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The Reentry Breakup Recorder: A "Black Box" For Space Hardware

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Abstract

Unless specifically designed to survive, space hardware reentering the Earth's atmosphere will break apart due to aerodynamic heating and loads. Some materials will survive this severe environment and impact the earth, posing a hazard to people and property on the ground. At present, there is very little data that can be used to calibrate reentry breakup and hazard prediction models, yet these same models are used to predict risk and determine when satellite owners must plan for deorbiting into ocean areas—increasing mission cost and limiting payload mass. Occasionally, reentered debris is recovered on the Earth's surface, but as a rule, little information is available on the reentry environment experienced by those objects, so information from this source is limited.

The Aerospace Corporation is developing a "Reentry Breakup Recorder" (REBR) to fill this void. This small, lightweight, autonomous, self-contained device will be attached to satellite or launch stage and will record temperatures, attitude rates, and other information during the reentry and breakup of the hardware. Protected by a heat shield, it will survive reentry and will broadcast its data after the reentry has completed, but befor it impacts the earth's surface. Information recovered by the recorder is expected to dramatically improve reentry hazard and survivability estimates, ultimately leading to designs of space hardware that respond in predictable and repeatable ways to the reentry environment.

REBR may also be useful as a "black box" for reentry vehicles that are designed to survive, insuring that data on breakup of the vehicle will be returned should the vehicle unexpectedly fail during reentry. It may also be helpful in precisely calibrating the breakup characteristics of deorbit modules and other hardware associated with reentry vehicles.

This paper discusses the recorder concept, its development and testing plans, and required resources. The paper will also discuss possibilities for how the data might be used to develop more accurate predictions of the reentry breakup process and how such predictions might affect space hardware design.

Development and use of the recorder present opportunities for joint research projects and collaboration on the hardware itself, on launch and reentry opportunities, and on analysis of data returned.

Introduction

General

As mankind's use of space increases, hazards to objects in space from collisions with other manmade objects increases. Similarly, hazards posed to people and property on the ground by surviving portions of reentering spacecraft, launch hardware, and the like increase as well.

The Aerospace Corporation established the Center for Orbital and Reentry Debris Studies (CORDS) in 1997 to be a focal point for corporate research on reentry breakup, collision avoidance and space debris mitigation issues. Since that time, CORDS has become a source of objective information on these topics for the world space-using community.

Reentry

Satellites in low Earth orbit will slowly lose altitude by atmospheric drag until the orbit decays and the object drops into the denser portions of the atmosphere and "burns up." Of course, satellites and other space hardware may also be purposefully deorbited to reenter and deposit debris in safe areas without any danger to people and property.

Reentry of space hardware is generally considered to begin when the spacecraft drops below an altitude of about 120 km (400,000 ft) and begins to experience significant heating and loads associated with motion through the atmosphere.

As reentry progresses, heating and loads increase and unprotected hardware will slowly disintegrate and "burn up." In reality, hardware doesn't actually burn up—it melts, ablates, breaks apart, and some material may survive to impact the earth[1]. It is estimated that between 10% and 40% of a spacecraft's mass will survive reentry.

In general, very little debris from reentries has been recovered—in fact, it is estimated that less than 250 fragments have been located in the last 40 years. This is in spite of the fact that on an average over 100 random reentries of large bodies have occurred per year during that period. The Space Shuttle Columbia accident has not been included in this total, as that vehicle was protected by thermal tiles for a portion of the reentry and was purposefully deorbited. Doubtless, much can and will be learned about reentry breakup and survival from studying debris from that accident.

Project Background

In October 2000, CORDS sponsored a feasibility study to see if a cost effective system could be designed to study reentry and breakup phenomena. This one-year study concluded that the concept appeared feasible. Some challenges were identified, but there were no "show-stoppers." The primary goal for 2001 and 2002 was to refine the REBR concept and develop a preliminary design, and this was accomplished. Currently, efforts are underway to raise funding necessary to develop a prototype unit for testing. REBR presents an excellent opportunity for collaboration with organizations interested in reentry breakup.

