Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview

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The successful flight of the Inflatable Reentry Vehicle Experiment (IRVE)-3 has further demonstrated the potential value of Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology. This technology development effort is funded by NASA's Space Technology Mission Directorate (STMD) Game Changing Development Program (GCDP). This paper provides an overview of a multi-year HIAD technology development effort, detailing the projects completed to date and the additional testing planned for the future.

The effort was divided into three areas: Flexible Systems Development (FSD), Mission Advanced Entry Concepts (AEC), and Flight Validation. FSD consists of a Flexible Thermal Protection Systems (FTPS) element, which is investigating high temperature materials, coatings, and additives for use in the bladder, insulator, and heat shield layers; and an Inflatable Structures (IS) element which includes manufacture and testing (laboratory and wind tunnel) of inflatable structures and their associated structural elements. AEC consists of the Mission Applications element developing concepts (including payload interfaces) for missions at multiple destinations for the purpose of demonstrating the benefits and need for the HIAD technology as well as the Next Generation Subsystems element.

Ground test development has been pursued in parallel with the Flight Validation IRVE-3 flight test. A larger scale (6m diameter) HIAD inflatable structure was constructed and aerodynamically tested in the National Full-scale Aerodynamics Complex (NFAC) 40by80 test section along with a duplicate of the IRVE-3 3m article. Both the 6m and 3m articles were tested with instrumented aerodynamic covers which incorporated an array of pressure taps to capture surface pressure distribution to validate Computational Fluid Dynamics (CFD) model predictions of surface pressure distribution. The 3m article also had a duplicate IRVE-3 Thermal Protection System (TPS) to test in addition to testing with the aero-cover configuration. Both the aero-covers and the TPS were populated with high contrast targets so that photogrammetric solutions of the loaded surface could be created. These solutions both refined the aerodynamic shape for CFD modeling and provided a deformed shape to validate structural Finite Element Analysis (FEA) models.

Extensive aerothermal testing has been performed on the TPS candidates. This testing has been conducted in several facilities across the country. The majority of the testing has been conducted in the Boeing Large Core Arc Tunnel (LCAT). HIAD is continuing to mature testing methodology in this facility and is developing new test sample fixtures and control methodologies to improve understanding and quality of the environments to which the samples are subjected. Additional testing has been and continues to be performed in the

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NASA LaRC 8foot High Temperature Tunnel, where samples up to 2ft by 2ft are being tested over representative underlying structures incorporating construction features such as sewn seams and through-thickness quilting.

With the successful completion to the IRVE-3 flight demonstration, mission concepts such as the HIAD Earth Atmospheric Reentry Test (HEART) are being developed which will demonstrate a relevant scale vehicle in relevant environments. HEART would employ a large-scale aeroshell (10m) entering at orbital velocity (~7km/sec) with an entry mass on the order of 4MT. Also, the Build to Print (BTP) hardware (built as a risk mitigation for the IRVE-3 project to have a "spare" ready to go in the event of a launch vehicle delivery failure) is now available for an additional flight experiment. Mission planning is underway to define a mission that can utilize this existing hardware and help the HIAD project further mature this technology.

Nomenclature

8ft HTT = NASA LaRC 8 Foot High Temperature Tunnel
°C = centigrade
ACS = Attitude Control System
AEC = Advanced Entry Concepts
AoA = Angle of Attack
BET = Best Estimated Trajectory
BBXI = Black Brant XI
cg = center of gravity
CFD = Computational Fluid Dynamics
FEA = Finite Element Analysis
FSD = Flexible Systems Development
FTPS = Flexible Thermal Protection System
HEART = HIAD Earth Atmospheric Reentry Test
HIAD = Hypersonic Inflatable Aerodynamic Decelerator
IAD = Inflatable Aerodynamic Decelerator
IRVE = Inflatable Reentry Vehicle Experiment
IS = Inflatable Structures
LCAT = Boeing Large Core Arc Tunnel
LEO = Low Earth Orbit
m = meter
MCR = Mission Concept Review
MEDLI = Mars Science Laboratory Entry/Descent/Landing Instrumentation
MPCV = Multi-Purpose Crew Module
MT = Metric ton
NFAC = National Full-scale Aerodynamics Complex
NIACS = NSROC Inertial Attitude Control System
NSROC = NASA Sounding Rocket Operations Contract
OCT = Office of Chief Technologist
PBM = Physics Based Model
PCM = Pressurized Cargo Module
SiC = Silicon Carbide
SRI = Southern Research Institute
TPS = Thermal Protection System
UPWT = Unitary Plan Wind Tunnel
WFF = Wallops Flight Facility

I. Introduction

The successful flight of the Inflatable Reentry Vehicle Experiment (IRVE)-3[1] has further demonstrated the potential value of Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology. This technology development effort is funded by NASA's Space Technology Mission Directorate (STMD) Game Changing Development Program (GCDP). The HIAD technology development was divided into three areas: Flexible Systems Development (FSD), Advanced Entry Concepts, and Flight Validation (see figure 1). This paper provides an overview of a multi-year HIAD technology development effort, both the projects completed to date and the additional testing planned for the future.

