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DEBRIS MITIGATION POLICIES AND PRACTICES

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ABSTRACT

Debris mitigation measures are required to dispose of the energy in space systems that is excess to their functional life. The excess energy can be in the form of residual propellants and pressurants remaining at the end of mission, or it can be the kinetic energy in the spacecraft or upper stage due to its orbit. Until the energy is removed, it remains a potential threat to other objects and the future state of the environment. In Low Earth Orbit or transfer orbits with low perigee, the most efficient methods are to cause the object to enter the Earth's atmosphere. In the high energy orbits, semisynchronous and geosynchronous, displacement to a storage orbit is the only practical scheme. There is an emerging consensus among the present space systems operators as to the significance of the debris issues and the cost-effective methods of dealing with the problem.

One way of speaking of space enterprises is to note that we invest a significant amount of energy in the positioning of an instrument in an orbital position so that it provides a unique perspective on the Earth. To quantify the relationship, one can note that, in general, the mass on the launch pad is 85% fuel, 14% launch system and 1% payload. Launch consists of converting the chemical energy of the fuel into the kinetic energy required for the orbit to which the spacecraft is targeted.

For many reasons, the operational life of the instrument is short relative to the expected orbital lifetime. The function of the spacecraft may depend upon a cooling fluid for maintaining sensitivity in the infrared spectrum, it may have mechanical or electronic components that have limited life, or it may have a limited supply of energy with which to maintain the unique geometry which makes its function attractive and economic. Its very success in supplying a product may so stimulate the market that a greater, more detailed, more subtle set of data is required, so the current instrument becomes obsolete.

Most of the energy invested in spacecraft is kinetic energy, the product of mass and the square of the velocity, to establish and maintain the desired orbital geometry. A small amount of the energy is the propellant for station keeping and the propellant for control moment gyros used to maintain orientation. The kinetic energy of the object may be such that its expected orbital lifetime before decay and entry is 50 or 200 times as many years as its expected operational lifetime. Figure 1 illustrates the relationship of expected orbital lifetime to altitude during the extremes of the solar cycle which determines the atmospheric drag in the upper thermosphere. In the orbits of greatest applications value, the lifetimes are quite long.

Since one can expect that most spacecraft will be replaced at the end of their operational lifetime if the function is economically rewarding, it is clear that the growth of mass and surface area of objects on orbit will increase consistently over time, and such is in fact the historical experience.

One should also note that the path of the object in space, due to the perturbations on bodies in orbit around the Earth, is such that over time the area "swept" by any particular object is quite large. Given that there are large numbers of objects each in slightly different orbits, it is clear that on the time scales of orbital lifetime, hundreds to thousands of years, the probability of two objects occupying nearly the same point in space at the same point in time approaches certainty not once, but repeatedly.

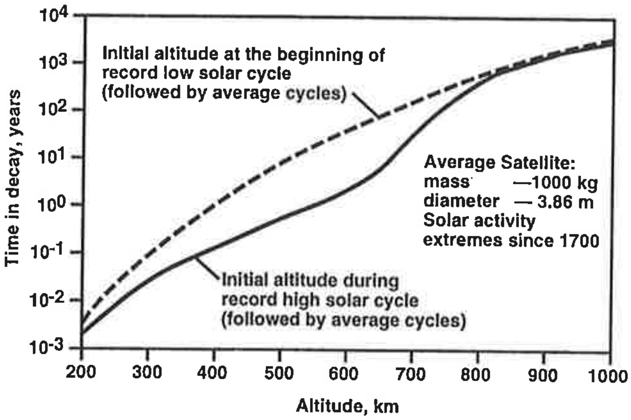

Figure 1. Extremes of average satellite lifetimes due to solar activity.

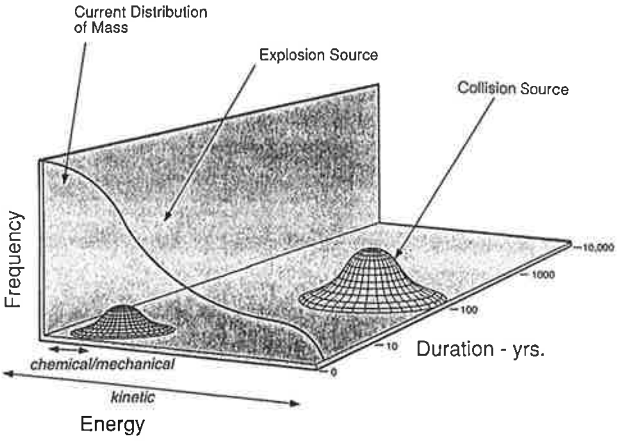

Figure 2. Orbital debris characteristics.

