A MODEL FOR THE GENERATION OF MICRO-DEBRIS RESULTING FROM ATOMIC OXYGEN IMPACT

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ABSTRACT

The majority of quantitative empirical data on space debris is associated with debris which can either be tracked or inferred as a result of its impact upon systems which are returned to earth. In the case of the latter data, which describes the micro-debris population, the limited amount of data available from returned objects results in difficulty in assessing accurately the micro-debris component in the environment. Maclay and McKnight [1] were the first to identify potential sources for micro-debris. In this paper we focus upon one of the mechanisms identified, namely the erosion of material resulting from atomic oxygen (atox) impact.

1. INTRODUCTION

The majority of research into the effects of space debris has concentrated on potential impacts which may lead to either the loss of or severe damage to a vehicle. Considerable effort has been made to develop models which are able to predict the current state of the debris environment as a result of known events including satellite launches, break up of upper stage vehicles and other known fragmentation events. Consistency between these models and the "measurements" made on the environment can potentially provide a secure basis for predicting the future debris population of objects. One of the principal problems however for model validation, is the low collision frequency between objects that are trackable, since collisions are so infrequent amongst these bodies.

The majority of collisions arise from the high population density of objects which are too small to be tracked. This results in difficulty in making appropriate comparisons between predicted and observed collision frequency, since only a limited number of objects have been returned to the ground to enable such an analysis to be performed.

Probably the most comprehensive analysis has been of LDEF, which showed in excess of 34,000 impact features. A recent paper by Maclay and McKnight [1] presented an analysis of these impacts, including their size and origin. Origin of such impacts, whether man-made or naturally occurring, is vital. Of the impacts (crater size > 30 μm) whose origin could be determined (i.e. natural vs artificial), nearly a quarter (24%) were found to be of artificial origin. Due to the nature of the analysis, this is believed to be an under-estimate of the artificial objects, and must be the result of a substantial population of micro-debris particles.

Maclay and McKnight proposed a variety of sources for the production of micro-debris, which they refer to as debris wakes. In this paper, we concentrate on just one of these sources - atox reactivity.

2. THE MODEL

The model presented here is not expected to reflect accurately the micro-debris production mechanism. We are however interested in the potential volume of material which might arise from the interaction between atox and space vehicle surfaces. This simplified analysis, therefore, assumes that the production rate in a debris wake is solely due to the volumetric reaction rate (i.e. in cm^3/atom) of atox with surfaces flying through the low earth orbit (LEO) environment. This approach is a significant distortion from the probable reaction mechanisms likely to occur. The value of the method however lies in recognition that this should *under-estimate* the volumetric production rate. The probable mechanism for paint flaking (likely to be the nature of micro-debris) will arise from the synergy between atox, changing the thermo-mechanical properties of surfaces, and thermally induced micro-cracks. Atox alone

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will yield volatile reaction products as part of this process. These volatiles alone are, therefore, the minimum amount of material released into the environment as a result of interactions with atox.

The starting point for the analysis is the trackable debris environment. Using the two line element data it is possible to assign a time weighted distribution of the number of objects in any given altitude band. This distribution is compared with the data available for satellite orbital elements at injection. Figure 1 shows the two distributions resulting from these different sources. It is clear from this that the two distributions are broadly similar. This enables a simplification to be made in the analysis since it implies that it is not necessary to distinguish between types of object and orbital parameters. As a first approximation it is then possible to assign a certain fraction of the objects to be of a certain type (e.g. upper stage bodies), for the overall two line element derived time weighted altitude distribution.

The objects included in our analysis have been categorized in three groups: satellites, upper stage bodies and mission-related objects. Excluded from the analysis are those defined to be of fragmentation origin. The percentage distribution of these is given in Table 1. Fragmentation objects were excluded from the analysis since both their size distribution and their origin (and hence material) are uncertain. The exclusion of these objects will lead to an under-estimate in the production of micro-debris.

The size distribution assumed for each category of objects was based upon the historical launch manifest [5]. These were used to determine an average size for each category.

Using the data of Table 1, together with the time-weighted altitude distribution of objects, it is possible to define for each altitude band considered, the annually exposed area of surfaces in LEO. These data need some consideration if they are to be equated to a surface area for reaction. Uncontrolled objects, of whatever origin, will have some residual angular momentum. The spin of such an object will be about the axis of maximum moment of inertia. This axis may in principle be oriented at any angle relative to the velocity vector of the centre of mass. For a cylindrical body, two extreme cases can be considered, in one case an end-over-end rotation along the trajectory, and in the second case rotation perpendicular to the velocity vector, as in the case of a propeller. King Hele [2] considered both this type of body, and other shapes. He concluded that for cylindrical objects, the average cross-section differed from the product of length and diameter by less than 13%. The calculation of effective area for aerodynamic drag in rarefied gas flows is different from the calculation of 'wetted' surface area for atox reactivity in one notable aspect: atox will react with an exposed surface with efficiency varying with direction of impact.

