FLIGHT PERFORMANCE OF THE INFLATABLE REENTRY VEHICLE EXPERIMENT II

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ABSTRACT

The Inflatable Reentry Vehicle Experiment II launched August 17, 2009, from NASA Wallops Flight Facility. The three mission objectives were to demonstrate inflation and re-entry survivability, assess the thermal and drag performance of the re-entry vehicle, and to collect flight data for comparison with analysis and design techniques used in vehicle development. The flight was a complete success, with the re-entry vehicle separating cleanly from the launcher, inflating as planned, and demonstrating stable flight through re-entry and descent while on-board systems telemetered video and flight performance data to the ground.

1. INTRODUCTION

The Inflatable Reentry Vehicle Experiment II (IRVE-II) launched August 17, 2009 [1], from Wallops Flight Facility on a Black Brant IX sounding rocket [2]. After burnout of the launch vehicle's upper stage, the reentry vehicle was successfully released from the payload shroud and separated cleanly from the launch vehicle nose cone telemetry module. The reentry vehicle reached an apogee of 218km, and inflated as intended to its reentry configuration. The spin-stabilized vehicle demonstrated stable flight throughout reentry (80km to 40km) and descent, reaching a maximum dynamic pressure of 1180Pa at 56km altitude and a peak stagnation heating of 2.20 W/cm2 at 45km altitude. The internal nitrogen bottle maintained inflation pressure above ambient conditions until it was exhausted at 15km. In-flight telemetry of sensor and video data, along with ground tracking data, allowed a thorough reconstruction of the IRVE-II flight and thermal analysis of the reentry performance. Several future flights are anticipated.

2. SYSTEM DESCRIPTION

The IRVE-II reentry vehicle consisted of a conical inflatable aeroshell attached at the leading edge of a rigid cylindrical centerbody. In launch configuration the deflated aeroshell was packed around the centerbody, and was restrained with a soft fabric cover with an outer diameter of 0.419m (16.5in). After separation from the launch vehicle and removal of the fabric restraint, the aeroshell was inflated to its reentry configuration of a 60 degree sphere-cone, with an outer diameter of 2.93m (115in). Reentry vehicle mass, after removal of the restraint, was 124.6kg.

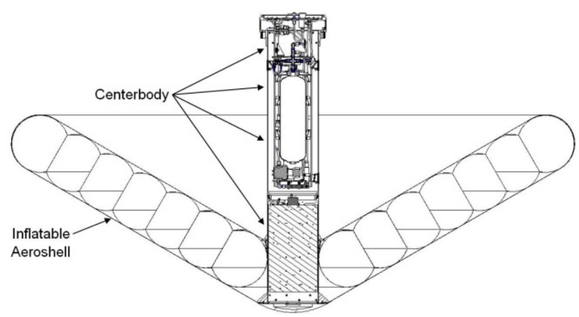

Fig. 1. The inflated aeroshell.

The inflatable aeroshell used a multi-layer design, with outer layers of high-temperature fabric protecting the internal structure. The forward surface was composed of three layers of Nextel 312 AF-14 fabric, followed by three layers of Kapton film as a gas barrier. The aft surface, with its lower heating environment, used one layer each of the same materials. The internal structure was composed of seven pressurized toroids of silicone-coated Kevlar fabric, covered by two layers of uncoated Kevlar fabric for additional strength.

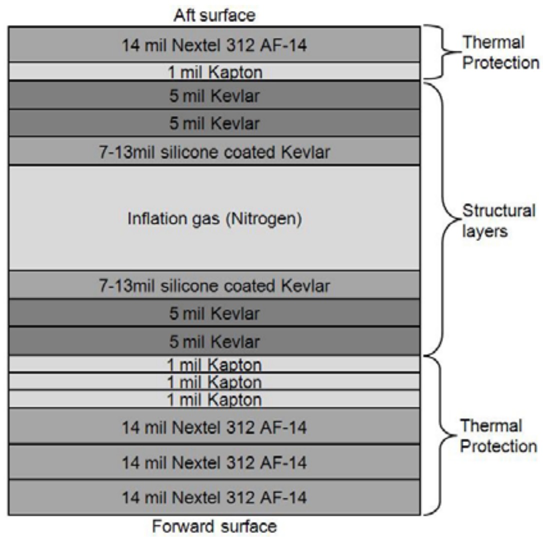

Fig. 2. The aeroshell layup.