Figure 2 represents the conceptual space we have just characterized. The ordinate represents the energy dimension, the abscissa, the expected frequency of an event, and the z coordinate, time duration or its equivalent, orbital altitude.

In the past, upper stages and spacecraft have been abandoned at the end of their operational life, a few hours at most for upper stages and a few years for spacecraft. In consequence, of the 6000 objects in Low Earth Orbit (LEO), only 300 are functional spacecraft. Of the remaining 95%, 35% are spent stages and spacecraft no longer operational and 60% are debris fragments from breakup events and pieces jettisoned in operational sequences. Since the velocity in LEO is approximately constant for all objects between 600 and 2000 km, one can characterize the distribution of objects on the energy dimension by indicating a large frequency at the low end to account for the stored chemical and mechanical energy in the abandoned stages and spacecraft and the small breakup and operational debris objects. At the high end of the energy dimension are the intact stages and spacecraft.

At the low end of the energy dimension, in the moderate level of expected frequency and in the region of 3 months to 15 years on the duration dimension, one can indicate that three to five explosion events have occurred each year, on average. Some of these are propulsion event failures, some are deliberate detonations or collision intercepts, but most in the last decade appear to be autogenous explosions of hypergolic propellants following failure of a common bulkhead. Such events account for the largest number of the cataloged objects even though the fraction of the orbiting mass of these objects is only 1 or 2% of the total.

The larger and fewer intact objects are the potential future source of more objects as a function of collision. As we continue to add objects to the orbiting population, even if we totally eliminate explosions, our models indicate that the future environment will be dominated by collision events not by past chemical explosions.

Defining the issue in this conceptual space has the advantage of not only illustrating the nature of the problem, but also indicating when and how mitigation procedures can be effected to control the future course of the environment.

Since chemical events are subject to control only during the short duration of the stage operation, they must be dealt with while there is still communication and command and control of the spacecraft or stage. The most straightforward and simple manner in which to control this threat is to deplete the stored energy by venting the propellants and pressurants. Such measures are becoming the standard practice among the operators of launch vehicles. The U. S. Delta and Atlas vehicles have had such procedures in place for several years, as have the Japanese. Ariane adopted such procedures for its LEO launches in 1990 and has now extended the practice to all launches. China has plans to implement the practice for the Long March. Russia has implemented the practice on some, but not all, of its upper stages. In the future, these practices should gradually reduce the observed rate of explosion events.

The long lifetime of the most desirable orbits for LEO applications spacecraft means that there is increasing probability of collision among these satellites as the number of units on orbit continues to grow. Growth in numbers accrues as failed units are replaced, but the abandoned units are left in place as new applications and research systems are added. The issue is exacerbated by the fact that most of the explosion events have been in the orbits favored for these functions.

A further consideration is that there is now active planning to place in LEO significant numbers of communication satellite constellations for both data and voice. Such "store and forward" communications constellations are attractive because at low altitude the inverse square law minimizes the power requirements and they can communicate with low power hand-held units anywhere in the world and do not require the size and power in ground stations needed for geostationary communications. Such systems, however, require significant numbers of orbital units, ordered in constellations, to provide continuity of coverage for users.

These factors could lead to much more rapid growth of the mass and target area of large objects on orbit and inevitably increase the expected frequency of collision. Since the orbital mechanics make the expectation of any one event random and the expectation of the next succeeding event equally random, it is not predictable when the collisional process will begin or how rapidly it may progress. But the limit case is obvious. An exponential rate of collisions can occur until the target area and mass is made relatively small and numerous and the system stabilizes at a new equilibrium which is significantly more hazardous to new operational spacecraft.

It is equally clear that the only control over this long-term outcome must be exercised while the operator still has operational control of the spacecraft or stage. The control measures are equally clear: Make the expected lifetime of the orbit small relative to that of the total population and do so after the spacecraft or stage has executed its primary function. This can be done by lowering the perigee of the satellite's orbit sufficiently so that the expected duration is less than 5 years or some small percentage of the nominal expected duration. Such a measure cannot be achieved if control of the spacecraft is lost, but one can reasonably expect that to be infrequent. If such a procedure is agreed upon, there will, of course, have to be procedures to preclude "cheating."

