AIAA SPACE 2012 Conference & Exposition
11 - 13 September 2012, Pasadena, California

AIAA 2012-5271

Reentry Breakup Recorder: Concept, Testing, Moving Forward

Michael A. Weaver* and William H. Ailor†
The Aerospace Corporation, El Segundo, CA, 90245

Decommissioned satellites and spent rocket stages routinely reenter the atmosphere from low-Earth and low-perigee orbits. Though seldom recovered, debris of significant size and mass survive to ground impact. Reentry survivability models are intended to predict these hazards in advance of launch and reentry, but models have tended to under-predict the survivability, relative to observable data and recovered debris. In order to improve and validate models, a growing need developed for more information on the environment and response of unprotected reentering bodies. The Aerospace Corporation conceived a new device that would collect data during the reentry and breakup of a satellite or launch stage, would protect the data through the severe heating and loading phases, would break away as the host vehicle disintegrated, and would transmit the recorded data before ground impact, eliminating any need for hardware retrieval. The Reentry Breakup Recorder (REBR) was successfully flight tested in 2011 during reentry of the Japanese HTV2 supply vehicle from the International Space Station. An overview is provided of the motivation for REBR, its design, the data from the HTV2 flight test, the future evolution of REBR, and the technology transition approach.

I. Introduction

Since the beginning of the space age, human-made objects have been reentering the atmosphere. Initially, models predicted that major reentry breakup events occurred at high altitudes, resulting in predictions that most debris would not survive reentry and that debris that did survive would impact over very long ground footprints. Measurements made during actual reentries in the 1970s showed that breakup altitudes were much lower than predicted, that ground footprints were much shorter than previously estimated (a finding of much interest to mission planners), and that large numbers of debris fragments, some large enough to be hazardous to people and property, could survive. In 1997, the latter point was emphasized when a 250 kg (570 lbm) stainless steel propellant tank landed near a farmer's home in Texas. As efforts to mitigate the growing population of space debris encourage the removal of satellites and launch stages from orbit at end of mission, accurate estimates of hazards to people and property became more important. As a result, there was a growing need for more information on the environment faced by these unprotected reentering objects and the response of these objects to that environment.

In the early 2000s, a new device[1] was conceived by The Aerospace Corporation (Aerospace). Dubbed the Reentry Breakup Recorder (REBR), the device would collect data during the reentry and breakup of a satellite or launch stage, would protect the data through the severe heating and loading phases, would break away as the host vehicle disintegrated, and would transmit the recorded data before impact. After ten years of low level research and development, the first reentry flight tests took place in 2011. Two REBRs were launched on 22 January 2011 to the International Space Station (ISS) from Tanegashima Space Center in Japan aboard the H-IIB launch vehicle. After arrival at the ISS, one REBR was installed on the Japanese HTV2 supply vehicle, and one installed on the European ATV-2 supply vehicle. A pre-launch photo of the REBR installed on HTV2 is shown in Figure 1. Controlled reentry of the HTV2 occurred on 29 March 2011, with that REBR successfully recording and returning data. Controlled reentry of the ATV-2 occurred on 21 June 2011, but that REBR did not return data. A repeat of these flight tests is in progress, with two more REBRs launched to ISS from Tanegashima Space Center on 20 July 2012, intended for reentries aboard HTV3 in late August and ATV-3 in late September. An overview is provided here on the REBR design, the flight test mission, the data returned from HTV2, the future evolution of REBR, and the technology transition.

* Section Manager, Fluid Mechanics Department, 2310 E. El Segundo Blvd., MS M4-965, AIAA Senior Member.
† Principal Engineer, Vehicle Systems Division, 2310 E. El Segundo Blvd., MS M4-961, AIAA Associate Fellow.

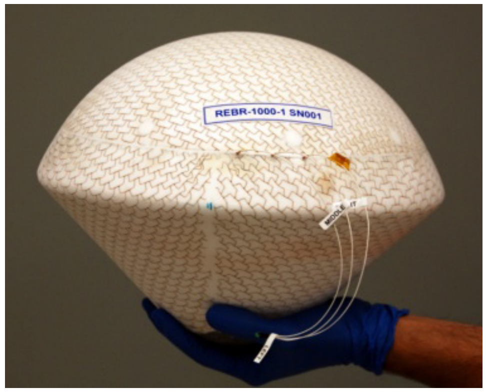


Figure 1. REBR used on HTV2 reentry for first successful flight test.

II. Design and Configuration

The Reentry Breakup Recorder (REBR) is a small, autonomous, battery-powered device that records temperature, acceleration, rotational rate, global positioning system (GPS), and other data related to the reentry of space hardware into the Earth's atmosphere and its subsequent breakup due to aerodynamic heating and loading. As shown in Figure 2, all equipment is contained within a protective heat shield. This assembly attaches to the host vehicle within a protective copper housing and using a custom interface adapter. REBR is designed to release from the reentering host vehicle during the breakup process, fly free, emerge from the copper housing, aerodynamically stabilize, and then uplink recorded data to the Iridium network for downlink to a ground station. Since all recorded data are transmitted before Earth impact, recovery of REBR is not required.

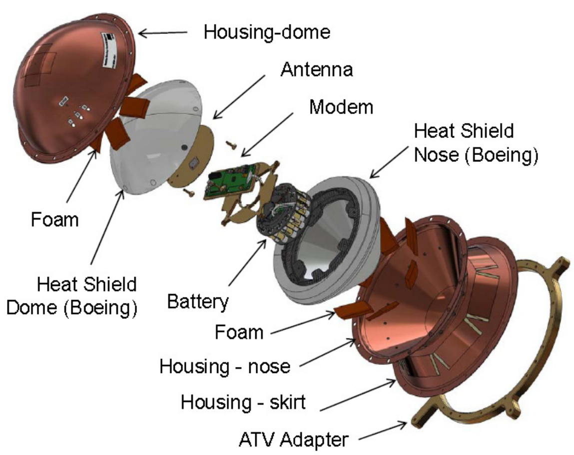


Figure 2. Exploded view of REBR assembly.