In conclusion, following the work by King Hele and reflecting on specific issues associated with atox reactivity for this preliminary evaluation, which will at best provide an order of magnitude evaluation, it is reasonable to equate the average cross-sectional vehicle data with the area exposed to atox erosion.

The next element considered in the model is the surface material model for the three classes of object. Two satellite models were considered: a three axis stabilized and a spin stabilized case. In the former case, there are two components - a body (33% of the exposed surface) extensively shrouded in thermal control blanket and a solar array. The array was assumed to be planar, the front surface consisting 95% borosilicate glass and 5% silver and the rear surface to be Kapton. The spinning satellite was assumed to have 75% cover in solar cells (again with the silver component) and 25% thermal blanket. The rocket body and the mission-related object were assumed to be painted. Table 2 includes the data used for atox reactivity. For the satellite data, the surface reactivity is fairly well established. For mission-related objects and rocket bodies the situation is less clear. Paints used on these are generally different from those used for thermal control purposes on satellites, for example, the Sylda fairing uses Aerostat-B, which is similar to paints used in the aircraft industry. As a result, the reactivities for these paints with atox have not been presented in the literature. To gain some impression of surface erosion, however, two different types of paint have been assumed: Z302 and A276.

Atox fluence on the surfaces was derived from the Jachia atmosphere [3]. Low, medium and high solar activity levels for species concentration assumed exospheric temperatures of 700, 900 and 1500 K respectively. The atmospheric model calculates atox number density only, not fluence. Conversion to fluence requires the swept volume by a surface to be determined. Whilst it is apparent from the two line element data that debris is not exclusively in circular orbits, a substantial fraction [4] of debris is nearly so. As a result, in order to calculate fluence for this analysis, the mean circlar velocity in each altitude band was used in conjunction with the density figures.

3. RESULTS

The model described above has been used to evaluate the annual volumetric release of material from debris due to atox erosion. Figure 2 shows graphically the volumetric release as a function of altitude for the different object categories. The calculations sumarised in this figure are for the case of medium solar activity. It can be seen that the most significant contribution arises from the 3 axis stabilised model spacecraft. This is not surprising since this configuration contains the largest area of Kapton. In this figure, Z302 is assumed to be the paint used. The overall trend in each of the curves follows the exponentially decreasing number density of atox.

Figure 3 shows how the yield varies with solar activity for the case of a spinning satellite together with mission related objects and upper stage launch vehicles painted in low reactivity paint. On these curves the yield of material is quantified in terms of equivalent 7 µm particles. This unit has been chosen to enable comparison to be made with the results quoted in [1]. Figure 4 shows data for the 3 axis controlled satellite and high reactivity paint. It should be noted that the rather curious result shown for the highest solar activity (1500K) is as a consequence of the combined effects of slow decrease in atox density at this rather high level of activity, and the increase in number of satellites (as indicated by the time weighted residence distribution) in this altitude band. This effect is not noticable in the lower solar activity cases because of the more rapid reduction in density under these conditions.

DISCUSSION

The results in [1] quote the required volume of material to be consistent with LDEF results. Due to the relatively low residence time of micro-debris, their calculation indicates the necessary total annual release of material above the LDEF orbit (taken to be 475km). Their results imply a release of between 10^{13} and 10^{14} particles depending on the level of solar activity. Using the model described here, results are given in table 3 for the cases considered. An additional case of a spinning satellite without any silver is indicated in this table to provide a minimum yield of material. The overall conclusion that may be drawn from this table is that it appears that the volume of material released due to potential volatiles arising from reactions with atox, is the same order of magnitude as that indicated by the LDEF impact results.

It is apparent from figure 2 that above 300km, the yield of material is dominated by satellites rather than the other objects. This is important since the reactivity of paint used on this latter catagory of object is poorly defined. Further analysis should therefore concentrate upon a more detailed defintion of the satellite material model, rather than the materials used on upper stages and mission related objects.

CONCLUSIONS

The analysis presented here provides a highly simplified description of a potential source for micro-debris. The results indicate that on the basis of volumetric yield, atox recession of surfaces is of the correct order of magnitude to comply with the observed impact data on LDEF. It is important to note however that this does not confirm that the erosion by atox is necessarily responsible for the impact data. The way in which atox erodes material must be considered in much greater detail before this conclusion could be reached. However, it is clear from the analysis that atox effects on materials must be considered to be a major contribution to the production of micro-debris.