The centerbody was an aluminum cylinder 0.273m (10.75in) in diameter by 1.58m (62.2in) tall, housing the flight electronics and the inflation system. The flight electronics included an event timer operating on a pre-programmed timeline; sensors for thermal, pressure, and attitude data; video cameras to observe deployment and reentry; and a data system with an S-band transmitter to relay the flight data to ground stations. The inflation system, once initiated by the event timer, used mechanical regulators to control the flow of nitrogen gas from a 20.7MPa (3000psi) storage bottle to the inflatable aeroshell. The inflation system initiation was timed to raise the aeroshell pressure to at least 10.3KPa (1.5psi) by atmospheric interface, based on thorough ground testing including a complete system deployment test inside NASA Langley Research Center's 16m vacuum sphere.

The IRVE-II mission was a reflight of the original IRVE design, which launched September 6, 2007, on a Terrier Orion sounding rocket. The IRVE launcher failed to release the reentry vehicle from the launch shroud, so the flight provided no data on the performance of the inflatable reentry vehicle. IRVE-II used an inflatable aeroshell built to the original IRVE design, with some modifications to the reentry vehicle electronics due to hardware availability. The launch vehicle shroud size was increased to provide additional deployment clearance, requiring use of a more capable launcher, and the launcher was ballasted to limit the reentry heating, since the inflatable aeroshell was not re-designed to be compatible with the full performance of the larger rocket.

The mission objectives of IRVE-II were essentially the same as the original IRVE mission: to execute a flight test that demonstrates the inflatable aerodynamic decelerator inflation and reentry survivability; to assess the thermal and drag performance of the inflatable reentry vehicle; and to collect flight data for comparison with the analysis and design techniques used in the development of the inflatable reentry vehicle. All mission objectives and mission success criteria were successfully accomplished on the IRVE-II flight.

3. INFLATION SYSTEM PERFORMANCE

The inflation system used two pyrotechnic valves to isolate the high-pressure bottle from the rest of the system through launch and release from the launch vehicle shroud. Once opened by the event timer, the pyrotechnic valves allowed nitrogen to flow through the two mechanical regulators controlling the flow from the bottle into the 34KPa (5psi) manifold that fed the aeroshell inflation lines. The system was designed to pressurized the aeroshell to 10.3KPa (1.5psi) by atmospheric interface, with a maximum pressure of 24.1KPa (3.5psi) over ambient during descent. System components were individually tested before assembly, and system performance was measured during ground testing before and after the assembly-level vibration test. During inflation system performance tests, the inflation lines were fed into a small vacuum chamber to simulate the flight environment. Later, during the complete system test, the aeroshell was packed in its launch configuration and the entire reentry vehicle was placed inside a large vacuum chamber, and the system was operated autonomously as if in flight. All systems operated as desired during the final complete system test; the event timer followed its programmed timeline, releasing the aeroshell restraint cover and opening the pyrotechnic valves at the specified times. The aeroshell deployed to its reentry shape within a few seconds and inflated as planned to the desired reentry pressure.

The inflation system performance measured during the complete system test, combined with the calculated minimum trajectory time to the start of reentry, was used to set the inflation start time programmed into the even timer [3]. Since the gas flow was initiated with single-use pyrotechnic valves, flow could not be halted when the aeroshell reached reentry pressure. Inflation to reentry pressure was therefore timed to closely precede the start of reentry, to minimize the amount of inflation gas vented through the relief valves.

The in-flight performance of the inflation system closely matched that seen in ground testing. Inflation of the aeroshell began on command 297sec after launch, and all toroids reached the specified 10.3KPa (1.5psi) 92sec later, 27sec before the start of reentry. The inflation system maintained pressurization of the aeroshell through the reentry pressure and heat pulses, and continued to maintain pressure over ambient until the pressure bottle was exhausted at 680sec, at an altitude of 15km. Video from the on-board cameras showed the inflatable aeroshell maintained its conical shape until 858sec, at an altitude of 8km, when it folded inward against the centerbody.

