portion of that peak heat load to off peak times. The public often resists shutting off their air-conditioning because they want to maintain their comfort levels. In general, the larger the peak demand, the greater the need for air-conditioning on those days.

The research discussed in this report outlines a concept to shift a portion of that peak heat load to off-peak times. The concept relies on the use of a Phase Change Material (PCM) Slurry to store that energy. The fluid consists of a PCM, water, and an emulsifier. The fluid is a mixture of

small oil droplets dispersed in water. The emulsifier is used to prevent the droplets from coalescing into larger droplets, or to prevent the oil from completely separating from the water.

As the name implies, the PCM is a material in the fluid that will undergo a change of phase. The fluid will change from a solid to a liquid, and back again. As the PCM undergoes a change of phase it requires the addition or rejection of significant amounts of energy. Correctly selecting a PCM that melts at a desirable temperature can devise a fluid that stores a large amount of energy for a small fluid temperature change. One effectively ends up with a fluid that has a great heat storage capability when compared to other fluids over that same temperature range. The advantage of using a PCM slurry is in its ability to store more energy per unit volume than other fluids in the same operating temperature.

Four objectives were defined for the project in order to assess whether the system would function as suggested. These objectives were to

1. Develop PCM slurry mixture with 30 percent or greater PCM volume fraction.
2. Design PCM slurry system to absorb 30 percent or greater of the peak A/C load.
3. Demonstrate concept by building and testing bench-scale system.
4. Document research and assess system potential.

Several tasks were associated with each objective. The completion of all the tasks would determine if the concept was feasible.

Several PCM slurry mixtures with greater than a 30 percent PCM volume fraction were successfully developed. The process of developing these slurries included developing small test samples for examination under the microscope, stability testing by storing the materials for extended periods of time, and then the eventual testing of potential slurry mixtures in a small flow apparatus. Hexadecane was chosen as the PCM to be used in the small scale and bench scale testing. Mixtures with 40 percent PCM were successfully pumped, cooled, and heated in the small test apparatus. The fluids show good heat absorption and demonstrated the ability to pump these fluids at higher concentrations.

The fluids did exhibit some supercooling during testing. Supercooling is the phenomenon where a fluid is lowered below its melting point and does not solidify until some crystallization starts within the fluid. This phenomenon resulted in the point of phase change occurring around 9-12°C, well below the phase change point of 17-18°C reported for hexadecane.

The second objective focused on the type of design criteria necessary to build a system to absorb 30 percent or more of the peak air-conditioning load. This work included an examination of a typical peak electrical demand curve. It was estimated that an operating period of approximately 4 hours was adequate for either a residential or commercial setting. In order to operate and store that amount of energy, minimum operating conditions, or design criteria were specified. This knowledge was then used to design the bench-scale system.

The third objective was the culmination of the work completed in objectives one and two. A bench-scale system was built and tests were conducted. The tests were successful and

demonstrated the ability of the system to store portions of the peak heat load. The design goals were exceeded during the testing. Test results show that 40 percent (average value) of the peak air-conditioning heat load can be absorbed by the PCM slurry system. In addition, the system was able to operate at an efficiency level 10-12 times greater during the hottest part of the day than existing air-conditioning systems. The net effect is a system that can absorb a significant portion of the peak heat load and operate at low energy consumption levels.

The bench-scale tests also exhibited supercooling during the solidification of the PCM. This resulted in long solidification times for the tests. This problem can be overcome by selecting a higher melting point PCM and take into account the supercooling. The phase change would then occur at a temperature that would allow for more rapid cooling of the PCM during off-peak operations. In the bench-scale tests, the solidified PCM was found to separate out from the rest of the fluid and resulted in a “slushy” layer at the top of the storage tank. This presented no problems for system performance (no plugging of pipes).

The bench-scale tests have been successfully completed and offer a new option to utilities and residential users to control peak air-conditioning loads in California. The system design and evaluation is by no means completed, but the first steps have been encouraging. The system offers the potential to shift significant portions of the residential and commercial cooling loads to off-peak times.

The next steps in the project should be to find a lower cost PCM material that melts at a slightly higher temperature. This would make the system more cost effective and operate more efficiently during the cooling portion of the cycle. Efforts should also be made to refine the system design, build a full-scale prototype, and to install/test the system in a realistic residential setting. Some refinements on the fluid composition could also be made to see if the solidified PCM could be made to remain suspended in the fluid rather than separating out.

Introduction

PIER has specified six program areas for potential funding. The work completed here was directed towards the *Building End-use Efficiency Program* area. The PCM slurry system can conserve energy by reducing demand for electricity associated with peak air conditioning loads. This in turn will benefit the consumer by reducing their expenditures on energy and the utility by decreasing the total peak demand for electricity.

Excess electrical generating capacity has slowly decreased over the last 10 years (see Figure 1). The excess capacity has decreased because additional capacity (new plants) has not increased as fast as the peak demand has increased. If peak demand is not decreased or shifted to off-peak times, electrical outages have and will continue to occur. These outages are a detriment to manufacturers, businesses, and those who depend on air-conditioning for health reasons. These problems have been readily apparent in California (summer 2000).

The Phase Change Material (PCM) Slurry system decreases peak electrical loads due to air-conditioning and shifts this portion of the cooling load to off-peak times. Heat is absorbed by the PCM slurry during the hottest part of the day, and then rejected to the air-conditioning system later in the day. Unlike other systems for load shifting, the PCM slurry system does not require an additional compressor and refrigerant, it relies on the existing air-conditioning unit.

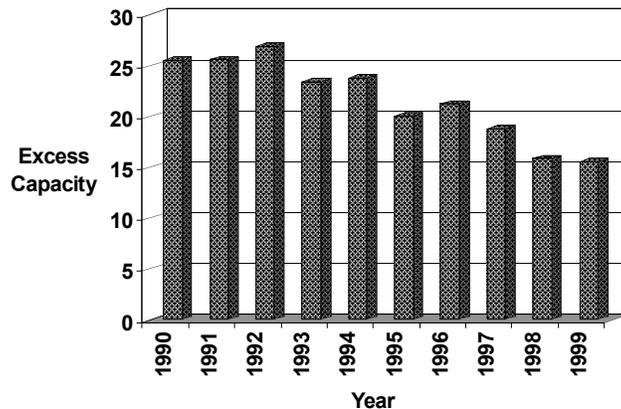


Figure 1 - Excess generating capacity ((Capacity - Peak)/Capacity * 100). Data taken from Electric Power Annual Volumes I & II from the years 1994, 1996, and 1999.

The severity of power outages and the impact on businesses was clearly portrayed by events in California (January 2001 as seen on national news). California was also in the news during the summer of 2000. During that time, power shortages occurred in California because of the high electrical demand from air-conditioning systems. Across the nation, air-conditioning loads are the predominant cause of the peak electrical loads during the summer months. These high peak electrical demands are a concern to utilities because of the high costs associated with either buying more power, or building generating facilities for the peak load.

These peak electrical demands can be dealt with in a number of ways. Possible solutions are to develop more efficient air-conditioning equipment, thermal energy storage (shift the peak demand to an off-peak time), to eliminate electrical loads by shutting them off during peak periods, or to add more peak generating capacity. The PCM slurry system is designed to shift the cooling load to off-peak times (thermal energy storage) for *residential or industrial* users.

The PCM slurry system works in conjunction with an existing air-conditioner. A portion of the heat load is absorbed by the PCM slurry system, hence decreasing the cooling load for the air-conditioner. The combination of the two systems leads to a 30-40 percent reduction of electrical demand during the hottest part of the day. Operating costs for the PCM slurry system are low because the only work is associated with pumping the slurry and for the pressure drop across the fan. Fluid storage volumes are low because only a portion of the cooling load is absorbed during the day. This is an advantage over competing “ice-storage” technologies (realistically these systems are only used for commercial applications).

The *Draft Plan for Research in Residential and Non-Residential Buildings End Use Efficiency* (Prepared by the PIER Buildings Team, July 1, 1999) also indicates the need for dealing with peak electrical loads. The draft plan lists four issues related to buildings that they see as significant. Issue 1 is applicable to this proposal and states “Energy consumption is increasing in hotter, inland areas as new building construction increases in these areas.” They go on to indicate how building thermal loads during peak periods increase the electrical demand for air conditioning, which in turn can lead to system outages. In addition, they stress the need for research to investigate energy efficiency and load shifting.

The problem is peak electrical demand from air-conditioning loads. The proposed solution was the development of a PCM slurry system to absorb a portion of the peak heat load. To evaluate the potential for this concept, four objectives were established in the proposal.

1. Develop PCM slurry mixture with 30 percent or greater PCM volume fraction.
2. Design PCM slurry system to absorb 30 percent or greater of the peak A/C load.
3. Demonstrate concept by building and testing bench-scale system.
4. Document research and assess system potential.

The remainder of the report contains sections on the Project Approach, Project Outcome, Conclusions and Recommendations, Development Stage Assessments, and the Appendices.

The Project Approach section of the report presents the objectives and the tasks that were undertaken to meet each objective. Details for each task are presented and discussed. Background information on PCMs is also presented to give the reader a better understanding of how the system functions. The intent of each task was to provide data that supported each objective. The tasks determine whether the objective can be met.

The Project Outcome Section presents the test results. Test data for the selection of a PCM slurry will be presented, along with flow testing, and test results from the bench-scale system.

The report will show that all objectives were successfully completed.

Project Approach

Each of the four objectives was met through specific project tasks associated with that objective. This section of the report will present a brief discussion of those tasks and the work completed to demonstrate the proposed objectives. Prior to discussing the specific tasks, a brief discussion on PCMs will be presented because how the fluid functions is a key to the process.

Materials can absorb sensible heat or latent heat. Sensible heat is when the material increases in temperature as it absorbs energy. Latent heat is associated with energy absorbed when a material undergoes a phase change, or a change in structure while still remaining in the same phase. In this application, a PCM is a material that has the ability to absorb large amounts of thermal energy (heat) when it undergoes a solid to a liquid phase change. Proper selection of a PCM for a particular application can result in the ability to absorb large amounts of energy for small temperature changes.

There are 3 general classes of PCMs that include paraffins, non-paraffin organics, and hydrated salts. The melting points for the different classes of materials range from near 0°C to over 900°C. These melting points are also referred to as the phase change temperature. Once the material is melted (end of the heating cycle), it must be cooled and resolidified for the next heating cycle. Paraffins are a good candidate for the present application because they offer a wide range of melting points (function of the number of hydrocarbon chains) and are relatively inexpensive.

The PCM can be used in different forms. Here, a novel and effective use of PCMs is in slurry form. The slurry consists of a carrier fluid and small PCM particles. The particles can either be microencapsulated PCMs or the result of placing a PCM directly into the fluid with an emulsifier. Particle sizes can range from a few microns up to 1,000 microns. Particle size will vary for different applications.

PCM slurries can be used in heat transfer systems to enhance the ability of the fluid carrying them to absorb more energy. In addition, the PCM particles enhance the heat transfer in the system because the particles disturb the boundary layer. The small PCM particles melt, absorbing more energy over a small temperature range than the fluid alone could absorb.

Figure 2 shows the relationship between enthalpy (energy storage) and temperature for water and a PCM slurry. Note that the large change in enthalpy over small temperature changes near the melting point of the PCM slurry. For the example shown, the slurry mixture stores 30-50 percent more energy than does the water alone.

A detailed discussion of each objective and the tasks will now be presented in the next Section.

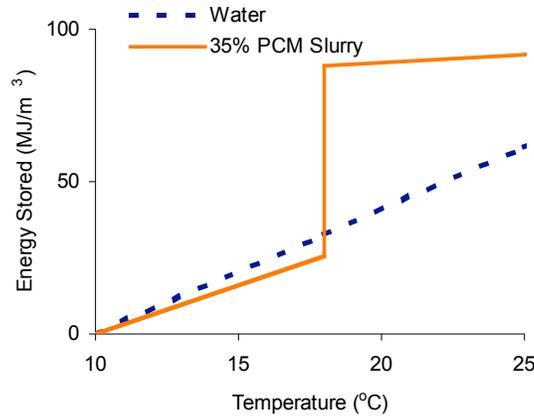


Figure 2 - Heat storage comparison of water and a PCM slurry between 10 and 25°C.

Objective 1: Develop PCM slurry – greater than 30 percent PCM.

Task 1-1: Selection of a PCM(s)

Task 1-2: Evaluation and selection of potential emulsifier(s).

Task 1-3: Selection of aqueous PCM and emulsifier composition.

Task 1-3a: Stability testing.

Task 1-3b: Flow testing.

The goal is to develop an emulsion that contains oil, water, and an emulsifier that has good heat transfer and heat storage characteristics. An emulsifier is a surface-active agent that modifies the surface tension of the oil to form small particles of oil in the water. The emulsifier is to also stabilize these particles so that they do not stick together (agglomerate). In layman’s terms, this surface-active agent is many times called a “surfactant.” A common surfactant is soap. The challenge here is to pick the “right” emulsifier for this application.

In order to develop a useful PCM slurry, there is the need to pick a PCM-emulsifier pair that will form a stable emulsion. Stable is a relative term. The present application would require an emulsion that would remain stable for several months during a period of time when the system is not being used.

Several PCMs were considered as candidates for the PCM slurry composition. The characteristics of an ideal PCM include

- A melting point suitable to solidification with an existing off-the-shelf air conditioner,
- Not exhibit any significant supercooling (application dependent),
- Be environmentally safe and non-toxic,
- Exhibit good heating and cooling characteristics,
- Be able to store large amounts of energy when undergoing a change of phase (high heat of fusion is more desirable), and
- Have a low cost.

Potential phase change materials were located through library searches, review of technical publications, discussions with vendors, and a search of the Internet. Potential materials include those shown in Table 1.

Three types of materials were examined: paraffins, inorganic compounds, and hydrated salts. The majority of the research centered on paraffins because they are the most commonly used materials in PCM slurries. The last two items are listed in the table for reference purposes only.

The types of paraffins examined here are similar to common candle wax, except that the materials of interest melt at lower temperatures. These materials are considered environmentally safe and not generally hazardous to the user.

Hydrated salts have been widely used for energy storage in the past, but this author knows of no one that has tried to develop a slurry using these materials for heat storage applications. The materials actually lose water molecules in the “phase change” process. It is uncertain if a fluid composition could be made that allowed the loss and ultimate reattachment of the water molecules in some sort of slurry. For this reason, hydrated salts were not seriously considered in the present application.

Table 1 - PCMs examined for use in slurry.

Name	Melting Point (°C)	Heat of Fusion (KJ/kg)	Material Type
Tetradecane	6	227	Paraffins
Pentadecane	10	207	Paraffins
Hexadecane	18	236	Paraffins
Heptadecane	22	214	Paraffins
1-octadecene	18	129	Paraffin
Caprylic Acid	17	150	Inorganic
Potassium Fluoride Tetrahydrate	18.5	231	Hydrated Salt

Two materials, hexadecane and 1-octadecene were of primary interest to the project because of their melting points. The initial goal was to have a PCM slurry that could potentially reject heat to the earth, drastically decreasing the peak load energy requirements and decreasing the off-peak energy requirements. The melting point of these materials falls between the return air temperature and the groundwater temperature. Neither the hexadecane nor 1-octadecene has been used to formulate a PCM slurry (see Appendix I for brief literature review relating to previous PCM slurry research).

The particles in an emulsion need to remain as individual particles and not return to two separate fluids. There are five mechanisms that can breakdown an emulsion. These mechanisms are Ostwald ripening, creaming, aggregation, coalescence, and partial coalescence. Two things can

be done to overcome these mechanisms: mechanical devices (mixers) or the addition of emulsifiers. Here, an emulsifier has been used to aid in keeping the particles in the mixture.

The second task to aid in meeting Objective 1 was the selection of an emulsifier. The emulsifier works to modify the surface tension characteristics of the oil so as to form small droplets of oil in the water. The emulsifier is an important component of the slurry. The type of emulsifier chosen will have hydrophilic and hydrophobic groups on each end of the molecular structure. The hydrophilic group “likes” water and orients itself towards the water and the hydrophobic group “dislikes” water and orients itself away from the water. This effectively puts a layer around the surface of the particle.

Table 2 shows seven different emulsifiers that were considered for the project.

Table 2 – Potential emulsifiers.

Item	Name
1	Tween 20
2	Tween 60
3	Tween 80
4	Triton X-100
5	Aktaflo-E
6	Sodium Dodecyl Sulfide (SDS)
7	Brij 35 (30% solution)

Based on available information, PCM slurry samples were made and examined for stability. Stability of the samples was based on the ability of the samples to remain as emulsions (small droplets of oil in the water) rather than the PCM separating back out again. 500 ml samples with variations in the amount of PCM, emulsifier, and water were formulated. A discussion of these test results can be found in the section on Project Outcomes and details of the particle sampling process can be found in Appendix III.

A satisfactory formulation will be one that forms an emulsion and remains in that state for a period of time without the need for mechanical agitation. A time period of 6 to 8 months of inactivity would be common for a PCM slurry system that would work with an AC system. Test data will be shown in the Project Outcomes Section demonstrating the selected compositions stability.

Once an acceptable formulation was selected, a larger volume of the fluid was made and tested in a small flow apparatus. The flow apparatus is shown in Figure 3. The apparatus consisted of an insulated tank, two pumps, a heated section, and a cooled section. One of the pumps pumped the slurry through the tubes, and the other was used to pump a cooling fluid. All of the pipes were made of copper for good heat transfer. A heat tape was wrapped around one of the copper tubes for heating the PCM slurry. The cooling of the fluid was performed by a simple concentric tube heat exchanger. Photos of the system are shown in Figure 4.

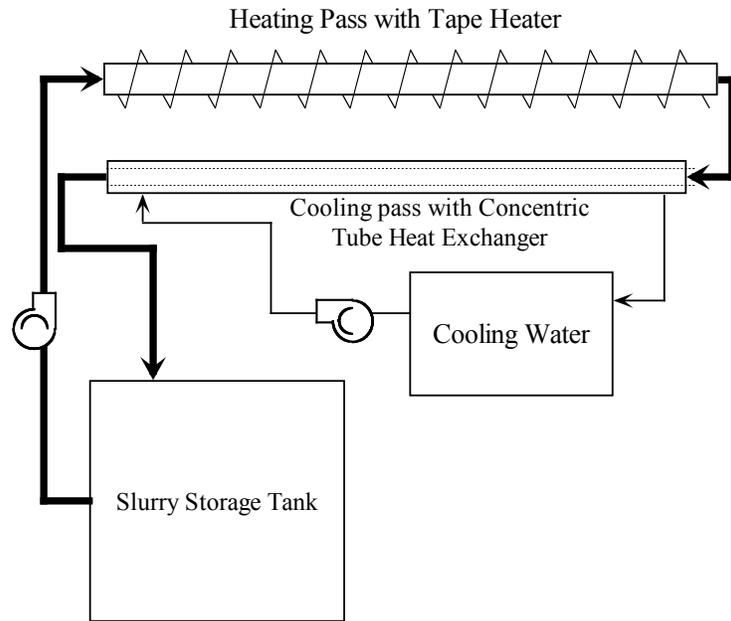


Figure 3 - Schematic of small flow testing apparatus.

