# Active Thermal Control System for CubeSat

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## ABSTRACT

The use of CubeSat systems for low-orbit data collection has increased due to their low cost development and light weight designs. For efficient data collection to occur, it is imperative that the satellite's internal components remain fully functional throughout its mission life. To ensure the components remain in their operational range, an internal thermal control subsystem must be developed to effectively combat the transfer of heat. The standard size and payload of a CubeSat eliminates the possibility of designing a conventional fluid flow piping system. Through the development of a phase change material (PCM) thermal control system, the internal components will experience smaller temperature variations, while remaining within their operational limits. The melting temperature for optimal PCM performance, with a component operational range from 0-40□, is currently desired to be 45□, and the selection between Organic and Inorganic materials can be found below. The calculations developed in this report assume that the outside radiation and ultraviolet heat sources will minimally impact the temperature of the interior structure, allowing for further focus on the component heat generation. This paper presents preliminary designs and calculations towards the development of a low cost and replicable active thermal control system for the interior of CubeSats and is originally intended for implementation on Florida International Universities' NEESAT.

## Keywords

Heat transfer, Conduction, Radiation, Phase change material (PCM), Thermal control system, CubeSat, 3U, FUNSat, NEESat

## NOMENCLATURE

| | |
|---|---|
| $Q$ | Thermal Energy, $W$ |
| $k$ | Thermal Conductivity, $W/_{m*K}$ |
| $A$ | Cross-Sectional Area, $m^2$ |
| $l$ | Section Length, $m$ |
| $D$ | Diameter, $m$ |
| $T_h$ | Hot Temperature, $°C$ |
| $T_h$ | Cold Temperature, $°C$ |
| ρ | Density, $kg/m^3$ |

## 1. INTRODUCTION

The increase in popularity of CubeSat systems has allowed for large scale research towards the development of low cost, low weight and effective in-orbit data collection. The Florida International University's Near Earth Explorer Club is currently manufacturing a 3U picosatellite for use in the NASA FUNSat competition, with the goal of further developing existing CubeSat research. To minimize the systems payload while remaining in the satellite's internal boundaries (10 x 10 x 30 *cm*), the overall weight and size of the thermal control system must be minimized. To achieve this goal, the current system design integrates the use of a PCM to provide the necessary thermal control to allow the multiple internal components (seen in *3.1 – Components*) to operate efficiently throughout the intended twenty-year mission life.

A PCM, or phase change material, is a description given to any substance that has a sharp melting point and a large heat of fusion [1]. This combination of properties allows PCMs to have vast applications in the thermal control of space equipment and vehicles. Through the use of chemical bonds, PCMs are able to store and release large amounts of latent heat energy while consistently having a low temperature difference [1]. The latent heat storage method developed through PCMs has 5-14 times more heat capacity per unit volume when compared to materials used in sensible heat storage systems, further increasing their effective usage in a CubeSat cooling subsystem. The most common and effective PCM transformation is the solid-liquid because of the small volume change necessary for implementation, when compared to vaporization and sublimation [2]. Due to the complexity of the design, the large volume changes that occur during the vaporization and sublimation phase transition rules out their potential utility in a thermal storage system [3].

A PCM material needs a high latent heat of fusion per unit mass to be able to store a large amount of latent heat energy in a small volume of material. A high thermal conductivity is necessary to increase the temperature gradient required for charging the storage material so the material could absorb large quantities of heat in a short period of time. With a large density value, a smaller volume of material will provide an ease for encapsulation method designs, while maintaining proper absorption and rejection parameters. To ensure a stable system life, the phase change material must have minimal chemical decomposition, as well as an increased thermal stability [1]. PCMs are categorized into three main material groups:

organics, inorganics and eutectic (combination or organic and inorganic materials), as seen in Figure 1 – '*Classification of PCMs*' below.

