CUBESAT MATERIAL LIMITS FOR DESIGN FOR DEMISE

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ABSTRACT

The CubeSat form factor of nano-satellite (a satellite with a mass between one and ten kilograms), has grown in popularity due to its ease of construction and low development and launch costs. In particular, its use as a student-led payload design project has increased due to the growing number of launch opportunities. Increasingly, CubeSats are deployed as secondary or tertiary payloads on U.S. commercial launch vehicles or from the International Space Station (ISS). The focus of this study will be on CubeSats launched from the ISS.

From a space safety standpoint, the development and deployment processes for CubeSats differ significantly from those of most satellites. For large satellites, extensive design reviews and documentation are completed, including assessing requirements associated with re-entry survivability. Typical CubeSat missions selected for ISS deployment have a less rigorous review process that may not evaluate aspects beyond overall design feasibility. CubeSat design teams often do not have the resources to ensure their design is compliant with re-entry risk requirements.

An analysis examined methods to easily identify the maximum amount of a given material that can be used in the construction of a CubeSat without posing harm to persons on the ground. The results demonstrate there is not a general equation for determining the maximum amount of mass that can be used for a given material. It is possible, however, to set a limit based on the object's heat of ablation that can be used to decide if reentry analysis is needed for an object. In addition, the specific limits found for a number of generic materials, used previously as benchmarking materials for re-entry survivability analysis tool comparison, will be discussed.

1. DEFINITION OF A CUBESAT

The CubeSat design specification was developed and is maintained by California Polytechnic San Luis Obispo, California in [1]. CubeSat dimensions are typically referenced as 1U, 2U, 3U, etc., referring to CubeSat units, where 1U has dimensions of 10 x 10 x 10 cm and a mass of approximately 1.33 kg. The small size and mass of these vehicles permits them to be added as secondary payloads, additional objects deployed by the launch vehicle; and tertiary payloads, objects deployed by a another satellite, on numerous launch vehicles.

Both the Orbital Sciences Cygnus and SpaceX Dragon vehicles used for resupply of the International Space Station (ISS), as well as the ISS itself, currently have deployers installed allowing for the release of CubeSats. The large number of available launch opportunities has resulted in a low cost method for university and small commercial satellites to get into space. In addition the NASA Launch Services Program funds a number of opportunities through its Educational Launch of Nanosatellites (ELaNa) Project.

Currently, there are no special exemptions or permissions for CubeSats in the NASA or U.S. Government Debris mitigation guidelines. For many missions, however, the CubeSats are often in the later stages of their design cycle before they are offered a flight opportunity. Unfortunately projects often have not evaluated their vehicles for orbital debris (OD) mitigation guideline compliance prior to being provided a flight opportunity. The result is that any compliance issues could significantly impact a vehicle's ability to fly as it may be too late in the design process to make any necessary changes to ensure compliance.

2. RE-ENTRY REQUIREMENTS AND ANALYSIS

NASA requirements for OD mitigation can be found in the NASA Standard (NS) 8719.14 [2]. Of particular interest to this study is requirement 4.7-1, which limits the risk to the population of 1:10,000 from impacting debris. An object is considered to be a hazard if it impacts with more than 15 J of kinetic energy (KE). The policy requires the use of either the NASA Debris Assessment Software (DAS) or the higher fidelity NASA Object Re-entry Survivability Analysis Tool (ORSAT) to verify compliance is met [3].

NASA ORSAT includes 78 materials that can be used to model spacecraft components to determine re-entry survivability. Included in this list are three generic materials that are typically used for comparison with other re-entry tools: aluminum, stainless steel, and titanium.

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3. ANALYSIS ASSUMPTIONS

This analysis was initially prompted by questions regarding compliance with reentry risk requirements for CubeSats being launched from the ISS. The analysis assumed an uncontrolled re-entry from 51.6° inclination with an initial velocity of 7.5 km/s at 122 km and initial flight path angle of -0.1°. The CubeSats were modeled from 122 to 78 km assuming no heating, with an initial temperature of 300 K. It was also presumed that the CubeSat breaks apart at 78 km, exposing the interior components to heating.

