ANALYSIS OF REENTERED DEBRIS AND IMPLICATIONS FOR SURVIVABILITY MODELING

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ABSTRACT

Over the past seven years, several fragments of space hardware have been recovered on the ground following the reentry and destruction of the host vehicles. Fragments include two 250 kg stainless steel fuel tanks, two 30 kg titanium pressure spheres, two 50 kg titanium solid rocket motor casings, a small, lightweight fragment that struck, but did not injure, a person, and thousands of fragments from the Space Shuttle *Columbia* following that tragic accident. Several of these surviving fragments have been analyzed to gather data that might help understand the reentry breakup process. This paper gives the pre-reentry, pre-breakup configuration for each primary object, the best-estimate reentry trajectory for each, the condition at impact of each object and the results of the metallurgical and laboratory analyses. These reentries can help calibrate reentry survivability models and illustrate what we know and do not know about the reentry breakup process.

1. INTRODUCTION

When orbiting space hardware enters the earth's atmosphere, it does so with a velocity generally exceeding 7 km/sec. Over a period of tens of minutes, the reentry process slows the object to a few hundred meters per second. Much of the object's original kinetic energy is converted to heat in a pulse that lasts 6 minutes or less. This intense heating can melt structures and generally disassemble an object that may have taken years to construct, spreading debris over a ground footprint that can be tens of kilometers wide and hundreds of kilometers long.

On average, there are about 100 reentries of large objects each year[1], and debris from each reentry generally survives to impact on the ground or in the water. A rule of thumb suggests that the mass of surviving debris will total between 10 and 40% of the pre-reentry mass of the object. As noted, this debris will be spread over a long footprint. Major debris from the *Columbia* accident, more than 84000 objects, was spread over a footprint approximately 1000 km long and 40 km wide. The mass of the debris recovered from the *Columbia* accident totals 38000 kg, approximately 38% of the dry mass of *Columbia*.

Unfortunately, debris from reentering objects is rarely found on the ground, and any that is found is rarely analyzed. Exclusive of *Columbia* debris, it is estimated that fewer than 250 items have been recovered over the 40-plus years mankind has been launching hardware into space. During this period, a number of large and potentially deadly (due to their size) objects have survived to impact, but there have been no known injuries or deaths caused by reentered material. Exclusive of the *Columbia* debris, it is estimated that fragments from fewer than a dozen reentries have been analyzed in laboratories.

Despite this fact, there is increasing interest in the hazard posed by space-hardware debris surviving reentry, with current guidelines[2] or regulations[3] stating that space hardware must be deorbited in a controlled fashion if the casualty expectation for an uncontrolled reentry exceeds 1×10^{-4}. Information of this type is also required for environmental analyses for current and future programs and could lead to inclusion of reentry hazard reduction features in the design of space hardware.

These emerging requirements places increased emphasis on our ability to develop accurate estimates of what will and will not survive reentry and to estimate the final hazard associated with each surviving fragment. As shown in Table 1, several models of varying complexity have been developed for this task. Models vary from those that assume a reentering object breaks into simple components at a specified altitude to models that simulate the full 6 degree-of-freedom motion of an object and the heating and loads to individual components to the greatest extent possible. In all cases, engineers have been forced to use best judgment as a substitute for relevant experimental data to calibrate these models. The 78 km breakup altitude used in several models is based on previous analyses of data from spacecraft deorbits.[4]

Since no data accumulated during the breakup of an unprotected spacecraft is available (although an approach for collecting such data is being developed[6]), analysis of recovered debris must be used to gather insights on the breakup process. This paper gives an overview of what has been learned from reconstructing reentry trajectories and analyzing recovered items from

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

two reentries: the 1997 reentry of a Delta II second stage and the 2001 reentry of a Delta II third stage. In each case, a best estimate of the reentry trajectory is provided, along with times of significant events (e.g., ballistic coefficient changes), reference heating rates, and details of metallurgical analyses. The paper concludes with what has been learned from these analyses that might be applied to reentry hazard estimation in general.

Table 1. Reentry survivability models.

