Design and Development of an In-Space Deployable Sun Shield for the Atlas Centaur

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The Centaur, by virtue of its use of high specific-impulse (Isp) LO_2/LH_2 propellants, has initial mass-to-orbit launch requirements less than half of those upper stages using storable propellants. That is, for Earth escape or GSO missions the Centaur is half the launch weight of a storable propellant upper stage. A drawback to the use of liquid oxygen and liquid hydrogen, at 90 K and 20 K respectively, over storable propellants is the necessity of efficient cryogen storage techniques that minimize boil-off from thermal radiation in space. Thermal blankets have been used successfully to shield both the Atlas Centaur and Titan Centaur. These blankets are protected from atmospheric air loads during launch by virtue of the fact that the Centaur is enclosed within the payload fairing. The smaller Atlas V vehicle, the Atlas 400, has the Centaur exposed to the atmosphere during launch, and therefore, to date has not flown with thermal blankets shielding the Centaur.

A design and development effort is underway to fly a thermal shield on the Atlas V 400 vehicle that is not put in place until after the payload fairing jettisons. This can be accomplished by the use of an inflatable and deployable thermal blanket referred to as the Centaur Sun Shield (CSS). The CSS design is also scalable for use on a Delta upper stage, and the technology potentially could be used for telescope shades, re-entry shields, solar sails and propellant depots.

A Phase I effort took place during 2007 in a partnership between ULA and ILC Dover which resulted in a deployable proof-of-concept Sun Shield being demonstrated at a test facility in Denver. A Phase II effort is underway during 2008 with a partnership between ULA, ILC, NASA Glenn Research Center (GRC) and NASA Kennedy Space Center (KSC) to define requirements, determine materials and fabrication techniques, and to test components in a vacuum chamber at cold temperatures. This paper describes the Sun Shield development work to date, and the future plans leading up to a flight test in the 2011 time frame.

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Acronyms and Definitions

ULA = United Launch Alliance
ILC = ILC Dover Corp.
KSC = Kennedy Space Center, NASA
GRC = Glenn Research Center, NASA
CSS = Centaur Sun Shield
GSO = Geosynchronous Orbit
LO_2 = Liquid Oxygen
LH_2 = Liquid Hydrogen
LN_2 = Liquid Nitrogen
GH_2 = Gaseous Hydrogen
GO_2 = Gaseous Oxygen
K = degrees Kelvin
Centaur = Atlas Upper Stage Vehicle name
Atlas 400 = Atlas launch vehicle with a 4 m payload fairing
Atlas 500 = Atlas launch vehicle with a 5 m payload fairing
CFA = Centaur Forward Adapter; structure to which payload and Avionics modules are attached
RAL = Reverberant Acoustic Lab; test facility in Denver
IPP = NASA's Innovative Partnership Program
θ = Sun Shield Cone Angle
β = Atlas vehicle orientation with respect to the sun
Btu/hr = British Thermal Units per hour (0.293 Watt)
GMM = Geometric Math Model
TMM = Thermal Math Model
VDG = Vapor-Deposited Gold
DAK = Double Aluminized Kapton (vapor-deposited aluminum on Kapton, both sides)
TVAC = Thermal Vacuum Chamber
PBI = Polybenimidazole Fiber
MLI = Multi-layer Insulation
PLF = Payload Fairing
EDS = Earth Departure Stage
Isp = Specific Impulse
Q = Solar Radiation
IR = Infrared Radiation
RCS = Reaction Control System
Bij = Radiation Interchange Factor

I. Introduction

Space based assets currently available for cryogenic propellant storage are limited for operations within hours. This resource limitation hinders and restricts options for future space missions, such as human return to the Moon and Mars exploration envisioned to occur in the next 20 to 30 years, requiring extended period of cryogenic capabilities in months not hours. Engineers in launch services from both NASA and industry have recognized this asset limitation and have identified the lightweight inflatable-deployable sunshield technology as a potential enabler for future missions needing long duration cryogenic storage. The development of a lightweight, inflatable and deployable sun shield to extend cryogenic capabilities will also aid in the development of other space based inflatable structures such as antennas, solar arrays and re-entry ballutes.