This conceptual "model" of the environment illustrates why orbital debris is currently a minor problem but can become a major issue for future spacecraft design and operations, and indicates both the general timing and the nature of the mitigation measures that can and should be considered. If action is initiated in a timely manner, then the options elected and the dates of implementation can be phased in a cost-effective manner. If the problem is allowed to get out of control, then even draconian measures will take very significant amounts of time, generations for system operators, for the mitigation measures to have appreciable effect.

Debris mitigation requires that we dispose of the kinetic energy that exceeds the functional life of the system shortly after the end of functional utility. A potential criterion for the time allowed to effect such measures might be that the environmental protection measures are completed in no more than the same amount of time that the system operated productively, i.e., a 10-year operational life provides a 10-year period during which to remove the system.

The most efficient manner of doing so is to cause the system to enter the Earth's atmosphere where the aerodynamic friction will convert the energy to heat and destroy the system. In most cases, nothing significant will fall to Earth in populated areas, but in the case of very large and massive objects, it is prudent to target the entry trajectory to open ocean areas.

Table 1 illustrates the most recent breakup events. It is noteworthy that the number of events continues to be significant. It is also noteworthy that most of the events continue to occur in the altitudes that have long expected lifetimes.

						Large Fragments	
Date	Parent	Breakup Height (km)	Apogee Height (km)	Perigee Height (km)	Inclination (deg)	Fragments Cataloged	Fragments Estimated
12/18/93	Cosmos 2225 (photo reconnaissance)	--	337	179	65	8	1000
1/12/93	Gorizont 18 kick stage (SL-12 ullage motor)	--	30747	257	47	1	>18
12/26-30/92	Cosmos 2227 r/b (SL-16 2nd stage)	830	854	847	71	200	>200
12/17-18/92	Gorizont 17 kick stage (SL-12 ullage motor)	--	17577	197	48	1	>30-40
9/5/92	Cosmos 1603 kick stage (SL-12 ullage motor)	835	846	835	67	15	>62
7/92 (approx)	Cosmos 2054 kick stage (SL-12 ullage motor)	**	27238	208	47	1	>18
12/29/92	Cosmos 1710-1712 kick (SL-12 ullage motor)	4728	18886	654	65	2	>26
12/6/91	Cosmos 2163 (photo reconnaissance)	210	259	187	65	1	1000

Table1. Recent fragmentations (revised 12 March 1993).

Figure 3 indicates a family of Monte Carlo runs for continuing present practices and launch rates. There is large uncertainty both as to when the process might start and as to how rapidly it might progress.

Figures 4 and 5 illustrate the effect of implementing various mitigation strategies at various times. Merely eliminating the major present cause of debris by eliminating explosions does not improve the environment, it merely delays the onset of collisional generation of debris. The removal of spacecraft and upper stages does improve the environment over time if the level of activity remains at the level characteristic of recent years, but it only holds the environment to present levels if the launch rate increases.

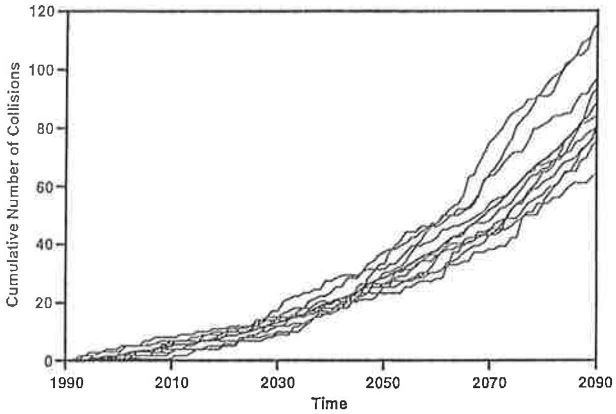

Figure 3. Monte Carlo expectation of collisions among satellites under present operating practices.

- Case 1
  Follow historical precedents: "business as usual"
  - Constant launch rate
  - Explosions continue at historical rates
  - Leave all S/C, upper stages, and launch debris in environment
- Case 2
  Introduce easily achieved debris mitigation measures
  - Constant launch rate
  - Eliminate explosions after year 2000
  - Leave all S/C, upper stages, and launch debris in environment
- Case 3
  Introduce more aggressive debris mitigation measures
  - Constant launch rate. Eliminate explosions after year 2000
  - Remove upper stages after 2000, remove S/C at end of mission life after 2030, leave no launch debris after 2030

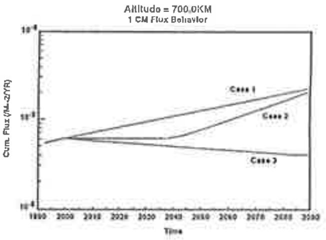

Figure 4. Evolve population projections (cases 1, 2, and 3).

