# FLIGHT PERFORMANCE OF THE INFLATABLE REENTRY VEHICLE EXPERIMENT 3


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## ABSTRACT


The Inflatable Reentry Vehicle Experiment 3 (IRVE-3) launched July 23, 2012, from NASA Wallops Flight Facility (WFF) on a Black Brant XI suborbital sounding rocket and successfully performed its mission, demonstrating the survivability of a hypersonic inflatable aerodynamic decelerator (HIAD) in the reentry heating environment and also illustrating the effect of an offset center of gravity on the HIAD's lift-to-drag ratio. IRVE-3 was a follow-on to 2009's IRVE-II mission, which demonstrated exo-atmospheric inflation, reentry survivability – without significant heating – and the aerodynamic stability of a HIAD down to subsonic flight conditions. NASA Langley Research Center is leading the development of HIAD technology for use on future interplanetary and Earth reentry missions.


## 1. MISSION DESCRIPTION

IRVE-3 performed its required mission flawlessly. The Black Brant XI launch vehicle accurately delivered the payload to the desired trajectory, the yo-yo de-spin mechanism eliminated the launch-stabilizing rotation, and the launch vehicle separated cleanly from the payload. The attitude control system (ACS) then stabilized the payload, and the launch vehicle nosecone separated cleanly as well, leaving the reentry vehicle with its hard-packed inflatable aeroshell to coast through an apogee of 469km. The aeroshell launch restraint cover was pyrotechnically released, and the inflation system inflated the aeroshell from the on-board high-pressure nitrogen tank; the inflation system maintained the aeroshell at full pressure through reentry and into descent. The ACS accurately aligned the vehicle for reentry, and also minimized roll motion during reentry and descent. The center-of-gravity (CG) offset mechanism introduced a lateral CG offset just prior to reentry, to demonstrate the effect of the resulting lift vector on the reentry vehicle trajectory. Reentry heat flux reached a peak of 14.4 W/cm$^2$, and reentry deceleration reached 20.2G's, which the TPS and inflatable structure handled as planned [1]. Performance data from the entire flight was telemetered to the ground in real-time for later analysis. All mission success criteria, both minimum and comprehensive, were successfully met.

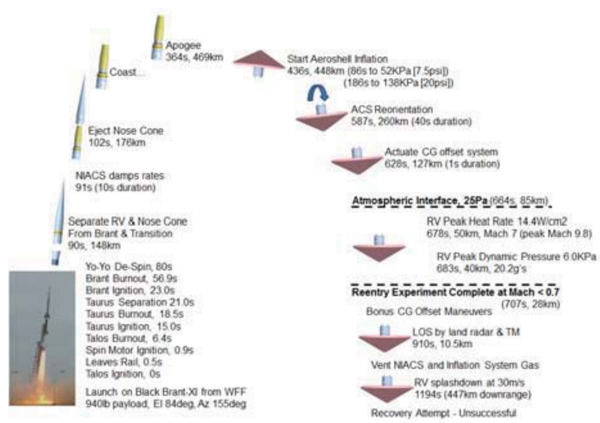


Fig. 1. IRVE-3 Mission Events

After the reentry experiment was complete, the CG offset mechanism performed four "bonus" maneuvers, providing additional data on the dynamic response of the aeroshell to changes in CG position. Recovery of the vehicle after splashdown was also attempted, but unfortunately the reentry vehicle had sunk before the recovery boat was able to reach it.

## 2. REENTRY VEHICLE DESCRIPTION

IRVE-3 inflated to the same 3m diameter 60° cone, with the same general configuration, as the earlier IRVE-II mission [2]; however, it represented a significant step forward in both vehicle design and the test environment. The inflatable structure was redesigned to handle increased loads while reducing the leak rate. As shown in Fig. 2, the inflatable structure kept the stacked-toroid approach, but added individual structural straps connecting the toroids to each other and to the centerbody.

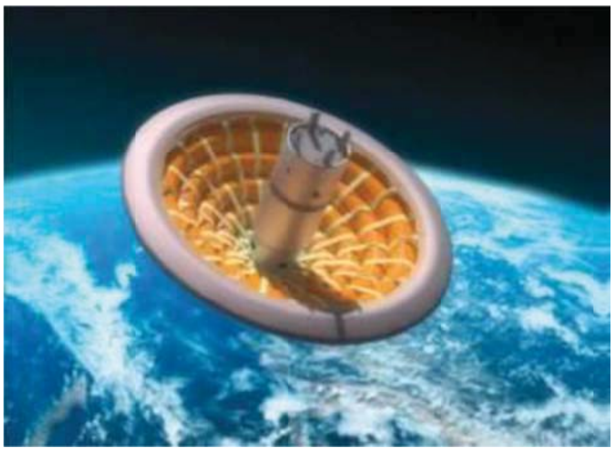

Fig. 2. Artist Rendering of IRVE-3 Reentry

The thermal protection system (TPS) was upgraded from the layered Nextel fabric used on IRVE-II to a multi-layer system able to handle flight-relevant heating levels. The new TPS covered not only the forward surface and shoulders of the inflatable aeroshell but also covered the rigid nose of the centerbody, allowing installation of enhanced sensors in the nose TPS, since that portion of the TPS did not get folded while being packed for launch. As shown in Fig. 3, the centerbody still houses the inflation system and telemetry module (TM), but also contains the new CG offset mechanism and the ACS. These additions resulted in a heavier reentry vehicle, which combined with the more energetic launch vehicle to increase the reentry heat flux.