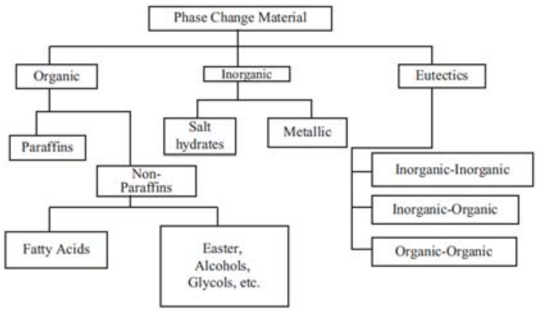


**Figure 1 – Classification of PCMs [3]**

## 2. THERMAL CONTROL SYSTEM FOR INTERNAL HEAT GENERATION

The thermal control system serves the main function of maintaining the internal components within their operational temperatures throughout the proposed mission life. The NEESat system is composed of multiple heat generating subsystems, each with their own components, as follows: optical, attitude determination and control, communication and computing, as seen in *3.1 – Components*, below. A major challenge in the development of the PCM thermal control system lies in the configuration of the separate subsystem components within the overall CubeSat structure. Multiple phases of thermal calculations were performed to gather a fundamental understanding of the effects of parameter variations within the preliminary design. An example of a PCM thermal control system can be seen in Figure 2 – *PCM 'Thermal-Control System for Short-Duty-Cycle Electronic Components'*, below.

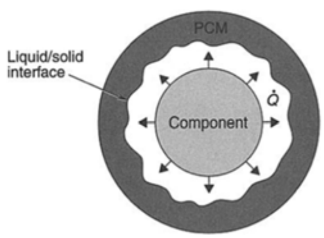


**Figure 2 - PCM Thermal-Control System for Short-Duty-Cycle Electronic Components [2]**

In this thermal control system, the PCM is component dependent, meaning that each component requires its own thermal control system. A CubeSat system containing many heat generating internal components would not benefit from such a system due to the strict payload and space parameters. A design containing a centralized PCM thermal control system would have the greatest advantage for a CubeSat system because it will centralize the heat and transfer it equally throughout the system.

### 2.1 Components

As previously mentioned, the proposed components for the NEESat are separated into the following subsystems: optical, attitude determination and control, communication and computing, with a more detailed list shown in Table 1 – '*NEESat Components per Subsystem*', below.

**Table 1 – List of Components per System [4]**

| **Subsystem** | **Component** | **Max Power Req. (W)** |
|---|---|---|
| Optical | CMOS | 0.38 |
| | OV14810 CMOS | 0.64 |
| | SeekThermal | 0.28 |
| | TMP36 (x10) | 0.00 |
| | IR Temp Sensor (x6) | 0.08 |
| Attitude Determination and Control | LSM9DS0 | 0.04 |
| | Sun Sensor (x6) | 1.5 |
| Communication | USRP + GPS + Antenna | 3.0 |
| | Power Amplifier | 7.0 |
| Computing | Arduino Mega | 5.0 |
| | BeagleBone Black (x2) | 22.01 |
| Total | | 39.93 |

For the mission of the NEESat system to be fully achievable, the thermal control system must be designed to combat the maximum power output achievable by the internal components. The components require the temperature to be maintained between 0-40□ because of the lower operational temperature range of the onboard lithium polymer batteries, as seen in Table 2 – '*Internal Component Operating Temperatures*.'

**Table 2 – Internal Component Operating Temperatures [4]**

| Internal Components | Operating Temperatures [□] | |
|---|---|---|
| | $T_{min}$ | $T_{max}$ |
| CMOS | -40 | +85 |
| OV14810 CMOS | -30 | +70 |
| SeekThermal | -30 | +70 |
| TMP36 | -40 | +125 |
| IR Temp Sensor | -40 | +125 |
| Arduino Mega | -40 | +85 |
| BeagleBone Black | -40 | +90 |
| Lithium Polymer Battery | 0 | +45 |

An example of some of the components used in the optical system can be seen in Figure 3 – '*Sensor Components used in Optical Subsystem'* below. The sizes of the individual components and computing chips vary, but each poses a challenge for the design of a centralized heat exchange system.

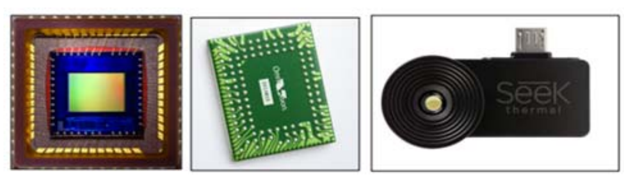


**Figure 3 – Sensor Components used in Optical Subsystem [4]**

The NEESat system is composed of multiple subsystems, each with its own set of components, example seen in Figure 3 above and Figure 4 below. Figure 3 shows an example of the SeekThermal and CMOS chips, both located in the optical system. Figure 4, below, shows an example of the LSM9DS0 sensor which is used in the attitude and orbital control system, developed by a previous FIU FUNSAT team, to orient the CubeSat towards the sun [5].

