Zero-Boil-Off System Trades Applied to Nuclear Thermal Propulsion

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ABSTRACT

A National Aeronautics and Space Administration (NASA) team at Glenn Research Center (GRC) and Marshall Space Flight Center (MSFC) are studying cryogenic thermal storage using zero boil-off technology applied to a liquid hydrogen propellant tank of a Nuclear Thermal Propulsion (NTP) vehicle. To achieve zero-boil-off, efficient cryocoolers and high performing insulation are required. These designs have been studied previously, however, this iteration updates the modeling tool regarding the heat removal of an upper cooling stage, the broad area cooling system, line insulation, as well as tank insulation seam and penetration losses. The application to a near rectilinear orbit decreases the exposure temperature of the insulation, reducing the heating rate of the liquid hydrogen. The trades presented optimize the number of MLI layers, the number and size of the cooling loops on the tank and shield, and shows the system size with single and two stage cryocooling.

INTRODUCTION

NASA GRC and NASA MSFC are presently performing analysis and conducting trade studies to update the NTP mission concept of operation and vehicle architecture. That architecture requires a 720 day duration loiter period (see Figure 1) in space to assemble the three In-Line NTP stages and the Core stage into a vehicle to begin the 160 day trip to Mars. While at Mars, a return vehicle

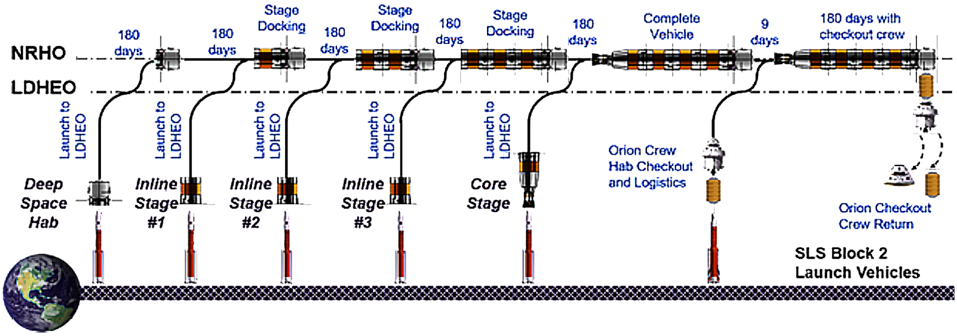

Figure 1. NTP mission timeline for vehicle assembly in NRO.

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orbits for over 600 days. The return trip is also 160 days. The present plan to rendezvous and assemble the stages into a vehicle in the Near Rectilinear Halo Orbit (NRHO or NRO), an orbit near the Lagrange points that creates a much colder environment than near Earth orbits. Still, the environment temperatures are warmer than that of liquid hydrogen, which is used as the propellant.

To achieve zero boil-off (ZBO) of liquid hydrogen (LH_2) it is critical that the heat loads into the tank, particularly the tank structure, are as low as possible. Also, it is necessary to advance the state-of-the-art in LH_2 temperature cryocoolers for flight, which are at a relatively low state-of-the-art for the propellant storage application. This advancement is important in that the present state-of-the-art 20K cryocooler technology has a lift capacity of less than 1 W, much less than the projected tank heat leak rates, while offering no ability to distribute the cooling. Because of this, the NASA is advancing the development of a 20W, 20K class reverse turbo-Brayton cycle cryocooler.[1] This paper will clarify the usefulness of a 20W capacity with this NTP mission using the NRO orbit, with the goal of minimizing power and mass. The issues of power availability and the expense of power systems limits the consideration of active cooling. Mass is also critical as it increases the size and cost of the launch vehicle and reduces potential payload mass.

