New Approach for Thermal Protection System of a Probe During Entry

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ABSTRACT

One of the biggest challenges for any thermal protection system (TPS) of a probe is to provide a sufficient barrier for heat generated during descent in order to keep the temperature inside of the probe low enough to support operational temperature of equipment. Typically, such a goal is achieved by having the ceramic tiles and blankets like on the Space Shuttle, silicon based ablators, or metallic systems to cover the probe external surface.

This paper discusses the development of an innovative technique for TPS of the probe. It is proposed to use a novel TPS which comprises thermal management of the entry vehicle. It includes: a) absorption of the heat during heat pick load by a Phase Change Material (PCM), b) separation of the compartment which contains PCM from the rest of the space vehicle by a gap with a high thermal resistance, c) maintaining temperature of the internal wall of s/c cabin temperature by transfer heat from the internal wall to the "cold" side of the vehicle and to reject heat into the space during the flight and on a ground, d) utilization of an advanced heat pipe, so called Loop Heat Pipe to transfer heat from the cabin internal wall to the cold side of the s/c and to reject the heat into environment outside of the vehicle. A Loop Heat Pipe is capable of transferring heat against gravity.

INTRODUCTION

An important element of planetary missions is the design of TPS capable of shielding the vehicle from aero-heating during the atmospheric entry. Currently, depending on the aero-thermodynamic heat loads, Shuttle ceramic tiles, ablators, or metallic thermal protection systems are used.

The new proposed approach for thermal management of probe TPS is to use a Phase Change Material (PCM) to store the incident heat generated during an intense transient heating environment of descent. This stored heat is then rejected back into the environment, once the high heat load has dissipated. Due to the magnitude of the expected heat loading and the likely operating environments, it would be desirable to use a PCM with a high melting temperature. This, however, creates heat transfer from the PCM to the probe's payload compartment. Management of this heat flux is accomplished through the use of insulation, a secondary PCM, and a use of Loop Heat Pipe (LHP).

CONCEPTUAL DESIGN

Three heat loads, low, medium and high, are considered in the current effort (see Table 1). The total heat load was calculated assuming 1 minute of a heat flux which profile is depicted in Fig.1.

	Peak Stagnation Heat flux.	Total Heat Load
Low	50 (w/cm^2)	59.8 Mega Joules
Medium	100 (w/cm^2)	120 Mega Joules
High	200 (w/cm^2)	239 Mega Joules

Table 1: Minimum, Nominal, and Maximum heat load cases

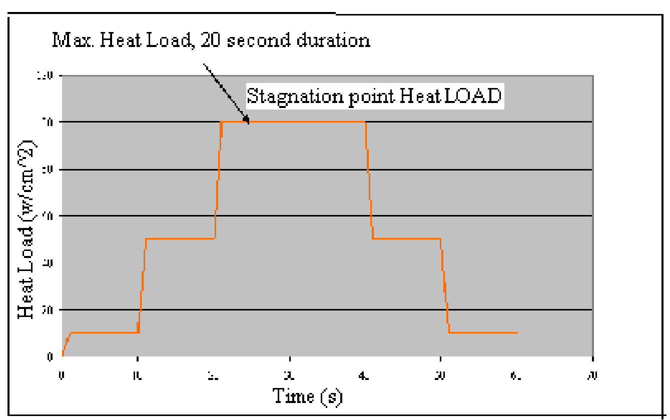

Figure 1: Normalized heat load vs. time

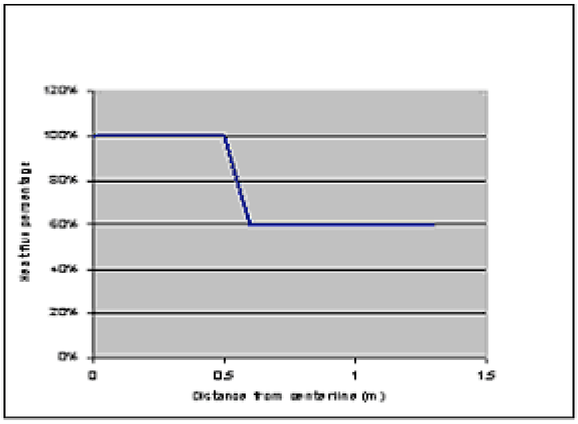

Figure 2: Heat flux distribution over the heat shield surface, as a percentage of the heat flux at the stagnation point.