**Figure 4 – LSM9DS0 Sensor used in Attitude and Orbital Control [5]**

For the development of preliminary thermal calculations, the overall power consumption for each NEESat subsystem was determined through past experiences, as well as literature research, and is populated in Table 1, above. The overall component power consumption of ~40 Watts will be used to aid in the determination of the various centralized PCM parameters, as seen in section 3.2 – *Thermal Calculations*.

## 2.2 Thermal Calculations

The preliminary calculations developed in the following phase sections were determined using the heat transfer equations and fixed parameters, shown below. The development of the thermal control system required that the maximum power consumption of the electronic components be equal to the maximum heat generated, as seen in Table 4 below. Designing in terms of the worst possible scenario will ensure that the components will remain in their operational range. The first equation (1), as seen below, was used to determine the average conduction temperature of the PCM in the centralized heat pipe system design with the following fixed parameters:

**Table 3. Fixed Parameters in Phase 1**

| Parameter | Value | Units |
|---|---|---|
| Thermal Conductivity [$k$] | 401 | $W/m*K$ |
| Cross-Sectional Area [$A$] | 0.053 | $cm^2$ |
| Heat Pipe Length [$L$] | 1 | $cm$ |
| Component Temperature [$T_h$] | 35 | □ |

The thermal conductivity value of 401 $W/m*K$ stated above is taken from the copper heat pipe material, while the heat pipe length was fixed for preliminary calculations. The cross sectional area value was determined from the diameter value of 2.59 $mm$ in 10 gauge copper wire. The temperature of the component was set to 35□ because of the maximum operational temperature of 40□ for the internal components.

$$Q = \frac{kA}{L} * (T_h - T_c) \tag{1}$$

$$T_c = T_h - \frac{QL}{kA} \tag{2}$$

Equation (1) was then manipulated to determine the temperature at the end of the heat pipe secured to the central PCM encasement, as seen in Equation (2) above.

With the use of Equation (2), the PCM temperature for each of the components, with the parameters detailed above, were determined and noted in Table 4 – '*Determined PCM Temperature per Component*'.

**Table 4. Determined PCM Temperature per Component**

| Component | Total Heat Output [W] | Determined PCM Temperature [□] |
|---|---|---|
| CMOS | 0.38 | 33.22 |
| OV14810 CMOS | 0.64 | 31.95 |
| SeekThermal | 0.28 | 33.67 |
| IR Temp Sensor | 0.08 | 34.61 |
| LSM9DS0 | 0.04 | 34.83 |
| Sun Sensor | 1.50 | 27.89 |
| USRP + GPS + Antenna | 3.00 | 20.77 |
| Power Amplifier | 7.00 | 1.81 |
| Arduino Mega | 5.00 | 11.29 |
| BeagleBone Black | 22.01 | -69.37 |

### *2.2.1 Phase 1 – Average Temperature of PCM*

The first phase of calculations will determine the average temperature of the centralized PCM encasement by utilizing the component data provided in Table 4, as well as the fixed parameters detailed in Table 3. With the total heat output being ~40 Watts, it was determined that the average temperature of the PCM with all the components generating heat is 16.07 □.

### *2.2.2 Phase 2 – Heat Pipe Length Variations*

The three components with the largest heat generation were selected to determine the thermal effect when changing the heat pipe length. The parameters selected for the second phase of preliminary calculations can be found in Table 5 below.

**Table 5. Fixed Parameters in Phase 2**

| Parameter | Value | Units |
|---|---|---|
| Thermal Conductivity [$k$] | 401 | $W/m*K$ |
| Cross-Sectional Area [$A$] | 0.053 | $cm^2$ |
| Heat Pipe Length [$L$] | 2 | $cm$ |
| Component Temperature [$T_h$] | 35 | □ |

The effect of doubling the heat pipe length for the BeagleBone Black, power amplifier and Arduino Mega can be found in Table 6 below.

**Table 6. Length Variation Effect on Component Temperature**

| Component | Total Heat Output [W] | Determined PCM Temperature [□] |
|---|---|---|
| Arduino Mega | 5.00 | -12.42 |
| Power Amplifier | 7.00 | -31.39 |
| BeagleBone Black | 22.01 | -173.75 |

As seen in Table 6, it was determined that doubling the length of the heat pipe resulted in a lower average temperature for the central PCM system. To be able to properly design a centralized PCM thermal control system, the final design will have varying heat pipe lengths for each component, which will be determined in a future calculation phase.

## 2.3 PCM Selection

To effectively combat the ~40 Watt heat output of the internal components, it was determined that a material with a ~45□ phase change temperature is effective at regulating the large temperature variations. The PCM types being considered for use in the NEESat internal thermal control subsystem are Organic and Inorganic, as seen in Figure 1 above. The NEESat internal thermal control research conducted will focus on organic PCMs due to their environmental and financial benefits, but will also include inorganics because of their high heat of fusion and availability [3].