As the 20K class cryocooler is the most challenging aspect of achieving LH_2 ZBO, a heat leak analysis to reduce the 20K cooling load is required. Our goal is to minimize mass and power while keeping the 20K cryocooler size minimal. To accomplish this, a second stage of cooling is considered. The second stage, a nominal 90 K cryocooler system, was found to have reduced tank heat leak by 60%, as measured by the heat reduction of the components cooled by the cryocooler, in Reduced Boil-Off (RBO) testing at NASA Glenn[2,3] (see Figure 2). A schematic representation of the two circuits of cooling envisioned, using both the 90K class cooling system and a 20K class cryocooler system, is shown in Figure 3.

Figure 2. Reduced boil-off test article.

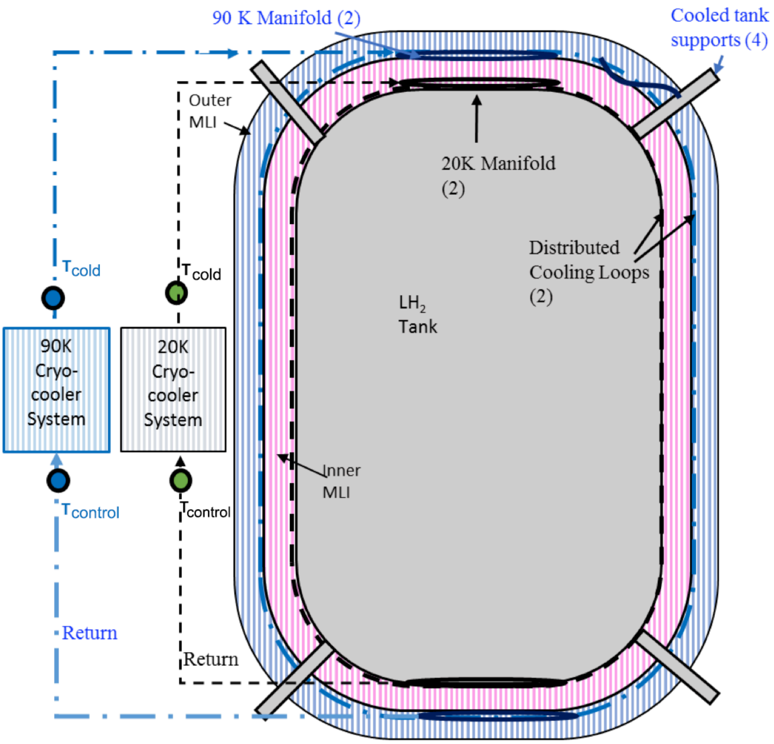

Figure 3. Two stage cooling schematic of LH_2 tank

This paper specifically sizes a flight active cooling system to achieve ZBO of LH_2 for the long duration NRO orbit environment. The Cryogenic Analysis Tool[4] has been updated to reflect developments in the 20K class cryocooler and the 90K class cryocooler, to improve the calculation of the heat leak to the 90K class broad area cooled shield system, and to add advancements in insulation modeling. A comparison of single stage 20K cryocooler cooling versus a two stage cryocooling with a broad area cooling (BAC) shield is presented. A trade study on the broad area cooled shield temperature is presented. Also, multi-layer insulation (MLI) trades are conducted for this vehicle at the NRO orbit. The results show the predicted lift requirement of the 20K class cryocooler system along with the 90K class cryocooler system, the MLI configuration, the power, and the mass of the ZBO system.

ANALYSIS DEVELOPMENTS

This study is conducted using the GRC heritage Cryogenic Analysis Tool (CAT), updated in 2011 to incorporate the reverse turbo Brayton cycle cryocooler system.[4] Several updates to modeling the ZBO system were implemented. First, the advancements in the 20W-20K cryocooler design, which is in the final phase of development, projects a specific power of 48 W/W at 24.2K (LH_2 temperature at 40 psi) and a specific mass of 3.6 kg/W. The second development is the direct calculation of the heat transfer to the broad area cooled shield, which was recently described[5] and folded into the CAT model. This improvement takes into account the contact resistance of the cooling straps and the loss in moving that heat to the cryocooler. Beyond the strap resistance, the cooling tube flow velocity was calculated and used to find the gas pressure drop in the distributed tubing coupled to the tank. Previously, a nominal pressure drop of 0.1 psi was assumed. This allows for the optimization of cooling tube size.

