Orbital Debris Remediation: Technical, Economic and Policy Issues

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By concentrating on the largest (primary) orbital debris (OD) objects in near- Earth space, $\geq$ 1m, a combination of preventative technical guidelines on new and de-orbit activities on existing primary debris can economically curtail growth in secondary OD and remediate a significant portion of current OD over time, especially in the densely populated low earth orbit (LEO). The former requires a built-in (rocket) capability for immediate de-orbiting of boosters and the latter the robotic de-orbiting of inactive satellites and related large booster OD. A dynamic impact/momentum transfer analysis supports a priority of removing the largest OD in LEO via robotic de-orbiting using an autonomous re-usable space-plane. Putative OD preventive and remedial policy guidelines from organizational and strategic perspectives are outlined.

1. Introduction

Its getting crowded and dangerous in near-Earth space (NES). In addition to the continuous accretion of cosmic dust by the Earth [1] and meteoroids, currently there are > 1,000, and growing, operational satellites several meters in size orbiting in NES in regions from 200 - 2,000 km in low Earth orbit (LEO), 2,000 - 35,000 km in mid-Earth orbit (MEO), and at 35,800 km in geosynchronous orbit (GEO) [2]. Added to this are the rapidly proliferating (currently ~ 100/y), unregulated and inexpensive, so-called CubeSats- small, ~ 10 cm and getting smaller, ~ 1 kg, with orbital lifetimes 25 – 100 y or greater and currently no de-orbit mechanism [2].

LEO is primarily used for Earth (both military and civilian) reconnaissance, remote sensing, the space station, the Hubble space telescope, and the Iridium system. MEO is primarily used for navigation and GEO for communications and (TV) broadcasting. Beyond ~ 36,000 km is a so-called “graveyard orbit” (GO) where some post-operational satellites can be de-commissioned. Among the space faring nations the US controls ~ 1/2, Russia ~ 1/10, China ~ 1/16, India and the UK and other countries with lesser amounts of operational satellites.

Satellites in NES are critical for commerce, environmental monitoring, and international security. However, eventually these satellites become non-operational primary OD and must be de-orbited before presenting collision risks to one another or are impacted by existing smaller pieces of OD that co-orbit in NES with operational satellites. Primary OD is made up of spent rocket upper stages, defunct satellites and larger pieces of space detritus that if not remediated, OD will achieve a threshold density establishing conditions for catastrophic evolutionary growth into a series of chain reactions initiated by accidental collisions up to ~ 10’s km/s. This dynamic scenario, if left unchecked, will result in a critical OD density level that will be a hazard to operational satellite that may ultimately deny access to the “commons” of NES in the foreseeable future [3] . Such an event will have severe immediate global economic repercussions that from several perspectives will jeopardize international security and commerce. It is the objective of this document to quantitatively outline and critique technical solutions and operational policy guidelines to manage the OD risk by mitigating against future catastrophic collisions in NES.

2. Orbital debris concentrations, collisions fragmentation, and vaporization

An estimated OD population [2] is listed in table 1. Some of this is radioactive material leaking from several Russian older nuclear reactors that may threaten active satellites in LEO. The U.S. Defense department Space Surveillance Network (SSN) has cataloged trackable OD ranging ~ 12,000 objects > 10 cm, but there is also a more rapidly growing population of OD in the range of $> 10^6$ objects at ~ 1cm.

Most OD is in LEO where, numerically, active satellites represent a very small portion of NES objects. Because of their high orbital velocities, from ~ 7.8 km/s in LEO to ~ 3.1 km/s in GEO, OD has a specific orbital kinetic energy from ~30 MJ/kg in LEO to ~ 5 MJ/kg in GEO. At these impact velocities a 1 cm^3 particle of aluminum alloy may substantially damage an active satellite or larger piece of OD depending on the relative velocity of impact as determined by orbital altitude, eccentricity, and inclination of the intersecting orbits [4,5,6]. In LEO collision velocities may vary from ~ 0-15 km/s.

