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Removing Orbital Debris with Less Risk

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Deorbit concepts have been proposed for dealing with the growing problems posed by orbital debris. Most devices use large structures that interact with the atmosphere, magnetic field, or solar environment to deorbit large objects more rapidly than natural decay. Some devices may be better than others relative to the likelihood of collisions during their use. Current guidelines attempt to address this risk by applying the metric of area-time product to compare the probability of a large object experiencing a debris-generating impact. However, this approach is valid only for collisions with very small debris objects. The peak in the distribution of the area of orbital debris occurs for objects with a characteristic size close to 2 m. For collisions with such objects, some of which are operating satellites, it is important to incorporate the augmented collision cross-sectional area, which takes into account the size of both colliding objects when computing the area-time product. This new approach leads to a more valid comparison among alternative deorbit approaches, which now indicates that inflatable drag enhancement devices result in the least risk. Finally, one deorbit device, an electromagnetic tether, is shown to have a very large collision cross section for disabling operating satellites.

I. Introduction

SPACE debris is a growing problem in many orbital regimes, despite numerous and pervasive debris-mitigation policies enacted and followed internationally. This space environmental issue has been discussed and studied for years, but many critical parameters continue to increase. For example, the number of significant satellite breakup events has averaged about four per year and the cataloged debris population has increased at a nearly constant linear rate of 200 objects per year since the beginning of the space age. At the same time, many potential future debris-generating events have been eliminated by the debris-mitigation guidelines, and the understanding of the numbers of objects in orbit has improved significantly over the last two decades. However, the capability to remove large amounts of mass already deposited in orbit has been a major deficiency in debris-mitigation strategies. The ability to remove large objects from orbit is critical because a large object is not only more likely to be involved in an accidental collision due to its large collision cross section, but the large mass has the potential to be the source for thousands and thousands of smaller debris if involved in a collision. This issue is underscored by the recent collision of a defunct Russian military communications satellite (Cosmos 2251) with an operational Iridium (33) spacecraft over Siberia in February 2009, which resulted in nearly 2000 trackable objects and, likely, tens of thousands of smaller, yet still lethal, fragments. It should be noted that the Russian and Iridium satellites had not been in low Earth orbit (LEO) long: 16 and 12 years, respectively. Because of the growing hazard of orbital debris, this paper will focus on mechanisms to remove large, derelict (i.e., incapable of being moved via propulsive means) objects without adding to the collision risk for other objects or creating more debris.

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II. Orbit Debris Problem and Its Implications to Space Operations

The orbital debris problem places pressure on the removal of spent payloads and rocket bodies from orbit, so that they do not contribute to the problem anymore. The requirement for deorbit can increase spacecraft costs and launch mass requirements, which will in turn increase launch costs. Propulsive deorbit techniques, which require an operational satellite to maneuver into a reentry trajectory, can require fuel mass fractions of 10–20% of the mass of the spacecraft, depending on propellant type and orbit altitude. The mass fraction of propulsive deorbit can be much more if the mission of the satellite did not originally require a propulsion system. In addition, added propulsive system mass, for a fixed launch mass, may reduce the mission-specific hardware that can be carried. Incorporating deorbit propulsion into a spacecraft can be quite expensive (10–20% of the satellite cost) if the mission does not already require a propulsion system.

The Earth has a mature and growing orbital debris problem. It is known that there are over 20,000 unwanted satellite debris items in low Earth orbit, and the number is increasing in many altitudes. The total number of orbital debris in Earth orbit has increased fairly steadily since the launch of the first satellite in 1957. Over 100 major breakup events have contributed to the large increase in the debris population, though some debris with low perigees have been cleansed from low Earth orbit. The 11 year solar cycle is a key parameter that drives the cleansing of orbital debris because high solar activity causes the atmosphere to expand and increases the atmospheric density for a given geometric altitude accelerating the orbital decay. This cyclic phenomenon, which is more distinct at altitudes below 800 km, results in minor orbit lowering during solar activity minimum periods and accelerated orbit lowering during periods of high solar activity [1].

Since the beginning of the space age, over 4000 launches have taken place by a wide range of international players. These launches have produced orbital objects, including separation nuts and bolts, lost equipment from space walks, spent and exploded launcher stages, solid-rocket fuel components, paint chips, nuclear reactor coolant, and derelict and operational satellites. An overwhelming majority of all current objects in orbit can be regarded as space debris. As of October 2011, the orbital box score (U.S. Space Command) was 3428 payloads and 16,108 tracked debris objects. Figure 1 (courtesy of NASA) displays the growing orbital debris problem as of late 2011. The step-function increase in debris at the start of 2007 is