Reentry Survival Models

Models of the survivability of reentering spacecraft are typically built from first principles, using the basic equations of vehicle flight dynamics, aerothermodynamics, and heat transfer coupled with structural models of varying complexity.[2] Current operational re-entry survival models now in use include: ORSAT[3] (Object Reentry Survival Analysis Tool) developed by National Aeronautics and Space Administration (NASA)/Johnson Space Center; (SCARAB)[4] (Spacecraft Atmospheric Reentry Aerothermal Break-up) developed by European Space Agency (ESA); and AHaB (Atmospheric Heating and Breakup) developed by The Aerospace Corporation. These models yield a sequence of events for spacecraft breakup (component separation), assessments of the size and mass of components surviving to impact[5], and component data used for casualty-expectation risk analysis[6].

Model Verification

There are several serious limitations in the current reentry survival modeling capabilities. Heating environment models used for reentry survival analyses rely on well-established theory backed by experimental data, mostly from ground testing. As has been mentioned, there is very little first-hand information on the breakup process.

Additionally, all of the operational numerical models for reentry survivability (ORSAT, SCARAB, AHaB) are deterministic in nature, neglecting uncertainty at many levels. Many simplifying assumptions are typically made, including boundary conditions, initial states, spacecraft attitude, and local heat transfer rates. These assumptions are necessary to make the problem computationally realizable, but there is little or no actual data from reentering spacecraft to support these assumptions.

Further, there is very little information about the behavior of non-metallic structural materials (e.g., composites, ceramics, plastics, etc.) in reentry environments, so assumptions are required when these materials are of interest.

When measurement data from an actual reentry is available, there is evidence that these models may not be providing representative results in some cases. For example, for reasons that are not well understood, aluminum components usually fail later (i.e., at lower altitudes) than predicted, and material is sometimes recovered, while models would predict their demise.

Despite this background, these models are the best available and continue to be used. It is clear that all could benefit from the validation and calibration that good, in situ data would allow, on the localized aero-thermodynamic environment, component temperatures, vehicle attitude and accelerations during reentry, and specific information on reentry breakup events.

Unfortunately, this type of data is difficult and expensive or impossible to acquire through remote observation of a reentering body and requires a system that is physically attached to the host vehicle during reentry and "rides the vehicle down" through reentry and breakup. This need is filled by REBR.

