Thermal Optimization of an On-Orbit Long Duration Cryogenic Propellant Depot

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A Cryogenic Propellant Depot (CPD) operating in Low Earth Orbit (LEO) could provide many near term benefits to NASA's space exploration efforts. These benefits include elongation/extension of spacecraft missions and requirement reduction of launch vehicle up-mass. Some of the challenges include controlling cryogenic propellant evaporation and managing the high costs and long schedules associated with the new development of spacecraft hardware. This paper describes a conceptual CPD design that is thermally optimized to achieve extremely low propellant boil-off rates. The CPD design is based on existing launch vehicle architecture, and its thermal optimization is achieved using current passive thermal control technology. Results from an integrated thermal model are presented showing that this conceptual CPD design can achieve propellant boil-off rates well under 0.05% per day, even when subjected to the LEO thermal environment.

Nomenclature

α	Absorptivity
ε	Emissivity
Beta	Angle between the Orbital Plane and the Ecliptic Plane
BTU	British Thermal Unit
CPD	Cryogenic Propellant Depot
ft	Feet
GMM	Geometry Math Model
Hc	Convection Heat Transfer Coefficient
Hv	Heat of Vaporization
in	inches
IR	Infrared Radiation
ITM	Integrated Thermal Model
KSC	Kennedy Space Center
Lbs	pounds
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
MLI	Multi Layer Insulation

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mT	Metric Ton
nm	Nautical Mile
PSI	Pound per Square Inch
Q	Average Heat Leak Rate
RAAN	Right Ascension of Ascending Node
RadK	Radiation Conductor
Theta	Angle between the CPD Minor Axis and the Ecliptic Plane

I. Introduction

A long duration CPD is a conceptual space vehicle that can store large quantities of cryogenic propellant for extended periods. A CPD would function as an on-orbit refueling station for 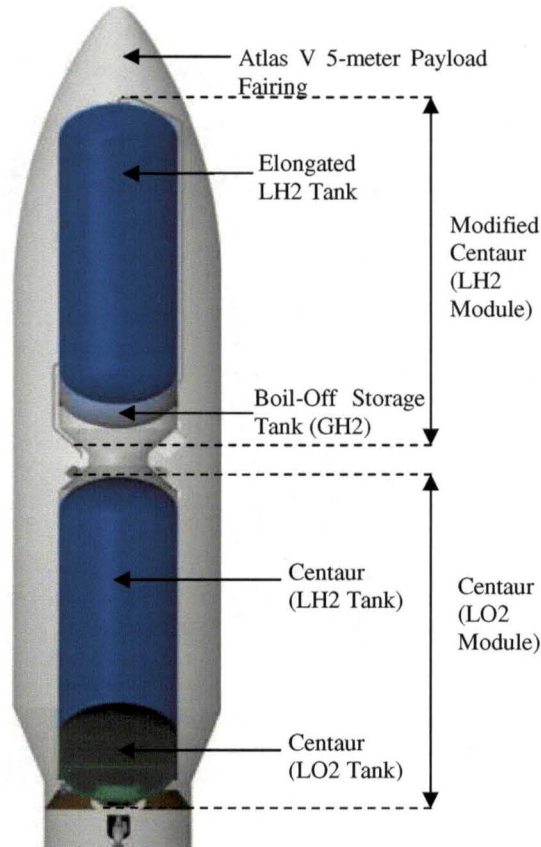in situ spacecraft and/or launch vehicles. A CPD could potentially provide many benefits to the NASA space exploration program, including the extension/elongation of spacecraft missions and reduction of rocket mass requirements.

As shown in Fig. 1, the CPD concept considered in this analysis is a dual propellant storage configuration based on the current Atlas V Centaur design. In this CPD concept, the forward end of an Atlas V Centaur is mated to the aft end of a modified Atlas V Centaur. The modified Centaur would consist of an elongated LH2 tank connected to a small boil-off storage tank. At launch, both the Centaur and modified Centaur would be encapsulated within the Atlas V 5-meter payload fairing. Once on orbit, residual LH2 within Centaur would be transferred to the modified Centaur; the residual H2 would be purged with Helium. The Centaur would then be refilled, on-orbit, with LO2. Consequently, the modified Centaur functions as the on-orbit LH2 storage module, and the Centaur functions as the on-orbit LO2 storage module.

The dual propellant CPD concept has the advantage of storing both LH2 and LO2. Further, the concept utilizes existing, or slightly modified, flight hardware. To achieve its target boil-off rate, the CPD will need to stow cryogenic propellant for extended periods with minimal evaporative losses. This will require, in part, a Thermal Protection System (TPS) specifically designed to minimize the cryogenic propellant boil-off associated with each module.