To safeguard the optimal functioning of active satellites OD levels in NES must be constrained and remediated, while minimizing frivolous activities such as CubeSats. Velocity distribution of OD released upon collision and ensuing orbital fratricide and associated OD generation will depend on the mass, material properties, velocities, densities and structural configuration (geometry) of both the target satellite and impactor. For an OD particle ~ 1g impacting a large target, (> 100 kg) the relative (orbital) momentum transfer to that of the target will be minimal.

Table 1 shows relative mass concentrations of OD is overwhelmingly concentrated in large objects > 10 cm. This population must be given remediation priority.

OD Size (cm)	***Number***	***% OD***	***% Mass***
> 10	8,000	0.02	99.93
1 –10	110,000	0.31	0.035

0.1 – 1	35,000,000	99.67	0.035

Table 1. Estimated OD Population (2) Natl. Res. Council, Interagency Rept., 1995). Cataloged objects make up ~ 99 % of the OD mass and thereby pose the greatest OD collision and cascading fragment generation hazard. Haystack detections are ~ 600 - 1,600 km and radar cut-off at ~ 0.6 LEO extends well above 1,000 km the Haystack numbers at higher altitudes may be too low (~ 2 x) because of radar resolution limits. For 0.5 cm particles, $\sigma_{0.5\ \mathrm{cm}} \approx 10^{-4}$ /y-m^2, but may be higher. For OD ≥ 0.1 cm ($\sigma_{0.1\ \mathrm{cm}} \approx 8 \times 10^{-4}$ /y-m^2), structural damage and space erosion may become an important factor.

The enormous energy released during high speed OD impacts rapidly initiates a very complex dynamic sequence of events depending on relative density, mass (size), strength, and thermodynamic properties of the interactants. When kinetic energy/kilogram exceeds the vaporization energy per kilogram, a high energy density (HED) process generates a plasma/ablation region at the collision interface. Analysis [7] suggest a 1g OD mass impactor undergoes massive vaporization at a relative impact velocity ~ 5-10 km/s. For targets, such as satellites that are orders of magnitude more massive than the OD impactor, much of OD impactor energy is partitioned into self-melting and vaporization. Satellite and OD materials with similar structure and roughly equivalent masses will be partially vaporized with the bulk of the more massive satellite remaining intact while generating massive amounts of secondary OD ejecta. Fragmentation and OD is commensurate with impact velocity and satellite size. Table 2 [7] describes impact phenomenology in terms of HED energy partition regimes.

Relative impact velocity (km/s)	Energy (MJ/kg)	Thermomechanic effect
3 – 5	4.5 – 12.5	Solid OD fragmentation/spallation dominates with some melting and minor vaporization depending on impactor size.
> 5	> 12.5	Major portions are melted with some vaporization.

> 7	> 25.9	Vapor/plasma dominates interface impact process and propels very high velocity secondary OD.

Table 2. High Energy Density Impact Regimes. High speed impact processes are divided into three groups according to the amount of energy released per kilogram at impact and the collective processes through which this energy is transformed; vaporization energy ~ 10^6-10^7 J/kg.

To quantitatively support arguments for OD remediation appendix 1 estimates effective collision rate and subsequent OD fragment generation number, F, as a function of target area for a range of OD and meteoroid sizes. Appendix 2 calculates energy distributions of OD impact at a relative velocity of 10 km/s as a function of OD mass. The model for collision/fragmentation roughly estimates the relative secondary OD fragment generation based on target volume, projecting a much higher secondary OD generation from larger (satellite) targets. Increasing OD target mass slightly reduces available internal kinetic energy/kg and thus the mean velocities of non-vaporized (surviving) OD fragments. For 5 and 50 kg OD particles all but ~ 0.25 and 2.27 x 10^9 J respectively are in the center of mass system. Relatively small amounts of specific (internal) energy (49.5 and 45.5 x 10^6 J/kg) in the reduced (internal) mass system are available to damage, fragment, melt, and establish plasma vapor that propel fragments from the main satellite body. Respective average fragment velocities achieved from the 5 and 50 kg mass OD are 2.59 and 2.43 km/s. The highest fragment velocity is achieved by a 1 g OD at 2.60 km/s. Substantially increasing OD impact mass only slightly reduces fragment velocities but generates significantly more secondary OD collision fragments, F. If OD mass is kept below 5 kg, secondary OD flux will be low (i.e. it is arbitrarily assumed that there will be ~ 50,000 1g particles vs. 500,000 1 g particles for a 50 kg OD interception). Small and fast OD particles minimize production of secondary OD. For M