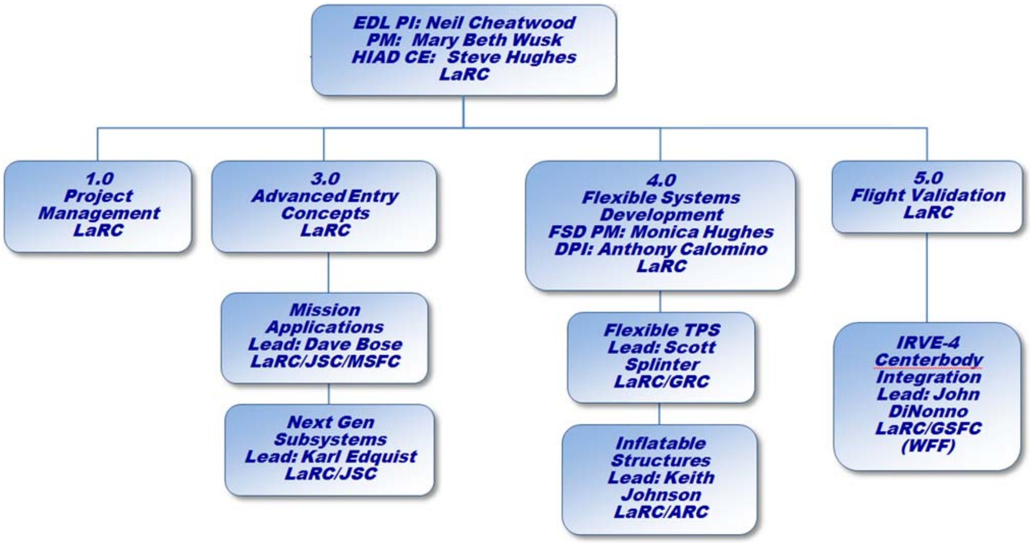


Figure 1HIAD Project Organizational Structure

II. HIAD Project

As stated earlier HIAD was divided into three areas: Flexible Systems Development (FSD), Advanced Entry Concepts (AEC), and Flight Validation. FSD was divided into two elements a Flexible Thermal Protection System (FTPS) element and an Inflatable Structures (IS) element. The FTPS effort focuses on manufacturing processes for TPS materials and assemblies, material thermal response properties over the range of environments in which the materials have to operate, incorporating those material properties into a physics based model to predict the thermal response to the applied aerothermal heating environment, Computational Fluid Dynamics (CFD) simulation to determine the correct environment to apply in aerothermal heating facilities to replicate the design flight environment, and finally aerothermal performance testing to subject instrumented materials to the environments proving capabilities of the materials and providing data to verify the physics based response models. The IS effort focuses on manufacturing processes for IS materials and assemblies, material structural response properties over the range of environments in which the materials have to operate, incorporating those material properties into a Finite Element Analysis (FEA) to predict the load and deflection response to the applied environment, Computational Fluid Dynamics (CFD) simulation to determine the correct environment to apply to the structure to simulate the design flight environment, and finally performance testing to subject instrumented inflatable structures to the environments proving capabilities of the materials and providing data to verify the FEA. The AEC effort is divided into the Mission Application Trade Studies and Next Generation Subsytems. Mission Apps is developing concepts (including payload interfaces) for missions at multiple destinations for the purpose of demonstrating the benefits and need for the HIAD technology. Next Gen is investigating methods for generating lift on blunted cones focusing on aerodynamic trim surfaces. Flight Validation efforts up until this point had been focused on the IRVE-3 flight and the associated data reduction. A flight spare unit of the IRVE-3 centerbody hardware, referred to as Build to Print (BTP), was built as a risk reduction to have hardware available in the event of an IRVE-3 launch vehicle failure. This unit is now available for a new mission and is being proposed as a new start mission to STMD-GCD. Additional flight validation work has been performed in support of the HIAD Earth Atmospheric Reentry Test (HEART) a proposed HIAD which leverages the Orbital Sciences Corp. Cygnus Pressurized Cargo Module (PCM) as ballast as part of an entry demonstration flight test, resulting in achieving a TRL7 for HIAD entry technologies.

III. FSD - FTPS

FTPS development has progressed significantly in the two years of work performed for the HIAD project to date. Thermal and structural property tests have been performed for many candidate materials over a range of temperatures and pressures at both Southern Research Institute (SRI) and in-house test facilities at NASA LaRC and GRC. TPS layups have been mechanically aged at SRI to determine if there is any problematic degradation in material response properties after being hard packed, environmentally cycled and deployed. Aerothermal tests have been performed on various candidate layups in many configurations. Testing has been performed on large 2ft by 2ft samples in the 8-Foot High Temperature Tunnel, a vitiated flow blow down facility at NASA LaRC, but the Boeing Large Core Arc Tunnel (LCAT) has become the workhorse aerothermal test facility for the HIAD project. A custom designed shear wedge fixture (see Figure 2) was developed and used for many material candidate layups at a range of test conditions. Difficulties getting the HIAD physics based thermal performance model predictions to match tested layup temperatures caused the project to re-evaluate the test approach. As a result, a decision was made to change to stagnation testing to help achieve model correlation by reducing the number of environment variables. A stagnation test fixture (see Figure 3) was designed based on the outer mold line of a test fixture extensively used at LCAT by the Mars Science Laboratory Entry, Descent, and Landing Instrumentation (MEDLI) project. Stagnation testing revealed an issue with the heat flux distribution across the test sample surface in the new stagnation model holder. The outer sample plies were melting at the perimeter at fluxes previously survived in the shear fixture and laser heating tests. CFD modeling of the test setup indicated there was roughly a 25% rise in heat flux from the center of the sample to the sample perimeter in the current stagnation configuration. Working with the LCAT personnel the stagnation sample holder was redesigned (see Figure 4) and heat flux variation across the face of the sample was cut to approximately 10%. Additionally LCAT personnel developed the control to run heating profiles in the LCAT to match preliminary HEART design simulation trajectory heating profiles (see Figure 5). This capability was a significant improvement over the traditional square pulse heating approach because the FTPS materials respond much more favorably to realistic profile heating than to a square pulse. As a result of these two improvements, materials that would have been classified as incapable of sustaining a 40W/cm^2 heat rate survive heating profiles with peak heating in excess of 50W/cm^2. Finally, aerothermal testing of the full scale IRVE-3 nose assembly was performed in the JSC Test Position 2 arc jet (see Figure 6). Two “build to print” copies of the flight nose TPS assembly were tested at heating rates and total integrated heat loads far in excess of the IRVE-3 flight predictions. To address scalability concerns an FTPS was designed with the current baseline materials to be integrated with a 6m stacked torus inflatable structure and is currently under construction. An FTPS physics based thermal response model has been under development incorporating the material thermal properties as they are acquired in testing. Sufficient thermo-physical phenomena and property data are now incorporated in the model to demonstrate reasonable agreement between model ply temperature predictions and aerothermal testing data for the baseline FTPS layup.