Aside from the TPS design, the CPD orbit will also play an important role in determining the propellant boil–off rate. From a logistics standpoint, LEO represents the most desirable orbit to fly the CPD. LEO would provide easy access for both on–orbit refueling and CPD maintenance/resupply. Conversely, LEO represents the least desirable orbit from a thermal management standpoint. Having significant amounts of solar, albedo, and Earth's IR, LEO constitutes the most severe on–orbit thermal environment and, undoubtedly, would be the most challenging orbit from which to manage cryogenic propellant boil–off. Because it is both logistically desirable and thermally challenging, LEO is considered to be the ideal orbit to investigate in this analysis. It was felt that a CPD design achieving the desired boil-off rate in LEO could also achieve, or exceed, this boil-off rate in higher, less thermally severe, Earth orbits (i.e., geosynchronous, Lagrangian, etc.). In this sense, LEO provides the ultimate test of CPD storage capabilities.

Figure 1. Cryogenic Propellant Depot Concept (Launch Configuration)

II. Development of the CPD ITM

The CPD ITM was developed in Thermal Desktop™ Version 5.3. Thermal Desktop™ is a thermal analysis tool that facilitates the development of sophisticated computer aided design based thermal models. The development process involves generation of a Geometric Math Model (GMM) using the Thermal Desktop™ built-in AutoCAD tool. Thermal and optical properties are assigned to the GMM using the Thermal Desktop™ property edit forms. The Thermal Desktop™ pre-processor is used to compile the above data into a Systems Improved Numerical Differencing Analyzer (SINDA) thermal network. Radiation conductors are added to the SINDA thermal network using Thermal Desktop's™ radiation analyzer tool, RadCAD™. The combined RadCAD™ – SINDA thermal network can be solved using any of the various Thermal Desktop™ built-in numerical solvers. The CPD ITM developed for this analysis consists of the CPD structures, cryogenic propellant, and on-orbit thermal environment. Development of the CPD ITM is described in detail in the following sections.

A. On Orbit Thermal Environment

As previously stated, the CPD was assumed to be in LEO for this analysis. The LEO thermal environment consists of the following heating parameters: 1) solar radiation, 2) albedo, 3) Earth's IR and, 4) deep space IR. Table 1 summarizes the specific values used for the LEO heating parameters.[1] For this analysis, the CPD was assumed to be in a circular orbit (i.e., orbital eccentricity equals zero) in which the Right Ascension of the Ascending Node (RAAN) was always equal to 90° (i.e., orbital precession rate equals zero). These simplifying assumptions ensure that the solar angle (beta) will always be equal to the orbital inclination and, further, that the radiant flux incident on the CPD will be constant as a function of orbital cycle. Table 1 summarizes the specific values used for the CPD orbital parameters.

Table 1. Summary of CDP Orbital Parameters

Altitude (nm)	Beta Angle (degrees)	RAAN (degrees)	Orbital Period (hr)	Orbital Eccentricity	Theta (degrees)*	Tracking
365	0 – 30	90	1.6378	0	-10 – +10	+Z Solar

The attitude of the CPD is defined in Table 2 and Fig. 2. The basic criteria for designing the CPD attitude was to try to minimize the amount of orbital flux that can reach the CPD tanks. Preliminary analysis indicated that this could best be achieved by orienting the CPD such that its primary axis was perpendicular to the ecliptic plane and, further, to select beta angles that would protect the aft end of the LH2 module from incoming albedo and Earth's IR. Orientating the CPD such that its primary axis is perpendicular to the ecliptic plane ensures that the aft end of each storage module (LO2 and LH2) has a constant view of deep space. Further, this attitude minimizes the amount of direct solar radiation that can reach the propellant tanks. However, Earth's IR and albedo can still be problematic for this attitude. As both are emitted diffusely, significant amounts of Earth's IR and albedo can traverse the open end of each sunshield and, subsequently, impinge upon the propellant tanks. Preliminary analysis suggested that the LH2 module was particularly sensitive to Earth's IR and albedo during the illumination phase of the orbit. To mitigate this impact, beta angles were chosen such that, during illumination, the open end of the LH2 module sunshield faced away from the incoming Earth's IR and albedo. While this orientation minimizes the amount of Earth's IR and albedo incident on the LH2 module during illumination, it has the opposite effect during eclipse. Fortunately, both the albedo and Earth's IR flux are very low during the eclipse portion of the orbit.

Within Thermal Desktop, the CPD orbit was simulated by using 18 discrete steady-state orbital positions. To simulate the on-orbit radiation exchange, 5000 rays per node were shot to calculate the CPD radiation conductors (RadK's) and orbital heating rates (solar, Earth's IR and albedo). A sensitivity study determined that further increasing the number of rays and/or orbital positions had little effect on the fidelity of the solution. It is important to note that all predicted heating rates in this analysis represent orbital averages (average from all eighteen orbital positions).