Model Name	Type	Originator
ORSAT[5]	3-DOF, assumes breakup at 78 km altitude	NASA
SCARAB[6]	6-DOF, predicts breakup	ESA
AhaB[7]	3-DOF, predicts breakup	Aerospace
DAS[8]	Scaled trajectory, assumes major breakup at 78 km	NASA

2. DELTA II SECOND STAGE

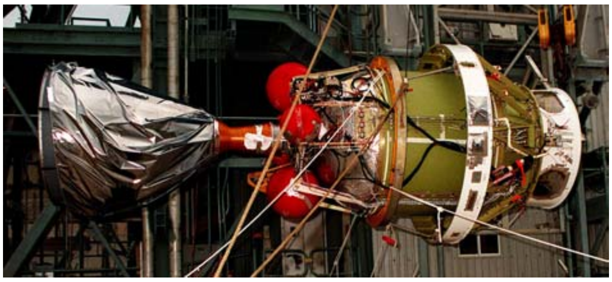

Figure 1. Delta II Second Stage (photo courtesy NASA).

Fig. 1 is representative of the pre-reentry configuration of the Delta II Stage 2 (Aerojet AJ10-118K) that was used to place an Air Force satellite into orbit on April 24, 1996. The stage reentered over Canada and the United States on January 22, 1997.

The propellant tank for the AJ10-118K (located forward of the spheres) has a cylindrical sidewall with hemispherical caps attached to each end. An interior hemisphere joins with the aft end-cap to form a spherical tank for nitrogen tetroxide oxidizer. The remainder of the internal volume above the oxidizer tank holds Aerozine-50 fuel. The entire propellant tank assembly is constructed of AISI 410 stainless steel. A fuel depletion burn is performed following spacecraft separation, so the tank is empty at reentry. Structural hardware is aluminum. Total dry weight of the stage is 920 kg.

The propellant system is pressurized with gaseous helium and nitrogen, contained in four spherical pressure vessels. There are two large and two small pressure spheres, all made from Ti-6Al-4V titanium alloy. One small sphere contains nitrogen, with the remaining three containing helium. A single large sphere was recovered after reentry.

Table 2. Delta II Stage 2 propellant tank dimensions and weight.

Diameter	1.74 m
End-cap radius	0.87 m
Length (total)	2.73 m
Length (cylinder)	0.99 m
Thickness (cylinder)	1.9 mm
Thickness (end-cap)	1.1 mm
Material	AISI 410 stainless steel
Weight (kg)	250

Table 3. Delta II Stage 2 pressure sphere dimensions and dry weights.

Item	Diameter (m)	Thickness (mm)	Weight (kg)
Large	0.59	5.7	30.4
Small	0.41	4.3	10.0

2.1. Reentry Trajectory and Recovered Debris

Fig. 2 shows the four debris items that were recovered after the reentry. Impact locations of each item are given in Table 4.

Table 4. Impact locations of debris items.

Item	Geodetic Latitude (deg)	Longitude (deg E)
Fragment	36.249	264.044
Propellant Tank	30.644	262.378
Sphere	29.712	262.121
Thrust Chamber	29.576	262.080

A best estimate of the reentry trajectory of the stage was constructed using the last NORAD tracking state vector estimate (Table 5) and other sensor data. The known impact points of the three debris pieces were also used to help reconstruct the breakup event. A wind profile for the central portion of the United States for the time of reentry was included in the reentry trajectory simulation.

A batch least squares technique was used to find the best trajectory fit of available data. Experience has shown that ballistic coefficients vary as an object disintegrates, loses material, or changes dynamics, so the drag profile was represented by a piecewise constant table as a function of trajectory time, where the breakpoints can be selected by the user or they can be solved for as parameters in the least squares optimization. Similarly, estimates of the orbit state vector can include tracking and propagation errors, so the least squares technique allows the initial orbit state vector components to be fixed or solved-for parameters.

Figure 2. Debris from Delta II Second Stage reentry: clockwise from top left: Lightweight fragment, propellant tank, thrust chamber, sphere. Photos courtesy Tulsa World (staff photo by Brandi Stafford), NASA, Aerojet, NASA, respectively.

Fig. 3 shows the best estimate trajectory flown by the propellant tank. The wind moved each fragment off of the original ground track consistent with its ballistic coefficient. The small fragment was moved more than 33 km off-track, the large fuel tank 8 km, and the titanium sphere only 6 km.

Figure 3. Best-estimate trajectory for the propellant tank.