PCMs contain many important physical and chemical properties that allow them to be useful and efficient in thermal energy storage environments. A PCM requires a high latent heat of fusion per unit mass to be able to store large amounts of latent heat energy in a small amount of material [1]. A high thermal conductivity is necessary to increase the temperature gradient required for charging the material to a phase change temperature to aid in the capturing of latent heat [1]. With a larger density value, a small volume of material will reduce necessary space requirements for the method of centralized PCM encapsulation. In comparison to inorganics, organic materials have a moderate thermal energy storage density, which requires a larger surface area to combat the effect of the lower conductivity. . Besides having a melting point in the desired temperature parameters for the application, a PCM should be non-poisonous, non-flammable and non-explosive to minimize the health and safety requirements needed to develop and operate such a system, as well as minimizing the ecological and environmental impacts of its production and use. To ensure a stable system life, the phase change material must have minimal chemical decomposition, as well as an increased thermal stability [1].

Research was conducted to determine commercially available and cost effective PCM materials ~45□ melting, or phase change, temperature. The organic and inorganic PCMs proposed for possible use in the NEESat internal thermal cooling subsystem can be found in Tables 7 – '*Organic PCMs Proposed for NEESat Application'* and 8 – 'Inorganic *PCMs Proposed for NEESat Application'* seen on the following page..

**Table 7. Organic PCMs Proposed for NEESat Application**

| Material | Phase Change Temperature [□] | Density $[kg/m^3]$ | Latent Heat Capacity $[kJ/kg]$ |
|---|---|---|---|
| PureTemp 42* | 42 | 940 | 218 |
| PureTemp 48* | 48 | 900 | 230 |
| A43** | 43 | 780 | 165 |
| A44** | 44 | 805 | 242 |
| A46** | 46 | 910 | 155 |
| A48** | 48 | 810 | 234 |

* Material and technical information gathered from Entropy Solutions, LLC

** Material and technical information gathered from PCM Products.

**Table 8. Inorganic PCMs Proposed for NEESat Application**

| Material | Phase Change Temperature [□] | Density $[kg/m^3]$ | Latent Heat Capacity $[kJ/kg]$ |
|---|---|---|---|
| S44** | 44 | 1584 | 100 |
| S46** | 46 | 1587 | 210 |

** Material and technical information gathered from PCM Products.

Tables 7 and 8 show a direct comparison between the latent heat capacities of organic and inorganic PCMs. Although the latent heat per mass values vary by ~100 $kJ/kg$, the value that contributes to the large thermal capacity of inorganic PCMs is the density. The lower material densities of organic materials will require a larger volume, which could be inhibited by the NEESat internal space parameters.

Although extremely beneficial to space and component limited thermal energy storage systems, PCMs experience degradations such as phase segregation and super cooling. Organic phase change materials constantly operate in a melting and freezing cycle without any phase segregation, or congruent melting, they crystallize with little super cooling and they usually share non-corrosive properties [3]. Salt hydrate inorganic PCMs succumb to the problem of phase separation and super cooling, which decreases the temperature at which the material solidifies. [6]. When salt hydrates are melted, multiple other hydrates form. These newly developed hydrates settle out over time and reduce the overall volume available for the storage of latent heat [6]. With the addition of multiple different chemicals and materials to PCMs, such as conductive particles into organic paraffins or nucleating agents in inorganic salt hydrates, these problems could be effectively countered [6].

## 2.4 Proposed Design

The thermal control system for the internal heat generating components of the NEESat will consist of a centralized PCM heat exchange design. The proposed PCM thermal energy storage (TES) design will thermoregulate the electrical components by direct conduction through a heat pipe alternative, as seen in Figure 5 – '*Central PCM TES System*' below. In this thermal energy storage system, the energy lost from the electronic components during its hot atmospheric orbit is transferred directly into the central PCM, through heat pipes, with the indirect intention of heating the system during its cold atmospheric orbit [2].

