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ORBITAL DEBRIS AS AN ENERGY MANAGEMENT PROBLEM

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ABSTRACT

Managing the hazards from orbital debris is fundamentally an issue of managing the residual energy associated with operations in space. Access to and operations in space require a large expenditure of energy. Current objects placed into orbit contain a large amount of residual energy. This energy can include stored energy in the form of unburned propellant, batteries, or pressurized containers, but always includes an even larger amount of energy in the form of kinetic energy. The importance of this residual energy is that it is the energy source for re-distributing the kinetic energy into various debris sizes. The only natural "sink" for the residual energy is atmospheric drag, which is more fundamentally expressed as an energy loss rate.

By approaching orbital debris as an energy management rather than object management problem, some of the fundamental issues concerning orbital debris become more obvious. For example, the amount of kinetic energy in orbit far exceeds the amount of stored energy; consequently any long-term debris management strategy must consider managing kinetic energy. These principles can be applied to both low Earth orbit and Geosynchronous orbit and illustrate the need for different strategies in these two regions.

INTRODUCTION

The launch and operations of spacecraft require a large expenditure of energy. A large quantity of launch fuel is converted to potential and kinetic energy in order for an object to obtain orbit. Because objects in orbit are not necessarily traveling in the same direction, sometimes even in opposite directions, their kinetic energy relative to one another can be greater than the kinetic energy relative to the launch site. Once in orbit, both the payload and the upper stage used to achieve orbit also contain stored energy. The upper stage usually contains about 5% of its initial fuel, as well as pressurize containers and a battery. The payload usually includes some sort of propulsion system which can include fuel, pressurized containers, or momentum wheels, plus batteries. After payload operations stop, some of this stored energy may remain. The energy that remains in orbit after completion of operational objectives is residual energy. This residual energy in the form of potential, kinetic and stored energy is eventually dissipated. How and at what rate this dissipation occurs are the essential questions in managing the orbital debris environment under an energy management approach.

Current strategies to manage orbital debris depend on models which describe the number of fragments of various sizes as a function of time. These models depend heavily on breakup models which are highly uncertain and depend on a number of parameters. The uncertainty in these models may obscure the best strategy. However, much of the uncertainty in breakup models may not be important for determining a strategy for debris management. For example, the size distribution resulting from the fragmentation of a particular satellite may be uncertain because of the construction of the satellite, or type of energy causing the breakup. However, the fact that a certain amount of energy caused the total or partial fragmentation of a satellite is important; whether that energy produced a certain number of large fragments and few small fragments, or lesser number of large fragments and a larger number of small fragments is of secondary importance, because no matter what size the fragments, some parameter in the environment will be adversely affected by the breakup. Most of the kinetic energy of the initial object is still present...it has simply been re-distributed to affect the environment more adversely; the rate of this re-distribution of kinetic energy depends on the amount, conditions, and rate of residual energy release.

RATE OF RESIDUAL ENERGY RELEASE

Over the past 20 years, the world launch rate has been slightly more than 100 launches per year in order to maintain about 400 operational payloads. Currently, about 15 of these launches per year go into GEO, and 6 go to the SSR. A small fraction go into interplanetary space, and most of the remainder go into LEO. The approximately 80 launches per year that go into LEO have resulted in an average of about 5 satellite breakups per year, most the result of an explosive stored energy release. Recent operational changes to vent residual fuel from upper stages is expected to reduce the rate of these breakups. However, breakups from stored energy release is not likely to go to zero, because some stored energy is required to operate satellites and accidents will occur. A breakup from stored energy release usually occurs fairly soon after launch, because if it does not occur, stored energy will slowly leak, dissipating harmlessly. Consequently, for a constant level of operations in space, one might expect the rate of explosive stored energy releases to be constant, and be proportional to the amount of stored energy present.

However, because the operational lifetime of an upper stage or payload is usually short compared to its orbital lifetime, the rate of fragmentation due to kinetic energy will increase in time for a constant level of operations in space. The rate of collisions is proportional to the square of the number of objects in orbit, and as long as that number is increasing, either by launch activity or by the explosive release in stored energy, the rate of fragmentation by collisions will also increase. Changes in operational procedures can reduce the orbital lifetime of future spacecraft; however for regions of space which naturally have long orbital lifetime, these changes in operations will, at best, lead to a constant rate of fragmentation. These trends are illustrated in figure 1.

