Thermal Assessment of Paraffin Phase Change Material Mini-Packs on IceCube 3U CubeSat in Flight

Michael K. Choi*
NASA Goddard Space Flight Center, Greenbelt, MD 20771

Three paraffin phase change material (PCM) mini-packs were flown on the IceCube instrument in the International Space Station (ISS) orbit. They contained a total of 40.69 g of n-Hexadecane. In flight, from Day of Year (DOY) 250-255 in 2017, the IceCube instrument operation scheme was "Day-On Every Other Orbit". The instrument power-on time was approximately 45.6 minutes longer than the design power-on time. Its power-off time was 47 minutes longer than the design power-off time. Flight temperature telemetry data revealed that latent heat change of the paraffin PCM maintained the instrument temperatures at about 18°C most of the time. It validated the functionality of the paraffin PCM mini-packs.

Nomenclature

3U	=	three unit (30 cm x 10 cm x 10 cm) CubeSat
C	=	carbon
DOY	=	Day of Year
H	=	hydrogen
ISS	=	International Space Station
IFA	=	Intermediate Frequency Assembly
LEO	=	low Earth orbit
MLA	=	Mixer LO Assembly
PCM	=	phase change material
U	=	one unit (10 cm x 10 cm x 10 cm) CubeSat
UTC	=	Coordinated Universal Time

I. Introduction

IceCube was a three-unit (3U) CubeSat mission at NASA Goddard Space Flight Center. The nanosatellite was brought to the International Space Station (ISS) on the OA-7 mission, which was launched from the Kennedy Space Center on April 18, 2017. Then on May 16, 2017, the IceCube was deployed from a NanoRacks deployer on the ISS. Figure 1 shows an image of the deployment. The IceCube orbit is the same as the ISS low Earth orbit (LEO), which has a 400 km average altitude and a 51.6˚ inclination, and is nearly circular. The primary scientific goal of the IceCube mission was to measure cloud ice from space. Figure 2 is a schematic of the IceCube. The sun sensor, which is located at the -Y side, always points along the solar vector. The IceCube spins about the Y-axis at 3 minutes per revolution. The instrument consists of four components: Mixer LO Assembly (MLA), Intermediate Frequency Assembly (IFA), Receiver Interface Card (RIC) and Power Distribution Unit (PDU). It is accommodated by the upper (+Z) 13 cm x 10 cm x 10 cm volume of the IceCube. The spacecraft internal components are accommodated by the remaining volume. There are two deployable solar array wings. Each has two panels hinged together, with solar cells on the –Y side. The outboard panel of each wing also has solar cells on the +Y side, which serve as backup for off-nominal scenario when sunlight impinges the –Y side. There is a fixed two-unit (2U) solar array panel on the –Y side and a fixed one-unit (1U) solar array panel on the –Z side of the IceCube body. The latter serves as a backup. Figure 3 shows the IceCube, with the closeout panels on the +Y side removed, during integration and testing.

* Senior Aerospace Engineer, Heat Transfer, AIAA Associate Fellow.

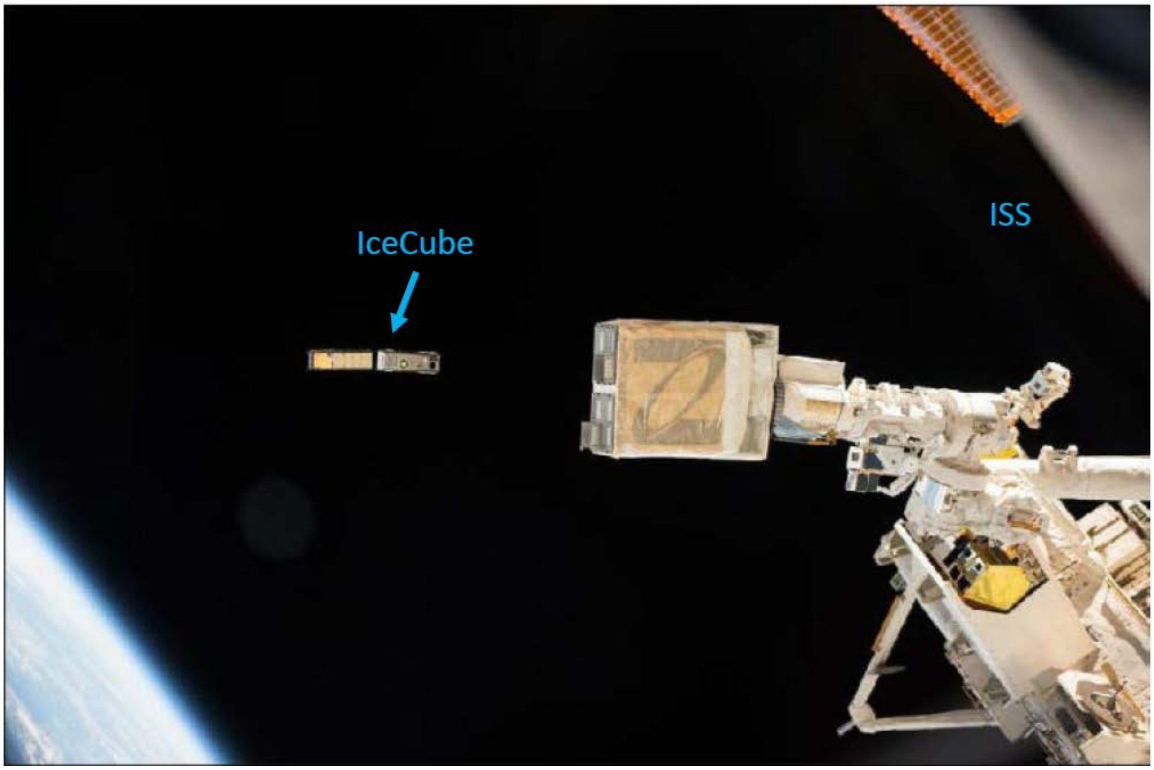

Figure 1. IceCube (and CXBN-2) Deployed from NanoRacks Deployer on ISS (Credit: NASA).