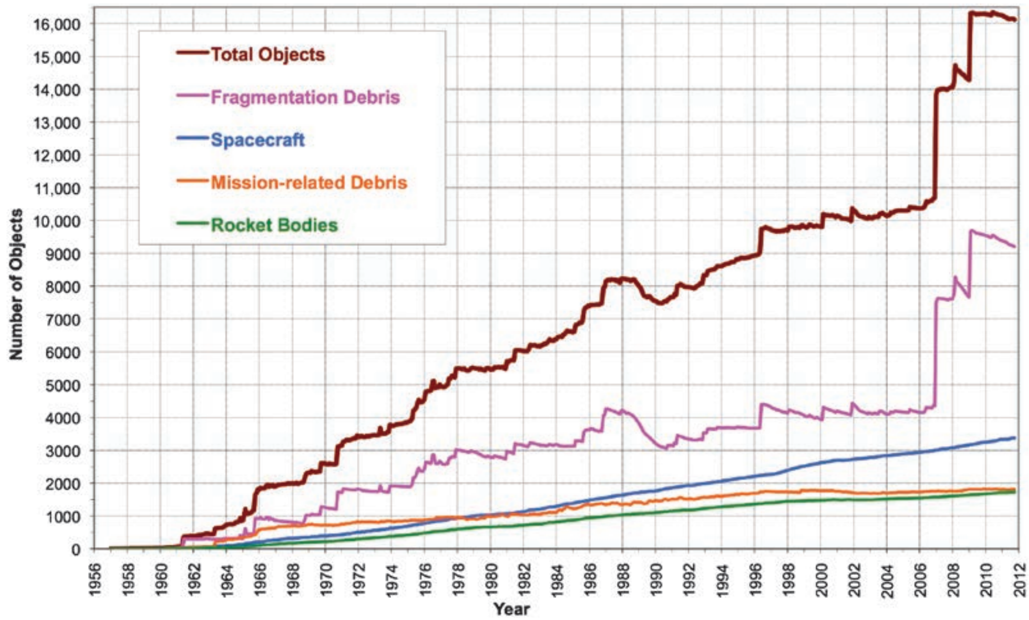

Fig. 1 Yearly increase in number of tracked objects in Earth orbit (courtesy of NASA).

the result of the Chinese Fengyun-1C satellite antisatellite test that created over 2300 new debris fragments in one event, a 23% increase in orbital debris in just one day. Overall, the number of objects between 1 and 10 cm is estimated at over 500,000 [2]. Figure 2 shows the spatial density distribution (objects per cubic kilometer) of tracked orbital debris (generally 10 cm or greater) as a function of altitude (in 20 km altitude bins) for 5 June 2009 [3]. Figure 2 also illustrates the concentration of orbital debris in orbits occupied by a number of communications, weather, and surveillance satellites between 750 km and about 900 km altitude. The orbital debris numbers are increasing at higher altitudes because the rate of natural decay is not high enough to counteract the addition of debris from breakups and operational activities. By removing larger orbital debris, such as spent stages and derelict satellites from orbit, the debris problem will improve because these objects can no longer act as debris generators from catastrophic hypervelocity impacts with other objects or from explosions of objects with available energy sources such as batteries, propellants, etc. The kinetic energy of a 1 kg object traveling at a relative velocity of 10 km/s is about 50 MJ which is the explosive equivalent to ~11 kg of TNT and comparable to the chemical energy liberated in past debris-causing chemical explosions. In addition, collision-induced fragmentations create more small particles at higher ejecta velocities than explosively triggered events, creating a more dispersed debris cloud [4].

As a result of the orbital debris problem, individual government agencies, including NASA, the U.S. Department of Defense, and the Federal Communications Commission, along with international organizations and interagency groups, have established guidelines, policies, and directives for mitigating the orbital debris problem, especially in high-value orbits (i.e., LEO and geosynchronous

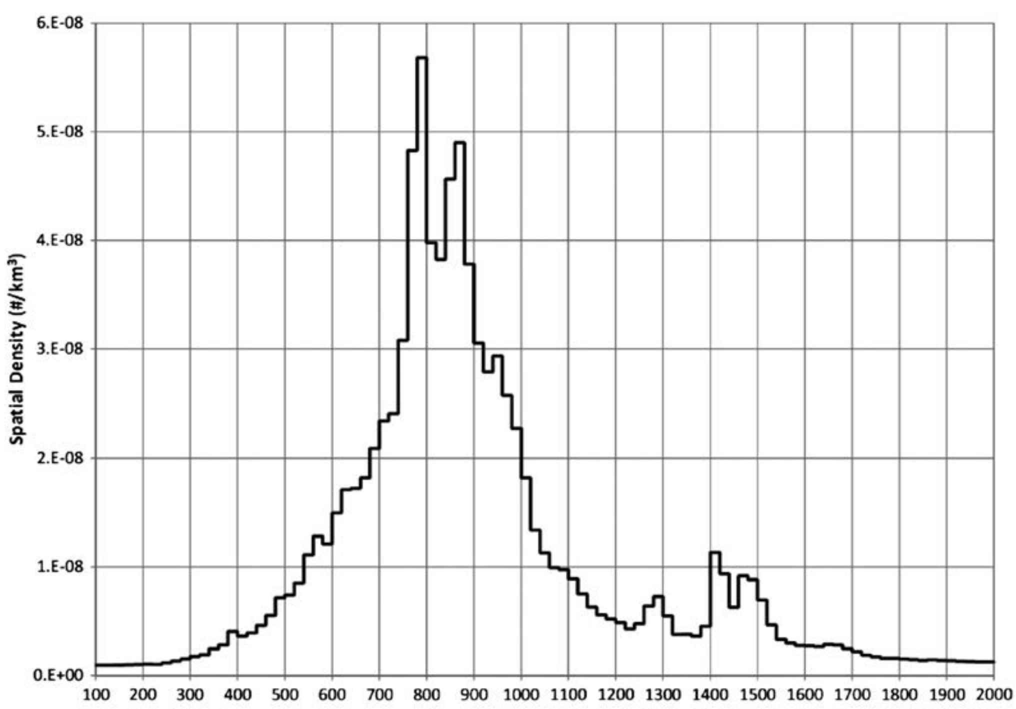

Fig. 2 Spatial density distribution of tracked orbital debris as a function of altitude (courtesy of NASA).

