

USING THE DESIGN FOR DEMISE PHILOSOPHY TO REDUCE CASUALTY RISK DUE TO REENTERING SPACECRAFT

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Recently the reentry of a number of vehicles has garnered public attention due to the risk of human casualty from fragments surviving reentry. A number of NASA programs have actively sought to minimize the number of components likely to survive reentry at the end of their spacecraft's life in order to meet and/or exceed NASA safety standards for controlled and uncontrolled reentering vehicles. This philosophy, referred to as "Design for Demise" or D4D, has steadily been adopted, to at least some degree, by numerous programs. The result is that many programs are requesting evaluations of components at the early stages of vehicle design, as they strive to find ways to reduce the number of surviving components while ensuring that they meet the performance requirements of their mission.

This paper will discuss some of the methods that have been employed to ensure that the consequences of the vehicle's end-of-life are considered at the beginning of the design process. In addition this paper will discuss the technical challenges overcome, as well as some of the more creative solutions which have been utilized to reduce casualty risk.

I. INTRODUCTION

While the 2011 reentries of UARS and ROSAT were high profile, it is important to realize that, on average, for the last 50 years some man-made object has reentered the atmosphere every day. When this fact is combined with the continually growing population of the Earth, the result is an increasing risk of a person being killed by reentering debris. Since for many vehicles, a controlled reentry over unpopulated regions of the globe is not an option, the reduction of surviving debris should be addressed during the design phase of a project.

The goal of reducing the amount of hazardous debris reaching the surface of the Earth led to a joint venture by personnel at the NASA Goddard Space Flight Center (GSFC) and the NASA Johnson Space Center (JSC) known as Design for Demise (D4D). The D4D philosophy encourages that early in the design and development phase of a new space mission, preferably no later than Phase A, the spacecraft bus, payloads, and structural components are evaluated for the potential to survive an uncontrolled reentry. This drives an iterative process between the reentry survival specialists, who identify components likely to reach the Earth's surface, and satellite designers, who seek to minimize the number and mass of such objects in a cost-effective manner. The process begins with objects that contribute most to the human casualty risk, and continues until the

risk is either eliminated, or reduced to an acceptable level.

II. BACKGROUND

Since 1995 NASA has held a maximum human casualty risk of 1:10,000 for the reentry of any satellite, launch vehicle, or any related hardware. This limit has since been adopted by all U.S. government agencies and many other national space agencies, as well as the multinational European Space Agency. In order to assess compliance with this requirement, analysts at JSC employ the use of the Object Reentry Survival Tool (ORSAT), a specially designed computer model developed at JSC.

II.I Reentry Risk Requirements

NASA Standard 8719.14A establishes the requirement and defines how to calculate human casualty risk. Simply stated the first step in determining the risk is to calculate the expected debris casualty area (DCA), as in Equation 1.

$$DCA = \sum_{i=1}^N (0.6 + \sqrt{A_i})^2, \quad [1]$$

where N is the number of objects that survive reentry and A_i is the area of the surviving piece in m^2 . The term 0.6 represents the square root of the average cross-sectional area of a standing person, as viewed

from above. Debris with impacting kinetic energies (KE) less than 15 Joules are no longer considered. The total expected human casualty, E, can then be defined as in Equation 2,

$$E = D_A \times P_D, \quad [2]$$

where P_D is equal to the average population density for the particular orbital inclination and year of reentry.

II.II The ORSAT Code

The ORSAT code was developed at JSC to perform assessments of spacecraft, launch vehicle stages, and other man-made component survivability during atmospheric entry from orbital, sub-orbital, and deep space trajectories. To perform an analysis it is necessary to have vehicle trajectory information, as well as detailed construction information including the location, shape, dimensions, mass, and materials of all components. Once the model is complete, ORSAT outputs the demise altitude, for objects that do not impact the ground, or the location, surviving mass, and KE of impact, for those that do (1).

Survivability of an object is determined by the amount of heat absorbed into the component. The rate of heat transfer into an object during reentry is strongly influenced by the object's size and its velocity. The velocity is dependent upon its ballistic coefficient, i.e., mass and shape.