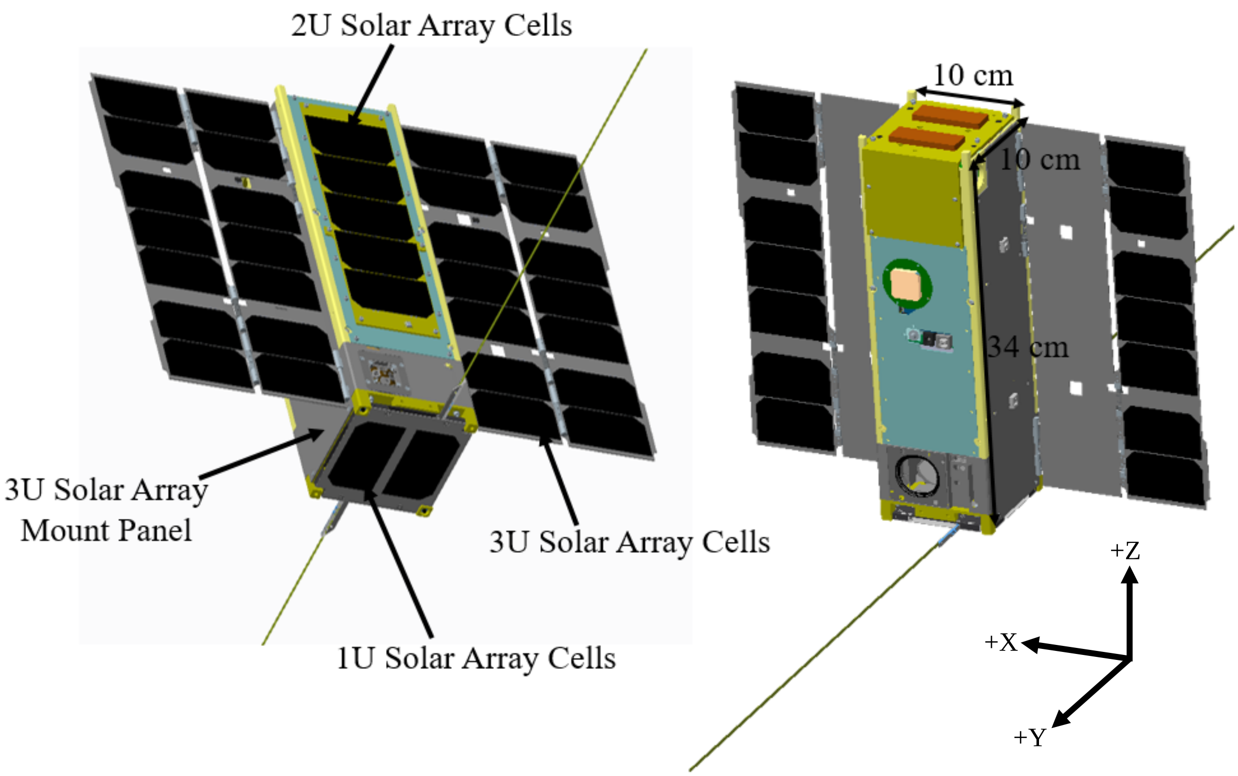

Figure 2. Schematic of IceCube.

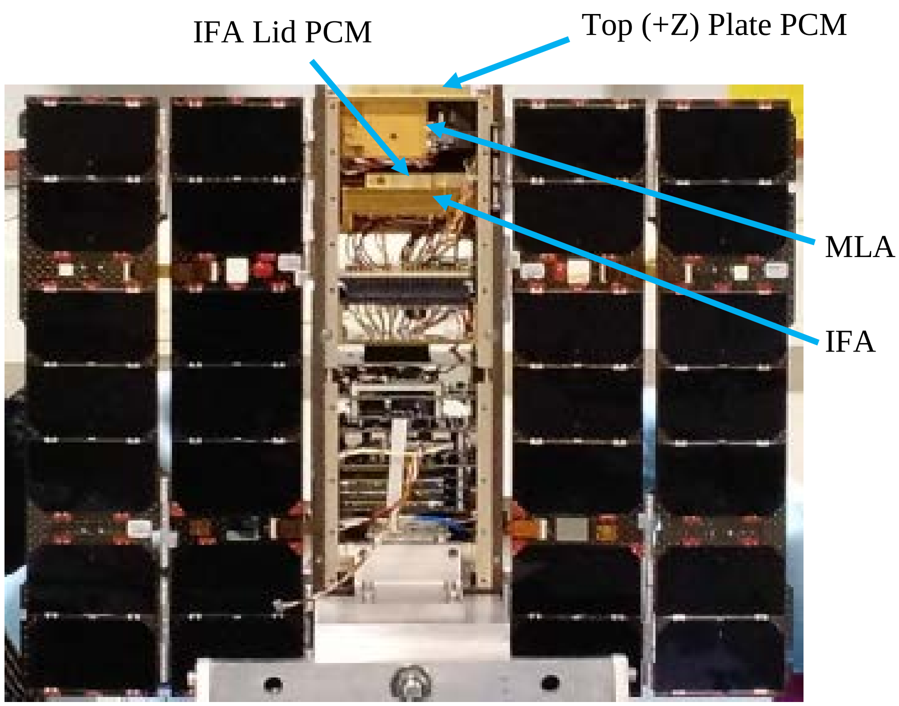

Figure 3. IceCube during Integration &Testing (Credit: NASA).

II. Why Paraffin PCM is Flown on IceCube Instrument?

Table 1 presents the IceCube instrument power dissipation and thermal requirement used for thermal design and analysis at the Critical Design Review.[1] The thermal environment of the ISS LEO orbit is very unstable due to solar beta angles in the -75˚ to +75˚ range, sunlight and eclipse. Additionally, the instrument is powered off in the eclipse to conserve electrical power. In order to satisfy the instrument thermal requirement, the following thermal design techniques were used. The MLA and IFA assembly is thermally isolated from other spacecraft or instrument components. The +Y plate and +Z plate are used as radiators for the MLA and IFA. The two plates are bolted together to allow heat conduction. Three paraffin phase change material (PCM) mini-packs are used.[1] They are attached to the exterior of the top (+Z) plate, interior of the +Y plate, and the top of the IFA lid, respectively. They were intended to be thermally shared by the MLA and IFA through the conduction paths to the two radiator plates. The paraffin is n-Hexadecane ($C_{16}H_{34}$), which has a melting point of 18°C and a 235 kJ/kg enthalpy of fusion.[1-4] Figure 4 depicts the instrument thermal features. Figure 5 displays the flight paraffin PCM mini-packs before they were integrated to the instrument. Table 2 presents a comparison of the mass of the flight paraffin PCM mini-packs. The total weighed mass of paraffin PCM is 40.69 g. It is capable of storing 9.562 kJ of thermal energy as latent heat. The PCM mini-packs had a fill temperature of 60°C.

