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Centaur Upperstage Applicability for Several-Day Mission Durations with Minor Insulation Modifications

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In its storied and illustrious past, the Centaur upperstage has flown over 175 military, NASA, and commercial flights, including missions up to 12 hours in duration. With its light-weight pressure-stabilized tanks and high ISP of its LO_2/LH_2 propulsion system, the efficient Centaur is ideal for maximizing payload capacity. Current thermal protection limits the propellant boiloff to slightly less than 2% of loaded propellants per day. Incorporating thermal enhancements to its existing design, long mission durations, such as lunar explorative missions, are within the near-term grasp of Centaur. From a vehicle performance perspective, reducing boiloff of the LO_2 and LH_2 cryogen propellants is essential to extending Centaur's capability to longer duration flights. This translates into the goal of minimizing the net heating to the pressure-stabilized propellant tanks. With relatively slight modifications/upgrades through the use of existing technology, enhancing its thermal insulation would enable Centaur to fly missions from several days in length up to week-long durations, depending upon payload requirements. By applying several more layers of MLI insulation to the Centaur sidewall acreage, system boiloff rates of slightly more than 1 %/day are realistic and achievable. Going one step further, Variable Density Multiple Layer Insulation (VDMLI) radiation shielding provides the necessary characteristics to enhance Centaur's thermal insulation via further reduction in acreage heating. VDMLI is both relatively mature and demonstrated, where the key challenge is the repeatable application to flight hardware. Projections show that system boiloff can be reduced to 1% of loaded propellants per day, making 3-day mission durations feasible in the near-term.

Nomenclature

n = number of layers of radiation shields

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I. Introduction

THE Centaur upperstage rocket has flown over 175 military, commercial, and NASA flights. Most of the missions have either been GTO (Geo-Transfer Orbit) or LEO (Low Earth Orbit) type flights, where the "coast" lengths have generally been short. Herein, "coast" is used to identify the mission phase between Centaur main engine burns; this is distinguishable from "ascent" which is the booster portion of flight, and the separation coast where the space vehicle separation, i.e., payload separation, occurs subsequent to the final Centaur engine burn.

To date, Centaurs on the two Titan/Centaur programs, TIII/C and TIV/C, are the only ones to fly long duration coasts (loosely defined here as coasts greater than 2 hours). All Atlas/Centaur flights (AII, AIII, and AV) have possessed coast time shorter than 2 hours. Figure 1 shows the evolution of the Centaur.

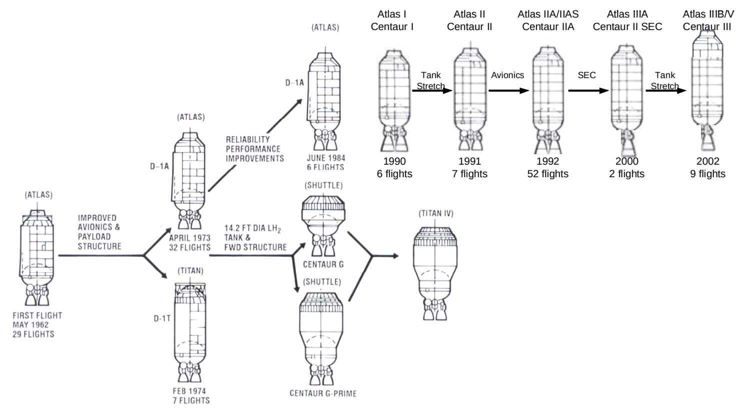

Figure 1. Evolution of Centaur Upper Stage.