orbits). The U.S. Government Orbital Debris Mitigation Standard Practices [5] recommends the postmission disposal of spacecraft by placing them into orbits with perigees greater than 2000 km in altitude, high enough that their reentry will not occur for thousands of years, or that they be placed in orbits that will decay within 25 years. Another important element of this standard practice is the recommendation that, if drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product (ATP) of the system or will not cause spacecraft and large debris to fragment if a collision occurs while the system is decaying from orbit. Finally, a recent National Space Policy has specified orbital debris-mitigation goals and guidelines [6].

III. Deorbit System Concept Descriptions

In this section, several deorbit system concepts that have been considered are briefly described. These concepts only include those ideas for systems that can be attached to a satellite before launch or attached by an orbital tender spacecraft after the satellite, stage, or other debris object is spent. Remote (e.g., ground-based laser) or suborbital collider concepts are specifically not discussed.

A. Propulsive Deorbit or High Parking Orbit

If a satellite carries a propulsion system, has sufficient propellant, and is operational, its propulsion system can raise the orbit altitude above the altitude of concern (>2000 km) or, preferably, lower the perigee low enough to deorbit the satellite or to increase the atmospheric drag, so that natural orbit decay causes the satellite to enter the atmosphere within 25 years. Deorbit is the preferred orbital debris-mitigation method for launch vehicle stages.

The cost of propulsive deorbit can be very high in terms of launch mass requirements and satellite cost if the satellite does not require a propulsion system to carry out its nominal mission. Even when the satellite's mission requires a propulsion system for orbit changes during its mission, and the cost of adding propellant to the satellite for deorbit is only incremental, it can still be more expensive compared with some alternate deorbit schemes. This high cost of propulsive deorbit is the reason there has been so much interest and research in nonpropulsive deorbit concepts. Figure 3 illustrates the mass fraction of fuel needed to lower the perigee of an object, which has a ratio of cross-sectional area to mass $0.01\ m^2/kg$, from an initial circular orbit, such that the orbit then decays by natural atmospheric drag (solar activity index of 130) over a number of years [7]. This combination of fuel and drag requires significantly less fuel than direct reentry using just propulsion. The current NASA requirement is to complete the reentry within 25 years, corresponding to the line labeled B in the figure.

Although it is tempting to assume that a satellite with a propulsion system should use that system for eventual deorbit, a dedicated separate nonpropulsive deorbit system does allow an operator to deplete the propellant completely for mission use. In addition, using a propulsion system for deorbit usually means counting on a still-operating spacecraft for the deorbit maneuver. There are many ways in which a spacecraft can fail that will not affect a dedicated and autonomous primary deorbit system, which can be optimized for highly reliable long-term storage and ultimate deployment. Furthermore, the mass of propellant needed is often greater than the mass of a dedicated primary deorbit system. Of course, if a spacecraft is still operable, but has no residual value, and has an operational propulsion system, then any residual propellant should be used first to enhance the ultimate use of the dedicated primary deorbit system and minimize the total risk of creating new debris.

B. Electromagnetic Tether

Electromagnetic tethers (EMTs) operate using a high-voltage power supply to cause a flow of electrons along a conductive tether that is oriented vertically by gravity gradient torque. The flow of current interacts with the Earth's magnetic field to produce a force perpendicular to the tether and in a direction that depends on the local direction of the magnetic field. When the geometry is favorable, this force can be used to alter the trajectory in a desired fashion. It can be used to boost the orbital altitude, lower it, or cause a change in the orbit plane. Power is supplied by the spacecraft (using solar panels) when the EMT is increasing orbital energy. For deorbit purposes, the desired direction of the force would be opposite the velocity vector to reduce orbital energy, causing the system to lose altitude and eventually enter the Earth's atmosphere. In this case, orbital energy is converted into electrical energy and the tether effectively generates power. The current flows one way along the tether, and the electric circuit is closed through the plasma of the Earth's atmosphere. An electron emitter is attached at one end of the tether and an electron collector is used at the opposite end. These are devices designed to allow the electrons to be exchanged with the surrounding plasma. Figure 4 illustrates the EMT concept [8].

C. Boom-Supported Film Aerobrake

In a boom-supported film aerobrake (BSFA), a very thin and lightweight film is stretched between one or more support booms, creating an augmented drag area. The booms can be solid structures or inflated and self-rigidized, either by a chemical reaction after deployment in the presence of UV photons or by the hardening of a metal foil during deployment. Figure 5 illustrates two examples of boom-supported film aerobrake concepts. On the left, is a prototype system built by Astrium. The middle figure illustrates this system in one operational configuration, and the right-hand figure illustrates a multiple-boom system concept developed by AeroAstro.