III. CHANGING COMPONENT DESIGNS

Once an object is identified as contributing to human casualty risk, a decision must be made on how to change the design to reduce risk. There are four main ways to accomplish this goal: reduce the amount of energy required for the object to demise; increase the heating rate; layering; or containment. By combining these methods, vehicle designers are able to control cost while either reducing the number of objects striking the earth, or reducing the KE to an acceptable level at impact.

III.I Reduce Energy Required for Total Demise

For a component to demise, it must absorb enough energy to raise its temperature from an initial temperature to its melting temperature and then absorb enough additional energy to melt the object. The amount of energy required to increase the temperature is determined by the specific heat, C_p . The heat of fusion, h_f , determines the amount of energy required for the material to melt. Both C_p and h_f are unique to each material and are defined per units mass, meaning that if the mass of a material increases, the total energy required to melt an object

increases. In order to reduce the energy required for a component to demise, some combination of material change and mass reduction must be utilized.

III.I.I Change of Material

Materials such as titanium and stainless steel have long been used for the construction of satellites and launch vehicles, due to a variety of physical attributes, particularly inherent strength. Unfortunately many of these materials also have high melting temperatures resulting in the components comprised of them having a high likelihood of surviving reentry.

Figure 1 shows a comparison of the demise factor versus time for two spheres with the same dimensions and initial mass, so that the ballistic coefficient is the same, but one is aluminum (melting temperature 880 K), while the other is titanium (melting temperature 1670 K). The demise factor is defined as the total amount of energy absorbed divided by the total amount of energy required to raise the temperature from 300 K to the object's melting point, plus the heat of fusion for the entire mass. As can be seen, the aluminum sphere demises early in the reentry process, while the titanium sphere survives to the ground.

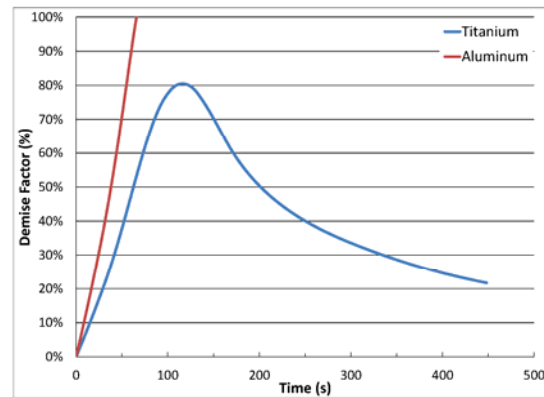


Figure 1: The demise factor versus time for two aerodynamically similar spheres composed of different materials

For the Global Precipitation Measurement (GPM) Spacecraft, the debris casualty area (DCA) was a budgeted quantity much like mass or power. As part of the D4D initiative, a number of components were evaluated early in the spacecraft design process, including the propellant tank and the reaction wheel, which together contributed to a large proportion of the human casualty risk for the entire spacecraft. To address this risk the spacecraft

designers opted for a change of material for these objects.

The DCA budget assigned to the GPM reaction wheels was zero, meaning there could be no surviving components that reached the ground with an impact energy greater than 15 J. A study to compare the survivability of commercially available reaction wheels was undertaken, with the result that none of the examined reaction wheels met this requirement. In response, GSFC developed and qualified a fully demisable reaction wheel by replacing the high temperature melting point materials with aluminum (2).

In a similar manner, the propulsion system was assigned a maximum DCA of zero. Once again the satellite designers were unable to locate an acceptable tank from already existing commercial suppliers, so the decision was made to develop a tank as well. In the case of the fuel tank, the idea of using an aluminum tank for hydrazine was novel, resulting in a question about chemical compatibility between the fuel and the tank. After a number of experiments and studies GSFC was able to design the tank and propellant management device using aluminum, which will completely demise during reentry (3).