This document is comprised of three parts. Firstly, a review of the tank heating rates experienced on the recent Centaurs will be investigated. Of particular interest will be the acreage heating intercepted by the Centaur sidewalls. The acreage heating is an important contributor to the overall tank heating, and its reduction is the primary focus of reducing net tank heating to the Centaur propellant tanks for near-term multi-day missions. A review of the tank heating experienced on recently flown flights for different sidewall insulations will be investigated, namely, white painted fixed-foam (considered equivalent to white decal covering the fixed-foam), a single layer radiation shield, and multi-layer insulation radiation shield (MLI). Short-coast Atlas flights routinely fly with bare fixed-foam on the propellant tank sidewalls; GTO flights with coast durations in the 8-20 minute range are short enuf that the increased boiloff due to the lesser insulated sidewall is not a concern. The sidewall insulations listed above have been employed for recent Centaur long-coast flights. Secondly, the simple benefit of adding several more MLI layers to the acreage heating will be discussed. Straightforward projections indicate that simply adding more layers of MLI can reduce the Centaur propellant boiloff rate to just over 1 %/day. Thirdly, a review of the testing of VDMLI and its applicability to future Centaur vehicles will be briefly discussed. Projections will be presented showing that with straight-forward upgrades to the acreage insulation (primarily the sidewall), the Centaur system boiloff can be reduced to 1% per day. Reducing the Centaur system boiloff rates to 1% or below make 3-day to week-long missions within the near-term grasp of Centaur. Longer term more involved Centaur modifications may be able to further reduce Centaur boiloff by an order of magnitude, but are beyond the scope of this paper.

II. Review of Tank Heating Rates on Recent Centaur Flights

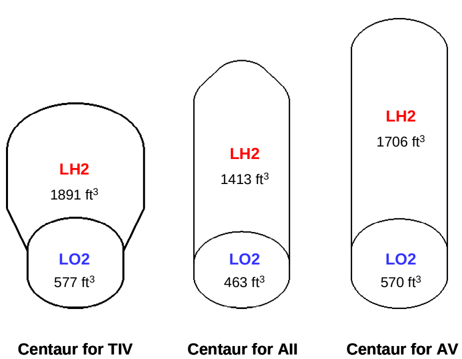

Figure 2. Relative Sizes of the Centaur G-Prime (Titan IV), Centaur II (Atlas II), and Centaur III (Atlas IIIB and Atlas V).

Tank heating rates were derived from data matches using an LMA in-house thermodynamic computer code. Post-flight reconstructions were performed for several different vehicle configurations: Atlas II, Atlas III, Atlas V, and Titan IV. The Centaur upperstage propellant tanks on Titan IV are similar in volume to those on Atlas III & V, but not identical. Two T/C flights were reconstructed; both of which were Titan IV/Centaur missions. The relative sizes and geometry of the various Centaurs are shown in Fig 2 including the loaded tank volumes for each tank. Because the Centaur upperstage utilizes the pressure-stabilized steel-balloon concept, the propellant tanks actually stretch and increase several cubit feet when pressurized to higher levels during flight. The LH2 tank heating can be categorized as intermediate bulkhead (IB), sidewall, forward bulkhead, and penetration heating. The LO2 tank heating is comprised of intermediate bulkhead, sidewall, aft bulkhead, and penetration heating. Note that the intermediate bulkhead, also referred to as the common bulkhead, is a unique feature of all Centaur vehicles. Heating across the vacuum insulated IB simultaneously affects both tanks, where the LH2 tank always incurs positive heating and the LO2 tank always realizes a heat loss across the IB. The G-Prime LH2 tank on Titan IV/Centaur has the unique feature of conical and cylindrical portions of its sidewall. As mentioned earlier, three different sidewall insulations were investigated: white painted fixed-foam, single layer radiation shield, and three-layer radiation shield. Table 1 summarizes the sidewall insulation for the vehicles analyzed. Figures 3 - 6 display photos of various Centaur showing the different sidewall insulations.

Table 1. Centaur Sidewall Insulation.

	LH2 Tank Sidewall	LO2 Tank Sidewall
AC-167	Not Included	White painted foam
AC-206	Not Included	White painted foam
AV-003	Not Included	White decal on foam
AV-005	Not Included	White painted foam & single-layer radiation shield
TC-11, 15	3-layer MLI overwrapping 3/4" open-cell foam	3-layer MLI