D. Solar Sails

Solar Sails have been proposed as deorbit devices and are similar in construction to BSFA in that they are large, thin films supported by

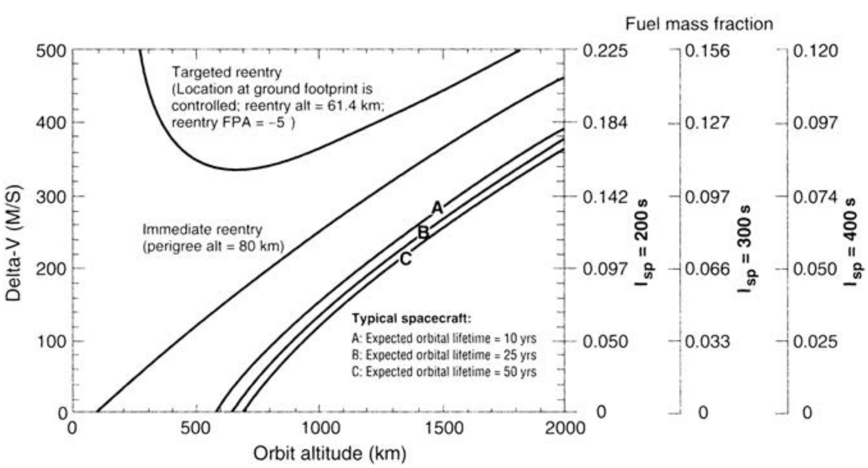

Fig. 3 Satellite disposal propulsion requirements (FPA refers to reentry flight path angle in degrees) [7].

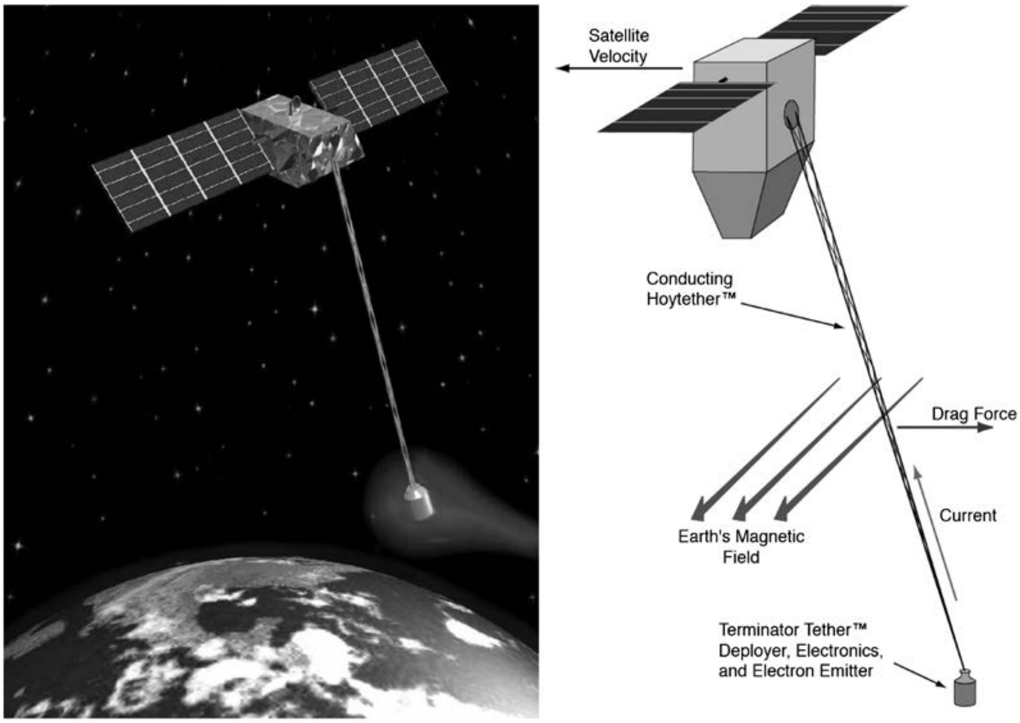

Fig. 4 Example electromagnetic tether concept [8].

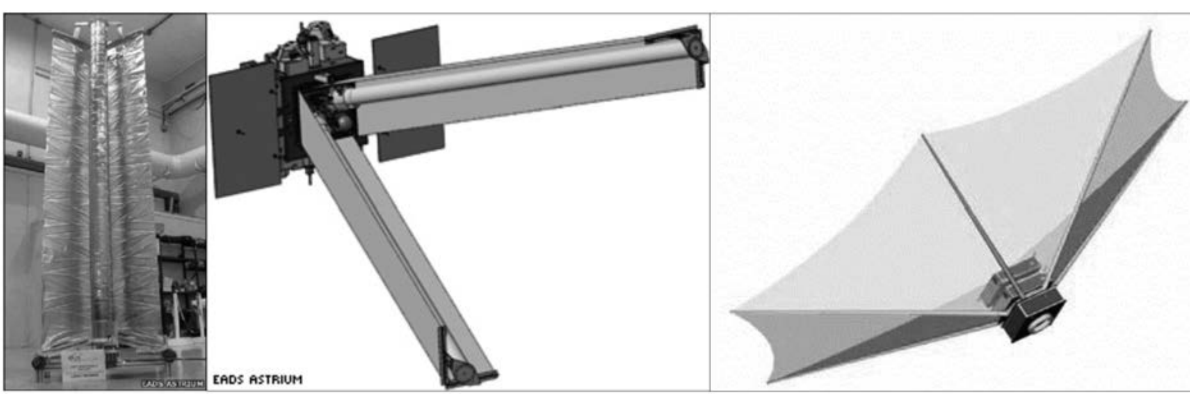

Fig. 5 Example of boom-supported film aerobrake concepts.