The combination of LO_2 and LH_2 provide the ideal propellants to support in-space transportation due to the high Isp, relative ease of handling and capability to generate high thrust. However, missions requiring long durations are challenged by the cryogenic nature of these propellants, specifically how to efficiently store and handle them. Historically, cryogenic storage has been enabled through the use of multi-layer insulation (MLI)[1,2] MLI has proven to be quite effective at reducing incident radiation from both solar and Earth sources. However, MLI must be protected during launch to avoid aerodynamic forces from ripping the MLI from the vehicle. For systems where the cryogen stage is exposed to the atmosphere during ascent, such as the Atlas V Centaur 4m PLF vehicles, the Delta IV upper stage or the Ares V EDS, the MLI must be protected by a shroud or the designer must find alternative insulation options. Because the Centaur and Delta IV upper stages have sidewalls exposed to solar radiation, they currently must accept high boil-off rates and the resulting restricted mission durations of less than 3 and 8 hours respectively. This cryogen storage challenge has forced NASA to plan on launching the Ares I and Ares V on the same day to keep the EDS boil-off within acceptable levels.

A deployable sun shield provides an alternative method of shielding large cryogenic systems from solar and Earth radiation. Numerous studies have shown the thermal benefit of a sun shield, either on its own or in combination with MLI[1]. For example, the James Webb Space Telescope will utilize a very large deployable sun shield to provide a stable, very cold environment for this international instrument[1]. A deployable sun shield can be stowed during ascent and deployed once on orbit to effectively insulate large cryogenic stages.

After surveying the industry for existing state-of-the-art deployable sun shield technologies, ULA has joined with ILC Dover, NASA KSC[2] and NASA GRC to pursue development of an inflatable deployed sun shield. The benefits of pneumatic deployment include:

1. Small storage volume which is critical to avoid interference with the launch vehicle payload (satellite for Atlas and Delta or the Altair stage for Ares V)
2. Boom robustness and flexibility allowing the stage to perform a burn while the sun shield is deployed.
3. Very light weight system which is especially true when the deployment gas is GH_2 or GO_2 boil-off from the cryogenic tanks.

ULA began an internally funded investigation into using a deployable thermal shield for the Atlas Centaur upper stage in 2005[3]. In 2007, a partnership was formed between ULA and ILC Dover to continue with the design and development of a Centaur Sun Shield. Some work was done on defining the requirements for a sun shield, and thermal analysis was done to determine the performance improvement provided by a sun shield surrounding the LH_2 and LO_2 tanks of the Centaur. Also during 2007, ULA and ILC applied for and were granted an Innovative Partnership Program (IPP) grant from NASA to supplement the internally funded efforts of both ULA and ILC. The IPP grant has been used during the 2008 phase of the program to fund ILC Dover in refining the design of the CSS mechanical components, and in the selection and testing of materials to be used in the inflatable booms, thermal shields and other components making up the CSS.

II. Concept of Operations

The CSS will be mounted to a composite stowage ring structurally attached to a payload adapter. After payload fairing and booster jettison, and while the Centaur upper stage is not accelerating, the command to deploy the CSS will initiate. All petals will inflate and deploy independently from each other while on-board instrumentation monitors the deployment. The booms and shield assemblies will be designed to withstand vehicle acceleration during subsequent engine burns. The inflated booms will flex during acceleration, and will return to the CSS conic shape after vehicle acceleration is complete. Figure 1 shows the CSS operational stages after booster and payload fairing jettisons.