Four Atlas/Centaur flights were analytically matched to determine LO2 propellant tank heating rates: AC-167 (AII), AC-206 (AIII), AV-003 (AV) and AV-005 (AV). The tank heating rates quoted herein are based on the sunlit portion of the Park Orbit Coasts (POC). The coast durations ranged from 1.0 – 1.5 hours. LO2 tank heating over the long, *settled* Park Orbit Coasts (POC) afforded the best opportunity for accurate heating rate reconstruction. The rise in tank ullage pressure and the increase in liquid temperature over the coast provide measurable parameters to match. No venting is performed in the LO2 tank during the POC. Thus, tank heating is the primary source of tank pressure change over the steady-state portion of the coast until the tank is pressurized immediately prior to 2nd burn. Heating is also the primary contributor to the increase in liquid temperature over the coast until pressurization for 2nd burn. Bubbler pressurization prior to 2nd burn slightly decreases the liquid temperature, but this is accounted for in the analytical thermodynamic model. For A/C, a determination of the LH2 tank heating is much more difficult. Over the POC, the LH2 tank is continuously vented, which then makes it much more problematic to accurately match a tank pressure and/or liquid temperature rise over the coast. Thus, no LH2 tank reconstruction data is presented.

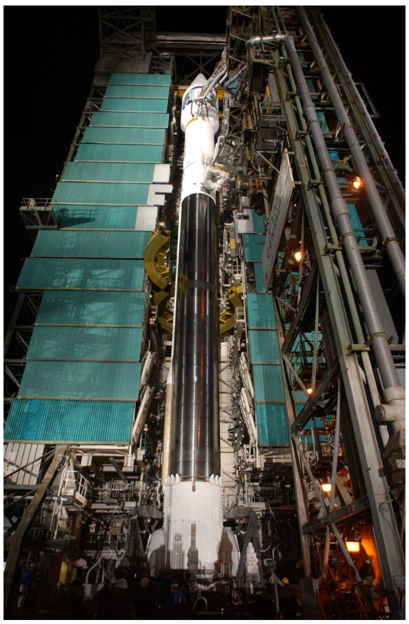

Figure 3. AC-206 at CLX36 Showing the White Painted Centaur Sidewalls

Figure 4. AV-005 During Final Assembly With Single-Layer Radiation Shield (that does Double Duty as a Foam Debris Shield) On Sidewall

Figure 5. AV-003 Being Hoisted at the Vertical Integration Facility Showing the White Decal on Centaur Sidewalls.

For Titan/Centaur, two flights were investigated: TC-11 and TC-15. The tank heating rates quoted herein are based on the sunlit portion of the Transfer Orbit Coast (TOC). The TOC durations were greater than 5.25 hours. On T/C, the long, *unsettled*, zero-g coasts allow for accurate heating rate reductions in both propellant tanks (LH2 and LO2) via tank pressure increase. During the zero-g TOCs, the liquid migrates to the outer walls, which results in all external

Figure 6. A G-Prime Centaur Tank in Clean Room Showing 3-Layer MLI on Centaur Sidewalls.

heating being intercepted by the liquid. As the ullage is surrounded by cold liquid, the ullage temperature approaches liquid temperature and the propellant tanks asymptotically approach thermodynamic equilibrium. Due to the propellant tanks being near equilibrium, the ullage pressure over the coast provides an excellent measurable parameter for heating assessment. In the LO2 tank, bubbler pressurization retains a cold ullage during the main engine burns and keeps the tank in a relatively stable, close-to-equilibrium environment. Thus, the LO2 tank enters the TOC after 2nd burn already relatively close to equilibrium. As on A/C, the LO2 tank is not vented over the coast; thus, the vapor pressure change over the coast provides an additional confirmation of tank heating for the LO2 tank.

Typical LO2 tank ullage pressure matches of Atlas/Centaur and Titan/Centaur vehicles are shown in Figures 7 and 8, respectively. Note that the steady-state pressure rise is approximated very closely after the initial transient period, which provides a high degree of confidence that the heating rates are modeled correctly in the post-flight reconstruction models. Both flights spent a predominant amount of their coasts in direct sunlight, broadside to the sun, rolling in a rotisserie-type fashion at 1.0-1.5 deg/sec for thermal considerations.