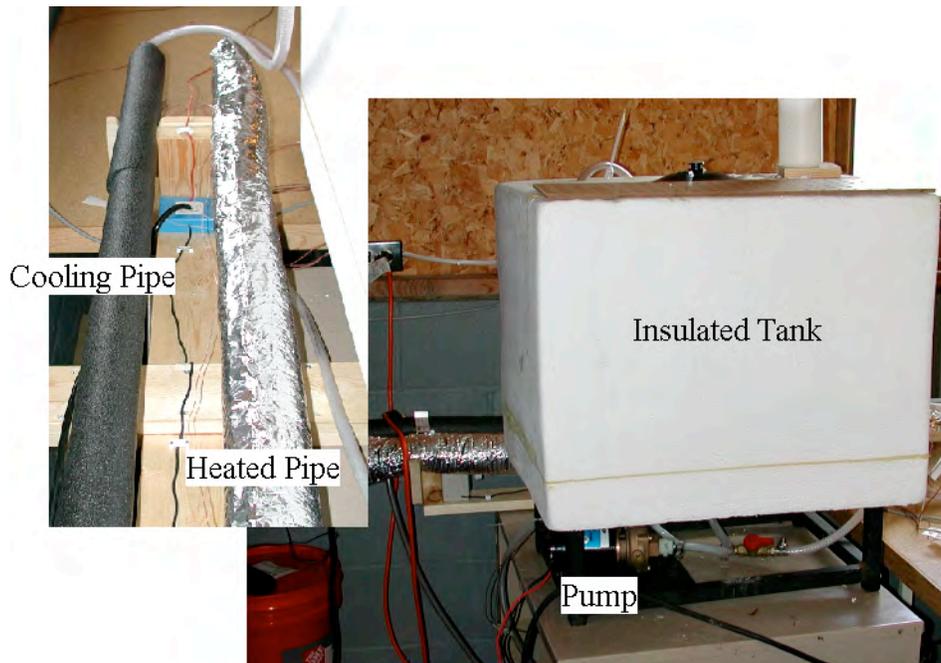


Figure 4 - Photos of flow apparatus used to evaluate slurry flow.

Test results for this apparatus will be discussed in the Project Outcomes Section of the report.

Objective 2: Design PCM slurry system to absorb 30 percent or greater of the peak A/C load.

- Task 2-1: Establish design criteria for a residential system.*
- Task 2-2: Perform design calculations and parametric studies.*
- Task 2-3: Design bench-scale apparatus to evaluate concept.*

The residential system must function for a period of time that is long enough to decrease the peak demand for the electric utility. Decreasing demand for any shorter period of time would make the system ineffective.

Table 3 shows the critical design parameters for the PCM slurry system, plus includes some comments on the basis for those design criteria.

Table 3 - Baseline design criteria for PCM slurry system.

Design Issue	Design Criteria	Comments
Operating time	4 hrs	Based on peak AC load data
Heat Absorption	> 30 %	Minimum capacity
Energy Storage	45,580	Based on storing 30% of peak heat load for a 3 ton AC unit (KJ)
Baseline Heat of Fusion	200	KJ/Kg
PCM Concentration	> 30 %	minimum value
Fluid Temperature Range	10 °C	Temperature change from lowest temperature to highest temperature for normal operations
Fluid Volume	150	Volume assumes fluid, 30% PCM
Tank Volume	180	Assumes 20% additional volume for expansion of PCM for solidification
Melting Point - PCM	15 - 20 °C	Acceptable range between operating conditions of AC unit and air temperature
Air Flow Rate	400 CFM / ton	Typical cooling airflow rate

The most important factor in designing the system is in determining how long the system should reduce the peak heat load. Figure 5 shows a typical peak demand curve during the cooling season in California. This type of data will vary day-by-day, but what is shown is some of the best data available for examining peak loads. As shown, the duration of peak demand is roughly 6 hours, from 1:00 p.m. to 7:00 p.m.

Figure 6 goes one step farther and examines the types of peaks produced by residential and commercial cooling. The data for these curves was extracted from Figure 5. Note that the peak commercial air-conditioning load occurs much earlier in the day. The residential peak occurs approximately 4 hrs after the commercial cooling load peaks. The commercial peak occurs around 2:00 p.m., while the residential peak occurs at 6-7:00 p.m. in the evening.

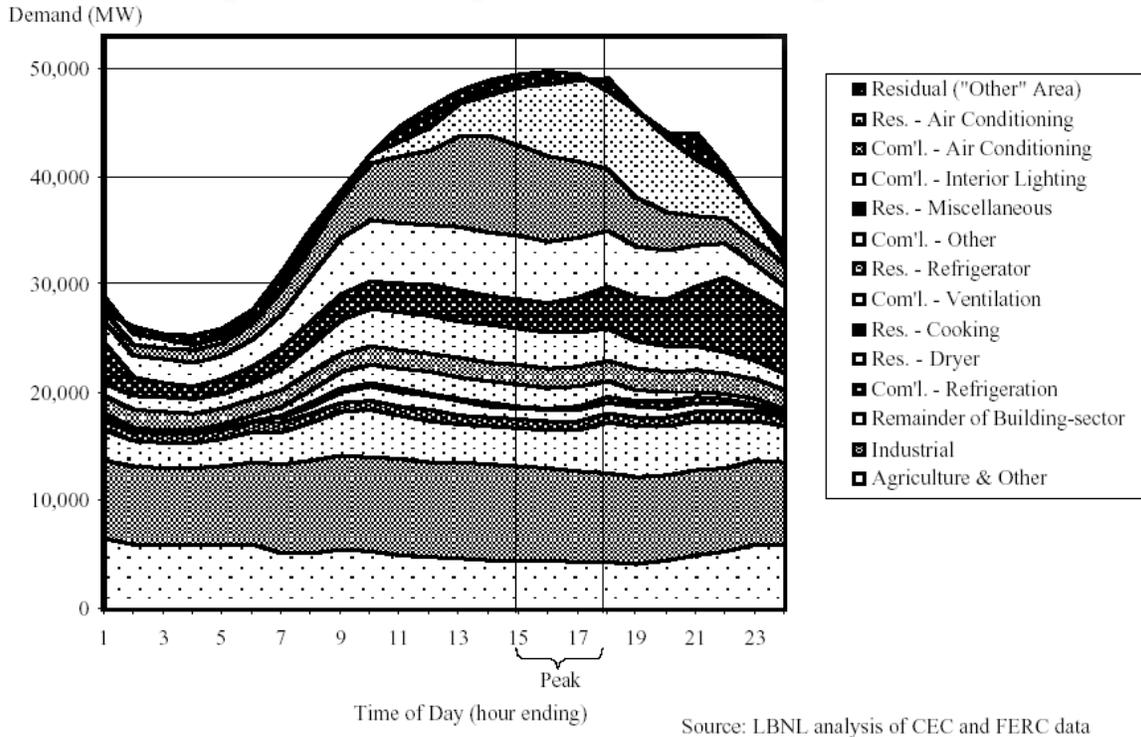


Figure 5 – Peak electrical demand data for California (taken from “Electricity Use in California: Past Trends and Present Usage Patterns,” LBL-479992, by R.E. Brown and J. G. Koomey, June 2001, DRAFT).

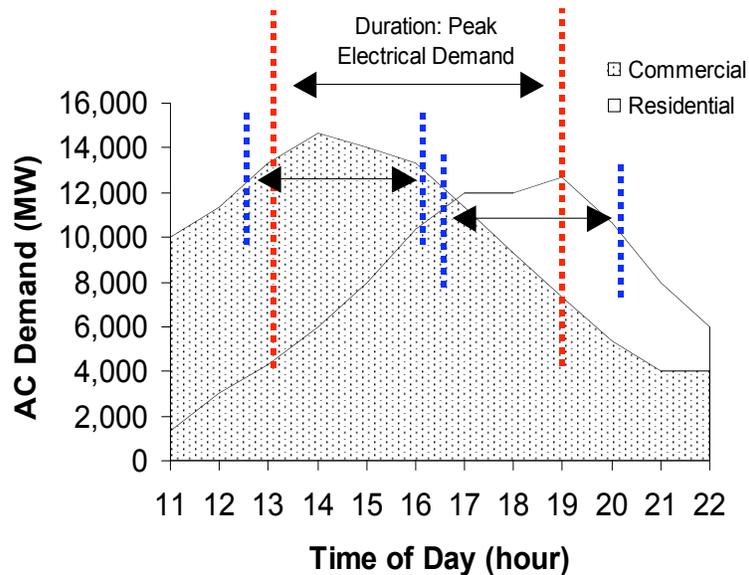


Figure 6 - Duration and time of peak air-conditioning electrical loads for commercial and residential applications. Peaks of the two main air-conditioning loads occur at different times, but both last approximately 4 hours. (Plot based on data extracted from Figure 5)

Figure 7 shows the changes that occur if the commercial and residential loads are decreased by 30 percent for a 4 hour time period. The net effect is a significant reduction in peak demand over the 6-hour peak demand period. Based on the impact a 4-hour operating period has on the residential and commercial AC loads, it was decided 4 hours for heat absorption was adequate.

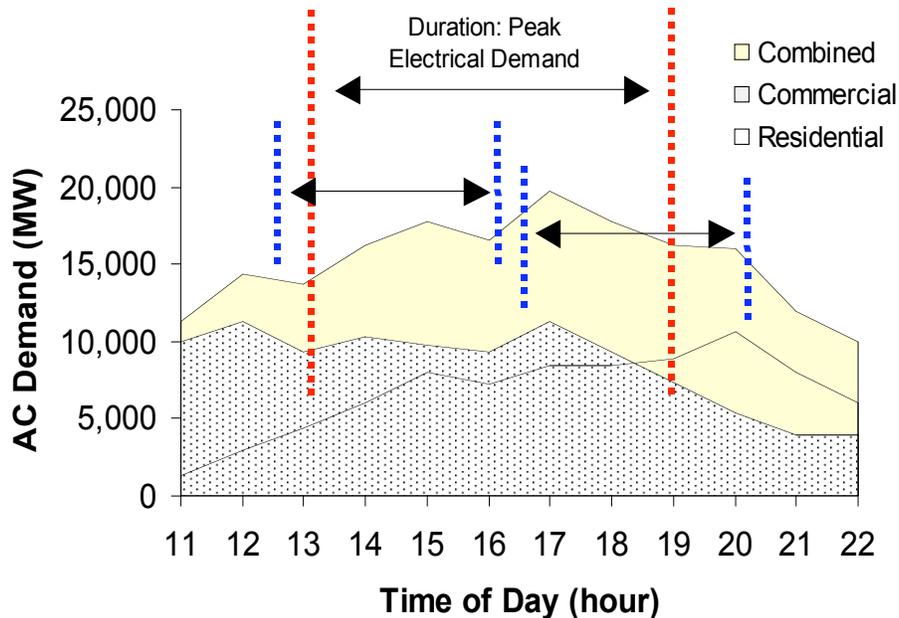


Figure 7- Effect of having a PCM slurry system operating for a 4-hour time-period and reducing the cooling load by 30 percent. (Plot based on data extracted from Figure 5 and reducing that load data by 30 percent)

Design calculations were carried out for the design criteria specified in Table 3. The intent of the design calculations was to gain insight into designing a system that would operate efficiently for a specified fluid flow rate.

The most important issues in designing this energy system is the amount of energy that must be expended to make the system work, and the amount of energy stored. If it takes a lot of energy during the peak electrical demand time of the day to absorb energy (cool the hot air) into the PCM slurry, the system will be no more effective than existing air-conditions. So, for the system to be considered effective, it has to cool the air (PCM slurry absorbs energy) much more efficiently than an air-conditioning system does. The model attempts to make these estimates to guide the design process of the bench-scale system.

For the PCM slurry system, the amount of work expended consists of pumping costs and fan costs. These costs are represented by pressure drops (pump is needed to move the fluid) and by a fan (pressure drop in ductwork or across a heat exchanger). The energy stored here is the amount of energy absorbed by the PCM slurry. If the PCM slurry system is to be effective, the energy efficiency rating (EER) of the PCM slurry system had better be much larger than the EER (or a more commonly referred to term, the Seasonal Energy Efficiency Rating – SEER) of the

AC system. The SEER can be thought of as a seasonal efficiency parameter. The EER is defined as

$$EER = \frac{\text{Cooling Load}(BTU/hr)}{\text{Energy Input}(W)}$$

The Department of Energy has recently increased the required minimum SEER value to 12, from 10.

The modeling results to be presented here took into account the following factors or made the following assumptions:

- Finned tube, cross-flow heat exchanger (similar to a radiator in a car – aluminum fins with copper tubes).
- Fluid consisted of 30 percent PCM and 70 percent water. General thermal properties were assumed to be a linear composition of each constituent.
- PCM was assumed to have a 200 KJ/Kg heat of fusion (energy storage capability).
- Heat exchanger performance relied heavily on data supplied by manufacturer. This data included estimated performance for average operating conditions (overall heat transfer coefficients, pressure drops, etc.).
 - 3/8-inch tube diameters with 0.016 wall thickness.
 - Aluminum fins, 0.0055 inch thickness.
 - Pressure drop was assumed to occur for two passes through a tube (once down and then once back to the fluid header).
 - Internal heat transfer coefficients were scaled from a general pipe-flow heat transfer coefficient. The scaling was based on general results obtained by other researchers (amount of increase in heat transfer from a non-slurry fluid).
- Pressure drop in the piping was estimated for a number of equivalent lengths (based on engineering judgment). Actual piping was plastic tubing, much smoother than typically used in piping systems.
- The “melting point” of the fluid in the model was assumed to be 15°C.
- Average air temperature assumed to be entering the heat exchanger at 32°C.

Figures 8 and 9 present some general results of the modeling effort for a system having a 15-gallon per minute PCM slurry flow rate. Three designs are presented in each figure. The only difference between each design is the number of rows of tubes in the heat exchanger. Design A is the system of interest here because it best represents the bench-scale system to be discussed later in this report. The heat exchanger in Design A represents the one selected for the bench-scale system. Briefly, the heat exchanger is a crossflow heat exchanger, 30 tubes, 10 inch by 30 inch face area, aluminum fins, and 3/8 inch diameter tubes. Designs B and C add 2 and 4 additional rows of tubes respectively. These designs are included to show how overall performance can degrade.

The design criteria for a system was the absorption of at least 30 percent of the cooling load. For a 1.5 Ton (12,000 BTU/hr) unit, 30 percent of the load is 0.45 Tons of cooling. The airflow rate for a 1.5 Ton unit should be approximately 600 CFM. The results in Figure 8 shows approximately these results at the intersection of the 600 CFM flow rate and Design A.

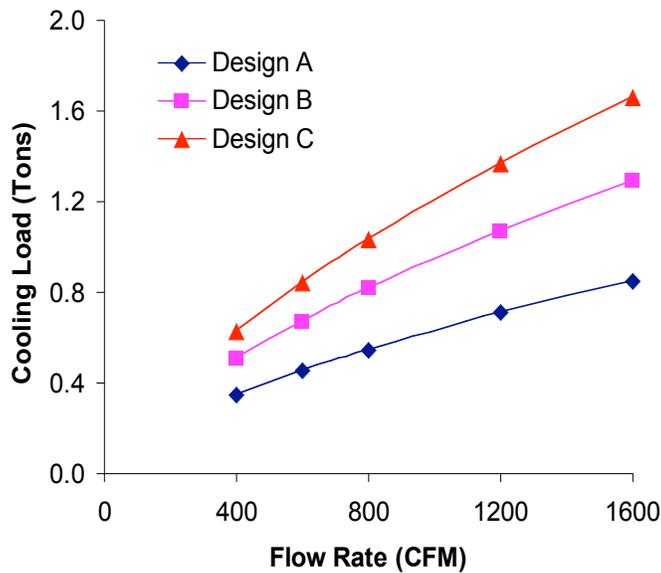


Figure 8 - Estimated cooling performance for a 30% slurry composition flowing at 15 gpm. This flow rate was chosen to reflect conditions that would exist in bench-scale apparatus.

The results shown in Figure 8 only represent one portion of the overall picture – energy absorption. The second portion of the problem is the amount of energy expended in order to absorb this energy. Figure 9 shows the estimate EER for the 3 proposed designs. Design A has optimum performance at the desired airflow rate of 600 CFM. The EER is approximately 120, 10 times more efficient than required by the DOE for air-conditioning units.

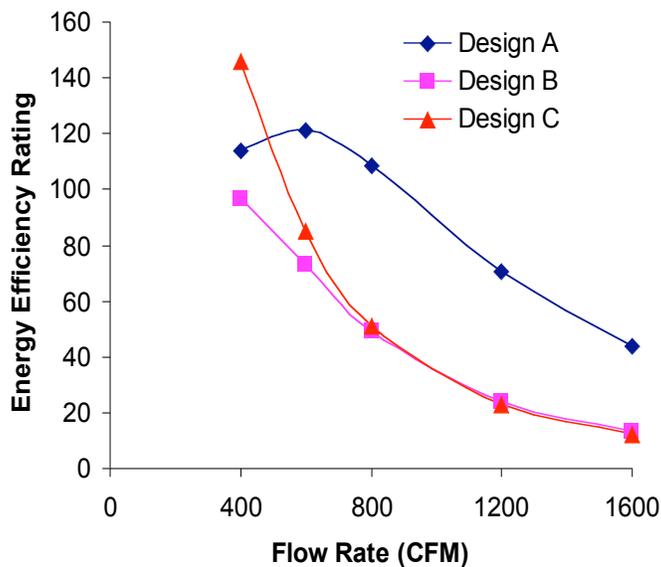


Figure 9 - Energy efficiency estimate for system sized similarly to bench scale system. Design A is appropriate for bench scale apparatus.

The EER drops off quickly because the fluid flow rate through the heat exchanger remains constant in Figure 9. If one considers that the heat transfer coefficient between the fluid and the tube does not increase in this situation and that only the heat transfer off of the finned crossflow heat exchanger increases, it is clear that performance could degrade quickly. The total heat transfer would only increase slowly, while the amount of energy required to force the air over the heat exchanger can increase more rapidly. This results in the energy costs increasing more rapidly than the energy absorbed, hence the degradation in performance. Keep in mind, these are only estimates because there is a large uncertainty in the internal heat transfer coefficient between the PCM slurry and the tube.

The design criteria and design studies have indicated that

- The proper sizing of the heat exchanger in relation to the fluid flow rate available for a given pump is critical. Inadequate flow can result in less absorption than required and poor overall performance.
- Pressure drop on the fluid side of the system must be minimized at all cost to insure efficient operations. This can require short piping runs, location of the tank in close proximity to the heat exchanger, and a minimum number of valves.
- If mixing is required in the tank to keep the slurry mixed, this is an additional energy cost that hurts system performance. (Note: Some mixing was used in the experimental portion of this project, but none was used for the bench-scale tests so that realistic performance could be obtained. This information is discussed later in this report and only included here for completeness.)
- Poorly selecting a pump can lead to inefficient operations. Pump selection is a critical component of the system. Pump should have high efficiency and deliver the flow necessary for a given set of operating conditions.

The bench-scale system was designed around an available 1.5-ton air-conditioning unit. The system was small and compact and could be located in the test facilities. The remainder of the system was then sized accordingly. The design calculations presented above were used to select components for the system. Details of the system are presented under the discussion surrounding Objective 3 (start of next section).

Objective 3: Demonstrate concept - build and test bench-scale system.

Task 3-1: Procure, fabricate, and assemble bench-scale apparatus.

Task 3-2: Develop test plan.

Task 3-3: Perform bench-scale tests.

A schematic of the bench-scale system is shown in Figure 10. The system consisted of a blower, heating coil, ductwork, two heat exchangers for the PCM slurry, a 1.5 ton air-conditioning unit, a PCM slurry storage tank, piping and valves, a mixer, and a pump. A two heat exchanger system was designed to simplify the ductwork design for the bench-scale apparatus. One of the heat exchangers was used for heat the slurry (upstream of the AC unit) and the other was used for cooling the slurry (downstream of the AC unit). The mixer was periodically used to mix the fluid within the storage tank. Complete details of the apparatus can be found in Appendix IV.

Approximately 100 gallons of PCM slurry was placed into the storage tank for testing purposes. Initially, a 30 percent mixture was used to demonstrate the concept. The first step in the process was to cool the PCM slurry, causing the PCM to solidify. The next step was to then heat the slurry to demonstrate the heat storage capabilities.