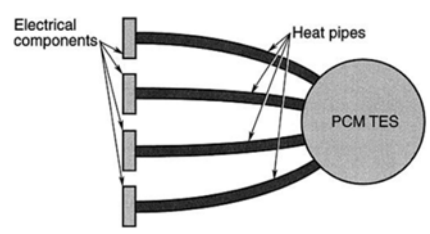


**Figure 5 – Central PCM TES System [2]**

The proposed system design will be composed of PCM encapsulated in a metallic, chemically compatible, container with a direct and secure connection to one end of the heat pipe. The other end of the heat pipe will be securely fastened to the surface of the electrical component, to ensure that connections remain fixed through the vibrations experienced during the CubeSat's journey to orbit. The heat pipe will be developed through use of commercially available copper wire, as seen in Figure 6 – '*NEESat Proposed Copper Wire Heat Pipe*' below, with the final gauge size to be determined for each component through further simulation and testing. Copper was chosen as the heat transfer medium due to its high thermal conductivity of ~401 $W/m*K$, its low cost and commercial availability.

**Figure 6 – NEESat Proposed Copper Wire Heat Pipe**

Through a series of precise solders, the heat pipe could be securely fastened to the proposed encapsulation sphere of the PCM. One challenge of thermal regulation in space is the limitation to conductive methods of heating and cooling, which increases the difficulty of securing the remaining end of the heat pipe to the components surface. A component friendly method of securing the heat pipe to its respective surface will ensure efficient operation throughout the systems desired mission life.

The preliminary phase calculations seen in section 3.2, above, use the average temperature value of the PCM to determine the average heat pipe length for the system. It is important to note that this phase of calculations does not reflect the heat pipe length of each individual component in the system.

# 3. DISCUSSION

This paper presents an active thermal control system for the internal regulation of CubeSat systems, with specific implementation on the FIU NEESat. The proposed design incorporates a centralized phase change material encasement, previously discussed in section 3.4, which will thermoregulate the 40 Watts of internal heat generated by the components through a series of conductive heat pipes. Section 3.2 details the preliminary phase thermal calculations conducted to begin the determination of the final PCM as well as the parameters necessary to design an efficient system. The PCMs average temperature through the hot atmospheric orbit was determined to be 16.07 □ with the initial parameters set in section 3.2.1. The initial heat pipe length of 1.0 cm was varied in section 3.2.2 to determine the relationship between temperature variations with the length values. It was determined that doubling the heat pipe length from 1.0 to 2.0 cm resulted in a large decrease in the PCMs average temperature. Further research, analysis and development will be conducted towards the final design of the centralized PCM internal thermal control system through use of two simulation software, SolidWorks and ANSYS, as well as laboratory vacuum chamber testing at FIU's Advanced Materials Engineering Research Institute (AMERI).

# 4. CONCLUSION

The proposed internal thermal control subsystem design offers a cost effective, commercially available and easily adaptable method of thermoregulating a wide range of CubeSat applications. This report outlines the research, calculations and analysis performed towards the development of an interior cooling system for the FIU NEESat, which will be competing in the 2016-2017 NASA FUNSat competition. The active thermal control system offers payload and space advantages while thermoregulating the ~40 Watts of maximum component heat generated into the system.

The proposed subsystem was designed using the parameters on the existing NEESat structure, the FUNSat competition standards, the CubeSat standards, as well as the multiple parameters listed in section 3.2. Along with the finalization of the proposed thermal control system design, the individual components must be simulated and tested for their conductive heat generation as well as the determination of the PCM thermal regulating rates.

# 5. ACKNOWLEDGMENTS

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# 6. REFERENCES

[1] A., Sekar, Siddhartha Jain D.N., Govinda K.V., and Arun Kumar S. "Phase Change Materials (PCM) for Thermal Control During Spacecraft Transportation." *International Journal of Mechanical and Industrial Engineering* 3.1 (2013): 1-5. Web.

[2] Bledjian, L., M.J. Hoover, and M.J. O'Neill. "Phase-Change Materials." (n.d.): 373-403. Web.

[3] Rathod, Manish K, and Jyotirmay Banerjee. "Thermal Stability of Phase Change Materials Used in Latent Heat Energy Storage Systems: A Review, "*Renewable and Sustainable Energy Reviews"* 18 (2013): 246-58. Web.

[4] Hernandez, Sergio, Walter Salas, Cruz Philippe, Elijah Newman, Paul Frosik, and Jonathan De Groot. RoarSAT. Thesis. Florida International University, 2016. N.p.: n.p., n.d. Print.

[5] Shinde Pradeep, Newman Elijah, Tansel Ibrahim, Tosunoglu Sabri. Design of FIU FUNSAT System: Attitude Control for the 3U CubeSat. FCRAR 2016.

[6] Lane GA. Solar heat storage: latent heat material, vol. 1, Background and scientific principles. Florida: CRC Press; 1983.