PLANNED FLIGHT OF THE TERRESTRIAL HIAD ORBITAL REENTRY (THOR)

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ABSTRACT

The Terrestrial HIAD Orbital Reentry (THOR) is planned for flight in 2016 as a secondary payload on an Orbital Sciences Corporation (OSC) commercial resupply mission to the International Space Station (ISS). THOR will launch with its Hypersonic Inflatable Aerodynamic Decelerator (HIAD) stowed as a small cylinder between the second stage motor and the Antares launch vehicle fairing. Once the Cygnus cargo vehicle has separated from the second stage, THOR will likewise separate, autonomously re-orient itself, perform a de-orbit burn, then inflate the HIAD to a 3.7m diameter cone before atmospheric interface. THOR is a follow-on mission to the Inflatable Reentry Vehicle Experiment 3 (IRVE-3) flight test of 2012. The high energy of orbital reentry will allow THOR to demonstrate the performance of its improved, second-generation inflatable structure and flexible thermal protection system (TPS) materials, in a more energetic entry environment than previous suborbital test flights.

This paper discusses the sequence of events planned to occur as part of the THOR mission. Specific topics will include the THOR mission concept, reentry vehicle design for the expected flight environment, the on-board sensors that will allow quantification of vehicle performance, and flight data retrieval from a reentry vehicle splashing down in international waters.

1. BACKGROUND

In 2009, IRVE-II launched on a two-stage sounding rocket and performed the first fully successful HIAD flight test [1]. The reentry vehicle (RV) reached an apogee of 218km, inflated to a 24KPa (3.5psi), 3m diameter cone before reentry, and demonstrated that the inflatable aeroshell would remain inflated and stable through reentry and descent. Deceleration loads on the 125kg reentry vehicle peaked at 8.5G's, and maximum reentry heating was under 2W/cm^2, but those were sufficient to confirm that trajectory and thermal models were conservative.

In 2012, IRVE-3 launched a redesigned RV with the same general vehicle configuration, an improved inflatable structure and flexible TPS, and additional hardware to laterally shift the center of gravity (CG) and to provide attitude control in flight [2]. A three-stage sounding rocket boosted the RV to an apogee of 469km, producing more energetic reentry conditions. Before reentry the RV inflated to a 140KPa (20psi), 3m diameter cone, shifted its CG laterally 1.8cm (0.7”), and reoriented nose-forward for atmospheric interface. Deceleration loads on the 280kg RV peaked at 20.2G's, with maximum heating of 15W/cm^2. IRVE-3 demonstrated the survival of a HIAD in the reentry heating environment, and also illustrated the effect of an offset CG on the HIAD's lift-to-drag ratio and flight path angle [3].

NASA Langley Research Center is leading the development of HIAD technology for use on future interplanetary and Earth reentry missions.

2. MISSION CONCEPT

THOR is planned for flight in 2016 as a follow-on mission to the previous HIAD flight tests. THOR will launch as a secondary payload on an OSC commercial resupply flight to ISS, in the available space between the Antares launch vehicle's 2.3m diameter second stage motor and the 3.9m diameter payload fairing, as shown in Fig. 1. After the second stage motor burns out and the Cygnus spacecraft separates to proceed to ISS, THOR will separate and autonomously perform its reentry demonstration mission.