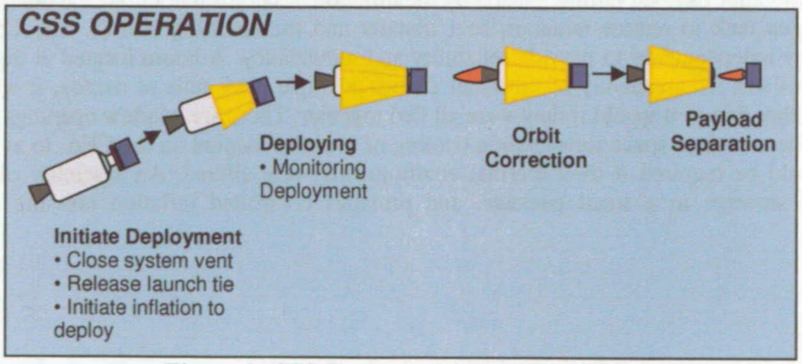

Figure 1: CSS Concept of Operations Schematic

III. Deployabe Demonstration Test

Early in 2007 ULA and ILC decided to concentrate the design and development effort for that year on building and testing a deployable test article that could demonstrate the mechanical and pneumatic systems that might be used in space for a flight version. A test article was designed and built that was full-scale for the forward diameter and approximately 2/3's scale for the height. The height was limited to save cost on the materials, to use off-the-shelf available materials and to fit within the deployment test facility identified at the start of the design effort. (A high bay test facility was subsequently identified and used after the design and build was well underway.) A three-layer shield mockup was fabricated with the two outer most layers being clear Mylar so that shield unfurling during deployment could be observed. A series of deployment tests was done during December 2007 in the RAL test facility operated by Lockheed Martin Space Systems in Denver. Figure 2 shows the CSS demo unit in its stowed configuration to the left and its fully deployed configuration on the right. The grey cylinder is a mock-up of Centaur and is approximately one-half the height of the actual Centaur. The white skin and stringer structure forward of the grey cylinder is the Centaur Forward Adapter (CFA) with Avionics modules mounted to the conical surface. Part of the test was designed to prove the sun shield could deploy without getting hung up on any components on the top of the Centaur. The wires and frame shown in the photos are part of a "gravity negation" system designed to counter balance the small boom tip loads from the composite plug and strongback located at the end of the vertical boom, loads the system does not see in space.

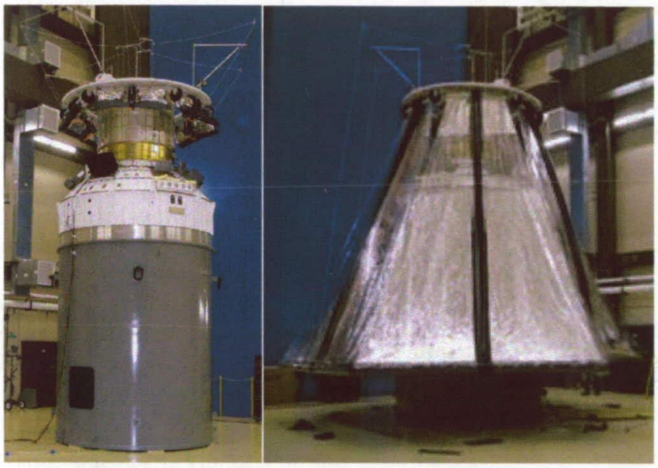

Figure 2: CSS 2007 Deployment Test; Stowed & Deployed Configurations

IV. Design

The sun shield design is a light weight, segmented thermal radiation blanket that launches in a stowed configuration; deploys after payload fairing jettison by the inflation of booms that unfurl the blankets; and surrounds the Centaur's cryogen tank to reduce radiation heat transfer and the resulting boiloff. The CSS is made in six segments that deploy independently to provide reliability and redundancy. A boom located at the center of each of the six trapezoids inflates independently of the other five. If a single petal fails to deploy, it will not prevent the deployment of the other five as it would if they were all tied together. There are window openings at the forward end of the CSS to provide a view to space for radiation cooling of avionics located on the CFA, to avoid requalification modules which would be required if their thermal environments were altered. An assembly called a columnator provides for boom stowage in a small package, and provides controlled inflation pressure and speed during deployment.

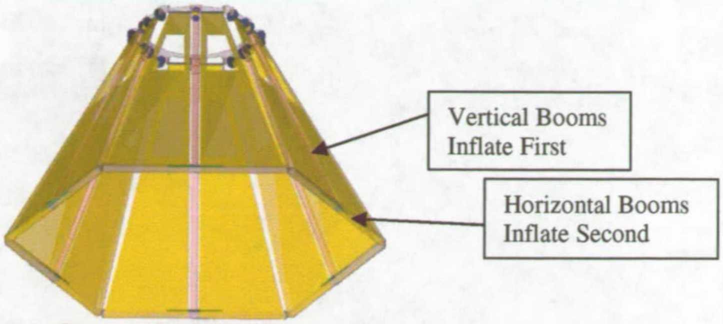

Figure 3: Centaur Sunshield Computer Model

The columnator is located inside the forward end of the vertical boom. It acts as an inflation port and packing volume for the boom, and has the appropriate packing volume for boom length. The middle gland is adjustable externally from the boom, and is used during the packing and deployment stages. It is compressed for the deployment stage, allowing it to regulate the speed and the pressure of the boom deployment. It is decompressed and retracted for the packing stage. The top disc of the columnator helps stabilize and straighten the vertical boom during deployment. During the deployment stage, the inflation gas pushes the aft end of the vertical boom extruding the boom out and over the columnator, inflating the vertical boom.