A breakup time of 9:36:7 GMT yielded the smallest errors in the tank and ball impact locations, so this was chosen as the most likely time for the Delta II Stage 2 breakup. The best-fit orbital elements at reentry and breakup are listed below in Table 5. Table 6 gives the derived ballistic coefficients for each object.

2.2. Results of Laboratory Analysis

Lightweight Debris

A small portion of the lightweight object that landed in Turley, OK was examined to verify that the item originated from the Delta II second stage reentry and to estimate the peak reentry temperature. The piece was first examined with an optical stereomicroscope, after which small representative pieces were removed for more detailed analyses using a scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDXS) for qualitative chemical analyses, and using an X-ray diffractometer for identification of crystalline compounds.[10]

Table 5: The osculating orbit state vector for Delta II Stage 2 at reentry and breakup.

	At Reentry	At Breakup
Epoch	Jan 22, 1997	Jan 22, 1997
Time (hms) (GMT)	9:02:32.42	9:36:7.42
Altitude (km)	119.1642	78.8538
Relative Velocity (mps)	7899.5985	7697.0553
Apogee (km)	131.7581	75.0938
Perigee (km)	102.6075	-629.0727
Argument of Perigee (deg)	98.2508	311.1371
Inclination (deg)	96.5716	96.5230
RAAN (deg)	344.6985	344.7484
True Anomaly (deg)	262.0620	189.0524
Longitude (deg)	87.2738	264.3496
Geodetic Latitude (deg)	0.3128	39.6888

Table 6: Adjusted ballistic coefficients for recovered debris

Object	Adjusted Ballistic Coefficient (kg/m^2)
Pre-breakup	9.12
Fragment	0.20
Fuel Tank	3.39
Helium Pressure Ball	5.08
Thrust Chamber	5.08

Visually, the sample provided appeared to be a piece of black colored woven fabric approximately 5 x 1.5 x 0.5 cm in size (Fig. 4). Initially, it was thought to be a piece of carbon or graphite fiber cloth because of its color. However, upon closer examination it was determined that the fibers were colorless, with a very dark coating. There were also colorless fused-looking deposits containing many bubbles and small ($\cong$ 1 mm) silvery-metallic particles. It was concluded that the metallic particles were resolidified aluminum with a very thin aluminum oxide surface layer.

The main body of the Delta II second stage thrust chamber was recovered from near Seguin, Texas. It consists of an inner silica-phenolic liner and asbestos-phenolic insulator, which is covered with several layers of fiberglass fabric overwrap in a phenolic matrix, followed by a final layer of glass roving. The forward flange of the thrust chamber is constructed of 6061 aluminum and thin aluminum fingers extend about 15 cm aft of the flange.

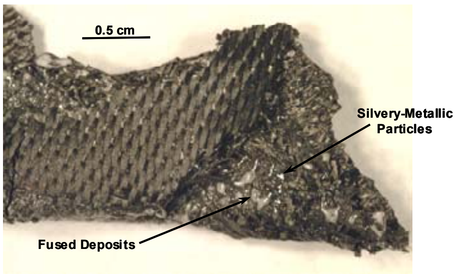

Figure 4. Optical photograph of as-received debris from Turley, OK.

Representative pieces of the fiberglass/phenolic overwrap and glass roving were received from Aerojet, the manufacturer of the thrust chamber, for comparison with the debris piece. The chemical composition and weave pattern of the glass roving (E-glass) matched the debris. The black color of the debris probably resulted from rapid pyrolysis of the phenolic resin during reentry. The metallic deposits on the fabric are believed to be residue from the aluminum flange or "fingers," which melted during reentry. E-glass has a "softening" point of around 850°C and a "melting" point of approximately 1200°C. The large number of bubbles trapped in the fused glass indicates the material was relatively fluid and had reached a temperature above the melting point of E-glass during reentry.

Stainless Steel Tank

Metallurgical analyses were performed on the Delta II Stage II stainless steel propellant tank. Photographs (Fig. 2) show that that the Stage II tank was largely intact upon landing on earth. The Stage II tank had a long circumferential crack and a flattened top resulting from impact damage (see Fig. 5).