Figure 2 shows a distribution of the heat flux over the surface of the fore body that presents simplified version of an actual distribution of the heat flux over the heat shield.

The current study assumes that the stagnation point temperature of the outer skin of the fore body does not exceed 825 K, due to the effect of the Phase Change Material, discussed below.

The major goals of two proposed designs (see Fig. 3 and Fig. 4) are: a) absorb coming heat during heat pick load by a PCM, b) separate the compartment which contains PCM from the rest of the probe by a gap with a high thermal resistance, c) maintaining temperature of the internal wall of the probe cargo compartment.

Design I and II consists of the same components. The incoming heat is conducted through the outer skin of the fore body (1) and gets absorbed by the Primary Phase Change Material (2) with a high melting point. The Primary PCM (2) is separated from the probe cargo compartment by a gap with a support structure (3). The gap limits heat transfer from the Primary PCM to the probe cargo compartment. The heat leak from Primary PCM into the cargo compartment is due to radiation between gap walls and conduction through the support structures. The role of the secondary PCM (4) with low melting point is to absorb heat leaks through the gap and to control the cargo compartment wall temperature. It should be noted that the roles of the Primary PCM and Secondary PCM are distinct. While the Primary PCM is used to absorb heat conducting from the heated outer skin thus maintaining the outer skin at a desirable temperature, the secondary PCM exists to regulate the temperature of the wall of the cabin. The LHP evaporator (5) takes in heat accumulated by the Secondary PCM (4) and transfers the heat via transport lines (6) to the LHP condenser (8) shown together with a radiator situated on the afterbody. The internal wall of the cargo compartment is covered with MLI (9) for better protection of the cargo compartment.

Environment temperature should be less then secondary PCM temperature in order to remove heat from the secondary PCM. Design I is suitable for a cold environment with temperatures around 273 K or below. This could be a limitation for some mission requirements, like landing during a hot season.

<u>Design I</u>

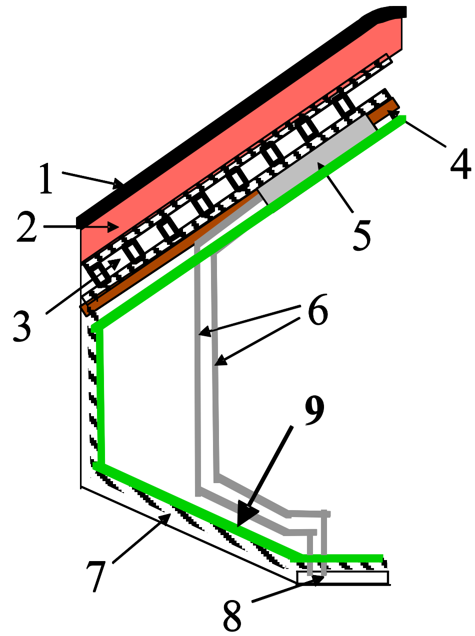

Figure 3: Design I. 1 – heat shield, 2 – primary PCM, 3- gap with support structure, 4 – secondary PCM, 5 – LHP evaporator, 6 – LHP transport lines, 7 – cargo inner wall, 8 – LHP condenser with radiator, 9 – LMI