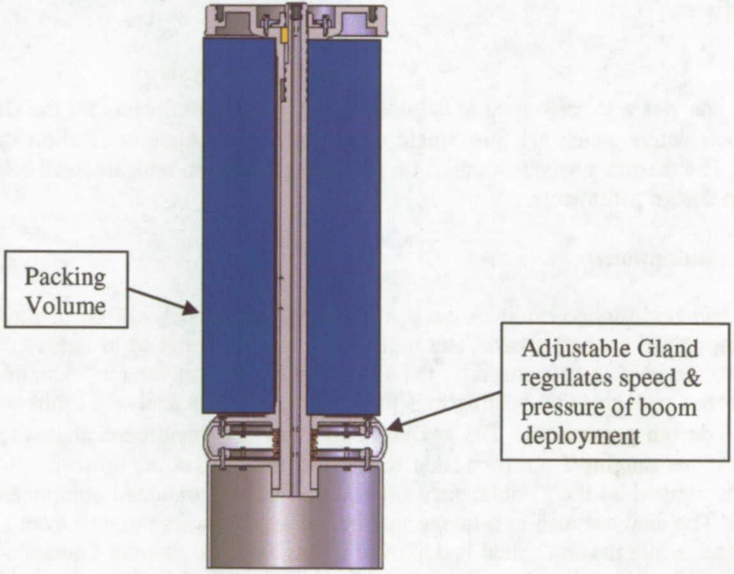

Figure 4: CSS Columnator Model

The sun shield MLI is attached to rollers located on both sides of the columnator. The shields are rolled onto the shaft and packed between the two discs, which guide the shields during both packing and deployment. The rollers have a torsion spring inside the shaft which helps tension the shield by retracting the shades back to its packed position during deployment. On one end of the roller there is a ratchet and pawl locking mechanism which tensions the shields and prevents the torsion spring from rolling shields back to their packed configuration.

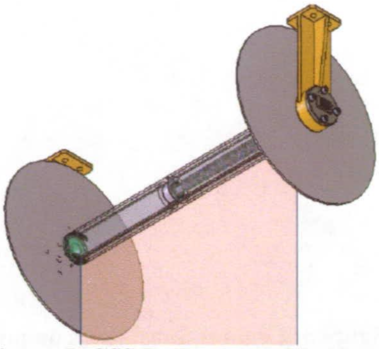

Figure 5: CSS Roller Assembly Model

The T-boom is the interface between the horizontal and vertical booms. The interface has two cradles that hold and grip a portion of the horizontal boom. It acts like a clamp and opens and closes during the deployment and packing stage. The cradle helps with packing the horizontal boom, and integrates the horizontal and vertical booms. The interface can rotate along the vertical axis so that the horizontal boom can be aligned or clocked to the vertical boom for proper deployment. During the packing stage, part of the horizontal boom is packed inside the cradle and the rest is packed in front. The interface has an inflation system which inflates the horizontal boom after the vertical boom fully inflates.

V. Thermal Analysis

A thermal analysis was performed to help define key design parameters for the CSS. Figure 6 illustrates the key CSS design parameters which are Sun Shield cone angle (θ), vehicle orientation with respect to the Sun (β), and shield lay-up. The thermal analysis focused on predicting hydrogen tank sidewall heating performance as a function of those shield design parameters.