A. Aerodynamics

The outer mold line of REBR is based on the NASA Mars Microprobe[2,3]. It uses a 45°-angled forebody, with a nose radius of curvature that is 25% of the maximum diameter D, producing a so-called 4525 blunt cone. The afterbody is a spherical segment. The overall shape is specified in Figure 3. In addition to Refs. 2 and 3, applicable aerodynamic data are also available in Ref. 4. Subsonic wind tunnel testing for REBR was performed at the NASA Ames Fluid Mechanics Laboratory. Data from these tests were used to verify subsonic drag and to determine static stability limits. Computational fluid dynamics simulations at hypersonic conditions were performed at Aerospace to verify high-speed aerodynamics and hypersonic heating environments.

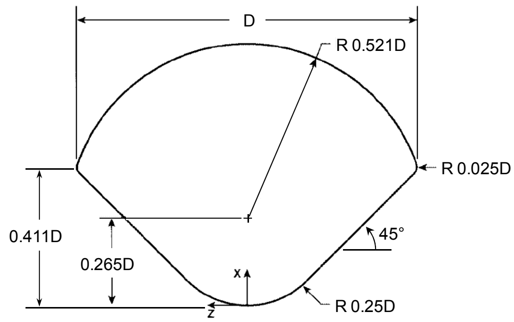


Figure 3. REBR aerodynamic configuration.

With proper placement of the center of mass (CM), the REBR configuration is self-righting and statically stable in hypersonic, supersonic, transonic, and subsonic flight. The CM design envelope enforces a 7° trim limit in subsonic flight, a 10° trim limit in transonic flight, and a 3.5° trim limit in hypersonic flight. These result in an overall envelope with a lateral CM limit of ±1%D from the centerline, and an aft longitudinal limit of 44%D from the nose. Measured values for the HTV2 flight test article were a maximum diameter of 0.310 m (12.2 in), a longitudinal CM of 39.3%D, and a lateral CM offset of 0.3%D. Measured mass (without housing) was 4.44 kg (9.79 lbm), including 0.18 kg (0.40 lbm) of forward ballast. For the ATV-2 article, maximum diameter was 0.310 m (12.2 in), longitudinal CM was 39.8%D, and lateral CM offset was 0.3%D. Measured mass (without housing) was 3.95 kg (8.7 lbm), including 0.45 kg (1.0 lbm) of forward ballast. Mass differences between the two REBRs were due only to variations in heat shield fabrication.

For data uplink to Iridium, REBR needs adequate fall time at terminal velocity with the Iridium antenna pointing to zenith. The minimum design time for uplink is 5 minutes (300 seconds). Likely release altitudes for REBR, due to host vehicle breakup, range from 65 to 85 km. A trajectory parameter study under these conditions shows that a ballistic coefficient of 73 kg/m^2 (15 psf) provides approximately 20% margin in fall time. This result is insensitive to release altitude over the range examined, as illustrated in Figure 4. Additional sensitivity studies showed that a 20% increase in ballistic coefficient would still provide for a 6.7% margin (20 seconds) in fall time. For the HTV2 flight test article, the final nominal subsonic ballistic coefficient was 73.5 kg/m^2 (15.1 psf), based on predicted drag coefficient, measured mass, and diameter. To allow for potential drag uncertainty and mass growth, a subsonic ballistic coefficient of 80.8 kg/m^2 (16.6 psf) was used for planning during fabrication and assembly, providing an additional 10% margin above expected fall time margin. For the ATV-2 article, the final nominal subsonic ballistic coefficient was 65.4 kg/m^2 (13.4 psf). The value including 10% margin for mission planning was 71.9 kg/m^2 (14.7 psf).

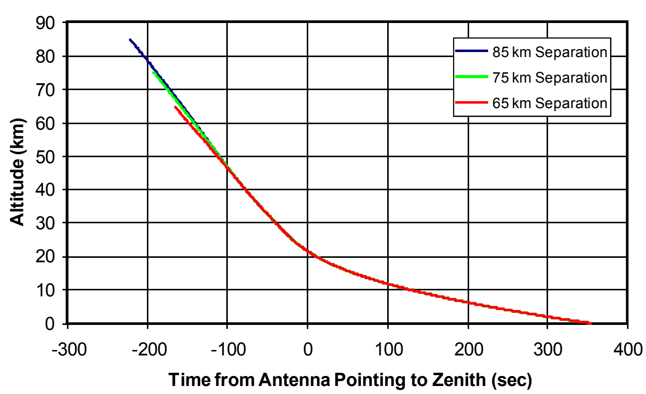


Figure 4. REBR fall time after release from host vehicle for three assumed breakup altitudes.

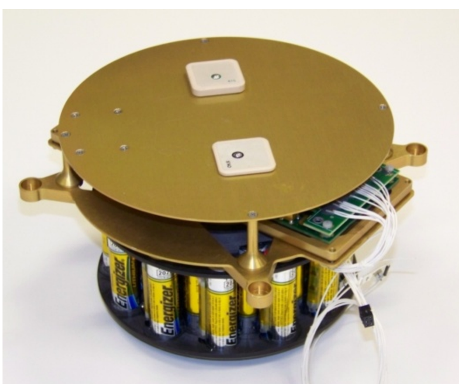
B. Heat Shield

The heat shield protects the interior of REBR from the reentry heating environment, and bears the brunt of any potential external insult during breakup of the host vehicle. It consists of the thermal protection system (TPS) and the aeroshell. The TPS surface serves as the aerodynamic outer mold line, and the aeroshell is the structural support for the TPS. The REBR aeroshell consists of attached fore (windward) and aft (leeward) halves, with a corresponding fore and aft TPS attached to each half. These heat shield assembly halves are shown in Figure 2.

The heat shield was designed and fabricated by The Boeing Company, under contract to Aerospace. Among requirements specified for competitive bids, were that the aeroshell must provide internal load-bearing attachment points for the REBR structural chassis, that the aft heat shield must be radio-frequency (RF) transparent for operation of the onboard Iridium modem and GPS receiver, that the heat shield backface temperature must remain below 400 K (127 ^{o}C or 261 ^{o}F) until ground impact, and that the outer mold line must adhere to the provided geometry (see Figure 3). Mass and peak heating limits were also defined, based on expected reentry trajectories and fall time requirements. Boeing provided a design using BLA-20 (20-pcf density Boeing Lightweight Ablator) material with UltraFlex Honeycomb Core (made by Ultracor, Inc.) for the acreage TPS, Dow Corning 93-104 material for the nose region TPS, a quartz-based composite for the aft aeroshell, and a graphite-based composite for the forward aeroshell. While tapered TPS thicknesses could have been used to reduce mass, uniform thicknesses for the fore and aft TPS were selected to resist debris impact damage and to account for tumbling of REBR before aerodynamically stabilizing, when released from the host vehicle.