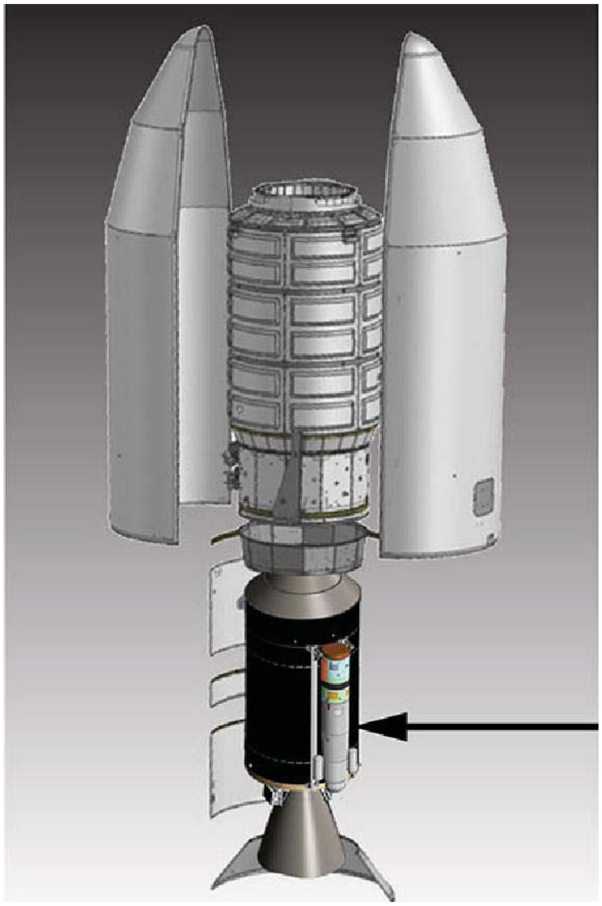

Fig. 1: THOR on Second Stage

Reentry from the predicted 200-250km orbit provides much more energetic test conditions than the previous sub-orbital flights. The THOR RV will fly at a shallow flight path angle to produce a reentry heat pulse several minutes long, representative of LEO or Mars entry missions; this will also limit the peak cold wall heat flux to 40-45W/cm^2. Peak deceleration loads along this trajectory are predicted to be 8-10G's for the estimated 315kg RV.

THOR will use the existing IRVE-3 Built-To-Print centerbody, containing a duplicate of the IRVE-3 inflation system, CG offset system, avionics, and attitude control system (ACS). These systems will be somewhat modified to accommodate a 3.7m diameter inflatable aeroshell fabricated using second-generation HIAD structural and TPS materials. The improved structure can handle higher temperatures than the previous designs while maintaining structural performance. Initial load tests indicate that it will be able to handle deceleration loads with adequate margin while inflated to approximately 105KPa (15psi). The improved TPS has been shown in ground testing to be capable of handling cold wall heat flux profiles peaking at 65W/cm^2, with longer test durations than the THOR reentry.

The THOR aeroshell will be fabricated with a 70deg half-cone angle, instead of the 60deg angle used on the previous flights, to demonstrate the stability and drag differences between the two geometries and somewhat offset the increased inflation volume of the larger diameter vehicle. The larger aeroshell diameter requires an additional structural toroid, as well as a slight increase in the minor diameter of each toroid.

3. HARDWARE UPDATES

As shown in Fig 2, the THOR inflatable structure maintains the stacked-toroid approach of the previous HIAD flights, allowing it to inflate and reach its flight configuration prior to atmospheric interface. THOR also maintains the IRVE-3 toroid configuration, forming individual toroids from a thin film gas barrier reinforced with woven fibers, and attaching the toroids to each other and to the centerbody with structural straps. The main design change of the second-generation structure is the replacement of IRVE-3's Kevlar fibers, which could only handle brief exposure to a 250C environment before losing performance, with Zylon fibers that maintain usable strength at 400C. The higher temperature tolerance of the structure permits a similar increase in the TPS aft surface temperature, allowing use of a thinner TPS layup.

