ANALYSIS OF POST-REENTRY HEATING AND SOAK-BACK AFFECTS IN UNSEALED REENTRY VEHICLES

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ABSTRACT

Maintaining low temperature payloads through atmospheric reentry and ground recovery is becoming a larger focus in the space program as work in biology, cryogenic and other temperature dependent sciences becomes a higher goal on the International Space Station (ISS) and extraterrestrial surfaces. Paragon analyzes reentry system thermal control, particularly technology regarding small thermally controlled payloads anticipated for use in sample return from the International Space Station.

To minimize system mass and utilize the powerful insulative properties of a hard space vacuum the internal cavity of a small reentry vehicle can be left open. Thermally this causes concern during reentry, as even at very high altitudes there is enough pressure to cause a significant impact on insulation stratagems, such as MLI that rely on a high vacuum. At lower altitudes the vehicle is moving much slower, so the intense heat load of reentry is finished but soak-back from outer heated surfaces to the payload is a significant issue when air is present to facilitate heat transfer between layers. Initial assumptions that the cold temperatures of the upper atmosphere would cause a net cooling affect in the post-reentry times were overturned by a simple analysis set done in Thermal Desktop involving worst and best case scenarios as air starts to enter the vehicle. Additionally, CFD low pressure zones were shown to exist behind the vehicle where it is open to the atmosphere when the vehicle is travelling at extreme reentry speeds. These pressures are not so low however to prevent air from entering the vehicle. The impacts of this now apparent soak back, during the last phases of an atmospheric reentry were investigated leading to the conclusion that analyses of lower atmospheric portions of a reentry are critical to reentry studies and significantly changed the results.

An updated design is theorized using the knowledge gained from the preliminary studies called the Cryogenic Extended Duration and Reentry Thermal Control System (CEDR TCS) and the design is fully passive making it a low-complexity, zero-power system that does not necessitate the use of any consumables. The CEDR TCS uses a two-way pressure relief valve or “breather valve” that would allow the pressures inside and outside the vehicle to equilibrate once a great enough pressure differential is applied. This will allow air to leave while the unit is in space vacuum and prevent air from coming in until much later in the re-entry after much of the reentry heat has had a chance to convect to the upper atmosphere. Through further analysis CEDR is hoped to display a capability of near cryogenic temperatures through an atmospheric reentry and long durations on the ground.

INTRODUCTION

This paper will focus on the design considerations and analysis of the last phases of an atmospheric reentry. The last phase in this case is after the primary heating from re-entry is finished and before the unit is recovered. A previous study conducted to analyze the heat profiles of a small atmospheric reentry vehicle will be examined and discussed to identify problems with soak back in a small open reentry vehicle going through a multi-stage reentry. Figure 1 shows an overview of each of the stages examined in the study. In the concept of operations, following the orbital stage (Stage 1) of the vehicle from the ISS to Earth, a Tube Deployed Re-entry Vehicle (TDRV) is ejected from the external structure of the primary vehicle Small Payload Quick Return (SPQR) for re-entry (Stage 2). Re-entry is the primary heating domain of the TDRV. The Payload Containment and Thermal Control Unit (PCTCU) (which was thermally analyzed in detail) being inside the TDRV.