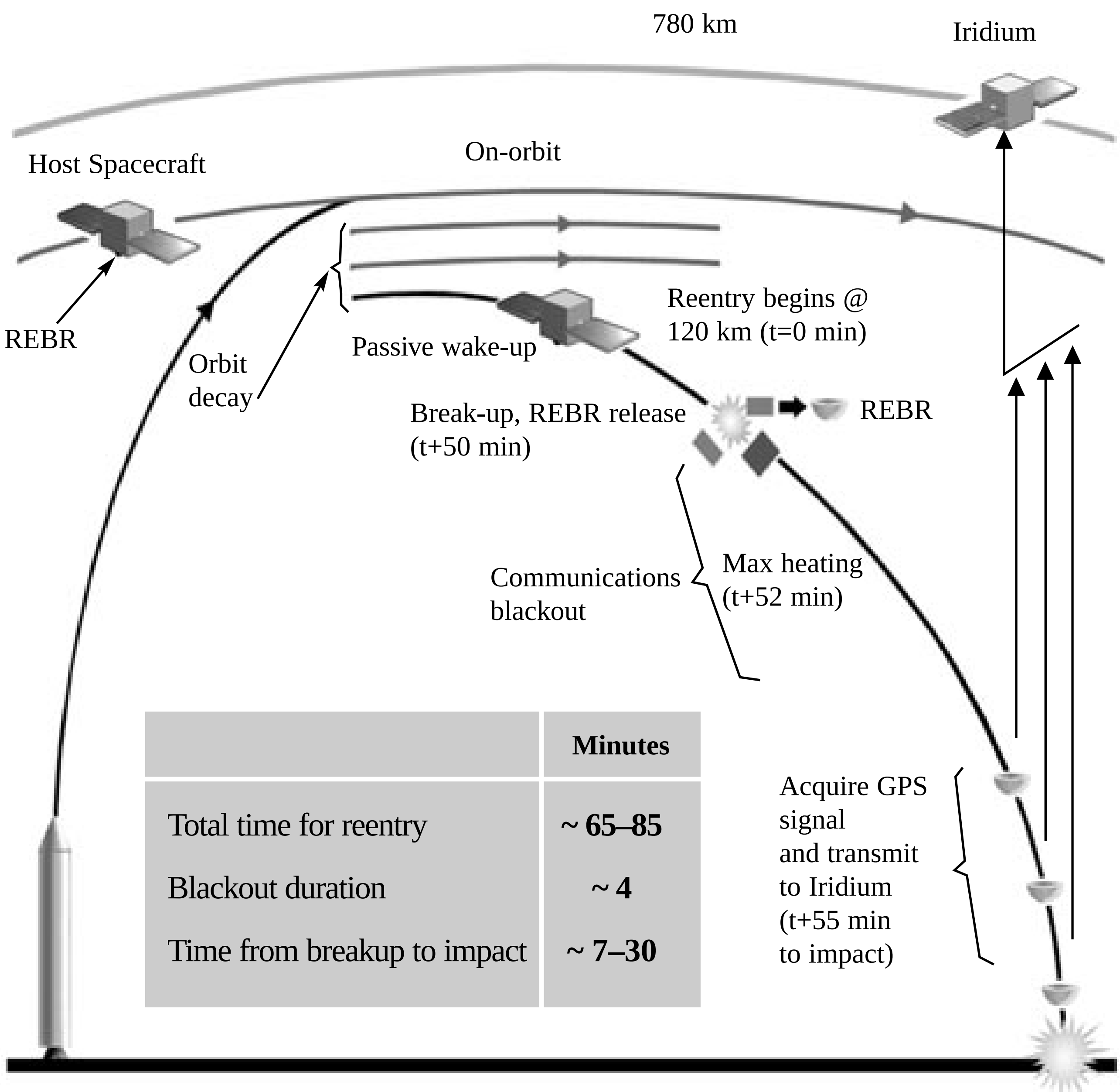
The REBR Concept

Overview

REBR is a small, lightweight, autonomous, self-contained data collection system that will measure the characteristics and record breakup of reentering objects. A REBR assembly will be attached to a host spacecraft or launch vehicle upper stage prior to launch and requires no electrical interfaces with the host. REBR has three primary systems: power, data storage, and communications. Sensors may be selected from a suite of those available, which includes temperature sensors, acceleration and attitude rate sensors, GPS sensors, etc. Some of these sensors could be mounted external to the REBR device and would demise as reentry progresses.

The Concept of Operation

Figure 1 illustrates the concept of operation for a typical random reentry. REBR is dormant during the launch and operational lifetime of the host vehicle. As the host reenters the atmosphere, REBR wakes up and initializes itself. REBR acquires and stores data from its



	Minutes
Total time for reentry	**~ 65–85**
Blackout duration	**~ 4**
Time from breakup to impact	**~ 7–30**

Figure 1. REBR Concept of Operation

sensor suite during reentry and breakup of the host vehicle.

A heat shield protects the REBR electronics from heating as reentry progresses, allowing REBR to survive while major parts of the host vehicle melt or ablate. REBR separates from the host vehicle during the breakup process, and transmits the stored data through an overhead communication system (e.g., Iridium) prior to impact.

The times from the beginning of reentry to breakup and from breakup to impact will vary depending upon each unique situation, but generally REBR has approximately 5 minutes to broadcast its data prior to impact.

A host vehicle may carry several REBRs for redundancy and to record data specific to a particular location on the body or other area of interest.

Benefits of REBR Concept

REBR will acquire insightful new data during actual spacecraft reentries. This data will provide physical evidence on the effect of the reentry environment on a reentering object as a function of time and altitude.