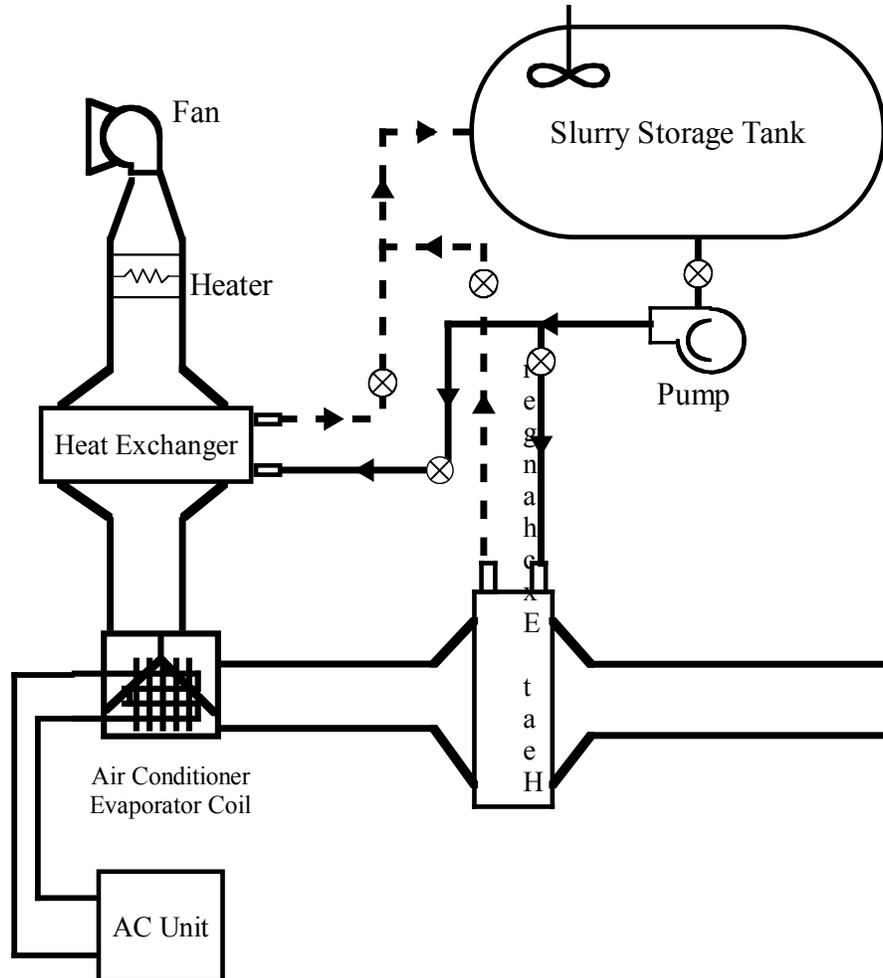


Figure 10 - Schematic of bench-scale apparatus.

The bench-scale tests were very useful and successfully demonstrated the ability of the system to store over 30 percent of the peak heat load. Results will be shown in the Project Outcomes Section that document system performance.

While the system was being procured and built, attention was given to a test plan. The overall goal of the project was to demonstrate the concept and to determine if it was feasible to absorb a portion of the total air-conditioning load. With this in mind, a minimum number of tests were planned. The tests included

- **Tank filling and flow rate measurements.** These tests were to assist in assessing the flow rates associated with the pump(s) selected for the system. In addition, these tests

were to insure that the emulsion was completely mixed prior to starting the next series of tests.

- **Evaluation of pump and heat exchanger performance.** As indicated above, the interaction of these two components can greatly impact performance. The purpose of these tests was to evaluate the rate at which the PCM slurry was heated and cooled. For example, the uncertainty of the PCM slurry heat transfer coefficients made it difficult to accurately predict the required fluid flow rate. For example, if the rate of cooling or heating was inadequate, changes to the pumping configuration could be made.
- **Airflow measurements.** Tests were also to be conducted to measure the airflow rates for the given fan, ductwork, and heat exchanger configuration. Changes could then be made to increase or decrease the flow as necessary.
- **Bench-scale System Evaluation.** The system would be operated in a typical mode of operation to measure overall system performance. The collected data would be analyzed and changes made to the system as necessary.

These four simple sets of tests were adequate to improve the experimental apparatus and to demonstrate the operation of the system. Test results are presented in the Project Outcome Section.

Objective 4: Document research and assess system potential.

Task 4-1: Prepare final report.

This last objective was met by the quarterly reports and the completion of this final report.

Project Outcome

The project was successful in meeting each of the three major objectives (see Project Approach Section for detailed discussion of Objectives). These objectives can loosely be grouped into two categories: developing a PCM slurry with greater than 30 percent PCM and designing/testing a bench-scale system to demonstrate system performance.

Test Results Supporting the Development of a Slurry with Greater than 30 Percent PCM

The compositions are based on the amount of material mixed to form the composition. For example, a 30 percent hexadecane, 70 percent water, and 1 percent emulsifier composition would start from 3 liters of hexadecane, 7 liters of water, and 0.03 liters (30 ml) of emulsifier. The percentage of emulsifier is based on the volume of PCM placed in solution. In the present example, this would be 1 percent of the 3 liters of PCM, hence the 0.03 liters.

A concern was that the materials be non-toxic. The final composition consisted of water, hexadecane, and Triton X-100 for the emulsifier. The individual material data safety sheets for these materials can be found in Appendix II. Both of the materials can be considered non-toxic and safe environmentally. In addition, the Triton X-100 is used in very low concentrations in the

PCM slurry. For the example listed above, the concentration of Triton X-100 would be 0.03 liters out of a total of 10 liters, or 0.3 percent.

Summary of MSDS issues for hexadecane:

- Health Rating: 2 – Moderate
- Flammability Rating: 1 – Slight
- Reactivity Rating: 1 – Slight
- Contact Rating: 1 – Slight
- Treatment issues include
 - **Skin Contact:**
 - Remove any contaminated clothing. Wash skin with soap or mild detergent and water for at least 15 minutes. Wash clothes before reuse. Get medical attention if irritation develops or persists.
 - **Eye Contact:**
 - Immediately flush eyes with plenty of water for at least 15 minutes, lifting lower and upper eyelids occasionally. Get medical attention immediately.

The first step in meeting Objective 1 was to prepare a number of different PCM slurries and evaluate them for the proposed system. Table 4 shows all of the different compositions mixed in 500 ml batches for preliminary evaluation. Each of these samples was examined under a microscope to examine particle size. Periodically, the samples were shaken and the particles were again examined under the microscope. Figure 11 shows a few of the typical particle pictures taken by microscope.

The particles in Figure 11 have different compositions and “ages.” The lower center photo represents a sample taken after being pumped in the small slurry test apparatus. The pumping clearly breaks up the larger particles, generating smaller particles.

The particles will become larger as a result of the mechanisms discussed earlier in this report (see Project Objectives Section) over time because the emulsion is inherently unstable. For the emulsion to be “acceptable” for the current application, it should remain as an emulsion for a minimum of 6 months – the maximum amount of time between system operations.

All of the emulsions with less than 50 percent PCM remained in a dispersed state for periods greater than 6 months. Each container was stored at room temperature (PCM remained liquid) and tightly sealed to prevent evaporation of the water or emulsifier. Some of the higher concentration slurries (greater than 50 percent PCM) had started to separate into a liquid layer, an emulsion layer, and a water layer (see Figure 12). Even these samples returned to a dispersed state once agitated.

Figure 13 shows evidence the proposed slurries are stable and will remain as an emulsion. The three particle distributions show Sample D over a period of 7 months. The first chart (12-20-01) shows a particle distribution with most of particles under 15 microns. The second chart (7-19-02) shows a particle distribution with much larger particles. The larger particle distribution indicates that the particles had coalesced and become larger. But, after shaking the mixture by

hand on 7-30-02, the particles were again much smaller, indicating that a small amount of mechanical agitation can disperse the oil into smaller particles in the emulsion.

Table 4 - PCM slurry compositions made for evaluation purposes (500 ml sample size). All of these samples were made with Triton X-100.

Label	Percent PCM	Percent Water	Percent Emulsifier
I	40	60	2
A-55	40	60	1
C	30	70	6
E	30	70	2
D	20	80	2
B	20	80	4
G	10	90	6
F	10	90	4
A	10	90	2
Higher Concentration Mixtures			
H	50	50	2
Y	50	50	1
O	65	35	1.54
L	70	30	2.85
J	70	30	0.7
K	70	30	1.4
JJ	70	30	0.7
N	80	20	2.5
M	80	20	1.25

Results presented so far demonstrate that

- A PCM was selected with desirable heat storage capabilities and a melting point acceptable for the proposed application.
- Slurries with PCM concentrations greater than 30 percent can be formulated.
- Slurries with PCM concentrations of 40 percent were stable for over 7 months while stored at ambient conditions. Other concentrations were found to be stable for time periods of 6-8 months. It is anticipated that these samples will remain stable for longer periods of time, but the contract reached its conclusion and closed the stability testing as reported here.
- Particle sizes did increase while the particles were stored, but minor agitation of the sample resulted in the breakup of the larger particles into smaller particles.

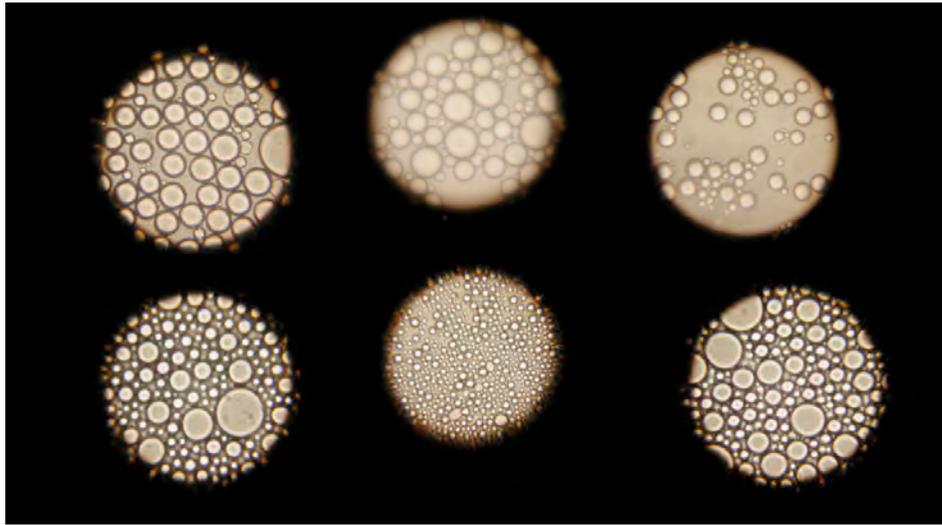


Figure 11 - Representative particle pictures taken by microscope at 40X magnification. Upper left – H (50% PCM, 2% Triton X-100); Top center – B (20 % PCM, 4% Triton X-100); Upper right – E (30 % PCM, 2% Triton X-100); Lower left - M(80 % PCM, 1.25% Triton X-100); Lower center - I (pumped) (40 % PCM, 2% Triton X-100); Lower right – N (80 % PCM, 2.5% Triton X-100).

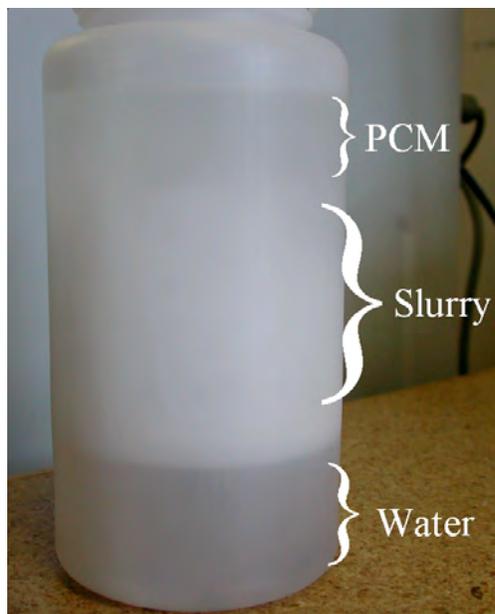


Figure 12 - Photo of sample JJ (70% PCM, 0.7% Triton X-100) after being stored over 6 months without any agitation. Upper layer represents particles that have coalesced, breaking down from an emulsion.

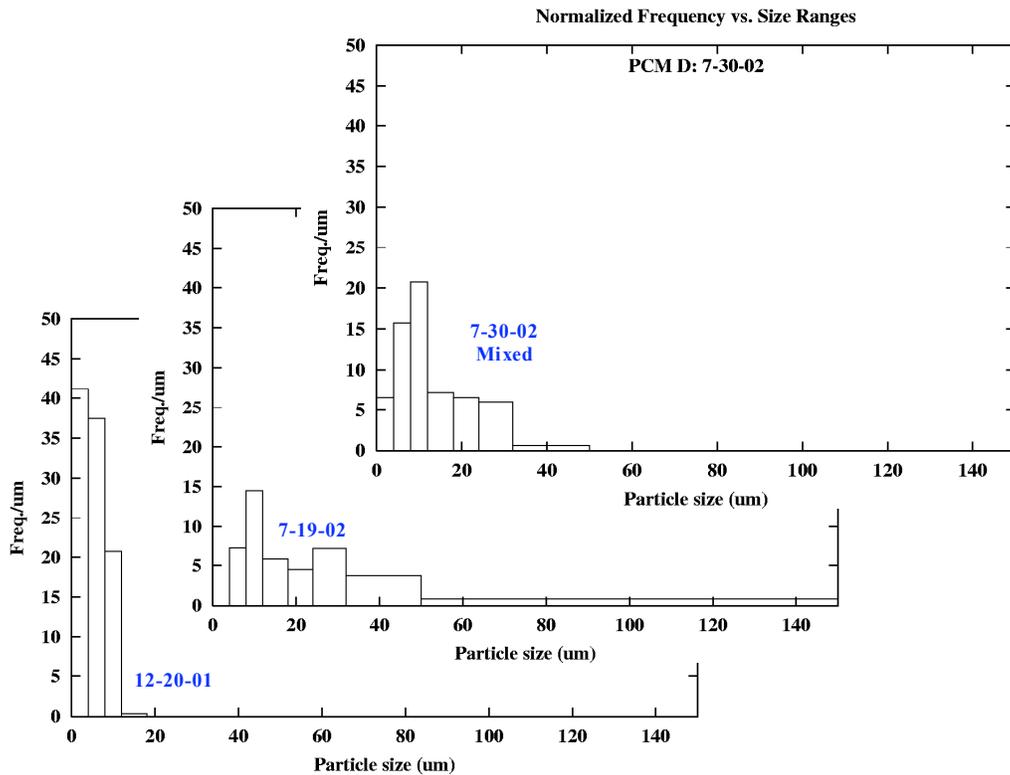


Figure 13 - Comparison of particle size distributions. 12-20-01 results were after the sample was vigorously shaken; 7-19-02 results are after a period of inactivity (no stirring or shaking) and the 7-30-02 results are after mild shaking. Representative results are for Sample D (20% PCM and 2 percent Triton X-100 emulsifier).

The last portion of the work completed to meet Objective 1 was to perform flow testing on a small sampling of the potential PCM slurry mixtures. There are two competing factors in selecting a slurry composition for pumping and heat storage: energy storage capabilities and increasing viscosity as PCM concentration increases. The higher PCM concentrations lead to greater the heat storage capabilities. This has to be balanced with increased pumping costs as the PCM concentration increases (higher amount of solids when the PCM solidifies as small particles).

Slurries with PCM concentrations greater than 50 percent are most likely to create pumping problems. Consider a bed of packed spheres surrounded by a fluid. If the spheres are spherical in shape and packed together tightly, the “bed” will consist of roughly 65 percent spheres (solids) and 35 percent fluid. Clearly, to be able to pump a solution like this there would be the need for some amount of fluid greater than the amount contained in a packed bed.

The PCM hexadecane will increase in volume by 12-13 percent as it changes from a liquid to a solid. If the slurry contained 50 percent PCM by volume as a liquid, it will contain even more PCM as a volume percentage when the PCM is solidified. For a 50 percent liquid mixture that has undergone solidification, approximately 56 percent of the cooled mixture is now PCM.

Effectively this leaves 44 percent water. If a packed bed of spheres contains 35 percent water, it is doubtful that a composition with much less than 40-45 percent water could be easily pumped.

Based on this logic, PCM slurry compositions ranging from 30 to 40 percent liquid PCM by volume were tested in the small flow apparatus. Figure 14 shows a typical result of cooling and then heating a 35 percent PCM slurry mixture. More results for 30 to 40 percent mixtures and a detailed description of the apparatus can be found in Appendix IV.

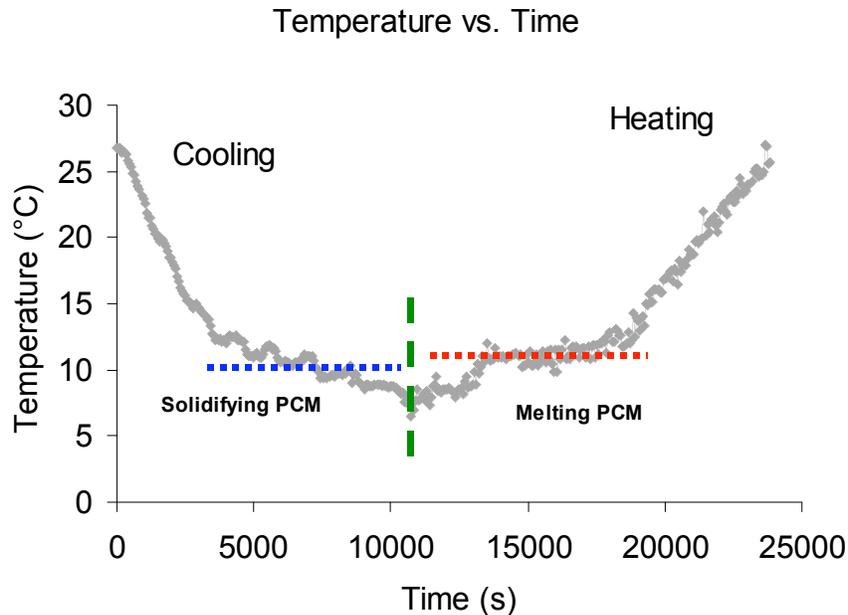


Figure 14 – Average bulk PCM slurry temperature for the testing of a 35% hexadecane and 1 % Triton X-100 slurry mixture.

The results from the small test apparatus were successful and provided insight into the use of a PCM slurry. The melting point of hexadecane is 18°C and as can be seen by the cooling curve of Figure 14, the solidification actually occurred between 9 – 12°C. This indicates that small hexadecane particles do exhibit some supercooling during solidification. The same characteristics are noted during the heating portion of the curve as well. The effect of adding the PCM is clearly shown by these “flat” spots on the temperature vs. time curve.

A mixer was used in the storage tank. It was run during the experiments to insure the fluid was well mixed. The fluid could be best described as “runny ice cream” when the PCM was solidified. Figure 15 shows the fluid coating a wooden spoon used to examine the fluid during cooling or heating.



Figure 15 - Thickened slurry mixture shown on spoon for flow test apparatus.

Demonstration of a PCM Slurry System to Absorb 30 Percent of the Peak Heat Load – Bench Scale Testing Results

The bench-scale apparatus was designed to demonstrate the ability of the system to absorb 30 percent of the peak heat load. A system schematic is shown in Figure 10. A two heat exchanger design was used for simplicity in the building of the bench-scale system. One heat exchanger was used for cooling the PCM slurry, while the other was used during the heat absorption portion of the cycle. A schematic with component photos is shown in Figure 16. The tests used to evaluate and improve system performance are not reported here. The most important bench-scale system tests are reported and discussed in detail.

The system was run continuously, not cycled on and off. Running continuously shortened the time necessary for each experiment. Cycling the system or running continuously does not impact the validity of the test results. In a residential setting, the AC system cycles on and off as the thermostat senses a temperature rise. The inlet air temperatures used for the tests conducted here are typical of what would be found for a residential system (combination of return air and makeup air). The air temperature leaving the AC unit would be typical for a PCM slurry system. This air temperature is cooler than normal because of the cooling load provided by the PCM slurry system. Cooler air temperatures entering the room result in less operating time for the AC system, hence a savings in operating costs.

The system was designed for simplicity and to rely on off-the-shelf components as much as possible. Brief descriptions of the system and components are listed below.

- Fan: Squirrel cage fan, electric motor, pulley sizes easily varied to obtain the desired airflow rates.
- Simple heating coil was used to heat the air up to typical inlet air temperatures for AC systems.