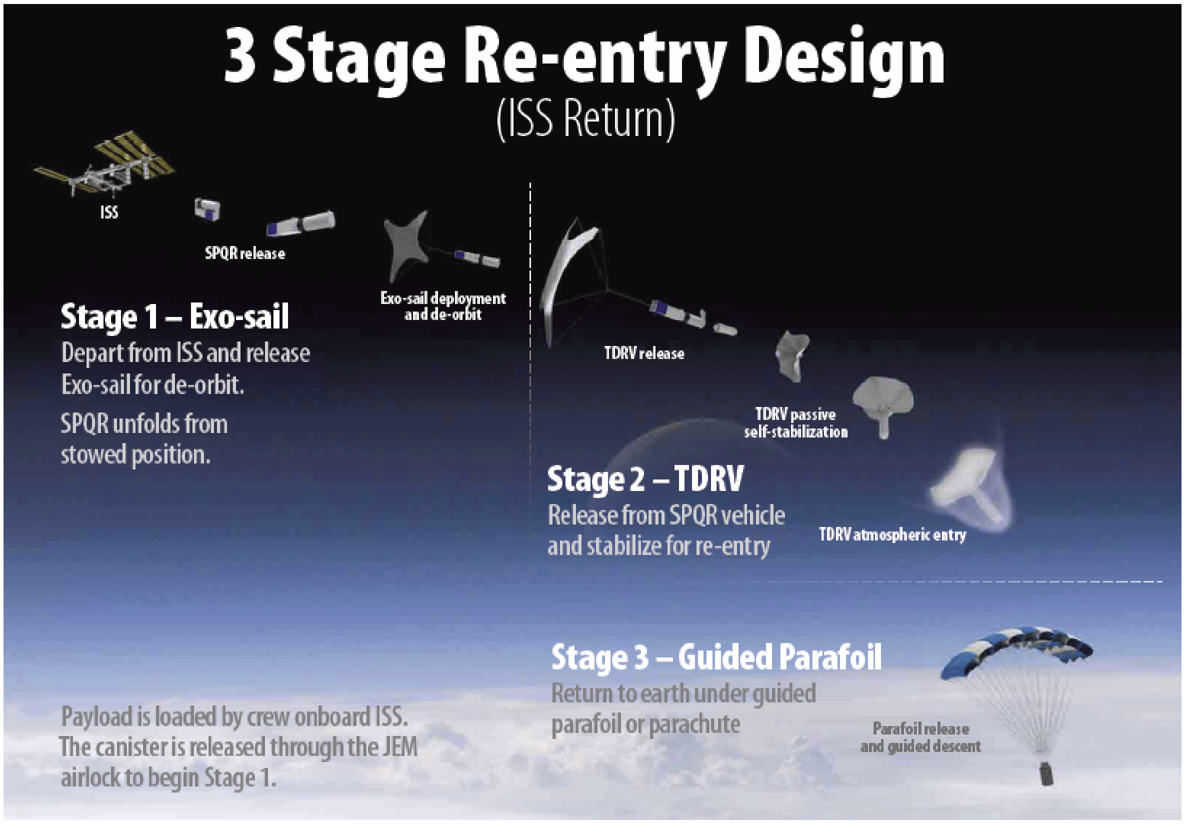


Figure 1. SPQR re-entry overview

After the discussion of the SPQR vehicle a new design, CEDR TCS, will be presented. This design would go through the same thermal environment SPQR saw in stage 3 only carrying a cryogenic payload and dwelling on earth for a period of time before pick up.

PREVIOUS ANALYSES

The original analysis exposing problems with soak-back was that of the SPQR vehicle. The SPQR vehicle is being developed by NASA Ames Research Center (ARC) as a thermally controlled, on-demand, downmass solution for the ISS. (Ref. [1]) The PCTCU is specifically designed to be a passive, simple, low-mass, low-cost solution for keeping a payload at refrigerated temperatures through multiple days in space and a hot atmospheric reentry to immediate recovery on the ground or an air capture. The PCTCU technology is limited to maintaining payload temperatures from 2°C to 4°C, rather than cryogenic temperature payloads.

Through the development of the PCTCU, several studies were performed assuming a roughly 20 kg reentry vehicle which has provided the team with temperature profiles over a range of altitudes and times. Using outer shell temperature profiles varying spatially across the shell, relatively high fidelity analyses were run.

To keep the structure lightweight, the back of the SPQR vehicle is open allowing it to be at equilibrium with the air pressure around it and with space during orbit. Thermally this caused concern during reentry, as even at very high altitude there is enough pressure to cause a significant impact on insulation stratagems, such as MLI that rely on a high vacuum. At lower altitudes the vehicle is moving much slower, so the intense heat load of reentry is finished but soak-back from heated surfaces is a significant issue when air is present, facilitating heat transfer between layers.

Thermal Model

A transient thermal model was created using Thermal Desktop (ver. 5.2). The model examined the heat transfer phenomena from the TDRV into the PCTCU, representing a multi-stage reentry with an insulated payload canister. This model replicated stage 2 conditions to have a starting place for stage 3. A more in-depth model of stage 2 was made and compared to insure correlation. The model starts the analysis at stage 2 to precondition it to the right temperature profile for stage 3 which starts 200 seconds in. The model then finishes in 1500 seconds by which time it is presumed that the payload has been picked up and is being cooled by external forces.