A. Analysis Assumptions

The CSS will be installed on an Atlas V 400 series vehicle and will be deployed on-orbit after the effects of ascent aeroheating are washed away. The initial CSS will be designed to reduce on-orbit hydrogen tank sidewall heating rates to the levels experienced by the Titan Centaur launch vehicle. The initial design goal was defined to limit the hydrogen tank sidewall heating to ≤ 850 Btu/hr. For this analysis, limits were placed on the ranges of the key sun shield design parameters. The analysis considers sun shield cone angles ranging from $\theta = 0°$ to 45°, and vehicle orientations ranging from broadside to the sun, where $\beta = 0°$, up to $\beta = 24°$ off of normal. The vehicle orientation was limited so the Centaur forward end and aft end mounted components will still meet their thermal requirements. The analysis also considered number of shield layers ranging from 1 to 5, and two different shield material lay-ups. While the sun shield is deployed it was assumed that the Centaur vehicle will be rolling about the flight axis such that it is evenly heated. It was also assumed that the Centaur is far enough away from Earth that albedo and Earth IR heating is negligible and can be ignored. The space heating solar constant was set at a maximum value of 450 Btu/hr/ft^2. In modeling the heat transfer thru the sun shield, a radiation shield degradation factor was applied to account for on-orbit optical property degradation and contact between individual shield layers. The liquid hydrogen was modeled as a boundary condition and was constrained to a temperature of -420°F. It was assumed that the entire hydrogen tank sidewall is wetted.

B. Methodology

In order to predict tank heating performance a Thermal Desktop[9] geometric math model (GMM) representing the full scale geometry of the sun shield design and Centaur propellant tanks was created. The GMM modeled the preliminary right-cone sun shield design which provided the ability to automatically iterate on sun shield cone angle and vehicle orientation. This GMM was used to calculate the radiation interchange factors, Bij, between the inner CSS surface and outer tank surface, the inner sun shield surface and deep space, and the outer tank surface and deep space. These radiation interchange factors were then used as an input into the SINDA[10] thermal math model (TMM) in order to model radiation heat transfer between these surfaces. The TMM modeled a one square foot section of the tank sidewall, the tank insulating foam, and the appropriately scaled-down section of sun shield. The TMM also automatically iterates on the various sun shield parameters and outputs a unique heat rate per square foot to the liquid hydrogen for each combination of sun shield cone angle, vehicle orientation and shield lay-up. This heat rate per square foot is then scaled to provide the tank heating performance prediction by multiplying it by half of the total surface area of the tank sidewall. It is scaled by half of the total surface area of the tank sidewall because only half of the sun shield is sun-lit.

As stated previously, two separate shield material lay-ups were considered. The only difference between the two shield lay-ups is the outermost material. The two shield lay-ups are described in Table 1. The shield's optical properties were dispersed for this maximum heating analysis and are shown in Table 2. The second shield lay-up was analyzed to illustrate the benefit of optimizing the optical properties of the outer most layer. It is important to note that the shield material lay-ups that were analyzed do not represent the final sun shield lay-up. These two shield material lay-ups were merely selected in order to show analysis results.

C. Results

Figures 7 and 8 show the predicted sidewall tank heating performance as a function of the various shield design parameters. From the results of this analysis it is shown that the initial hydrogen tank sidewall heat rate goal can be met depending on the sun shield design parameters. With the glass cloth-VDG as the outer layer the heating rate goal can be met with a 3 to 5-layer blanket. By changing the outermost shield layer to silver coated Teflon, with its lower solar absorptivity, a 50% decrease in tank heating is realizable with the same number of layers.

Table 1: Centaur Sun Shield Material Lay-Ups used for Analysis

	Shield Material	
Shield Layer	Case 1	Case 2
Outermost layer	Glass Cloth-VDG	Silver coated Teflon
Middle Layer(s)	DAK	DAK
Innermost Layer	DAK	DAK

Table 2: Shield Material Optical Property Data

	Optical Properties			
	Outboard		Inboard	
Shield Materials	emissivity	absorptivity	emissivity	absorptivity
Glass Cloth-VDG	0.81	0.35	0.03	0.21
Silver Coated Teflon	0.85	0.1	0.85	0.1
DAK	0.05	0.14	0.05	0.14