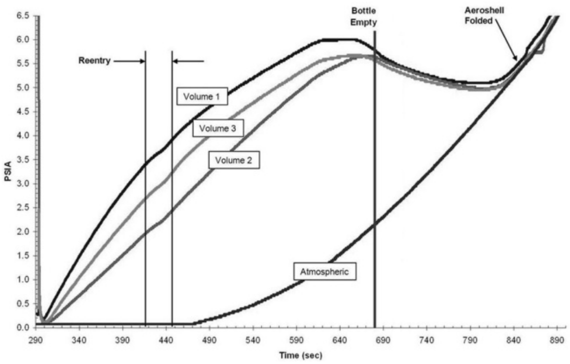

Fig. 3. Pressure vs time.

4. TRAJECTORY RECONSTRUCTION

The IRVE-II reentry vehicle was tracked in flight by multiple ground radars. On-board sensors provided three-axis acceleration and roll rates, and also magnetometer and sun angle data. These data were combined to produce vehicle position and orientation time histories. Meteorology rockets launched before and after the IRVE-II flight provided atmospheric density, pressure, temperature, and horizontal wind profiles from 30km to 92km altitude, which were used for aerodynamic performance calculations.

While pre-launch analyses had predicted a nominal apogee of 212km, launch vehicle performance exceeded nominal values by roughly one sigma, producing a reentry vehicle apogee of 218km. This more energetic trajectory, combined with the day-of-flight atmospheric conditions, increased the reentry velocity, dynamic pressure, and peak heating. The pre-flight nominal trajectory showed a maximum Mach number of 5.5; the post-flight reconstruction peaked at Mach 6.2. The pre-flight nominal trajectory showed a maximum dynamic pressure of 1040Pa; the post-flight data showed 1180Pa, with a maximum deceleration of 8.5G's. The pre-flight nominal trajectory showed a peak heating of 1.97W/cm2; the post-flight analysis showed a peak of 2.20W/cm2.

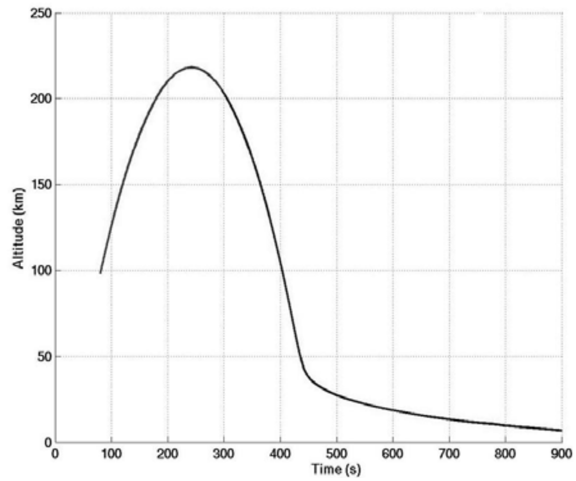

Fig. 4. Altitude vs time.

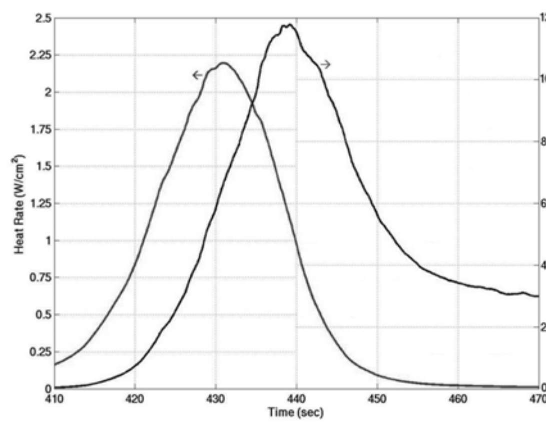

Fig. 5. Heat rate and dynamic pressure vs time.