Figure 2 LCAT Shear Fixture

Figure 3 LCAT 3.5in Stagnation Fixture

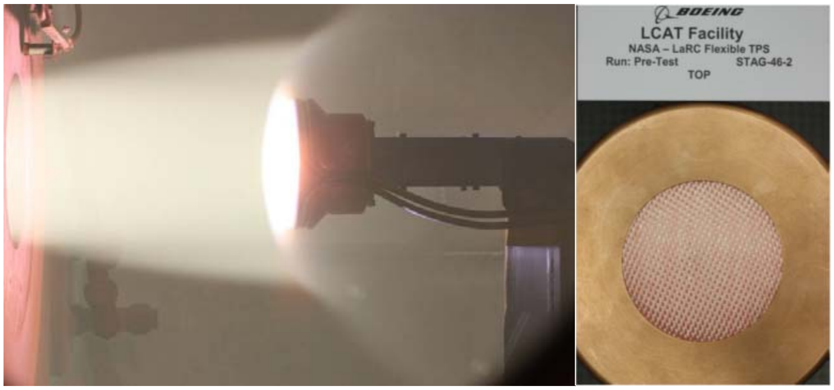


Figure 4 LCAT Redesigned 4.5in Stagnation Fixture

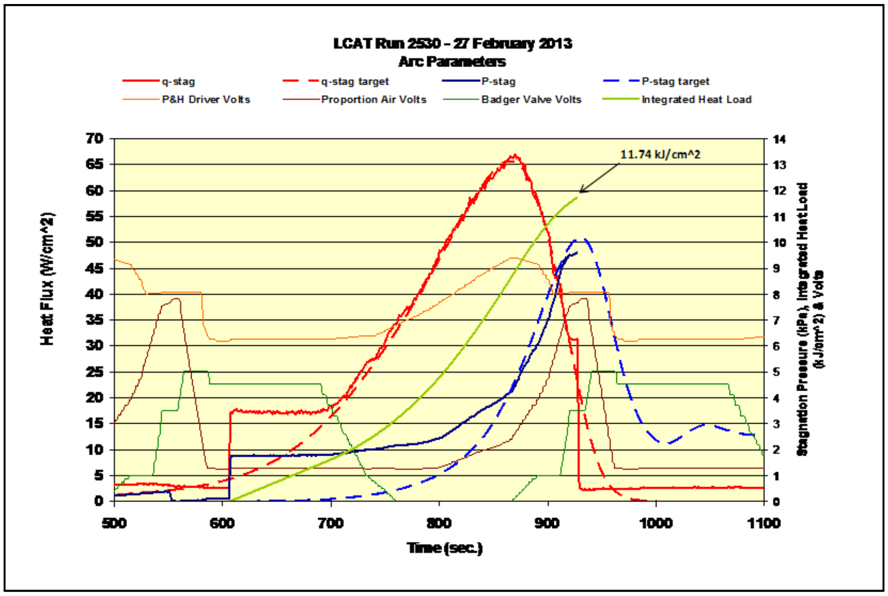


Figure 5 LCAT Profile Heat and Pressure Pulse

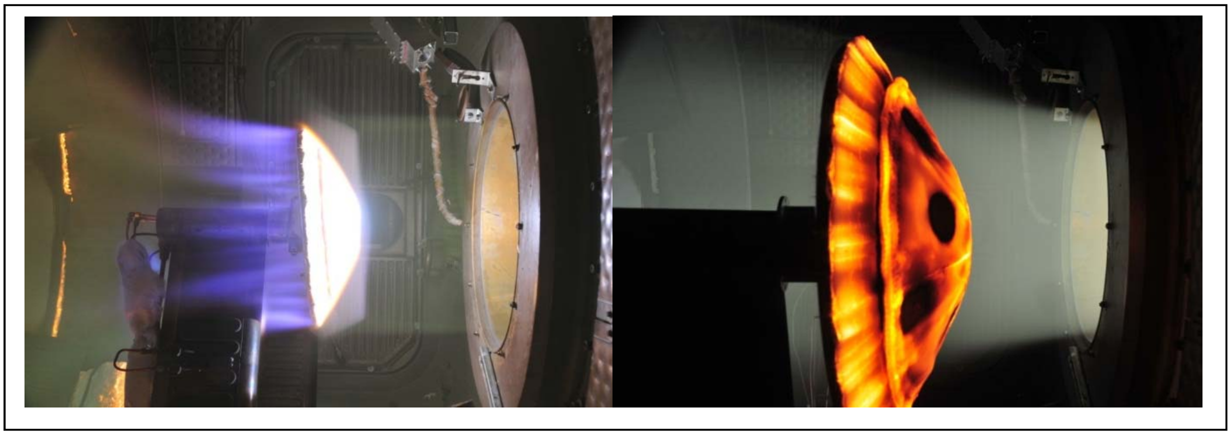


Figure 6 IRVE-3 Nose Assembly in JSC TP2

Future FTPS development will include aerothermal testing of the sample layups mechanically aged at SRI. Development will also continue on next generation materials. The most pressing material development is with the outer cloth. The latest trajectory simulation and CFD modeling of the HEART design mission are indicating the aerothermal heating environment may be in excess of what the baseline outer material, BF20, is capable of surviving. The replacement candidate, SiC, is an excellent aerothermal performer, but needs to increase technical maturity in the areas of manufacturing the base cloth, construction (stitching and joining) of the FTPS assembly, and mechanical durability to withstand the rigors of construction, packing, and deployment. Additionally, a sub scale 3m assembly of the next generation FTPS is planned for FY2014. New candidate insulators have been identified and tested that demonstrate improved aerothermal performance and increased temperature capacity, but in-kind manufacturing and handling requirements as the baseline insulator.