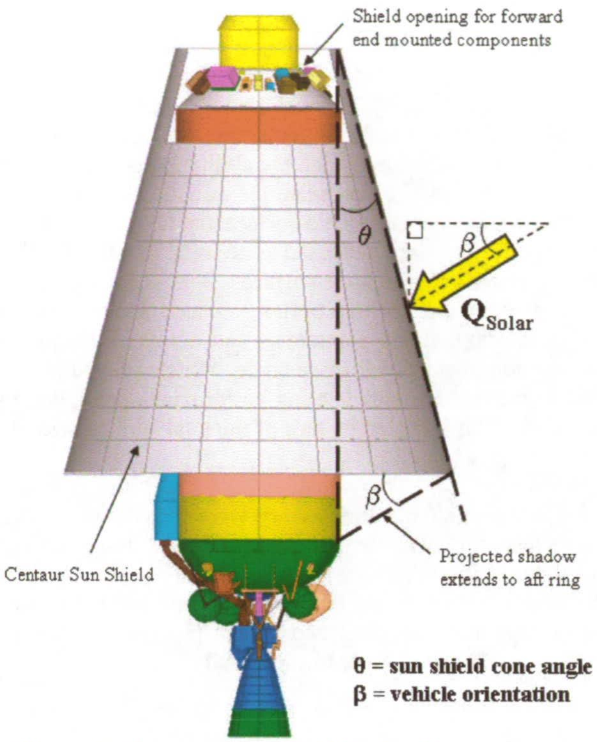

Figure 6: Centaur Sun Shield Design Parameters

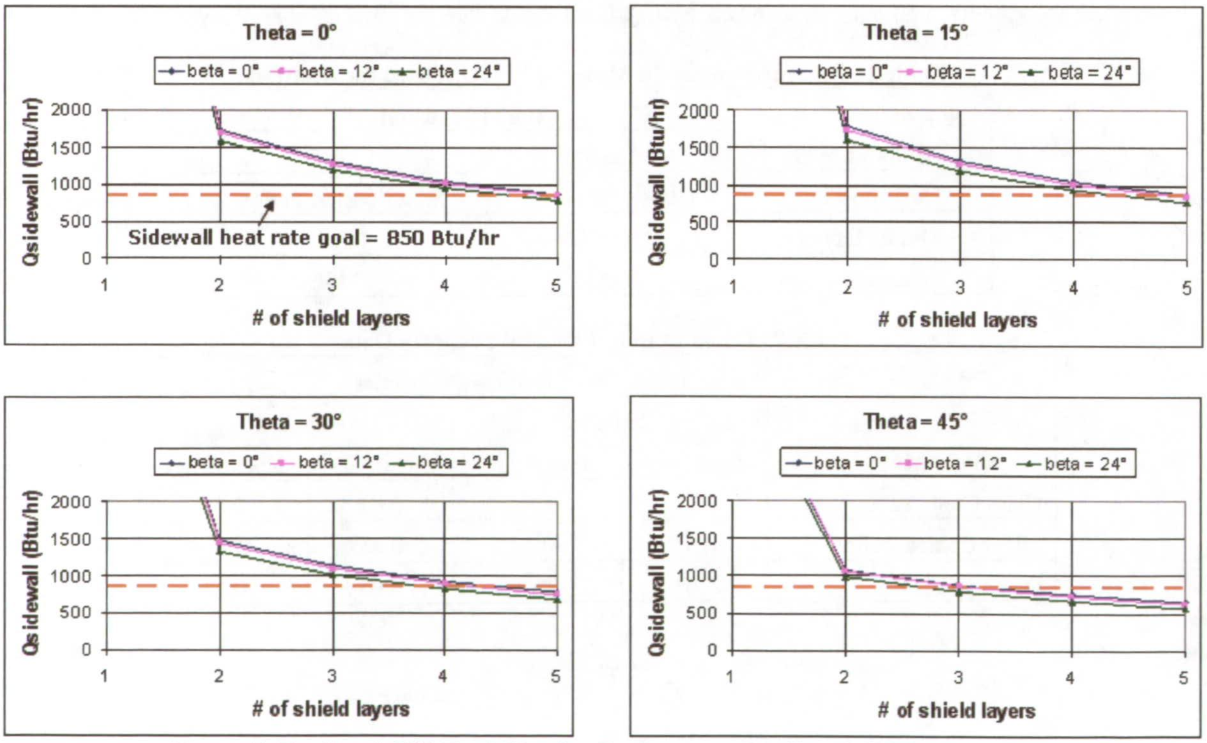

Figure 7: Predicted CSS Tank Heating Performance for Case 1 Shield Lay-up

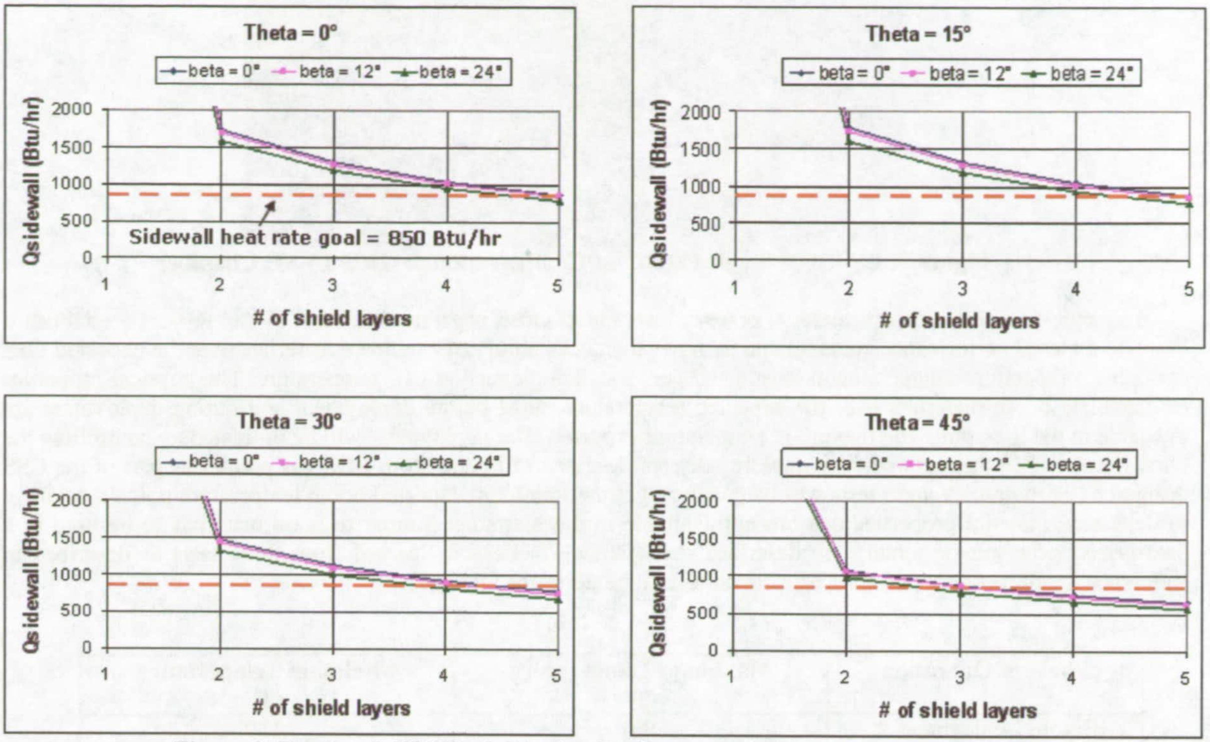

Figure 8: Predicted CSS Tank Heating Performance for Case 2 Shield Lay-up

VI. Testing

Moving beyond the deployment demo unit designed and built in 2007, the CSS development team is working toward a subscale engineering unit for a series of thermal vacuum chamber (TVAC) deployment tests. The planned TVAC tests will include sun shield deployment, structural dynamic and thermal tests. Separate from the TVAC tests (at a different location and time), a number of material coupon tests will also be performed at low temperature to ensure proper material and system performance at the expected CSS operating temperature. The TVAC test is scheduled for November of 2008. A successful completion of the subscale Sun Shield TVAC deployment tests will advance the technology readiness level of this system.

The TVAC tests will be in at least three parts. The first test will be an inflatable deployment of the single petal's vertical and horizontal booms at its expected in-space deployment temperature of -150°F. This test will allow for the observation and measurement of the CSS mechanical and pneumatic components' operation within a vacuum. The second test will measure the dynamic damping characteristics of the inflated single petal at low temperature within a vacuum. The third test will measure the thermal performance of the sun shield's thermal blanket in vacuum at low temperature in a similar fashion as the tests described in Reference 7. These tests are planned to be conducted at the NASA Glenn Research Center in Cleveland in a 15 ft diameter TVAC chamber.