- Both heat exchangers were identical. These units were obtained from Super Radiator Coils (10" x 30") and consisted of copper tubes and aluminum fins (see Appendix V for complete details).
- Three different pump arrangements were tested. The pump shown in Figure 16 is a Hypro Model 9700B Aqua-Tiger centrifugal pump. The pump operated on 12 volts and required low power consumption. One of these pumps was eventually found to be adequate for the heating and cooling cycles. The total power requirement for this pump while pumping the slurry was 50 Watts.
- The storage tank was an insulated fiberglass tank. The tank held approximately 125 gallons of fluid. Approximately 100 gallons of PCM slurry was used for the tests.
- Typical plastic and metal valves, plastic tubing, and hose clamps were used to connect the necessary piping.

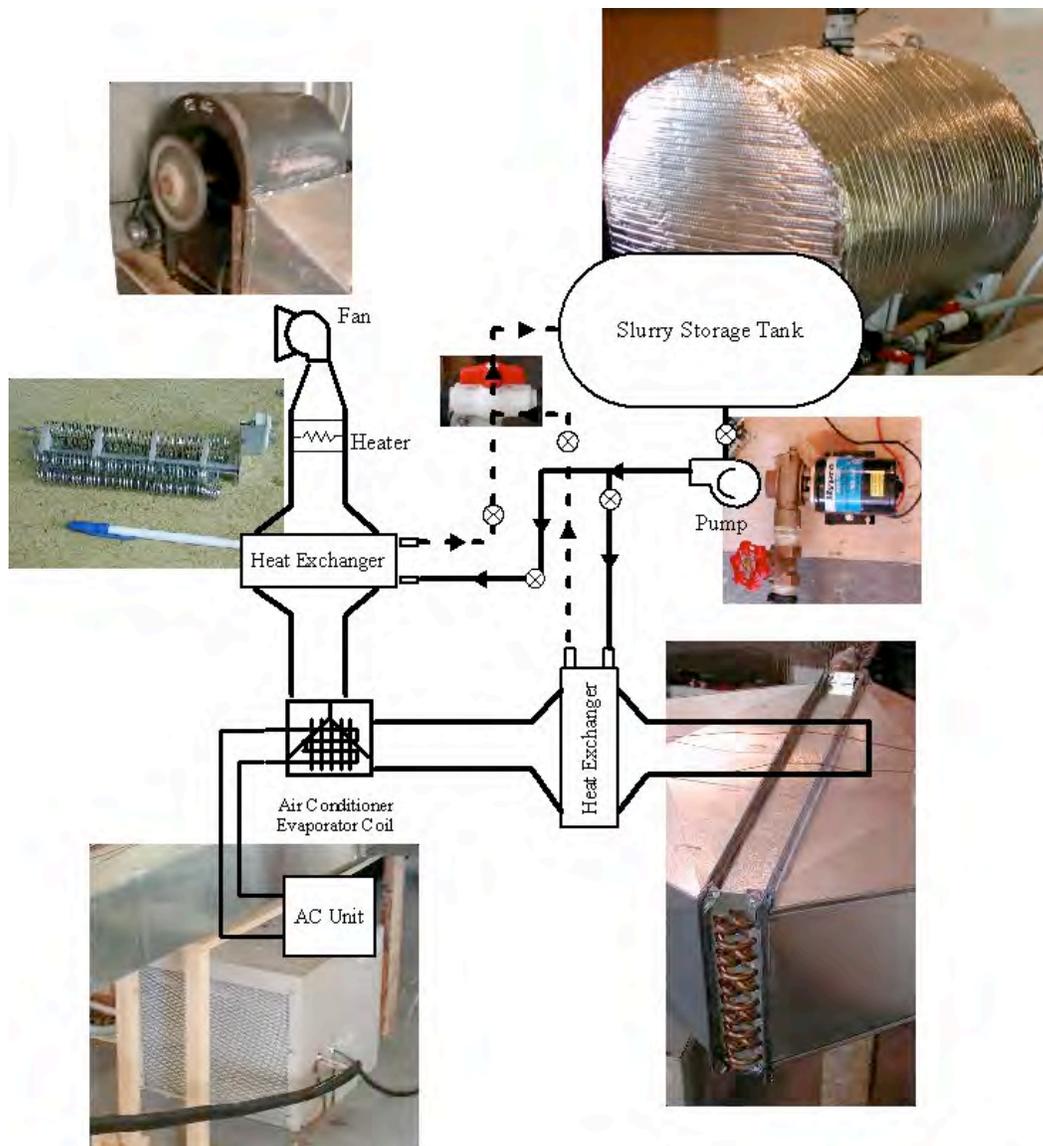


Figure 16 - Components and system schematic for bench-scale system.

It is important to note that all of the system components are readily available and can be purchased in quantity to reduce the overall system cost. Complete system details can be found in Appendix V.

A number of preliminary tests were conducted to test the operation of the system. The data for these tests was also recorded, but used primarily for troubleshooting and refining the proposed operating scheme. In addition, the data was analyzed for consistency (mass and energy conservation) to insure proper analysis of the data.

The findings from the preliminary tests included:

- The PCM slurry experienced supercooling prior to solidification.
- The time to cool the slurry was longer than desirable because the rate of cooling decreased as a result of the supercooling. Rather than having the cooling take place near 17-19°C, the solidification took place near 7-9°C. This resulted in a smaller temperature difference between the PCM slurry and the cold air stream of the AC unit, hence, slower rates of cooling.
- Some frost formation did occur on the A-coil (cooling coil) of the AC unit. The tests were conducted in a humid environment. The supercooling required a lower operating temperature than anticipated, which resulted in a lower coil temperature to cool the air. The air temperatures leaving the AC coil approached 1-2°C, which resulted in condensate freezing on the coils.
- Both problems (slow cooling and frost formation) would benefit by selecting a PCM with a higher melting point. The higher melting point and the supercooling phenomenon would result in a larger temperature difference between the cold air stream and the PCM undergoing solidification. This would increase the cooling rate and decrease the chances of frost formation.
- Using a closed-loop system for cooling can also decrease problems with moisture in the air stream during cooling. Rather than allowing fresh air into the system, dampers in the ductwork could be used to cycle air through the AC unit coil (cooling the air), through the PCM slurry heat exchanger (heating the air – cooling the PCM slurry), and then back to the air-handling unit. After a few passes through the system, any moisture in the air would have condensed out, leaving dry air and decreased the risk of frost formation.
- The energy necessary to run the pump decreased the rate of cooling because this energy effectively enters the flow stream and “heats” the PCM slurry. Initially, a standard low cost pump was used to pump the slurry. The work expended by the pump amounted to roughly ½ the cooling rate, which forced long test times for solidifying the PCM slurry. Decreasing the power requirements for the pumps was a priority from the start of the project. A smaller 12-volt pump replaced the 110-volt pump. With some changes to the piping, the smaller pump was more than adequate for cooling and heating slurry operations. The smaller single pump used less power and gave better overall operating efficiencies.

Typical results are shown in Figures 17 through 19. Figure 17 shows the cooling portion of the cycle. The cooling of the PCM slurry occurred over a two-day period. This cooling test was run over an extended period of time to insure that all of the PCM would be solidified. The two

“bumps” in the data are at the end of each cooling cycle. The increase in temperature at these points is the result of heat addition through the insulation of the tank, plus the result of the supercooling itself. When water is cooled below its freezing point (supercooling) and then starts to solidify, one sees a similar temperature increase as the crystallization starts. A similar phenomenon occurs here as well.

The long run times for the cooling of the PCM slurry were a combination of frost formation on the coils and the supercooling of the PCM slurry. Both of these problems would be eliminated by a PCM slurry that solidified at a higher temperature. The melting point of the PCM slurry could be increased by using a melting point PCM (longer hydrocarbon chain) or by the addition of additives to the PCM slurry to enhance the crystallization/solidification process. Higher melting point PCMs do exist and obtaining one presents no more problems than the procurement of hexadecane. Either of these modifications would lead to acceptable runs times for the cooling cycle.

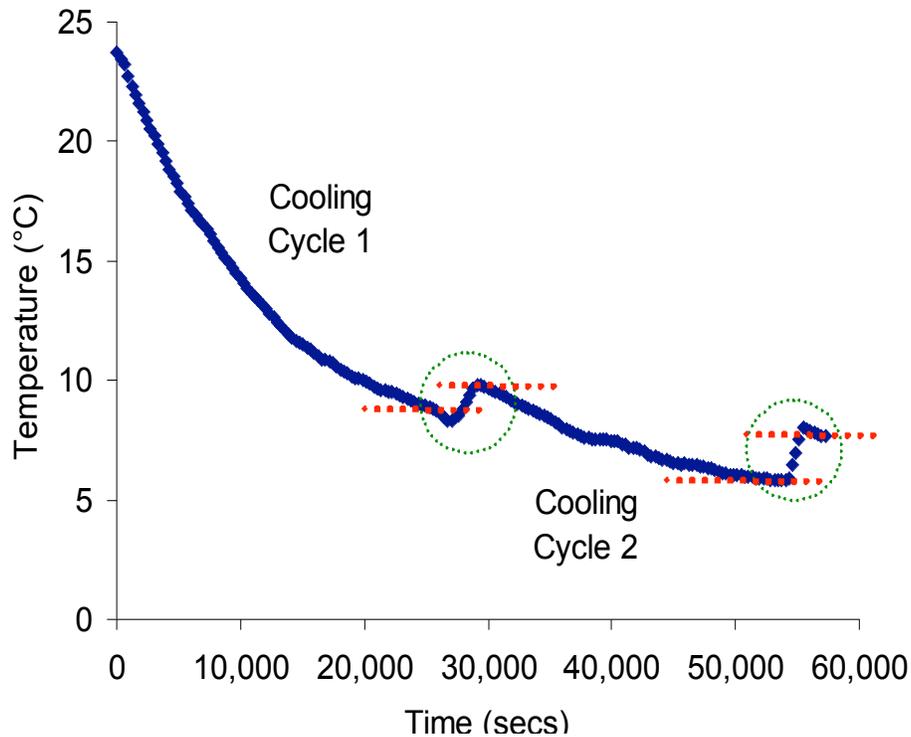


Figure 17 – PCM slurry temperature during cool down. Fluid composition: 30 percent hexadecane, 2 percent Triton X100. The only mixing that occurred in the tank was the result of inflow and outflow.

The small-scale tests were conducted with mixing in the storage tank. The PCM slurry was the consistency of “runny ice cream” when thoroughly mixed. Only minimal mixing was used in the bench-scale storage tank to decrease the amount of energy necessary to run the system. The consistency of the PCM slurry was distinctly different for the bench scale tests. Figure 18 shows a photo of the PCM slurry at a stage when much of the material was solidified.

A portion of the material was thickened and particulate in nature. The particles floated to the top of the tank and remained there. The return flow to the tank was near the bottom of the tank, while the outlet flow (inlet to the pump) was approximately 1/2 to 2/3 of the distance from the bottom of the tank. This allowed some recirculation of the particulate (solidified) material. No plugging or clogging of the heat exchanger pipes occurred (3/8 inch diameter copper lines).

The lack of vigorous mixing in the tank made it difficult to detect a “flat-spot” during the cooling of the PCM slurry (see Figure 14 for the small scale testing). The formation of the upper, solidified particulate layer indicates the material did solidify, but no “flat-spot” existed because the cooling occurred in the heat exchanger, particles probably formed there, then were separated from the fluid when they returned from the tank, not giving a good bulk fluid temperature.



Figure 18 - Consistency of solidified PCM slurry as it undergoes solidification. Photo shows a thickened, particulate type material that floats to the top of the storage tank. Minimal mixing was present in the storage tank. Fluid composition: 30 percent hexadecane, 1 percent Triton X100. Remainder of the fluid (below particulate surface layer) was slightly more viscous than water.

Figure 19 gives the first indication of system performance during heat addition. Two curves are shown: one for the slurry temperature, and the other for percent of total heat absorbed. The test was run for over 3 hours. The airflow rate was approximately 567 CFM (400 CFM per ton of cooling – 1.5 ton AC unit) and the flow rate of the PCM slurry was approximately 15 gallons per minute.

The percent of the *total energy absorbed* is calculated as shown below.

$$\% \text{ Absorbed} = \frac{\Delta T_{pcm}}{\Delta T_{pcm} + \Delta T_{AC}}$$

The temperature changes referred to in this equation represent the amount of cooling on the air as it passes through the heat exchangers. ΔT_{pcm} represents the amount of cooling that occurs as the air passes through the heat exchanger with the cold PCM slurry being pumped through it. ΔT_{AC} represents the cooling that occurs as the air passes through the cooling coil of the air conditioner. Overall, the ratio represents the percentage of total heat load (cooling) that is absorbed by the PCM slurry.

This is referred to as the *total energy absorbed* because the amount of cooling by the PCM slurry is the fraction of the cooling load from both the PCM and the air-conditioning unit. Recall that in the discussion of the design criteria, 30 percent of the *air-conditioning load* was to be absorbed. The *total* value is reported here to show that the PCM slurry system was able to absorb a significant portion of the total air-conditioning load.

The percent absorption (see Figure 19) ranges from near 40 to 20 percent over the duration of the test. The average heat absorption for this test was 28 percent. A more constant heat absorption could be obtained two ways: through the use of a variable speed pump or through more realistic cycling of the system. A variable speed pump could initially decrease the fluid flow rate (decreasing the heat transfer rate) and towards the end of the cycle the flow rate would be increased (increase the heat transfer rate). Cycling the system and the airflow rate would effectively do the same thing. Initially, the temperature of the air entering the rooms (leaving the AC system) is lower, which would require less airflow into the rooms to obtain the same comfort level. Later in the process, more typical airflow rates would be necessary to obtain 30 percent heat removal for the PCM slurry.

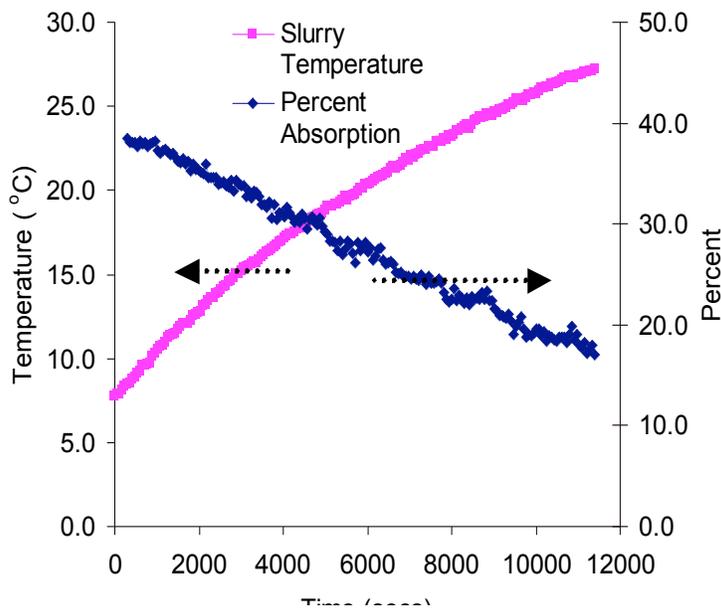


Figure 19 – PCM slurry temperature and percent heat absorbed during heat addition. Fluid composition: 30 percent hexadecane, 2 percent Triton X100.

Figure 20 answers the question whether the bench-scale system was able to absorb a minimum of 30 percent of the air-conditioning load. If the air-conditioner was to run full-time, the total cooling capabilities of the AC system used in the experiments would be approximately 1.5 tons. As Figure 20 shows, the AC unit supplied between 1.4 and 1.8 tons of cooling.

In order for the bench-scale system to meet the 30 percent requirement of a 1.5-ton AC unit, approximately 0.45 tons of cooling must be supplied by the PCM slurry system. The average cooling capacity of the PCM slurry system over the duration of this test was 0.6 tons, well in excess of the minimum required value of 0.45 tons. The cooling load of the PCM slurry averaged 40 percent of the air-conditioning unit cooling load for the duration of the test.

The data presented in Figure 20 is based on the temperature changes of the air stream. The AC cooling load is based on the temperature drop across the cooling coils. The airflow rate and operating conditions of the AC unit determine the temperature drop across the cooling coils. The temperature drop across the cooling coils was typical for residential AC units. The temperature drop associated with the PCM slurry system varied as the PCM slurry temperature increased.

The cooling loads were 1.6 and 0.6 tons for the AC system and PCM slurry systems respectively (Figure 20). If only the AC unit was to operate, the total cooling load would be approximately 1.6 tons. The combination of the two units provides an average cooling load of 2.2 tons. For a typical residential application, the ability to provide a higher cooling load would lead to shorter cycle times for a given heat load. Shorter cycle times lead to less electrical demand, and hence the electrical cost savings during peak demand. Another way to look at the operating efficiencies is to consider just the operation of the AC unit. If the AC unit was to provide the same amount of cooling as the AC and PCM systems together, the AC unit would have to operate for a longer period of time. A longer operating time results in greater electrical demand.

These tests results demonstrate the ability of the system to decrease operating times, and hence the ability to shift peak demand efficiently (see Figure 21 for documentation of the efficiency).

The last operating issue is the energy required while the system is absorbing energy. The system needs to absorb as much energy as possible (28% of *total* or 40% of *AC unit* for test shown) and not require a lot of additional energy to operate. For AC systems, the typical efficiency parameter is the Seasonal Energy Efficiency Rating (SEER) value. This can be thought of as a seasonal efficiency parameter. There is also the EER value, which is more of an operational parameter. The EER is defined as

$$EER = \frac{\text{Cooling Load (BTU / hr)}}{\text{Energy Input (W)}}$$

The Department of Energy (DOE) has recently increased the required minimum SEER value to 12, from 10.

The calculated EER value for the *absorption of energy* is shown in Figure 21. The EER value ranges from over 200 to slightly below 100. The average heat absorption EER value for the test shown is 154, over 12 times more efficient than required for new AC units. The only significant

energy source for operating the system is the small 12-volt pump used for pumping the slurry. The EER decreases as the amount of energy absorbed by the PCM slurry decreases.

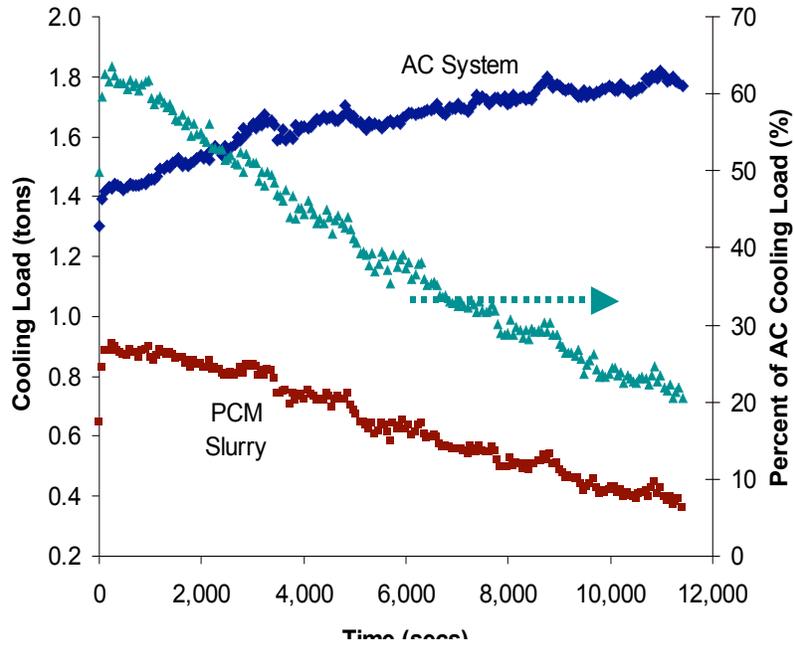


Figure 20 – Cooling loads for the AC unit and the PCM slurry unit. PCM slurry unit averaged 0.6 tons of cooling over the duration of this test. Cooling load of PCM slurry system averaged 40 percent of AC unit. Fluid composition: 30 percent hexadecane, 2 percent Triton X100.