The melting point for the tank is approximately 1500°C for 410 stainless steel. The forward dome of the tank had a large hole with a jagged periphery of resolidified molten metal (Fig. 5), which had a black, burned appearance. Splashes of molten metal were seen at many locations on the exterior surface. These splashes were particularly heavy around the molten hole. Other observations included erosion/melting of stainless steel brackets, usually in regions where molten metal splashes were present. The tank had numerous small holes (2–3 mm) on the tank skin from micrometeoroid impacts. Most of the small holes were located on the aft end of the tank.

Although thorough analyses were performed on all observed features on the tank[11], only analyses relevant to reentry survivability modeling, including the cause of the apparent molten hole on the forward end of the tank and analyses for estimating overall peak reentry temperatures, are summarized in this paper.

Figure 5. Photograph of reentered Delta II Stage II tank showing apparent molten hole (photo courtesy NASA).

EDXS analyses indicated that the molten metal splashes were aluminum. The tank had aluminum hardware attached to stainless steel brackets. It is theorized that the aluminum hardware melted from reentry heating and alloyed with the brackets causing the observed melting/erosion of some of the brackets. Some of the brackets, which have a melting point of around 1400°C, showed no evidence of melting. Therefore, it was concluded that the overall reentry temperature was >640°C (Al alloy melting point) and <1400°C.

Microstructural analyses were used to estimate overall reentry temperatures. Microstructural changes due to diffusion of aluminum splashes into the stainless steel tank in regions in which burning (discussed later) did not occur were used for the temperature analysis, and this showed that the peak overall reentry temperature on the tank was between 1200 and 1280°C.

3. DELTA II STAGE 3

The third stage of a Delta II launch vehicle used to place a Global Positing Satellite in orbit on May 13, 1993 reentered over Africa on January 12, 2001. Fig. 6 is representative of the pre-reentry configuration of the Star 48 motor, but does not include the aluminum structure required to attach to the payload or the second stage. Table 7 gives pre-reentry properties of the Star 48B rocket motor.

The Star-48B motor has two integral flanges, the lower for attachment to the third-stage spin table and the upper for attachment to the payload adapter (neither shown in the photo). The motor consists of a carbon-phenolic exit cone, Ti-6AL-4V titanium high-strength motor case, silica-filled rubber insulation system, and a solid propellant system using high-energy ammonium perchlorate and aluminum with binder.[12]

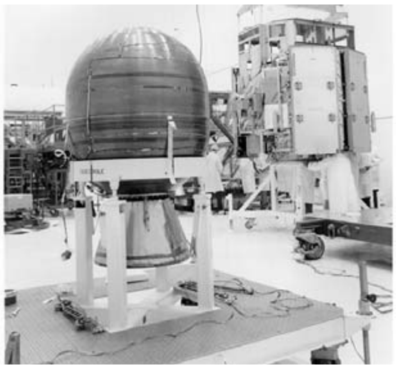

Figure 6. Star-48B rocket motor (photo courtesy U.S. Air Force)

Table 7. Star48B properties.

Diameter:	1.24 m
Length:	2.03 m (includes nozzle)
Thickness:	1.75 mm
Material:	Ti-6Al-4V titanium alloy

3.1 Reentry Trajectory and Recovered Debris

Table 8 gives an initial state vector for the Delta II Stage 3 prior to breakup. The trajectory reconstruction was performed using best available sensor data for the event. The results of the trajectory reconstruction show that the vehicle broke up at an altitude of 71.78 km over Saudi Arabia. The reconstructed ballistic coefficient prior to breakup was 1.1505 kg/m^2. The ballistic coefficient post breakup was 2.2906 kg/m^2. The predicted impact location for the stage was longitude = 44.5961 deg E, geodetic latitude = 23.7201 deg. A plot of the groundtrack during the final reentry is shown in Fig. 7.

3.2 Results of Debris Analysis

Fig. 8 shows the Delta 3rd Stage tank after reentry. Weight after impact was 67 kg, which included the weight of the nozzle remains. The tank had a small crack at the aft end, which was attributed to impact, but did not show significant deformation. It is believed that the composite exit cone made the initial impact with earth. The exit cone shattered, thereby absorbing most of the impact energy and minimizing damage to the titanium tank.