booms. At high altitude, where the atmospheric density is low, solar pressure forces could alter the orbit of a satellite being deorbited. At low altitude, the solar sail could act as a drag brake in a similar fashion as a BSFA, as discussed earlier. NanoSail-D is one example of a NASA solar sail flight experiment, whose goals included solar sail deployment and demonstration of deorbit capability.[§]

E. Gravity Gradient Tape

A gravity gradient tape is a long, thin film held close to vertical by Earth's gravity gradient torque. A counterweight is used both to extract the film and, as with the EMT, to keep it oriented using the gravity gradient torque. The film, which is very thin and low mass, greatly increases the drag area compared with the bare spacecraft. Figure 6 shows a schematic of one gravity gradient tape concept, showing the tape deployed above the satellite toward the zenith direction and oriented face-on to the ram or velocity direction.

F. Inflation-Maintained Ultrathin Envelope

An inflation-maintained ultrathin envelope is an option for creating enhanced drag area, in which one is willing to carry the required system elements (gas, sensors, and controls) to enable inflation and pressure maintenance in the Earth's meteoroid and orbital debris environment. A small amount of gas is required for typical applications because the pressures are exceedingly low. As gas leaks through holes created by particles, it is replenished to maintain proper pressure. In addition, as the ambient stagnation pressure increases as the orbital altitude is lowered, the pressure within the envelope must likewise be increased. External forces are

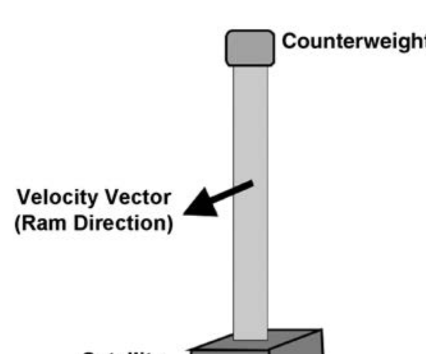

Fig. 6 Schematic of one gravity gradient tape concept.

[§]Data available online at http://www.nasa.gov/centers/marshall/pdf/484314main_NASAfactsNanoSail-D.pdf [retrieved 21 July 2011].

counteracted by envelope design and internal pressure within the envelope. Figure 7 illustrates an example of a deployed inflation-maintained ultrathin envelope attached to a large space observation platform.

G. Rigidizable Space Inflatable Envelope

A rigidizable space inflatable envelope (RSIE) is an option for achieving drag area augmentation if long orbital life is required in the meteoroid and orbital debris environment and if constant inflation is undesirable. In the rigidizable space inflatable envelope concept, an envelope is inflated and allowed to rigidize chemically or by metalworking. Figure 8 shows the Echo II balloon, an example rigidizable space inflatable envelope, being stress tested. In the case of the chemical rigidization, the envelope is made of a material that becomes rigid when exposed to UV photons or heat. In the case of the mechanical rigidization, a relatively thick, very soft metal film is layered on a polymeric film. At the end of deployment, the envelope is overinflated to ensure the metal is stretched a little beyond its tensile yield point. When the gas is later vented, the metal goes into compression (balanced by the residual tension in the polymeric film). This straightens out all the wrinkles and the metal supports the polymer in a stable shape without requiring internal pressure. As with the booms of the BSFA, the areal density of a RSIE is on the order of 100–200 g/m^2, depending on rigidizing concept. The Echo II balloon flown in 1964 had an areal density of only 40 g/m^2, however, Echo II was not attached to a large mass (i.e., a spacecraft) and, therefore, the envelope was quite lightweight because it did not need to support any loads caused by external forces (i.e., solar or drag forces).

IV. Hypervelocity Impacts in Space

In discussing any aspect of debris control measures, it is essential to understand the dynamics of two independent Earth orbiting objects. It is very difficult and fuel-consuming for two objects to be brought close to each other at low velocities. And so, any typical encounter in low Earth orbit must be assumed to be at relative velocities comparable to, or larger than, orbital velocities (i.e., 7–11 km/s). At these velocities, any encounter is considered to be "hypervelocity," which technically means the impact velocity is greater than the speed of sound in the target. The speed of sound in aluminum, a major component of spacecraft structures, is several kilometers per second, well below the typical impact velocity of objects in low Earth orbit. However, more pointedly, being in the hypervelocity regimes means that the impacts are devastating to both the impactor and target.

The physical significance of an impact being hypervelocity is that the shock wave propagates efficiently in all directions in the target and impactor so rapidly that little momentum transfer is seen between the two colliding objects. Typically, at low velocities, when two objects collide, the two independent objects before the event are greatly affected in the motion after the event by the encounter. For example, two cars that collide at right angles at an intersection often careen off each other at a 45 deg angle to the impact, roughly averaging the preimpact momentums of the two vehicles. For hypervelocity collision, the result is much different. After an event, the ensemble of fragments created typically continues on a nearly exact trajectory, as it would have before, except now in a thousand pieces. So, impact energy is efficiently and rapidly absorbed by the target and impactor resulting in rapidly expanding debris clouds, but with little momentum transfer.