= 500 kg, m = 5 kg, V = 7 km/s and v = -3 km/s, the satellite trajectory perturbation (to the first order) is $\Delta V \approx 30$ m/s. Over 1,000 s the target location is changed by ~ 30 km. Starting with a total reduced mass impact energy of 2.5 x 10^8 J, if equal amounts (5 kg each) of satellite target and OD material are vaporized at ~ 8 x 10^6 J/kg x 10 kg, then crushing, fragmentation, melting, vaporization energy extracts ~ 8 x 10^7 J. Also, if it is assumed that high pressure shock waves generate fifty kg of OD fragments from the satellite, ~ 168 x 10^6 J remain to accelerate fragments, at a root mean square fragment velocity $\approx$ 2.59 km/s.

3. OD prevention policy

Based on the preceding simplified OD collision models in appendices 1 and 2 where larger OD, over time, contribute most secondary OD, preventive OD remediation in NES is possible using an approach that distinguishes between removing existing OD and minimizing generation of new OD. For preventing OD it is suggested that a strict ban of active weapons in space, specifically weapons such as lasers, proximity mines, electromagnetic pulse devices, projectiles, etc. whose sole or primary purpose is to destroy or disable satellites and other orbital and sub-orbital, or even ground based assets [4]. It is a given use of active space orbital based weapons will inevitably generate disastrous OD levels either by destroying satellites or by being themselves destroyed in orbit. Their primary or only utility is to carry out destructive military options and as such must be stringently prohibited. Also, for other than passive strategic activities of reconnaissance, communication, and targeting, a clear military advantage from the proverbial “high ground” espoused by Sun Tzu (The Art of War ~500 BC) for terrestrial battles is not directly applicable to space engagements because assets are exposed and easily tracked and targeted [7]. The space advantage of passive assets which reduce the fog of war and the ensuing uncertainty and permit greater opportunity for attainment of limited military objectives, and hopefully a cease fire or peace, far exceeds those of targeted vulnerable active assets which are best sequestered on Earth [3].

The preceding requires resolution of the dual use dilemma by distinguishing active and passive space assets is critical. The military regularly uses large portions of commercial communication satellite capabilities. Virtually all space assets, via reconnaissance, communication, or OD remediation have by virtue of being in orbit, military utility and are inexorably intertwined as essentially dual use (passive) assets and may be permitted. This is distinct from active space weapons having a singular deliberate use - to destroy an adversaries capability to wage war - and such singular use assets that must be banned.

4. UN Outer Space Treaty and related recommendations

As a starting point, UN Outer Space Treaty 2007 voluntary guidelines listed below should be followed.

a) Limit debris released during normal operations.

b) Minimize the potential for break-up during operational phases.

c) Limit the probability of accidental collision in orbit.

d) Avoid intentional destruction and other harmful activities.

e) Minimize potential for post-mission breakup resulting from stored energy.

f) Limit the long term presence of spacecraft and launch vehicles orbital stages in LEO region after the end of their mission.

g) Limit the long term interference of spacecraft and launch vehicles orbital stages with GEO region after the end of their mission.

Specific efforts to minimize OD growth and collisions include:

1. Making nations responsible for OD (US, Russia, China, etc…) provide some form of commensurate support for (especially radioactive) OD removal active within a multilateral framework open to and governed by all space faring nations. OD is a common problem that must be collectively solved in an equitable manner. Towards this end sharing OD remediation technologies will benefit all.