Table 1. Instrument Power Dissipation and Thermal Requirement.

Component	Nominal Power Dissipation (W)	Operating Temperature (˚C)	Temperature Stability (˚C)	Survival Temperature (˚C)
MLA	3.07	20	± 1	-40 to 60
IFA	1.15	20	± 1	-40 to 60
RIC	0.3	-20 to 40	None	-40 to 60
PDU	2.42	-20 to 40	None	-40 to 60

Phase change of the paraffin PCM occurs at a constant temperature. It results in latent heat change due to heat addition or removal. It differs from sensible heat change, which is a result of temperature change to the thermal capacitance and does not involve phase change.

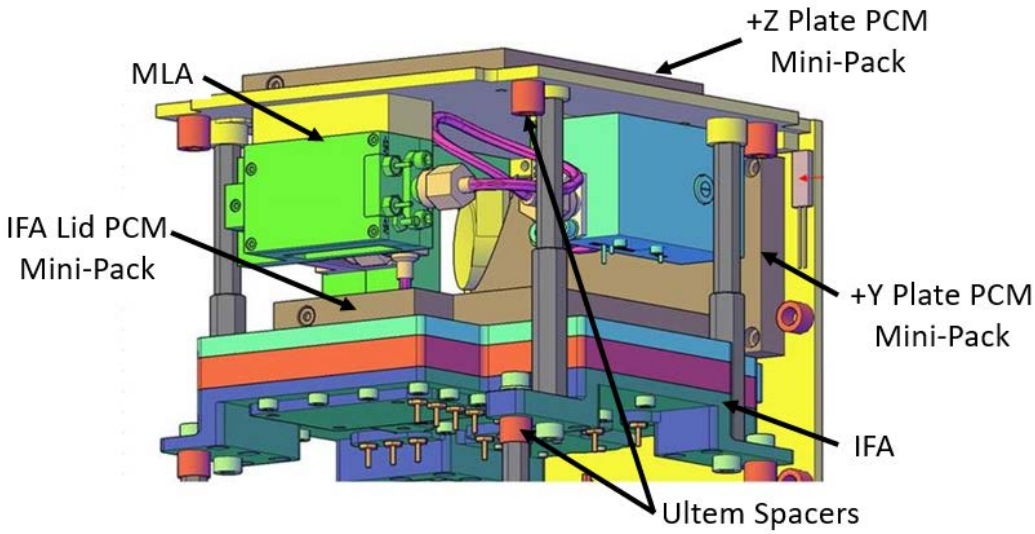

Figure 4. MLA and IFA Thermal Features.

Figure 5. IceCube Flight Paraffin PCM Mini-Packs.

Table 2. Comparison of Mass of Paraffin PCM Min-Packs.

	IFA Lid PCM Mini-Pack	+Y Plate PCM Mini-Pack	+Z Plate PCM Mini-Pack	Sum of Three PCM Mini-Packs
PCM Mass (g)	15.37	12.21	13.11	40.69
Structure (g)	16.25	13.74	13.67	43.66
Total Mass (g)	31.62	25.95	26.78	84.35

III. Design Power-On Time for IceCube Instrument

Solar beta angle in the ISS orbit affects the Earth albedo and infrared fluxes incident on the +Y plate and +Z plate of the instrument. The pre-launch instrument design power-on time per orbit to allow the 40.69 g of paraffin PCM melt completely versus the solar beta angle at the Critical Design Review is shown in Fig. 6.[1] The design power-off time, which allows the instrument to cool down, is the difference between the 92.6 minute orbit period and design power-on time. It allows the paraffin PCM to freeze completely. This power management scheme was designed to allow the paraffin PCM melt and freeze at 18°C continuously in flight, with no sensible heat change in the PCM.

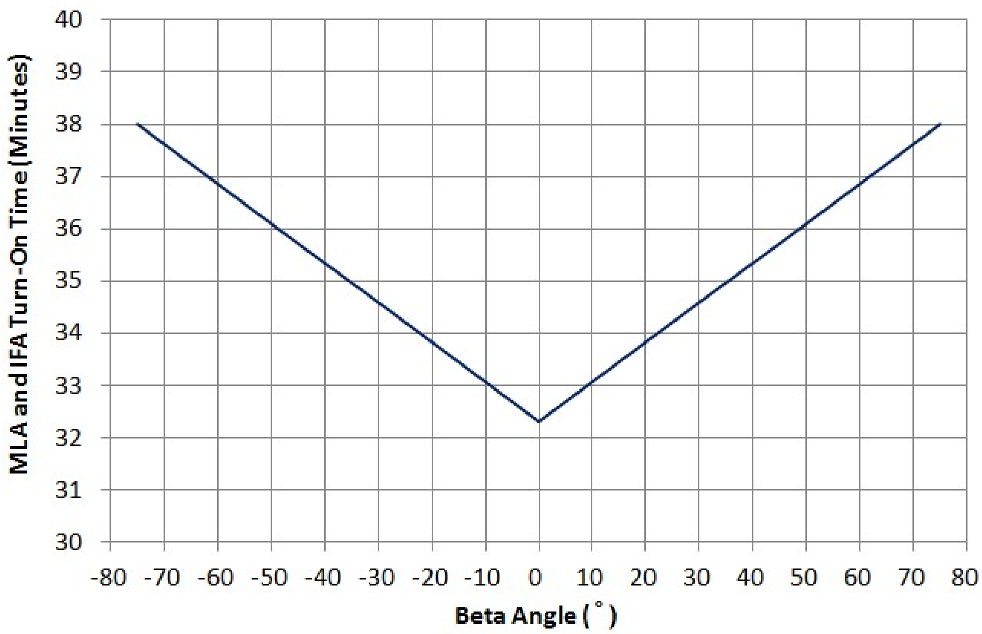

Figure 6. MLA and IFA Pre-Launch Designed Turn-On Time Required for Melting Paraffin.[1]

IV. Objective

The objective of this paper is to present a thermal assessment of the paraffin PCM mini-packs on the IceCube instrument in flight.

V. Thermal Assessment of Paraffin PCM Mini-Packs in Flight

The flight temperature telemetry data of the IceCube instrument are used to perform a thermal assessment of the paraffin PCM mini-packs. They are compared to the pre-launch thermal design and predictions.