Figure 7 shows the data match for AC-206, where the sidewall insulation was white painted fixed-foam and the coast time was approximately 1 hour. Figure 8's data match is for TC-15; the sidewall insulation was a 3-layer MLI blanket (standard for T/C flights) to better insulate the tank for longer coast durations. For TC-15, the TOC duration was greater than 5.25 hours. It should be pointed out that although the long coast flights provide excellent conditions to study the *net* tank heating experienced in flight, it is difficult to extract the *exact breakdown* of heating. For example, for LO2 tank reconstruction of a settled Atlas POC, the external heating to the ullage is comprised of the intermediate bulkhead heat loss, the sidewall heating, and the dry-wall portion of the aft bulkhead heating. Refer to Fig. 9, which displays the liquid oxygen settled surface levels during the coasts of the flights discussed in this report. (Recall that the Titan/Centaur flights were zero-g during the major portion of their TOC, i.e., they were not in a settled configuration.) The methodology to break out the individual heating was to start the data matching with a complete set of nominal pre-flight predicted heat rates. The intermediate bulkhead was assumed to always be nominal during flight since the boundary conditions on both sides of the bulkhead (cryogenic temperatures) are fairly constant. Furthermore, the low vacuum pressure inside the IB is consistent within a family of flights. The sidewall and aft bulkhead heating rates were then adjusted to match the ullage pressure profile and liquid vapor increase over the POC. Because the LO2 tank was not venting during the coasts for any flight discussed herein, the aft bulkhead heating primarily contributes to the liquid temperature increase over the coast (liquid-ullage interaction also affects the liquid temperature, but to a much lesser degree) for settled coasts. The aft bulkhead heating can then be determined

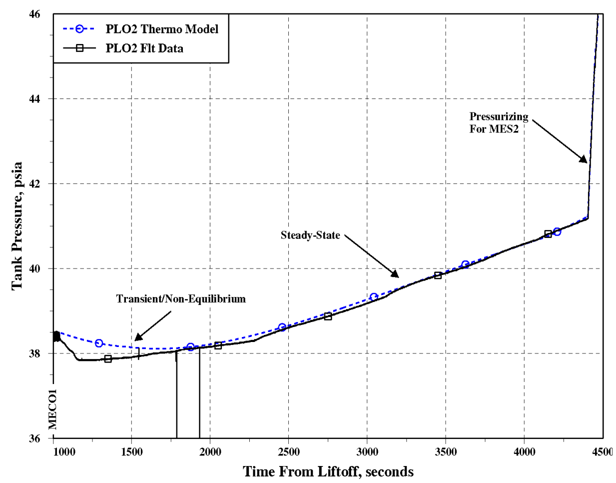

Figure 7. LO2 Tank Ullage Pressure Match for AC-206.

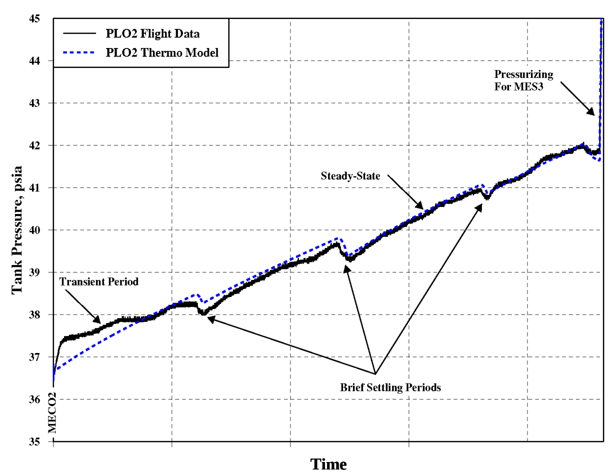

Figure 8. LO2 Tank Ullage Pressure Match for TC-15.