The model also includes heat leak through insulation seams, per recent insulation developments in measuring and characterizing types of MLI seams.[6,7,8,9] A geometric assessment of seam length was added to CAT. Also, to make certain the MLI heat leak estimate was more complete, an estimation of the number of pins in a traditional MLI blanket[10,12] was made and the thermal conductivity of those pins was added in the analysis. On the plumbing and tank structure, 20 layers of MLI insulation were included and the heat leak estimate was calculated. The associated Cryolite buffer seam heat leak to integrate tank MLI with penetration MLI was added.[8,11] A summary of the CAT updates is shown in Table 1.

Beyond the CAT modeling effort, a finite element thermal model of the NTP vehicle was created. This thermal model of the three dimensional vehicle configuration in the NRO orbit determined the MLI surface temperatures and the aft and forward adapter temperatures.

STRUCTURE AND PLUMBING

A model depicting the NTP Core Stage Conceptual Design is shown below in Figure 4. On the Core Stage aft end, there are three nuclear engines which interface with an aluminum shell thrust cone. The thrust cone interfaces with an aluminum skirt, both having an average thickness of 0.221 inches. Between the aluminum skirt and the 7 m diameter aluminum LH_2 tank is the tank aft truss structure which is comprised of thirty-two S-2 Glass Fiber Composite struts with titanium end fittings. Sixteen of these struts are mounted in-line and sixteen are mounted at approximately a forty-five degree angle relative to the tank centerline. The composite tube lengths are 21.02 and 35.82 inches, and the total strut lengths including the titanium end fittings are 35.03 and 59.69 inches for the in-line and angle mounted struts, respectively. Each composite tube is 6.0 inches in diameter, hollow, and has a wall thickness of 0.6 inches.

Similarly, on the Core Stage forward end, a 0.405 inch thick aluminum skirt containing the RCS tanks and stage avionics connects to the forward truss structure which interfaces with the propellant tank. The forward truss structure is also comprised of thirty-two S-2 Glass Fiber Composite struts of the same lengths. Each composite tube is 5.0 inches in diameter, hollow, and has a wall thickness for 0.3 inches.

On the In-Line Stage (see Figure 5) aft end, an aluminum skirt with an average thickness of 0.325 inches interfaces with the tank aft truss structure which is comprised of thirty-two S-2 Glass Fiber Composite struts with titanium end fittings. Sixteen of these struts are mounted in-line and sixteen are mounted at approximately a forty-five degree angle relative to the tank centerline. The composite tube lengths are 21.02 and 35.82 inches, and the total strut lengths including the titanium end fittings are 35.03 and 59.69 inches for the in-line and angle mounted struts, respectively. Each composite tube is 6.0 inches in diameter, hollow, and has a wall thickness of 0.9 inches.

Similarly, on the In-Line Stage forward end, a 0.168 inch thick aluminum skirt containing the RCS tanks and stage avionics connects to the forward truss structure which interfaces with the propellant tank.

Table 1. Cryogenic Analysis Tool Improvements

CAT Improvement	Specification
20 K-20 W Cryocooler Developments (24.2 K LH_2 storage temp)	48 W/W Specific Power, 3.6 kg/W Specific Mass
90K-150 W Cryocooler Development	9 W/W Specific Power, 0.36 kg/W Specific Mass
Cooling strap contact resistance	10 K/W[5]
Broad area cooling pressure drop	Tube gas velocity and pressure drop found
Tank insulation seam heat	Open butt seam assumed with 3mm gap.[6,7,8,9]
Tank insulation pin heat	1 pin every 30 cm,[7] Nylon
Penetration to tank MLI seam	Q estimated from parametric relationship assuming MLI butt with Cryolite[11]
Insulation on structure and penetrations	20 layers of MLI assumed, Modified Lockheed Eqn.[14] with scale factor 6 used