TABLE 1 Rate of Energy Release through Explosions, Breakups

Stored Energy:

LEO (observed explosions): 10^7 to 10^8 joules/year
SSR (estimated explosions): 10^5 to 10^6 joules/year
GEO (estimated explosions): 10^5 to 10^6 joules/year

Kinetic Energy (Based on 1993 catalogue population):

LEO (0.05 collisions/year at 10 km/sec)
Available: 1×10^{14} joules (2×10^6 kg)
Rate: 4×10^9 joules/year (1600 kg/collision)
SSR: (2×10^{-5} collisions/year at 4 km/sec)
Available: 1×10^{12} joules (1.5×10^5 kg)
Rate: 5×10^5 joules/year (3000 kg/collision)
GEO (1×10^{-4} collisions/year at 0.5 km/sec)
Available: 7×10^{10} joules (6×10^5 kg)
Rate: 4×10^4 joules/year (3000 kg/collision)

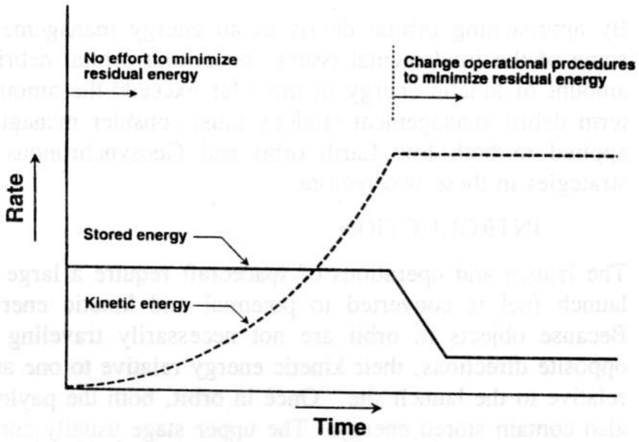

Fig. 1. Rate of residual energy release under assumption of constant activity in space.

The rate of explosive stored energy release in LEO can be determined from the history of past explosions in LEO /5/. However, the rates for SSR and GEO must be estimated based on analogy to LEO, considering the fact that fewer liquid upper stages are left at these altitudes.

The rate of kinetic energy release can be determined from the calculated average collision rate and the average kinetic energy in each collision, as was done in /6/, under the assumption that most of the kinetic energy and rate of release of kinetic energy is contained in the objects catalogued and maintained by the US Space Command. The results of these estimates and calculations are shown in Table 1. In all but GEO, the rate of kinetic energy release currently, or will soon, dominates. However, these rates are likely to be incomplete, because the catalogue is incomplete, especially at higher altitudes. The importance of these uncatalogued objects can be examined by understanding some of the key parameters controlling satellite fragmentations from collisions, and how these parameters affect the rate of kinetic energy release.

PARAMETERS AFFECTING THE RATE OF KINETIC ENERGY RELEASE

Because all satellite breakup models predict that most of the mass resulting from the breakup of a satellite remain in the larger fragments, these fragments will control the rate of kinetic energy release, at least in the near future. If a satellite fragments into more than one fragment that is capable of totally fragmenting another satellite, then the rate of kinetic energy release will increase as a result of that fragmentation. Tests have been conducted to determine both the ratio of target mass to projectile mass that will cause total fragmentation, and the number of fragments produced as a function of size /7,8/. The test results are usually assumed to scale according to the energy of the projectile for velocities above 5 km/sec. Below 5 km/sec, the proper scaling depends on parameters such as the physical construction of the satellite and likely has a different velocity dependency, which is unknown. For the purposes of this paper, both energy and momentum scaling will be assumed below 5 km/sec. The results of these tests and extrapolations are illustrated in figure 2.

In LEO, at the average velocity of 10 km/sec, a target satellite mass to projectile mass ratio of 1250 will cause catastrophic breakup of the satellite. For example, a 1250 kg satellite can be catastrophically fragmented by a 1 kg projectile at 10 km/sec. If all of the fragments had a mass of 1 kg, then 1250 fragments would be produced, each capable of totally fragmenting another satellite with a mass of 1250 kg. However, current tests and models /8,9/, scaled to 10 km/sec, predict that about 170 fragments with mass of 1 kg or greater would be produced, as shown in the lower line in figure 2. Consequently, in LEO the rate of kinetic energy release can be expected in increase as a result of collisions, leading to the possibility of uncontrolled growth of debris in LEO.