The data will be used to calibrate and validate breakup models, leading to better models of the breakup process and improvement in tools for estimating the associated casualty risks.

In the long run, better predictive models will allow manufacturers to alter their structural design and layout for more favorable breakup properties. Thus, better data will not only reduce the uncertainty regarding how spacecraft breakup during reentry, but will lead to satellite and upper stage designs with better-defined and potentially controllable ground impact risks.

System Description

Data Collection

The following baseline data may be collected:

1. Temperature at the wall of the host vehicle
2. Acceleration -- 3-axis
3. Angular rates -- 3-axis
4. GPS position, velocity, time (PVT)

This data will allow reconstruction of the heating environment of the host vehicle, the trajectory it followed, any sudden breakup events, as well as the general location of the debris footprint immediately prior to impact on earth.

While these sensors represent the baseline design, more data is always desirable. REBR is designed with enough computing, data storage, and data volume margin to have the flexibility to accommodate additional sensors if desired, and some of these sensors may be located external to the REBR device and would be sacrificed as reentry progresses.

Several candidate internal sensors have been identified, including two options for the GPS board and several MEMS options for the accelerometers and gyros.

Possible external sensors include stress and temperature measurement devices on critical structural members.

System Characteristics

A layout concept for the REBR assembly is shown in Figure 2. The attachment to the host vehicle is purely mechanical--there are no electrical interfaces for power or data, facilitating easy integration to the host vehicle.

The electronics boards include the GPS board and the Command & Data Handling (C&DH) board, which contains the processor, memory, MEMS sensors, and interface electronics to Iridium, GPS, or any of the sensors.