IV. FSD - IS

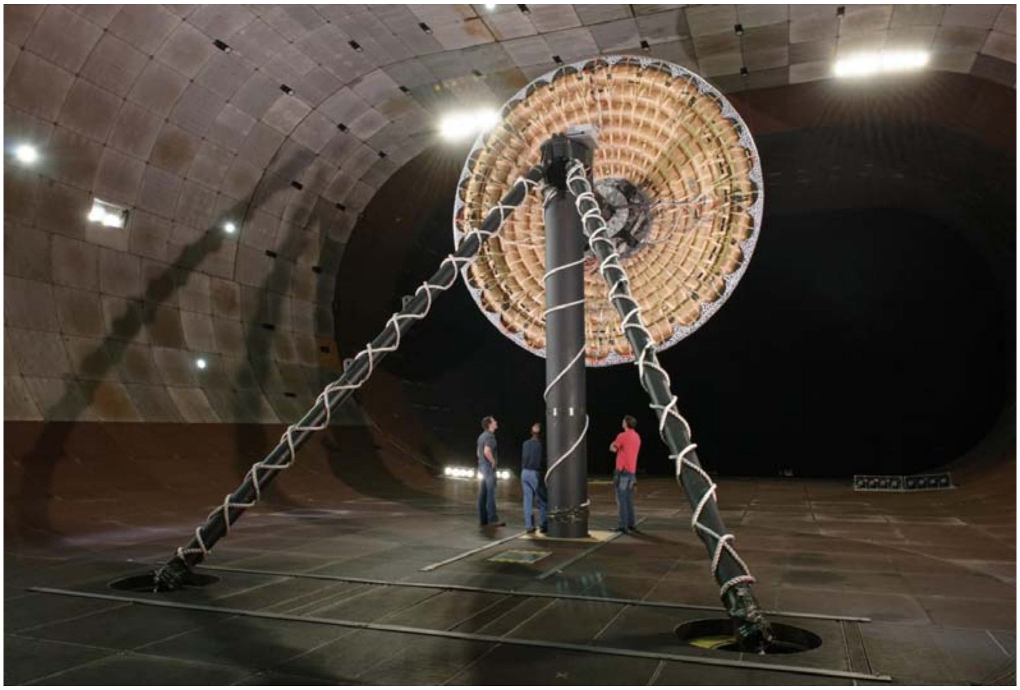


Figure 7 NFAC 40x80 Test Section with 6m HAID Test Article

The IS technical development has progressed as well in the two years of HIAD development. Uni-axial load testing at temperature has been conducted on all candidate materials and several potential next generation materials. 3m and 6m diameter IS assemblies have been manufactured and aerodynamically tested in the 40ftx80ft circuit of the National Fullscale Aerodynamics Complex (NFAC) at Ames Research Center (see Figure 7)[2]. Instrumentation has been developed to measure loads in the strap assemblies[3] and a photogrammetric measurement system has been adapted for use with these high-drag blunt bodies in the NFAC 40x80 test section[4]. Extensive effort has been expended to reduce and post-process the photogrammetric data[5] so that these data can be utilized to create deformed model geometry for CFD grid generation and for comparison to FEA predicted displacements. Data from the strap load cells have been used to help refine the structural model. The challenges of modeling the complexities of a stacked torus assembly have lead the project to take a step back and perform simple elemental testing in an effort to assure that the HIAD FEA can predict simpler single element tests. A series of straight air-beams with three different bias braid angles were manufactured in order to study the effect of braid angle on structural response as well as demonstrating that the project can verify that the FEA is accurately modeling the behavior of the constitutive elements. The straight beams (see Figure 8) are being used in 4-point bending and tension torsion testing. Additionally, several individual tori have been manufactured at three different major diameters with the same bias braid angle and axial cord strength to try and capture any effects of scaling. For one of the major diameters an additional test article was constructed with a different bias braid angle and another test article was being constructed with lighter weight axial cord. The individual tori will be subjected to a radially inward (compressive) load and a combination of inward load and torsion (see Figure 9). Again the effort is to verify the FEA accurately predicts the behavior of the element. New instrumentation is being developed for the elemental testing to make it possible to measure the strain in the axial cords during load testing. This instrumentation will allow the project to verify hypotheses about how the level of axial cord load affects the structural response of the torus. The instrumentation being developed is elastomeric and has the possibility of being tolerant of packing and deployment, potentially making the instrumentation applicable for in-flight measurement.

Figure 8 Elemental Straight Beam Hydrostatic Test Article

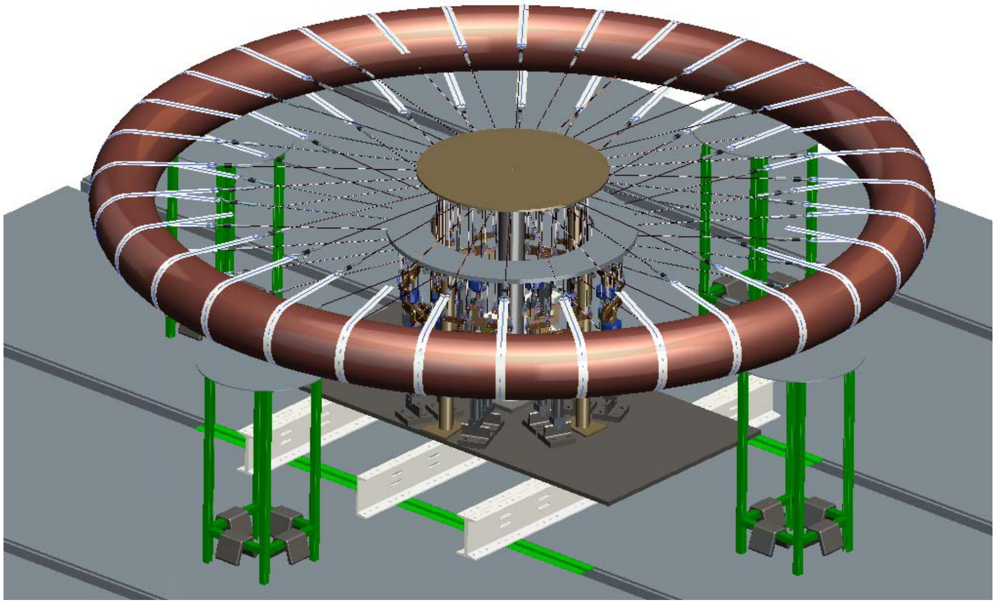


Figure 9 Preliminary Design Elemental Test Article Toroid Compression/Torsion Fixture