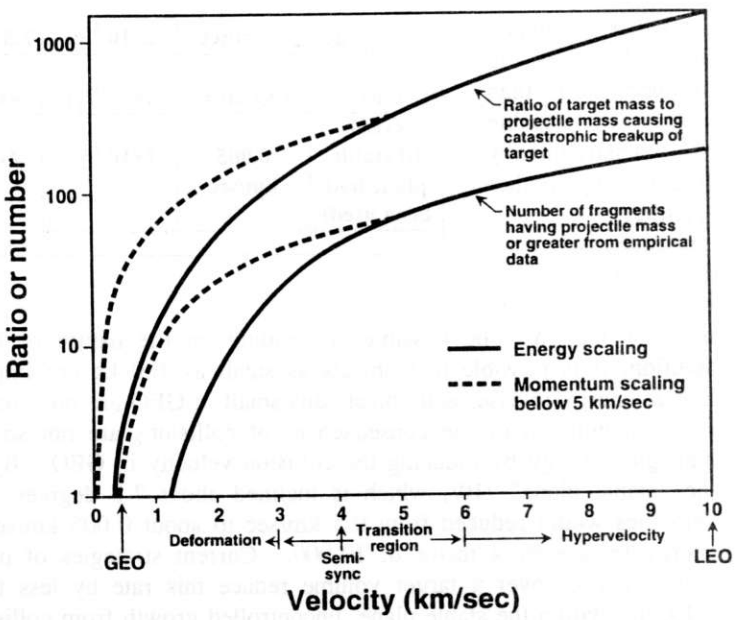

Fig. 2 Velocity dependency to produce sufficiently large fragments to lead to collisional cascading.

Therefore, uncontrolled growth should be expected in regions of LEO where orbital lifetimes are long compared to their operational life, as concluded in /6/. Since most intact objects in LEO have masses of about 1000 to 2000 kg, the average smallest size debris which is important to catastrophic collisions in LEO is about 1 kg. Since, on average, objects of this size or larger are likely to be cataloged in LEO, the uncatalogued population is not likely to be significant in determining the rate of catastrophic collisions in LEO.

Both the ratio of the target mass to projectile mass and the number of fragments having the projectile mass or greater decrease with decreasing velocity, as shown in figure 2. These two parameters also become more uncertain with decreasing velocity. In the SSR, the uncertainty is not so great that the following conclusions seem inescapable: The ratio of target mass to projectile mass causing total satellite breakup is about 200; consequently, objects as small as about 10 kg are important in understanding the rate of kinetic energy release in the SSR. Objects this small at the SSR altitudes are almost certainly not in the catalogue. The number of fragments produced in a collision that are capable of catastrophically fragmenting another satellite of the same size is expected to be about 50; since orbit lifetimes are very long in the SSR region, uncontrolled growth is inevitable without significant changes in operational procedures. Based on the catalogued population, the rate of uncontrolled growth is very slow; however, given the increased use of the SSR, and the fact that smaller, yet significant, sizes are not cataloged, this rate could soon be much greater.

TABLE 2 Kinetic Energy Characteristics in Earth orbit using 1993 US Space Command Catalogue

Region	Average Collision Velocity	Average Collision Rate	Average Kinetic Energy per Collision	Ratio of Target Mass to Projectile Mass Causing Catastrophic Breakup	Expected Number of Fragments Produced Large Enough to Cause Catastrophic Breakup
LEO	10 km/sec	0.05/yr	$8x10^{10}$ joules	1250	174
Semi-sync	4 km/sec	$2x10^{-5}$/yr	$2.5x10^{10}$ joules	200 (250)*	44 (54)*
GEO	0.5 km/sec	$1x10^{-4}$/yr	$4x10^{8}$ joules	3 (31)*	0 (2)*
GEO (if stable plane had been used)	0.005 km/sec	$1x10^{-4}$/yr	$4x10^{4}$ joules	much less than 1	0 (0)*

*(momentum scaling below 5 km/sec)

In GEO, the uncertainties in the consequences of collisions at 0.5 km/sec are sufficiently large that strong conclusions are not possible. For example, it is not clear that a collision in GEO would produce more than 1 fragment capable of catastrophically fragmenting another satellite; consequently, uncontrolled growth in the population may, or may not, be possible...depending on the nature of breakups at about 0.5 km/sec. In addition, it is possible that objects as small as 100 kg are important to understanding the rate of kinetic energy release, and objects this small in GEO are not catalogued. However, the uncertainties in the population or the consequences of collisions are not so great as to point to the benefit of managing energy by reducing the collision velocity in GEO. By placing objects at GEO altitude in the "stable plane" /10/, which is inclined about 7.3 degrees from the equator, relative collision velocities would reduced from 0.5 km/sec to about 0.005 km/sec /11/, reducing the rate of kinetic energy release by a factor of 10,000. Current strategies of using disposal orbits to disperse the kinetic energy over a larger volume reduce this rate by less than a factor of 10. At the lower velocities within the stable plane, uncontrolled growth from collisions is not possible. While such an orbit requires North-South ground tracking, it eliminates satellite North-South station keeping fuel requirements. These results for LEO, SSR, GEO, and GEO stable plane are summarized in Table 2.