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* Theta is the angle between the CPD minor axes and ecliptic plane (see Fig. 1).

Table 2. Summary of LEO Thermal Environment

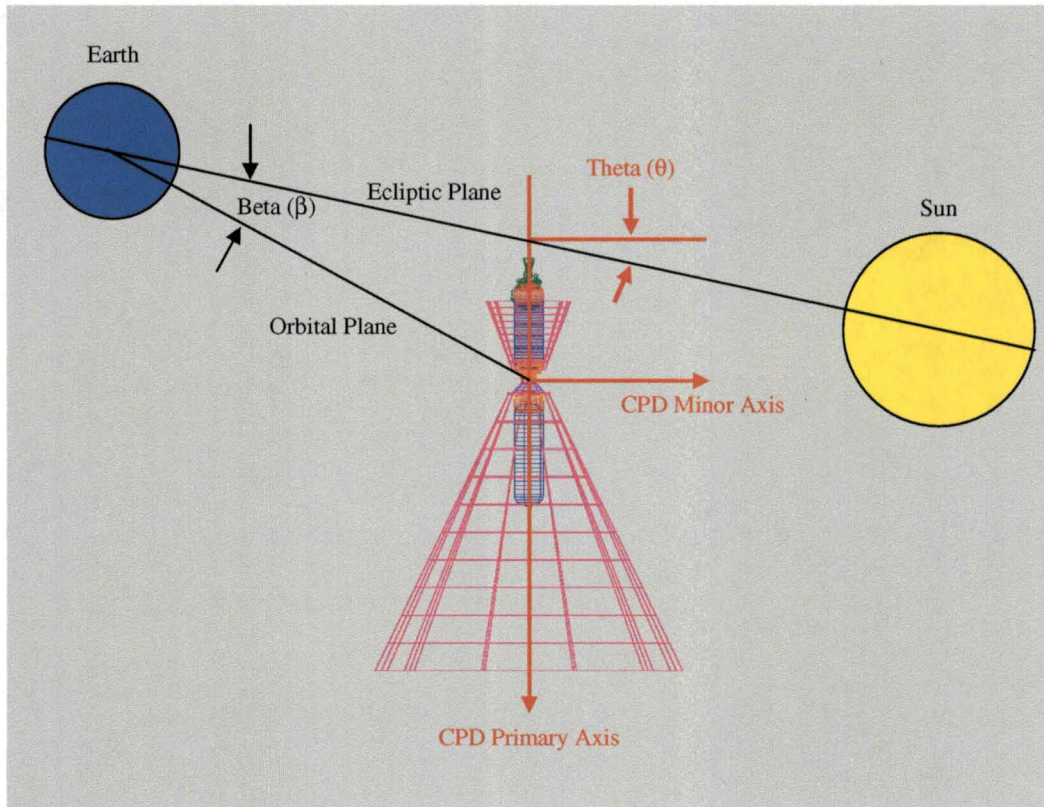| Solar Radiation (BTU/hr/ft²/°F)	Earth's IR (BTU/hr/ft²/°F)		Albedo	Deep Space IR (deg R)
	Illumination	Ellipse		
429.2	70.2	35.1	0.35	4

Figure 2. CPD Concept – Dual Propellant Storage Configuration (Broadside Vertical Attitude)

B. Structures

As shown in Fig. 3, the dual propellant CPD concept utilizes two separate modules to store cryogenic propellant on-orbit: the LH2 module and LO2 module. The LO2 module is based on an Atlas V Centaur design. The LH2 module is based on a modified Atlas V Centaur design. To thermally isolate the two cryogenic propellants, the LH2 and LO2 modules are separated by three pairs of composite struts.[7]

The CPD is launched from inside an Atlas V 5-meter fairing. To save weight, the LH2 module is launched without propellant. Once the CPD is on orbit, the remaining LH2 in the Centaur LH2 tank is transferred to the empty LH2 tank in the modified Centaur. After the LH2 transfer is complete, the remaining LO2 in the Centaur LO2 tank is transferred to the Centaur LH2 tank. Thus, the Centaur LH2 tank functions as an on-orbit LO2 storage tank. Further, the Centaur LO2 tank functions as an on-orbit GO2 storage tank, collecting boil-off from the Centaur LO2 storage tank[†]. The GO2 could be used to collect heat from the CPD structure and dissipate the heat back out to space. For this report it was assumed that the avionics boxes and batteries on the Block II avionics shelf were powered off, and the RL-10 was not operating. During on-orbit steady state operation, use of avionics and batteries would be kept to a minimum in order to reduce the amount of latent heat generation.