Design II

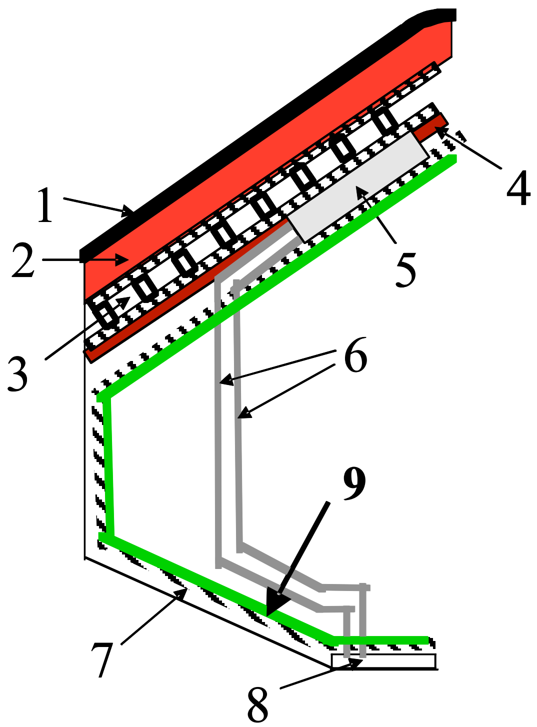

Figure 4: Design II. 1 – heat shield, 2 – primary PCM, 3- gap with support structure, 4 – secondary PCM, 5 – LHP evaporator, 6 – LHP transport lines, 7 – cargo inner wall, 8 – LHP condenser with radiator, 9 – LMI

This limitation is circumvented in Design II where the secondary PCM with elevated melting point is employed. It allows rejecting heat from the Secondary PCM into the hot environment. Since the operating temperature of the LHP evaporator is higher then 100 C, an additional layer of protection in the form of a gap is inserted between the LHP and the inner wall. Thus, in the Design II, the incident heat is absorbed by the Primary PCM (2). The heat leak through the gap (3) is absorbed by the Secondary PCM(4) which is not longer adjacent to the cabin wall. A gap is inserted between the Secondary PCM (4) and the cabin wall (7). The LHP evaporator (6) is embedded in the Secondary PCM (4). Heat transfer from the secondary PCM to the condenser/radiator assembly (9) via LHP evaporator (6) and transport lines (7).

LHP

The Loop Heat Pipe has been designed for operation against gravitational/acceleration forces [9]. Since its creation in 1970's, LHP moved from R&D stage into commercial applications. LHP is standard equipment now for some communication satellites.

The operating temperature for LHP has been relatively low in the past, less than 450 K. However, experiments have shown that LHP's can transfer heat at higher temperatures, using materials like Cesium as the working fluid [9]. LHPs are good choices for heat transfer in a planetary probe since LHPs capability of transfering heat is much less sensitive to the orientation relative to the acceleration vector then conventional heat pipes.

The LHP considered here is made out of Titanium with a copper wick. The choice of wick is based on the wetting properties of the fluid and its interaction with the wick. Results of the modeling using the SINDA/FLUINT pre-built LHP [11] model suggest that a LHP can transfer up to 2KW of heat from the Secondary PCM to the condenser at medium to high temperatures. For the two designs described here (Design I & Design II), intended to operate at an evaporator temperature of 373 K and 523 K respectively, the working fluids proposed are water, and Diphenyl-Diphenyl Oxide Eutectic, also known as "Thermex", respectively.

PCM

A good PCM candidate the TPS considered here should be of a high density, high specific heat, high heat of fusion and appropriate difference between melting and boiling points. A PSM with a high specific heat and a high heat of fusion will have high heat storage capability leading to more heat absorbed. It is also important to choose PCM with a high density since a higher density of material translates into lesser volume of PCM required for heat absorption.

PCM LiF with melting point of 848.2 C was chosen as the Primary PCM for Designs I and II. Material AlBr3 with melting point of 97.5 C is suitable for Design I as the Secondary PCM. TINO3 with melting point of 206 C is used as the Secondary PCM in Design II. All three PCMs are safe and don't present hazard to the payload. However, the PCM compatibility with probe structural elements and payload is beyond of the scope of presented effort and is not considered here.