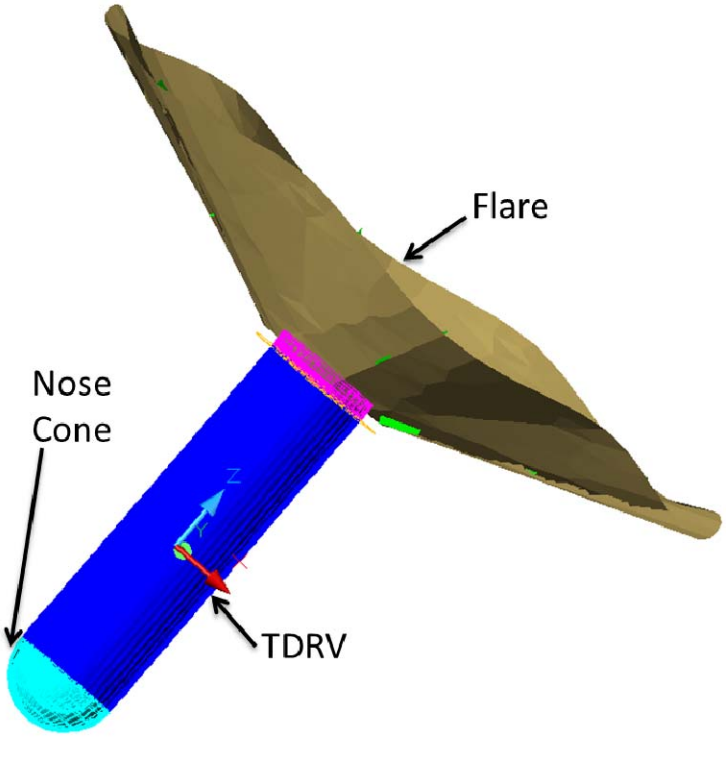


Figure 2. External Surfaces of SPQR

Structurally the device consists of the TDRV exterior shell, an internal casing, Pyrogel insulation (a high temperature insulation from Aspen Aerogel), the PCTCU pressure vessel, the pressure vessel lid, the forward mounting system (male and female components), a phase-change material (PCM) incorporated into the lid, nose cone, flair with mounting components and a payload of 2 kg of water. Figure 2 shows the external surfaces and Figure 3 depicts the internal layers.

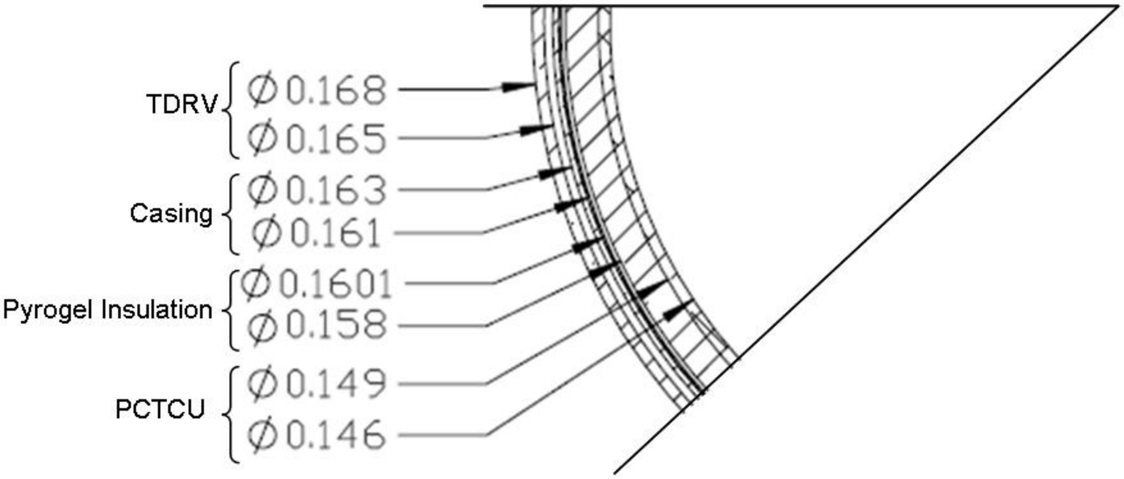


Figure 3. Cross Section Slice of Diameters of Components from TDRV to PCTCU in Meters

Heat rates provided by NASA ARC found in previous studies were applied to the external surface of the TDRV during stage 2. During stage 3 air convection was applied to external surfaces using a boundary node with varying temperature and properties taken from from *U.S. Standard Atmosphere* [2]. Radiation applied on the external surface was modeled as a worst case hot sink temperature of 25°C and for a worst case cold the sink was changed to 2.8°C. The average temperatures of the earth were taken from a table given by NOAA. [3] Radiation from the sun was done by applying a heat flux of 1120 W/m^2 times the projected area dived by the total surface area of half of the cylinder to half of the TDRV time the solar absorptivity of graphite, 0.93. An external radiation RadK group was added to account for any heat radiating from the flair.

Radiation conductors were set up between all inter surfaces in view of each other.

At 30 km (the start of stage 3) it is assumed that air starts to enter the vehicle. This is an initial assumption based on very preliminary models that will have to be examined further in future. This detail of the design proved to have a significant impact on the thermal results. In general the conclusion after these previous analyses was that two important assumptions about soak back were incorrect, those assumptions were:

1. The effects of air entering the vehicle at high altitudes are negligible due to the overall atmospheric density, the geometry of the vehicle and the extreme velocities of reentry.

2. The temperature of the upper atmosphere (very cold) will cause a net cooling effect on the vehicle, and the stage three (post reentry to recovery) can be neglected if cooling is not a concern.