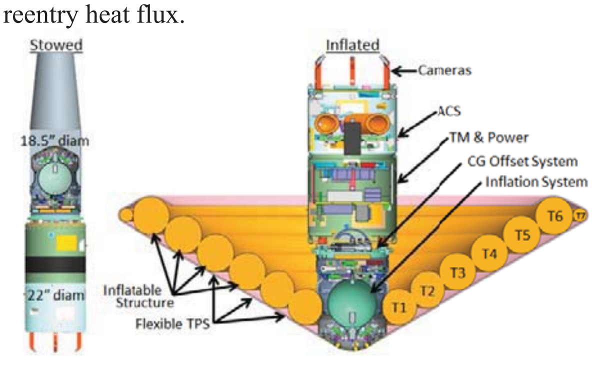


Fig. 3. Reentry Vehicle Cross-Section

## 3. INFLATION OF THE AEROSHELL

As shown in Fig. 3, the inflatable aeroshell was packed for launch in a roughly conical shape inside the launch vehicle nosecone. The volume allocated for the packed aeroshell was $7966in^3$; vacuum bagging and mechanical massaging during the packing process compressed the aeroshell down to $5994in^3$, for an as-packed density of $39lb/ft^3$. The forward end of the packed aeroshell was supported by a cup attached to the axial air spring inside the nosecone. After separation of payload from the launch vehicle, the air spring pushed the nosecone clear of the reentry vehicle.

The start of inflation during flight was timed so the aeroshell would reach its full 20psi before the start of reentry, even on the $2\sigma$ lowest-and-fastest trajectory. The inflation system performance had been verified during rigorous ground testing, including autonomous filling of the flight aeroshell in a Langley test facility depressurized to 0.3psi to simulate flight conditions, and performance in flight was essentially the same as predicted. Since the launch vehicle performance was very close to the nominal predictions, the aeroshell reached full pressure in flight approximately 40 seconds before the start of reentry. The IRVE-3 system had been upgraded from the IRVE-II blow-down design to include an actively controlled electromechanical valve that allowed gas flow to be shut off once the aeroshell was inflated, conserving the remaining gas for use later in the mission. As the atmospheric pressure increased during descent, the valve was adjusted to keep the aeroshell pressure at the desired 20psi above ambient conditions. Later in the trajectory, as the vehicle neared the point where it would lose radio contact around the curve of the planet, the valve was fully opened to vent the remaining nitrogen so the post-flight recovery crew would not need to handle pressurized systems.

Another inflation system enhancement was the addition of a heater inside the 3000psi nitrogen tank. During inflation of the aeroshell, gas pressure in the tank dropped, with a resulting drop in gas temperature that lowered the pressure even more; the heater warmed the remaining gas, raising the pressure so that more of the nitrogen was usable. The loss of convection during the zero-G portion of the flight produced an unexpectedly large decrease in heater performance; however, the enhanced convection during the 20G reentry deceleration pulse enhanced performance, resulting in slightly higher tank pressure at the end of the reentry experiment than had been predicted. There was approximately 1100psi remaining in the inflation tank at the end of the reentry experiment, and approximately 500psi by the time the vent command was issued at 11km altitude, 892sec after launch.

## 4. ATTITUDE CONTROL

The ACS used for the IRVE-3 mission was the NIACS (NASA Sounding Rocket Operations Contract (NSROC) Inertial ACS), which has a long heritage of successful use on sounding rocket flights. It performed exactly as intended, meeting all ACS mission requirements [3]. After the yo-yo de-spin of the launch vehicle, the ACS damped lateral motion and the remaining roll before the axial release of the nosecone. The unfolding and inflation of the packed aeroshell imparted additional motion to the reentry vehicle, which the ACS damped out as part of the orientation for reentry. The reentry orientation was timed to start after the aeroshell had inflated to half pressure (10psi) so that the aeroshell could be maneuvered as a rigid body; the timing also ensured that the reorientation would be complete before the start of the $2\sigma$ earliest reentry. During reentry the ACS shifted from 3-axis mode to only damp roll motion, to keep the lift vector pointed up and demonstrate the trajectory effects of the CG offset, while allowing the aerodynamic performance of the vehicle to control pitch and yaw.

The ACS thrusters were fed from two 5000psi argon tanks; at the end of the reentry experiment, half of the available ACS gas still remained. The ACS roll thrusters provided 11.4lbs thrust, but only operated at 50% duty cycle during the peak aerodynamic disturbance, demonstrating more than adequate performance margin. Like the inflation system, the ACS vented its pressure tanks before splashdown.

