REENTRY SURVIVABILITY RISK ASSESSMENT OF THE EXTREME ULTRAVIOLET EXPLORER (EUVE)

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ABSTRACT

A reentry analysis of the Extreme Ultraviolet Explorer (EUVE) spacecraft was performed using the Object Reentry Survival Analysis Tool (ORSAT) – Version 5.0. The analysis was done in response to a request by NASA Headquarters and Goddard Space Flight Center (GSFC) after a preliminary assessment using the NASA Johnson Space Center Debris Assessment Software (DAS) – Version 1.0 had shown that the EUVE reentry might produce a debris area greater than the limit set within the NASA Safety Standard 1740.14 guidelines. DAS predicted that an uncontrolled reentry of the EUVE spacecraft could result in a total casualty area of 12.41 m^2, which exceeds the 8 m^2 limit set in the NASA standards and implies a potential human casualty risk of approximately 1 in 5300. The ORSAT model enabled a higher fidelity thermal analysis of the EUVE spacecraft, utilizing sophisticated material and thermal properties such as emissivity, heat of oxidation, thermal conductivity, and material thickness inputs, which provided a foundation for a more in depth analysis of the reentering objects. Due to the conservative nature of the DAS study, it was reasonable to run ORSAT for only the ten objects shown to survive in the original DAS analysis. The result of the ORSAT study was a reduced casualty area of only 5.95 m^2, well within NASA safety limits. With the risk to human life now acceptably low, NASA can avoid having to take mitigation measures and allow EUVE to reenter the Earth's atmosphere uncontrolled.

1. INTRODUCTION

On June 7, 1992, the NASA Goddard Space Flight Center (GSFC) Extreme Ultraviolet Explorer (EUVE) (see Fig. 1) was launched from Cape Canaveral, Florida on board a Delta II rocket into a 528 kilometer, 28.5 degree inclination low earth orbit. EUVE is an astronomy mission to explore the extreme ultraviolet (70-760 Angstroms) band. The science payload of the EUVE consists of three grazing incidence-scanning telescopes and an extreme ultraviolet (EUV) spectrometer/deep survey instrument, all designed and built by Space Science Laboratory at the University of California, Berkeley.

Fig. 1. EUVE Spacecraft

With the spacecraft nearing its end of mission and a possible reentry into the Earth's atmosphere expected as early as October 2001, personnel at GSFC performed a reentry analysis using the NASA Lyndon B. Johnson Space Center (JSC) Debris Assessment Software (DAS) – Version 1.0 [1], in accordance with NASA Policy Directive 8710.3 [2]. The analysis predicted eighteen individual objects would survive, resulting in a total debris casualty area of 12.41 m^2 [3]. Guideline 7-1 of the NASA Safety Standard 1740.14, "Guidelines and Assessment Procedures for Limiting Orbital Debris" [4], limits the casualty area to 8 m^2 to minimize risk to the ground population to less than 1 in 10,000. The EUVE casualty area predicted by DAS implies a potential human casualty risk of approximately 1 in 5300.

The EUVE spacecraft was not designed with a propulsion system and therefore cannot perform a controlled reentry. In order to mitigate the potential risk to human safety from an uncontrolled reentry of the EUVE spacecraft, a retrieval of the spacecraft using the Space Shuttle was considered. However, use of the Space Shuttle would be a costly option and would be a difficult task to undertake with the current Shuttle program schedule. Since DAS is a lower fidelity model and tends to produce a more conservative result, a higher fidelity analysis was warranted. A decision needed to be reached quickly, therefore the Orbital

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expedited study of the EUVE reentry using the higher fidelity NASA-Lockheed Martin Object Reentry Survival Analysis Tool (ORSAT) [5] model to determine if taking such a measure would be necessary.

2. BACKGROUND ON NASA POLICY AND MITIGATION PRACTICES

In April 1993, NASA Management Instruction (NMI) 1700.8 [6] was issued with the aim of contributing to the preservation of the near-Earth space environment for future missions of exploration and application. NSS 1740.14 serves as the principal implementation instrument for the NMI with guidelines in the areas of mission-related debris, satellite breakups and collisions, and end-of-mission disposal. Since NSS 1740.14 promotes the removal of derelict spacecraft and rocket bodies from LEO within 25 years of mission completion, a policy restricting the risk to people on Earth from reentering debris was required.