The heat experienced by an object entering the atmosphere is strongly dependent on the size of the object and its velocity. During propagation the velocity is a function of the initial velocity and its ballistic coefficient, which is a function of size and mass. This requires that a varied set of initial conditions be applied. Specifically the analysis evaluated the re-entry survivability of components of 1U, 2U, 3U, 6U, and 12U satellites with mass and dimensions as defined in Table 1.

Table 1. CubeSat form factor dimension and mass definitions

Form Factor	X Dim (cm)	Y Dim (cm)	Z Dim (cm)	Mass (kg)
1U	10	10	10	1.33
2U	20	10	10	2.66
3U	30	10	10	4.00
6U	30	20	10	8.00
12U	30	20	20	1~~2~~6.00

The components inside the CubeSats were modeled as either spheres, cylinders, or boxes, all randomly tumbling once they are released from the parent at 78 km. For this analysis no objects were considered to be nested inside of other objects beyond the parent CubeSat.

The dimensions of these components varied from 1 x 1cm up to the maximum that would fit inside the parent being modeled. The maximum sphere size was a 10 cm diameter, while cylinders had maximum dimensions of 10 x 30 cm, and boxes a maximum of 30 x 20 x 20 cm. The mass was varied by altering the object wall thicknesses, with the minimum being set by a wall thickness of at least 1 mm. The maximum mass was limited to 1.25 times the number of CubeSat units (i.e., for a 1 U CubeSat the maximum mass of an object was 1.25 kg).

In this analysis we examined three hypothesis to determine if a simple relationship, suitable for engineering design, existed. These are the melting temperature versus the maximum allowable mass, the density versus the maximum allowable mass, and the object's specific heat of ablation versus the maximum allowable mass. Here the maximum allowable mass is defined as the maximum mass of a realistic object that will either demise or hit the ground with an impact energy less than 15 J. The specific heat of ablation is the amount of heat required to result in an objects demise divided by its mass and is calculated as in Eq. 1.

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$$h_{ablat} = \int_{T_i}^{T_{melt}} CpdT + h_f \qquad (1)$$

Where Cp is the material's constant pressure specific heat capacity, h_f is the material heat of formation, T_i is the initial temperature (300 K in this analysis), and T_{melt} is the material melt temperature.

4. RESULTS

In total more than 14,000 components were modeled. Figure 1 shows a demise altitude versus downrange distance plot for all of the components, which has been normalized by setting the 78 km break-up altitude as 0 km downrange. It is clear that many of the objects survive and the objects originate from all five sizes of CubeSat.

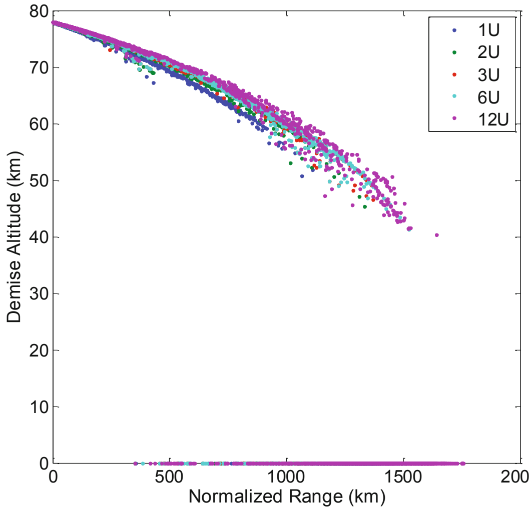

Figure 1. Demise Altitude (km) versus Downrange Distance (km) of all components analyzed. Objects along the x-axis are those that survive to hit the ground.

As illustrated in figure 2, the relationship between melting temperature and allowable surviving mass was not simple. There are a number of materials with lower melting temperatures which have relatively low limits on the mass that can be used. Conversely there are a number of materials with higher melting temperatures that demised even with the maximum allowable mass of material.

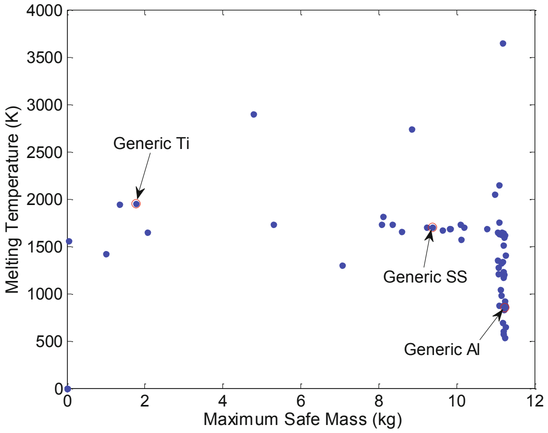

Figure 2. Melting Temperature (K) versus Maximum Safe Mass (kg) showing objects that demise or impact the ground with less than 15 J KE.