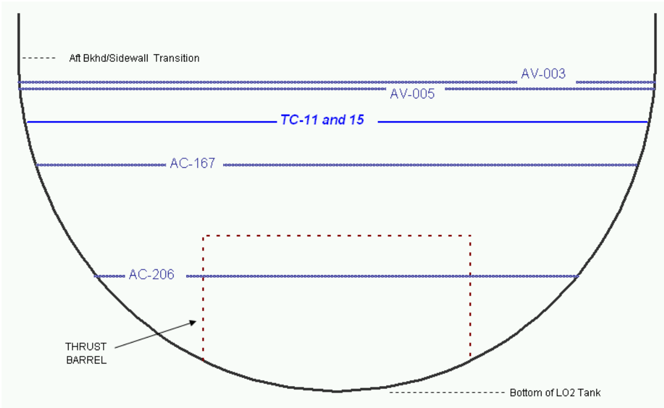

Figure 9. LO2 Settled Liquid Levels During Coasts

via the liquid vapor pressure change over the coast; the longer coasts enable the aft bulkhead heating to be "dialed in" with more certainty for the 3-layer MLI T/C configuration. Determining the aft bulkhead heating in this manner allows the sidewall heating to be de-coupled from the aft bulkhead heating for settled coasts. For unsettled T/C flights, the sidewall and aft bulkhead pre-flight nominal heating rates are scaled by the same factor until both the ullage pressure and vapor pressure changes across the coast are sufficiently reproduced.

Post-flight data reconstruction results of the Centaur LO2 tank heating are shown in Table 2. Included in the table for comparison is a summary of the sidewall insulation, coast duration, and the coast orbital geometry. The post-flight reconstruction shows that the sidewall heating is consistent with pre-flight expectations. The sidewall flux decreases as the thermal insulation is increased. The white painted foam consistently shows an average sidewall flux of 25 btu/hr-ft^2, with a significant reduction down to 4 btu/hr-ft^2 realized for the single-layer VDA fiberglass cloth radiation shield. The 3-layer MLI flown on T/C shows a further reduction down to an average of 3 btu/hr-ft^2. The 3-layer MLI flown on T/C was a combination of VDA fiberglass cloth and VDA kapton. As shown in Table 2, the T/C net LO2 tank heating rates translate into boiloff rates of 1.0 – 1.5 %/day. Technically, the heat load intercepted by the liquid for the flights analyzed experienced little to no boiloff because the LO2 tank was not vented (liquid vapor pressure was not held constant). However, for flight durations in excess of 8 – 12 hours, the LO2 tank would have to be vented to satisfy tank structural requirements. Thus, the boiloff rates in Table 2 pertain to holding the ullage and liquid vapor pressure constant over a long coast. The boiloff was calculated by simply dividing the net tank heating by the latent heat of vaporization. The boiloff was then characterized in historical terms of % of a fully loaded LO2 tank per day. One additional item is worthy of mention. Although AV-005's sidewall flux is comparable to those experienced on TC-11 and TC-15, the net tank heating is higher on AV-005 due to higher aft bulkhead heating and less IB heat loss due to design differences between the Titan/Centaur and Atlas/Centaur.

Table 2. Summary of LO2 Tank Heating from Post-Flight Reconstructions.

	AC-167 (LO2)	AC-206 (LO2)	AV-003 (LO2)	AV-005 (LO2)	TC-15 (LO2)	TC-11 (LO2)
Centaur Tank	CII	CIII	CIII	CIII	G-Prime	G-Prime
Sidewall Insulation	White paint	White paint	White decal	Single-layer Radiation Shield	3-layer Radiation Shields	3-layer Radiation Shields
Coast Orbit (nautical miles)	100 x 144 (POC)	90 x 611 (POC)	90 x 2249 (POC)	90 x 2882 (POC)	Highly Ellitical (TOC)	Highly Ellitical (TOC)
Coast Duration	59 minutes	58 minutes	78 minutes	86 minutes	> 6 hrs	> 6 hrs
Net Sidewall Flux into tank	25 btu/hr-ft^2 (1200 Btu/hr)	23 btu/hr-ft^2 (1700 Btu/hr)	25 btu/hr-ft^2 (1900 Btu/hr)	4 btu/hr-ft^2 (300 Btu/hr)	4 btu/hr-ft^2 (400 Btu/hr)	2 btu/hr-ft^2 (200 Btu/hr)
TOTAL LO2 TANK HEATING	2250 Btu/hr	2600 Btu/hr	3750 Btu/hr	3150 Btu/hr	2100 Btu/hr	1300 Btu/hr
TOTAL LO2 BOILOFF PER DAY (% of full LO2 tank per day)	1.9 %/day	1.8 %/day	2.6 %/day	2.2 %/day	1.5 %/day	1.0 %/day

Table 3 shows the results of the LH2 tank post-flight data reconstructions to determine the Centaur LH2 tank heating. The two T/C flights analyzed show good agreement considering the amount of variables that affect total tank heating. The acreage heating

Table 3. LH2 Tank Heating Summary from Post-Flight Reconstructions.