After reviewing other risk levels in industry and public life and taking into account the relatively infrequent reentry of large spacecraft and rocket bodies, a per event risk of human casualty of 1 in 10,000 was set. It was noted at the time that after more than 35 years of uncontrolled satellite reentries, no human casualty on Earth had been reported.

For spacecraft like EUVE, which were already in orbit or which had completed Preliminary Design Review (PDR) by April 1993, NPD 8710.3 required that the project office prepare an end-of-mission plan and submit it to the NASA Office of Space Flight (Code M) for review. The Orbital Debris Program Office at JSC on behalf of Code M then evaluates the plan for compliance with NASA policies.

In the case of EUVE, natural orbital decay assured that the spacecraft would reenter the atmosphere well within the 25-year guideline of NSS 1740.14. Furthermore, passivation of the vehicle, which carried no propulsion system, was straightforward. Thus, the primary issue to be addressed was the predicted casualty area of surviving components following an uncontrolled reentry.

3. REENTRY MODELS

The variation between the DAS and the ORSAT models can significantly affect the results of a reentry analysis. DAS was intended to provide quick, conservative results for orbital debris applications. In particular, it is used to aid in determining if a program is compliant with the safety standard guidelines. A compliance based on DAS alone will leave no doubt as to the ability of the program to meet the guidelines. However, a noncompliance implies that a higher fidelity model is necessary for determining if a program does in fact meet the guidelines.

3.1 ORSAT – Version 5.0

ORSAT was developed by NASA JSC and originally released in 1993. It was developed as a high fidelity tool to model atmospheric conditions, trajectory, aeroheating and aerodynamics of a reentering object and determine if and when the object demises. For a surviving object, ORSAT calculates the casualty area, provides the impact footprint and the risk to the ground population [5].

One of the key features of ORSAT is its ability to perform heat conduction through an object. For spheres and cylinders, an object can be divided up into layers. Each layer is represented by one node, and ORSAT allows for a maximum of 50 nodes per object. With this layering capability, the shell of hollow objects can be modeled, as well as different materials for the different layers. Furthermore, heat conduction enables reentering objects to melt away in layers, possibly reducing the debris area in the event the object survives. Flat plates and boxes, however, are not set up in ORSAT to utilize the heat conduction feature. They are modeled using a lumped mass approach. In this approach, the entire object will remain at whatever temperature the surface is at. When the surface reaches the melting temperature of the object, it will continue to stay at that temperature until enough heat is absorbed to ablate the object. At that point, the object is considered demised. If the heat of ablation is never reached, however, the object is predicted to survive.

ORSAT also makes possible the use of oxidation heating. The oxidation process produces heat which is absorbed by the surface wall of the object. The amount of the heat transfer to the surface wall is based on the chemical heating efficiency factor, τ. τ can range from 0 to 1.0 based on the material of the object. A τ of 1.0 would imply that all heat due to the oxidation will be absorbed into the wall. To the opposite end of the range, a $\tau = 0$ would imply that no heat is absorbed by the wall due to the chemical reaction.

Another aspect of ORSAT which affects the analysis is the emissivity of the object material. The emissivity is the ratio of thermal energy emitted by an object over the thermal energy emitted by a perfect blackbody at the same temperature. A perfect blackbody will emit the same amount of radiation that is absorbed, therefore the emissivity of a blackbody is one. In ORSAT, the emissivity can vary based on the object being evaluated.

3.2 DAS – Version 1.0

DAS Version 1.0 was written by R. C. Reynolds and Alejandro Soto of Lockheed Martin Space Mission Systems & Services in August 1998. This software originated in late 1995 and was created as a tool to aid NASA programs in performing the required mission risk assessments. The program is structured similarly to the NSS 1740.14 document, providing a straightforward method of determining guideline compliance as well as debris mitigation options when compliance is not attained.

The model used in DAS for predicting the survivability of spacecraft is a simplified version of the Miniature Object Reentry Survival Analysis Tool (MORSAT) [7], which was derived from the ORSAT model. MORSAT does not have all of the capabilities that are provided in the more robust ORSAT model. Consequently, DAS is designed to be slightly conservative, which is desirable for doing first order program risk assessments.

MORSAT, and therefore DAS, considers convective heating only and therefore does not take into account surface chemical heating. Furthermore, the emissivity in DAS is hard-coded to be one no matter what the material properties of the actual object are, thereby causing the object to lose heat faster. As a result of these DAS characteristics, there is an increased chance for survival.