IS has also continued to advance the temperature capability of the inflatable structure in an effort to reduce overall aeroshell system mass by reducing the quantity of TPS insulation required. The effort requires both a higher temperature capable fiber for the construction of the bias braid, axial cord, and suspension webbing as well as a higher temperature film for the inflatable bladder liner. IS has two leading fiber candidates, graphite and poly(p-phenylene-2,6-benzobisoxazole) PBO. Load tests at temperature have been completed for identical construction webbing from the two candidate materials. The PBO webbing has roughly 70% reduction strength at 400C, but even with that reduction is more than adequate to carry the required loads. The graphite only experiences roughly a 20% reduction in load, but is below the required load capacity. Discussions are underway with the narrow goods weaver to attempt to improve the initial strength of the graphite webbing to take advantage of the higher temperature capability of the fiber. The leading bladder liner candidate is an elastomeric polyimide film, Essar Stretch. The manufacturer reports use temperatures in excess of 400C and allowable elongation over 80%. High temperature testing of the Essar Stretch is currently underway at NASA LaRC in the structures lab. Tori with graphite axial cords and bias braid have been constructed (see Figure 10) to investigate the effects of packing and deployment on the graphite fiber, and these packing and deployment trials were successfully completed in the NASA LaRC structures lab. Currently, two more articles of the same shape and size are planned to be constructed: one with a PBO fiber construction and an elastomeric polyimide liner; and another with a graphite fiber construction and the same elastomeric polyimide liner.

Figure 10 Graphite Bias Braid and Axial Cord High Temperature Torus

Manufacturing process control is also being investigated by the IS project. The previous 6m and 3m NFAC test articles exhibited variation in load in straps that should have been identical during axisymmetric load testing. Manufacturing tolerances have a significant effect on strap preload. Procedures have been developed in an effort to reduce manufacturing variation. Those procedures are being applied to the construction of a new 6m inflatable structure that will be tested in an upcoming test series at NFAC 40x80. A larger portion of the model will be instrumented with the custom strap tension gauges and load pins during load testing to increase the sample set in an attempt to assure the load data being used for FEA model validation are a true representation of the strap loading and not statistical outliers. Strap load instrumentation is being incorporated in the manufacturing process as part of the attempt to improve process control and produce a more uniformly loaded assembly.

Another NFAC 40x80 test series is planned fiscal year 14. Plans for this series includes testing the new 6m structure with the accompanying FTPS manufactured from current baseline materials. Lessons learned from the previous NFAC test series will be incorporated into this new test series. Possible reconfiguration of the model support could reduce the model support flow interaction that created undesirable flow disturbances in the last test series. Addition instrumentation will provide better model coverage to help with FEA deflection and load prediction correlation.

V. Mission Application Trade Studies

HIAD Mission Application Trade Studies were conducted in the past year to determine which applications are suitable for incorporating a HIAD[6,7]. Hybrid Lunar Return evaluated the use of a HIAD in returning Multi-Purpose Crew Vehicle (MPCV) from a lunar mission via direct Earth entry. The term hybrid is applied because the HIAD is not the primary heat shield, but rather used to augment the existing MPCV heat shield. Hybrid Mars Return evaluated a HIAD for returning MPCV from a Mars mission via direct Earth entry. Launch Asset Recovery evaluated employing a HIAD to recover launch vehicle assets. This particular study focused on 1st and 2nd stage recovery of a Falcon-9 launch vehicle. L2 Lagrange Point to Low Earth Orbit (LEO) Transfer evaluated a HIAD for transferring an MPCV from an L2 condition to a LEO orbit through aerocapture. Mars Fast Transit was the evaluation of a HIAD in the transfer of MPCV to low or high Earth orbits in a Mars fast transit scenario. Mars Aerocapture evaluated a HIAD performing aerocapture at Mars. Finally, Mars Southern Highlands was the evaluation of a HIAD for performing direct-entry at Mars with access to higher altitudes such as those associated with the Mars Southern Highlands region. Year 2 of HIAD Mission Applications is focusing on exploring additional mission classes, as well as verifying key Year 1 findings through more detailed design and analysis of specific reference missions.

VI. AEC – Next Generation Subsystem

Next Gen has been concentrating on alternative lift effectors in particular Trim Tabs. In 2001Mars Smart Lander (MSL) obtained data for limited number of trim tab shapes in Unitary Plan Wind Tunnel (UPWT). In April of 2012 Next Gen expanded the supersonic aerodynamic trim tab database with a new UPWT wind tunnel test series for a parametric blunt body model with trim tabs (see Figure 11).

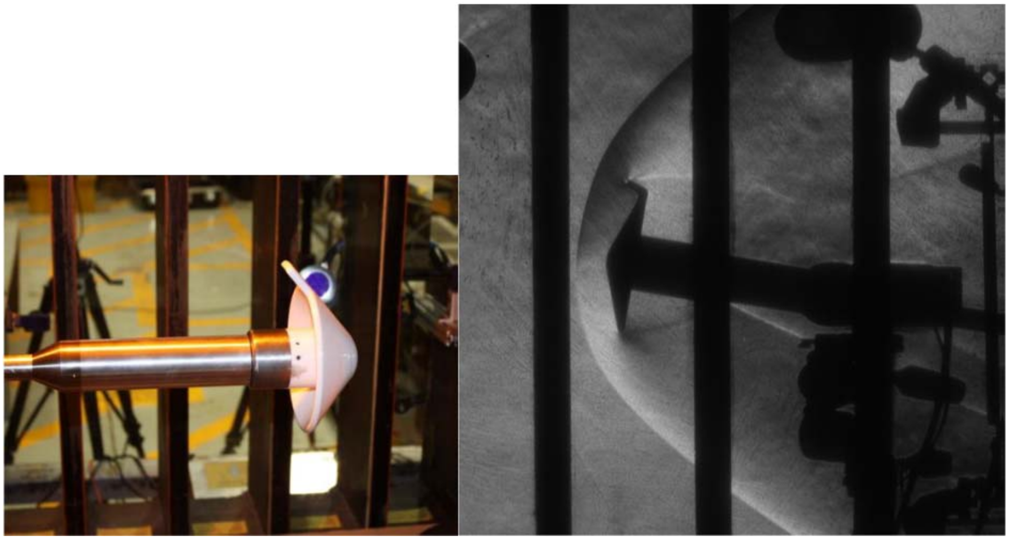


Figure 11 Trim Tab Models in UPWT

Additional wind tunnel testing has been performed in the LaRC 20-inch Mach 6 Air Tunnel investigating aerodynamic heating augmentation resulting from the distortion of the forward HIAD aerodynamic surface. A parametric study was conducted over a range of disturbance magnitude, Angle of Attack, and Reynolds number (see Figure 12).