The NASA Fermi mission, formally known as the Gamma Ray Large Area Telescope, used a variety of methods to reduce the number of surviving components. Of particular interest to this section were the optical bench struts, originally composed of titanium. When a reentry survivability analysis was performed on the struts, they contributed $\sim 4\text{m}^2$ to the overall debris casualty area of the vehicle. The satellite design team was able to replace them with graphite epoxy struts which met the structural requirements and completely demised during an uncontrolled reentry. (4)

III.I.II Mass Removal

If used in significant quantities even low melting point materials can survive reentry. This is often the case for structural support members. The use of strategically-located cut-outs in bulkheads allow components to retain structural integrity, while increasing the likelihood of demising by a combination of less mass and improved heat transfer processes.

Figure 2 shows the demise factor versus time for two aluminum boxes with identical dimensions. The first has a mass of 16.8 kg, while the second has a mass of 33.6 kg. This scenario illustrates that by finding creative methods to reduce the mass of an object, the likelihood of demise can be increased. It also has the added benefit of reducing the overall mass for the affected system, allowing the overall mass of the vehicle to be reduced.

To reduce mass, an increasing number of spacecraft and launch vehicles have begun to utilize composite overwraps. Adding multiple layers of composite materials increases strength, which permits the designers to reduce the wall thickness of the metallic tank shell. The GPM tank mentioned previously was, in fact, a composite overwrapped pressure vessel with an aluminum liner.

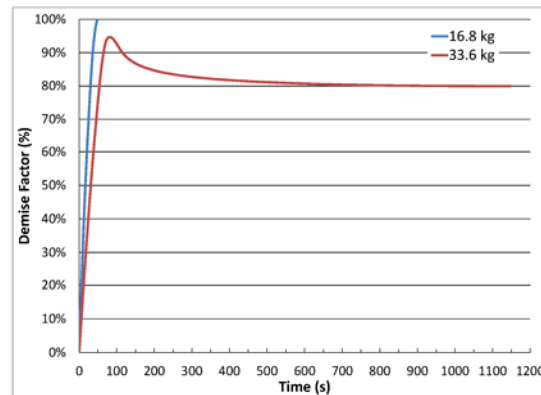


Figure 2: Demise factor versus time for two identically sized aluminum boxes with different masses of aluminum used.

III.II Altering the Ballistic Coefficient

The heat rate that an object will experience during reentry is driven primarily by an object's size and its velocity. In turn, the velocity is determined by the object's ballistic coefficient, i.e., mass and shape. Altering the ballistic coefficient of a component can result in the survivability of that component changing as well.

III.I.I Shape Considerations

Sometimes the shape of a component can affect how it will demise during reentry. In one NASA program the spacecraft included titanium flexures to support the primary instrument. These titanium flexures were found to survive re-entry with an impact energy greater than 15 J. Different materials were considered to replace the titanium, but none were acceptable. Instead, the shape of the flexures was altered, changing the ballistic coefficient enough to eliminate the re-entry hazard.

Figure 3 compares for the demise factor versus time for a sphere, cylinder, and box, all similarly sized and with the same mass, comprised of stainless steel. Since the masses are equal, but each shape has unique drag characteristics, the comparison illustrates the impact of geometry on survivability. In this case, both the sphere and cylinder demise relatively quickly, while the box survives.

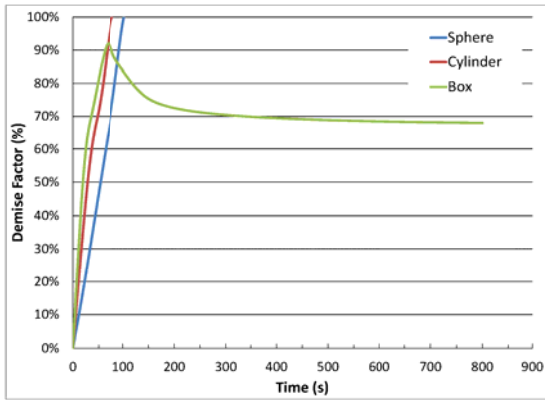


Figure 3: Demise factor versus time for three shapes.