[†] Note that in Fig. 3 and Fig. 4, the Centaur tanks are referred to by their on-orbit storage function.

Once on orbit, the CPD sun shields are deployed. As shown in Fig. 4, the LH2 module is fully enclosed by its sun shield; however, the LO2 module is only partially enclosed by its sun shield. This is due to the fact that, in order to mitigate plume heating from the Centaur Reaction Control System (RCS), the maximum length of the LO2 module sunshield is limited to just 24.55 feet.[§] Because it is fully enclosed by its sun shield, the LH2 module is primarily an IR and albedo dominant radiation environment (i.e., virtually no direct solar). The optical properties for the exterior surfaces of the LH2 and the GH2 tanks were chosen as to have low alpha and very low emissivity values. These optical properties enable the exterior surfaces of the LH2 and GH2 tanks to effectively reflect incident albedo and Earth's IR back to space. Because it is not fully enclosed by its sunshield, the LO2 module is subjected to much higher amounts of solar flux. Consequently, the optical properties for the LO2 and GO2 tanks were selected as to have low alpha values and high emissivity values (i.e., low α/ε ratio). These optical properties allow the LO2 and GO2 tank to effectively reflect incident solar radiation back to space, and effectively re-emit radiation in the IR spectrum. In order to protect the CPD from the LEO radiation environment, all propellant tanks were enclosed in ten layers of MLI. Due to its very low emissivity, aluminized Kapton® was selected as the optical coating for all MLI internal layers.[5] This selection takes advantage of the fact that MLI internal layers participate only in IR exchange (i.e., absorptivity is not important for MLI internal layers).

Table 3. Optical Properties for LO2 Module Sun Shield

Structure/Equipment Item	Material		Absorptivity/Emissivity		Ref.
Centaur Sun Shield[‡]					
Sun Shield Layer #1	Inner: Outer:	VDA Kapton® Silver Teflon®	Inner: Outer:	0.14/0.05 0.07/0.80	[4]
Sun Shield Layer #2	Inner: Outer:	VDA Kapton® SV5	Inner: Outer:	0.14/0.05 0.08/0.81	[4]
Sun Shield Layer #3	Inner: Outer:	VDA Kapton® SV5	Inner: Outer:	0.14/0.05 0.08/0.81	[4]
Primary Propellant Tank					
Sun Shield Layer #1	Inner: Outer:	VDA Kapton® Silver Teflon®	Inner: Outer:	0.14/0.05 0.08/0.70	[4]
Sun Shield Layer #2	Inner: Outer:	VDA Kapton® SV5	Inner: Outer:	0.14/0.05 0.08/0.81	[4]
Sun Shield Layer #3	Inner: Outer:	VDA Kapton® SV5	Inner: Outer:	0.14/0.05 0.08/0.81	[4]

For the LH2 and GH2 tanks, aluminized Kapton® was also selected as the optical coating for the MLI outer surface. This was acceptable due to the fact that very little solar radiation impinges on the LH2 and GH2 tanks and, thus, a low absorptivity to emissivity (α/ε) ratio was not required for these surfaces. Conversely, for the LO2 and GO2 tanks, silver Teflon® was selected as the optical coating for the MLI outer surface. This was due to the fact that the LO2 and GO2 tanks are receiving high amounts of solar radiation and, consequently, require an optical coating having a low α/ε ratio.

[‡] Sun shield half cone angle and length are 60° and 24.55 feet, respectively.