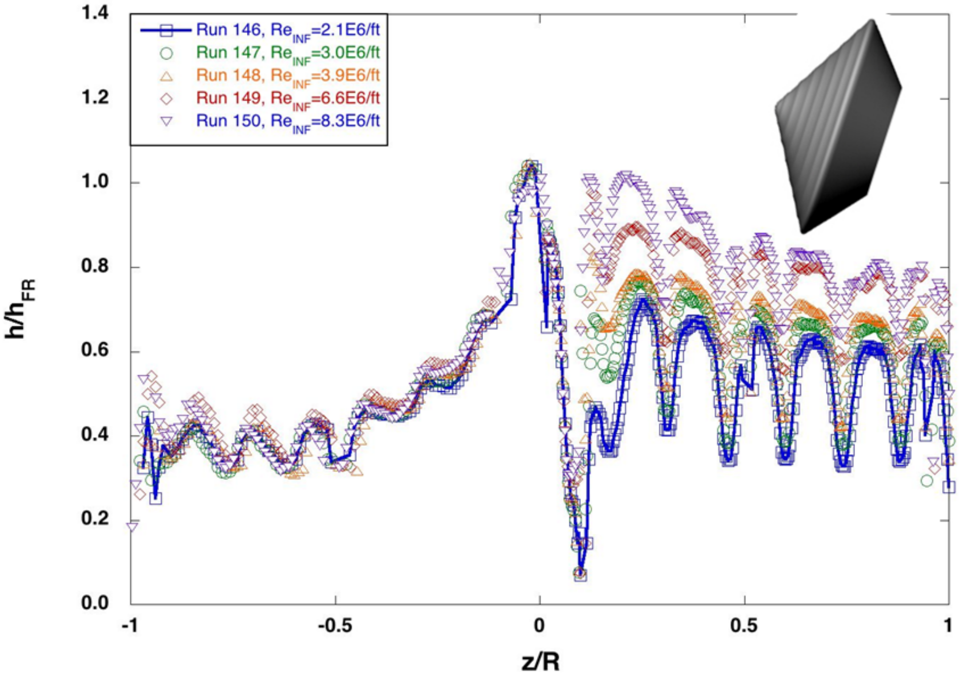


Figure 12 Deflected OML Heating α = 18-deg, LaRC 20-Inch Mach 6 Air Tunnel

Investigations have continued for adapting Moog Bradford's cold gas technologies currently scaled to service in helicopter offshore-flight application for a HIAD application (see Figure 13). Demo units output 1500 normal liters in five seconds (roughly 640 SCFM or 18,000 SLPM). As a point of reference the preliminary HEART design HIAD has an internal volume of 19,200 liters and if the same performance was achievable in a space hardened device it would take 12 units roughly 64 seconds to fill the HEART aeroshell to standard conditions as a best case.

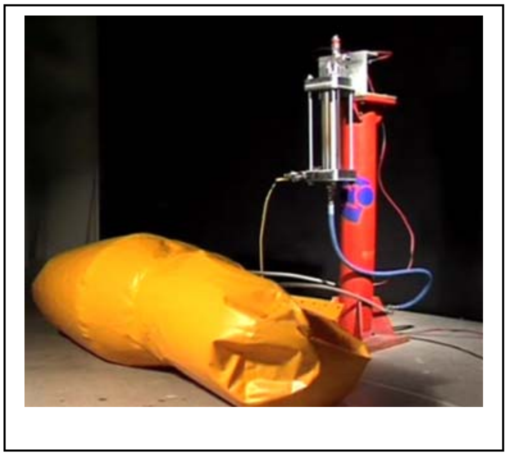


Figure 13 Moog-Bradford 1500nl Cold Gas Generator (silver cylinder) Filling a Helicopter Float

VII. IRVE-3

IRVE-3 launched from the Wallops Flight Facility July 23rd, 2012 (see Figure 14). The vehicle had a successful flight delivered to the proper trajectory completing all deployments and performing well from entry through all flight regimes[8]. The mission successfully demonstrated use of a radial cg offset to generate a lift vector while employing a flexible inflatable aeroshell. A NSROC Inertial Attitude Control System (NIACS) was successful in controlling roll angle while the vehicle was endo-atmospheric[9]. After the flight a series of “bonus Maneuvers” were successfully executed to study transient response of vehicle trim angle of attack to a shifting cg location. Flight vehicle data captured exo-atmospheric after the cg offset shift was used to calculate the aeroshell/centerbody interface stiffness in the free-free condition with no applied aerodynamic load and demonstrated the ground technique employed for pre-flight prediction produced an accurate value. An atmospheric anomaly, a ~10% low density strata, excited the structure as the vehicle was nearing peak pressure making it possible to calculate the aeroshell/centerbody interface stiffness in the free-free condition with a significant applied aerodynamic load (see Figure 15). Video data were used to analyze the global aeroshell deflection through the vehicle deceleration pulse and this deflection data were used to improve the accuracy of the structural model to predict the deformed state during entry. On-board GPS and IMU data were used to refine the best estimated trajectory for the for the IRVE-3 flight. Using the Best Estimated Trajectory (BET), CFD was performed at key points in the trajectory. Flux and pressure measurements appear to be in reasonable agreement with the CFD calculated values from the BET, however thermocouple measurements did not agree with temperatures calculated using the HIAD physics based model. An extensive effort was expended and the reasons behind the disagreement between the model and flight measurements have been determined to be mass of the instrumentation.