Even though the density of the air is rather low at 30 km, the mean free path is several orders of magnitude smaller than the distances of concern for the SPQR program. Rather than setting up convection an effective conductivity is set up between surfaces. The space is small and it is assumed to be enclosed with the free convection flow velocities being very small. The Grashof (Gr) number times the Prandtle (Pr) was calculated and found to be always below 2000 and as such stays inside the conduction regime. Equation 1 gives the relation between the conductivity and effective conductivity for vertical cylindrical enclosures.

$$\frac{k_e}{k} = 0.55 \cdot (Gr \cdot \Pr)^{0.25}$$

Equation 1

In equation 1 k_e is the effective conductivity, and k is the conductivity of the fluid, air. The effective conductivity changes as the properties of air and the temperature difference between the surfaces changes.

The PCM, water ice stored just forward of the nose of the vehicle is turned from a boundary node to a diffusion node at the end of stage 2 represented by a node of fully-melted water at 0C, . This is a conservative assumption as analysis indicates that it should still be partially frozen.

Results

Results, from initial runs, showed the PCTCU getting much too hot during the re-entry profile. Insulation of the PCTCU with Pyrogel and a lower emissivity coating on the casing was added to the model to improve the thermal performance.

Figure 4 and Figure 5 show the thermal response of SPQR’s many layered system to reentry. This is valuable to consider because the CEDR TCS vehicle’s reentry temperature profile should be qualitatively similar. Figure 5 is of particular importance as it highlights how at 200 seconds, when air is modeled to enter the vehicle, there is a dramatic increase in the soak back of heat.

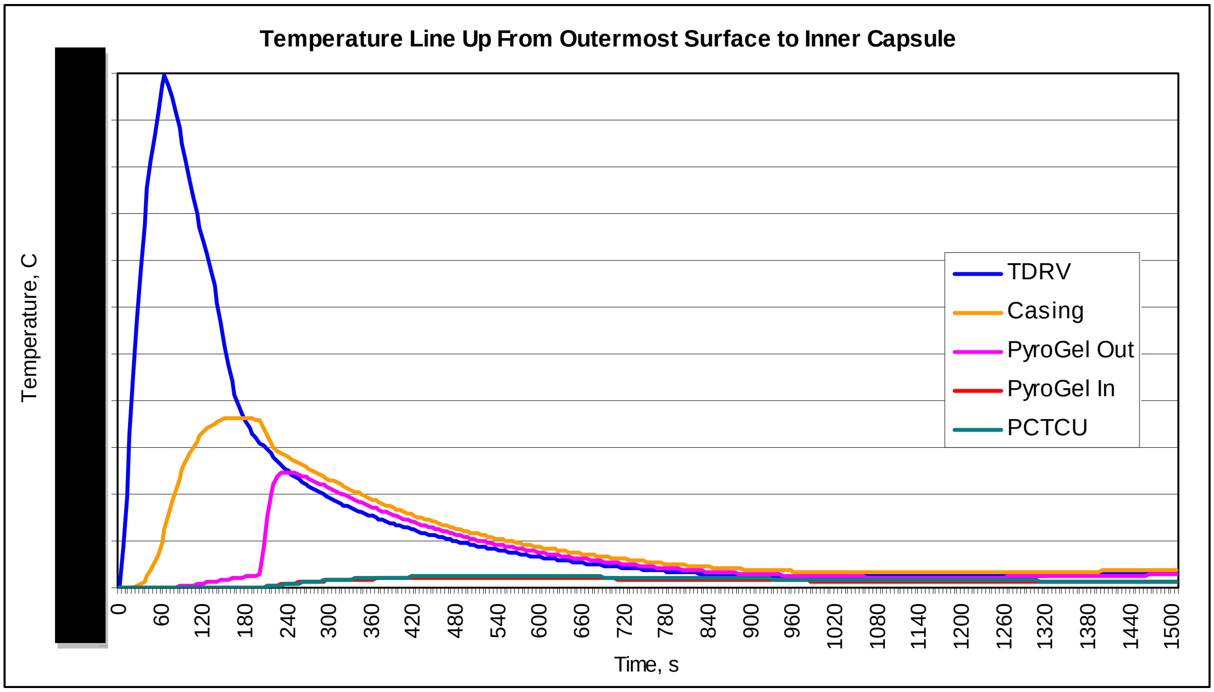


Figure 4. SPQR Layered Temperature Profiles during Reentry: The TDRV is the outermost layer of the vehicle, the next layer in is the casing which is a heat shield, than there is PyroGel which is insulation, and finally the PCTCU is the capsule that holds the payload.