C. Structures

All REBR equipment, electronics, and batteries are mounted to a load-bearing chassis. The chassis is divided into a 6061-T6 aluminum aft section and a Delrin 150 forward section, attached at four bolt locations. The full, loaded chassis is shown in Figure 5a, with the aft chassis toward the top of the image. This assembly has a mass of 0.97 kg (2.1 lbm). The heat shield forward aeroshell also attaches to the aft chassis at four bolt locations, with the aft aeroshell bolted to the forward aeroshell during close-out of the REBR assembly. The configuration just prior to close-out is shown in Figure 5b. The aft chassis also holds the antenna assembly and Iridium modem. The forward chassis accommodates the electronics board stack, all REBR sensors, two sets of twelve batteries, and diodes for each battery, connected in series, allowing the battery assembly to be added or removed as one unit. The entire structure, including the heat shield and excluding the housing, is designed to sustain a 100-g load. This is well above nominal expected 10-g and worst-case 30-g aerodynamic deceleration, but provides margin for the generally unknown environment during breakup of the host vehicle.

a) 

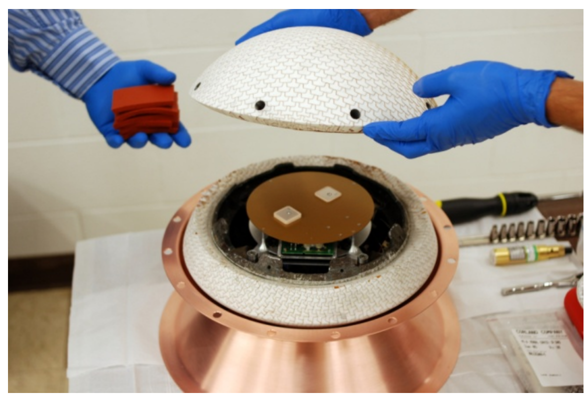
b) 

Figure 5. a) REBR chassis with installed hardware, and antenna ground plane at the top, attached to the aft chassis; b) Chassis attached to forward heat shield, with aft heat shield ready for close-out.

REBR is contained within a 4.5-kg (9.9-lbm) two-piece housing (see Figure 2) for attachment to the host vehicle, and for initial protection from mechanical insult during host vehicle breakup. An additional aluminum adapter ring (1.3 kg, 3.0 lbm) was used for attachment to ATV2. Silicone foam inserts are placed between the housing and heat shield to provide additional vibration and impact damping. The copper housing halves are held together with sixteen fasteners around the perimeter of the assembly. Each fastener uses a steel bolt and nut surrounded by an oversized Delrin flange, such that the bolt and nut will pull through the holes in the copper housing when the flange melts. The copper housing efficiently distributes heat, and melts at much higher temperature than the Delrin, ensuring that the copper halves separate before they can melt onto the heat shield. The copper housing also forms a Faraday cage as part of REBR triple redundancy against premature RF transmission, required by ISS partners. The REBR hardware is designed in accordance with ISS safety, launch load, and crew handling requirements.

D. Power

Power for REBR is provided by two 18 V lithium primary batteries. The dual configuration battery design uses twelve Energizer L91 Ultimate Lithium AA cells in series in each of the two strings. Each string has a 2 A fuse in the negative leg. Each cell has redundant parallel bypass diodes to protect against reversal and each string has redundant blocking diodes in parallel to protect against inadvertent charging. The L91 cells are rated for about 4.3 Whr at 21 ^{o}C (70 ^{o}F). At −20 ^{o}C (−6 ^{o}F) they are conservatively good for about 3 Whr, allowing the two batteries to provide at least 72 Whr. The batteries were tested from −40 ^{o}C to 76 ^{o}C (−40 ^{o}F to 169 ^{o}F). In stow mode, before activation, REBR draws about 325 μW. Over a six-month period, only 1.4 Whr of the 72 Whr would be used. After activation on ISS, REBR enters a power-saving 24-hour-timer mode to await undocking of the host vehicle, drawing an average of 16 mW. After the time-out, REBR goes into reentry-detection mode, drawing an average of 56 mW, in early-detection mode, and 95 mW in the full-detection mode. When reentry is detected by the flight software, all sensors are activated for data collection, and REBR draws about 458 mW. After the primary data gathering period, the modem is activated to dial up Iridium, drawing 2.4 W. Data transmission to the Iridium system draws 5 W. For a nominal reentry, well under 10 of the available 72 Whr are used before ground impact. After activation, REBR will remain capable of performing its full mission for more than a month.

E. Electronics

A flight computer and modem board, and an inertial measurement unit (IMU) and temperature sensor board comprise the REBR electronics. These printed circuit boards derive from Aerospace PicoSat heritage[5], which is an enabling technology for REBR. The stack of two round boards inserts into the annular forward chassis and attaches at four bolt locations. The flight-computer-modem board carries a real-time clock, four temperature sensors, a pressure sensor, and a battery voltage monitor; it also interfaces with the Iridium modem and receives data from the GPS receiver. The IMU-temperature board interfaces with accelerometer & rate gyro sensors, and interfaces with up to eight thermocouples.

On-board software includes algorithms for activation, reentry detection, false reentry detection, data sampling, data recording, and data transmittal. After activation and time-out, REBR gathers low-g acceleration data every 4 sec, until a threshold of 6 mg is passed, indicating the early phase of reentry. REBR then gathers low-g acceleration data every 2 sec to detect an expected reentry profile, determined through pre-flight trajectory simulations. When reentry is detected, REBR enters data-collection mode. For the first flight tests, planning was for 256 seconds of data collection, to focus on the period of reentry and breakup of each host vehicle. For future flights, data will be continuously collected, and then transmitted “first in, first out” until loss of power. The Iridium modem is activated and the connection is established when approach to terminal velocity is detected or a back-up timer is triggered, whichever happens first. Momentary loss of an Iridium connection results in repeated attempts to re-connect and to continue with data transmission, until loss of power.