## 5. CG OFFSET

The CG offset mechanism allowed IRVE-3 to launch with its CG on the axis of the launch vehicle, as required for launch stability, but reenter with the CG shifted to one side to produce a lift vector. Such a lift vector is typically used to steer a reentry vehicle toward a desired landing site, but IRVE-3 kept the vector fixed during reentry to measure the effect of the known lift vector on the trajectory of the inflatable. The CG offset mechanism used a DC motor to laterally shift the aft portion of the centerbody, about half the reentry vehicle mass, relative to the inflation system and the inflatable aeroshell. A set of eight roller bearings kept the halves of the centerbody aligned relative to each other, and a pair of string potentiometers measured the lateral translation of the mechanism during flight. Previous mass-properties tests had measured the vehicle CG as a function of mechanism displacement.

After the reentry experiment concluded, the CG offset mechanism shifted the vehicle CG four more times to provide data on the dynamic response of the vehicle trajectory to changes in the CG location. The inflatable aeroshell was shown to respond no differently than a traditional rigid vehicle.

## 6. TRAJECTORY RECONSTRUCTION

The NIACS system included an inertial measurement unit (IMU), and the TM included a global positioning system (GPS) receiver; an independent set of accelerometers was also flown, and the reentry vehicle was tracked as well by five ground radar stations. These and other flight data were used to reconstruct the as-flown trajectory [4] as closely as possible, to confirm the flight environment and evaluate the resulting heat flux. Numerous computational fluid dynamics models were used to calculate the effective heat flux on the vehicle TPS at different points in the trajectory.

The CG offset mechanism's lateral shift before reentry provided an unexpected clean set of structural vibration data. With the vehicle free-falling in a vacuum, the shift triggered structural vibrations which were measured by the IMU, allowing confirmation of the reentry vehicle's first vibration mode.

While most of the trajectory followed the expected smooth deceleration curve, there was a notable exception at about 46km altitude, when deceleration dropped from 16 to 14.5G's for approximately 100ms. This event showed up as a small dip in the data from each of the multiple independent sensors monitoring the trajectory. The flight video shows no corresponding jump in the inflatable aeroshell, indicating that the change was not a result of a shift of the aeroshell structure. Our best estimate of the cause would be a small pocket where atmospheric density has decreased by 11%; such pockets are not included in the traditional atmospheric models, but have been observed on space shuttle missions [5]. This unexpected event also triggered structural vibrations, allowing confirmation of the first vibration mode with the structure loaded in flight.

## 7. THERMAL PERFORMANCE

The IRVE-3 TPS consisted of two layers of high-temperature Nextel fabric covering Pyrogel insulation and a Kapton/Kevlar thin film gas barrier. Numerous thermocouples were embedded in the flexible TPS in between the various layers, for measurement of in-flight temperatures for post-flight performance analysis. The TPS covering the rigid nose of the centerbody did not need to fold up for launch, so it was possible to add additional sensors without them being damaged, or causing damage, during packing of the aeroshell for launch. Five heat flux gauges and five pressure ports were added to the nose TPS, in addition to the existing thermocouples.

The nose heat flux gauges provided flight data that closely matched the heat flux calculations from the trajectory reconstruction effort. The flight thermocouples, however, measured a peak temperature of 387C, much lower than expected. This was eventually traced to the large size of the flight thermocouple beads, which gave them enough thermal mass to slow their response to the surrounding environment. Since the reentry heat pulse was a fairly rapid transient, the flight thermocouples missed the peak temperatures. This effect was exacerbated by the thermocouples being embedded in layers of insulating fabric, whose low thermal mass put less energy into the thermocouples than a typical piece of rigid structure. Final thermal analysis results closely matched the flight temperature data, and the project generated a list of sensor recommendations to avoid these difficulties in the future.

Thermocouples on the aluminum skin of the centerbody provided temperature data from launch through reentry and loss of signal. The skins of the ACS and TM, which formed the outer surface of the launch vehicle and were thus exposed to aerodynamic heating during ascent, reached 140-150C before beginning to radiatively cool once the vehicle reached space. They continued to cool through reentry and descent, indicating that the inflated aeroshell protected the centerbody from significant reentry heating. The thermocouple in the center of the camera deck, on top of the centerbody, stayed at room temperature during launch since it was shielded from ascent heating by the skin of the launch vehicle's transition module. It began warming up about 200 seconds into the mission, from direct solar heating in combination with the video processing electronics mounted to the camera deck; by the end of the mission the camera deck had reached 50C. The thermocouple attached to the inflation system skin, on the inside of where the inflatable aeroshell connected to the centerbody, stayed essentially at room temperature throughout the entire flight.

## 8. CONCLUSIONS

The IRVE-3 reentry vehicle demonstrated that inflatable vehicles with flexible TPS can survive reentry with flight-relevant heating, and that an offset CG can be used to steer an inflatable vehicle as is done with rigid reentry bodies. All vehicle systems worked extremely well, and the authors would like to thank all of those involved in IRVE-3 for their long hours and dedication.

Development work conducted under Langley's HIAD project has advanced the capabilities of flexible TPS; current materials can tolerate more than three times the heat flux seen by IRVE-3 [6], and progress continues to increase that level. Several proposals are underway for future HIAD demonstration missions involving reentry from Earth orbit.

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