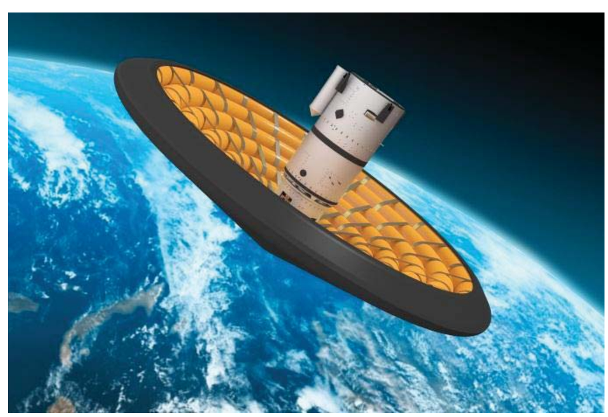

Fig. 2: THOR Reentry Vehicle

The second-generation TPS likewise maintains the overall configuration but changes to higher-performance materials. IRVE-3 used high-temperature Nextel fabric over Pyrogel insulation, while THOR uses higher-temperature silicon carbide fabric over carbon felt insulation. The higher temperature capability of the materials results in a TPS with higher heat flux tolerance, which has been confirmed in numerous ground tests.

All of the second-generation materials maintain compatibility with the traditional HIAD approach of hard-packing the materials into a small volume for launch, then deploying them to the reentry configuration in flight.

Separation from the Antares second stage in low Earth orbit requires a major hardware change from previous HIAD missions: the addition of de-orbit capability. Achieving that will require the addition of rocket motors to the existing flight hardware, along with the associated ignition circuitry and safety lock-outs. Current candidates for THOR flight use include two STAR 6B solid rockets in storage at Wallops Flight Facility and a pair of modified US Navy SR-121 JATO (Jet-Assisted Take Off) solid rockets. These motors will be attached to the outside of the THOR shroud, a structural support around the packed aeroshell that resembles the IRVE-3 sounding rocket nosecone. Since THOR launches inside the Antares payload fairing, the shroud is not aerodynamically necessary, but must still be present to brace the packed aeroshell against launch loads. The shroud provides a convenient mounting structure for the de-orbit motors.

The THOR ACS performance needs to be increased since the system is orienting the vehicle not only for reentry but also for the de-orbit burn, and also to handle the increased vehicle mass. While the ACS hardware has already been fabricated, it is fortunately possible to replace the typical Argon thruster gas with Freon. Freon has been previously used with this ACS hardware for launches from White Sands, NM, and is dense enough to significantly increase the ACS performance. The increased performance should give the ACS enough total impulse to perform the THOR maneuvers without additional hardware modifications.

THOR must also be spin-stabilized for the de-orbit burn, and de-spun before reentry. Rather than add these tasks to the ACS requirements, current plans call for using a pair of small solid rockets to perform each task. Solid motors in this size range are currently being tested by Wallops for flight use on an upcoming mission, and should be well-characterized by the time they are needed for THOR. These motors will be mounted on the aeroshell shroud near the de-orbit motors.

The inflation system must likewise be modified since the THOR inflatable structure will contain eight toroids instead of the seven used for IRVE-3. The inflation lines and pressure sense lines must be reconfigured, as well as the connecting lines that allow pressure to equalize among the toroids. The current HIAD structural analysis indicates that the inflatable structure will only require 105KPa (15psi) to resist the reentry deceleration loads; this will not require a change to the inflation system logic, as it was designed to allow adjustment of the set point. Flow analysis indicates that, with a leak rate in the inflatable structure no worse than that seen during IRVE-3, the 21MPa (3000psi) pressure tank at the center of the inflation system carries enough nitrogen to inflate the aeroshell and maintain the desired pressure through reentry.

Launching as a secondary payload puts the THOR reentry trajectory well outside the VA-Capes test range which tracked the earlier missions and recorded their flight data transmissions. Current splashdown calculations, based on uncertainties in the launch trajectory and the de-orbit burn, produce a splashdown footprint that is relatively narrow but is over 4,000km long. The Antares cargo flights to ISS launch approximately every six months, heading south-east from Wallops Island, and reentry as early as possible results in splashdown in the South Atlantic; later reentries result in splashdown in the South Indian Ocean, on an arc from offshore the south-east coast of South Africa to nearly the west coast of Australia. Most of this area lacks local ground stations for tracking and telemetry, and the sheer size of the footprint makes it impossible to cover the reentry corridor using a few pre-positioned ship-based assets.