F. Sensor Suite

REBR carries instrumentation for measuring host vehicle dynamics and the environment within the heat shield. Accelerations are measured with both a low-g six-degree-of-freedom inertial sensor (with range of ±1.7 g), and high-g three-axis accelerometer (with range of ±120 g). The low-g inertial sensor is used for detection of de-orbit burn and reentry. Higher accelerations during reentry are captured with the high-g accelerometer. The low-g inertial sensor also measures three-axis rotation rates (with range of ±300°/sec). The accelerometer and inertial sensor are MEMS (micro-electro-mechanical systems) technology, with no moving parts, and are both manufactured by Analog Devices, Inc. The flight computer board measures local pressure and temperature. Up to eight thermocouples can be accommodated on the special purpose temperature board. For the first flight tests, Boeing installed three thermocouples in each heat shield to measure proprietary thermal response at three locations across the thickness. Acceleration and rotation rate data are all sampled at 4 Hz during reentry. All other data are sampled at 1 Hz.

The Iridium modem includes a built-in GPS receiver. GPS data become available after REBR separates from the host vehicle, stabilizes for antenna lock, and then falls below speed and altitude limits placed on US commercial GPS receivers, 512 m/s and 18 km, respectively. GPS data collected by REBR at 1-sec intervals include UTC time, latitude, longitude, and altitude relative to mean sea level.

G. Communications

REBR software prevents transmission prior to host vehicle breakup, with the copper housing providing additional assurance. During reentry, REBR records data and will remain in this passive mode until acceleration first peaks above 5 g, and then drops below 1.7 g, as terminal velocity is approached. At this point, the Iridium modem is activated and attempts to dial-up the Iridium system. Once communications has been established, data are sent to the ground system via the Iridium system, until ground or water impact. If antenna pointing and structural integrity are maintained after impact, the process continues until loss of power.

Iridium uses right-hand circular polarization and operates over a 1616-1625.5 MHz frequency band. The modem from NAL Research Corporation can operate at 7 W maximum power during transmit events, though measured average output for REBR is 5 W. The data rate of the modem is 1200 baud. The L1-band GPS receiver on board the modem operates at 1575.42 MHz.

Two ceramic patch antennas, one for Iridium and one for GPS, are mounted to an aluminum ground plane on top of the aft chassis (see Figure 5a). These face upward through the RF-transparent aft heat shield dome (see Figure 5b), which will be zenith-pointing during terminal velocity. The antennas are commercially available, but modified by Aerospace for the REBR application. A SAW (surface acoustic wave) filter is utilized for rejection of Iridium signal coupling to the GPS receiver.

H. Thermal Control

For the flight tests from ISS, the host vehicles provide benign, shirt-sleeve environments prior to reentry. During reentry, the heat shield is designed to limit the heat shield backface temperature to 400 K (127 ^{o}C or 261 ^{o}F) until ground impact. In addition to heat from the heat shield backface, REBR equipment and electronics also generate waste heat during operation, contributing to the internal environment. The heat shield, by far, dominates this internal environment. The relatively hot heat shield cannot be used to reject the internal waste heat.

To maintain the electronics and equipment within their operating temperature limits, a three-part strategy is implemented. First, the inner surface of the forward aeroshell is covered with a conical, aluminized Kapton sheet. This low-emittance barrier minimizes heat radiated from the heat shield to internal components. Second, low-conductivity mounts are used at the four attachment points between the chassis and forward heat shield. This minimizes heat conducted from the heat shield to the chassis and attached components. Third, the thermal mass of the chassis structure and antenna ground plane materials are used to absorb internal waste heat. The strategy was confirmed with transient thermal analyses using detailed thermal math models. All components were predicted to remain within acceptable operating limits until ground impact.

I. Ground System

The RUDICS (Router-based Unrestricted Digital Interworking Connectivity Solution) commercial data service is the basis for the REBR ground system. RUDICS is co-located with the Iridium system gateway, and is offered by Iridium Communications, Inc. to customers for sending and receiving data traffic over the Iridium satellite network. Data calls can be connected to a specified Internet Protocol (IP) address, allowing an end-to-end IP connection between REBR and the ground system server. A commercial facility provides the server to guarantee continuous availability for reception of transmitted REBR data. When received, the data are simply published to a web page hosted on the server, and e-mailed to pre-determined addresses. The web interface is SSL encrypted, password protected, and firewall restricted to specific IP address ranges for remote access. The ground system architecture is illustrated in Figure 6.

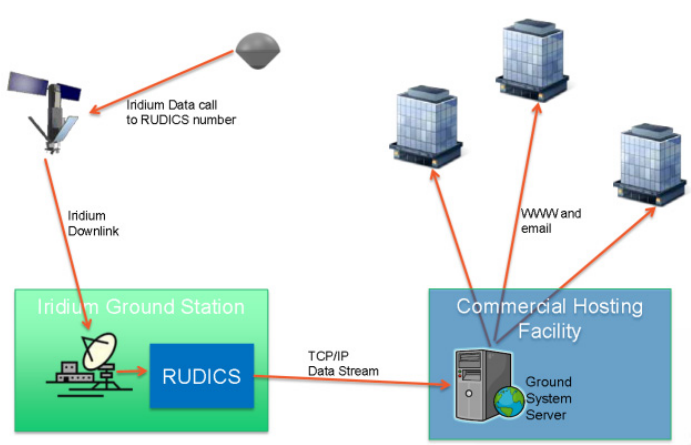


Figure 6. REBR ground system architecture.

III. Mission Profile

For the first flight tests on HTV2 and ATV-2, nearly identical mission profiles were applied. Both REBRs were stowed in Cargo Transfer Bags on the HTV2 vehicle, which was launched by the H-IIB to ISS on 22 January 2011. At ISS, the REBRs were stored for several weeks awaiting their respective missions. Each REBR was installed and activated about one day before departure from ISS and two days before reentry. The HTV2 undocked from ISS on 28 March, and reentered on 29 March 2011. The ATV-2 undocked from ISS on 20 June, and reentered on 21 June 2011.

A. Installation

For HTV2, REBR was strapped down to an available rack panel near the hatch, and then activated for reentry and hatch closure. This REBR was operationally referred to as REBR-S (soft-mounted). For ATV-2, REBR was first activated on ISS, and then moved to a rack adapter plate near an aft bulkhead in ATV-2, and attached using four captive fasteners. This REBR was operationally referred to as REBR-H (hard-mounted). With these exceptions in activation and attachment, the remainder of the planned mission profile was identical for each REBR. Activation and attachment procedures utilized electro-static discharge wrist-straps, and were photo and video documented.