The inflation of the aeroshell had been predicted to perturb the vehicle orientation only slightly, and the flight trajectory confirmed the prediction. When released from the launch vehicle, the reentry vehicle was spinning at 3.5Hz; when the aeroshell inflated, the spin rate dropped to 0.16Hz, and stabilized within 2sec. When released from the launch vehicle, the tip-off rate was 1.2deg/sec, well below the required 6.7deg/sec; when the aeroshell inflated, the tip-off rate increased to 5.3deg/sec, still inside the requirement and with most of the time until reentry already covered.

Total angle of attack was oscillating between approximately 14deg and 22deg at the start of reentry, and then rapidly decreased oscillations to between 5deg and 9deg through peak pressure and heating. The reentry vehicle demonstrated stable flight throughout reentry and descent, until the vehicle folded under the increasing external pressure.

The preflight nominal trajectory predicted splashdown 145km downrange. The reentry vehicle was tracked by ground radar until loss of signal 1046sec after launch, at an altitude of 2km; at that point the trajectory was almost straight down, pointed toward a splashdown 167km downrange and 17km crossrange.

5. THERMAL PERFORMANCE

The IRVE-II mission was a sub-orbital test flight, and did not reach the reentry heating levels of orbital missions. However, the inflatable aeroshell was instrumented with thermocouples to provide flight temperature data to correlate the thermal models. Eighteen "surface" thermocouples were placed behind the forward layer of Nextel fabric, and six "in depth" thermocouples were placed between the Kapton gas barrier and the Kevlar structure. The thermocouples were located in four rings at 0.21m, 0.62m, 1.04m, and 1.45m from the vehicle centerline. The hot wall thermal analysis applied a margined heat flux to the vehicle as a function of time, position, and local surface temperature. The conservative thermal model predicted that a two sigma high trajectory would raise the surface temperature during reentry to roughly 200C at the inner ring of thermocouples, and to approximately 80C at the outer ring on the shoulder of the inflatable.

The flight thermocouple data varied considerably, but largely confirmed that the analysis models had been conservative. The innermost ring of thermocouples was apparently shielded by the edge of the Teflon nose cap; the highest temperature seen in flight by these six thermocouples was 100C, only half of the predicted value. At the 0.62m ring, two of the three thermocouples showed a reasonable match with predictions, rising to 120C and 140C out of the predicted 150C and following the shape of the predicted curve; the third sensor, however, appears to have been in thermal contact with the vehicle structure, as it closely followed the temperature of the gas-filled toroids. At the 1.04m ring, one of the thermocouples closely matched the predicted temperature profile; however, four others stayed below half of the predicted values, and the sixth sensor appears to have been bent forward against or through the surface fabric, as its peak temperature was approximately 60C higher than predicted. The outer ring showed a reasonable match with predictions, rising to between 55C and 75C out of the predicted 80C.

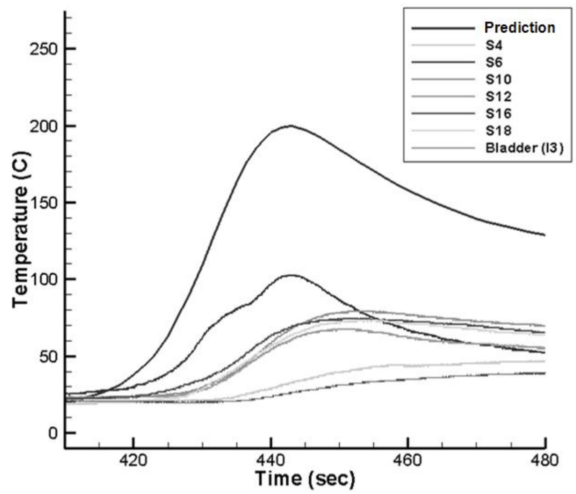

Fig. 6. 0.21m thermocouple ring.

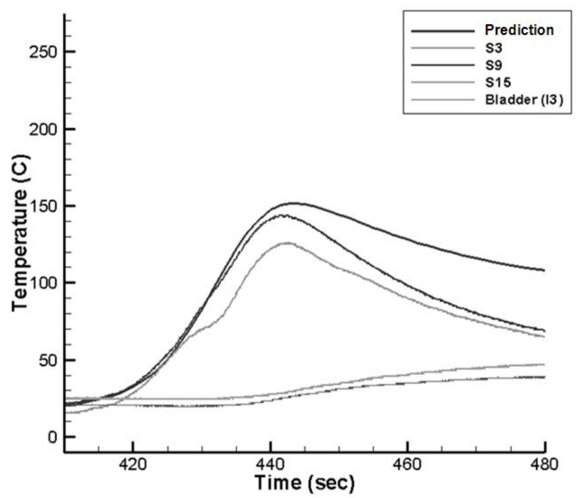

Fig. 7. 0.62m thermocouple ring.