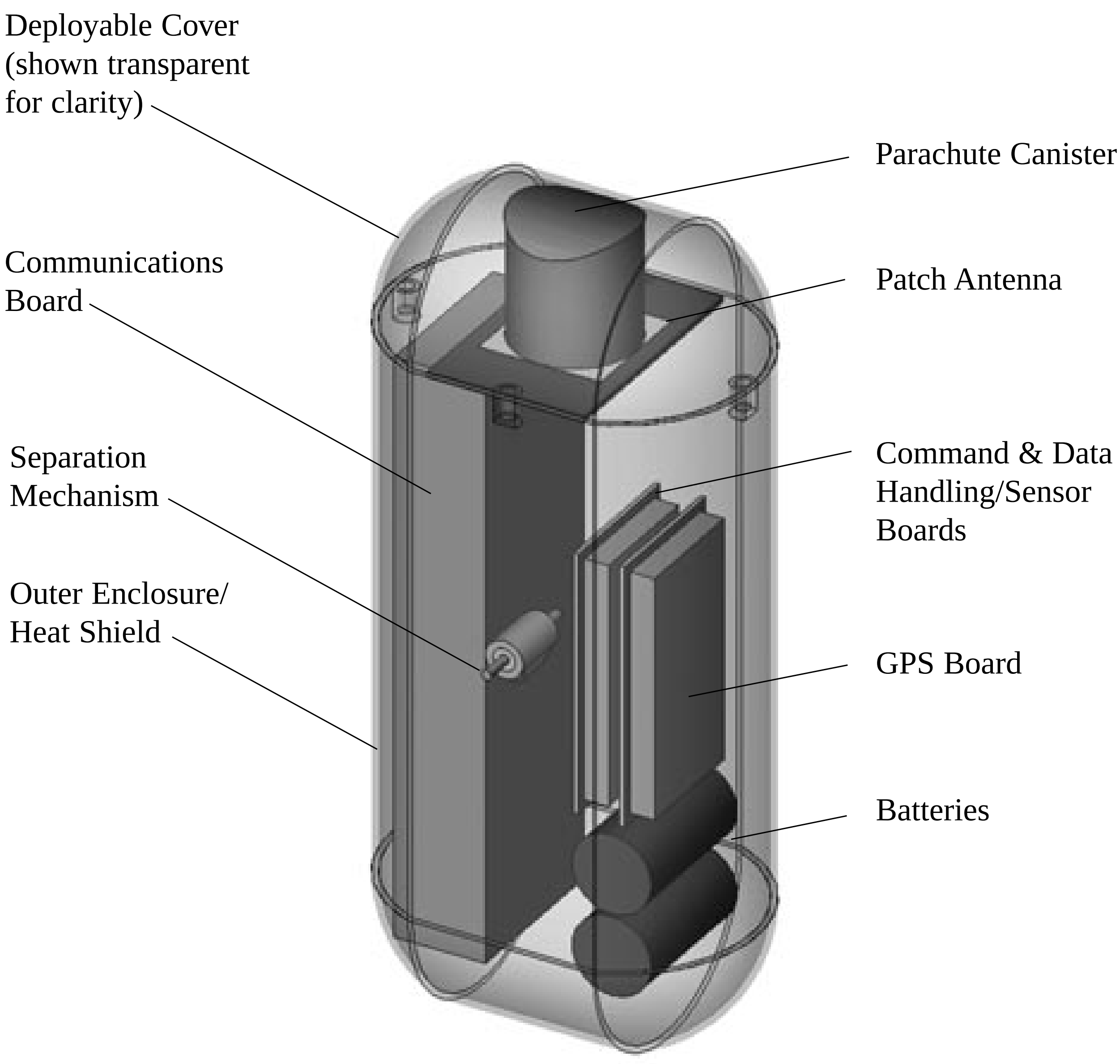


Figure 2. Layout Concept for REBR

The current estimates for the REBR mass and power are shown in the Table . Mass allocations are based on the best available data for each subsystem, but several trades are in work that could significantly affect the total system characteristics.

One specific trade study with potentially large mass implications is the trade between the heat shield and parachute (should it be required) for attitude control and ballistic coefficient tailoring. It may be possible, for example, to design the heat shield and mass distribution so that REBR assumes a stable attitude once in free flight, with antenna pointing up.

The mass for the current REBR design configuration is 2.9 kg, with dimensions of 13 x 6 x 4 inches, approximately. This design relies heavily on commercially available

Table. Mass and Power Allocations by Subsystem

SUBSYSTEM	MASS (g)	POWER (W)	ENERGY (W-hr)	COMMENTS
Sensors	205	3.0	1.5	GPS board, accelerometers/ rate gyros, environmental sensors
Structure & Mechanisms	345	25.0	0.1	Structure, separation mechanisms, wakeup sensor, drogue chute
Power	140	5.2	2.6	Li primary battery, power conditioning
C&DH	125	1.0	0.5	Micro-controller, data storage
Communications	425	0.9	0.4	Iridium transceiver, patch antenna
Thermal Protection	1,000	0	0	Carbon phenolic
Subtotal	**2,240**	**35.1**	**5.1**	
Margin	670		5.1	30% mass, 100% power
TOTAL	**2,910**		**10.2**	**Outer dimensions (inches): 13x6x4**

equipment and includes a conservative margin on both mass and power. These values will change as more detailed design is performed. The goal is to drive the weight to less than a kilogram and cut the size by about 50% (size of a paperback book).

Based on this mass allocation and size, the REBR ballistic coefficient is approximately 40 lb/ft^2.

Design Trades

Several important architecture-level trades were performed including: communications architecture, wakeup sensor, separation mechanism, and orientation/attitude control. These trades are discussed in detail below.

Communications Architecture

The following options were considered for the communications architecture: commercial GEO systems (Astrolink, Spaceway, and Inmarsat), commercial LEO/MEO systems (Iridium, Globalstar, ICO, and Orbcomm), dedicated GEO (TDRSS), and dedicated aircraft (P3 Orion).

After analysis of the requirements for coverage, availability, required power (Effective Isotropic Radiated Power) , and cost, Iridium was chosen as the preferred candidate for REBR. The main consideration for Iridium was its full-time global coverage coupled with its immediate availability with no advance scheduling required--REBR would simply "phone home" at the end of its mission. Based on this selection, more detailed analysis of the Iridium constellation was required, including an investigation of the effect of the vehicle position and velocity on the link.