Figure 2 shows the comparison of density versus maximum allowable mass. The result for the comparison was much the same as melting temperature. Some of the highest density materials tended to always demise, and a number of the lower density materials would survive in nearly all cases. Once again no simple relationship is found.

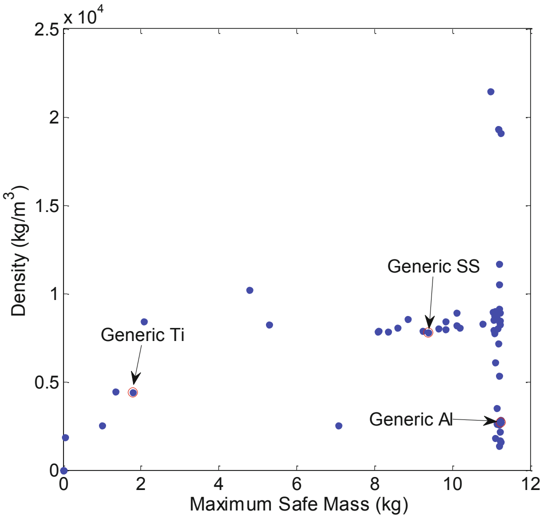

Figure 3. Density (kg/m^3) versus Maximum Safe Mass (kg) showing objects that demise or impact the ground with less than 15 J KE.

The final variable to explore was the specific heat of ablation for the object. Figure 4 shows a comparison between the heat of ablation and the maximum safe mass. For a specific heat of ablation below about 950 kJ, components pose no risk to people on the ground as any object impacting the ground does so with a KE < 15 J.

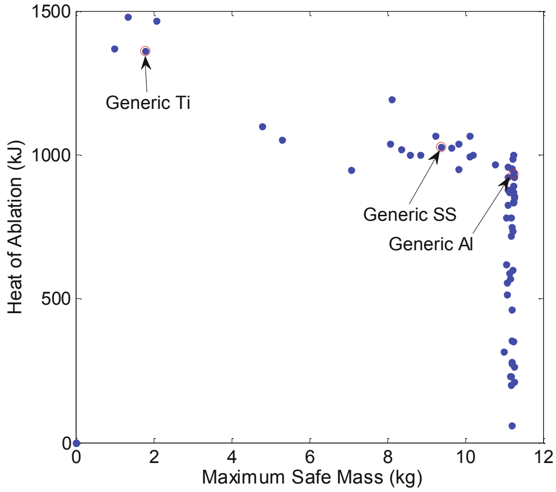

Figure 4. Specific Heat of Ablation (kJ) versus Maximum Safe Mass (kg) showing objects that demise or impact the ground with less than 15 J KE.

The data in Table 2 represents the results for generic aluminum, stainless steel, and titanium. Comparing the specific heat of ablation with the maximum safe mass shows that for a material with a specific heat of ablation less than 950 kJ, the limit of allowable mass is as high as the limit of analyzed mass. As the specific heat of ablation increases the allowable mass decreases.

Table 2. Results for generic materials used

Material	Melt Temp (K)	Max Safe Mass (kg)	Cp (J/kg-K)	hf (J/kg)	Spec. Heat of Ablation (kJ)
Al	850	11.2	1100	390000	934.5
SS	1700	9.4	600	270000	1026
Ti	1950	1.8	600	470000	1361

5. CONCLUSIONS

Major findings from this analysis prove there is no simple equation that will define how much mass of a given material can be used in the construction of a CubeSat. However, for an ISS-deployed object it is possible to eliminate analysis for components whose specific heat of ablation is below 950 kJ. For those objects with a higher specific heat of ablation, further analysis is required before a determination can be made regarding the risk to the public from reentering CubeSat components.

6. RECOMMENDATIONS

This analysis was limited to objects deployed from the ISS. It is recommended that further analysis be conducted to determine if the 950 kJ limit is constant across multiple inclinations, or if the orbital velocity variance changes the limit on the specific heat of ablation.

7. REFERENCES

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