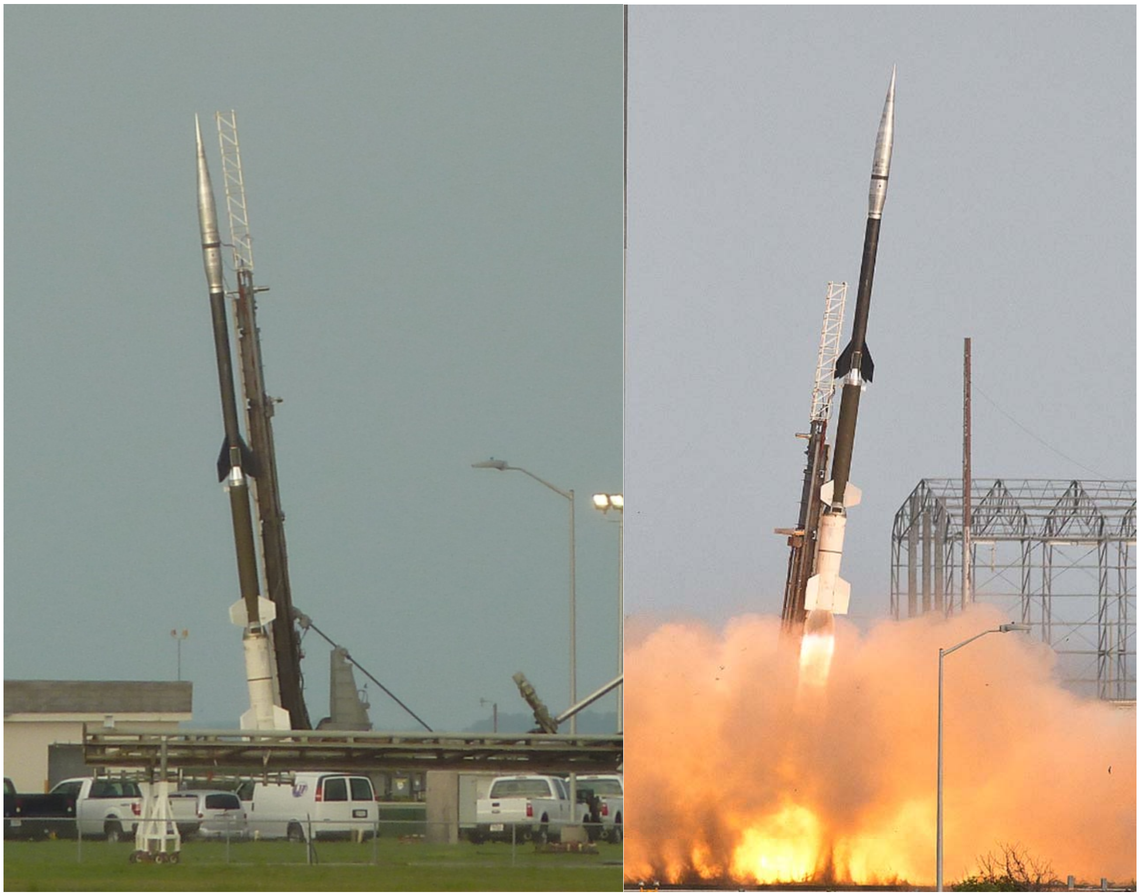


Figure 14 IRVE-3 Launch Photo Credit NASA LaRC Sean Smith

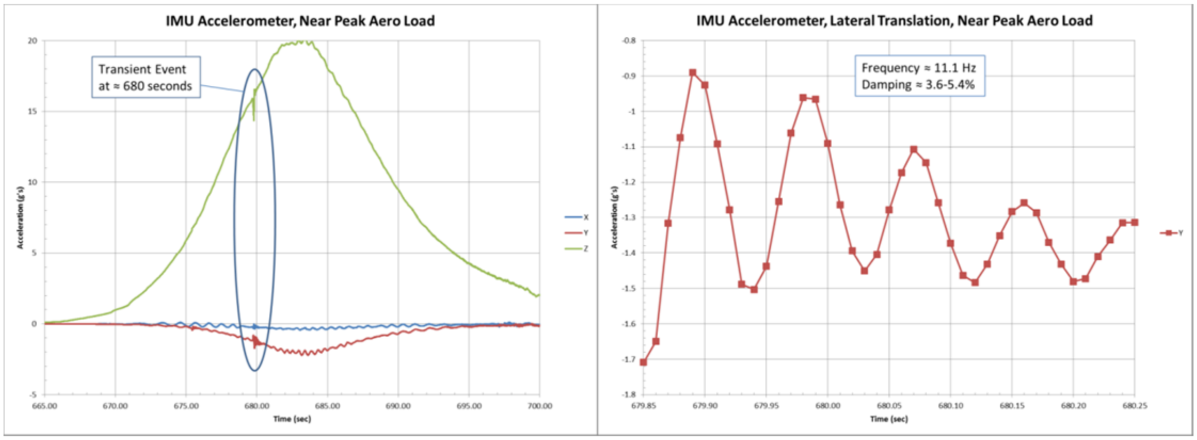
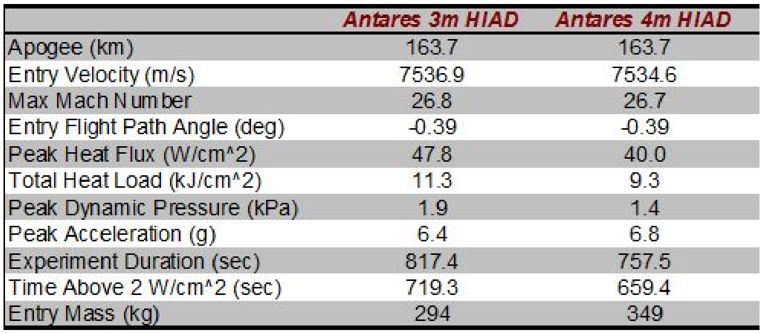