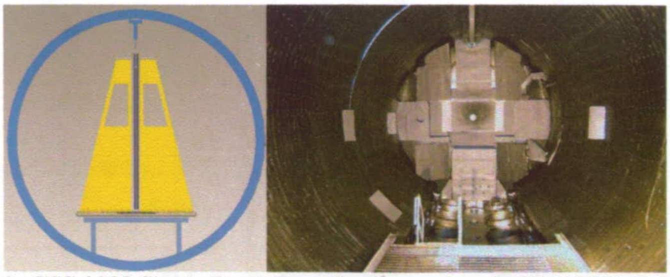

Figure 9: CSS 2008 Single Petal Test Configuration & GRC TVAC Chamber

As mentioned above, boom material coupon tests are planned separate from the TVAC tests. To establish a baseline material performance standard and to verify the acceptability of candidate materials over the expected CSS operating temperature range, coupon tensile and peel tests are planned at LH_2 temperature. The physical properties of candidate boom materials over the expected temperature range before deployment and during deployment are available in the literature. The maximum temperature expected after deployment will be mitigated by controlling the burst time of RCS thrusters, and by shielding discreet sections of booms from RCS gas plumes as part of the CSS design configuration. Coupon tests will be conducted at the minimum expected boom temperature post deployment to determine material properties that are not available in the literature. Similar tests on materials to be used in a pressurized stratospheric airship are described in Reference 8. Lessons learned from those tests as described in Reference 8 will be utilized in the CSS coupon tests to be performed this year.

Phase of Operation	Maximum Temperature °F	Minimum Temperature °F
Before Deployment & During Deployment	150	-139
Post Deployment	800*	-420

*RCS Thruster gas temperature

Table 3: CSS Operating Temperature Ranges

There are various design configurations for the inflatable booms, but all are dependent on having acceptable material properties over the CSS operating temperature range. There can be coated fabrics, film laminates, fiber and film laminates, or even a restraint and bladder system that can all be configured into a gas retaining boom for deployment of the sun shield. The configuration selected will be dependent upon the performance of the materials at the temperature extremes.

At the start of the program it was desired to select and fabricate the boom from a fibrous material that can withstand repeated flex cycles without degradation and ultimate failure. This characteristic is important as system acceptance testing and check out of such articles typically require multiple packaging, stowage, and deployment evaluations which can challenge even the friendliest of materials to these operations. Therefore, Vectran® was included as a candidate material based on its excellent resistance to flex fatigue at room temperature and at -112°F. However, while gathering performance data of materials at the low temperatures, a few candidate materials, including the Vectran® were submerged in liquid nitrogen at -320°F to subjectively evaluate the effect of exposure. The Vectran® was eliminated as a candidate as it became noticeably more brittle, less ductile. Two other candidate fabrics were submerged and both remained flexible and ultimately accepted as the baseline candidates for further cryogenic testing. The fabrics were 40:60 ratio of PBI/Kevlar, and 100% Kevlar fabric. The PBI/Kevlar fabric appears to be a more desirable fabric for use as the inflatable boom material since the presence of the PBI fiber will aid in resisting flex fatigue, and it also boosts slightly the high temperature capability of the fabric.

VII. Future Development

The development of the Sunshield for the Centaur Launch Vehicle thus far has been successful, but limited in progress and scope due to funding constraints. The initial concept development and ground deployment test described above has proved that a light weight sun shield system is viable, and the thermal analysis has shown the benefit of a CSS for extending mission life.

The next phase of development after the TVAC tests will be a full scale flight-like hanger demonstration test followed by flight demonstration. The hanger demo unit will likely contain proto-flight components that will eventually fly. The flight demo unit could either be a single panel unit or a full sunshade with multiple panels. A full multiple panels sunshade is preferred for a better performance characterization. The proposed first flight demonstration will be performed after the release of the primary payload to reduce the overall risk of the mission. That is, the first flight will be with a payload that does need a CSS for mission success. With adequate funding and a willing primary payload customer, a flight demonstration could be conducted in 2011.

VIII. Summary

A deployable CSS test article was successfully demonstrated in December 2007, and a second deployment test of a subscale single petal is planned for 2008 in a vacuum chamber at Glenn Research Center. Boom material properties are to be measured at LH_2 temperatures during 2008. Requirements definition is continuing, and valuable design and development information will be garnered from the TVAC and material coupon tests to be conducted this year. Thermal analysis has shown its potential for improving Centaur vehicle performance and has pointed the way to other potential applications such as propellant depots and its possible use on Delta upper stages.

Acknowledgments

The authors wish to thank United Launch Alliance's and ILC Dover's corporate management for funding this work under internal research and development; as well as NASA management for funding the work under its Innovative Partnership Program.

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