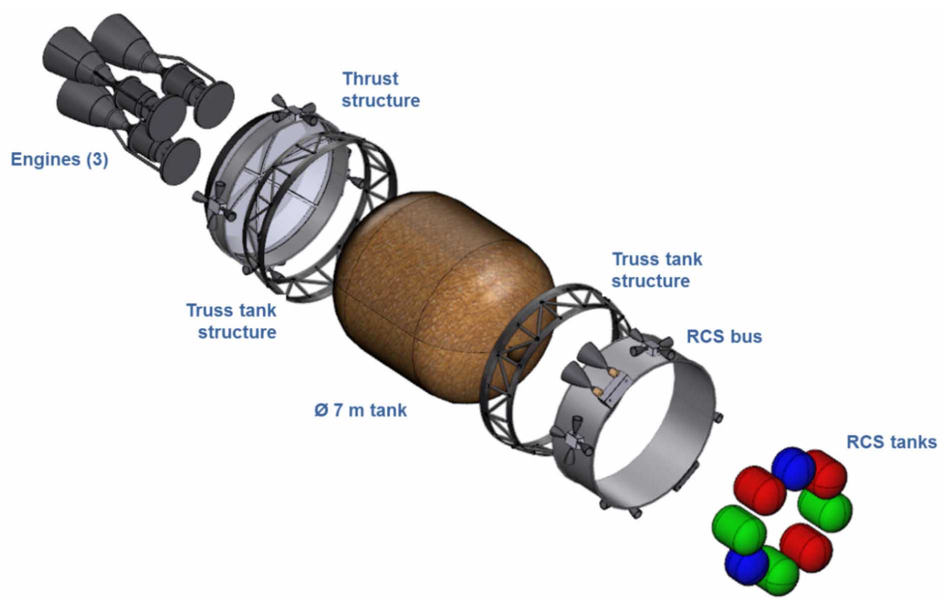

Figure 4. The NTP Core Stage Conceptual Design.

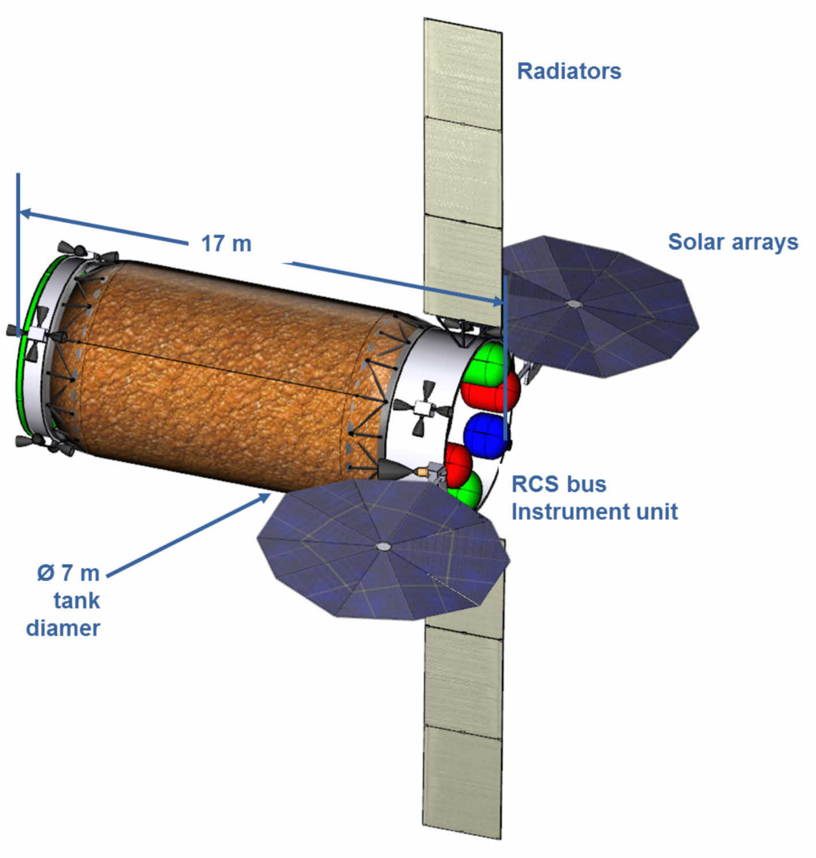

Figure 5. NTP In-Line Stage Conceptual Design.