B. Activation

For activation, an astronaut removes RF-protective copper tape on the housing, uncovering three wires with pin connectors and a light-emitting diode (LED) status light. The first pin is pulled, turning REBR electronics on in 24-hour-timer mode, and illuminating the LED, which verifies activation. When activation is verified, the second pin is pulled, turning off the LED. The third pin is then pulled to remove all mechanical attachment to the internal electronics, for clean separation during reentry. Four new pieces of copper tape are then placed over the activation wires and LED, completing the activation process.

C. Reentry Detection

After the 24-hour timer expires, REBR begins gathering low-g acceleration data every 4 sec, to check for early indication of reentry. This mode begins before the host vehicle has actually undocked from ISS. When a threshold of 6 mg is exceeded, then REBR enters full reentry-detection mode, gathering low-g acceleration data every 2 sec. For the first flight tests, reentry detection includes an increasing deceleration magnitude exceeding 12.5 mg, which is expected at an altitude of about 90 km (295 kft). A false-reentry algorithm filters out acceleration trends inconsistent with reentry, such as separation from ISS and de-orbit burns.

D. Data Collection

After reentry is detected, REBR enters full data-collection mode, and records 256 seconds of data. REBR continues to monitor deceleration profiles, not yet transmitting any data. After deceleration peaks above 5 g, and then drops below 1.7 g, approach to terminal velocity is indicated.

E. Data Transmission

The Iridium modem is then activated and the data connection is established. A back-up timer will also trigger the data connection, if the expected deceleration profile is not detected. Loss of connection will result in automatic re-dial and continuation of data transmission from the point of interruption. Data are sent through the Iridium system and RUDICS system to the ground server, and are automatically published for retrieval on a secure website. The retrieved binary data are then converted with ground software for use.

IV. Data Analysis

REBR data and results from reentry of HTV2 have been previously reported[6]. A brief summary is given here of those findings. Additional results are provided, illustrating derived dynamics for REBR after release, as well as derived aerodynamics for REBR falling at terminal velocity. A detailed description of the derived dynamics is planned for future publication. An overview of the HTV2 vehicle is shown in Figure 7a. REBR was installed in the Pressurized Logistics Carrier (PLC), just inside the hatch opening (unlabeled, but at the left end of the PLC in the image). A photograph of ISS astronauts in the HTV2 hatch opening in Figure 7b shows the copper REBR housing in the background. Also visible in the photograph is the extent to which HTV2 was filled with ISS waste. The white material behind and adjacent to REBR is packing foam from cargo containers previously delivered to ISS. Departing supply vehicles are typically filled with unwanted items for disposal during reentry.

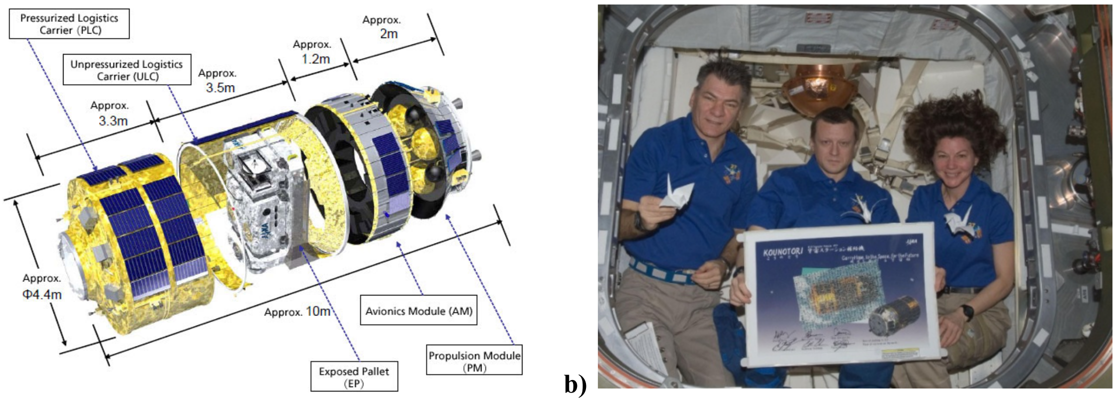


Figure 7. a) HTV2 vehicle overview (image courtesy of JAXA); b) REBR is the copper item attached to HTV2 in the background, behind the center astronaut. Astronaut Cady Coleman, right, activated REBR prior to HTV2 hatch closure. (photo courtesy of NASA).

A. Reentry Profile

HTV2 with the hatch facing aft passed through entry interface altitude (120 km, 394 kft) at a velocity of 7.6 km/sec (25 kft/sec). After 219 sec, HTV2 passed through 89.9 km (295 kft) at Mach 27 and still at 7.6 km/sec. At this point, REBR detected reentry and began recording data. Key events from the start of recording are summarized in Figure 8, which also shows the reconstructed REBR altitude history. According to REBR data, interaction with the atmosphere gradually slowed HTV2, put it into an unstable tumble, and heated its structure until breakup and release of REBR 196 sec later, at 66.5 km (218 kft) and Mach 23. REBR continued to record data for another 60 sec, while it initially tumbled, emerged from its housing, and aerodynamically stabilized. At end of recording, REBR was at 55.5 km (182 kft) and Mach 12. After another 87 sec, REBR established an Iridium connection and began data transmission, while at 31.0 km (102 kft) and Mach 1. GPS data became available below 12 km (39 kft). Transmission of recorded data was complete 181 sec later, at 9.2 km (30 kft) and Mach 0.2, and REBR continued transmitting real-time GPS data. REBR impacted the South Pacific Ocean 727 sec after start of recording, and 531 sec after breakup of HTV2. The connection to Iridium was lost at impact, but re-established by REBR, and GPS data continued to be transmitted for about 17 more hours, while REBR followed wind and ocean currents. Transmission presumably ended due to loss of battery power.