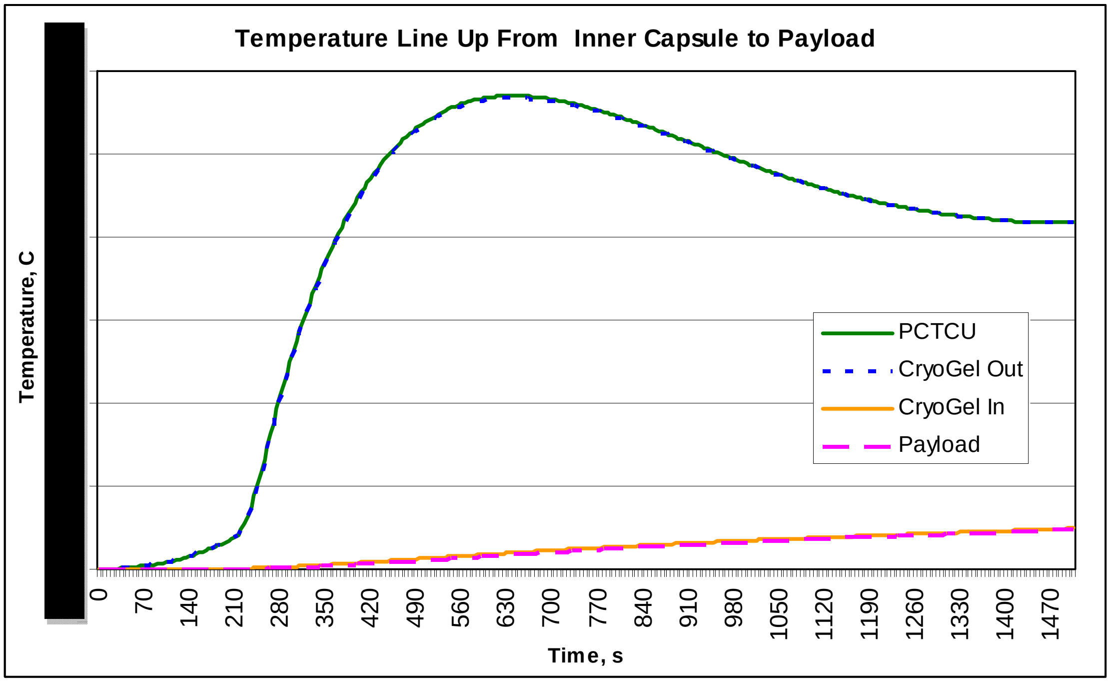


Figure 5. SPQR Payload and Payload Container Temperature Profiles during Reentry: The PCTCU is the capsule holding the payload (seen in Figure 1), CryoGel is insulation inside the

PCTCU, and the payload is modeled as water connected directly to the inside layer of the CryoGel.

These graphs show how using many layers to shield the payload from the intense heat transfer help the payload stay within the required temperature range of 2 to 4°C. The graphs also show the response of the system to the sudden increase in heat transfer at 200 seconds that results from ambient air entering the vehicle and conducting heat. The payload starts steadily increasing in temperature at this 200 second mark but is still within the requirements for an additional 25 minutes, at which time in the SPQR mission profile the payload is recovered and temperature control is taken over by a ground based system. The high heat also shows the need for a double vacuum flask design where the outer flask has high temperature MLI in its annulus. CEDR TCS's additional requirements for maintaining temperature for a period of time after return require more from the TCS. We will accomplish these goals by further isolating the payload and having layers that always maintain a vacuum.

CRYOGENIC EXTENDED DURATION AND REENTRY THERMAL CONTROL SYSTEM (CEDR TCS)

The new design will not only be hotter on the outer surface than the vehicle in the studies already conducted, but will also be carrying a significantly cooler payload, a payload at cryogenic temperatures as opposed to merely frozen temperatures, making the overall heat transfer potential much higher. The other significant difference is the duration for which the TCS needs to protect the payload in an ambient atmosphere environment as to allow for up to 24 hours to recover the payload. The new design will then deal with the further demands on the TCS along with the same soak back issues of a reentry discussed with SPQR.

During the SPQR program it was assumed that air did not get into the vehicle until the unit reached 30 km and all heating due to reentry was complete, so the design had to factor in the issue of soak-back but not reduce vacuum during reentry. The CEDR TCS design is assumed to allow equilibrations with ambient pressures. Its design is specifically tailored to deal with reentry environmental conditions. The temperature profile of SPQR's many-layered system is similar to the CEDR TCS design.

Design

The CEDR TCS design implements a duel vacuum flask system to accomplish this. The design concept is shown in Figure 6.