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Table 1
Distribution assumed for trackable objects by type

Type of Objects	Satellites	Upper stages	Mission-Related	Fragments
% of objects	27%	16%	12%	45%
Area	7.64m²	13.9m²	3.5m²	-

Table 2
Reactivity Data

Material	Reactivity
Kapton-H	2.2×10^{-24}/(cm³/atom)
Silver	10.5×10^{-24}/(cm³/atom)
Borosilicate glass	0.01×10^{-24}/(cm³/atom)
A276	1.0×10^{-21}/(mg/atom)
Z302	5.8×10^{-21}/(mg/atom)

Table 3
Release of 7 μm Particles above 475 km

	Temperature		
	700 K	900 K	1500 K
Spinning Satellite - Low reactive paint	1.6×10^{12}	1.1×10^{13}	1.8×10^{14}
3 axis satellite - High reactive paint	2.7×10^{12}	1.9×10^{13}	3.1×10^{14}
Spinning satellite (no silver) Low reactive paint	7.5×10^{11}	5.3×10^{12}	8.5×10^{13}

FIGURE 1. TIME WEIGHTED AVERAGE FOR SATELLITES AND TWO LINE ELEMENT OBJECTS

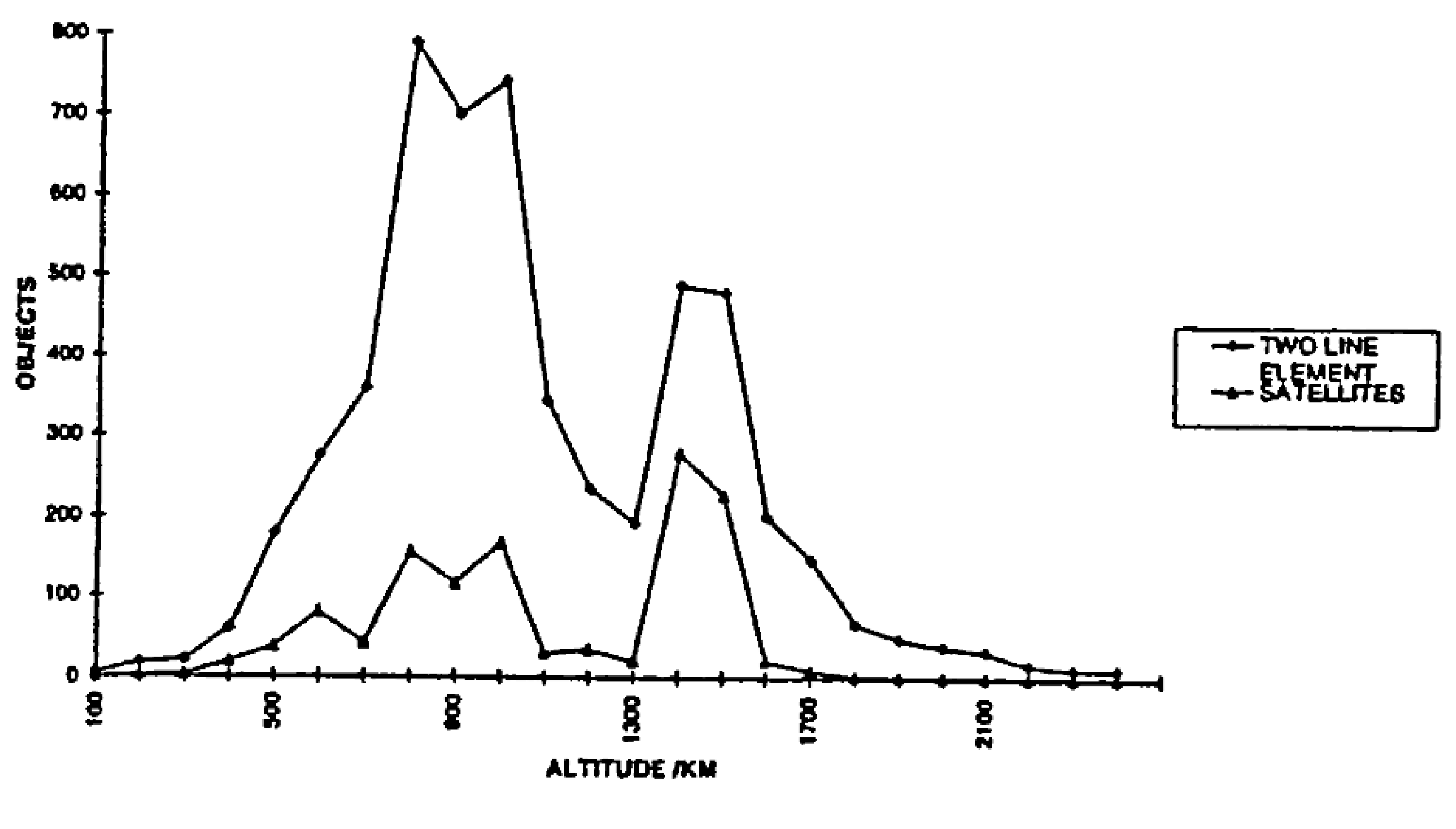

FIGURE 3. YIELD OF 7um PARTICLES FOR SPIN STABILISED, MISSION RELATED OBJECTS AND UPPER STAGES PAINTED IN A276

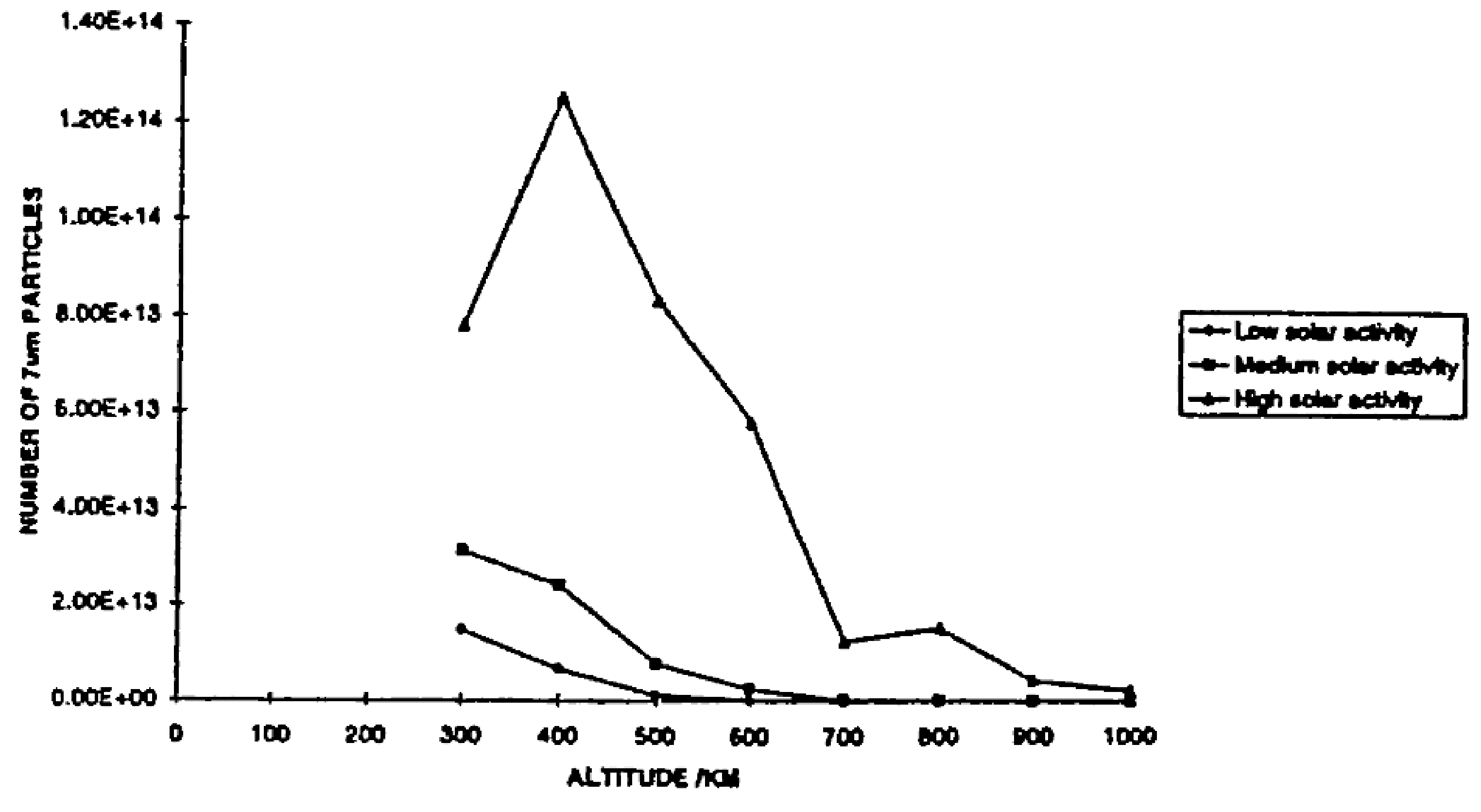

FIGURE 2. COMPARISON OF VOLUME RECESSED FOR DIFFERENT OBJECTS (900 DEG.)