Unlike ORSAT, DAS does not take into account heat conduction. DAS uses the lumped mass approach for all object types, therefore an object is assumed to demise once the total cumulative heat load reaches the material heat of ablation. Without heat conduction, if an object does not totally melt away, it will survive to the ground in its entirety. For a surviving object, this implies a larger debris area than if heat condition were considered and layers were enabled to melt away during reentry.

Objects modeled in DAS are also considered to be solid, as there is no way to input a thickness for objects which may be hollow or have thin shells with objects of different materials contained inside. This increases the chance of survival for many of the objects evaluated. However, an effective density approach has been determined viable for evaluating objects with significant empty space.

4. CASUALTY AREA

A surviving object will impact the ground and produce a casualty area, which is calculated by using the maximum cross-sectional area, A, of the object and adding a 0.3 m border around the object. In ORSAT, the debris casualty area, D_A, is calculated using Eq.1.

$$D_A = \left(0.6 + \sqrt{A}\right)^2 \tag{1}$$

The value for A varies based on object type. For a sphere, A is equal to πr^2, where r is the radius of the sphere. For all other object types, A is equal to the length multiplied times the diameter (or width for boxes and flat plates). The total debris casualty area would be the sum of the debris area calculated for each surviving component.

A review of the DAS 1.0 source code shows that the debris casualty area is calculated in a slightly different way, as seen in Eqs. 2-4.

$$D_{Asphere} = \pi(r + 0.3)^2 \tag{2}$$

$$D_{Acyl} = (length + 0.6)(diameter + 0.6) \tag{3}$$

$$D_{Aflatplate/box} = (length + 0.6)(width + 0.6) \tag{4}$$

Eq. 2 represents the method for calculating the debris area of a sphere, where r is the radius of the sphere. The equations used to calculate the debris area of a cylinder and flat plate or box are illustrated in Eqs. 3 and 4, respectively. Again, the total debris casualty area is simply the sum of each individual debris area calculated. The debris area equations used by DAS tend to produce larger debris casualty areas, thereby adding another conservative factor to the analysis.

5. EUVE COMPONENTS

In the EUVE ORSAT analysis, only the objects which were found to survive in the GSFC DAS analysis were evaluated. Although eighteen individual objects were predicted to survive in the original DAS analysis, due to duplicated items on the spacecraft, there are actually only ten unique object types. These types include the Collimator Back Plate, EUVE Instrument Grapple Assembly, Circular Transition Adapter (CTA), Solar Array Drive Hub, Solar Array Drive Interface fitting, Multi Mission Spacecraft (MMS) Grapple Extension, MMS Grapple Assembly, Torquer Bar, Reaction Wheel Assembly (RWA) Rim, and the Battery Pack.

In the GSFC DAS analysis, much manipulation was required to model many of the complex EUVE structures. Furthermore, boxes were modeled as cylinders, per NSS 1740.14 [4]. In order to provide quick results to aid in deciding if mitigation measures were required, these components were all created in ORSAT using the same design approach as done in the DAS analysis, with the exception of accounting for thickness where applicable. The following sections describe these components and how they were modeled in both the DAS and ORSAT studies [3].

5.1 Collimator Back Plate

The EUVE Deep Survey Spectrometer contains two collimators. The only portion of the collimator shown to survive in the DAS analysis was the molybdenum back plate, which measures 0.2347 m x 0.1406 m and has a mass of 1.63 kg. The collimator back plate was modeled in ORSAT as a flat plate with the same dimensions and material properties as used in DAS.

5.2 EUVE Instrument Grapple Assembly

The EUVE Instrument Grapple Assembly has a mass of approximately 12.7 kg and is constructed mostly of titanium. It was modeled as one solid component, assuming the titanium bolts holding the structural pieces together would not melt and allow the assembly to break apart. In both the DAS and ORSAT analyses, the Grapple Assembly was modeled as a titanium cylinder with a diameter of about 0.5 m and length of about 0.015m.

5.3 Circular Transition Adapter (CTA)

The 172 kg CTA is a large 1.7 m diameter, hollow aluminum annulus, or ring. Neither DAS nor ORSAT has the capability to model rings and therefore manipulation was required to create an object to best represent the CTA. GSFC used a cylinder to model the CTA where the actual height and mass of the ring were used, but a modified diameter was calculated based on the surface area of the original CTA ring face. The resulting dimensions for the cylindrical geometry used to model the CTA were a diameter of about 1.17 m and a length of about 0.15 m. In the ORSAT analysis, a thickness of approximately 0.005 m was also used to model the CTA.

