Using Paraffin with -10°C to 10°C Melting Point for Payload Thermal Energy Storage in SpaceX Dragon Trunk

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A concept of using paraffin wax phase change material (PCM) with a melting point between -10°C and 10°C for payload thermal energy storage in a Space Exploration Technologies (SpaceX) Dragon trunk is presented. It overcomes the problem of limited heater power available to a payload with significant radiators when the Dragon is berthed to the International Space Station (ISS). It stores adequate thermal energy to keep a payload warm without power for 6 hours during the transfer from the Dragon to an ExPRESS logistics carrier (ELC) on the ISS.

Nomenclature

C	=	carbon
CCD	=	charge coupled device
ELC	=	ExPRESS Logistics Carriers
FPA	=	focal plane assembly
FRAM	=	Flight Releasable Attachment Mechanism
H	=	hydrogen
IOB	=	instrument optical bench
ISS	=	International Space Station
LEO	=	low Earth orbit
MLI	=	multilayer insulation
NICER	=	Neutron Star Interior Composition Explorer
OTCM	=	ORU Tool Changeout Mechanism
PCM	=	phase change material
SPDM	=	Special Purpose Dexterous Manipulator
TEC	=	thermoelectric cooler

I. Introduction

The SpaceX Dragon trunk can accommodate up to three ISS payloads (Fig. 1).[1] The aft end of the unpressurized trunk is open. During the Dragon solo flight, the thermal environment for the trunk is extreme. When the Dragon is berthed to the Harmony Module of the ISS, the trunk's open aft end points at Earth (Fig. 2).[1] The duration of grapple and berthing is 1 to 7 days.[2] The total heater power available to the payloads in the trunk is 200 W.[2] If there are three payloads in flight, the heater power available to each payload is only 67.7 W. If there are only two payloads in flight, the heater power available is 100 W each. Figure 3 shows the locations of the Harmony Module and ExPRESS logistics carrier (ELC). During removal of a payload from the Dragon trunk by the Special Purpose Dexterous Manipulator (SPDM)/ORU Tool Changeout Mechanism (OTCM), as part of the transfer to the ELC, there are up to 6 hours without power for the payload. If the payload has large heat rejection system radiators, it will lose a significant amount of heat to space for up to 6 hours with no heater power available. Typically electronics boxes have a -30°C non-operating limit. It is necessary to store adequate thermal energy in the payload while it is still in the Dragon trunk. Since heater power is limited and the Dragon trunk aft end is open, it is a challenge to store adequate thermal energy in a payload that has large radiators.

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Figure 1. Dragon Payload Trunk[1].

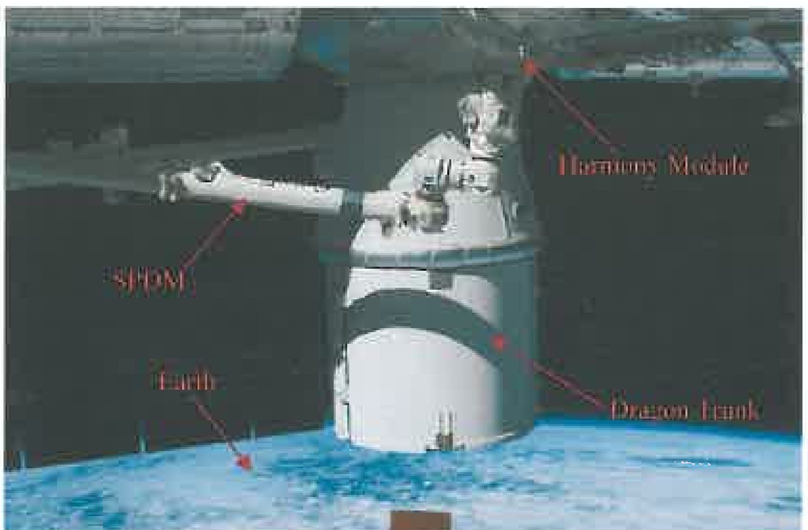

Figure 2. SpaceX Dragon Berthed to Harmony Module on ISS[1].