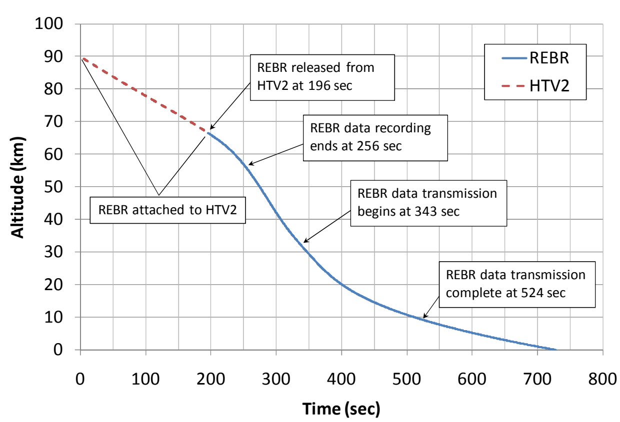


Figure 8. REBR altitude history from post-flight best-estimated trajectory for the HTV2 reentry.

B. Acceleration

The breakup of HTV2 and release of REBR are apparent in recorded accelerations. In Figure 9, magnitude of the acceleration measured by the high-g accelerometers is compared with the post-flight best-estimated trajectories of HTV2 and REBR after release. Acceleration magnitude of HTV2 gradually increases, until an abrupt change between 180 and 190 sec, believed to be initiation of catastrophic disintegration. Large variations are measured for about another 20 sec, after which acceleration magnitude settles above 5 g. The trend here compares well with predicted acceleration magnitude for the aerodynamically stabilized REBR. Additional measured data described in Ref. 6, including increase in heat shield temperature, imply release of REBR at about 196 sec, and initiation of major breakup of HTV2 as early as 120 sec, extending over an altitude range of 75.6 to 66.5 km (248 to 218 kft). Those data also show de-pressurization of the PLC on HTV2 at about 88 sec, at an altitude of 79.3 km (260 kft).

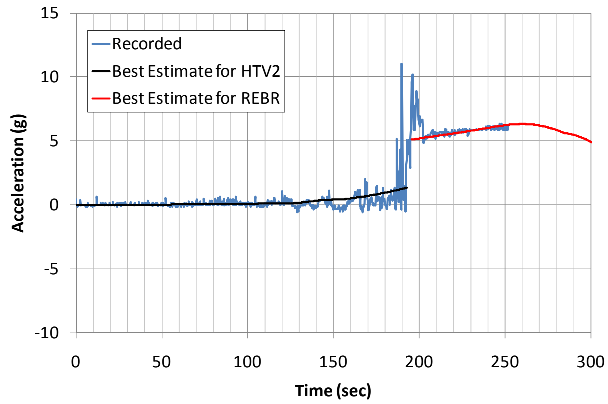


Figure 9. Acceleration magnitude measured by REBR's high-g accelerometer through breakup, compared with post-flight best-estimated trajectories.

C. Rotation Rate

Recorded rates give additional insight into HTV2 and REBR dynamics. The rotation rate history about one of two lateral axes, normal to the REBR longitudinal axis of symmetry, is shown in Figure 10. As reentry progresses, HTV2 experiences increasing rates due to aerodynamic moments, building to highly erratic behavior during the period of HTV2 breakup and REBR release. Beyond about 200 sec, the rates take on a damped oscillatory character. This is consistent with REBR stabilizing with its conical nose facing forward into the oncoming airstream. Rotation rate about the REBR longitudinal axis, shown in Figure 11, shows similar behavior for HTV2, prior to breakup. After REBR is released and stabilized, it is rolling at about 0.5 rev/sec, at the end of recorded data.

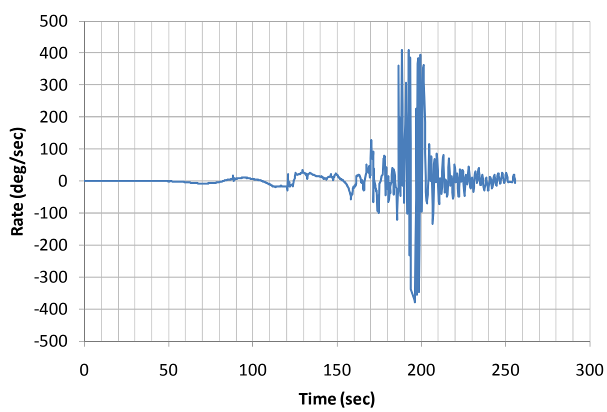


Figure 10. Rotation rate around a REBR lateral axis (axis is normal to the axis of symmetry).

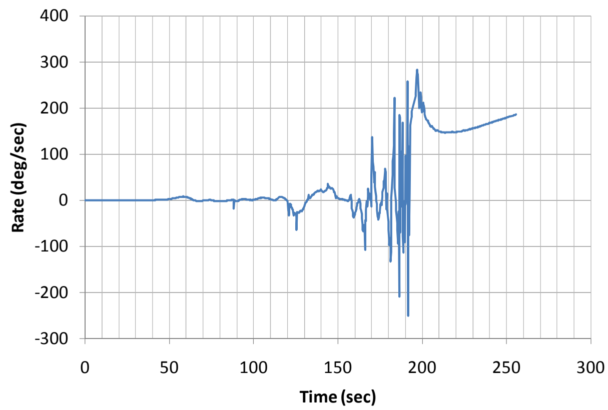


Figure 11. Rotation rate around REBR longitudinal axis (axis of symmetry).

D. Derived Dynamics

The full data set of three-axis accelerations and rotation rates can be used to derive vehicle dynamics, providing a history of orientation for both HTV2 and REBR. The analysis methodology is intended for future publication, but a brief overview is provided here for REBR after release. For illustration, the results can be expressed in terms of the absolute angle formed between the REBR longitudinal axis and the relative velocity vector. This angle is also called total angle of attack, and is shown in Figure 12. After release at 196 sec, REBR is tumbling and likely inside its housing. Values during this early phase are clipped at 30°, to emphasize detail at later times. REBR appears to be clear of the housing and stabilizing by about 200 sec. It then rapidly settles into an oscillation of about 5° total angle of attack, which would be produced by oscillations of about ±5° in angle of attack and sideslip. There appears to be a bias away from 0°, especially noticeable beyond 238 sec. Additional analysis, not presented here, shows that the oscillations have a magnitude closer to ±2.5°, with approximately a 2.5° offset. Reasons for the bias are unknown, but may possibly be due to alteration of the heat shield outer mold line, and/or some small change to lateral center of mass location. If a similar phenomenon is captured on future flights, then continuous collection of dynamics data should provide additional insight into the cause. The apparent offset of 2.5° is within the desired subsonic trim limit of 7°, and not considered a mission assurance issue.