Figure 15 IRVE-3 Atmospheric Low Density Anomaly

VIII. BTP

A flight spare unit of the IRVE-3 centerbody hardware, referred to as Build to Print (BTP), was built as a risk reduction to have hardware available in the event of a an IRVE-3 launch vehicle failure. With the successful flight of IRVE-3 the BTP unit is now available and has been proposed to be used on a new start mission to STMD-GCD. The most promising launch opportunity has just recently become available. With the successful launch of the Orbital Sciences Antares vehicle there is now actual flight boost performance data for the vehicle. That performance data combined launch manifests has revealed that there is nearly 800kg extra launch capacity the third cargo resupply mission. There is also a considerable volume between the outer diameter of the Castor second stage and the launch vehicle shroud. The BTP hardware could be configured to fit in the available volume using around half of the excess vehicle performance. The project is in discussions with Orbital about attaching the BTP hardware to the skin of the second stage and releasing the BTP payload shortly after the second stage de-orbit. As this re-entry opportunity would be from orbital velocity the heat rate and heat load would be significantly higher than previous sub-orbital tests. Conceptual entry simulation estimate of entry environment is shown in Figure 16, and a notional payload configuration is shown in Figure 17.



	Antares 3m HIAD	*Antares 4m HIAD*
Apogee (km)	163.7	163.7
Entry Velocity (m/s)	7536.9	7534.6
Max Mach Number	26.8	26.7
Entry Flight Path Angle (deg)	-0.39	-0.39
Peak Heat Flux (W/cm^2)	47.8	40.0
Total Heat Load (kJ/cm^2)	11.3	9.3
Peak Dynamic Pressure (kPa)	1.9	1.4
Peak Acceleration (g)	6.4	6.8
Experiment Duration (sec)	817.4	757.5
Time Above 2 W/cm^2 (sec)	719.3	659.4
Entry Mass (kg)	294	349

Figure 16 Preliminary Estimation of Environments Achievable for BTP on Antares

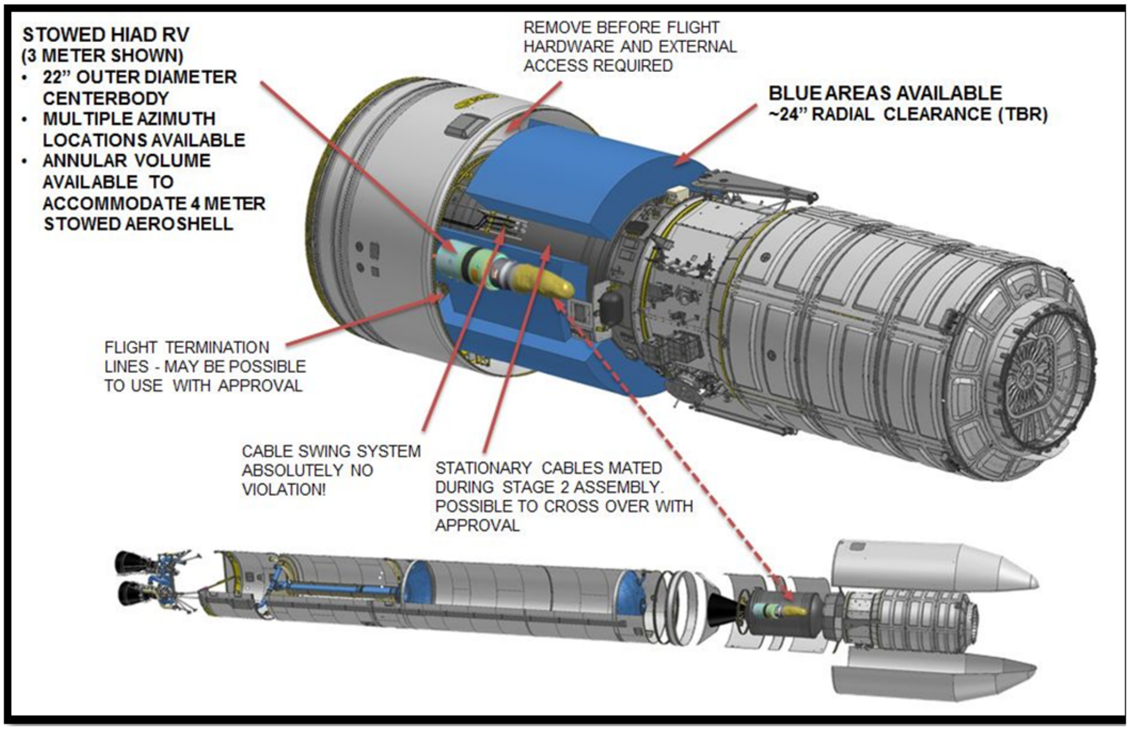


Figure 17 Notional BTP launch configuration

IX. Conclusions

The HIAD project has developed a coordinated approach to maturing the HIAD system to a TRL of 5 by the end of FY2014. Static and Aerodynamic load testing have been used to develop an inflatable structure that satisfies the current load requirements. Additional elemental and reconfigurable assembly load testing in the coming year should allow the fine tuning of the FEA model to the point where it can be used to optimize the structural configuration. Aerothermal performance of the baseline TPS has exceeded the original project requirements for a 1st generation system. Refined aero-aerothermal CFD analysis of the HEART design mission indicates TPS requirements may be in excess of what was initially deemed 1st generation TPS requirements. New candidates continue to be evaluated and a TPS capable of handling the new aerothermal requirements has been identified. In the coming year that new candidate layup will advance from coupon level testing to large scale assembly in order to prove out construction methods and evaluate mechanical durability of the system to the rigors of manufacturing assembly, packing and deployment. Mission Apps trade studies have identified several mission types where HIAD technology is beneficial to the missions. This year the Mission Apps team will complete a more detailed design in an attempt to determine the reasonableness of the outputs of the high level design tools currently used in the initial trade studies. BTP will complete the integration of the centerbody components, but there is no mission currently approved beyond this. Unfortunately, the uncertainties in the Federal Budget endanger all future HIAD technology development as the project must deal with the realities of ever shrinking funding.

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