The forward truss structure is also comprised of thirty-two S-2 Glass Fiber Composite struts of the same lengths. Each composite tube is 5.0 inches in diameter, hollow, and has a wall thickness for 0.2 inches.

At the time this analysis was conducted, the NTR vehicle was at a conceptual design level of maturity. The thermal conductivity of the S-2 Glass Composite was assumed to be 1.45 W/m K and the effect of the titanium end fittings was neglected. The plumbing associated with the Main Propulsion System (fill/drain lines, pressurization lines, vent lines, etc.) had not yet been defined. Understanding that the conduction paths associated with these tank penetrations can be significant, a ten foot feed-line constructed of 10 inch Schedule 5 stainless steel pipe was included on both the forward and aft end of each of the 7 m diameter tanks, and a fifty percent margin was added to the final heat load results to account for this uncertainty. As the NTP concept progresses in maturity from a preliminary to conceptual design, the tank penetrations will be included in the model and the margin carried will be adjusted accordingly.

THERMAL MODEL RESULTS

The Thermal Desktop[15] model of the In-Line tank found the MLI temperatures were slightly warmer and the stage is larger than the Core stage, indicating a worst case condition. Thus, the In-Line tank was selected as the focus of the study. The NRO orbit is highly elliptical and is well removed from the Earth and its moon, creating a very cold environment with an average MLI temperature of 106.5 K. Additionally, the forward adapter temperature was found to be 162 K, while the aft adapter temperature was 40K.

ASSUMPTIONS

The major NTP cryo related study assumptions are shown in Table 2. A main MLI assumption was that the insulation under the broad area cooled shield was 15 layers of self-supporting MLI. This concept has been proven to provide superior performance while having the structure necessary to support the broad area cooled shield. Given that the results in the RBO tests underestimated the inner MLI heat leak, which is still not understood, an increased scale factor (SF) of 5 was applied to the iterative radiation foil calculation used. The outer MLI was assumed to be traditional MLI, which was modeled using the Modified Lockheed Equation (MLE)[14] with a more typical scale factor of 3. Also, for the ZBO case with single stage cooling, traditional MLI was assumed with scale factor of 3. The assumptions and thermal model results are shown in Table 2.

Table 2. Cryogenic system assumptions and Thermal Desktop results for NTP study.

Characteristic	Specification
Tank Size	7 m dia, 10 m length, 19,000 kg LH_2
Tank Pressure	40 psi
Inner MLI	15 layer of SS-MLI, SF 5
Outer MLI	Nominally 25 layers, but variable in MLI trades. MLE with SF of 3 used.
Structure heat	44 W
Ave. structural forward adapter temp.	162 K
Ave. aft adapter temp.	40 K
Ave. outer MLI temp.	106 K
Engine feed-line	10” dia. by 10’ long, forward and aft
Radiator	292 K
Parasitic	15% added to Cryocooler lift

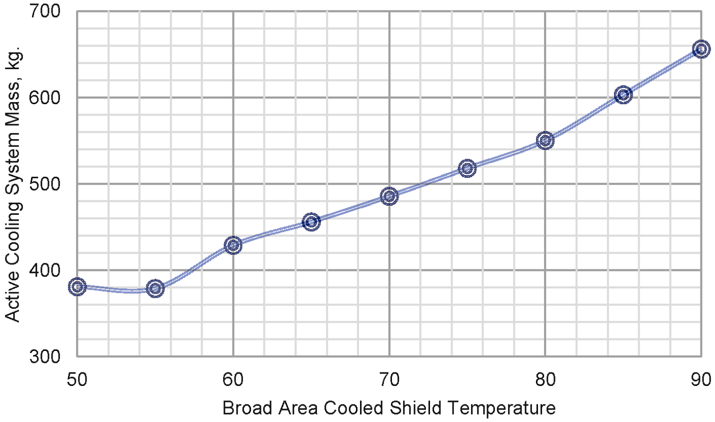

Figure 6. Active cooling mass vs shield temperature.