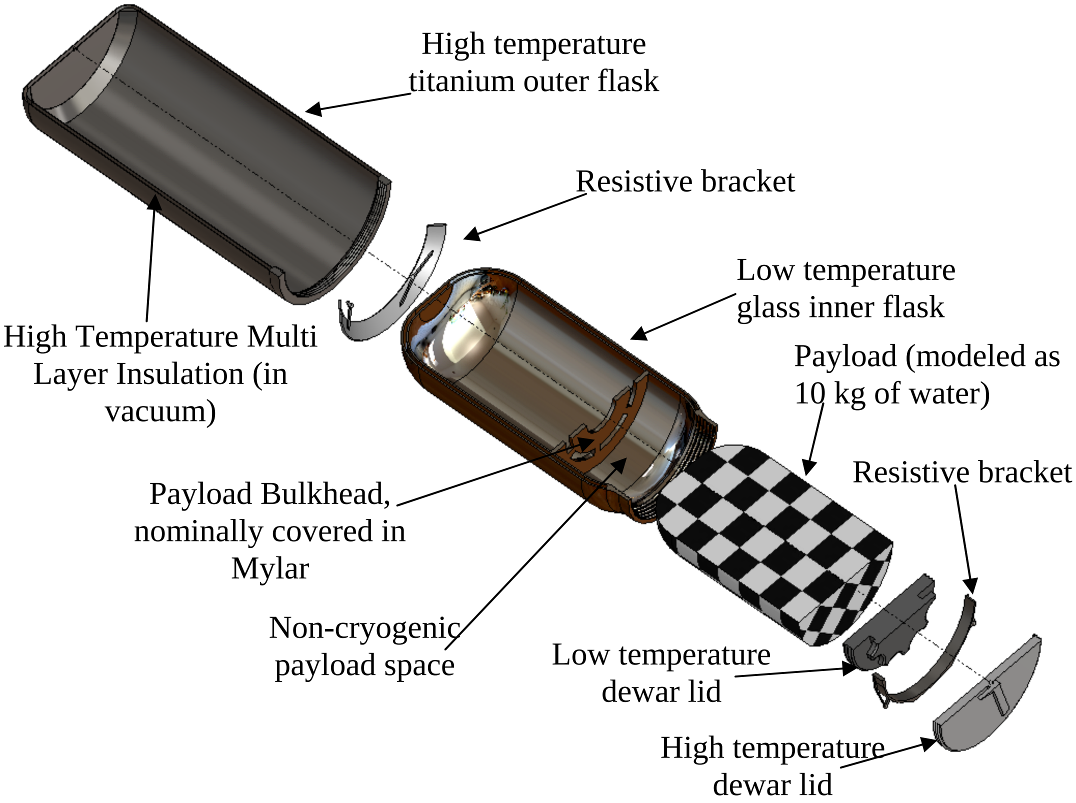


Figure 6. Configuration of the CEDR TCS Design

The outer or “hot” vacuum flask will be made of titanium coated with low emissivity and high temperature capabilities. The outer flask will use high temperature MLI in the vacuum annulus. The second inner flask is designed to minimize heat leak out from its cryogenic payload. It will have a more traditional design using glass for its low conductivity if structural analysis permits or titanium if glass is found to be structurally inadequate. The glass will be mirrored with vapor deposited aluminum. The payload is designed to be in the lower 3 quarters of the flask to minimize heat conducting through the lid from transferring to the payload. The payload bulkhead will also provide a thermal radiation shield for the payload from the lid. The lid will be designed to minimize heat transfer but in any vacuum flask system this is commonly where most heat leak happens. The lids of the two units will be sealed with silicone seals. Structural attachment points from the outer flask to the inner will be another design point where minimizing heat leak will be important. The two vacuum flasks will be connected with low conductivity brackets using a combination of kinematic single point contacts and traditional long low cross-sectional area conductance paths.

There are two elements that make this design possible; the lid seals and the resistive bracket design.

The Lid Seals

Figure 7. Two way breather valve

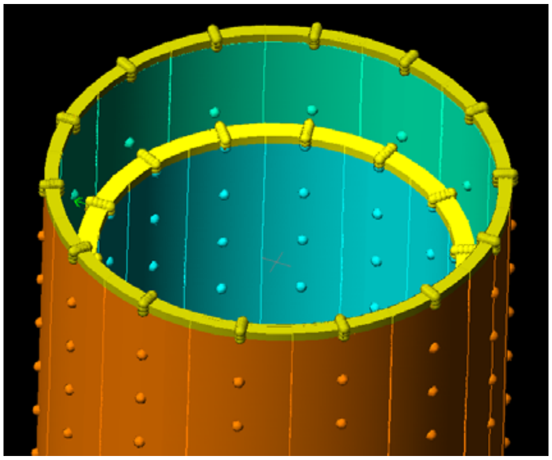
The vacuum annulus part of the flasks will always be in vacuum but the volume inside the flasks needs a seal, pictured in Figure 7. The payload (cold) inner flask will be fully sealed, acting as a pressure vessel. This will require a seal material that can handle very low temperatures and has very low thermal conductivity. The hot outer flask will require a similar low conductivity seal but must also allow gas into and out of the sealed region at a known pressure difference, but not exchange air between the environment and the flask when the pressures are equal. Not allowing gas to leave the outer flask while in vacuum would increase the thermal challenge as the air would act to increase thermal capacitance and conductance. To reduce the heat transported during reentry, a partial vacuum is designed for. The valve will act to minimize the layer of conductive air between the flasks during the hot reentry only allowing air in when the pressure difference could cause structural problems. This will insure a partial vacuum through the reentry period. The flask needs to avoid an explosion hazard during reentry while the internal gasses get hot and expand. Last, the unit cannot be exposed to ambient air while on the ground as the air will provide a constant convective heat source to the very cold inner payload flask. This seal will be a two-way pressure relief valve or “breather valve”. The breather valve mitigates forced convection caused by a high rate exchange of gas and minimizes natural convection by limiting the magnitude of the trapped gas.