2. A combination of cooperative shared (pooled) liability versus individual ownership responsibility should be explored in an open forum. The nation that launches the satellite should have primary responsibility for orbital tracking, overall management, and OD remediation under the jurisdiction and support of an internationally based guiding committee. If you can't track it, or have it effectively tracked by a major space fairing nation, you shouldn't launch it. Capability to avoid collision, e. g. by space maneuvers, and liability for collisions should also be considered. "If you break it you own it."

3. Adoptation to innovative technology standards that minimize creation of new OD. Examples include potentially effective innovative (e.g. laser, microwave, beamed solar power, or magnetic rail assisted) launch and OD remediation technologies, smaller boosters, combined with lighter, smaller collision cross section but higher technical performance and longevity satellites. Requirements for self- contained de-orbiting and collision avoiding propulsion systems should be mandatory (see remediation strategy).

4. Limit satellite density by designing more operationally efficient, longer lifetime,

smaller, and lighter satellites that will reduce the total number of satellites in use.

5. Shared use of satellites to optimize their utilization allowing all parties to access space.
6. A timely information dissemination system on emerging threats from natural (meteoroids) and manufactured OD and calculation of possible avoidance maneuvers.
7. Continued development of more efficient, innovative and robust solar photovoltaic energy panels so collision cross section is minimized and long term energy conversion performance is maximized.
8. Prohibit the orbiting of satellites for frivolous, activities, such as CubeSats [2], redundant or propaganda activities.

6. Remediation strategies

Strategic remediation guidelines follow from a simple, logically expedient approach using available technologies and capabilities in an operationally efficient and responsible way by concentrating on de-orbiting the largest objects. These objects generate the largest amount of OD with the highest collision probability in the immediate future. OD in LEO are most accessible, have the highest velocities, are densest in population, and have the potential to generate huge amounts of secondary OD upon collision in LEO (8) (appendix 1). This was demonstrated by the grazing collision at ~ 12 km/s of a defunct Russian Cosmos satellite with an Iridium communications satellite that generated thousands of secondary OD fragments > 10 cm and ~ 100,000's of smaller OD fragments that cannot be tracked or avoided. The larger high collision cross-section primary OD objects will produce huge amounts of secondary OD and require initial remediation. Recycling of OD in space sounds clever but with current technology is very difficult, economically dubious, and may even potentially add to the OD problem. However, this may change in the future with innovations in low gravity engineering operations. One must keep an open mind.

The issue is more of sharply controlled restraint and cooperation rather than aggressive capability and intimidation in the use of technology. Also, from an operations perspective, it is easier and more subtle to disable, especially by laser or other pulsed electromagnetic irradiation, an operating satellite in orbit than to de-orbit or destroy it.

Putative remediation methods for OD mitigation are outlined:

1. <u>Automatic de-orbiting after launch mission completion:</u> This requirement should be mandatory for all new satellite launching stages. Objects in LEO and MEO can de-orbited, using self-contained thrusters on both satellites (on becoming non-operational) and upper-stage boosters (once a clear de-orbiting trajectory is established), and ablatively dissipate in Earth's atmosphere. For example, if a minimal benchmark orbital velocity change of $\delta v = 100$ m/s, the corresponding energy change per kilogram required is

$$\delta\square = \tfrac{1}{2} (\delta v)^2 \qquad (1)$$

and $\delta\varepsilon = 5{,}000$ J/kg. For M kg of OD, the total energy E required to de-orbit is

$$E = M\,\delta\varepsilon. \qquad (2)$$

For a 500 kg piece of OD to undergo a reference orbital change of 100 m/s requires an energy of $E = 25 \times 10^5$ J. Ideally, a solid propellant de-orbiting system with an effective specific energy density of 5×10^5 J/kg, will require 5 kg of propellant to be expended for each 100 m/s de-orbiting velocity change for 500 kg of OD. The propellant system mass to the OD mass removal ratio is 1/00 for each 100 m/s de-orbiting velocity change (or 5 x 10^3 J propellant per kg of OD). Objects in GEO can be up-orbited, as some already have, (boosted) ~ 300 km to a GO until otherwise removed at some future time.