A side benefit of choosing Iridium was that the frequencies of the L1 carrier for GPS and the frequency of Iridium are within a few percent of each other, which allows a single antenna to be used simultaneously for both applications with appropriate filtering.

Wakeup Sensor

The wakeup sensor was identified as a significant challenge by the study. The main concern was to be able to wake up sufficiently in advance of the breakup event so that the GPS sensor could acquire data prior to breakup. The GPS sensor selected had a time to first fix (TTFF) of 5-7 minutes from a cold start, which meant that REBR had to wake up 8-10 minutes prior to breakup. There was no option identified that could meet this requirement, although for missions with short lifetime (e.g., a reentering launch stage), REBR could simply remain awake for the entire mission.

During the year, several methods were examined to satisfy a longer lifetime requirement. The most promising was Iridium-based whereby REBR periodically initiated a call to the ground, which informed the assembly how much time was left until it had to wake up. There were several significant problems with this approach, including establishing an Iridium link while in orbit, the need for ground tracking of the debris object, and limitations on the mounting locations and viewing angles for the host vehicle.

As a result, the requirement for GPS data prior to to breakup was eliminated, and a solution that only acquired GPS during the free fall part of the trajectory after breakup was deemed acceptable. A different GPS receiver with a much lower TTFF was selected as a new baseline.

Given these new requirements, a trade study was initiated that examined potential wakeup sensors. The main considerations were zero power (passive), low mass, allowable wakeup timeline, and controllability of wakeup time.

Based on the relative timing of heating vs. acceleration, a temperature-activated sensor was selected instead of an acceleration-activated sensor. The mechanism that best fit the REBR requirements and goals was a bimetallic thermostat, which is an entirely passive, thermally activated mechanism.

Orientation/Attitude Control

The initial concept for data transmission was to use two omni-directional antennas to get full-sky coverage of the transmitted data. This had a few drawbacks, including a high power requirement to continuously transmit using both antennas, high mass because of the additional hardware required, and data dropout if the vehicle is tumbling.

To simplify the communications architecture and reduce the mass and power requirement, a design that uses a single antenna was selected. This required a method of attitude control, so that the single antenna could point "up" toward the communications assets. This will be done through center of gravity management, aeroshaping of the heat shield to produce an aerodynamically stable freefall, or possibly the inclusion of a drogue system (such as a small parachute or streamer) attached to the rear end.

The drogue system would simultaneously provide a method for keeping REBR pointed opposite the velocity vector, as well as a method to increase the amount of time available to communicate with Iridium.

Separation Mechanism

The result of the vehicle orientation trade requires that the REBR be free flying during the post-breakup freefall, so that the attitude of the assembly is independent of the attitude of the host vehicle. This requires a method of reliably separating the REBR assembly from the host vehicle after the critical phase of breakup has passed. A separate but somewhat related issue is the need to protect the antenna from the heat of reentry, while still allowing a clear, unobstructed communications path between the antenna and the Iridium system. The design approach that was selected was a deployable rear cover made of the same material as the rest of the heat shield, which must be separated from the host vehicle at an appropriate time during the reentry timeline.

A new material called ElectRelease Epoxy was investigated as a potential separation mechanism for the rear cover. This epoxy acts like any other adhesive until an electric current is passed through the epoxy interface, at which time the epoxy debonds, releasing the two pieces that were joined. Although this material showed potential long-term promise, it had no space flight heritage and only limited terrestrial use, and was discarded after an initial investigation.

A passive approach is baselined for the separation between REBR and the host vehicle, which simplifies the REBR architecture. REBR is attached to the host vehicle using aluminum, or any other material that offers extremely high confidence that it will burn off or melt away during reentry. As the heat from reentry melts the attachment, REBR will passively separate from the host vehicle.