III.II.II Layering

Occasionally the need arises for mass to be added to a spacecraft for reasons such as proper balancing for attitude control, or as ballast to offset acceleration forces resulting from launch vehicles carrying payloads significantly below their maximum capacity. For a number of reasons it is often not possible to select low melting temperature materials for the mass blocks. The result is that the blocks typically pose a reentry hazard. A method to address this hazard is to replace the solid block of material with multiple thin layers, designed to either demise during reentry, or to impact with a kinetic energy less than 15 J. As can be seen in Table 1, by replacing one ballast mass of 0.96 kg with 24 thin sheets, the kinetic energy is reduced from 3974 J to 13 J.

Object	Qty	Mass (kg)	DCA (m ²)	KE (J)
Solid Mass Block	1	0.96	0.419	3974.2
Mass Block Layer	24	0.04	0.407	13.2

Table 1: DCA and kinetic energy for ballast masses

The NASA Radiation Belt Storm Probes was initially designed using a total of 30-40 tungsten weights with a mass of about 1 kg each. The reentry analysis of this vehicle predicted the tungsten weights would survive, resulting in a large human casualty risk. While a similar mass block constructed out of lead would demise, a number of the material's other properties eliminated it as a possible replacement. The project team proposed a novel solution to this problem. Each solid block of tungsten would be replaced with several thin plates held together with an aluminum band. Subsequent reentry analysis of this design showed that the band demises quickly, releasing the individual plates. While the thin tungsten plates still survived reentry,

they impacted the ground with a KE less than 15 J, thus posing no ground casualty risk.

III.III Containment

This method of reducing risk begins counter intuitively by causing a demising object to survive in order to reduce the number of items impacting the ground. As an example, consider a component that consists of an outer box with a number of components contained within it. If that outer box is designed so that it demises, but it does so at a low altitude, or if the components inside are made of high melting temperature materials, the result could be a large number of objects reaching the ground, adding to the vehicle's risk. By building the box in such a way that it survives, the inner components are never released, thus the casualty area is limited to only that which is associated with the box.

Figure 4 illustrates the possible outcomes mentioned above. The red spheres represent the DCA of a number of high melting temperature objects that were released when the aluminum box containing them demised. The green sphere represents the DCA resulting from the box being made of titanium instead of aluminum. The result is the DCA of the four surviving components from this scenario is 2.143 m², over four times the DCA for the box alone, which is 0.522 m².

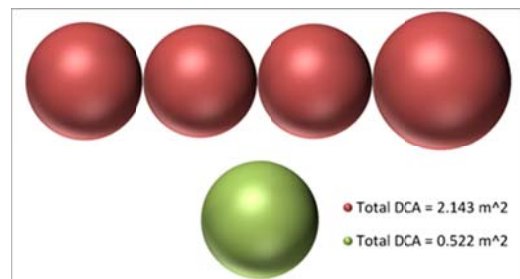


Figure 4: Comparison of the DCA contribution from a single box to that of its contents.

IV. CONCLUSIONS

There are a number of viable options for reducing the amount of surviving debris from a reentering spacecraft. By planning for end-of-life and making use of the D4D philosophy, projects can reduce the cost of compliance with risk regulations governing surviving debris. In scenarios where new components must be designed, the associated effort will be valuable for not only the project requiring the design, but also future projects that require similar components.

V. REFERENCES

1. Dobarco-Otero, J., Smith, R. N., Bledsoe, K. J., De Laune R. M. (2006). JSC-62861, User's Guide for Object Reentry Survival Analysis Tool (ORSAT) – Version 6.0, Vol. I.
2. Bundas, D. (2006). Global Precipitation Measurement Mission Architecture and Mission Concept, presented at *IEEE/AIAA Aerospace 2006*, Big Sky, MT, USA, NASA NTRS 20060012298.
3. Estes, R. H. and Moore, N.R. (2007). “An Overview of Demise Calculations, Conceptual Design Studies, and Hydrazine Compatibility Testing for the GPM Core Spacecraft Propellant Tank,” presented at *54th JANNAF Propulsion Conference (CPIA)*, Denver, CO, USA, NASA NTRS 20070023407.
4. Leibee, J., Ford, T., and Whipple, A. (2004). “NASA GLAST Project Experiences Managing Risks of Orbital Debris,” in *Eighth International Conference on Space Operations*, Montreal, Canada, American Institute of Aeronautics and Astronautics.