However, in real life, the situation is never quite that simple, especially when dealing with complex aerospace structures with many voids and different densities where the material properties change significantly. To determine when a complex structure would completely fragment, a series of experiments over many years (new ones are being conducted now to continue to refine algorithms) were conducted to determine the threshold of impact energy to mass ratio (EMR) of the target that would result in the target completely fragmenting. The threshold of 35–45 J/g was determined and has been verified several times since in independent impact experiments [9]. It should be noted, however, that this EMR threshold of 35–45 J/g was predicting when a target would completely fragment *and* produce debris that followed a power law of the distribution of fragment masses. In reality, a lower threshold could still produce a catastrophic breakup event, but the mass distribution might follow an exponential distribution (which more closely mimics an explosive event). This lower threshold has been determined to be about 10–15 J/g [9]. A few different collision scenarios relevant to the examination of deorbit options in low Earth orbit will now be examined.

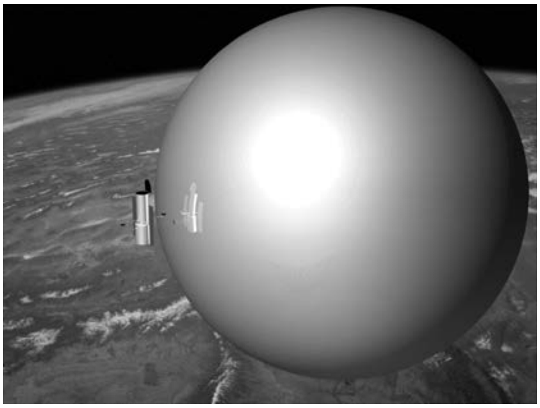

Fig. 7 Example inflation-maintained ultrathin envelope.

Fig. 8 Echo II rigidizable space inflatable envelope (courtesy of NASA).

A. Satellite-to-Satellite Impacts

In this section, the focus is on the physics of hard-body-to-hard-body impacts of satellites and the debris produced as a result. As discussed earlier, the impact of two large objects, like satellites or rocket bodies, will, in general, result in catastrophic fragmentation of the two objects into two expanding debris clouds centered on the trajectories of the original objects. The future hazard from orbital debris will be largely driven by the lethal debris population (any fragment greater than 5 mm in diameter) that will be created in the thousands from hard-body-to-hard-body collisions of large objects. Therefore, although it is desirable to control the growth of the small debris population, this is best done by removing large derelict objects that might later spawn the lethal fragments through collisions [4].

B. Satellite-Sized Object Impacts with Films, Tethers, and Booms

This section discusses the physics of the impact of a large object, like a spacecraft, with films, tethers, or booms of the types that could be deployed as part of a deorbit device. Here the focus is the degree to which the large object is disrupted by the impact with the film, tether, or boom, thus creating numerous and dangerous 10-cm-sized objects. In studying this problem, an example is used of a satellite-sized object mass of 1200 kg with a cross-sectional area of 4.4 m^2.

1. Film Impacts

If this satellite-sized object were to collide (normal impact) with a very thin film, a 4.4 m^2 area of the film would, in essence, "impact" the object. If the film were 6.35-μm-thick Kapton (areal density of 9 g/m^2), the total "projectile" mass would be about 0.04 kg. The energy of this projectile would then be 2×10^6 J if the projectile speed were 10 km/s. Because the object has a mass of 1.2×10^6 g (1200 kg) the EMR, as discussed earlier, would be 1.7 J/g, well below either threshold for breakup. Furthermore, these assumptions may be conservative because the breakup analysis assumes that all the energy is contained in a compact particle, not an extended thin film. For a normal impact with an enclosed envelope, there will actually be two impacts with film separated by a few milliseconds, depending on the envelope size and relative velocity. If, however, the envelope film were the areal density required for rigidizable space inflatables, the order of 100–200 g/m^2, the EMR would be between 18–36 J/g above the disruption limit of 10–15 J/g. Even though this analysis is conservative (i.e., it assumes all the energy of the film is contained in a single particle, not in an extended film), these EMR values indicate that there is a strong likelihood of satellite disruption if it impacted a rigidized space inflatable. This analysis can be extended to an object striking the edge of an enclosed envelope of a flat, thin film seen edge-on. Here, it is assumed that the object carves out a section of a large enclosed envelope that is 2 m wide by 10 m long. This equivalent projectile mass is 0.180 kg. Even still, the EMR is only 7.5 J/g, still below both breakup threshold limits. In this case, the impact will be absorbed by a section of the satellite and concentrated at the point of tangency. For rigidizable space inflatable films, the EMR would be between 75 and 150 J/g, well over the breakup threshold.