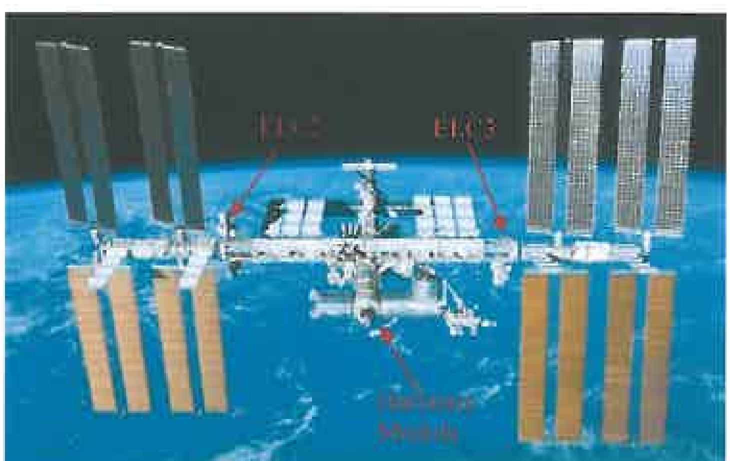

Figure 3. Locations of Harmony Module and ELC on ISS[1].

II. Objective

The objective of this paper is to present a thermal concept of using paraffin wax PCM with a melting point between -10 °C and 10 °C to store adequate thermal energy in a SpaceX Dragon trunk to keep payload warm without power for 6 hours during its transfer from the Dragon to an ELC.

III. Paraffin Wax Phase Change Material

Paraffin wax PCM has a high latent heat of fusion per unit mass, which is in the 155 to 253 kJ/kg range (Fig. 4)[4-8]. It also has a range of melting points (Fig. 5)[4-8], and is well within typical payload temperature limits. PCM potentially reduces the mass of the payload since latent heat, instead of sensible heat, is used for thermal energy storage. Paraffin PCM has flight heritage. Figure 6 shows a paraffin pack flown on the MDIS instrument in the NASA MESSENGER mission to Mercury. Two packs of Dodecane ($C_{12}H_{26}$), which have a melting point of -10 °C, maintain the CCD temperature no warmer than -10 °C when the MDIS radiators absorb heat from the planet near MESSENGER's periapsis.[9]

Typically the ratio of mass of paraffin to mass of shell is 2:1.[7] The technology readiness level (TRL) of paraffin PCM for spaceflight is at least 6.

Paraffin waxes, which have a carbon number from 12 to 15, provide a melting point in the -10 °C to 10 °C range used in the novel thermal concept presented in this paper.

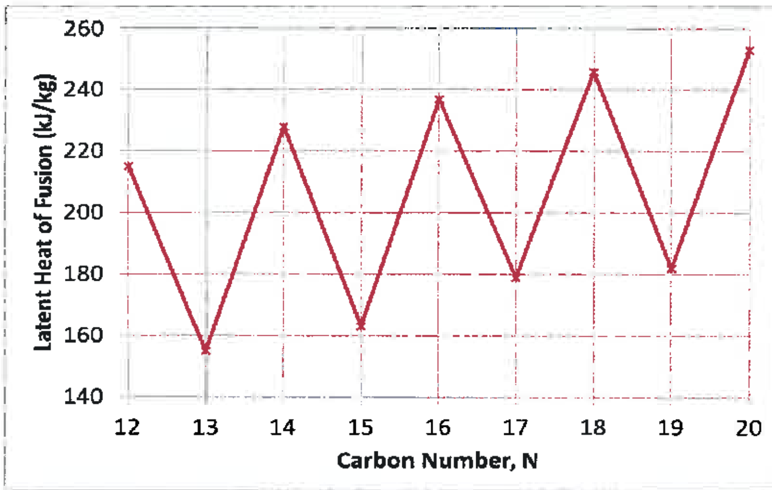

Figure 4. Latent Heat of Fusion of Paraffin (C_NH_{2N+2}).

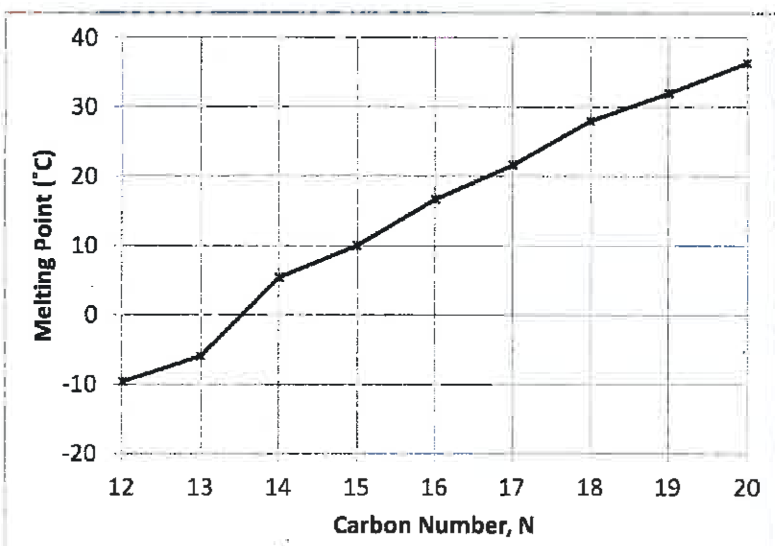

Figure 5. Melting Point of Paraffin (C_NH_{2N+2}).