[§] This length is based on the assumption that the sun shield has a cone angle of 60°.
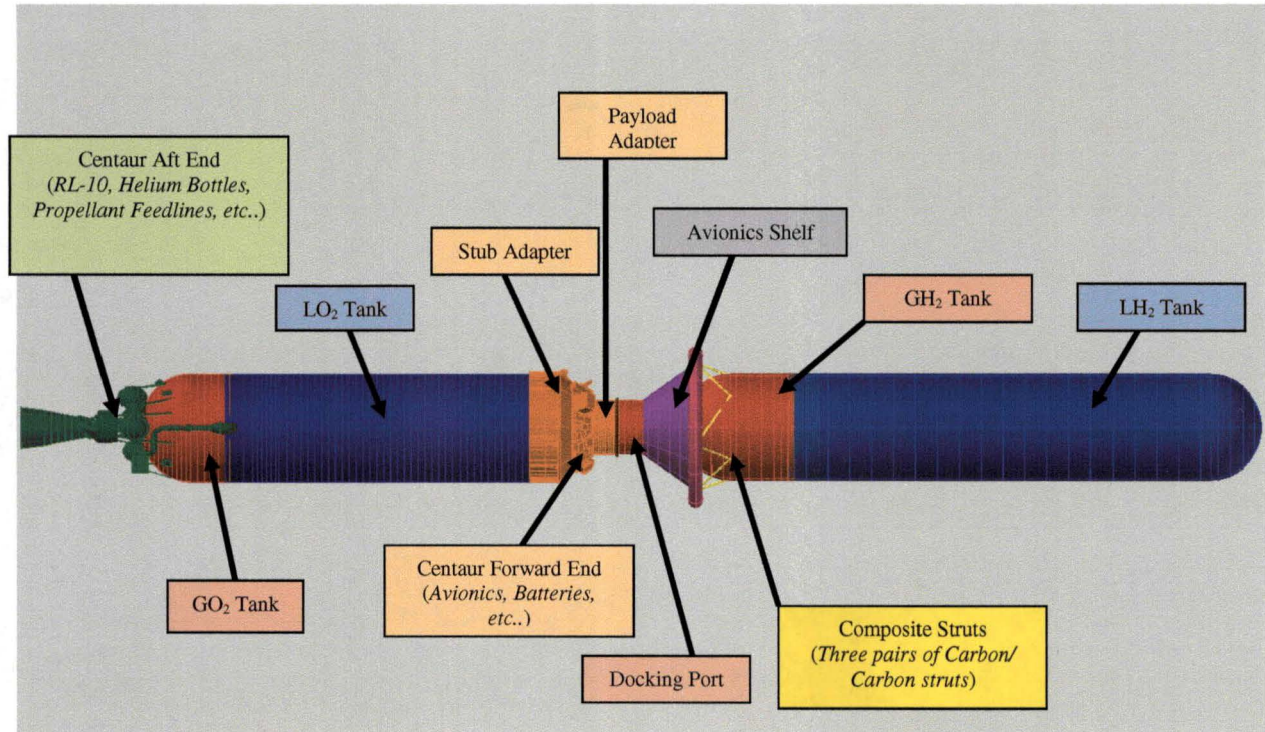
Figure 3. CPD Concept – Dual Propellant Configuration (Sun Shield Removed to Reveal Tank Detail)
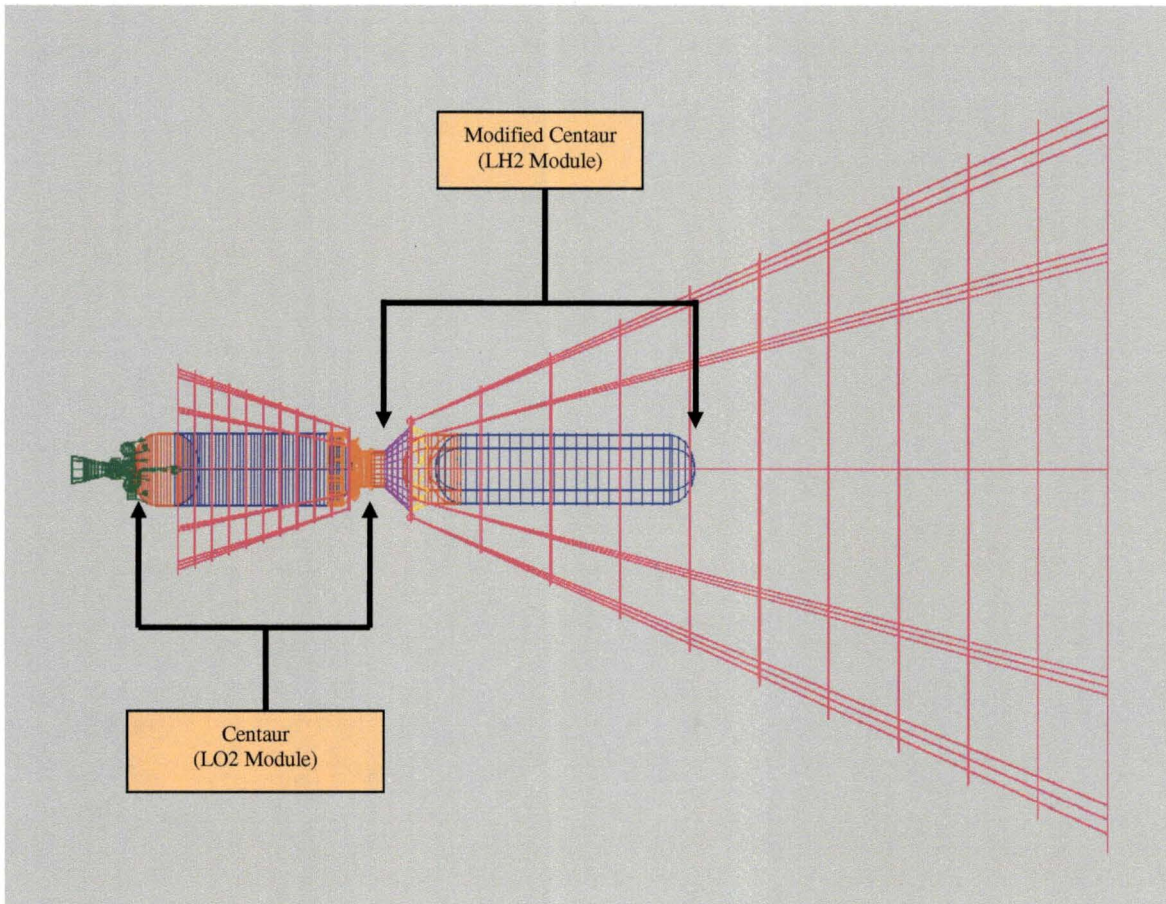