MLI

Multi-layer insulation (MLI) blankets provide heat-resistant transfer in or out of the body. It is proposed here to cover the internal wall of the cargo compartment with MLI in order to prevent heat from leaking into the cargo bay and harming the occupants or sensitive electronics. Several types of readily available MLI blankets can be used. A good example is Aluminized Kapton, which exhibits a desirable α/ε ratio for the exposed outer surface, and can comfortably sustain temperatures around 550 K for extended periods.

ANALYSIS

It is assumed that the probe landed with the heat shield down so that the gravitational vector is directed from after body towards the heat shield (Fig.5). The heat stored in the probe is rejected by radiation and convection (Fig. 5). The heat from the Primary PCM is removed from the heat shield by radiation and by natural conduction. The heat transferred from the secondary PCM to the radiator is also removed by radiation and natural conduction.

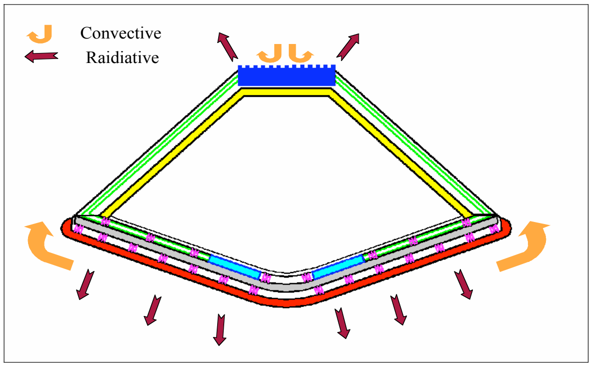

Figure 5: Cooling of the probe

No force convection is considered here in order to understate the convective cooling rates, thus maximizing the stress on the thermal management system. Only radiation between the fore body and the environmental surface is included into the model. The effect of the probe on the environment is neglected.

The convective and radiative cooling rates were calculated for a cold, diffuse CO_2 atmosphere which environmental conditions are listed in Table 2.

Table 2 Environment conditions during probe cooling

Environment	
	Assumed Surface Conditions
CO_2 Density g/m^3	1.21E-02
Temperature (K)	217
Pressure (Pa)	496
Prandlt Number	7.73E-04
Speed of sound (m/s)	230
specific heat (j/g k)	0.75443
Thermal Conductivity (W/m*k)	0.010647
Kinematic Viscosity (m^2/s)	9.01E-04
Thermal Diffusivity (m^2/s)	1.17E+00
Coef. of thermal expansion	0.004608295
Gravity (m/s^2)	3.7

Using LHP pre-build model of SINDA/FLUINT Version 1.0, the LHP has been sized for maximum of 2kW of heat rejection. The LHP parameters are shown in Table3.

Table 3. Parameters of 2kW LHP

Evaporator size	0.25 m length, 0.03 m OD
Transport line sizes	0.5 m length, 0.005 m ID
Condenser size	1.5 m length, 0.005 m ID
Radiator dimensions	0.59 m Ti base diameter, 1500 0.01 m diameter, 0.1 m length copper fins.

Heating and cooling of the probe for three levels of the heat load (see Table 1) were analyzed. Typical results of conducted analysis are show in Fig. 6 and Fig. 7.