Figure 6. Paraffin Pack Flown on MDIS Instrument in MESSENGER Mission.

IV. Technical Description and Novel Features of Thermal Concept

The SpaceX Dragon unpressurized trunk has a payload volume of 3.6-m diameter and a 2.3-m height.[1] The Flight Releasable Attachment Mechanism (FRAM) reference point is 2.146 m from the end of the trunk (Fig. 7).[3] The height could be extended to 4.3 m, if needed.[1] The trunk exterior has a white paint, which has a low absorptance (0.28) and a high emittance (0.87), for thermal control.[3] Its interior is insulated with a 7.62 cm thick acoustic blanket. The trunk interior an absorptance of 0.39 and an emittance of 0.79.[3] It can accommodate up to three ISS payloads. The aft end of the trunk is open. During the Dragon solo flight, the thermal environment for the trunk is extreme.[2] The coldest environment is in the Off-Nominal Attitude Possible Extreme Cold during which the Dragon nose points at sun. When the Dragon is berthed to the Node 2 nadir port of the Harmony Module on the ISS, the Dragon trunk's open aft end points at Earth for 1 to 7 days.

Figure 7. FRAM Reference Point is 2.146 m from the End of the Trunk.[2]

A. Example of ISS ELC Payload

An example of ISS payload that uses the novel thermal concept presented in this paper is the Neutron Star Interior Composition Explorer (NICER). It is proposed by NASA Goddard Space Flight Center for the ISS ELC. It was selected for Phase B implementation in April 2013. Figure 8 displays the thermal model for the NICER in the deployed configuration. The electronics boxes are mounted to a thermal sharing plate. The thermal sharing plate is thermally isolated from the instrument optical bench (IOB) bottom plate by titanium flexures. The size of the IOB is 1.13 m x 0.87 m x 0.82 m. The total power dissipation of the electronics boxes is 69 W. Most of the exterior of the electronics boxes has AZW/LA-II low absorptance white paint[10] to radiate heat to space and minimize the solar or albedo flux absorbed. The detectors are cooled by thermoelectric coolers (TECs). The hot side of the TECs is conductively coupled to a detector plate. The total waste heat rejected by the TECs is 33.6 W. The detector radiator wraps around the IOB and is an integral part of the detector plate. It also has AZW/LA-II low absorptance white paint. The 56 concentrators are mechanically supported by the concentrator plate. Each concentrator aperture has a thin aluminized polyimide film. There are 56 sunshades to prevent sunlight from entering the concentrators. They are thermally isolated from the concentrator plate. The IOB side plates, bottom plate and detector plate are insulated with multi-layer insulation (MLI) blankets. Figure 9 shows the thermal model for the NICER in the stowed configuration, and with two other payloads, in the Dragon trunk. Figure 10 displays the on-orbit thermal model when the Dragon is berthed to the ISS.