A. Flight Temperature Sensor Locations

Table 3 presents a summary of the locations of the five temperature sensors, PRT-1 through PRT-5, on the IceCube instrument. They are platinum resistance thermometers. Figures 7 through 9 depict the locations of these temperature sensors. PRT-1 is located at the IFA isolator. It has a good conduction path to the paraffin PCM mini-pack attached to the lid of the IFA. The latter has a good conduction path to both the +Y and +Z radiator plates. PRT-2 is located at the IFA detector, which has a good conduction path to the +Y plate radiator. PRT-3 and -4 are located at the MLA, which has a good conduction path to the +Z plate. A paraffin PCM mini-pack is mounted to the +Z plate exterior. PRT-4 is the most sensitive to the instrument power dissipation because it is near the heat source of the MLA. PRT-5 is located at the interior of the +Y plate radiator, which has a paraffin PCM mini-pack mounted to it. It is close to an open area, which is outside the paraffin PCM mini-pack of the +Z plate. Therefore, PRT-5 is the most sensitive to the external thermal environment.

Table 3. IceCube Instrument Flight Temperature Sensors.

Temperature Sensor	Location
PRT-1	IFA Isolator
PRT-2	IFA Detector
PRT-3	MLA; Close to +Z Plate
PRT-4	MLA; Close to +Z Plate
PRT-5	+Y Plate Interior; Not Far from PCM Min-Pack

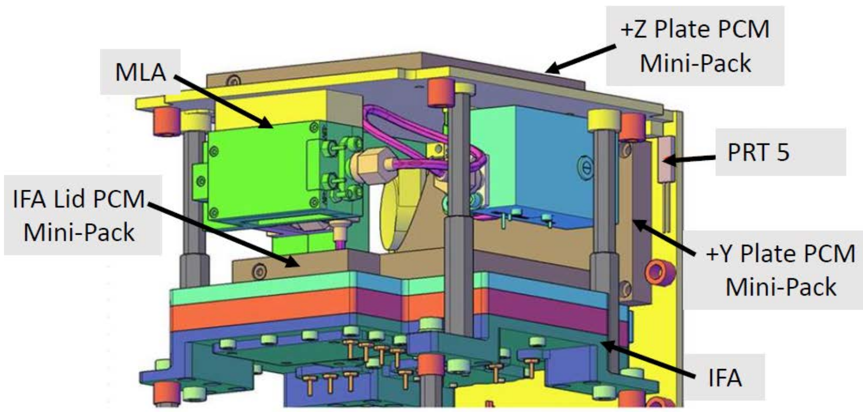

Figure 7. Locations of Paraffin PCM Mini-Packs and PRT-5.

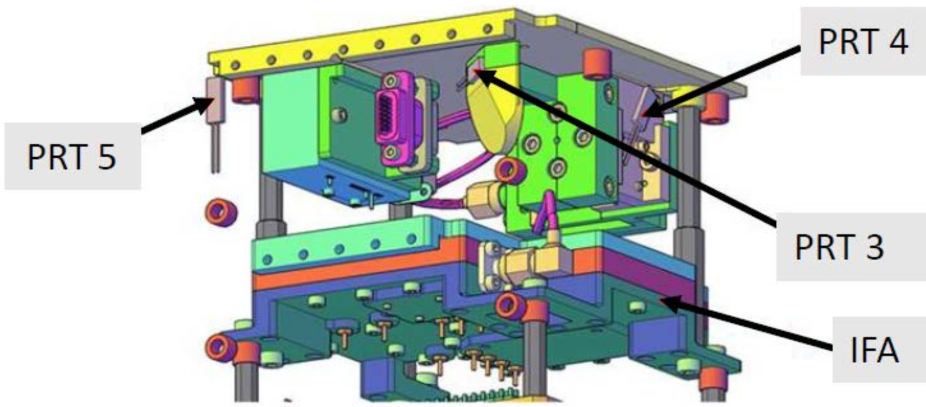

Figure 8. Locations of PRT-3, -4 and -5.

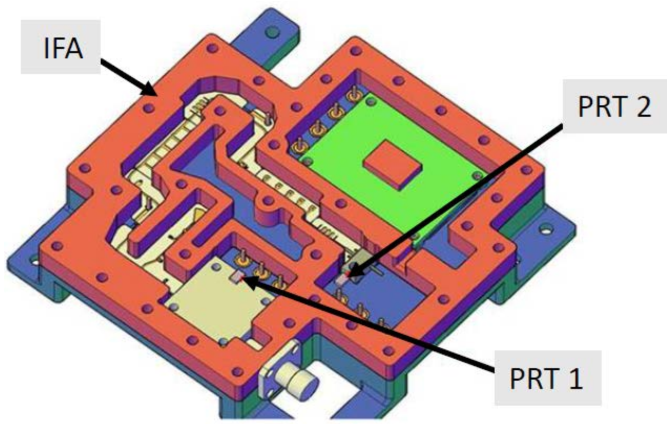

Figure 9. Locations of PRT-1 and -2.

B. Flight Temperature Telemetry Data during "Day-On/Night-Off" Operation

Figure 10 presents the IceCube instrument flight temperature telemetry data from DOY 159-161, in 2017.[5] The sunlight time and eclipse time were 56.6 minutes and 36 minutes, respectively. Prior to Coordinated Universal Time (UTC) 19:00 DOY 159 in 2017, the IceCube instrument was powered off. The instrument temperatures were at a -2°C minimum in the eclipse. At UTC 19:00 DOY 159, the instrument was powered on to begin its "Day-On/Night-Off" operation. That is, the instrument was powered on for 56.6 minutes, and powered off for 36 minutes in each orbit. The instrument power-on time was approximately 21.6 minutes longer than the pre-launch design power-on time. The maximum instrument temperature in the first orbit during this operation scheme was 10°C, which was 8.2°C colder than the melting point of the paraffin PCM. Therefore, the temperature change was by sensible heat change only in this orbit. The maximum instrument temperature in the second orbit was 18°C. The instrument temperatures started to bend over near orbit noon because of the effect of the paraffin PCM phase change from solid to liquid. From the third orbit to the sixth orbit, the amplitude of the instrument temperature oscillation decreased significantly, especially between the fifth orbit and sixth orbit. It is due to the latent heat change of the paraffin PCM during its phase change from solid to liquid. After the sixth orbit, the amplitude of the instrument temperature oscillation began to increase. The approximately 21.6 minutes longer operation time of the "Day-On/Night-Off" scheme than the design power-on time led to sensible heat change in the PCM. The instrument temperature rise at sunrise was slowed down by the paraffin PCM phase change. If the instrument operation time in sunlight were shortened to the pre-launch design power-on time, sensible heat change in the PCM would have been minimum, and instrument temperature stability would have been like, or better than, those between the fifth and sixth orbit. At the end of the eighth orbit, the instrument was powered off. The instrument temperatures began to decrease. In the ninth orbit, without power dissipation from the instrument, the instrument continued to radiate heat to deep space. As a result, the paraffin PCM phase change from liquid to solid occurred, and the instrument temperatures were stable. There was a 1°C to 2°C temperature gradient between the temperature sensors and the 18°C PCM melting point. It is expected, due to the thermal resistance between the paraffin PCM mini-packs and temperature sensors. After all the PCM changed from liquid to solid, the instrument temperatures decreased quickly due to sensible heat change only. After the ninth orbit, the instrument temperatures continued to decrease due to sensible heat change only.