2. Space Laser: This approach uses LIDAR guided orbital lasers to ablatively pulse energy, E, on small (~ 1 cm) OD mass, M, to impart a (de-orbiting) velocity change, δv, parallel to the laser beam where for m momentum coupling coefficient (9) C_M (dyne-s/J)

$$\delta v = C_M E/M \qquad (3)$$

For a uniform high energy density surface plasma pulse on a flat aluminum OD target in a vacuum, C_M ~ 2 dyne-s/Joules = 10^{-5} s/m (10). If E = 0.001 J, was generated by 1 ns laser

pulse (1 MW) directed on a ideally oriented flat 10g Al plate δv = 2 x 10^{-6} m/s per pulse, which is negligible compared to a minimally required orbital velocity change of ~ 100 m/s to initiate the de-orbiting process. There are additional problems with target engagement angle (11), focus, asymmetry, spinning, irregular coupling induced volatility, and inherent laser beam quality limitations (Strehl ratio) that collectively reduce the effectiveness of ablatively driven linear momentum transfer by ~ order of magnitude or more. Under these conditions minimally ~ ½ x 10^9 pulses would be required to achieve δv ~100 m/s. The total energy expended for 10 g of OD to be de-orbited by 100 m/s would be 0.5MJ (or 50 MJ/kg). A realistic overall laser system conversion efficiency from electricity would be ~ 1% , at best, requiring ~ 5 GJ/kg to de-orbit OD by 100 m/s. Compare this with 5 kJ/kg using rocket propellant. Also, after each of many shots, new LIDAR measurement must be carried out to re-target the laser beam pulse. Overall, this is a very inefficient process requiring power conditioning to charge capacitors from photovoltaic panels for hours (assuming minimal capacitor charge loss, if not days, of radiation to de-orbit a relatively small, ~ 10 g, piece of OD. Orbital maintenance and energy budget/supply to a high powered space based laser is also problematical. Although chemical lasers such as the CO_2 may ideally improve efficiencies by a factor of 10 to 20 times to ~ 500 MJ/kg, this method is still not effective on large (~ kg) OD.

3. Ground based lasers: This approach has the disadvantages of the space based laser with the addition of (turbulent) atmospheric transmission (~ 0.7), scattering (Strehl ratio ~ 0.25) and anisoplanatic effects on the target. The major advantage of ground based system is that it could put out more pulsed laser beam power and be more easily maintained. Equation (3) is still applicable for determining δv. Another problem with high powered laser pulses is their repetition rate which can be minutes to hours. But for small OD particles, with a critical need for removal, or collision avoidance without de-orbiting, this may be a viable option using an existing telescope and avoiding very expensive lift costs. However, the critical limiting issue in OD removal is the large > kg objects for which laser remediation under current technologies appears to be ineffective.

4. Robotic operated (recoverable) orbital spacecraft (ROS): Recently launched and recovered after 7 months in orbit, the X- 37B autonomous re-usable robotic space plane (12), a mini-version of the discontinued NASA space shuttle, has the potential to efficiently deploy and retrieve satellites, de-orbit large OD, and carry-out related tasks with considerable efficiency and risk and drama reduction because there is no crew or life support systems. Remote operational human control from Earth to LEO can be achieved virtually in real time (~ 0.1 s). Clearly, the ROS is a dual use technology that can be the critical element in large self-contained and operated OD removal. Operation in space of

even a robotic spaceraft is expensive but is achievable for retrieving satellites. The Soviet Union's Buran space shuttle, launched in1988, is similar to ROS in some ways.

5. Hybrid systems: Combination of a robotic spacecraft applying a laser driven propellant (eg volatile polymer) package with $C_M \sim 50 - 200 \times 10^{-6}$ s/m or a self-contained solid propellant retro-rocket package attached to a robotically oriented, de-spinned large OD fragment or satellite. This laser system drivng a highly volatile propellant is expected to be ~100 to 1,000 times as operationally effective as a laser ablating an arbitrary Al OD particle. The retro-rocket laser driven package is thought to be simpler, more energy efficient and robust then the laser system alone. This system can be used for intermediate sized (~ 1m) OD and non-operational satellites.