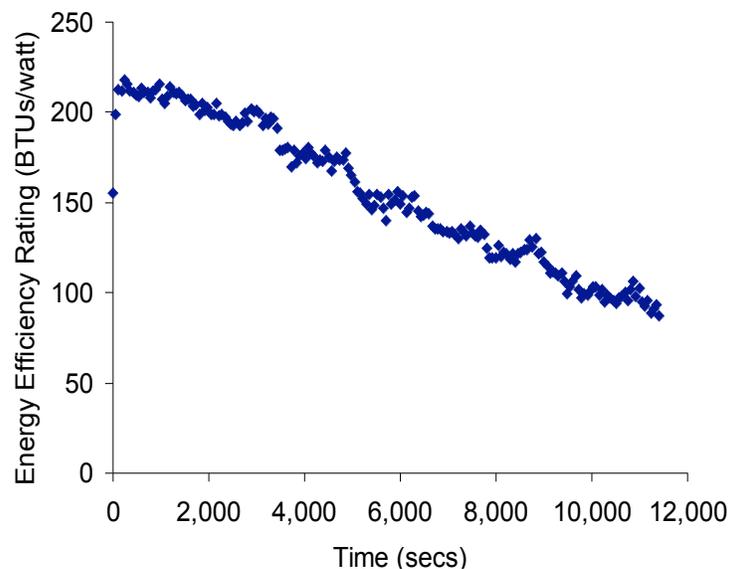


Figure 21 - Energy Efficiency Rating of PCM slurry heat absorption system during simulated peak heat load conditions. Average EER = 154.

Other tests were conducted and discussion on these tests can be found in Appendix V. A series of tests were conducted with a PCM slurry composition of 30 percent hexadecane and 1 percent Triton X100. In general, the same trends were found in those test results as shown above. In those tests, two pumps were used, which gave a slightly higher flow rate. The increased flow rate resulted in increased heat transfer during heating (average of 32 percent of total heat absorption) and a lower average EER (86) because of the increased pumping costs.

In general, the bench scale tests were successful. Over 30 percent of the total heat load can be absorbed by the PCM slurry and stored for later cooling. The slurry did not clog the pipes. The system was successfully built from off-the-shelf type components.

Peak demand is reduced and the cooling load that is absorbed during the day must be dealt with off peak. The total energy cost of this or any peak shifting system is typically more than just operating the system during the time of peak demand. The advantages are accrued because fewer inefficient peaking plants are needed, existing plants operate at a more constant rate, and the power supply system is more reliable for the consumer and the public.

Ground Loop Operating Issues

The second potential mode of operation for the PCM slurry system was to use a ground loop to cool and solidify the PCM slurry. This proposed method of operation would not only decrease peak demand, but it would also decrease the total energy demand for cooling. The ground loop would take the place of the AC system. The ground acts as a heat sink, absorbing the energy stored by the PCM during the day.

Heat rejection to the earth is used for ground source heat pumps (GSHP). Open or closed loops are used for heat sources or sinks. Ground or lake water is often used for the open loop systems. The closed loop systems use the earth as a heat sink or source. There are three commonly used types of ground loops that can be used for GSHP: horizontal, vertical, or the slinky type. The slinky type system typically has a lower cost, but slightly lower operating efficiencies.

The slinky type of ground loop would be an effective means of heat rejection for the PCM slurry system because it is low cost and because the total amount of heat rejection is reasonably low. Heat rejection is low because only 30 percent of the heat load is absorbed for 3-4 hours of the day. In addition, the heat rejection can occur over a several hour period during off-peak times, leading to a low heat rejection rate. Lower heat rejection rates would require less heat transfer surface area, hence lower coil lengths.

A typical slinky ground loop requires on the order of 700-1,000 feet of pipe in an 80-foot long trench per ton of cooling capacity (International Ground Source Heat Pump Association Guidelines). For the typical residential 3-ton system, the PCM slurry system would absorb 1 ton of cooling load for a 4-hour period of time (1/3 of peak load shifted). Assuming a 8-12 hour total operating time during the day implies that roughly 24-36 ton-hours of heat rejection would occur. The PCM slurry slinky system would require roughly 4 ton-hours. This implies that only

1/6 to 1/9 of the typical heat load rejection for a GSHP would be necessary to shift a third of the peak thermal load.

A 3-ton GSHP slinky system would roughly require 3 trenches 80 feet long containing 1,000 feet of pipe per trench. Simple scaling would imply that one trench 40 feet long with 500 feet of pipe would be needed. Granted these estimates are only rough approximations and do not take into account all of the thermodynamic irreversibilities, but it is safe to assume that the total length of slinky would be significantly less than the typical GSHP. Detailed engineering calculations for the melting point of the PCM slurry would be necessary to size the slinky ground loop.

The operation of this system requires a melting point of the PCM that is between the temperature of the earth and the lowest air temperature entering the AC system. The selection of hexadecane was intended to fall between these two operating temperatures. But, the initial testing of the PCM slurry indicated that 7-9°C of supercooling occurred during solidification of the PCM slurry. This degree of supercooling leads to solidification temperatures below the temperature of the earth, which effectively prevents the PCM from solidifying in a ground loop.

This does not imply that the ground loop would not be effective in the proposed application. What would be required is the development of a higher melting point PCM slurry. As previously mentioned, the current slurry could be modified by the use of a longer hydrocarbon chain PCM. A longer hydrocarbon chain gives a higher the melting point. Increasing the melting point and the effect of supercooling would lead to the desired solidification point. The same benefit could be accrued by evaluating additives to the PCM slurry that enhance the start of the crystallization process.

Conclusions

All of the project's objectives have been successfully completed. The objectives were to

1. Develop PCM slurry mixture with 30 percent or greater PCM volume fraction.
2. Design PCM slurry system to absorb 30 percent or greater of the peak A/C load.
3. Demonstrate concept by building and testing bench-scale system.
4. Document research and assess system potential.

A number of PCM slurry mixtures with greater than 30 percent PCM slurry were developed and analyzed. A limited number of tests were conducted on a small flow apparatus to assess their potential to be pumped and absorb heat. Supercooling was exhibited during the cooling of the PCM slurry. Choosing a PCM with a higher melting point could help alleviate any issues associated with supercooling. Compositions in the 30-40 percent PCM range were found to be stable for the duration of the project. The particles did coalesce in the mixtures, but upon being agitated again the particles broke apart and decreased in size.

Once it was known that an acceptable PCM slurry could be formulated, work was undertaken to analyze the design of a PCM slurry system. The modeling successfully modeled the design of a bench-scale apparatus. Useful information was obtained as a result of the modeling.

A number of tests were conducted to evaluate the operation of the bench-scale apparatus. Performance from the bench-scale system demonstrated the ability of the system to efficiently (average EER of 154) absorb over 30 percent of the air-conditioning load (40 percent absorption of the air-conditioner absorption). The pump type and configuration can greatly impact system performance. A “slushy” region did form on the top of the fluid in the tank during cooling. This layer was pliable and easily mixed back into the rest of the liquid in the tank.

Recommendations

Future work should include

- Selection of a PCM that melts at a higher temperature or one that does not exhibit supercooling during solidification in a slurry mixture.
- Evaluation of the impact of changing to a different emulsifier might have on the “slushy” layer formation at the top of the tank. The Triton X100 was nearing its solidification point because of the supercooling that was exhibited by the hexadecane.
- Search for a lower cost PCM. If this system is to successfully enter the marketplace, a lower cost PCM material will have to be found.
- Refining the design model to aid in developing a full-scale prototype that could be tested in a home environment. The prototype would have better controls and be able to vary the flow rate of the PCM slurry and the system would cycle on and off rather than running continuously.

Public Benefits to California

A new technology has been demonstrated to work for residential air-conditioning loads. This technology could potentially alleviate the growing problem in California of peak demand exceeding generating capacity. When peak demand is high, brownouts and blackouts can occur.

The next stages to this project include refining the fluid, designing a full-scale prototype, and testing the system in a residential environment. The successful development of this technology would provide a means to shift peak residential demand to an off-peak time. At present, no cost-effective technology exists that can meet this need and still provide cooling to a home.

If this project was successfully developed and widely implemented, there is the potential that significant amounts of residential and commercial air conditioning electrical loads could be shifted to an off-peak time. This benefits the utility because they do not have to build as many peak generating facilities. In addition, the chances they would have to purchase electricity for peak demand would drop off, resulting in less purchases of expensive “peak” electricity. The operation of the PCM slurry system benefits the utilities because it decreases their reliance on energy produced somewhere else at a much greater cost.

Energy savings estimates have shown that a 10 percent market could save up to 460 MW alone in the state of California (see Figure 22). Costs savings to the homeowner in this chart do not reflect any incentives provided by the utility to adopt any peak shifting technology.

	AC Homes
Number of Homes In CA	5.00E+06
% of homes	10
Heat Load (Tons)	3
Heat Load Reduction	33.333333
SEER of AC	12
SEER of PCM	150
Savings per home (W)	920
Savings in electricity (kW-hr)	4.6
Days per yr - savings	243.0
Cost of Electricity (\$/kW-hr)	0.111
Homeowner Savings (\$)	124.1
Net Savings: State (W)	4.60E+08

Figure 22 - Estimated energy savings if system is fully integrated into the energy system market.

Development Stage Assessment

Table 5 shows the status of the PCM slurry to decrease peak air-conditioning loads. In general, each of the categories is still at the Research and Bench-Scale testing phase. A brief discussion will be presented for each category to justify the current status of the project.

Table 5 -Development Assessment Matrix

Activity \ Stages	Stages							
	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Development	5 Product Development	6 Demonstration	7 Market Transformation	8 Commercialization
Marketing	█		█					
Engineering/ Technical	█		█					
Legal/ Contractual	█		█					
Risk Assess/ Quality Plans	█		█					
Strategic	█		█					
Production Readiness	█		█					
Public Benefits / Cost	█		█					

Marketing

The target market is a utility company because they have a vested interest in decreasing peak demand. The system is designed for a residential user, but unless the utility was to get involved and give significant incentives, the product would not find wide acceptance. Utilities already have incentive programs for peak shifting and this system could take advantage of those programs that are already in place.

The residential customer has less incentive to purchase a system just to decrease their energy costs. In addition, unless they are given financial incentives by the utility, they will not be likely to install the unit. Environmentally conscious users may purchase the unit, but the product would then only be a niche market product.

The utility companies have not been contacted yet, but they will be contacted for their views and participation in developing and testing a full-scale prototype. At the full-scale testing stage, it is critical to have utility participation to facilitate their acceptance of the product.

The market for this product is just not California (most of the need is presently in California though), but the rest of the U.S. as well. The existing residential market would include those homes that presently have central air-conditioning. The number of central air-conditioning units across the U.S. is shown in Figure 23. The regions correspond to the U.S. census regions. Over 47 million residential air-conditioners presently exist in the U.S.

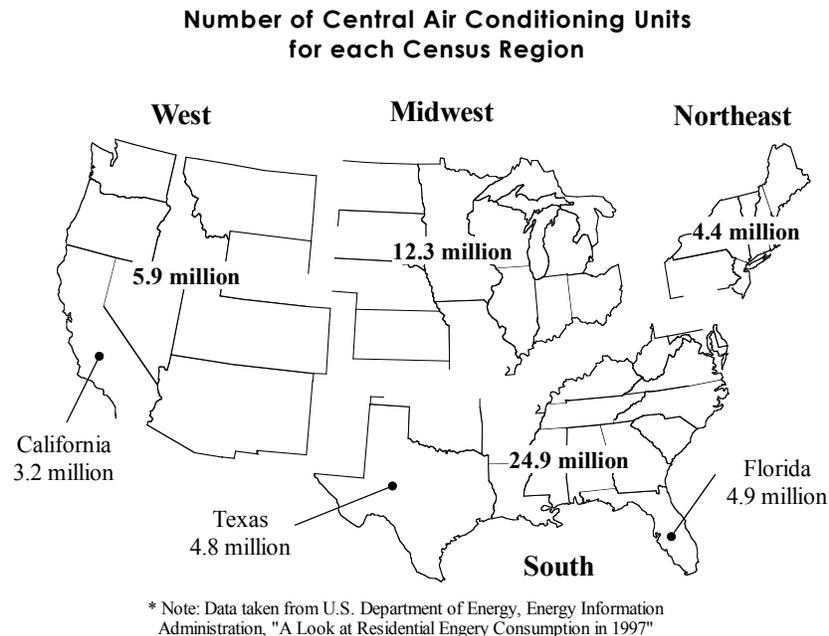


Figure 23 - Existing homes with central air-conditioning listed according to census region.

The second market is for new homes. The estimated number of new homes per year is approximately 1.3 million. The Air-Conditioning and Refrigeration Institute (ARI) reports that over 83 percent of the new homes install a central air-conditioning system.

The Air-Conditioning and Refrigeration Institute (ARI) reported that over 6.3 million residential size air-conditioning units were shipped in 1999. This total included 1.3 million heat pumps. Of all the new units, over half were for the retrofit market – replacing aging equipment. ARI also reported that 297,000 industrial size units were sold in 1999 as well. Residential units are considered to have 5 tons of cooling capability or less.

There seems to be some overlap on the data. ARI reports a net of 5 million non-heat pump units being sold yearly. But, the total number of new homes is only 1.3 million (part of which would be heat pump units). If slightly less than one half of the units sales are for new installs, that would imply roughly 3 million units are for new facilities. This is much greater than the estimated 1.3 million new homes a year. At present, it is not clear why the discrepancy exists. I will need to do more work evaluating this.

A preliminary look at a potential niche market is shown in Table 6. Table 6 shows some estimates for low market entry into the residential and commercial markets. The only market included for Existing homes, are the western and southern regions of the U.S. The table indicates a potential market that could reach 40,000 or more units a year.

Table 6 - Preliminary estimate of potential market size for the residential and commercial markets.

Market	Number of Homes (millions)	Market Entry (%)	Market Size
New Homes ^a	1.3	0.8	10,400
Existing Homes ^b			
California	3.2		
Remaining West ^c	0.9		
Texas	4.8	0.1 / year	29,000
Florida	4.9		
Remaining South	15.2		
	Number of Units	Market Entry (%)	Market Size
Commercial Market (new) ^d	297,000	0.5	1,485
Commercial Market (retrofit) ^e	3,000,000	0.05	1,500
Notes:			
a – Current growth rates indicate 1.3 million new homes per year. Air-Conditioning and Refrigeration Institute (ARI) indicates 83% of all new homes install air-conditioning. The assumed market entry rate of 0.8% takes this value into account. This value reflects an assumption of a 1 percent market entry.			
b – Number of homes with central air-conditioning (U.S. Department of Energy, Energy Information Administration, “A Look at Residential Energy Consumption in 1977”). Only homes in the hottest regions of the U.S. are presently being considered. A market for existing homes in the lower reaches of the Midwest also exists.			
c – Only 1/3 of the remaining homes were considered.			
d - Total number of <i>new</i> commercial units sold in 1999, based on Statistical Releases provided by ARI.			
e - Existing commercial units estimated at approximately 10 times the annual sale of new units.			

Engineering/Technical

The most progress has been completed in this stage. A bench-scale system has been developed and tested. The results show that the concept functions as desired, but there remain a few details to be resolved prior to full-scale testing. The items that remain are the search for a higher melting point, low-cost PCMs.

Preliminary plans and schedules have been developed to perform field-testing if additional funding can be obtained. The plan requires 18-24 months to refine the design, build several full-scale prototypes, and to spend some time searching for a cheaper, higher temperature melting point PCM.

Legal/Contractual

A provisional patent for the concept has been filed with the U.S. Patent and Trademark Office (Application No. 60/369,168 – Filed March 29, 2002). The firm of Dorsey and Whitney is representing Leading Technology Designs, Inc. in the process of obtaining a patent. The patent centers on the fluid itself, more than the design of the system.

The challenge in the patent process is to write the patent as broad as possible to prevent others from stealing the technology to develop other, similar products. The staff at Dorsey and Whitney are looking into ways to resolve this matter.

Risk Assess/Quality Plans

Work on a risk assessment of the system is in progress. At present, some of the environmental and safety concerns have been addressed through the selection of the working fluid. The fluids are reasonably benign, and pose little threat to the environment.

Strategic

At present, this project is not linked to any special PIER policy objectives. But, the project is considered to be of interest to the *Building End-use Efficiency Program* area under PIER.

Production Readiness

Efforts are underway to obtain additional funds through the Department of Energy, and I am in the process of developing a business plan to pursue Angel Investors. Once the additional funding has been obtained, work will commence in pursuing a partner for developing/manufacturing the product.

Public Benefits / Cost

Please see the section of this report entitled “Public Benefits to California” because more details are described there.

Appendix I - PCM Slurry Literature Review

The principal investigator and other researchers have successfully developed PCM slurries that are stable and effective in transferring energy. The previous basic and developmental research has laid the necessary groundwork to develop a slurry that uses soybean wax as the heat storage medium. The present proposal is the first attempt, known to the author, to use a soybean wax in a PCM slurry.

PCM slurry flows have been researched by a number of individuals. Relevant work includes the efforts of researchers D.P. Colvin, S.K. Roy, H. Inaba, Y.I. Cho, and K. Cho. These individuals have studied the use of PCM slurries for the cooling of electronic components or for energy systems. The work of the Principal Investigator is the most recent work completed on PCM slurries.

Some of the work relates to the use of a micro-encapsulated particle. A micro-encapsulated particle is where a paraffin material is encapsulated by an outer coating. This outer coating is very durable and insures that the particles do not agglomerate once placed in the water. The drawback of these materials is cost. The cost of the micro-encapsulated particles is on the order of tens of dollars per kilogram, while the cost of commercial grade paraffins are less than one dollar per kilogram in small quantities. Colvin (1989), Colvin, et al. (1997), Colvin, et al. (1992), Mulligan, et al. (1989) and Mulligan, et al. (1996) are works representative of microencapsulated research. These researchers found the particles to be durable and to significantly enhance heat transfer and energy storage. Charunyakorn, et al. (1990) and Charunyakorn, et al. (1991) also studied basic encapsulated slurry flows between parallel plates and in circular ducts.

The drawback of many load-shifting techniques is initial system cost. Installation of the systems by residential or commercial users is low because users are hesitant to make the additional capital outlay. In order to minimize cost, it is necessary to use a slurry that is not encapsulated. Therefore, slurries that are not encapsulated are the first choice for the soybean wax slurry system discussed here.

Choi and others at Drexel University studied the use of PCM slurries for district heating and cooling applications. Cho, et al. (1991a), Cho, et al. (1991b), Choi, et al. (1991), and Choi, et al. (1993) and document the research results for a PCM slurry using a hydrocarbon (paraffin/wax like). They also found enhanced heat transfer and increased heat storage capacities.

Recently, Cho and Choi (1999) in Korea studied the use of PCM slurries for the cooling of multi-chip modules (MCM), an electronics cooling application. These researchers used slurries with PCM concentrations ranging from 5 to 30 percent. Higher PCM concentrations lead to smaller storage tanks and greater heat storage capabilities. Research efforts here will focus on developing as high of soybean wax concentration as possible to maximize storage capacity.

Inaba, et al. (1994), Inaba and Morita (1995), Inaba and Morita (1996), Inaba and Sato (1996a), Inaba and Sato (1996b), Inaba and Sato (1997), and Inaba and Sato (1998) reported on research using a low melting point hydrocarbon with water. They were able to obtain slurries that were stable well over 1 year. This research was very fundamental and did lead to a patent, but no useful products have been developed as a result of this research, to the best of the Principal Investigator's knowledge.

The U.S., Japanese, and U.K. patent databases have also been searched to determine if anyone has proposed or developed a similar system. One Japanese patent was located (H. Inaba) for an air-conditioning application, but no information could be located on a commercial application of the proposed technology. Patents relating to microencapsulated slurries were located, but none of the systems were used for off-peak heat storage applications. The Principal Investigator has filed a provisional patent to protect intellectual property associated with the EISG research.

Summarizing the relevant PCM slurry literature finds that

- PCM slurries have been studied for a number of applications,
- Japanese researchers, Korean researchers, and the Principal Investigator have developed and tested stable PCM slurries that did not require encapsulation.
- Fluids have been developed with slurry concentrations between 5 and 40 percent (by volume),
- Heat transfer off surfaces is enhanced by 30 percent or more,
- Ability to store energy is greatly increased when compared to a fluid alone, and
- Little or no penalty in pumping energy occurs for slurry concentrations up to 30 percent.