It is clear that only by removing the large objects from orbit can the environment be kept to the present levels of hazard. Lesser measures delay the start of the deterioration process but do not significantly alter its progress once it is initiated.

Figure 6 indicates the velocity change and the fuel mass fraction required to achieve several different measures of control of the entry of a spacecraft. Clearly, the most costly option is to reenter the object to a controlled location in a single revolution. It is somewhat counterintuitive that the cost of such a maneuver should increase as the altitude declines; it is the consequence of the negative 5 degree angle-of-attack constraint imposed to ensure that the heating rate is sufficiently high to destroy the object. (At the lower altitudes, the constrained target altitude is significantly below 64 km.) Were such an angle-of-entry constraint not imposed, the heating rates would be low even though the total heat load would be the same. Heating rate, more than total load, destroys objects on entry.

- Case 4
  Increased use of space with easily achieved debris mitigation measures
  - Number of launches increases by ~5 per year
  - Eliminate explosions after year 2000
  - Leave all S/C, upper stages, and launch debris in environment
- Case 5
  Increased use of space with more aggressive debris mitigation measures
  - Number of launches increases by ~5 per year
  - Eliminate explosions after year 2000
  - Remove upper stages after 2000, remove S/C at end of mission life after 2030, leave no launch debris after 2030

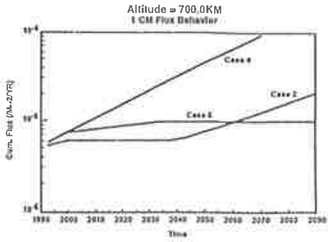

Figure 5. Evolve population projections (cases 4 and 5).

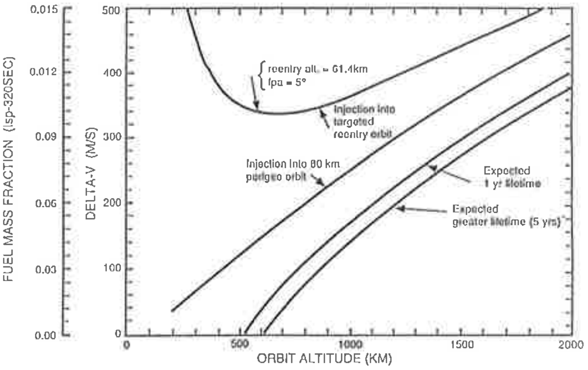

Figure 6. Delta-V requirements for disposal from circular orbit.

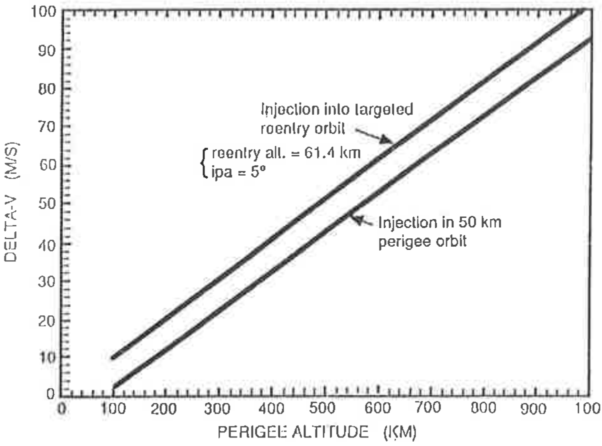

Figure 7. Delta-V requirements for deorbit from GTO.

Reducing the expected lifetime of the orbit is the less costly alternative, but it forfeits control of the time and location of entry. Since the object will eventually enter in any case and there is no control of location in that eventuality, this seems like a minor issue except for those few objects so massive that they represent a significant threat in the event they impact in a populated area. For such objects it may be necessary to incur the greater cost of controlling the impact area. If required, there are less costly but more complex strategies than those illustrated here.

Figure 7 illustrates the velocity change required to ensure entry of stages in the geosynchronous transfer orbit. Since the orbit is highly elliptical, a modest change at apogee significantly changes the perigee. The fuel mass fraction to effect the velocity change is less than 1%, but the battery weight required to extend the operating lifetime to execute the maneuver may be a mass comparable to the propellant requirement.

