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 their ease of construction and low development and launch costs. In particular, their use as student led payload design projects has increased due to the growing number of launch opportunities. CubeSats are often deployed as secondary or tertiary payloads on most US launch vehicles or they may be deployed from the 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 that 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.

A study was conducted to examine methods to easily identify the maximum amount of a given material that can be used in the construction of a CubeSats without posing harm to persons on the ground. The results demonstrate that there is not a general equation or relationship that can be used for all materials; instead a limiting value must be defined for each unique material. In addition, the specific limits found for a number of generic materials that have been previously used 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 cm x 10 cm 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 and tertiary payloads on numerous launch vehicles. Both the Orbital Cygnus and SpaceX Dragon vehicles used for resupply of the International Space Station (ISS) have included CubeSat deployer mechanisms and the ISS currently has a deployer 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 NASA funds a number of opportunities through its Launch Services Program Educational Launch of Nanosatellites (ELaNa) program.

There are currently 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 vehicles that vehicles 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 [2], the NASA Standard (NS) 8719.14. Of particular interest to this study is requirement 4.7-1 in [2] which limits the risk to the population of 1:10,000 from impacting debris. An object is considered to be a hazard if it impact with more than 15 J 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) described in [3].

ORSAT includes 78 built in 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.

3. Analysis Assumptions

This analysis was initially prompted by questions regarding CubeSats being launched from the ISS. This led to the analysis being performed assuming a random re-entry from 51.6° inclination with an initial velocity of 7.5 km/s at 122 km. The CubeSats were modeled from 122 to 78 km assuming no heating, with an initial temperature of 300 K.

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

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	12.00

Table 1. CubeSat form factor dimension and mass definitions

The components inside the CubeSats were modeled as either spheres, cylinders, or boxes, all randomly tumbling once they are released form 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 cm x 1cm up to the maximum which would fit inside the parent being modeled. The maximum sphere size was a 10 cm diameter, while cylinders had maximum dimensions of 10 cm x 30 cm, and boxes a maximum of 30 cm x 20 cm x 20 cm. The mass was varied with the minimum being the smallest mass that would result in a wall thickness of at least 1mm. 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).

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 for 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.

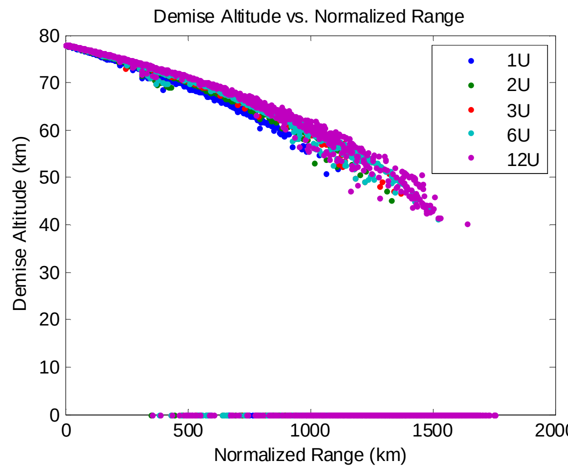

Figure 1. Demise Altitude (km) versus Downrange Distance (km) of all components.

Initially it was hypothesized that there may be a relationship between the melting temperature of a material and the maximum amount of mass of that material that can be used without being hazardous. As illustrated in figure 2, the relationship 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.

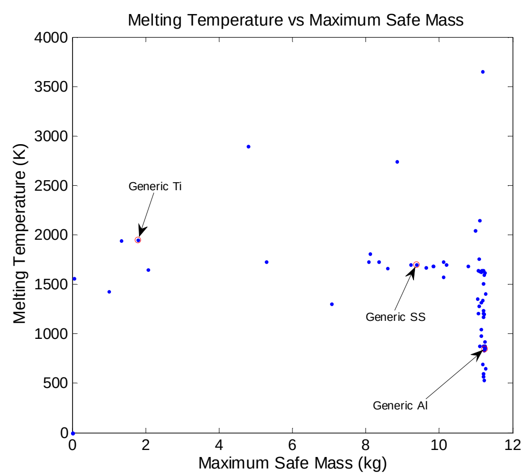

Figure 2. Melting Ttemperature (K) versus Maximum Safe Mass (kg)

With mass being a driving factor in determining the survivability of an object, the next hypothesis centered on the density. 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.

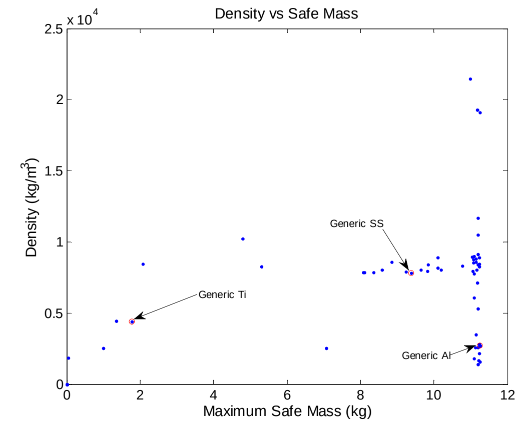

Figure 3. Denisty (kg/m^3) versus Maximum Safe Mass (kg)

The final variable to explore was the specific heat of ablation for the object. 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 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. 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.

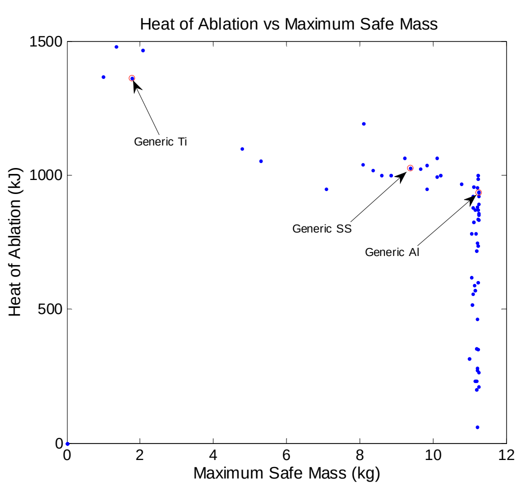

Figure 4. Specific Heat of Ablation (kJ) versus Maximum Safe Mass (kg)

The data in table 2 represents the results for generic aluminum, stainless steel, and aluminum. Comparing the specific heat of ablation with the maximum safe mass it can be seen that for a material illustrates 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.

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

Table 2. Results for generic materials used

5. Conclusions

There is no simple equation that will define how much mass of a given material can be used in the construction of a CubeSat. For ISS deployed object it is possible to eliminate the need for 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 on those objects 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 of the orbital velocity variance changes the limit on the specific heat of ablation.

9. REFERENCES

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