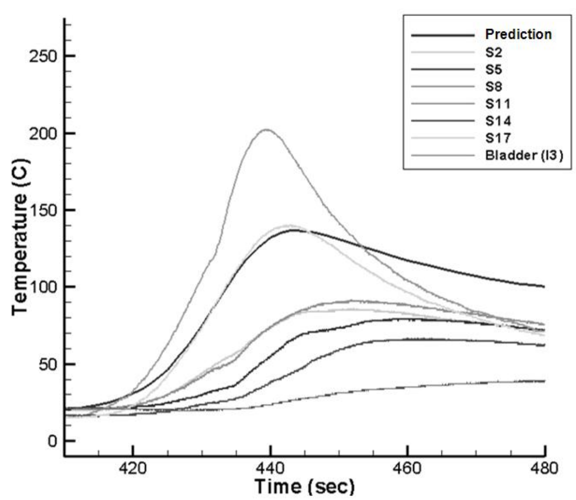

Fig. 8. 1.04m thermocouple ring.

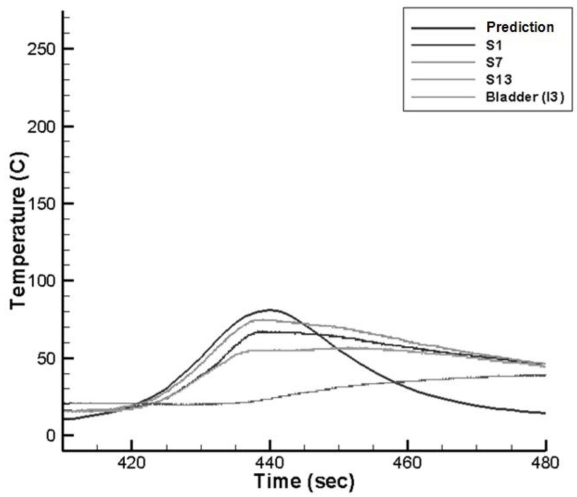

Fig. 9. 1.45m thermocouple ring.

Some of the temperature differences could also be due to differences in thermocouple placement. While the thermocouple positions were specified on the interface control drawings, the location of fabric seams were not; some thermocouples were potentially located next to seams in the fabric, where the additional thermal mass could reduce the flight temperatures.

6. FUTURE PLANS

IRVE-II demonstrated the survivability and acceptable flight dynamics of inflatable aerodynamic decelerators, corroborating methods and design principals used in IRVE-II flight dynamics and aerothermal analyses. Future flights will be needed to test the technology at higher reentry heat rates and at larger scales, for eventual use with reentry and descent of larger payloads.

IRVE-3 is planned for launch in spring 2012 on a Black Brant XI three-stage sounding rocket, with the mission objective of increasing the IRVE-II peak heat flux by a factor of five to ten. Reentry vehicle improvements envisioned for IRVE-3 span the range of on-board systems. The aeroshell structure and thermal protection will be improved using designs developed and tested in parallel with the IRVE-II project. The inflation system will include a re-sealable control valve, to reduce the inflation gas lost through the pressure relief valves. An attitude control system will be added to remove IRVE-II's reliance on passive aerodynamics, and the associated inertial measurement unit will provide more accurate trajectory and attitude data. Additional thermal sensors will be used, with heat flux gauges on the rigid nose of the vehicle and thermocouples secured between the layers of the inflatable aeroshell, far from seams in the fabric.

7. REFERENCES

1. IRVE-II Post-Flight Analysis Review, November 2009.
2. *NASA Sounding Rocket Program Handbook*, 810-HBK-SRP, June 2005.
3. IRVE-II Mission Timeline, IRVE-II-0018E, August 2009.