Resistive Bracket Design

Figure 8. Resistive bracket

The resistive brackets will have two very important jobs. The first is to provide a structural connection between the outer and inner flasks. Several very significant structural loads will be applied to the system, including intense vibration loads during launch and potential impact loads during landing. The brackets will need to stay intact and properly functioning through these loads with positive margins. The second job of the brackets is to thermally isolate the inner and outer flasks from each other. The thermal isolation between the layers is planned to be achieved through the use of low conductivity long low cross sectional area thermal paths with small contact points. The conduction is minimized this way because thermal conduction is proportional to its cross-sectional area and inversely proportional to its length. As can be seen in Figure 8 long struts will protrude out to spherical surfaces that will ride on conic planes, creating a kinematic mount. The kinematic interfaces will provide point contacts which have very small contact areas. Paragon has familiarity with thermally isolative structural brackets. (Ref. [4])

Feasibility of CEDR TCS- Thermal Analysis



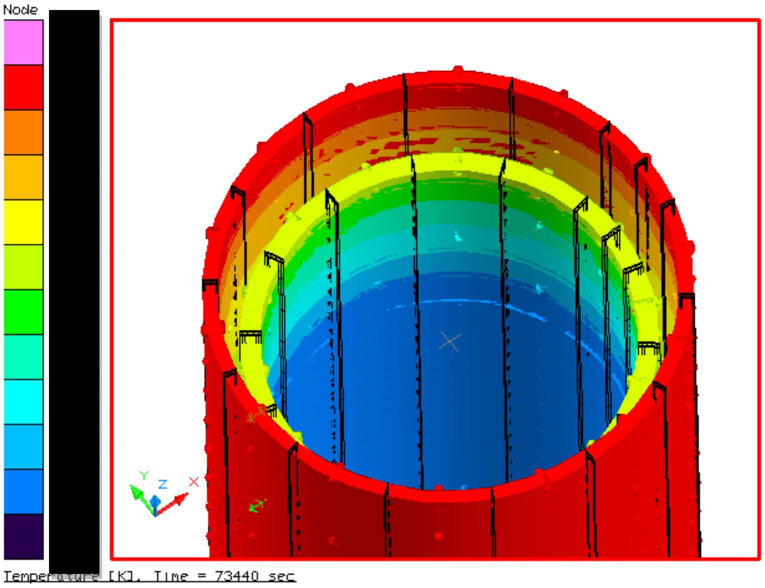


Figure 10. Temperature Distribution of the Vehicle after 24 Hours

The analysis done for SPQR showed how a many-layered system would survive atmospheric reentry with minimal heat leak back to the payload. However, SPQR is designed to be picked up immediately after landing. To test the design for the 24 hour period that CEDR TCS will be on the ground after reentry and before recovery, a simple thermal model was constructed as shown in Figure 9. The payload is modeled as a single block of 10 kg of water ice with no phase change energy. The payload starts at 100 K and the outside of the outer vacuum flask starts at and stays at just under 300 K, an ambient temperature through a large conductor. Air is assumed to be in the volume between the inner and outer vacuum flasks. Figure 10 shows the temperature gradient of the inner and outer flasks. Figure 11 shows the temperatures of the payload, outer surface of the low temperature inner flask, Inner surface of the high temperature outer flask, and outer surface of the high temperature outer flask after spending 24 hours at earth ambient temperature and pressure. The temperature of the inner surface of the low temperature flask is the same as the payload as it is assumed to be well thermally connected to it. The temperatures shown are of the lower end of CEDR TCS, away from the lid as part of the thermal design is to have a zone at the top where a warmer payload could go so that the heat path to the cryogenic payload is minimized.