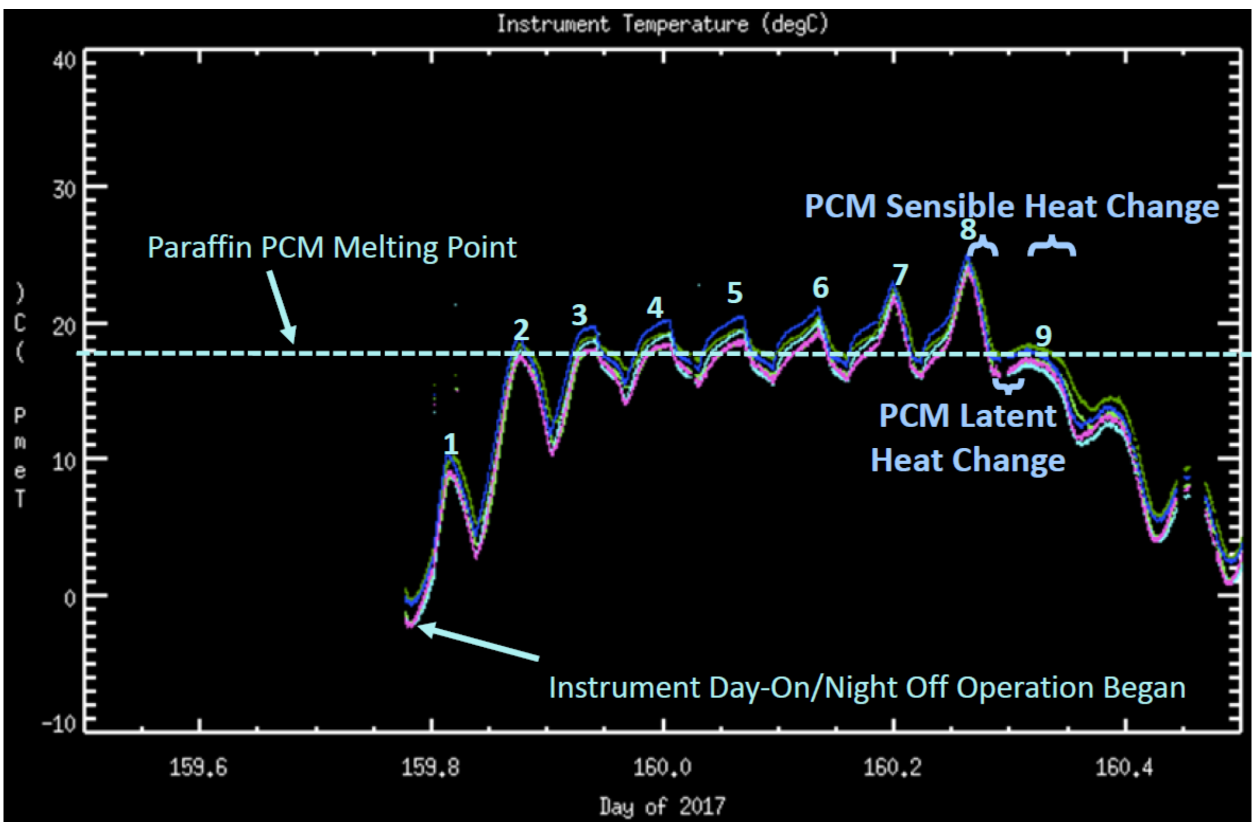

Figure 10. Instrument Flight Temperatures from DOY 159-161 in 2017.

Figure 11 presents the IceCube instrument flight temperatures from DOY 165-166 in 2017.[5] The sunlight time and eclipse time were 56.6 minutes and 36 minutes, respectively. Prior to UTC 17:00 DOY 165 in 2017, the instrument was powered off. The instrument temperatures were at a quasi-steady state of -2°C minimum in the eclipse and 5°C maximum in sunlight. At UTC 17:00 DOY 165, the instrument was powered on to begin its "Day-On/Night-Off" operation. That is, the instrument was powered on for 56.6 minutes, and powered off for 36 minutes in each orbit. The maximum instrument temperature in the first orbit during this operation scheme was 12°C, which was 6.2°C colder than the melting point of the paraffin PCM. The temperature change in this orbit was caused by sensible heat change only. The maximum instrument temperature in the second orbit was 18°C. The instrument temperatures started to bend over near orbit noon because of the latent heat change during the PCM phase change from solid to liquid. From the third orbit to the sixth orbit, the amplitude of the instrument temperature oscillation decreased significantly, especially between the fifth orbit and sixth orbit. After the sixth orbit, the amplitude of the instrument temperature oscillation began to increase and were settling at a quasi-steady state of 16°C minimum in the eclipse and 27°C maximum in sunlight. The approximately 21.6 minutes longer operation time of the "Day-On/Night-Off" scheme than the pre-launch design power-on time led to sensible heat change in the PCM. The instrument temperature increase at sunrise was slowed down by the paraffin PCM phase change from solid to liquid. If the instrument operation time in sunlight were shortened to the pre-launch design power-on time, sensible heat change in the PCM would have been minimum, and instrument temperature stability would have been like, or better than, those between the fifth and sixth orbit.

In terms of thermal energy balance, the "Day-On/Night-Off" instrument operation scheme in flight had large deviations from the pre-launch design power-on time for the 40.69 g of n-Hexadecane used. The mass of the paraffin is not adequate for this operation scheme. The results in flight are consistent with the pre-launch thermal model predictions for the instrument power-on time.