To quantify the significance of smaller debris to the rate of kinetic energy release, a simple model was constructed. The model assumed that some fraction of the intact population was converted to a number of fragments, each having a small area relative to an intact object, yet capable of catastrophically fragmenting an intact object. The ratio of kinetic energy release for the mixed population of intact and fragmented objects to the kinetic energy release for the intact population alone was then calculated. Under these assumptions, this ratio turned out to be independent of the initial number of intact objects, their flux, or spatial density; the ratio depended only on the fraction of intact objects converted to fragments and the number of fragments produced per intact object. The size of a fragment that will catastrophically breakup up another satellite depends on collision velocity, as discussed earlier and shown in figure 2. Figure 3 gives the results of this model.

The more energetic past explosions in LEO have produced 200 to 300 catalogued fragments per event /5/. Consequently, about 1% to 2% of the LEO population has been converted into 200 to 300 fragments per object. As discussed earlier, the catalogued population is sufficiently complete to describe the kinetic energy release rate in LEO. From figure 3, one concludes that the results of these explosions have increased the rate of fragmentation by a factor of 1.5 to 2. This factor is already included in the calculated rate of kinetic energy release for LEO given in table 1.

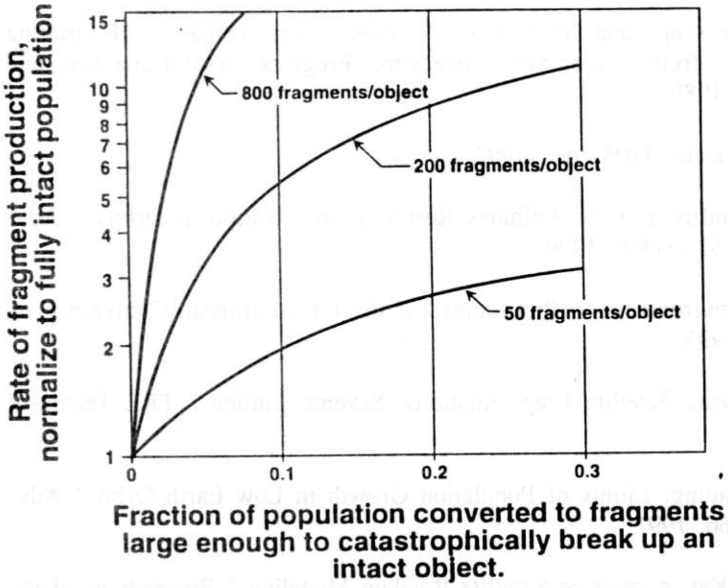

Fig. 3 Rate of Fragment Production From Kinetic Energy

However, in the SSR the fraction of the population converted to smaller fragments is unknown, and not included in table 1. If 1% to 2% of the population is converted into 200 fragments, then the SSR rate of kinetic energy release in table 1 should be increased by a factor of 1.5 or 2. However, from figure 2, 200 fragments/object in the SSR must be considered an upper limit for this altitude, and 50 might be an appropriate average. In this case, the SSR rate should only be increased by about 5% to 10%...well within the uncertainty of any rate calculations, and therefore not important. About 10% of the population would have to have been converted to 50 fragments each before increasing the rate by a factor of 2, and this is unlikely in the present, although not unlikely in the distant future.

The significance of the uncatalogued population is less ambiguous in GEO than in the SSR. Since the number of fragments produced by an explosion or collision that are capable of catastrophically breaking up a GEO satellite is even less than in the SSR, much more than 10% of the GEO population must be converted to fragments in order to increase the kinetic energy release rate by a factor of 2. Consequently, even thought a significant uncatalogued population may exist in GEO, that population is not likely to significantly contribute to the rate of kinetic energy release.

CONCLUSIONS

By examining orbital debris as a residual energy management problem rather than an object management problem, conclusions can be quickly reached concerning the priority of various strategies for managing the future orbital debris environment. For example, kinetic energy is found to be much more important than stored energy for future debris generation, especially for low Earth orbit and the Semi- Synchronous Region. The rate that kinetic energy produces debris decreases with altitude; consequently, debris management strategies should give higher priority to lower altitudes. This rate of debris production can be reduced by three techniques: 1. Using the Earth's atmosphere to dissipate kinetic energy so that the object is removed from orbit. This technique is a relatively inexpensive option for objects in low Earth orbit. 2. Dispersing the kinetic energy over a large volume of space. This option is already being used in geosynchronous orbit, and may be the only cost-effective option for the semi-synchronous region. However, it only reduces the rate of kinetic energy release, it does not reduce kinetic energy. 3. Selecting orbits which minimize the collision velocities. For all altitudes, there is a circular orbit where the relative velocity between orbiting objects will always be near zero. For low Earth orbit, this orbit has zero inclination. At geosynchronous altitude, this orbit has a 7.3 degree inclination. Selection of orbits whose planes are near these "stable planes" will decrease the kinetic energy between orbiting objects and minimize the rate of fragment production from kinetic energy.

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