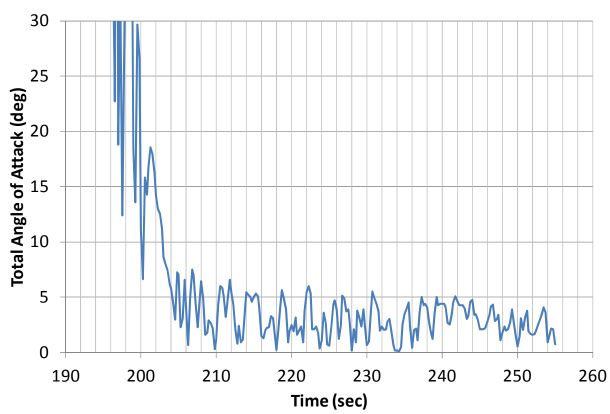


Figure 12. Total angle of attack for REBR after release from HTV2.

E. Derived Aerodynamics

While falling subsonically, GPS altitude history for REBR was available during data transmission. Simple processing of these data can be used to derive ballistic coefficient and drag coefficient for comparison with pre-flight predictions. Ballistic coefficient, in mass terms, is defined as the product of dynamic pressure with the ratio of mass to drag. Since REBR is at terminal velocity during subsonic descent, then REBR weight is equal to the drag, and the mass to drag ratio is the reciprocal of gravitational acceleration. Thus, ballistic coefficient at terminal velocity is the ratio of dynamic pressure to gravitational acceleration. Using velocity derived from GPS data and a simple atmosphere model for density produces the history in Figure 13. The result is in good agreement with the pre-flight ballistic coefficient of 73.5 kg/m^2 (15.1 psf). Disturbances in the history may be due to REBR oscillations (e.g., from wind effects), or may be due to noise in the GPS data. Future recording of REBR data to ground impact would allow distinguishing these possibilities.

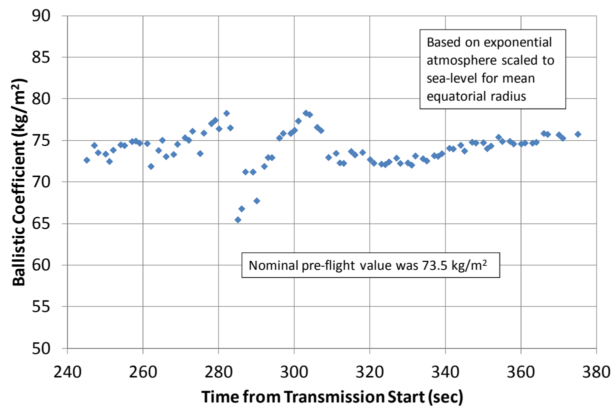


Figure 13. Derived REBR subsonic ballistic coefficient from HTV2 reentry.

Drag coefficient can be easily calculated from ballistic coefficient by specifying mass and drag reference area. Using nominal values for the REBR flown on HTV2 of 4.44 kg (9.79 lbm) and 0.075 m^2 (0.81 ft^2) produces the history in Figure 14. Consistent with the finding for ballistic coefficient, this result is also in good agreement with the pre-flight drag coefficient of 0.80, based on projected frontal area.

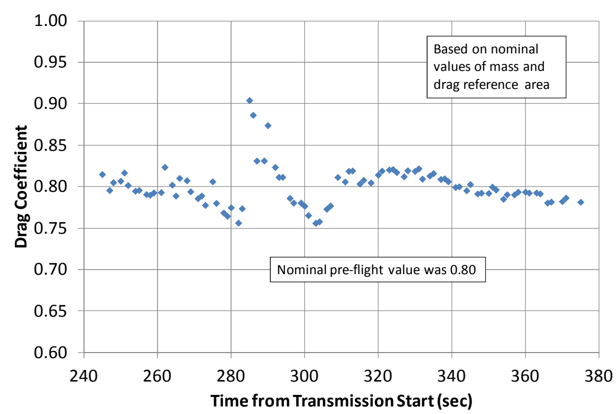


Figure 14. Derived REBR subsonic drag coefficient from HTV2 reentry.

V. Next Flight Tests

A second set of reentry flight tests is in progress at this writing. Two new REBRs launched to ISS from Tanegashima Space Center on 20 July 2012. Current planning is for HTV3 to undock from ISS on 6 September, and for ATV-3 to undock on 25 September 2012. In each case, the reentries should occur within one to two days of undocking. Minor mechanical changes were made to the REBRs for these flights. Software was modified to increase mission capability, through continuous recording and transmission of data, and to remove potential mission-assurance issues.

No data were returned from reentry of ATV-2. This prompted a detailed re-evaluation of REBR architecture, including mechanical systems and software. Airborne video and sensor observations from the reentry of ATV-1 on 29 September 2008 indicated a violent explosion of on-board propellants. On ATV-2, REBR was mounted adjacent to a bulkhead separating the pressurized compartment from the aft propulsion compartment. It is not known if a similar explosion occurred on ATV-2, but REBR will be installed on ATV-3 away from this bulkhead, to avoid potential direct exposure to exploding propellants. This location will also allow any intervening refuse, packed aboard ATV-3 for disposal, to help absorb a blast from the bulkhead direction. Unlike on ATV-2, REBRs on HTV3 and ATV-3 will be strapped down, as on HTV2. In addition, REBR hardware underwent new three-axis shock testing, at successive levels of 25 g, 50 g, 75 g, and 100 g. The testing included flight-like data recording and transmission. No issues or anomalies were identified in this testing, but confidence was gained in the robustness of the mechanical design.

In the course of the post-ATV-2 re-evaluation, and in the pre-flight testing for the second flight tests, additional areas for improvement were identified. The highlights are summarized here. Ground software was modified to eliminate data extraction errors. Improved 0-g calibration was added to flight software, and logic was added to prevent a potential system lock-up during activation. The mounting of electronics boards was modified to ease installation and removal during pre-flight test cycles. The antenna mounting structure was modified to reduce mass. Heat shield close-out bolts were changed from Phillips heads to hex heads to minimize potential for stripping. Internal debris capture bags were added to these bolt locations, and electronics boards were conformal coated to minimize foreign object damage. The 2 A fuses were replaced with 3 A fuses to add margin against inrush current. Finally, electro-static discharge protection circuitry was added to the housing and activation wire harness.