Figure 4. CPD Concept – Dual Propellant Configuration (Sun Shield Shown to Scale)

C. Cryogenic Propellant

It was conservatively assumed in this analysis that the entire internal area of both the Centaur LO2 tank and modified Centaur LH2 tank are in constant contact with their cryogenic propellant. Further, it is assumed that the heat transfer coefficient between the tanks and cryogenic propellants is a uniform value of 0.75BTU/hr-ft^2-R, which is representative of a low gravity orbital environment. Table 4 contains the physical properties for the cryogenic propellants that were used in this analysis. The cryogenic propellants inside the tanks were modeled as constant temperature boundary nodes. It was conservatively assumed that the cryogenic propellants were already at saturation temperature when the CPD was inserted into LEO. Consequently, all heat absorbed by the propellants while on-orbit immediately contributed to the vaporization process (i.e., no heat required to first raise the propellant to the saturation temperature).

Table 4. CPD Cryogenic Fluid Saturation Properties

Cryogenic Fluid	Pressure (PSI)	Boundary Temperature (R)	Heat of Vaporization (BTU/lbm)	Ref.
LO2	35	180	87	[3]
GO2	35	180	NA	[3]
LH2	35	42.67	182	[3]
GH2	35	42.67	NA	[3]

III. Results

Figure 5 through Fig. 7 summarize the predicted average heat leak rates entering the LH2 and LO2. The boil-off rates (% per day) that are presented in Fig. 7 were calculated using the following formula:

$$Boil\ Off\ (\%\ per\ day) = \frac{Q*100}{H_V*24*M} \qquad (1)$$

where M is the mass of the cryogenic propellant, H_V is the heat of vaporization, and Q is the average heat leak rate. The mass of the LH2 and the LO2 were assumed to be 5 mT (11060 lbs) and 55 mT (121660 lbs), respectively.[7]
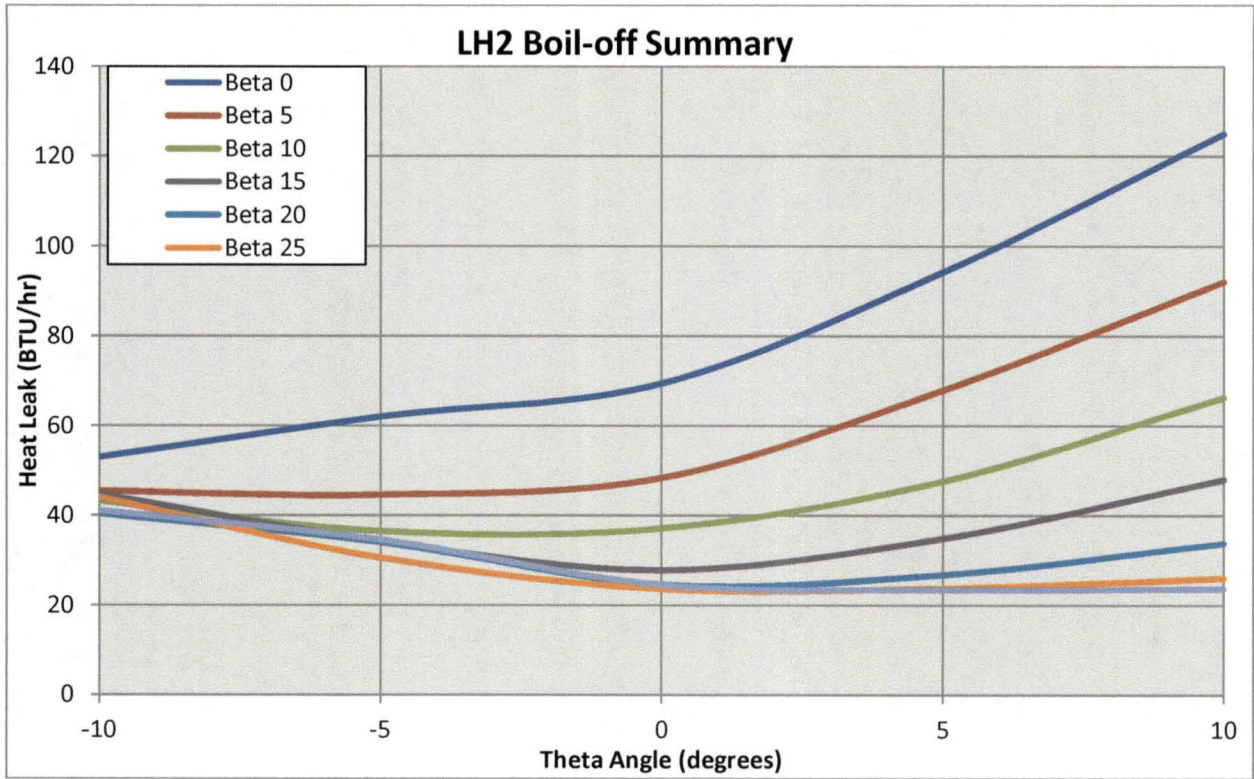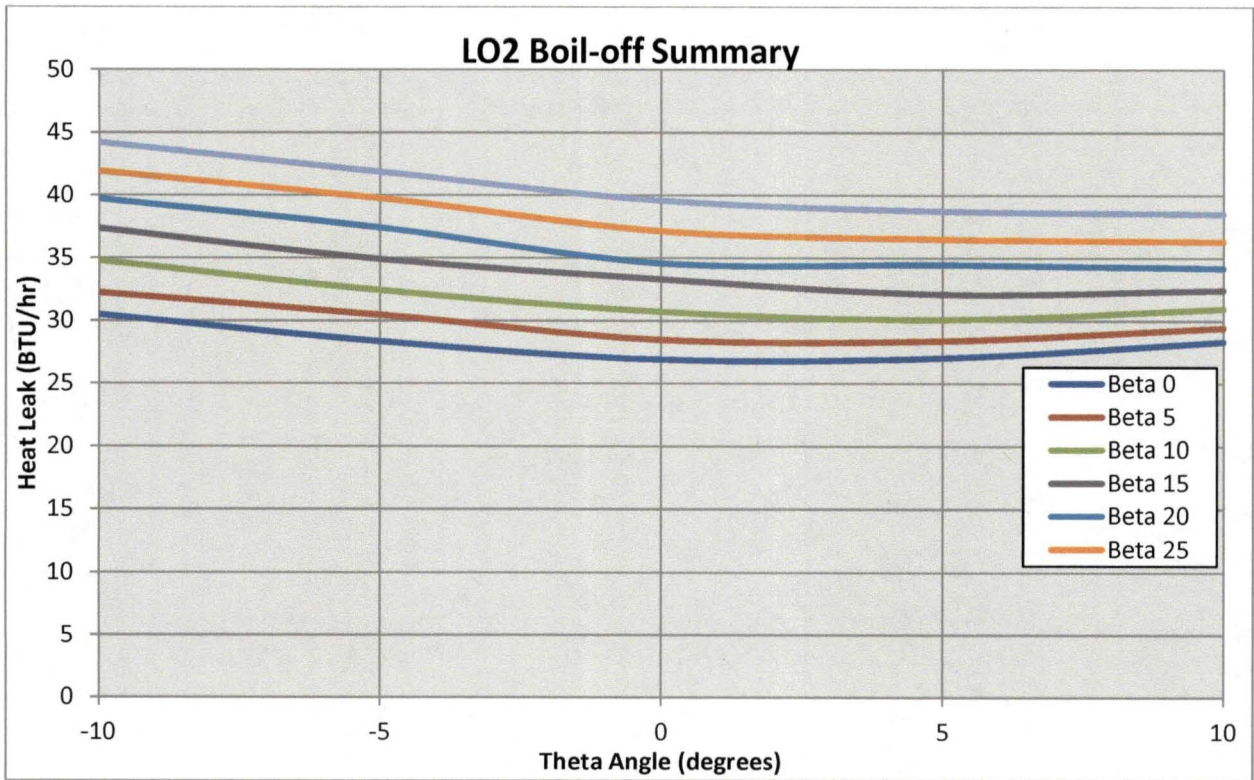
Figure 5. LH2 Heat Leak versus Theta Angle