	TC-15 (LH2)	TC-11 (LH2)
Net Sidewall Flux into tank	1 btu/hr-ft^2 (500 Btu/hr)	1.5 btu/hr-ft^2 (700 Btu/hr)
TOTAL HEATING	2500 Btu/hr	3100 Btu/hr
TOTAL LH2 BOILOFF PER DAY (% of full LH2 tank per day)	4.1 %/day	5.1 %/day

to the 3-layer shielded LH2 sidewall shows fluxes of 1.0 – 1.5 btu/hr-ft^2, which averages to roughly half of the reduced flux of the T/C LO2 sidewall. Because the LH2 tank sidewall makes up such a large percentage of the total external surface area of the LH2 tank, the sidewall heating is the most significant heating term to the LH2 tank. It follows that reducing the LH2 sidewall heating will directly and significantly contribute to lowering the LH2 boiloff shown in Table 3. The LH2 boiloff rates being larger than the LO2 boiloff rates are primarily an artifact of the lower loaded mass of LH2 (~7,500 lbm) than LO2 (~38,800 lbm). Additional contributors to the higher LH2 boiloff rates are the IB design (heat flow across the IB always occurs from the LO2 to LH2 tank), the colder LH2 temperatures, and larger LH2 tank surface area.

The G-Centaur which flew on Titan IV was the best insulated Centaur in order to accommodate the routinely flown 5.25 hr Transfer Orbit Coasts for its Geo-Synchronous Orbit (GSO) missions. Thus, it provides the best basis for flight-demonstrated Centaur boiloff capabilities and future projected capabilities. Table 4 summarizes the tank heating and boiloff data from Tables 2 and 3 for the TIV/Centaur configuration (TC-11 and TC-15) and also presents the combined boiloff in terms of total system boiloff per day. As shown in Table 4, the relatively simple 3-layer MLI thermal protection over the Centaur sidewall acreage yielded an on-orbit system boiloff of 1.6 to 2.0 %/day. Although there are some design differences, it is expected that the Atlas/Centaur with a 3-layer MLI shield would have similar boiloff. The T/C insulation was designed to meet the needs of approximately 8 hour GSO missions. Thus, relatively simple improvements to the Centaur thermal insulation can reduce the system boiloff rates to 1%/day, as discussed in ensuing sections. Specifically, improvements to the acreage heating via adding additional layers of MLI shielding are discussed.

Table 4. Summary of System Boiloff for Centaur on Titan IV.

	TC-15		TC-11	
	(LO2)	(LH2)	(LO2)	(LH2)
Net Sidewall Flux into tank	4 btu/hr-ft^2 (400 Btu/hr)	1 btu/hr-ft^2 (500 Btu/hr)	2 btu/hr-ft^2 (200 Btu/hr)	1.5 btu/hr-ft^2 (700 Btu/hr)
TOTAL HEATING	2100 Btu/hr	2500 Btu/hr	1300 Btu/hr	3100 Btu/hr
TOTAL BOILOFF PER DAY (% of full LO2 or LH2 tank per day)	1.5 %/day	4.1 %/day	1.0 %/day	5.1 %/day
SYSTEM BOILOFF PER DAY (% of full LO2 + LH2 tanks per day)	2.0 %/day		1.6 %/day	