VI. Future Direction

The REBR design records temperature and other data from internal sensors; however, the ultimate goal is to collect data from distributed sites around the host vehicle. Temperature and heat flux data would provide for direct comparison with predictions from existing reentry survivability models, used for reentry risk assessment. Pressure and strain rate data would complement the thermal data for determination of vehicle response and breakup sequence during reentry. Such data collected aboard unprotected reentering objects is virtually non-existent, and relevant data from vehicles designed to survive reentry are sparse or restricted. The availability of open, quality, directly applicable data would allow rigorous improvement and validation of models, and enable broad application of design for demise – a strategy to design satellites and upper stages for minimal reentry risk.

The Aerospace Corporation has proposed the REBR-Wireless (REBR-W) concept, utilizing much of the existing REBR system, in combination with remotely located wireless sensors. The remote sensors would be placed around the host vehicle on components of interest for model comparison and characterization of vehicle response. With current fiscal year corporate research & development funding, design and demonstration of a prototype system in a laboratory environment is underway. A supplier for wireless sensors and architecture has been selected, the wireless hardware has been purchased, and integration with REBR hardware and software is in progress. The REBR-W prototype demonstration is expected by the end of the fiscal year. Findings from the demonstration exercise will guide definition of flight system requirements, supporting design of a REBR-W flight system. Multiple flight opportunities for REBR-W from domestic and international sources have been offered, and necessary funding is being sought for pursuit of those flights.

VII. Technology Transition

In accordance with corporate technology transition objectives, The Aerospace Corporation sought opportunities to commercially license REBR technology. One strategy for this approach would be for a commercial licensee to offer REBR-derived reentry data as a service. The necessary hardware and integration would be provided by the REBR licensee to the funding organization in need of data. Ideally, Aerospace would maintain access to collected data for reentry model improvement and validation, in its role supporting the national interest. In addition, licensees may envision other commercial applications for REBR technology, unrelated to Aerospace objectives.

In 2012, Aerospace entered into an exclusive licensing agreement with Terminal Velocity Aerospace (TVA), LLC[7], for REBR technology and the underlying patent[1]. TVA will offer a variety of REDs (ReEntry Devices), directed at markets in reentry debris safety and utilization of space. The first product currently available is called RED-Data, based on REBR, to collect and return host vehicle reentry breakup data. Under the agreement, TVA will make a good-faith effort to provide collected data to Aerospace, subject to approval from the host-vehicle owner. Future products are envisioned to provide space and reentry flight testing of materials and technologies (RED-Test), space flight and return of small personal items (RED-Treasure), black-box and structural-health monitoring data for reusable space vehicles (RED-SafeReturn), and wireless collection of reentry breakup data (RED-Sensor), based on REBR-W. Aerospace maintains a cooperative relationship with TVA for ongoing research and development related to REBR technology and applications.

Acknowledgments

REBR was conceived, designed, and fabricated by The Aerospace Corporation (Aerospace). Major funding was provided by Aerospace, the USAF Safety Center, the USAF Space & Missile Systems Center (SMC) Development Planning Directorate (XR) and Engineering Directorate (EN), and NASA Goddard Space Flight Center. The heat shield was designed and fabricated by The Boeing Company. NASA Ames Research Center provided in-kind support for heat shield preliminary design studies and experimental characterization of low-speed aerodynamics.

REBR was evaluated by the Department of Defense (DoD) Space Experiments Review Board, and manifested for launches to ISS, both under sponsorship from SMC/XR. REBR flight tests from ISS were integrated and flown under the direction of the DoD Space Test Program (STP), which also provided much-appreciated testing and mission-assurance support.

The authors gratefully acknowledge the support of the entire REBR team, with major technical contributions from: D. L. Rumsey (electronics, software, and sensors); D. A. Hinkley, P. Karuza, and G. A. Maul (mechanical design, system integration, fabrication, testing, and communications); A. S. Feistel (trajectory and flight data analysis); R. P. Patera and G. Fruth (dynamics flight data analysis); M. R. Keough and F. A. Roybal (structures); J. S. Halpine and J. D. Cardema (power); D. G. Gilmore and M. H. Chang (thermal control); E. R. George (ground system); N. C. Harnagel and J. C. McLeroy (mission assurance and liaison to STP team). The first author was responsible for aerodynamics, assisted with project management, and managed post-flight data analysis. The second author managed the overall project, and envisioned the original REBR concept.

References

[1]Ailor, W. H., Bywater, R. J., and Gurevich, L., The Aerospace Corporation, El Segundo, CA, "Spacecraft Reentry Breakup Recorder," US Patent No. 6,895,314, filed 11 Jun 2003, issued 17 May 2005.

[2]Mitcheltree, R. A., Moss, J. N., Cheatwood, F. M., Greene, F. A., and Braun, R. D., "Aerodynamics of the Mars Microprobe Entry Vehicles," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, 1999, pp. 392-398.

[3]Braun, R. D., Mitcheltree, R. A., and Cheatwood, F. M., "Mars Microprobe Entry-to-Impact Analysis," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, 1999, pp. 412-420.

[4]Brooks, J. D., "Some Anomalies Observed in Wind Tunnel Tests of a Blunt Body at Transonic and Supersonic Speeds," NASA TN D-8237, June 1976.

[5]Hinkley, D., and Hardy, B., "Picosatellites and Nanosatellites at The Aerospace Corporation," In-Space Non-Destructive Inspection Technology Workshop, NASA Johnson Space Center, Houston, TX, 29 Feb - 1 Mar 2012, URL: http://www.nasa.gov/pdf/626635main_inspace-4-3-hinkley.pdf [cited 23 Jul 2012].

[6]Ailor, W. H., and Weaver, M. A., "Reentry Breakup Recorder: An Innovative Device for Collecting Data During Breakup of Reentering Objects," 5th IAASS Conference, Versailles-Paris, France, 17-19 October 2011.

[7]Terminal Velocity Aerospace, LLC, URL: http://www.tvaero.com [cited 23 Jul 2012].