5.4 Solar Array Drive Hub

There are two Solar Array Drive Hubs on the EUVE. Each is constructed with titanium and has a mass of approximately 13.8 kg. The Solar Array Drive Hub was modeled as a solid titanium cylinder with a diameter of 0.27 m and a length of 0.15 m

5.5 Solar Array Drive Interface Fitting

The Solar Array Drive Interface Fitting is the titanium main hinge assembly which attaches to the Solar Array Drive Hub. There are a total of two interface fittings on the EUVE, one for each titanium hub. The Solar Array Interface Fitting was modeled as a solid titanium cylinder with a diameter of approximately 0.3 m and a length of 0.076 m. The mass of the interface fitting is about 3.34 kg.

5.6 MMS Grapple Extension

The EUVE MMS Grapple Extension is the support fixture for the Grapple Assembly. It is made of titanium and has a mass of approximately 3.8 kg. The Grapple Extension was modeled as a solid titanium cylinder with a diameter and length of about 0.29 m and 0.01 m, respectively.

5.7 MMS Grapple Assembly

The MMS Grapple Assembly is identical to the EUVE Instrument Grapple Assembly and was therefore modeled with the same geometry and mass.

5.8 Torquer Bar

The Torquer Bar has a solid cylindrical iron core which is approximately 0.029 m in diameter and 1.1 m long. A copper wire is wrapped around the iron, extending the diameter of the whole structure to roughly 0.043 m. In the DAS analysis, each layer was modeled separately. In ORSAT, however, both the copper wire and the iron core were considered one multi-material object, allowing for heat conduction from the copper layer to the iron layer.

5.9 RWA Rim

There are a total of four RWA Rims on the EUVE spacecraft. Similar to the CTA, the stainless steel RWA Rim is a ring-shaped structure, which is impossible to model in DAS or ORSAT without some manipulation. Again the original height, or length, and mass of the RWA Rim were used for the cylindrical geometry model. The values of the length and mass are approximately 0.025 m and 2.04 kg, respectively. The surface area for the face of the ring was calculated and then used to determine the diameter of the cylinder such that the surface area would be maintained. The resulting diameter dimension used in the DAS and ORSAT cylindrical models of the RWA Rim was calculated to be roughly 0.11 m.

5.10 Battery Pack

The EUVE has a total of three Battery Packs. Each Battery Pack consists of 22 battery cells arranged into 2 rows of 11 cells each. The battery pack itself measures approximately 0.31 m wide by 0.44 m long by 0.14 m high. Each battery cell measures about 0.03 m wide by 0.13 m long by 0.14 m high. The 45.8 kg battery pack, assumed to be stainless steel, was modeled intact (i.e. does not break apart and release the individual cells during reentry). The original length of 0.44 m was used as the length of the battery cylindrical model and the equivalent diameter was calculated using the surface area of the 0.31 m x 0.44 m surface.

6. ORSAT ANALYSIS

Reentry of the EUVE spacecraft was considered to occur at an altitude of 122 kilometers with the breakup occurring at 78 kilometers. The EUVE parent body was modeled as a 3243 kg aluminum cylinder with diameter of 1.88 m and length of 3.937 m. An initial relative velocity of 7410 m/s was used based on an inclination angle of 28.5 degrees. The initial relative flight path angle was assumed to be –0.5 degrees. In ORSAT, the parent body is only used to determine the trajectory conditions down to the breakup altitude. At the breakup altitude, the fragments of the parent object inherit these trajectory conditions and are then considered exposed to the heating effects of the Earth's atmosphere.

In the initial analyses approach using ORSAT, the chemical heating efficiency factor, τ, was set to zero, implying that no chemical heating was being applied. Furthermore, a lumped mass approach was used for all components with the exception of the multi-material Torquer Rod for which heat conduction was implemented (four nodes were used for the copper layer and one node was used for the iron core layer). In this run, both the CTA and the Torquer Rod demised. All other objects survived. In the next run, the heat of oxidation was implemented and τ was set to 1.0, which implies maximum heating due to oxidation. This case resulted in the demise of 6 objects with 4 objects surviving. Since using 100% chemical heating efficiency is probably overestimating the actual amount of oxidation heating, the same run was performed again, but this time with τ reduced to 0.5. Again, the same 6 objects demised.