While some real time RV position and orientation data will be reported via satellite, given our available power the full flight data set is simply too large to use this approach for all of it. Aeroshell pressure and thermal measurements, engineering performance data, and the four flight video streams will instead be recorded in flight on a buoyant, hardened, solid state recorder. The RV will sink after splashdown, so the recorder will be ejected sideways by the descending RV at low altitude and will begin reporting its GPS coordinates via satellite to assist in post-flight recovery. Current plans call for using an aircraft to bring telemetry equipment to the splashdown vicinity, then using the satellite link to command the data recorder to begin high-speed transmission while the aircraft circles nearby. The data recorder will store enough power to keep transmitting its GPS coordinates for months; if severe weather interferes with aircraft operation, recovery operations can wait until the weather clears.

4. PRE-FLIGHT TESTING

Mechanical separation systems will be tested repeatedly during development using mass models of the flight hardware. All THOR subsystems will go through functional and environmental testing to ensure compatibility with flight conditions before integration with the launch vehicle. Ground testing at NASA Langley will be capped by a complete system test of the flight hardware in one of Langley's large vacuum chambers, where the event timer will autonomously run through the mission scenario, commanding the pyrotechnic release of the aeroshell launch restraint cover, inflation to reentry pressure, and movement of the CG offset system.

The time required for inflation to reentry pressure during the vacuum test will be used to adjust the mission timeline so that the inflatable structure will reach full pressure shortly before the 2-sigma earliest start of reentry. The timing will also need correction for zero-G effects; the IRVE-3 inflation tank heater was less effective in flight than during ground testing due to the absence of convective mixing, except during the 20G deceleration pulse where convective mixing was greatly enhanced.

The hardened data recorder will receive thorough environmental testing, including a planned drop test from flight altitude to demonstrate proper functioning through splashdown and data retrieval. The real time satellite data link will also receive additional testing, currently planned to include not only extensive simulations but also a flight test on an Antares launch to confirm proper operation at orbital speeds before use on THOR.

5. FLIGHT INSTRUMENTATION

THOR will carry several dozen thermocouples to measure the thermal performance of the second-generation TPS protecting the inflatable structure. The rigid nose of the RV will be covered by the same TPS material and will likewise carry multiple thermocouples. The nose TPS will also be instrumented with several heat flux gauges and pressure ports, which are possible in this area since the TPS over the rigid nose is not folded during pre-flight packing. Additional thermocouples will monitor the centerbody surfaces, and the aft surface of the inflatable structure.

Low data rate GPS information sufficient for initial trajectory reconstruction and aeroshell drag performance estimates will be transmitted via the real time satellite link once THOR separates from the Antares second stage. Higher frequency GPS data will be stored on the recorder, along with data from the on-board inertial measurement unit and accelerometers, to permit a higher resolution trajectory analysis once the data is retrieved. Engineering performance data including inflation pressures, position of the CG offset system, power system voltages and current draws, and ACS actions are likewise stored in the recorder.

Video from the four cameras near the aft edge of the centerbody will also be recorded, providing 360deg coverage of the aeroshell as it deploys, inflates to full pressure, and deflects under reentry loads. Movement of the CG offset system will be visible in the video as a lateral shift of the aeroshell relative to the aft portion of the centerbody.

6. FUTURE PLANS

Authority to Proceed with THOR is anticipated by the start of fiscal 2015. Potential future uses of HIAD technology include delivery of more massive payloads to the Mars surface at higher altitudes than possible with a rigid capsule, and Earth reentry protection for valuable hardware that currently burns up in the atmosphere, such as launch vehicle engines or ISS hardware too large to fit inside the existing Soyuz or Dragon capsules.

7. REFERENCES

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