Appendix I - References

Charunyakorn, P., Sengupta, S., and Roy, S.K., 1990, "Forced Convection Heat Transfer in Microencapsulated Phase Change Material Slurries: Flow Between Parallel Plates," ASME HTD-Vol. 129, *General Papers: Phase Change and Convective Heat Transfer*, ASME, AIAA/ASME Thermophysics and Heat Transfer Conference, Seattle, Washington, June 18-20, pp. 55-62.

Charunyakorn, P., Sengupta, S., and Roy, S.K., 1991, "Forced Convection Heat Transfer in Microencapsulated Phase Change Material Slurries: Flow in Circular Ducts," *International Journal of Heat and Mass Transfer*, vol. 34, no. 3, pp. 819-833.

Cho, K., and Choi, M., 1999, "Comparison of Thermal Characteristics of a Test MCM Using Water, PF-5060 and Paraffin Slurry," EEP-Vol. 26-2, *Advances in Electronic Packaging*, volume 2, pp.1499-1505.

Cho, Y.I., Choi, E., Lorsch, H.G., 1991a, "A Novel Concept for Heat Transfer Fluids used in District Cooling Systems," ASHRAE Transactions vol. 97, (IN-91-6-1), pt. 2, pp. 653-658.

Cho, Y.I., and Lorsch, H.G., 1991b, "Development of Advanced Low-Temperature Heat Transfer Fluids for District Heating and Cooling," Report No. DOE/CE/26592-2, prepared for the U.S. Department of Energy, Agreement No. DE-FG01-89CE26592.

Choi, E., Cho, Y.I., and Lorsch, H.G., 1991, "Effects of Emulsifier on Particle Size of a Phase Change Material in a Mixture with Water," *International Communications in Heat and Mass Transfer*, vol. 18, pp. 759-766.

Choi, E., Cho, Y.I., and Lorsch, H.G., 1993, "Forced Convection Heat Transfer with Phase-Change-Material Slurries: Turbulent Flow in a Circular Tube," *International Journal of Heat and Mass Transfer*, vol. 37, no. 2, pp. 207-215.

Colvin, D.P., 1989, "Microencapsulated Phase-Change Materials for Storage of Heat," NASA Tech Briefs, July, p. 72.

Colvin, D.P., Moody, D.B., Driscoll, J.C., von Windheim, J., Jagannadhan, K., and Mulligan, J.C., 1997, "Thermal Management of Electronic Systems Using Diamond Heat Spreaders and Microencapsulated PCM Coolants," Paper No. AIAA 97-3888, 1997 National Heat Transfer Conference, Baltimore, MD, August 10-12.

Colvin, D.P., Mulligan, J.C., and Bryant, Y.G., 1992, "Enhanced Heat Transport in Environmental Systems using Microencapsulated Phase Change Materials," SAE Technical Paper Series No. 911224, 22nd International Conference on Environmental Systems, Seattle, WA, July 13-16.

Inaba, H., Morita, S., and Nozu, S., 1994, "Fundamental Study of Cold-Heat Storage System of O/W-Type Emulsion Having Cold Latent-Heat-Dispersion Material. Part 1," *Heat Transfer – Japanese Research*, vol. 23, no. 3, pp. 292-312.

Inaba, H., and Morita, S., 1995, "Flow and Cold Heat-Storage Characteristics of Phase-Change Emulsion in a Coiled Double-Tube Heat Exchanger," *ASME Journal of Heat Transfer*, vol. 117, May, pp. 440-446.

Inaba, H., and Morita, S., 1996, "Cold Heat-Release Characteristics of Phase-Change Emulsion by Air-Emulsion Direct Contact Heat Exchange Method," *International Journal of Heat and Mass Transfer*, vol. 39, no. 9, pp. 1797-1803.

Gardner, D., 2002, "House that Soy Built Leaves Visions of Soybeans Dancing in Their Heads," *Agri Marketing*, March, vol. 40, i3, p.38.

Inaba, H., and Sato, K., 1996a, "A Measurement of Interfacial Tension Between Tetradecane and Ethylene Glycol Water Solution by Means of a Pendant Drop Method," *Fluid Phase Equilibria*, vol. 125, pp. 159-68.

Inaba, H., and Sato, K., 1996b, "Fundamental Study on Latent Cold Heat Storage by Means of Direct-Contact-Freezing Between Oil Droplets and Cold Water Solution," *ASME Journal of Heat Transfer*, vol. 118, August, pp. 799-802.

Inaba, H., and Sato, K., 1997, "Latent Cold Heat Energy Storage Characteristics by Means of Direct-Contact-Freezing Between Oil Droplets and Cold Water Solution," *International Journal of Heat and Mass Transfer*, vol. 40, no. 13, pp. 3189-3200.

Inaba, H., and Sato, K., 1998, "Fundamental Study of Latent Cold Heat Energy Storage by Means of Oil Droplets at Low Freezing Point (Numerical Calculation of Motion and Solidification Characteristics of Oil Droplets Ascending in a Cold Water Solution due to Buoyancy)," *JSME International Journal, Series B*, vol. 41, no. 3, pp. 641-49.

Kasza, K.E., and Chen, M.M., 1985, "Improvement of the Performance of Solar Energy Waste Heat Utilization Systems by Using Phase-Change Slurry as an Enhanced Heat-Transfer Fluid," *ASME Journal of Solar Engineering*, pp. 229-236.

Mulligan, J.C., 1989, "Phase-Change Heat-Storage Module," NASA Tech Briefs, April, p. 103.

Mulligan, J.C., Colvin, D.P., and Bryant, Y.G., 1996, "Microencapsulated Phase-Change Material Suspensions for Heat Transfer in Spacecraft Thermal Systems," *Journal of Spacecraft and Rockets*, vol. 33, no. 2, March-April, pp. 278-284.

Roy, S.K., and Sengupta, S., 1991, "An Evaluation of Phase Change Microcapsules for Use in Enhanced Heat Transfer Fluids," *International Communications in Heat and Mass Transfer*, vol. 18, pp. 495-507.

Royon, L., Perrot, P., Guiffant, G., and Fraoua, S., 1998, "Physical Properties and Thermorheological Behaviour of a Dispersion Having Cold Latent Heat-Storage Material," *Energy Conversion and Management*, vol. 39, no. 15, pp. 1529-35.

Yamagishi, Y., Takeuchi, Hiromi, Pyatenko, Alexander T., and Kayukawa, N., 1999, "Characteristics of Microencapsulated PCM Slurry as a Heat-Transfer Fluid," *AIChE Journal*, vol. 45, no. 4, pp. 696-707.

Appendix II - Material Data Safety Sheets

HEXADECANE

MSDS Number: H1211 --- Effective Date: 11/02/01

1. Product Identification

Synonyms: n-Hexadecane; cetane

CAS No.: 544-76-3

Molecular Weight: 226.45

Chemical Formula: CH₃(CH₂)₁₄CH₃

Product Codes: J.T. Baker: N105

Mallinckrodt: H223

2. Composition/Information on Ingredients

Ingredient	CAS No	Percent	Hazardous
Hexadecane	544-76-3	90 - 100%	Yes

3. Hazards Identification

Emergency Overview

DANGER! HARMFUL OR FATAL IF SWALLOWED. HARMFUL IF INHALED. CAUSES SEVERE SKIN IRRITATION. MAY CAUSE EYE AND RESPIRATORY TRACT IRRITATION. PROLONGED EXPOSURE CAN CAUSE NARCOTIC EFFECTS.

J.T. Baker SAF-T-DATA^(tm) Ratings (Provided here for your convenience)

Health Rating: 2 - Moderate

Flammability Rating: 1 - Slight

Reactivity Rating: 1 - Slight

Contact Rating: 1 - Slight

Lab Protective Equip: GOGGLES; LAB COAT

Storage Color Code: Orange (General Storage)

Potential

Health

Effects

Information on the human health effects from exposure to this substance is limited. **Inhalation:** Inhalation of vapors may be irritating to the mucous membrane and upper respiratory tract. May cause narcosis.

Ingestion: Harmful if swallowed. Direct aspiration into the lungs may cause chemical pneumonitis and may cause lung damage. **Skin Contact:** Causes severe skin irritation based on Draize information for humans and animals.

Eye Contact: May cause eye irritation.

Chronic Exposure: No information found.

Aggravation of Pre-existing Conditions: No information found.

4. First Aid Measures

Inhalation: Remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Call a physician.

Ingestion: If swallowed, DO NOT INDUCE VOMITING. Give large quantities of water. Never give anything by mouth to an unconscious person. Get medical attention immediately. Aspiration hazard.

Skin Contact: Remove any contaminated clothing. Wash skin with soap or mild detergent and water for at least 15 minutes. Wash clothes before reuse. Get medical attention if irritation develops or persists.

Eye Contact: Immediately flush eyes with plenty of water for at least 15 minutes, lifting lower and upper eyelids occasionally. Get medical attention immediately.

5. Fire Fighting Measures

Fire:

Flash point: > 100C (> 212F) CC

Autoignition temperature: 205C (401F)

Explosion: Above the flash point, explosive vapor-air mixtures may be formed. Above flash point, vapor-air mixtures are explosive within flammable limits noted above.

Fire Extinguishing Media: Dry chemical, foam, carbon dioxide, or water spray. Water may be ineffective.

Special Information: In the event of a fire, wear full protective clothing and NIOSH-approved self-contained breathing apparatus with full facepiece operated in the pressure demand or other positive pressure mode. Water spray may be used to keep fire exposed containers cool.

6. Accidental Release Measures

Ventilate area of leak or spill. Remove all sources of ignition. Wear appropriate personal protective equipment as specified in Section 8. Isolate hazard area. Keep unnecessary and unprotected personnel from entering. Contain and recover liquid when possible. Use non-sparking tools and equipment. Collect liquid in an appropriate container or absorb with an inert material (e. g., vermiculite, dry sand, earth), and place in a chemical waste container. Do not use combustible materials, such as saw dust. Do not flush to sewer!

7. Handling and Storage

Keep in a tightly closed container, stored in a cool, dry, ventilated area. Protect against physical damage. Isolate from any source of heat or ignition. Isolate from incompatible substances.

8. Exposure Controls/Personal Protection

Airborne Exposure Limits: None established.

Ventilation System: A system of local and/or general exhaust is recommended to keep employee exposures as low as possible. Local exhaust ventilation is generally preferred because it can control the emissions of the contaminant at its source, preventing dispersion of it into the general work area. Please refer to the ACGIH document, *Industrial Ventilation, A Manual of Recommended Practices*, most recent edition, for details.

Personal Respirators (NIOSH Approved): For conditions of use where exposure to the substance is apparent and engineering controls are not feasible, consult an industrial hygienist. For emergencies, or instances where the exposure levels are not known, use a full-facepiece positive-pressure, air-supplied respirator. **WARNING:** Air purifying respirators do not protect workers in oxygen-deficient atmospheres.

Skin Protection: Wear impervious protective clothing, including boots, gloves, lab coat, apron or coveralls, as appropriate, to prevent skin contact.

Eye Protection: Use chemical safety goggles and/or a full face shield where splashing is possible. Maintain eye wash fountain and quick-drench facilities in work area.

9. Physical and Chemical Properties

Appearance: Clear, colorless liquid.

Odor: No information found.

Solubility: Insoluble in water.

Specific Gravity: 0.77

pH: No information found.

% Volatiles by volume @ 21C (70F): 100

Boiling Point: 287C (549F)

Melting Point: 18C (64F)

Vapor Density (Air=1): 7.8

Vapor Pressure (mm Hg): 1 @ 105.3C (221F)

Evaporation Rate (BuAc=1): No information found.

10. Stability and Reactivity

Stability: Stable under ordinary conditions of use and storage. Hygroscopic.

Hazardous Decomposition Products: Carbon dioxide and carbon monoxide may form when heated to decomposition.

Hazardous Polymerization: Will not occur.

Incompatibilities: Strong oxidizers.

Conditions to Avoid: Heat, flames, ignition sources and incompatibles.

11. Toxicological Information

No LD50/LC50 information found relating to normal routes of occupational exposure. Irritation data; skin, human: 50 mg/48H Severe

-----\Cancer Lists\-----

Ingredient	---NTP Carcinogen---		IARC Category
	Known	Anticipated	
Hexadecane (544-76-3)	No	No	None

12. Ecological Information

Environmental Fate: When released into the soil, this material may biodegrade to a moderate extent. When released into the soil, this material is not expected to leach into groundwater. When released into the soil, this material may evaporate to a moderate extent. When released into water, this material may biodegrade to a moderate extent. When released into water, this material may evaporate to a moderate extent. This material has an estimated bioconcentration factor (BCF) of greater than 100. This material has a log octanol-water partition coefficient of greater than 3.0. This material is not expected to significantly bioaccumulate. When released into the air, this material is not expected to be degraded by photolysis. When released into air, this material is expected to have a half-life between 10 and 30 days.

Environmental Toxicity: No information found.

13. Disposal Considerations

Whatever cannot be saved for recovery or recycling should be managed in an appropriate and approved waste disposal facility. Processing, use or contamination of this product may change the waste management options. State and local disposal regulations may differ from federal disposal regulations. Dispose of container and unused contents in accordance with federal, state and local requirements.

14. Transport Information

Not regulated.

15. Regulatory Information

-----\Chemical Inventory Status - Part 1\-----

Ingredient	TSCA	EC	Japan	Australia
Hexadecane (544-76-3)	Yes	Yes	Yes	Yes

-----\Chemical Inventory Status - Part 2\-----

Ingredient	--Canada--			
	Korea	DSL	NDSL	Phil.
Hexadecane (544-76-3)	Yes	Yes	No	Yes

-----\Federal, State & International Regulations - Part 1\-----

Ingredient	-SARA 302-		-----SARA 313-----	
	RQ	TPQ	List	Chemical Catg.
Hexadecane (544-76-3)	No	No	No	No

-----\Federal, State & International Regulations - Part 2\-----

Ingredient	CERCLA	-RCRA-	-TSCA-
		261.33	8 (d)
Hexadecane (544-76-3)	No	No	No

Chemical Weapons Convention: No TSCA 12(b): No CDTA: No
 SARA 311/312: Acute: Yes Chronic: No Fire: No Pressure: No
 Reactivity: No (Pure / Liquid)

Australian Hazchem Code: No information found.

Poison Schedule: No information found.

WHMIS: This MSDS has been prepared according to the hazard criteria of the Controlled Products Regulations (CPR) and the MSDS contains all of the information required by the CPR.

16. Other Information

NFPA Ratings: Health: 0 Flammability: 1 Reactivity: 0

Label Hazard Warning: DANGER! HARMFUL OR FATAL IF SWALLOWED. HARMFUL IF INHALED. CAUSES SEVERE SKIN IRRITATION. MAY CAUSE EYE AND RESPIRATORY TRACT IRRITATION. PROLONGED EXPOSURE CAN CAUSE NARCOTIC EFFECTS.

Label Precautions: Keep container closed. Use only with adequate ventilation. Avoid breathing vapor. Wash thoroughly after handling. Avoid contact with eyes, skin and clothing.

Label First Aid:

If swallowed, DO NOT INDUCE VOMITING! Aspiration hazard. Call a physician immediately. If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. In case of contact, immediately flush eyes or skin with plenty of water for at least 15 minutes. In all cases call a physician.

Product Use: Laboratory Reagent.

Revision Information: MSDS Section(s) changed since last revision of document include: 8.

TRITON(R) X-100

MSDS Number: T7332 --- Effective Date: 09/14/00

1. Product Identification

Synonyms: Octylphenoxypolyethoxyethanol nonionic surfactant; An alkylphenol-hydroxypolyoxyethylene; Alkylaryl polyether alcohol; Octyl phenol ethoxylate
CAS No.: Not applicable to mixtures.

Molecular Weight: 624 (average)

Chemical Formula: C14H22O(C2H4O)n where the average number of ethylene oxide units per molecule ranges from 9 to 10

Product Codes:

J.T. Baker: X198, X200

Mallinckrodt: H282

2. Composition/Information on Ingredients

Ingredient	CAS No	Percent	Hazardous
Polyethylene Glycol Octylphenyl Ether	9036-19-5	> 97%	Yes
Polyethylene Glycol	25322-68-3	< 3%	No
Dioxane	123-91-1	< 0.0055%	No
Ethylene Oxide	75-21-8	< 0.001%	No

3. Hazards Identification

Emergency

Overview

DANGER! CAUSES EYE BURNS. HARMFUL IF SWALLOWED OR INHALED. ASPIRATION MAY CAUSE LUNG DAMAGE. CAUSES IRRITATION TO SKIN AND RESPIRATORY TRACT.

J. T. Baker SAF-T-DATA^(tm) Ratings (Provided here for your convenience)

Health Rating: 1 - Slight
Flammability Rating: 1 - Slight
Reactivity Rating: 1 - Slight
Contact Rating: 2 - Moderate
Lab Protective Equip: GOGGLES; LAB COAT; VENT HOOD; PROPER GLOVES
Storage Color Code: Orange (General Storage)

Potential

Health

Effects

Inhalation: Causes irritation to the respiratory tract. Symptoms may include coughing, shortness of breath.

Ingestion: Causes irritation to the gastrointestinal tract. Symptoms may include nausea, vomiting and diarrhea. Aspiration into the lungs may occur during swallowing or vomiting, resulting in lung damage.

Skin Contact: Brief contact may have no effect. Prolonged or repeated contact may cause irritation, redness, itching and pain.

Eye Contact: Can cause severe eye irritation with symptoms of inflammation, tearing, blinking, redness, swelling of the conjunctiva, and chemical burns of the cornea.

Chronic Exposure: No information found.

Aggravation of Pre-existing Conditions: No information found.

4. First Aid Measures

Inhalation: Remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention.

Ingestion: If swallowed, DO NOT INDUCE VOMITING. Give large quantities of water. Never give anything by mouth to an unconscious person. Get medical attention immediately.

Skin Contact: Immediately flush skin with plenty of water for at least 15 minutes. Remove contaminated clothing and shoes. Get medical attention. Wash clothing before reuse. Thoroughly clean shoes before reuse.

Eye Contact: Immediately flush eyes with plenty of water for at least 15 minutes, lifting lower and upper eyelids occasionally. Get medical attention immediately.

Note to Physician: There is no specific antidote. Treatment of overexposure should be directed at the control of symptoms and the clinical condition of the patient. Any material aspirated during vomiting may cause lung injury. Therefore, emesis should not be induced mechanically or pharmacologically. If it is considered necessary to evacuate the stomach contents, this should be done by means least likely to cause aspiration (e.g., gastric lavage after endotracheal intubation).

5. Fire Fighting Measures

Fire: Flash point: 251C (484F) CC Slight fire hazard when exposed to heat or flame. Contact with strong oxidizing or reducing agents may create a fire or explosion hazard.

Explosion: Not considered to be an explosion hazard. Sensitive to static discharge.

Fire Extinguishing Media: Water spray, dry chemical, alcohol foam, or carbon dioxide. Do not use heavy stream of water; material will float, and spread fire.

Special Information: In the event of a fire, wear full protective clothing and NIOSH-approved self-contained breathing apparatus with full facepiece operated in the pressure demand or other positive pressure mode.

6. Accidental Release Measures

Ventilate area of leak or spill. Remove all sources of ignition. Wear appropriate personal protective equipment as specified in Section 8. Isolate hazard area. Keep unnecessary and unprotected personnel from entering. Contain and recover liquid when possible. Use non-sparking tools and equipment. Collect liquid in an appropriate container or absorb with an inert material (e. g., vermiculite, dry sand, earth), and place in a chemical waste container. Do not use combustible materials, such as saw dust. Do not flush to sewer! Guard against falls as material is slippery. US Regulations (CERCLA) require reporting spills and releases to soil, water and air in excess of reportable quantities. The toll free number for the US Coast Guard National Response Center is (800) 424-8802.