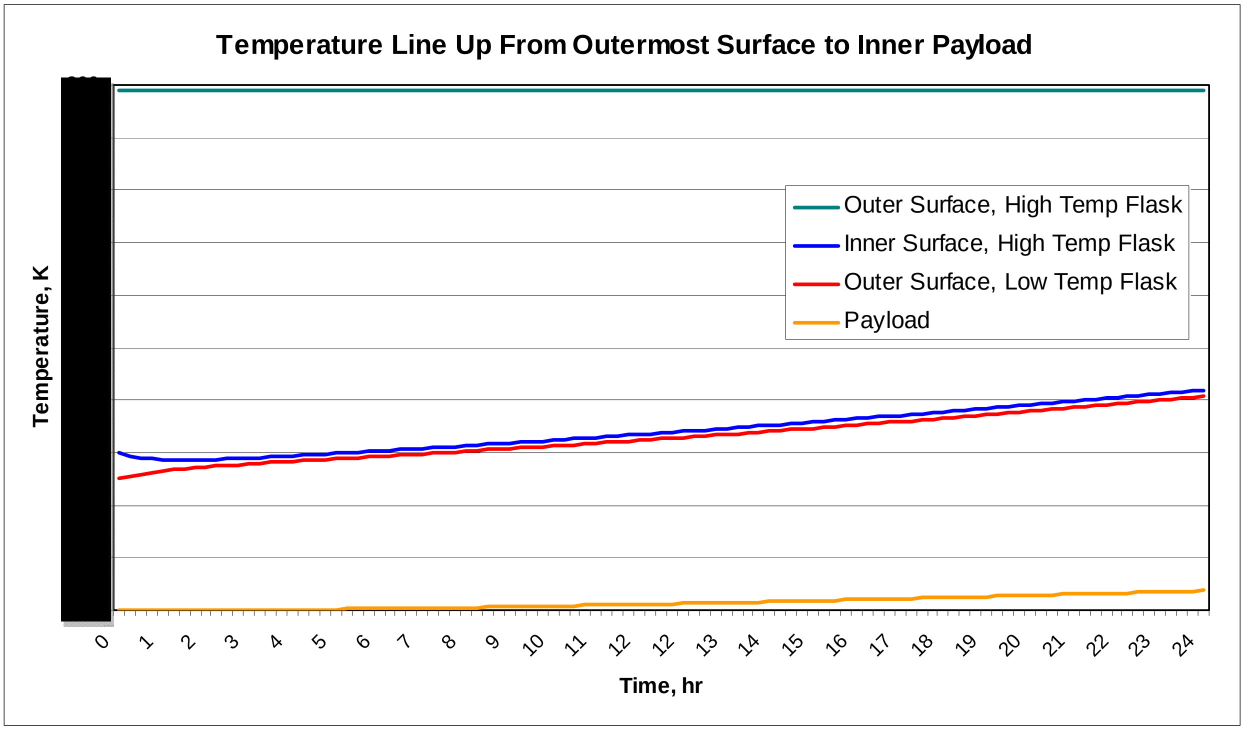


Figure 11. Temperature of the Unit over a 24 Hour Time Period on the Ground

The assumptions discussed are conservative in many aspects; however one non-conservative assumption is that the structural connections are not fully incorporated into the model which will be a key aspect of design that will increase its fidelity. The result of the payload increasing in temperature from 100 K to 107 K is considered to be more than reasonable at this level of development.

CONCLUSIONS

Given the stated assumptions, the SPQR vehicle investigated could keep a payload below 4°C for a stage 2 and 3 that is less than or equal to 1500 seconds, where the payload is greater than or equal to 2 kg worth of water heat capacity. There are, however, key assumptions made that should be considered. Greater research is needed to find the point at which the air gets into a small reentry vehicle. The rate of flow and temperature that air enters a vehicle is also an important point to clarify. This is the single biggest ambiguity that could greatly affect the final results of the study performed on the SPQR vehicle presented. The use of insulation both internal and external to the PCTCU greatly mitigates this risk and shows the importance of insulation in small open reentry vehicles. If air gets in earlier and/or with greater convection currents it could result in a rapid increase in the payload temperature, without insulation present. If air is getting in only at the 30 km altitude, even with greater convection currents, it is believed that the insulation could adequately protect the payload. However, as part of the future work it would be more conservative to start at 120 km. The low emissivity coating on the casing was also shown to be a needed step in decreasing heat transfer to the payload. Currently, all of the parts of the

SPQR vehicle do not have a high heat capacity relative to the payload, which helps insure that the vehicle cools rapidly before too much heat can soak back into the payload. Any large changes to the thermal capacity of the vehicle would quite clearly necessitate more analysis.

The CEDR TCS is a proposed system which would bring a payload through an atmospheric reentry which could then spend up to one full day at ambient temperature and pressure on the ground. To accomplish this, two vacuum flasks designed to maintain a vacuum annulus through changing pressures. The system is anticipated to be fully passive allowing for a low-complexity, zero-power system that does not necessitate the use of any consumables.

ACKNOWLEDGEMENTS

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NOMENCLATURE

CEDR TCS	Cryogenic Extended Duration and Reentry Thermal Control System
ISS	International Space Station
CFD	Computational Fluid Dynamics
TDRV	Tube Deployed Re-entry Vehicle
PCTCU	Payload Containment and Thermal Control Unit
SPQR	Small Payload Quick Return
NASA ARC	NASA Ames Research Center
PCM	phase-change material
Gr	Grashof
Pr	Prandtle

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