From this analysis, it is concluded that an impact between a satellite-sized object and a rigidizable space inflatable film will cause disruption of the satellite-sized object. For impacts with very thin films or even a deployed enclosed envelope constructed of a very thin film, catastrophic fragmentation and breakup of the object will not occur. However, the separation of appendages from the object is expected due to the high, induced relative velocities of the object with respect to its appendages after impact. Figure 9 illustrates just such an impact. In the very unlikely event of a collision between a thin film and an operating spacecraft, damage to that spacecraft may well interfere with its continued operation, but complete disruption resulting in a lot of new and large (10 cm) debris is not expected to occur. The degree of damage to the satellite will depend on the nature of the satellite and the geometry of the impact.

2. Impacts

One can also calculate the EMR of satellite-sized objects to tether collisions to see if these collisions can cause catastrophic disruption of the impactor. If one assumes the tether mass to be about 3 kg per kilometer of length, its mass will be about 3 g per meter of length. If the reference satellite-sized object cross-sectional area were to strike this tether, about 2.1 m of tether would be impacted (assuming a square cross-sectional shape). The mass of this segment of tether would therefore be 6.3 g. The EMR of this impact is considerably less than the thin film at about 0.26 J/g. One can conclude that impact of a spacecraft-sized object with a typical tether used in deorbit systems would not disrupt the object, however, similar to the thin-film impact, it is likely to damage an operating spacecraft.

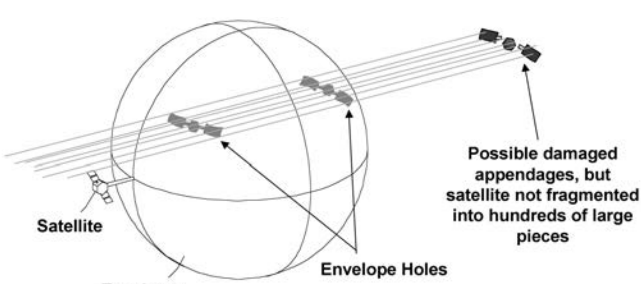

Fig. 9 Notional satellite impact with an ultrathin spherical envelope.

3. Boom Impacts

Booms deployed in deorbit systems could include rigid metal or composite rods or tubes or rigidizable space inflatable films in the form of booms, which are used to extend very thin films for creating drag area. These booms need to be strong enough to withstand the aerodynamic forces on them without buckling, especially as the orbit is lowered and the atmospheric density increases. Depending on the size of drag brake, typical booms will have a linear density between about 200–400 g/m. Given this range, the EMR of a satellite-sized object colliding with such booms will be about 17–35 J/g, which is above that required for a catastrophic breakup event of the satellite-sized object.

C. Small Particle Impacts with Extended Structures

Here, the concern is with the impact of small particles with extended structures of deorbit systems. Extended structures can be conducting tethers, long booms that assist in deploying thin-film drag-augmentation areas, or extended thin-film tapes deployed via gravity gradient forces to augment drag area. There are two classes of impacts with extended structures of concern to deorbit devices and their safe operation. First, there are impacts of small particles with these structures that can damage or sever the extended structure and, second, impacts with large objects that can not only sever the extended structure, but which can cause failure of operating satellites and/or catastrophic debris-generation events.

Particles as small as the order of a 10th the diameter of an extended structure can sever or severely damage it. Most of the emphasis on the safety of space tethers has been the potential for small meteoroid and orbital debris (MOD) particle impacts, which can sever the tether. In the case of a small diameter tether, say 1 mm, MOD particles as small as 0.1 mm can sever it. These size particles are numerous in LEO, which means that the order of 200 impacts would be expected per square meter, per year of operation, according to the NASA Orbital Debris Environment Model 2000 for a 833 km altitude, 98.2 deg inclination orbit [10].

For a 20-km-long tether, typical of deorbit tether devices, this environment could cause a very high probability of the severing of a tether in as little as a 10th of a day. For this reason, space tethers have employed innovative, multistrand structures to significantly reduce the probability of severing the tether during operation. Extended boom structures have a similar problem, however, the size of the particles must be larger and the booms are shorter than tethers, hence the probability of a severing impact is lower. In addition, if multiple booms are deployed, the implication of impact severing of the structure on drag device operation can be much less.

D. Small Particle Impacts on Thin Films

This section focuses on the impact of small particles with thin films that can be components of drag-augmentation deorbit devices. Such films can be deployed as a single sheet or as a gas-filled enclosed envelope. In the former case, particle impacts, and the holes they create, will not substantially reduce the effectiveness of the drag-augmentation device. However, for a gas-filled envelope, leakage of gas through impact-generated holes will deform the envelope and reduce its cross-sectional area, thus reducing its drag performance. Therefore, this type of impact is relevant primarily to enclosed envelopes made of thin films. Because the concern is about enclosed envelopes, it is important to understand the possibility of creating no holes or one or two holes by a particle impact. Figure 10 illustrates the spectrum of holing possibilities.