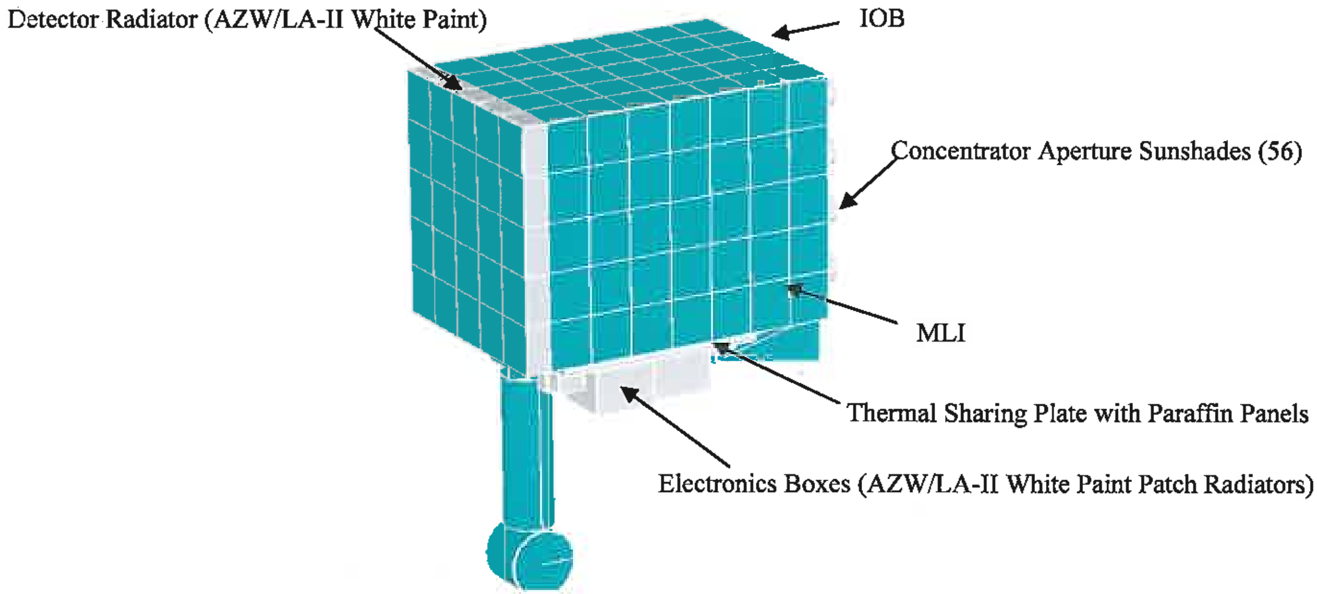

Figure 8. NICER in Deployed Configuration.

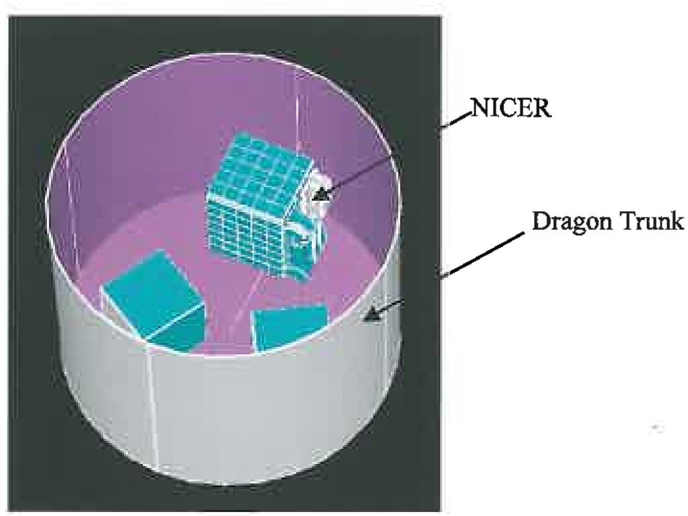

Figure 9. NICER Payload in Dragon Trunk.

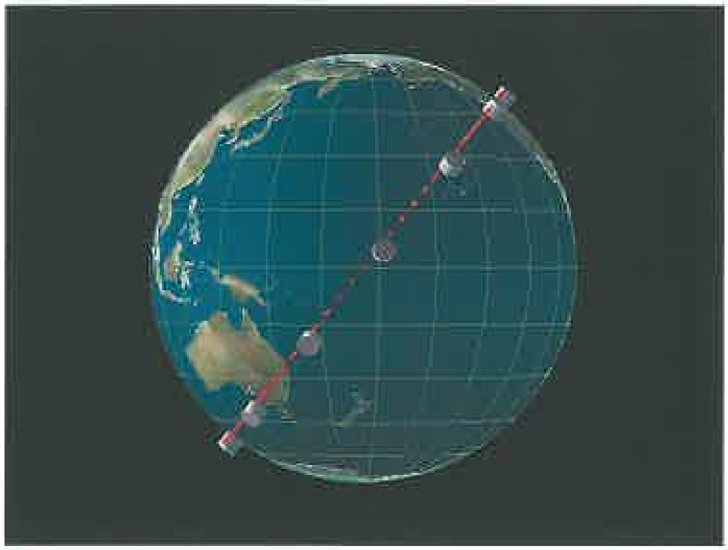

Figure 10. Reduced Thermal Model for NICER in Dragon Trunk Berthed to ISS.

B. Dragon Berthed to ISS

When the Dragon is berthed to the ISS, pre-heaters on the NICER payload are powered by 66.7 W at 106 V-126 V and controlled by mechanical thermostats. The set point of the thermostats is 30°C so that the heaters utilize all the 66.7 W available power for thermal energy storage. With 67.7 W of heater power, its worst cold case quasi-steady state average temperature prediction is 13.2°C. Sunlight and eclipse in the ISS low Earth orbit (LEO) lead to quasi-steady state instead of steady state temperatures.