7. Handling and Storage

Keep in a tightly closed container. Protect from physical damage. Store in a cool, dry, ventilated area away from sources of heat, moisture and incompatibilities. Containers of this material may be hazardous when empty since they retain product residues (vapors, liquid); observe all warnings and precautions listed for the product. This product may contain trace amounts of ethylene oxide, a condition which creates the potential for accumulation of ethylene oxide in the head space of shipping and storage containers and in areas where the product is being handled or used. Ethylene oxide is a potential carcinogen for humans. At excess levels, ethylene oxide can present dangerous health hazards to humans. If this product is handled with adequate ventilation, the presence of these trace amounts is not expected to result in any short or long term hazard.

8. Exposure Controls/Personal Protection

Airborne Exposure Limits: For Ethylene oxide: - OSHA Permissible Exposure Limit (PEL) - 1 ppm (TWA), 0.5 ppm (Action level), 5 ppm (STEL). - ACGIH Threshold Limit Value (TLV) - 1 ppm (TWA), A2 - suspected human carcinogen. **Ventilation System:** In general, dilution ventilation is a satisfactory health hazard control for this substance. However, if conditions of use create discomfort to the worker, a local exhaust system should be considered. **Personal Respirators (NIOSH Approved):** Not expected to require personal respirator usage. For conditions of use where exposure to the substance is apparent and engineering controls are not feasible, consult an industrial hygienist. For emergencies, or instances where the exposure levels are not known, use a full-facepiece positive-pressure, air-supplied respirator. **WARNING:** Air purifying respirators do not protect workers in oxygen-deficient atmospheres. Where respirators are required, you must have a written program covering the basic requirements in the OSHA respirator standard. These include training, fit testing, medical approval, cleaning, maintenance, cartridge change schedules, etc. See 29CFR1910.134 for details. **Skin Protection:** Wear protective gloves and clean body-covering clothing. **Eye Protection:** Use chemical safety goggles and/or a full face shield where splashing is possible. Maintain eye wash fountain and quick-drench facilities in work area. **Other Control Measures:** This product may not be exempt from OSHA's Ethylene Oxide Standard, 29CFR1910.1047. Users should comply with all applicable provisions.

9. Physical and Chemical Properties

Appearance: Transparent pale yellow, viscous, liquid.

Odor: Mild odor.

Solubility: Miscible in water

Specific Gravity: 1.067

pH: 7 (5% solution)

% Volatiles by volume @ 21C (70F): 0.0065

Boiling Point: > 200C (> 392F)

Melting Point: 6C (43F)

Vapor Density (Air=1): > 1.0

Vapor Pressure (mm Hg): < 0.01 @ 20C (68F)

Evaporation Rate (BuAc=1): < 0.01

10. Stability and Reactivity

Stability: Stable under ordinary conditions of use and storage. Viscosity increases as temperature decreases and handling becomes difficult below 68F. **fHazardous Decomposition**

Products: Carbon dioxide and carbon monoxide may form when heated to decomposition.

Hazardous Polymerization: Will not occur.

Incompatibilities: Strong oxidizers, strong acids and strong bases. Corrosive to copper and brass.

Conditions to Avoid: Heat and incompatibles.

11. Toxicological Information

Toxicological Data: For Triton X-100: LD50 oral rat 1800 mg/kg. For Polyethylene glycol octylphenyl ether: LD50 oral rat 4190 mg/kg; Irritation (Std Draize, eye, rabbit) 1% severe. Investigated as a mutagen. Polyethylene glycol has been investigated as a mutagen.

Carcinogenicity: This product may contain trace amounts of ethylene oxide and dioxane. Ethylene Oxide: NIOSH considers this substance to be a potential occupational carcinogen. Regulated by OSHA as a carcinogen.

Dioxane: NIOSH considers this substance to be a potential occupational carcinogen. EPA / IRIS classification: Group B2 - Probable human carcinogen, sufficient animal evidence.

```

-----\Cancer Lists\-----
                                ---NTP Carcinogen---
Ingredient                        Known    Anticipated    IARC Category
-----
Polyethylene Glycol Octylphenyl
Ether (9036-19-5)                 No        No              None
Polyethylene Glycol (25322-68-3)  No        No              None
Dioxane (123-91-1)                No        Yes             2B
Ethylene Oxide (75-21-8)          Yes       No              1
  
```

12. Ecological Information

Environmental Fate: No information found. **Environmental Toxicity:** For Triton X-100: The LC50/96-hour values for fish are between 1 and 10 mg/l. This material is expected to be toxic to aquatic life.

13. Disposal Considerations

Whatever cannot be saved for recovery or recycling should be handled as hazardous waste and sent to a RCRA approved waste facility. Processing, use or contamination of this product may change the waste management options. State and local disposal regulations may differ from federal disposal regulations. Surfactants can cause foaming problems in biological wastewater treatment plants and other high shear operations. Dispose of container and unused contents in accordance with federal, state and local requirements.

14. Transport Information

Not regulated.

15. Regulatory Information

```

-----\Chemical Inventory Status - Part 1\-----
Ingredient                        TSCA  EC   Japan  Australia
-----
Polyethylene Glycol Octylphenyl Ether
(9036-19-5)                        Yes   No   Yes    Yes
Polyethylene Glycol (25322-68-3)   Yes   No   Yes    Yes
Dioxane (123-91-1)                 Yes   Yes  Yes    Yes
Ethylene Oxide (75-21-8)           Yes   Yes  Yes    Yes
  
```

```

-----\Chemical Inventory Status - Part 2\-----
                                --Canada--
Ingredient                        Korea  DSL  NDSL  Phil.
-----
Polyethylene Glycol Octylphenyl Ether
(9036-19-5)                        Yes   Yes  No    Yes
Polyethylene Glycol (25322-68-3)   Yes   Yes  No    Yes
Dioxane (123-91-1)                 Yes   Yes  No    Yes
Ethylene Oxide (75-21-8)           Yes   Yes  No    Yes
  
```

```

-----\Federal, State & International Regulations - Part 1\-----
Ingredient                        -SARA 302-  -SARA 313-
RQ    TPQ    List  Chemical Catg.
-----
Polyethylene Glycol Octylphenyl Ether
(9036-19-5)                        No    No    No    No
Polyethylene Glycol (25322-68-3)   No    No    No    No
Dioxane (123-91-1)                 No    No    Yes   No
Ethylene Oxide (75-21-8)           10   1000  Yes   No
  
```

```

-----\Federal, State & International Regulations - Part 2\-----
Ingredient                        CERCLA      -RCRA-      -TSCA-
                                CERCLA      261.33      8 (d)
-----
Polyethylene Glycol Octylphenyl Ether
(9036-19-5)                        No          No          Yes
Polyethylene Glycol (25322-68-3)   No          No          No
Dioxane (123-91-1)                 100        U108        No
Ethylene Oxide (75-21-8)           10         U115        No
  
```

Chemical Weapons Convention: No TSCA 12(b): No CDTA: No
 SARA 311/312: Acute: Yes Chronic: No Fire: No Pressure: No
 Reactivity: No (Mixture / Liquid)

WARNING: THIS PRODUCT CONTAINS CHEMICALS KNOWN TO THE STATE OF CALIFORNIA TO CAUSE CANCER AND BIRTH DEFECTS OR OTHER REPRODUCTIVE HARM.

Australian Poison **Hazchem** **Code:** No information found.
Schedule: S6

WHMIS: This MSDS has been prepared according to the hazard criteria of the Controlled Products Regulations (CPR) and the MSDS contains all of the information required by the CPR.

16. Other Information

NFPA Ratings: Health: 2 Flammability: 1 Reactivity: 0

Label Hazard Warning: DANGER! CAUSES EYE BURNS. HARMFUL IF SWALLOWED OR INHALED. ASPIRATION MAY CAUSE LUNG DAMAGE. CAUSES IRRITATION TO SKIN AND RESPIRATORY TRACT.

Label Precautions: Do not get in eyes. Avoid contact with skin and clothing. Wash thoroughly after handling. Avoid breathing mist. Keep container closed. Use only with adequate ventilation.

Label First Aid: In case of eye contact, immediately flush eyes with plenty of water for at least 15 minutes. If swallowed, DO NOT INDUCE VOMITING. Give large quantities of water. Never give anything by mouth to an unconscious person. In case of contact, immediately flush skin with plenty of water for at least 15 minutes. Remove contaminated clothing and shoes. Wash clothing before reuse. If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. In all cases, get medical attention.

Product Use: Laboratory Reagent.

Revision Information: MSDS Section(s) changed since last revision of document include: 8, 11.

Appendix III - Procedure for Measurement of Particle Size

The method of measuring particle diameters consisted of using a setup with a microscope and digital camera. The microscope used was a National Microscope Model 161 with an attachment for mounting a digital camera. The digital camera used was a Nikon CoolPix 990. Both items are shown in Figure 24.



Nikon Cool Pix 990
Digital Camera



National Microscope Model 161
with Digital Camera Mount

Figure 24 - Equipment used for particle pictures.

The procedure for photographing the samples contained the following steps. First, a slide sample was prepared using 1 to 3 drops of the PCM slurry, depending on the degree of solidification for the sample. If the sample was too thick, drops of water were added to separate the particles. After the sample had been created, the slide was placed on the stage. The digital camera was mounted to the microscope and then zoomed out to its widest possible angle. The microscope lens was set to 40x and was then focused based on the image seen in the LCD of the digital camera. Once the image was focused, 5-10 photos were taken depending on the size and density of the particles. The intention of these photographs was to get enough sample images to measure between 500-600 particles.

In order to measure the particles, a scale with known size divisions was photographed using the same method as stated for the particle samples. Using Adobe Photoshop 6.0, the image of the scale was layered over the particle sample image (see Figure 25). Using a layer multiply command in the program, we were able to make the scale a transparent overlay. Each particle was then measured individually by moving the scale and recording the sizes.

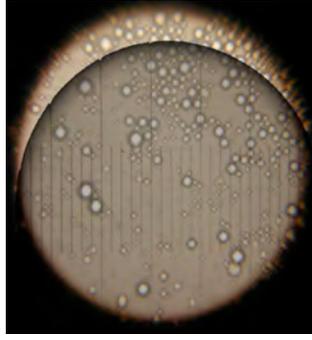


Figure 25 - Particle Sample With Scale Overlay.

Once the particles had been measured, the values were input into Microsoft Excel. Distributions were then calculated based on the diameters for frequency, normalized frequency, mass distribution, and ratio. In addition, an average mass and a geometric mean were also calculated. The particle analysis was then concluded with the generation of distribution plots.

Appendix IV - Detailed Discussion of Flow Testing Results

The apparatus used for these experiments consisted of a polystyrene insulated tank with 3/8" inch plastic tube used for an outlet and 3/4" inch plastic tube used for the inlet. Throughout the experiments, two different pumps were used to drive the slurry flow. Initially, a ShurFlo Diaphragm Pump (12 VDC, 5 Amps) was used. However, in later tests a Hypro Aqua-Tiger 9700B Centrifugal Transfer Pump replaced this pump.

The slurry heating was accomplished by using an Omegalux SRT051-120 Heating Tape. This tape was wrapped around a 5/8" copper pipe to provide a constant power input of approximately 180 Watts. Using a Speco ACM-3A Clamp Meter to measure the current at 1.8 amps and then multiplying by 110 volts to get the power determined this value.

The slurry cooling was performed by using a simple concentric tube heat exchanger constructed with copper pipes. The inner tube was made from 5/8" pipe while the outer shell was made of 1 1/2" pipe. A Versa Gold Series G210AG20 Submersible Pump initially pumped water into the shell, but this pump was later replaced by a Hypro Aqua-Tiger 9700B Centrifugal Transfer Pump. This was done to increase the Reynolds Number of the cooling water, thereby increasing heat transfer.

Analysis was done regarding the heat transfer coefficient of the shell and tube heat exchanger. A bucket and stop watch were used to measure the flow rates of the slurry and the cooling water. This is obviously not the most accurate of methods, but it presented useful enough data to get a good qualitative understanding of the heat transfer in the exchanger. The flow rate on the cold side of the exchanger was determined to be approximately 6500 mL/min. Using this value along with the cross sectional flow area, the average flow velocity was found to be .0802 m/s.

The Reynolds Number was then calculated based on hydraulic diameter. The hydraulic diameter was calculated for the concentric tube annulus exchanger by subtracting the inner diameter from the outer diameter. This value was .0415 meters.

$$Re_D = \frac{\rho \bar{U} D_h}{\mu} \quad (1)$$

The Reynolds number was determined to be 1311, which signified laminar flow. Because of the fact that our flow was taking place in a relatively short length of tube, it was necessary to consider the hydrodynamic entry length. From Langhaar [1], the hydrodynamic entry length for laminar flow can be expressed as the following:

$$\left(\frac{x_{fd,h}}{D}\right) \approx 0.05 Re_D \quad (2)$$

The hydrodynamic entry length was found to be 1.87 m, but the length of our tube exchanger was only 1.37 m. This meant that the convection coefficient calculation would need to be calculated as an entrance region problem. Using data from Kays and Perkins presented by Incropera and Dewitt, a fully developed laminar flow value for the Nusselt number in a

concentric tube annulus was estimated to be 7. This, in combination with a Hausen correlation presented in [1] led to the following equation for the average Nusselt number.

$$\overline{Nu}_D = 7 + \frac{0.0668(D/L) Re_D Pr}{1 + 0.04[(D/L) Re_D Pr]^{2/3}} \quad (3)$$

Then with

$$\overline{Nu}_D = \frac{\bar{h}D}{k} \quad (4)$$

We have a convection coefficient of $299 \frac{W}{m^2K}$. This concluded the analysis for the cold side of the shell and tube heat exchanger.

For the hot side of the exchanger, it was necessary to assume values for the properties of the slurry. To simplify the calculations, the density, viscosity, and Prandtl number were considered to be the same as water.

The Reynolds number was calculated to be 7228. This signified turbulent flow. With this Reynolds number, fully developed turbulent flow was assumed and the *Dittius-Boelter equation* [1] for cooling was used.

$$Nu_D = 0.023 Re_D^{4/5} Pr^{-3} \quad (5)$$

$$h = 2590 \frac{W}{m^2K}$$

Combining these two calculated heat transfer coefficients and neglecting the effect of the copper tube due to its thin wall and high thermal conductivity, a calculated overall heat transfer coefficient was found to be $\approx 268 \frac{W}{m^2K}$.

This value was compared to a heat transfer coefficient derived from experimental cooling data. The data was used to develop an average cooling rate and temperature difference; and the area was measured to calculate the heat transfer coefficient in the experiment.

$$Q = hA(T_h - T_c) \quad (6)$$

$$Q \approx 185.7 \text{ W}$$

$$(T_h - T_c) \approx 10 \text{ K}$$

This equation produced an overall heat transfer coefficient of $271.36 \frac{W}{m^2K}$. This was in extremely good agreement with the calculated value.

Preliminary calculations were performed with the slurry compound to determine an estimate for the amount of heat that must be removed to solidify the hexadecane particles in the slurry. Noting that the heat of fusion for hexadecane was approximately 229 kJ/kg, with 5.85 kg, 1339.7

kJ of heat needed to be removed from the mixture. The following calculation was used to determine the amount of time required to solidify the hexadecane:

$$\frac{1339.7}{t} = UA(\Delta T) \quad (7)$$

Assuming ΔT to be approximately 7 K on average and $U=271.36 \frac{W}{m^2K}$ from the water experiments, t was calculated to be 10306 seconds, or 2.9 hours.

This value was lower than the actual amount of time that it had been taking to solidify the particles of the slurry. This led to the conclusion that the U value was less than what occurred for the water. Because of the fact that many studies have said that PCM's have superior heat transfer characteristics compared to water, it was reasoned that the flow rate must have been decreasing with the slurry, which lowered the Reynolds number and thereby decreased the heat transfer coefficient.

Some observations of possible problems during the cooling were the fact that chunks began forming during the process. This was most likely occurring due to poor mixing of the slurry, which caused the solidifying particles to float to the top of the mixture and group together. To solve this problem, a drill mountable paint mixer was purchased and used to provide a constant mixing for the slurry. This provided for a different observation during the cooling. The slurry became very viscous and coated any object placed into the fluid.



Figure 26 - Slurry with mixing.

Eventually the viscosity of the slurry became so great that there was plugging at the outlet of the tank. This was due to the fact that we had a *very small* 3/8" diameter tubing running out of the tank outlet and into the pump. No plugging was exhibited on the bench-scale apparatus (larger pipes for inlet/outlet, plus very small diameter tubing 3/8 inch).

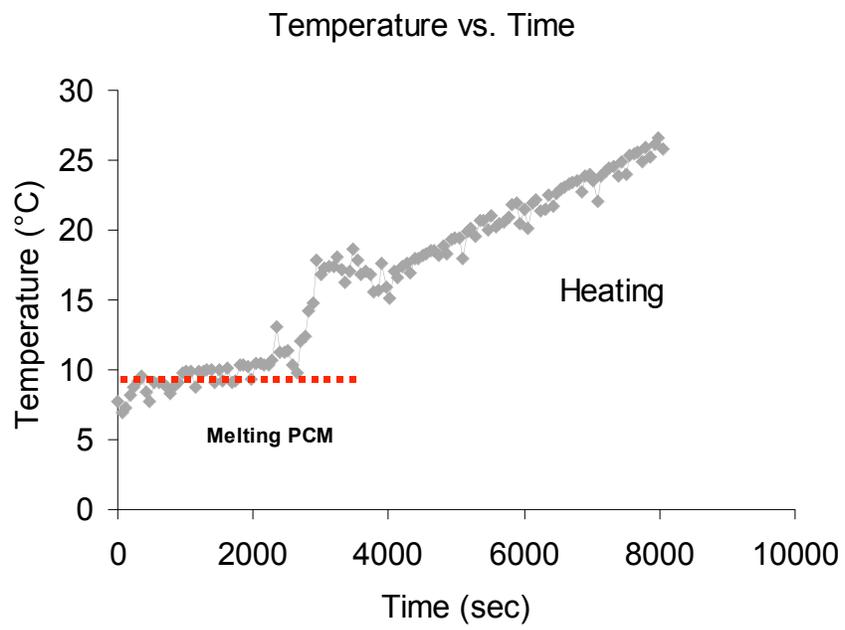


Figure 27 - Testing of a 40% hexadecane and 1% Triton V100 slurry mixture (6-4 heat_7).

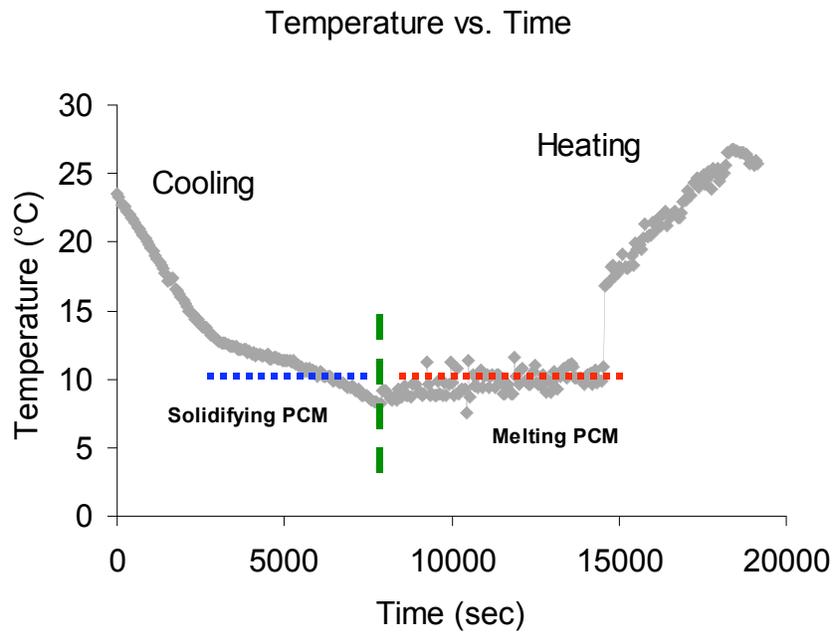


Figure 28 - Testing of a 35% hexadecane and 1% Triton V100 slurry mixture (6-12).