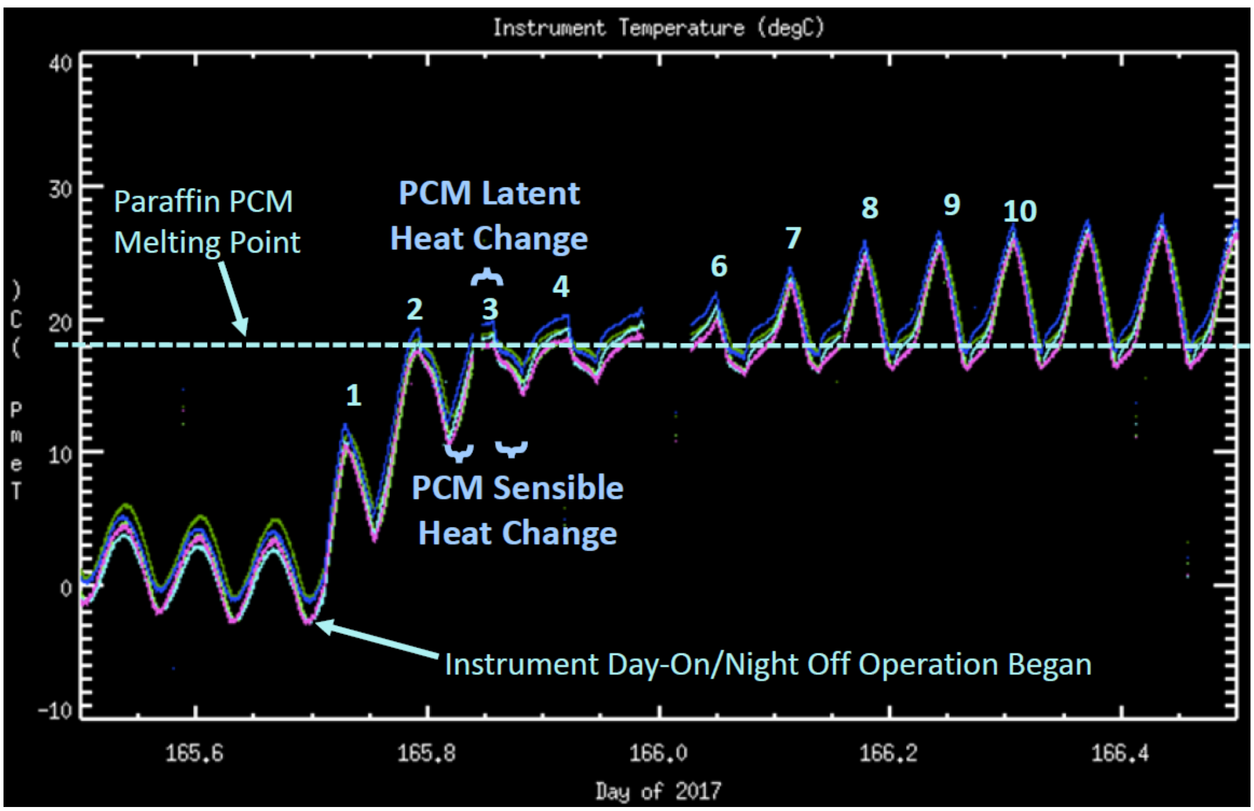

Figure 11. Instrument Flight Temperatures from DOY 165-166 in 2017.

C. Flight Temperature Telemetry Data during “Day-On Every Other Orbit” Operation

On DOY 250, 2017, the instrument operation scheme was changed to “Day-On Every Other Orbit”. The instrument was powered on in sunlight (i.e., during the Day) every other orbit. Additionally, when the temperature sensor PRT-4 dropped below 16°C, the instrument was powered on again even if it was in the eclipse (i.e., during the Night). When eclipse began, the instrument was powered off. As a result, the instrument power-on time was the sum of the remaining eclipse time in the first orbit, after the PRT-4 temperature dropped below 16°C, and the sunlight time in the second orbit. Figures 12 through 14 display the flight temperature telemetry data of the instrument from DOY 251-252, DOY 252-253, and DOY 254-255, respectively.[6] They also showed the relationship between the instrument temperatures, the instrument counts and spacecraft battery voltage. When the instrument power was on, there were instrument counts telemetry data. When the instrument power was off, there were no instrument counts telemetry data. When the IceCube was in sunlight, the battery voltage was 8.3 V. When eclipse began, the battery voltage began to decrease. It reached 7.7 V at the end of the eclipse. When the PRT-4 temperature dropped below 16°C in the eclipse, the instrument was powered on again. The minimum battery voltage was 7.5 V. After the eclipse, the IceCube was in sunlight and the battery voltage increased sharply.

From these figures, the sunlight time and eclipse time were 60.6 minutes and 32 minutes, respectively. Also from these figures, the instrument power on time was approximately 80.6 minutes. It was 45.6 minutes longer than the pre-launch design power-on time. Every two orbits, when the eclipse began and the instrument was powered off, the instrument temperatures began to decrease. Sensible heat change took place until the paraffin PCM temperature reached its melting point of 18°C. At that time, latent heat change began, due to phase change of the PCM from liquid to solid. As a result, the instrument temperatures stabilized at close to 18°C. With the instrument powered off, the paraffin PCM continued to freeze. After all the PCM changed from liquid to solid, the instrument radiators continued to radiate heat to deep space. The PCM temperature began to decrease, due to sensible heat change in the solid phase of the PCM. When the PRT-4 temperature (green curve) dropped below 16°C, the instrument was powered on again. The total power-off time was 104.6 minutes, which was approximately 47 minutes longer than the pre-launch design power-off time. After the instrument was powered on, the PCM temperature began to increase due to sensible heat change. When the PCM temperature reached 18°C, latent heat change began, due to phase change of the PCM from solid to liquid. The instrument temperatures continued to stabilize. After about 30.2 minutes, all the PCM had melted, the PCM temperature began to increase due to sensible heat change in the liquid phase of the PCM. The 30 minutes time of melting all the PCM is close to the pre-launch design power-on time for 40.69 g of n-Hexadecane. Before the eclipse began, the instrument temperatures reached a maximum of 21.5°C. When the eclipse began, the instrument was powered off. It began to cool down because its radiators continued to radiate heat to deep space. Sensible heat change took place until the paraffin PCM temperature reached its melting point of 18°C. At that time, latent heat change began, due to phase change of the PCM from liquid to solid. For this instrument operation scheme, there was sensible heat change between the PCM melt-and-freeze cycles. It validated the functionality of the paraffin PCM mini-packs, despite the operation scheme did not provide an exact timeline for the PCM to melt and freeze, with latent heat change only, all the time.