Paraffin selection is strongly dependent on the quasi-steady state temperature prediction of a payload. Both Dodecane ($C_{12}H_{26}$) and Tetradecane ($C_{14}H_{30}$) have a high latent heat of fusion per unit mass (217 kJ/kg and 228 kJ/kg respectively). However it is important to ensure all the paraffin is melted and has adequate margin. Hence Tetradecane, which has a 6°C melting point (i.e., 7.3°C margin), is not chosen. Tridecane ($C_{13}H_{28}$), which has a -5°C melting point, is also not selected because its latent heat of fusion per unit mass is only 155 kJ/kg. A lower latent heat of fusion per unit mass requires more mass. Dodecane, which has a -10°C melting point, is chosen.

C. Paraffin PCM Locations and Contamination Mitigation

The locations of paraffin PCM for the NICER payload are described. For the electronics boxes, paraffin PCM panels are attached to the thermal sharing plate which is shown in Fig. 8. A total of four paraffin panels are used. Each panel has 0.5 kg of paraffin PCM. The paraffin panels are sandwiched between the Electronics Boxes thermal sharing plate and IOB base-plate. The exposed area of these panels is very small. Kevlar is used on this small area to increase protection from micro meteoroid damage. For the IOB, paraffin PCM panels are attached to the side plates of the IOB. A total of six paraffin panels are used to wrap around the side plates. Each panel has 0.38 kg of paraffin PCM. These six paraffin panels are internal to the IOB which includes base-plate, detector plate, concentrator plate and side plates. For the side-plates, there is a black polyimide/Kevlar layer, under the MLI, to add protection against micrometeoroid damage. A total of 4.28 kg of Dodecane stores 929 kJ of thermal energy as latent heat.

A 50°C maximum temperature limit is used for Dodecane in the NASA MESSENGER mission. The same limit is being used for the NICER payload. The bakeout temperature for the NICER paraffin panels during ground testing will be limited to 50°C.

D. Removal of Payload from Dragon Trunk

During removal of the NICER payload from the Dragon trunk by the SPDM, there are up to 6 hours without power. The electronics box and detector radiators will continue to radiate heat to space. Also there will be heat leaks through the MLI blankets and through the concentrator thin aluminized polyimide film aperture covers to space. For the thermal analysis to be conservative, no sunlight is assumed to be incident on the NICER payload during the transfer. Figure 11 presents the NICER temperature predictions during the removal from the Dragon trunk and transfer to the EOTP. When NICER cools down to -10°C, the paraffin PCM begins to freeze at its melting point.

When all the paraffin has changed to solid, its temperature continues to decrease. When it arrives at the EOTP after 6 hours without power, the temperature prediction is -13°C, which has a 17°C margin and is adequate.

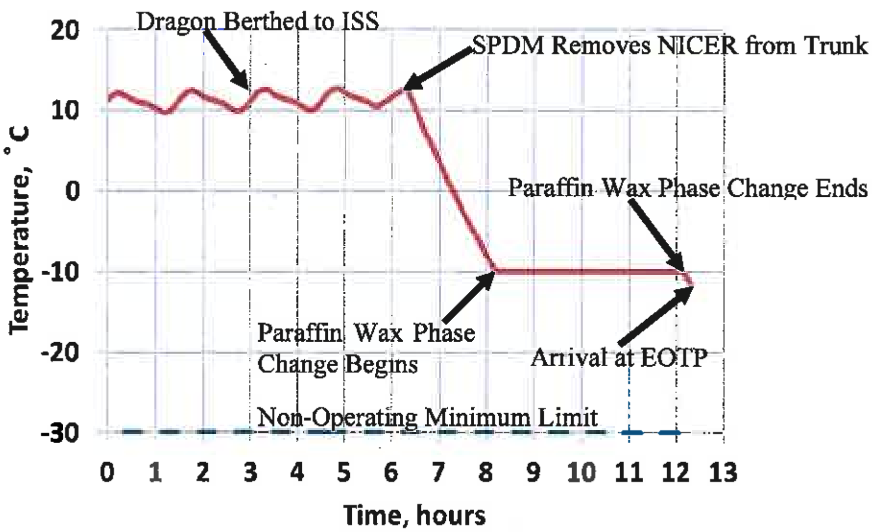

Figure 11. NICER Temperature Predictions during Removal from Dragon Trunk and Transfer to EOTP.

V. Conclusion

The novel thermal design concept presented in this paper uses paraffin PCM with a -10°C and 10°C melting point to store thermal energy in a payload with large radiators while in the SpaceX Dragon trunk. It overcomes the problem of not enough heater power to increase the temperatures to higher than the -10°C and 10°C range. If paraffin stores enough thermal energy and changes phase at -10°C to 10°C during 6-hours without power, the payload temperature is above the -30°C survival limit when it arrives at the EOTP at the end of the 6-hour cool-down period.

References

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