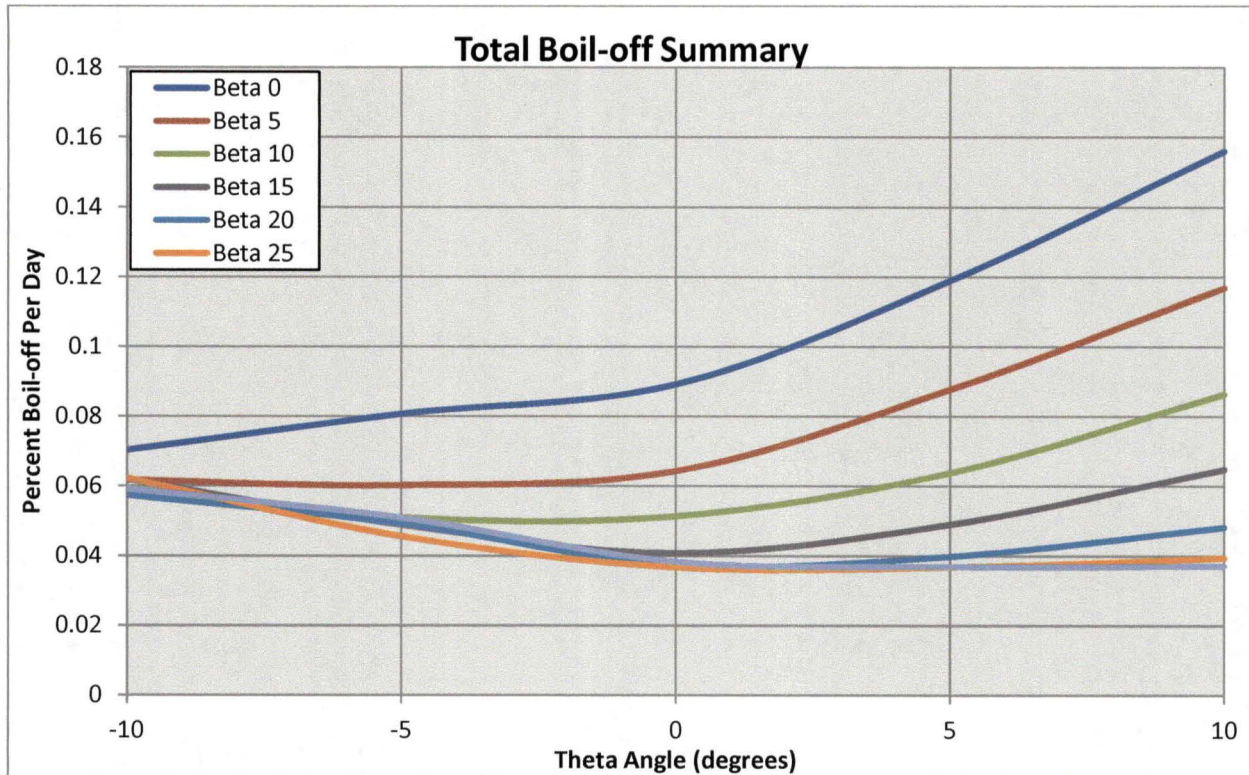Figure 6. LO2 Heat Leak versus Theta Angle

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Figure 7. Total Boil-off (% Per Day) versus Theta Angle

IV. Conclusion

Figure 7 contains the summary of the total boil off (% per day) for an on-orbit CPD. From Fig. 7, it is clear that the current CPD design has achieved the goal of a total boil off rate that is less than 0.05% per day. Figure 5 and Fig. 6 are also critical because the total boil-off rate can determine if a certain CPD attitude (i.e. Beta, Theta) is desired based on a specific mission need to store one propellant longer/shorter than the other, or store both propellants at the same boil off rate.

From the results presented in this report, the optimal combination of CPD Beta and Theta angles for reducing LO2 boil-off is 0^0 and 0^0, respectively. Because of the reduced length of the Centaur sunshield, the LO2 tank has direct solar radiation impingement. At Beta and Theta equal to 0, the direct solar radiation on the LO2 tank is minimal. The optimal combination of Beta and Theta with regards to reducing LH2 boil-off is 30^0 and 5^0, respectively. In Fig. 6, there were several observed trends. For a constant Theta, the heat leak entering the Centaur tends to increase as Beta increases. Conversely, for a constant Beta the heat leak entering the Centaur tends to decrease as Theta increases. These trends underscore the fact that the heat leak entering the LO2 tank was more sensitive to Beta than Theta. At Beta and Theta equal to zero, the LH2 module's sunshield is able to fully enclose the LH2 tank from any direct solar radiation. Therefore, the thermal environment inside the LH2 module sunshield is dominated by IR. However, because the CPD is composed of both the Centaur and the LH2 module, the overall lowest heat leak was for a Beta and Theta of 20^0 and 0^0, respectively. There were several trends observed in Fig. 5. For a constant Theta angle, the heat leak entering the LH2 module tends to decrease as Beta angle increases. Conversely, for a constant Beta, the heat leak entering the LH2 module tends to increase as Theta deviates from zero.

Acknowledgments

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