6. Embedded systems: This system uses attached de-orbiting retro-rockets initially attached to an upper stage booster (before launch) that ignite after placing the satellite in orbit. To de-orbit by 100 m/s requires an energy release of 500 J/kg. Similarly, deflecting guidance plates in the upper stage booster engines can be used to de-orbit itself with residual fuel after placing the satellite in orbit. A similar system can be adapted, sacrificing some efficiency, to de-orbiting satellites using vernier maneuvering rockets.

V. Organizational needs

The above preventative and remediation strategies will require an international independent organizational framework oriented towards OD technical problem solving and not towards politically motivated ideology. To effectively carry this out as a common objective for the OD conventions an interdisciplinary operational organization structure must include a:

1. monitoring and verification agency,

2. governing council, and
3. permanent secretariat.

Membership and input into the above should include technically trained staff from aerospace and communication companies, government space, environment, and military agencies, United Nations, academia, and independent consultants from the space-faring nations. This membership should be heavily represented technical expertise in communications, space science and astronautics with a strong emphasis on innovative problem solving.

VI. Conclusion

Given present distributions of OD, active satellites in regions of NES, and available technology and cost, the prevention of new and remediation of existing OD is described as a cost effective solvable problem. The first part of the solution, to be used in future satellite launches, is the pre-launch attachment of de-orbiting or maneuver booster rockets to satellites and orbital upper stage boosters; the former to be used at the end of the satellites useful lifetime or for a collision avoidance maneuvers and the latter immediately after boosting the satellite to its operational orbit. The second part of the solution is to be used to de-orbit existing larger OD in LEO by using a robotic spacecraft system that can, depending on OD size, either place a self-contained (guided) de-orbiting solid propellant booster on the OD directly or use a laser to irradiate a propulsion packet attached to the OD; the former configuration apparently being simpler. Special case satellites containing substantial amounts of radioactive materials should be managed in a manner that minimizes additional leakage and may require integral orbital recovery using a robotic spacecraft. Given operational efficiencies and collision hazards, the largest OD in LEO can and should be the first to be remediated.

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Appendix 1: Collision rate relative for OD fragment generation per collision

The collision rate, dN/dt, is proportional to the number of targets, N, the collision cross section, σ, and the cross sectional area, A, of the target satellite where

$$dN/dt = \sigma\ N\ A \tag{A1-1}$$

OD Size	$\sigma^*(1 / m^2 - y)$	$A(m^2)$	N	Collisions/y	$F/\alpha \times 10^6$	Result
≥ 1 cm	**4×10^{-5}**	**12**	**1,000**	**0.48**	**1**	**huge amounts of secondary OD and severe satellite damage**
projected	**1×10^{-4}**	**12**	**1,000**	**1.2**	**1**	
≥ 0.5	**10^{-4}**	**12**	**1,000**	**1.2**	**0.125**	**some secondary OD and satellite damage**
≥ 0.1	**8×10^{-4}**	**12**	**1,000**	**9.6**	**0.001**	**minor secondary OD and satellite degradation**

Meteoroid size

≥ 0.3	**2×10^{-4}**	**12**	**1,000**	**2.4**	**0.027**	**minor secondary OD and satellite degradation**

Table A1. Orbital Debris Flux in LEO. Average annual collision rate is provided for three OD sizes and one meteoroid size reference for a projected 1,000 satellite targets in LEO each with an assumed area of 12 m^2. Damage will depend on how well the satellite is protected and where and at what velocity the impact occurs. The relative number of target fragments, F, from a given collision is normalized to the number of 1 cm^3 particles proportional to the impactor mass (radius cubed) divided by a structural collision factor, α, taken to be the same for each impactor size. * Cross-sectional flux of a given size and larger (Johnson et al 2001)

The number of collision fragments, F, equals the target volume multiplied by α, a target fragmentation factor that depends on the impact velocity, materials strengths of impactors and targets, and structures, where

$$F = \alpha \; 4/3 \, \pi R^3 \qquad \text{(A1-2)}$$

Collisions in LEO range from 0-15 km/s. Assuming an average collision velocity of 8 km/s and energy of 3.2×10^7 J/kg is deposited in the target and impactor. Vaporization and fusion energies of aluminum (target and impactor materials) are 8×10^6 and 4×10^5 J/kg respectively, suggesting ~ cm OD collision interactions are self liquidating. Larger (target) pieces (> 10cm) of OD are capable of generating more secondary OD.