RESULTS

The first calculation done was on a single stage 20 K class ZBO system. The tank heat leak for that case is 114 W, which equates to a boil-off of 16500 kg over the 720 day period. The single stage active cooling mass to eliminate this boil-off is 1439 kg. The active system mass includes the cryocooler(s), broad area cooling system, its associated electronics mass, the radiator, and the solar array power system sized to achieve ZBO. This was compared to the active cooling mass with an additional second stage with a broad area cooled shield. The shield mass is 85 kg. The two stage active cooling mass for all configurations is less than 700 kg. Also, the power requirement is significantly reduced. The single cryocooler system mass and power was significantly higher than for any two stage system.

The second calculation was a parametric study to find the broad area cooling shield temperature that corresponded with the lowest mass solution. The number of MLI layers was assumed to be 40, with 15 layers of self-supporting MLI under the shield. The first case considered was 90 K, which corresponds to a low mass result[4]. Given that the outside MLI temperature was just 106 K, the other shield temperatures considered decreased from there. The results are shown in Figure 6. The lowest mass solution is at approximately 55 K. Note that the two stage system mass with a 55 K shield is less than 400 kg. The 20K class cryocooler lift at this temperature 18 W, a substantial reduction from 114 W with one stage of cooling.

Following the shield temperature trades, the number of MLI layers was varied over the broad area cooled shield. As shown in Figure 7, 40 total layers was the starting point, 15 under and 25 over the shield, and the calculations went up to 70 total layers, which corresponded to approximately

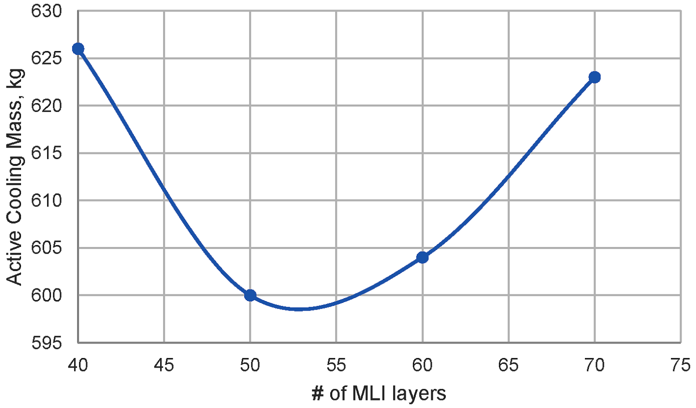

Figure 7. Mass vs. # MLI layers.

Table 3. Two stage cooling system characteristics that meet the NTP mission requirements.

	Temperature, K	Lift, W	Cryocooler Mass, kg	Input Power, W
20K Class	24.2	16.5	99	1150
90K Class	55	94	42	880

2.5 inch thickness of MLI. The system mass, including 20 and 90 K class cryocooler systems and the insulation, bottomed out at slightly more than 50 layers of MLI.

Using 50 layers of MLI and a shield temperature of 55 K, the two stage cryocooler system characteristics, assuming a floating cryocooler size, were determined and are shown in Table 3.

SUMMARY

In summary, ZBO systems were sized for a NTP rocket architecture with a near rectilinear orbit, creating a much colder environment than that typically considered. Given the present cryocoolers under development, 20 K-20 W and 90 K-150 W, indications are that these will be adequate to achieve ZBO with approximately 2000 W input power. The system mass is the lowest if the broad area cooled shield operates at 55 K and the tank has 50 layers of insulation. With a 55 K shield and 50 layers of MLI, the active cooling mass is 380 kg, dramatically less than the expected LH_2 boil-off of 16,500 kg over the 720 day period in NRO.

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