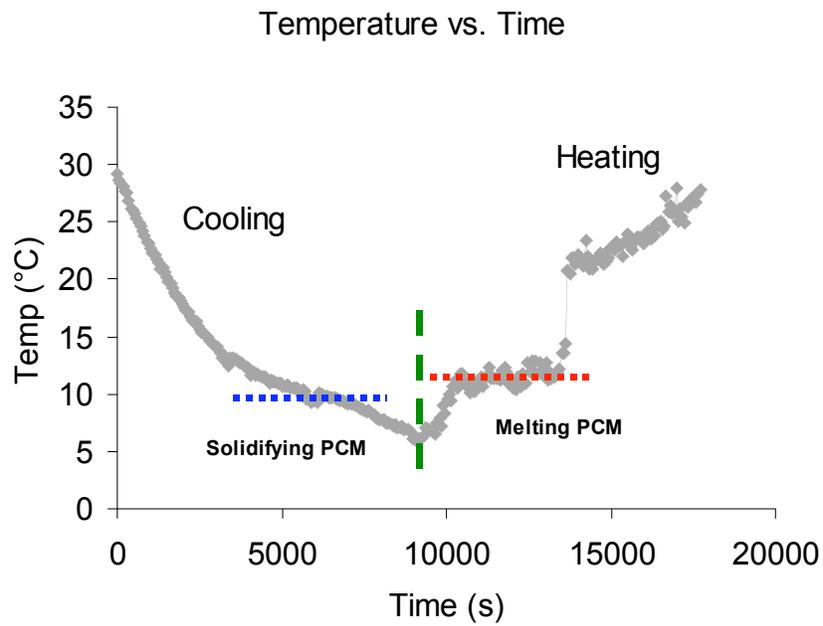


Figure 29 - Testing of a 35% hexadecane and 1% Triton V100 slurry mixture (6-13).

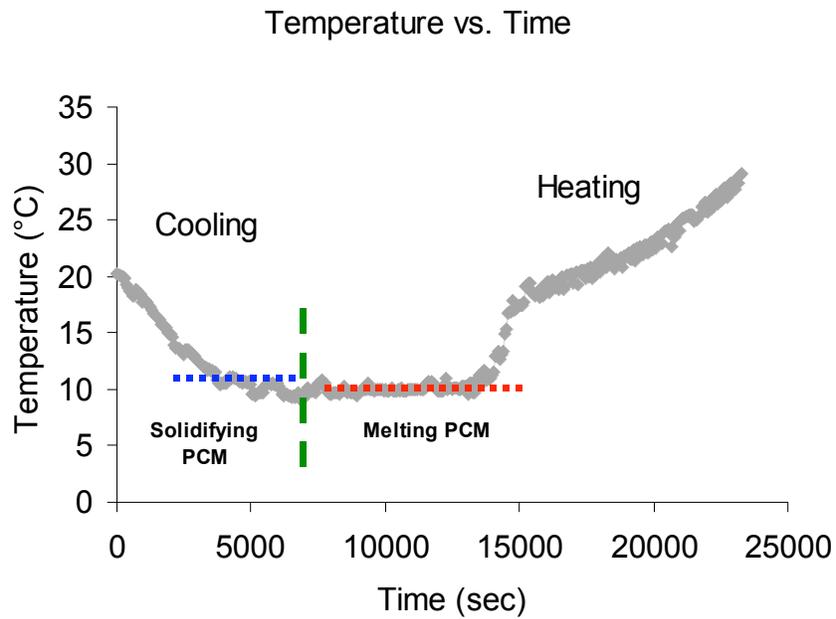


Figure 30 - Testing of a 30% hexadecane and 1% Triton V100 slurry mixture (6-18).

A number of test results have been shown above. In general, all of the results show a distinctive flat spot in the data during solidification or melting. The PCMs solidified and demonstrated the ability to make a PCM slurry that could be pumped.

Appendix V - Detailed Results for Bench-Scale Testing

Bench Model Design

The bench model consisted of 6 major components; a fan blower, a resistance heater, an air conditioner with an evaporator coil, a slurry storage tank, two PCM heat exchangers and a pumping system.

The system was set up with the blower discharging into 8" x 16" aluminum ductwork. The air then passed through a slurry heat exchanger that would be used to cool warm air prior to it entering the air conditioner coil. After the air conditioner coil, there was another slurry heat exchanger that was used to cool and solidify the slurry when the heater was not running.

The fan blower was used as the means of circulating the air through the ductwork and heat exchangers. It was capable of moving ~500 SCFM of air with a 3-inch pulley wheel attached to the motor and ~700 SCFM with a 4-inch wheel attached. These airflow values provided good agreement with practical HVAC applications. Experiments were performed using both of these pulleys, depending on the amount of air that needed to be moved. A size 4L520 belt was used to connect the pulley wheel to the 10-inch blower wheel.



Figure 31: Fan Blower

The air conditioner was a salvaged Gibson 1.5 ton unit attached to an A-coil. The unit provided an adequate amount of cooling for our needs.



Figure 32: AC Unit and Hookup

Because of the fact that the fluid properties of our slurry were not well known or documented, selecting a compact heat exchanger core to suit our needs required a great deal of speculation and estimation. In the end, the coil chosen was a Super Radiator Coils Dry Glycol Coil (Model No. 10x30-3R-38/96). This coil was designed for a working fluid of glycol with air temperatures of 90° F and 80° F for the inlet and outlet, respectively. Two of these coils were used; one for heating the slurry and one for cooling the slurry.



Figure 33: Slurry Heat Exchanger

The heater was a Chromalox 240 Volts 4750 Watts resistance heater. With our blower and airflow rate, this heater was capable of raising the air temperature to approximately 35 ° C, which corresponded well to inlet air temperatures for a warm summer day.



Figure 34: Chromalox Resistance Heater

The slurry storage tank was a chemical tank salvaged from an agricultural sprayer. Its exact volume was unknown, but was estimated to be roughly 125 gallons. For the initial experiments presented in this report, it was filled with a 100 gallon slurry mixture with 30% hexadecane concentration and 2% Triton X-100. The tank was covered with two insulation layers. The intermediate layer consisted of foam rubber. This layer was then covered with aluminum bubble wrap insulation. The insulation was secured using aluminum foil tape.



Figure 35: Un-insulated and Insulated Slurry Tank

There were a number of different options available for the pumping of the slurry through the heat exchangers. Initially, a single Hypro Model 9700B Aqua-Tiger Centrifugal pump was intended for use. This pump, however, did not provide an adequate flow rate to create favorable heat transfer inside the heat exchanger. To overcome this problem, using a parallel pump configuration was considered. However, a head loss analysis revealed that there was no simple way to combine the pumps without creating major losses at connections such as tees and elbows. The next solution was to purchase a larger pump.

The pump used was a Wayne $\frac{1}{2}$ Horsepower Portable Pump Model PC4. This pump created a flow rate of nearly 23 gpm, which was a large improvement over the 12 gpm obtained from the Hypro pump. The initial tests were conducted using the Wayne pump.

Upon continued use of the Wayne pump, it was noticed that the work input from the pumping was greatly reducing the cooling rate of the slurry. This led to incredibly long cooling times, which were making it very difficult to run the experiments. Also, the pump was increasing the heating rates, causing less air heat to be absorbed by the slurry.

The next pumping solution analyzed was a series connection of Hypro pumps. Preliminary pump analysis of this configuration yielded a likely flow rate of 15 to 16 gpm with our particular system. Although this flow rate was not as high, these pumps put much less energy into the fluid and this led to more favorable cooling and heating rates than displayed with the Wayne pump.



Figure 36: Wayne Pump and Hypro Series Setup

The slurry tank was connected to the heat exchangers through a series of hoses and valves. With the valves, it was possible to control the route of the flow. Also, sections of the tubing could be isolated if repairs or measurements were needed. Flow was directed from the tank outlet to the pumps using $\frac{3}{4}$ " flexible hose. The fluid then left the pumps through a 1" tube that was considerably stiffer than the $\frac{3}{4}$ " hose. That tube then split at a T-intersection allowing the flow to go through either slurry heat exchanger. The flow was carried to the heat exchangers in the same 1" tubing. It then left the heat exchanger via $\frac{3}{4}$ " hose. The $\frac{3}{4}$ " hose from both heat exchangers converged at another T-intersection that lead back to the inlet of the tank. The hose configuration is displayed in Figure 37.

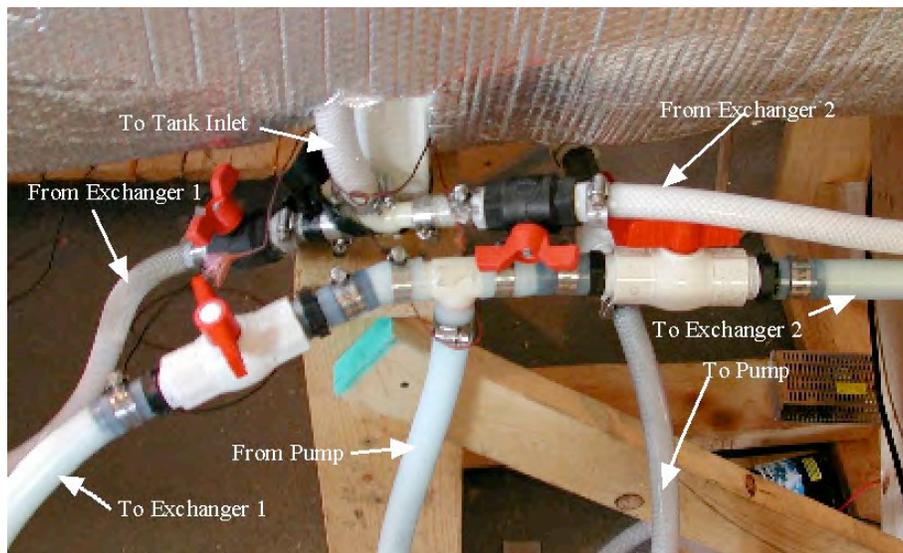


Figure 37: Hose Intersections

Flow with the bench scale model was controlled with six valves. Four of the six valves can be seen in Figure 37. These four valves were ball valves and were used to control the inlet and outlet flow of the heat exchangers. The black valves were $\frac{3}{4}$ " diameter and the white valves were 1" diameter. In addition to these four valves, there was another 1" white valve controlling the outlet of the tank and a $1\frac{1}{4}$ " Mueller gate valve controlling flow from the pumps.



Figure 38: Mueller Gate Valve

All hose connections were made with hose barbs and hose clamps. This created a leak free junction between hoses and fittings. As for threaded unions, Harvey's TFE Paste with Teflon was used to prevent leakage.

The procedure for cooling the slurry was to pass air through the air conditioner and then through the second slurry heat exchanger. The slurry would be pumping through the heat exchanger, and the cool air would remove heat from the slurry. Based on the temperature rise of the cool air across the slurry heat exchanger and the airflow rate, we could calculate how much energy was being removed from the slurry.

During the slurry cooling, the 4" pulley wheel was used on the blower to give an increased flow rate. In addition, an 8" circular, insulated, and flexible duct was used to redirect the cool air flow back to the blower. This allowed for cooler air out of the air conditioner, which aided in the cooling of the slurry.

During the heating stage of the experiments, the 3" pulley wheel replaced the 4" wheel to give a flow rate more typical for a home HVAC system. The fan would blow air across the heater, and then through the first slurry heat exchanger. The slurry heat exchanger was pumping the cooled slurry, thereby pre-cooling the air before it reached the air conditioner. The air then continued through the air conditioner and passed out through the ductwork. It should be noted that the circular duct was removed for this aspect of the experiment and that no slurry was being pumped through the second slurry heat exchanger.

Temperature data was gathered using Omega GG-E-24-SLE thermocouple wire. The ends were connected with manual twisting. There were a total of 15 different temperature-reading points. Four readings were taken before the first slurry heat exchanger. Two readings were taken between the first slurry heat exchanger and the air conditioner coil. Five readings were taken between the air conditioner coil and the second slurry heat exchanger. Two readings were taken between the second slurry heat exchanger and the air outlet. Finally, there were two readings taken inside the tank; one at the bottom and one at the top. The number of thermocouples between each component had a great deal to do with the available duct length between the components. All thermocouples were attached to a CIO-EXP16 data board and the data was then read into a program that recorded readings at a constant, user specified time increment.

Air flow rates were measured using a Testo 405-V2 Anemometer with a digital display. Taking measurements at 9 intervals in the duct and then averaging the nine values determined the value of the flow rate. Although it is preferable to have more measuring points, the diameter of the anemometer limited the ability to gather more data.



Figure 39: Anemometer

The bench model system was a relatively small system with short duct and hose lengths. However, testing was performed with airflows and temperatures representative of practical values. For these reasons, the analysis performed on this system will be accurate and applicable to full scale system predictions.



Figure 40 - View from the top of the tank, showing the "slushy" PCM slurry mixture.



Figure 41 - View of the PCM slurry material as it is removed from the tank.

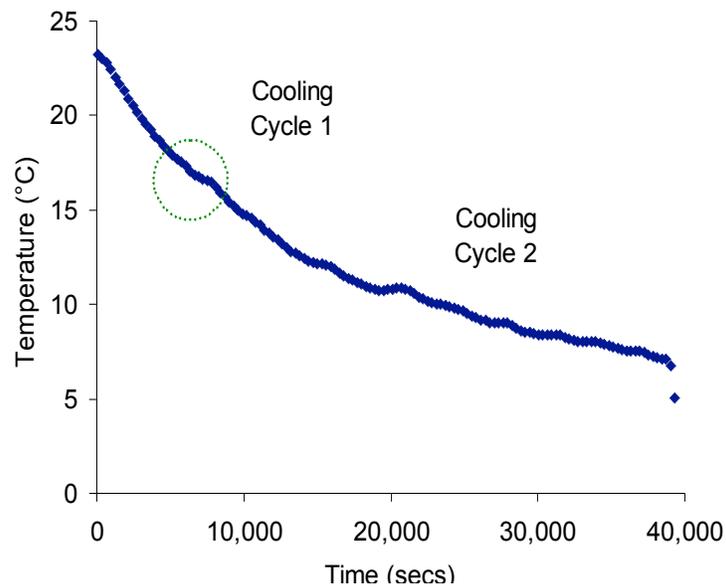


Figure 42 - PCM slurry temperature during cooling. Circle indicates end of cooling cycle 1 and the start of cooling cycle 2. Note, there is no noticeable temperature rise, indicating phase change and supercooling has not yet occurred. PCM Slurry Composition: 30 percent hexadecane, 1 percent Triton X100.

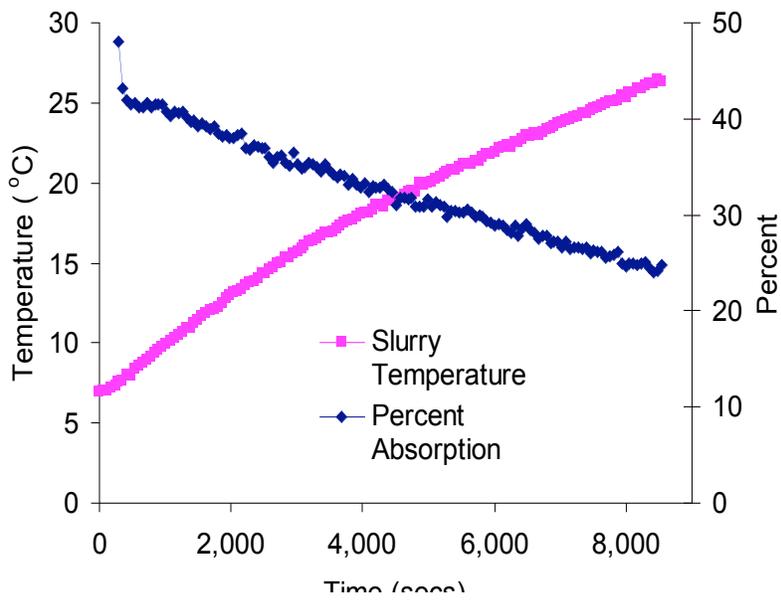


Figure 43 – PCM slurry temperature and percent energy absorbed. Average percent energy absorbed is 33 percent. PCM Slurry Composition: 30 percent hexadecane, 1 percent Triton X100.

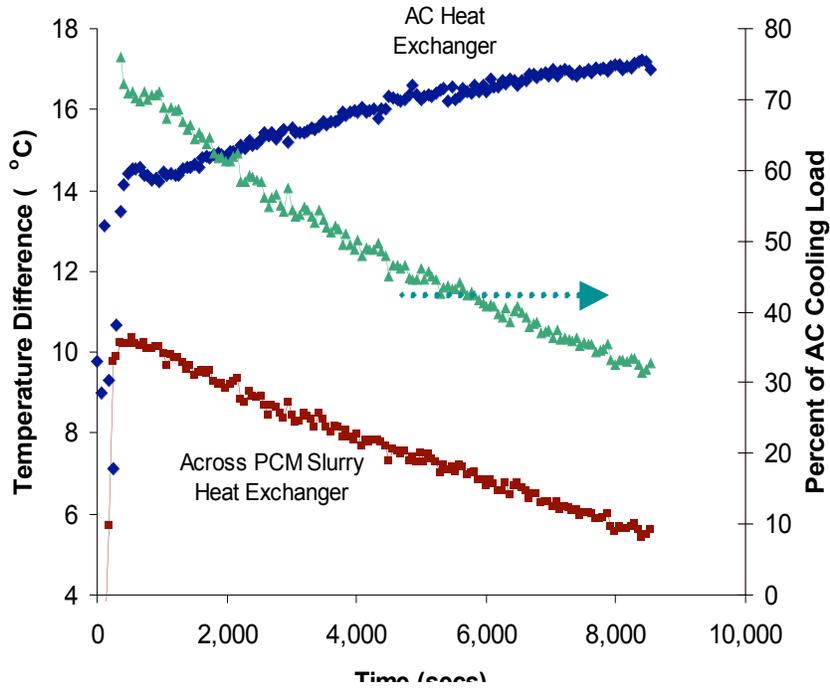


Figure 44 – Comparison of temperature drops across PCM slurry heat exchanger to the amount of energy lost across the AC unit. PCM Slurry Composition: 30 percent hexadecane, 1 percent Triton X100.

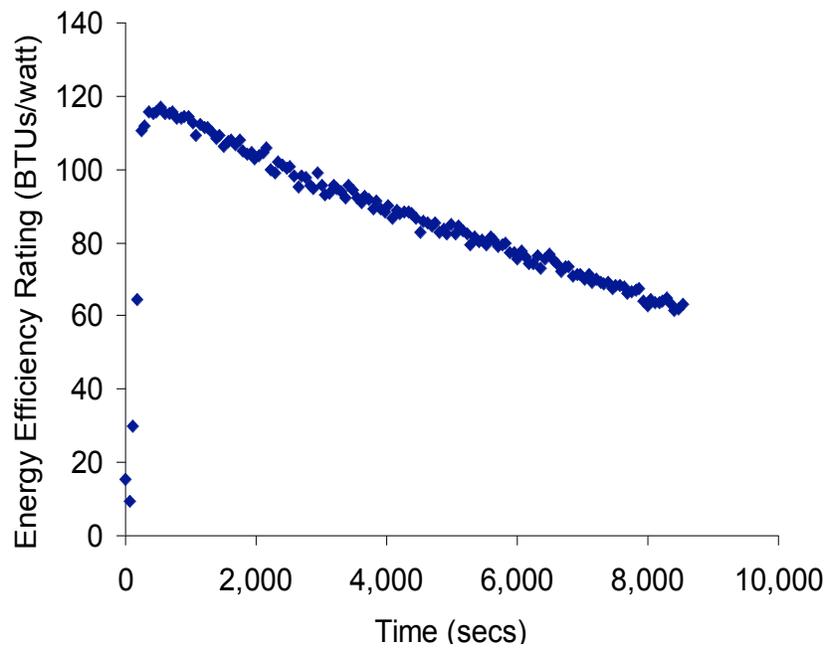


Figure 45 - Average EER = 86 for two pump configuration. PCM Slurry Composition: 30 percent hexadecane, 1 percent Triton X100.

The last set of figures here demonstrates that other tests were conducted to demonstrate that the PCM slurry system functioned as envisioned.