Reentry analyses predicted that the titanium tank would not reach its melting point (≅ 1650°C for the Ti-6Al-4V alloy) during reentry. However, the forward dome of the tank had a large hole with a jagged boundary. No evidence of micrometeoroid impact damage was observed. A thorough analysis was performed on all observed features of the tank[13], but only results of analyses relevant to reentry survivability modeling are summarized here.

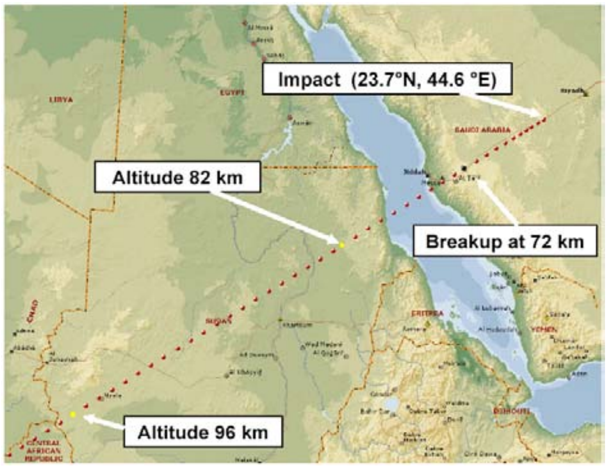

Figure 7. Ground track for reentry of Delta II stage 3.

Table 8: Osculating orbit state vector for Delta II Stage 3 prior to and at breakup.

	At Reentry	At Breakup
Epoch	Jan 12, 2001	Jan 12, 2001
Time (hms) (GMT)	16:37:0	16:38:38.7
Altitude (km)	81.6435	71.7835
Relative Velocity (m/s)	7421.0256	6196.7567
Apogee (km)	98.1822	74.4085
Perigee (km)	-105.1038	-2907.7351
Argument of Perigee (deg)	179.4186	217.2829
Inclination (deg)	34.6006	34.3566
RAAN (deg)	7.4533	7.1124
True Anomaly (deg)	214.8164	183.6305
Longitude (degE)	35.2187	40.7924
Geodetic Latitude (deg)	18.7460	21.8218

Figure 8. Photograph of reentered Delta Third Stage tank showing molten holes.

Ti-6Al-4V is a two-phase alloy, and the peak reentry temperature can be estimated from the final microstructure. From the proportions and morphology of the phases, the peak reentry temperature for the titanium tank was estimated to be between 1050 and 1200°C.

4. IMPLICATIONS FOR MODELING

Analysis of the two recovered tanks indicates a probable scenario for the localized melting observed on both[11,13]. It is hypothesized that the holes seen in both tanks were created by localized heating generated by burning of the heavy aluminum splashes during reentry. It is postulated that as the surface of the molten aluminum oxidized, the high shear force generated by the atmosphere during reentry immediately removed the oxide layer, allowing fresh aluminum to oxidize. Thus, a continuous oxidation process was established, which caused significant heating in addition to the frictional heat of reentry. Eventually, the high heating caused the aluminum to ignite. The burning aluminum could then produce heat intense enough to melt or ignite the stainless steel and Ti-6Al-4V tanks.[14] This scenario was supported by microstructural and EDXS analyses, which showed the presence of heavily oxidized, resolidified tank alloy at the periphery of the holes. It should be noted that this augmented heating from burning aluminum is generally not included in reentry breakup models.

5. SUMMARY

This paper provides basic information on the reentry of two Delta II stages that can be used to help calibrate reentry breakup models. Best estimates of the state prior to, at, and after breakup have been developed using the best information available for each case. The analyses indicate that major breakup occurred at 77.8 and 71.8 km for the objects. Ballistic coefficient changes for debris pieces indicate that each continued to have some degree of shape change as heating continued. Maximum temperatures between 1000 and 1300°C were indicated.

Analysis of the recovered debris also indicates that heat generated by oxidation, "burning," of aluminum may be a factor that should be included in estimating the overall survivability of some objects. This effect could have a major role in the breakup of objects containing significant amounts of aluminum. It is recommended that debris objects from additional reentries be examined to further characterize this effect.

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ACKNOWLEDGEMENT

This work was done as a cooperative effort between The Aerospace Corporation and the United States Air Force Space and Missile Systems Center. Our thanks to Ms. Frankie Shelton and Mr. John R. Edwards for their support and assistance.