Table 2 lists the various forces available that might be applied to cause entry of LEO objects. Clearly, propulsive methods are the most obvious and simple, if available. They can deal with both the

1. Propulsive
    - Upper Stages
    - Payloads'
2. Aerodynamic Drag
    - Basic Ballistic Characteristics
    - Enhanced Drag Systems
3. Solar Pressure
    - Solar Sails
        - Escape
        - Entry
4. Tether Techniques
    - Momentum Exchange at Deployment
    - Momentum Exchange at Retrieval
    - Electromagnetic Drag
5. Solar-Lunar Perturbations
    - Time of Launch Constraint
    - Geosynchronous or other deep elliptical orbits

There are no other forces available with which to influence the orbit of satellites.

Table 2. Methods to remove objects from orbit.

explosion and collision hazard by using the flight performance reserve as a portion of the propellant for the perigee lowering maneuver. The other methods may have some attraction in particular circumstances, but in most cases will be heavier and more complex than a propulsive maneuver. To date, none of these alternative techniques has been demonstrated in flight, though all of them have been the subject of considerable analytic study and numerical simulation.

The least cost-effective and functional is the general class of "after-the-fact debris removal systems." They require adding new mass and systems into the environment, their operations are complex and threatening to functional units which are difficult to distinguish from "debris," and they must address a more difficult problem than one need address if reasonable preventive prudence is exercised. While they are technically feasible and an interesting design challenge, these systems are not viable candidates in the real world of economic considerations.

Drag enhancement and tether devices may be effective complements to limited propulsive capability in some instances. It may be more economic and mass efficient to add drag enhancement or a tether to a spacecraft rather than resize its propulsion capability or add a propulsion system to a spacecraft that uses control moment gyros and magnetic torquers to avoid mass ejection systems and their associated contamination. These are quite reasonable ways to limit orbital lifetime, but provide control of the entry point only at the price of significant complexity.

In the high energy orbits, the only strategy is to move objects from the high value orbit to a disposal orbit area. It is best if this is done in a series of maneuvers since at the end of spacecraft life, uncertainty is high as to the quantity of the remaining propellant. Four or more burns is a good manner in which to ensure that the desired displacement is achieved before propellant exhaustion.

The minimum objective in geostationary orbit should be 300 to 400 km with an additional allowance for solar pressure effects on large area spacecraft. It is also prudent to vent any residuals and pressurants, and otherwise remove all sources of stored energy, to passify the vehicle at the end of its life to preclude autogenous explosions or the release of the stored energy due to a minor impact event.

At the geosynchronous altitude, there is a stable orbit inclined 7.3 degrees to the equator with a right ascension of the ascending node of zero. In this orbit, the perturbing forces are at a minimum and no north-south station keeping is required. This places some limitations on service at high inclinations and requires some tracking by ground antennas, but for some services should be attractive since the mass otherwise allocated to maneuver propellants can be allocated to solar arrays or antenna size. A further attraction is that when spacecraft are raised above the service arc at end of life, they continue to have very low relative velocity with respect to other objects in this plane (approximately 50 mps versus 800 mps in geostationary).

At this time, most of the organizations that operate space systems have an informal or formal policy that they will minimize orbital debris consistent with economic achievement of mission objectives. There are a variety of interpretations of the meaning of such a criterion, and there is an emerging consensus as to the most cost-effective strategies.

It is our expectation that in the next few years, the space operating organizations will formulate a plan for implementing a policy and practice that will be consistent among all organizations, and will wish to see that set of concepts embodied in some instrument to ensure uniform compliance so that economic competition is on a "level playing field." Toward that end, NASA has arranged with the U. S. National Academy of Engineering to conduct an International Workshop to review the accomplishments since the issuance of the ESA, U. S. and Japanese assessments of the debris issue, and to formulate a coordinated baseline for the future research and definition that would support a coordinated international approach to implementing mitigation measures (fig. 8).

- Sponsor -National Academy of Engineering, Aeronautics and Space Engineering Board
- Participants - Twenty to thirty international representatives from government, academia and builders and operators of space systems
- Objective - Define what is the present state of understanding of the issues and what the research activities for the near term future should be
- Time - Fall of 1993
- Product - A report for broad national and international distribution

Figure 8. Technical assessment study.

If these efforts succeed, the space community may set a significant precedent for the management of an environment before the contamination became a major threat to not only those who must operate within it but also the public at large.

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