In terms of thermal energy balance, the “Day-On Every Other Orbit” instrument operation scheme in flight was more in line with the pre-launch design power-on time and power-off time distribution for the 40.69 g of n-Hexadecane used. The mass of the paraffin is nearly adequate for this flight operation scheme. The results are consistent with the pre-launch thermal model predictions for the instrument power-on time.

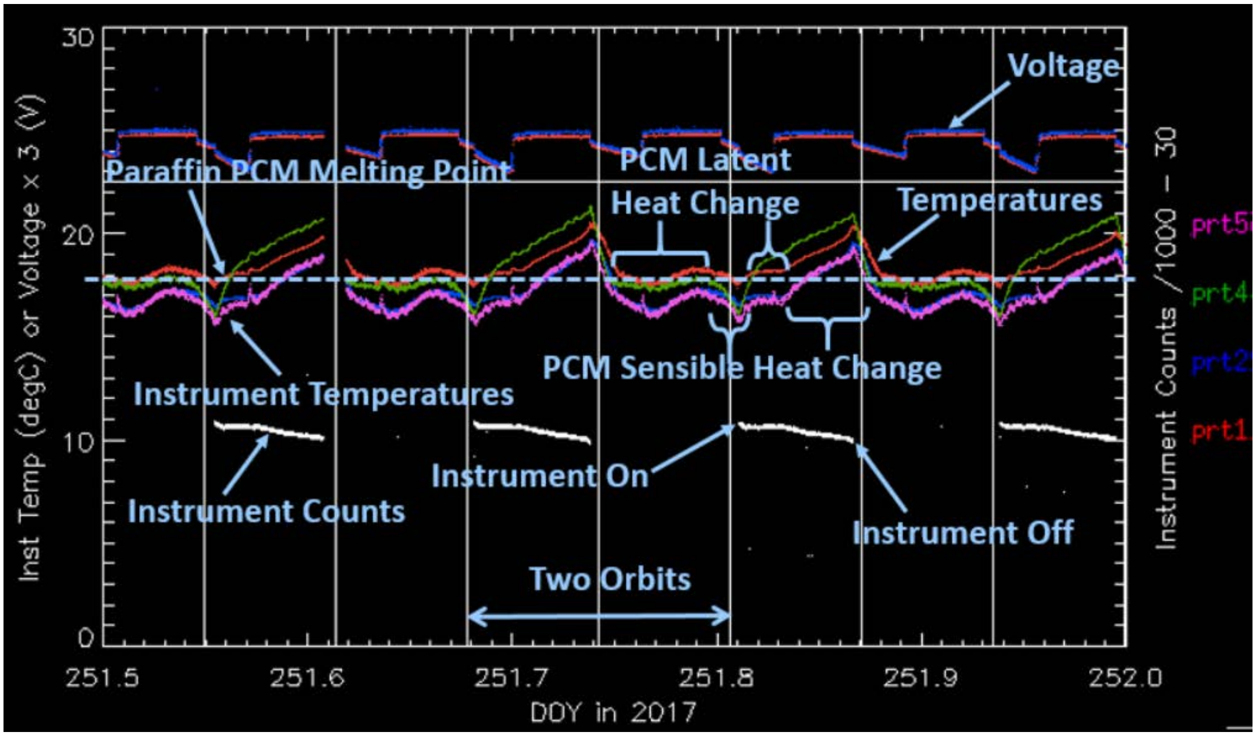

Figure 12. Flight Temperatures of Instrument on IceCube from DOY 251-252 in 2017.

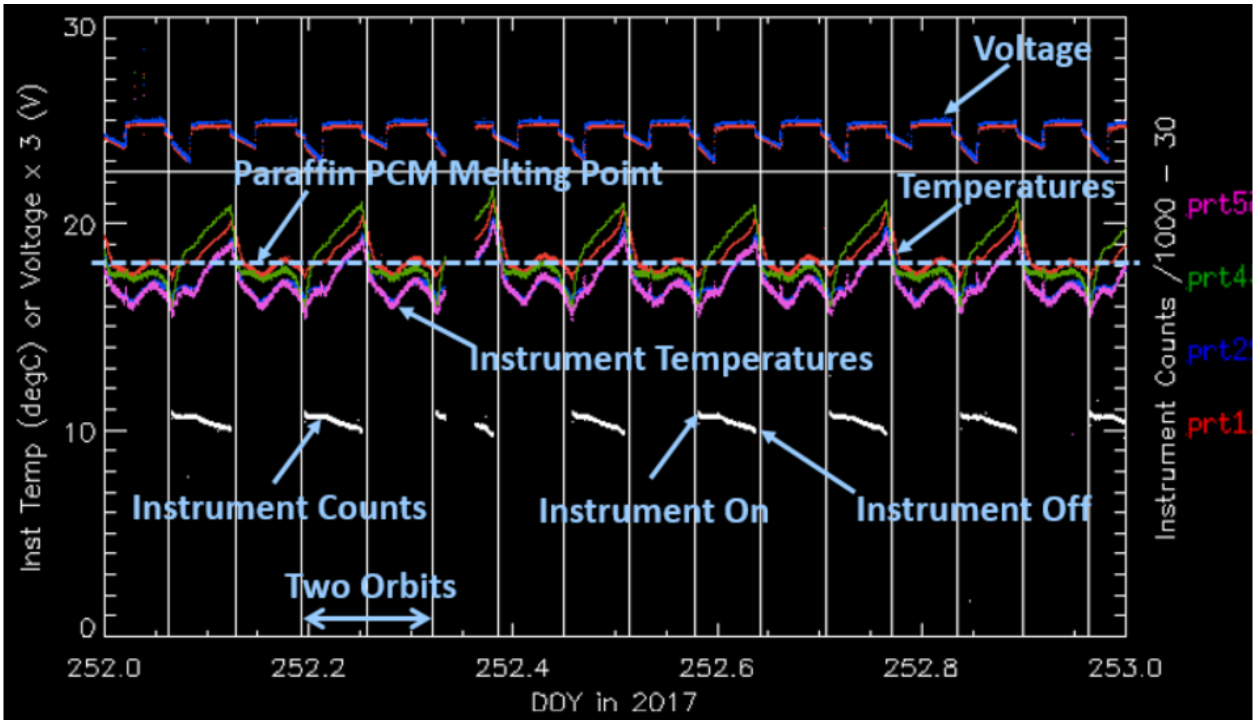

Figure 13. Flight Temperatures of Instrument on IceCube from DOY 252-253 in 2017.