III. Additional MLI layers

Table 4 showed that the flight-derived system boiloff rates experienced on T/C averaged 1.8 %/day, when a simple 3-layer MLI insulation scheme was used on the sidewalls. Theoretically, heat leak through layers of radiation shielding is proportional to 1/(n+1), where n is the number of layers of shielding. Simply adding more layers of MLI (approximately 20 to 25 layers) would reduce sidewall and the forward bulkhead heating rates to smaller values, because both the sidewall and forward bulkheads are largely comprised of acreage heating. These relatively simple modifications could reduce the net LH2 tank heating by a factor of two to approximately 1500 Btu/hr, or 2.5% per day boiloff. Because of the large number of penetrations on the LO2 tank aft bulkhead, the addition of MLI is likely to only reduce the net LO2 tank heating rate to approximately 1100 Btu/hr (0.8% per day boiloff). This proposed additional MLI would result in a system boiloff rate of approximately 1.1 %/day as summarized in Table 5. This illustrates the simple steps that can be taken to reduce the Centaur system boiloff rate to approximately 1 %/day.

Table 5. Projected System Boiloff for G-Prime Centaur Using Additional Layers of MLI

	(LO2)	(LH2)
TOTAL HEATING	1100 Btu/hr	1500 Btu/hr
TOTAL BOILOFF PER DAY (% of full LO2 or LH2 tank per day)	0.8 %/day	2.5 %/day
SYSTEM BOILOFF PER DAY (% of full LO2 + LH2 tanks per day)	1.1 %/day	

IV. Review of VDMLI Test Results and Extensibility to Centaur

Variable Density MLI optimizes the radiation insulation capability of standard MLI by controlling the spacing of the layers of MLI. The concept behind VDMLI is to space the inner layers (near the cold cryogenic tank) further apart than the outer layers (warm region of MLI) where radiation heat transfer dominates. The variable spacing is accomplished by utilizing non-conductive bumper strips of variable thickness between layers. Theoretically, VDMLI reduces the heat load to the cryogenic tank it is thermally protecting and also results in a weight reduction. Figure 10 illustrates a representative VDMLI cross section, showing the variable gap-thicknesses between shield layers. In practice, the spacing would not be gradually reduced from the innermost to outermost layer. Instead, as was done for the testing, 3 regions could be defined as shown in Fig. 10; a low density region for the innermost layers, an intermediate density for the middle layers, and a high density region for the outermost layers.

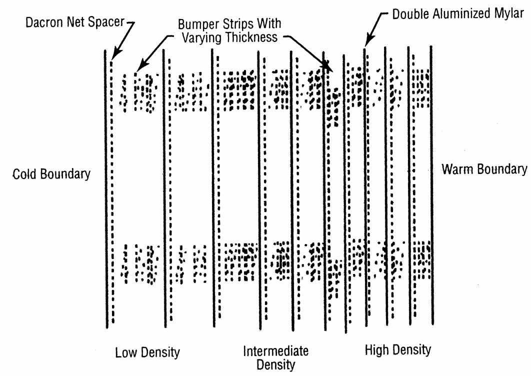

Figure 10. Representative Cross Section of VDMLI

Testing of VDMLI was performed during 1993 at Marshall Space Flight Center (MSFC) east test area thermal vacuum facility. Testing was done using the LH2-filled multi-purpose 10 foot diameter hydrogen test bed (MHTB), which reasonable represented a full-scale Centaur LH2 tank. The MHTB was actually insulated with a foam/VDMLI combination, where the inner foam layer is designed for thermal protection on the ground and the VDMLI is suitable for on-orbit applications in low-pressure environments. A 45 layer VDMLI blanket was tested. Testing was performed to simulate ground conditions, ascent phase of flight, and steady-state on-orbit environments. The MHTB was encapsulated within a large vacuum chamber that enabled on-orbit environments at low external pressures to be simulated. References 1and 2 contain further details of the testing and the analytical modeling of the VDMLI. (As an aside, it should be pointed out that the MLI on the T/C LH2 tank was applied over ¾" thick open-cell foam. Additionally, the single-layer radiation shield on AV-005 over-wrapped the standard closed-cell fixed foam on the LO2 and LH2 tank sidewalls. The foam has very little insulation capacity in low-pressure environments and should not affect the post-flight reconstruction tank heating results from the previous section.)