Appendix 2. Energy distributions at impact

Energy distributions for a 500 kg satellite target mass, M, traveling at velocity, V = 7 km/s and five OD masses, m, of 0.001, 1, 5, 10, 50,100 and 500 kg impacted head-on at velocity v = - 3 km/s are given in table A 2 where

$$E_{Total} = \tfrac{1}{2} M V^2 + \tfrac{1}{2} m v^2 \qquad \text{(A2-1)}$$

$$E_{CM} = \tfrac{1}{2} (M + m)[(MV + mv)/(M + m)]^2 \qquad \text{(A2-2)}$$

$$E_{Int} = \tfrac{1}{2} [M m /(M + m)] (V - v)^2 \qquad \text{(A2-3)}$$

Assuming 1/10 mass fragmentation, vaporization energy $E_V = 2 (0.9) m \times 8 \times 10^6$ J/kg.

The root mean square velocity, v_{rms}, of the fragmented particles is obtained from (A2-4) below where v_{rms} is proportional to the square root of the fragmentation fraction,

$$E_{Int} - E_V = ½ ((M + m) /10) v_{rms}^2 \qquad (A2-4)$$

OD mass	**0.001**	**1**	**5**	**10**	**50**	**100**	**500**	**kg**
$\mathbf{E_{Total}}$	12.25	12.25	12.27	12.30	12.48	12.70	14.50	x 10^9 J
$\mathbf{E_{CM}}$	12.25	12.20	12.02	11.79	10.20	8.52	2.0	x 10^9 J
$\mathbf{E_{Int,}}$	0.05	49.9	247.5	490	2,273	4,167	12,500	x 10^6 J
$\mathbf{E_{Int,}/M_{OD}}$	50	49.9	49.5	49.0	45.5	41.7	2.5	x 10^6 J/kg
v_{rms}	0.02	1.4	2.6	3.7	7.5	9.5	10.3	km/s

Table A2. Fragment velocities from a 10 km/s impact as a function of OD mass. Total system energies, E_{Total}, interaction energies, E_{Int}, OD interaction energies/kg, and specific internal energy, $E_{Int}/M_{OD,}$ The rms velocities, v_{rms}, of OD fragments ejected from a OD/satellite impact at a relative velocity of 10 km/s depend on OD mass; larger OD collisions generate higher velocity secondary OD fragments and therefore be more dangerous.

Increasing OD mass only slightly reduces (available) internal kinetic energy/kg but substantially increases mean velocities of non-vaporized (surviving) OD fragments. For 5 and 50 kg OD particles all but ~ 0.25 and 2.28 x 10^9 J respectively are in the center of mass system. Relatively small amounts of specific (internal) energy (49.5 and 45.5 x 10^6 J/kg) in the reduced mass system are available to damage, fragment, melt, and establish plasma vapor that propel fragments from the main satellite body. Respective rms fragment velocities from the 5 and 50 kg mass OD impact are 2.6 and 7.5 km/s. The highest fragment velocity is achieved by a mutual 500kg OD at 10.3 km/s. Substantially increasing OD impact mass increases fragment velocities and generates significantly more secondary OD collision fragments, F. If the OD mass is kept below 5 kg, secondary

OD flux will be low (i.e. it is arbitrarily assumed that there will be ~ 50,000 1g particles vs. 500,000 1 g particles for a 50 kg OD interception). Small and fast OD particles impacting large (energy absorbing) targets are destroyed minimizing production of secondary OD.