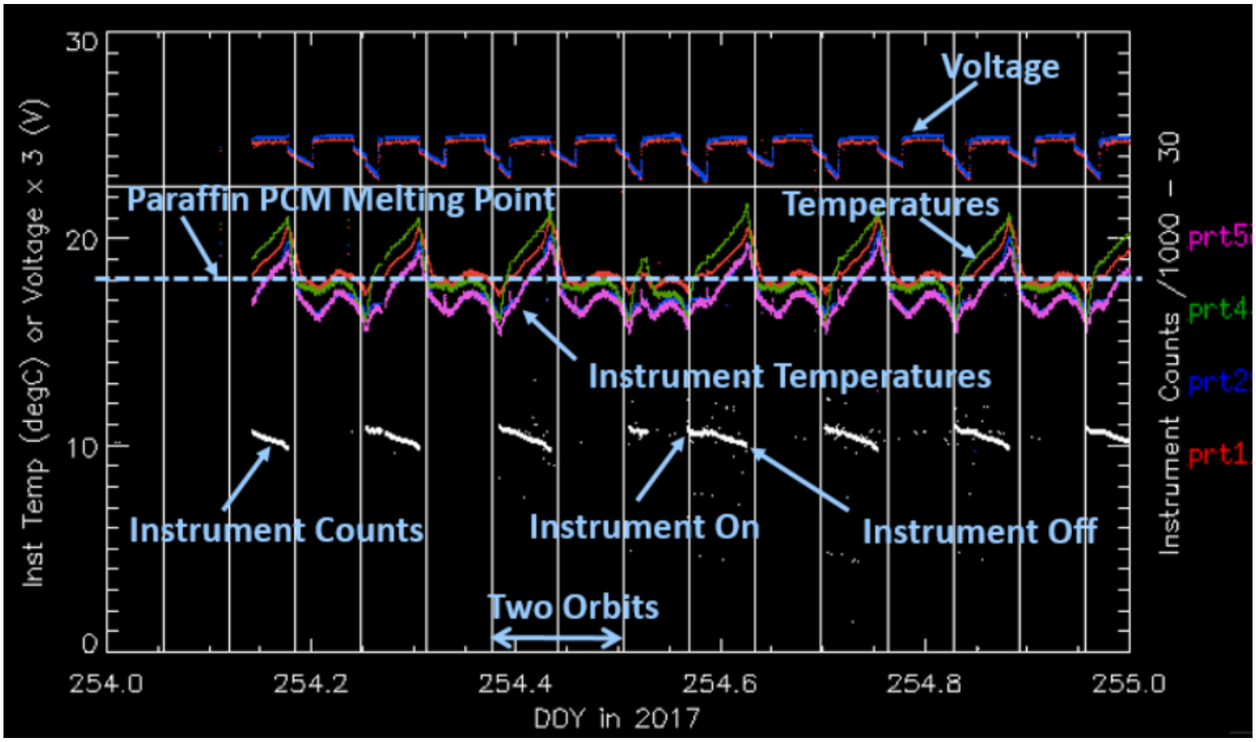

Figure 14. Flight Temperatures of Instrument on IceCube from DOY 254-255 in 2017.

VI. Conclusion

At the Critical Design Review, the MLA and IFA of the instrument on the IceCube required a 20˚C temperature and a thermal stability of ±1˚C. The thermal environment of the ISS orbit for the IceCube is very unstable due to solar beta angles in the -75˚ to +75˚ range, which has an eclipse time from 0 to 36.3 minutes. Additionally the instrument was designed to power off in every eclipse to conserve electrical power. Radiators, thermal isolation and paraffin (n-Hexadecane) PCM mini-packs were designed to meet the temperature and thermal stability requirements of these instrument components. With a 40.69 g mass of n-Hexadecane, the pre-launch instrument design power-on time in sunlight was in the range of 32.3 minutes at a 0˚ solar beta angle to 38 minutes at a 75°solar beta angle. In flight, from DOY 159-161 in 2017, the "Day-On/Night-Off" operation scheme was used. The instrument was powered on for 56 minutes, and powered off for 36.6 minutes in each orbit. The instrument power-on time was approximately 20 minutes longer than the pre-launch design power-on time. Flight temperature telemetry data of the instrument revealed phase change of the paraffin PCM occurred, and sensible heat change dominated the instrument heat change. If the instrument operation time in sunlight were shortened to the pre-launch design power-on time, the instrument temperatures are expected to be stable at about 18°C. From DOY 250-255 in 2017, the instrument operation scheme was changed to "Day-On Every Other Orbit". The new scheme also added a criterion for power-on. When the temperature sensor PRT-4 dropped below 16°C, the instrument was powered on again, even if it was in the eclipse. Not only the instrument power-on time was approximately 45.6 minutes longer than the pre-launch design power-on time, but also its power-off time was 47 minutes longer than the pre-launch design power-off time. Flight temperature telemetry data of the instrument from DOY 250-255 revealed that latent heat change of the paraffin PCM played a much larger role in the instrument heat change. As a result, the instrument temperatures were close to the design temperature. It validated the functionality of the paraffin PCM mini-packs, despite the operation scheme did not provide an exact timeline for the PCM to melt and freeze, with latent heat change only, all the time. Additionally, it validated the thermal design of using a 40.69 g mass of n-Hexadecane PCM and the design instrument power-on time to maintain the instrument temperature stable and close to the 18˚C PCM melting point.

Acknowledgments

The author thanks Dr. Dong Wu of Goddard Space Flight Center for distributing the IceCube flight telemetry data.

References

[1]Choi, M.K., "Paraffin Phase Change Material for Maintaining Temperature Stability of IceCube Type of CubeSats in LE**O**", AIAA Propulsion and Energy Forum 2015, Orlando, FL, Paper AIAA-2015-3984.

[2]Knowles, T. R., "Phase Change Composite Thermal Energy Storage", Energy Science Laboratories, Inc., San Diego, CA, Sept. 2007.

[3]Hale, D.V., et al., 1971, Phase Change Materials Handbook, NASA-CR-61363.

[4]Humphries, W.R., and Griggs, E.I., 1977, A Design Handbook for Phase Change Thermal Control and Energy Storage Devices, NASA-TP-1074.

[5]Wu, D.L., Personal Communication, July 26, 2017.

[6]Wu, D.L., Personal Communication, Sept. 19, 2017.