Table 6. Projected System Boiloff for G-Prime Centaur Using VDMLI

	(LO2)	(LH2)
TOTAL HEATING	950 Btu/hr	1350 Btu/hr
TOTAL BOILOFF PER DAY (% of full LO2 or LH2 tank per day)	0.7 %/day	2.4 %/day
SYSTEM BOILOFF PER DAY (% of full LO2 + LH2 tanks per day)	1.0 %/day	

References 1 and 2 discuss an analytical model that was correlated to the VDMLI test results. A combination of test results and analytic model predictions from References 1 and 2 indicate that the VDMLI blanket reduces radiation heat transfer by 58% when compared to the G-Prime sidewall insulation assuming an equal number of MLI layers. Part of this impressive 58% reduction was due to special care being taken to use seamless shielding and minimize all penetration sources. Considering these factors, a reasonable heat rate reduction of 40 – 50% could be expected from using VDMLI. Thus, applying an equivalent number of layers as needed in Table 6, the net Centaur heating is projected to be 950 btu/hr to the LO2 tank and 1350 btu/hr to the LH2 tank. As shown in Table 6, the resulting system boiloff rate is 1 %/day. It is estimated that the weight increase associated with a 45 layer VDMLI blanket covering the entire external surface area of the Centaur tank (sidewalls and bulkheads) is approximately 200 lbs. Hence, a 20-25 layer VDMLI blanket should weigh in the neighborhood of 100 lbs.

V. Long Term Projections

More extensive Centaur modifications can further reduce the Centaur boiloff, potentially by an order of magnitude as illustrated in Fig. 11. These improvements include improved IB insulation, a deployable sun shield, incorporation of vapor cooling, and reducing the number of penetrations on the LO2 aft bulkhead. The current IB insulation relies on a felt mat spacer to keep the two metal domes separated with an internal vacuum. Replacing this felt mat insulation with much more efficient glass bubbles will significantly reduce the LO2 to LH2 heat transfer across the IB. A deployable conic sun shield can minimize the Solar and Earth albedo radiation illuminating the Centaur sidewall and aft bulkhead. This sun shield in conjunction with VDMLI can significantly reduce the external tank heating. Vapor cooling can be used to intercept heat flow from the forward structural interface, between the LO2 and LH2 tanks, and the primary engine tank interfaces. The RCS (Reaction Control System) system is currently mounted directly to the LO2 tank aft bulkhead. Relocating the RCS to the payload adapter will eliminate this primary penetration heat source and eliminate the potential of freezing the N2H4 propellant. With these changes, it may be possible to reduce the existing Centaur system boiloff rate down to approximately 0.1%/day.

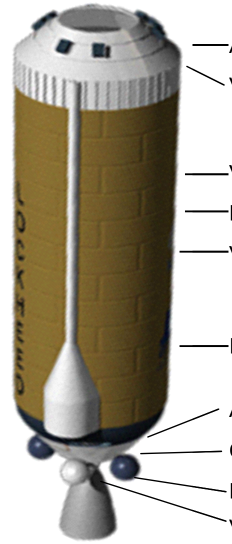

Figure 11. Projected Long Term Centaur Modifications to Reduce System Boiloff Rates Down to 1 %/day.

VI. Conclusion

As shown in Table 4, data reduction from T/C flights indicates that system boiloff rates of 1.6 to 2.0 %/day were experienced. These boiloff rates correspond to a simple 3-layer MLI insulation system utilized on the sidewall acreage of the Centaur G-Prime tank flown on T/C. Increasing the layers of MLI shielding and using the VDMLI concept, reasonable projections indicate that the Centaur system boiloff rates can be reduced to 1 %/day (Table 6). Thus, obtaining a system boiloff rate of 1%/day is achievable in the near-term future simply by employing an improved VDMLI shielding. Multiple layers of radiation shielding is an oft-utilized feature of insulation systems; T/C flights showed repeatable heating rates using a modest 3-layer MLI blanket coverage. The VDMLI concept has been demonstrated through testing; the biggest hurdle is the repeatable application to flight hardware. Obviously, increasing the number of layers of radiation shield insulation has a diminishing-returns effect. There comes a point where penetration heating becomes the dominant heating term. Thus, without further more extensive modifications, a Centaur system boiloff rate of 1 %/day is probably a reasonable minimum.

Acknowledgments

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