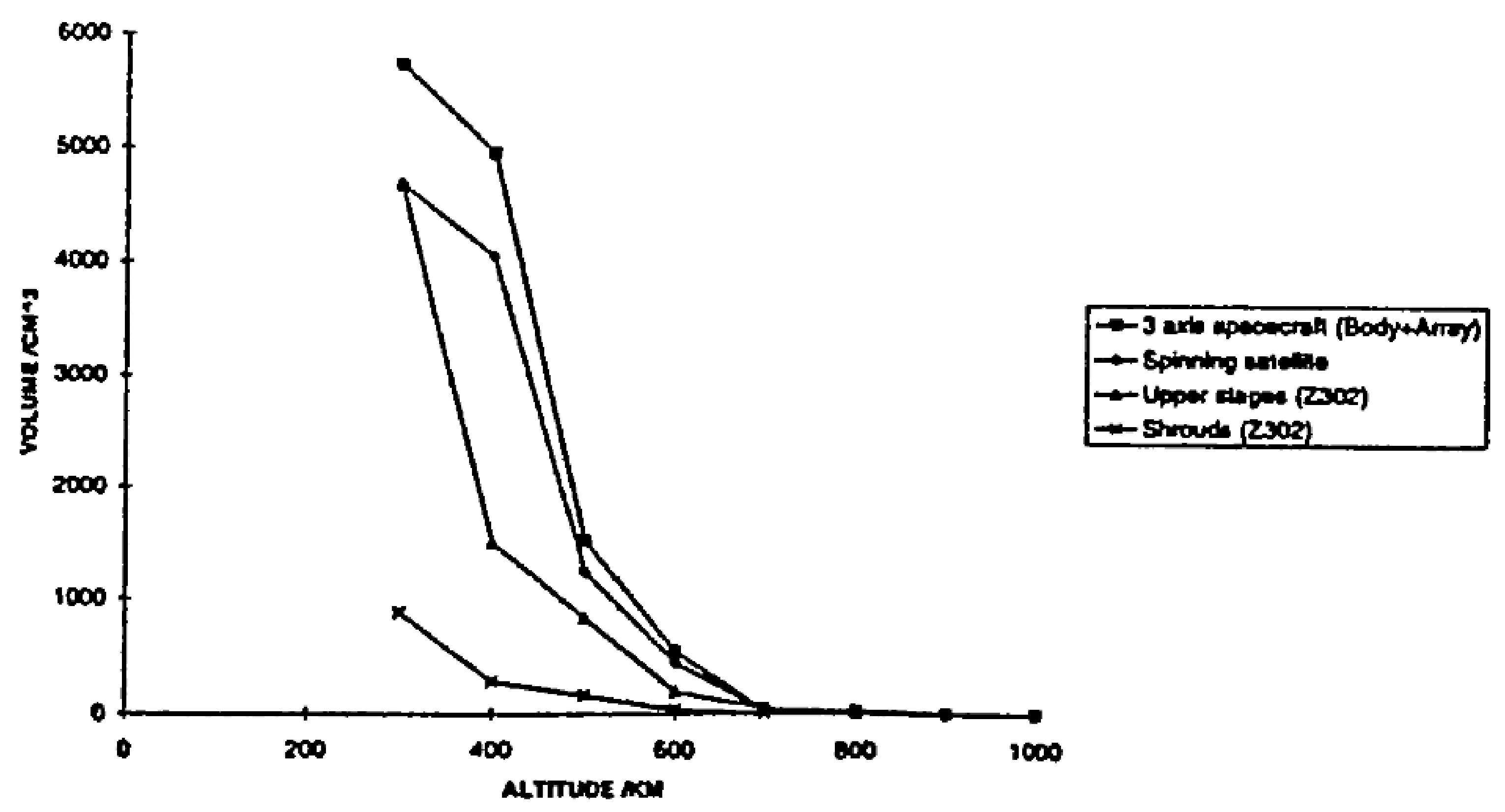

FIGURE 4. YIELD OF 7um PARTICLES FOR 3 AXIS STABILISED SATELLITES, MISSION RELATED OBJECTS AND UPPER STAGES PAINTED IN Z302