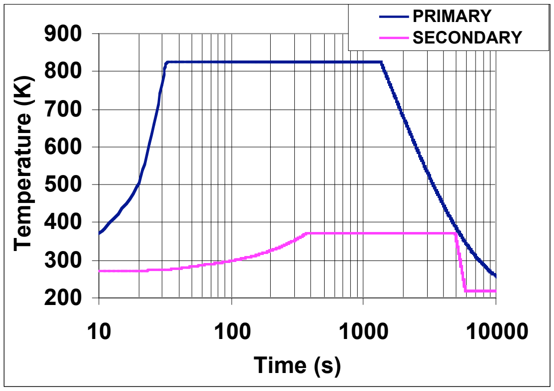

Figure 6. Temperature of Primary and Secondary PCMs for high heat load (200 w/cm^2)

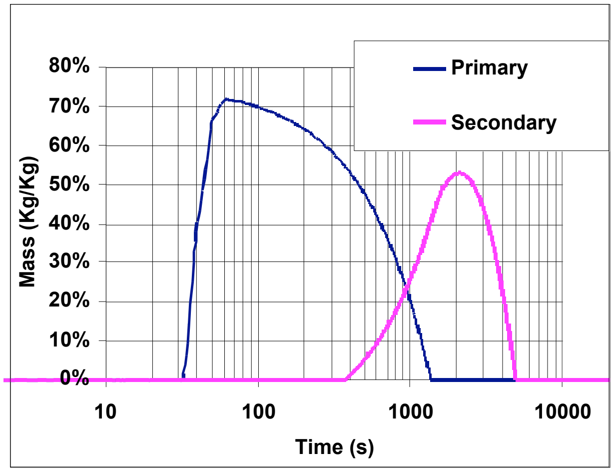

Figure 7. Melted mass as percent of PCM mass for high heat load (200 w/cm^2)

Table 4 contains the results summary for all three heat loads considered here.

Table 4. Simulation Results Summary

	low	medium	high
	50 W/cm^2	100 W/cm^2	200 W/cm^2
Primary PCM			
mass [kg]	43.7	87	173.9
time to reach melting point [sec]	33	33	33
Time for completed solidification [sec]	382	704	1352
melted mass maximum [%]	71.2	71.9	71.9
Secondary PCM			
mass [kg]	5	5	10
time to reach melting point [sec]	188	187	370
Time for completed solidification [sec]	1186	2526	4910
melted mass maximum [%]	22.1	55.1	52.8

As presented results indicate, the proposed TPS is capable of absorbing incident heat and dissipating it in reasonable time. The Primary PCM reaches the melting point before the heat load ends. After this point, the incoming heat melts the Primary PCM. An accumulated in the Primary PCM heat is rejected by radiation and convection. When all accumulated heat of fusion dissipates and PCM is fully solidified, the Primary PCM temperature starts to drop. As data in Fig.6 and Fig. 7 shows, the Secondary PCM temperature reaches melting point at the time when the Primary PCM is almost solidified.

As data in Table 4 indicates, the chosen amount of the Primary PCM provides almost 30 % safety margin. It means that amount of the Primary PCM could be reduced if the safety margin is considered too high. The Secondary PCM margin is even higher (see Table 4). It allows the reduction of an amount of the Secondary PCM in particular for the low heat loads.

One of the additional advantages of using PCM is ability to maintain the temperature of the heat shield at or below the required temperature level, which can be quite lower the existing TPS. It creates an opportunity to use a metal for the outer skin of the fore body which could lead to change of characteristics of a boundary layer and extend the transition point from laminar to turbulent flow.

CONCLUSION

Conceptual designs of integrated multiple layers of PCM, complemented by an LHP, were proposed as possible layouts of the PCM-LHP based re-usable TPS.

It was shown that the proposed TPS is capable of absorbing incoming heat and maintaining the temperature of the probe cargo compartment. One of the advantages of proposed TPS design is ability to maintain a required temperature of the outer skin of the fore body.

PCM technology was studied and determined possible candidates for the Primary and Secondary PCM. The amount of PCM, which provides at least 30% of safety margin, was determined. It was shown that all components of the proposed TPS are available or under development now.

The current effort presents the conceptual design of the re-usable TPS. Future work is required to determine all parameters of the system including but not limited to:
compatibility of the PCMs and structural elements of the probe; performance envelop of LHP during flight and after landing; structural strength of the system; etc.

Cost analysis also needs to be done.

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