There was some concern that this might not offer enough controllability of the release time, so a trade study of commercially available separation mechanisms was performed. This study emphasized low power, low mass, and reliable performance and heritage in the space environment. Frangibolts were identified as the most suitable mechanism for separation of the rear cover from the remainder of REBR, as well as a backup for the passive separation of REBR from the host vehicle.

Developmental Testing Plans

Ground Testing

In the near term, several demonstrations of critical subsystems and interfaces of the REBR assembly will be performed on ground and in laboratories. Demonstrating these potentially risky items prior to building the flight article will offer greater confidence in the ability of the REBR system to operate as designed during the relevant parts of the reentry timeline.

The first demonstration will be a communications systems test, which will demonstrate establishing a connection to Iridium, verify published data rates, demonstrate signal acquisition with the expected Doppler shift as REBR falls, measure the gain pattern of the Aerospace antenna (patch) design, and demonstrate frequency filtering. Expected communication link margins will be verified. Some simulations are planned using Aerospace tools.

Several other risk-reduction demonstration efforts are planned, including tests of the wake-up sensor, separation mechanism, and the communications and data handling (C&DH) prototype in the laboratory. The tests for the wake-up sensor and the separation mechanism will demonstrate the performance of the mechanisms in the expected thermal environment, as well as the survivability of the mechanism in the expected on-orbit environment without actuation.

The test of the C&DH prototype will demonstrate the electronic interfaces, commanding of the sensors and subsystems, storing of sensor data, and transfer of the stored data through Iridium.

Finally, thermal vacuum testing will be performed before the flight test.

Initial Flight Test

A full-up drop test will demonstrate passive attitude control, GPS signal acquisition from a cold start, record and transmit sensor data, and the ability to establish and maintain a communications link at high altitude and velocity.

Estimated Required Resources

A task analysis was performed for all future REBR efforts to deliver the initial flight test unit. A preliminary cost estimate was generated which included all the testing identified above, a preliminary and detailed design effort, manufacturing and/or procurement of the flight unit, and environmental testing of the flight unit.

The estimated cost for the remaining two-year effort is $2.1 M for the delivery of the first flight test unit.

Potential Participants

Several potential participants were identified and contacted during 2002. To name a few: multiple NASA centers, Federal Aviation Administration (FAA), Defense Advanced Research Projects Agency (DARPA), and Sandia National Laboratories. Interests include:

- NASA/Goddard Space Flight Center (GSFC) is leading the Reentry Debris Mitigation Initiative. Aerospace is assisting on a multi-year proposal to NASA Headquarters. Also, GSFC is working on a GPS receiver and C&DH/Sensor board that could meet REBR requirements with some modifications.

- NASA/Langley Research Center has expertise in the design of parachutes and thermal protection systems, including heat shield materials and aeroshaping.

- NASA/Johnson Space Center has interest in space debris in general. There is a potential application of REBR for International Space Station crew transfer/return vehicles.

- Jet Propulsion Laboratory's Mars Exploration Program can benefit from REBR capabilities on their lander/rover missions. Possible REBR applications are on future planetary missions that contain Radioisotope Heating Units or Radioisotope Thermoelectric Generators. Also, Prometheus/Jupiter Icy Moons Orbiter (JIMO) project may need to address safety concerns with regards to nuclear propulsion.

- FAA has responsibilities in range safety and commercial launches (expendable and reusable launch vehicles).

- DARPA is very interested in event-driven autonomous data collection and transmission systems.

- Sandia National Laboratories has experience building a similar type of data recording device for a different application.

Also, contacts have been made with several academic institutions all over the U.S. with aerospace and MEMS interests and capabilities for possible collaboration.

Conclusions

The data collected by REBR will provide actual physical evidence about the environments encountered by a host vehicle during reentry, as well as the response of the vehicle under those conditions. This will be used to validate and calibrate reentry survival models, leading to better models of the reentry process and the associated casualty risks. Also, this data will help spacecraft manufacturers to design space hardware that will respond in predictable and repeatable ways to the reentry environment.

Referencess

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