Furthermore, since the CTA and RWA rims are actually shielded by other components, another case was executed for each to determine the impact of holding off heating until a lower altitude. The RWA rims are housed in the Modular Attitude Control System (MACS) and are therefore protected from the initial reentry heating. The demise altitude of the MACS according to DAS is approximately 63.37 kilometers. This altitude was therefore used as the start altitude for the reentry analysis of the RWA rims. Similarly, the CTA analysis was started at an altitude of 60.54 kilometers, which was the demise altitude of the Platform Equipment Deck (PED). Both the RWA rims and the CTA would normally experience some heating before these altitudes due to thermal conduction. However, in order to maintain some conservatism in the analysis, thermal conduction from the MACS and the PED to the RWA rims and the CTA, respectively, was not taken into account. However, with τ set to 0.5, both of these objects are still predicted to demise.

Most of the objects had been analyzed using the lumped mass approach. For objects which survived, another analysis was performed using up to 10 nodes. The Collimator Back Plate was not evaluated since only a lumped mass analysis is possible for flat plates. The Solar Array Drive Hub, Solar Array Drive Interface Fitting, and MPS Battery Pack analysis with 10 nodes all resulted in the same debris area, implying that not even the first layer of each object had melted away. This is due in part to the high melting temperatures of both titanium and stainless steel, which are approximately 1943 K and 1698 K, respectively. Aluminum, in comparison, has a melting temperature of only about 850 K.

7. RESULTS

The results of the EUVE analysis are shown in Table 1. Four of the ten object types were predicted to survive. This equates to a total of nine actual surviving components out of the eighteen DAS had predicted would survive. Table 1 shows a comparison of the total debris casualty area for each object using the two different models. The individual debris areas for objects which survived in both analyses varied slightly due to the difference in the calculation methodologies, as discussed in Section 4. The ORSAT analysis produced a total debris casualty area of approximately 5.95 m^2 compared to the higher 12.41 m^2 casualty area originally predicted in the DAS analysis.

Table 1. ORSAT EUVE Analysis Results

Object	Suface Material Used	Model Geometry	Diam. (m)	Leng. (m)	Thickness (m)	Mass (kg)	Demise or Survive?		ORSAT Debris Area (m^2)	Quantity of Objects	ORSAT Total Debris Area (m^2)	DAS Total Debris Area (m^2)
							$\tau = 1.0$	$\tau = 0.5$				
Collimator Back Plate	Molybdenum	Flat Plate	0.2347	0.1406		1.6300	Survived	Survived	0.5306	2	1.0613	1.24
EUVE Inst Grapple Assembly	Titanium	Cylinder	0.4974	0.0147		12.7006	Demised	Demised	0.0000	1	0.0000	0.68
CTA	Al 2219-T8xx	Cylinder	1.1684	0.1524	0.00556	172.3651	Demised	Demised	0.0000	1	0.0000	1.33
Solar Array Drive Hub	Titanium	Cylinder	0.2667	0.1461		13.7900	Survived	Survived	0.6358	2	1.2717	1.30
Solar Array Drive Interface fitting	Titanium	Cylinder	0.3023	0.0762		3.3400	Survived	Survived	0.5652	2	1.1303	1.22
MMS Grapple Extension	Titanium	Cylinder	0.2921	0.0127		3.7760	Demised	Demised	0.0000	1	0.0000	0.55
MMS Grapple Assembly	Titanium	Cylinder	0.4974	0.0147		12.7006	Demised	Demised	0.0000	1	0.0000	0.67
Torquer Bar	Copper (layer 1) Iron (layer 2)	Cylinder	0.0425 (1) 0.0287 (2)	1.1176		11.3398 (1) 5.6840 (2)	Demised	Demised	0.0000	1	0.0000	1.10
RWA Rim	Steel AISI 304L	Cylinder	0.1128	0.0254		2.0412	Demised	Demised	0.0000	4	0.0000	1.80
Battery Pack	Steel AISI 304L	Cylinder	0.2400	0.4000		45.7820	Survived	Survived	0.8278	3	2.4834	2.52
TOTAL									2.5594	18	**5.9467**	**12.41**

8. CONCLUSIONS

The ORSAT reentry analysis performed on the EUVE spacecraft reduced the predicted casualty area from the original 12.41 m^2 as predicted by DAS to only 5.95 m^2. This is well under the 8 m^2 limit set in the NASA guidelines. The ORSAT analysis is considered more reasonable since ORSAT is a higher fidelity tool than DAS. The reduced casualty area confirms that a future uncontrolled reentry of EUVE is of an acceptably low risk to human safety, thereby avoiding the need for costly mitigation measures.

9. REFERENCES

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