The vertical axis represents the EMR of the particle/film impact (energy of the film participating in the impact divided by mass of particle, which is considered the "target" here), and the horizontal axis represents the particle size. Very small particle impacts, with high EMR, will create craters but no holes. Large particle impacts, even with low EMR, will create two holes in an enclosed film. In between, there is a particle size for which only one hole will be

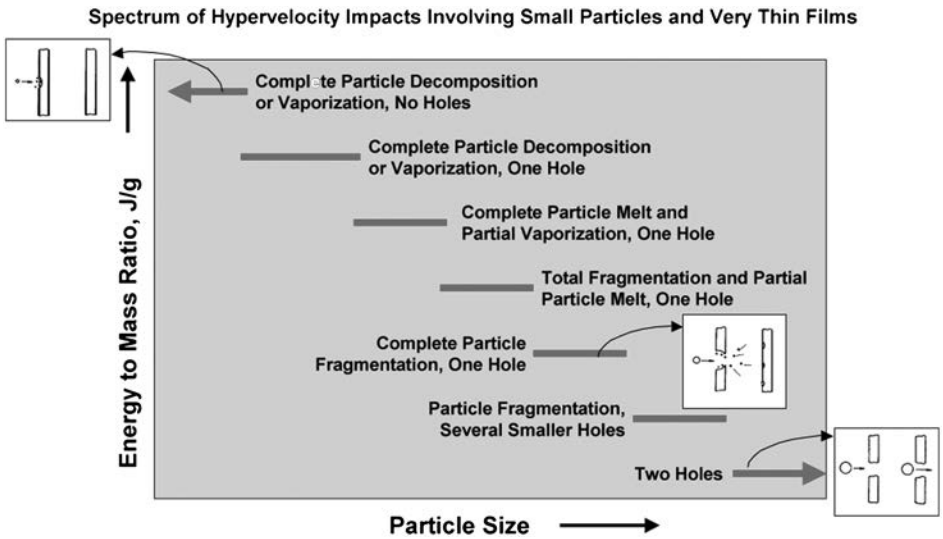

Fig. 10 Spectrum of holing possibilities.

created because the particle completely disintegrates at impact. Hole sizes, for large particle impacts, are generally a little larger than the impacting particle [11]. Using the hypervelocity impact physics of Sawle [11], EMR physics [9], and assuming an envelope 3.0 μm thick and a particle made of Al_2O_3, a very common component of orbital debris, the largest particle size that causes complete decomposition into molecules is found to have a diameter of $1.05e-5$ m. Any particle smaller than this will only form one entrance hole and no exit hole. For larger particles up to a certain size, the impact will result in particle fragmentation. If this fragmentation is complete enough, the remaining particles will not be large enough to cause a hole in the opposite wall of an enclosed envelope. For a 37-m-diam spherical envelope operating in the typical meteoroid and orbital debris environment seen in 833 km altitude, sun-synchronous orbits, it is calculated that holing buildup will be less than 1 cm^2 per day. For typical overpressures required to maintain envelope shape, this level of holing will require less than 1 kg of helium gas over a one year deorbit, a reasonable level of inflation gas [12].

V. Area-Time Product Considerations

This section discusses the concept of ATP and how it relates to deorbit system operation and the risks of making the problem worse. The ATP is the projected area of an object as viewed along its orbital flight path, multiplied by the time the object spends in orbit. If a spacecraft has a projected area of 4 m^2 and it spends 1000 years in orbit, then its ATP is $4\ m^2 \times 1000\ \text{years} = 4000\ m^2 \cdot y$.

ATP is referred to in orbital debris-mitigation guidelines written by several different organizations. For instance, the U.S. Government Orbital Debris Mitigation Standard Practices [5] state, "If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the ATP of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit." It is clear from this language that the authors implicitly assume that risk of collision is proportional to ATP. To a certain extent, this is valid. However, it will be shown that there are subtleties that should not be neglected in a careful risk analysis. To the extent that ATP is a surrogate for collision risk, ATP is useful because it is much simpler to calculate than actual probability of collision. With the use of the appropriate areas, instead of just the simple projected area, ATP can be used to make valid risk comparisons between different systems without actually calculating absolute probabilities.

There are several ATPs of interest relative to deorbit systems. These include the drag ATP that determines how rapidly an object's orbit will decay; the ATP for collisions of very small MOD objects with spacecraft; the ATP for impacts of the bare spacecraft with large debris objects, which typically will completely disrupt both objects and create significant new large debris (>10 cm); and the ATP for collisions between very lightweight elements of deorbit systems and other spacecraft or debris, which do not typically create significant new debris, although they may damage the other spacecraft.

A. Drag Area-Time Product

The drag ATP is the ATP discussed in all the policies, procedures, and guidelines mentioned earlier. This ATP is strictly the cross-sectional area (CSA) of a space object as it relates to atmospheric drag contribution (i.e., the drag CSA). This is the average area of the spacecraft projected along its flight path, multiplied by the time spent in orbit. Devices have been proposed that will significantly increase the area of a spacecraft after it has completed its useful mission. The idea is to increase the small aerodynamic drag and thereby reduce the time spent in orbit. However, it turns out that the time to deorbit is exactly inversely proportional to the increase in area and, as a result, the drag ATP is the same with either the small area or the larger area. This is illustrated in Fig. 11.

In this example, a bare spacecraft has a projected drag CSA of 4 m^2. Starting at an altitude of 833 km, computation of the orbital decay shows that the orbit will lower by 2 m over a time period corresponding to 25 orbits around the earth. The air density at this altitude is very low, and so it takes a long time to reduce the orbital energy. From this starting point, it would take several centuries for the spacecraft to finally enter the Earth's atmosphere. In the example, a very large, very thin balloon is inflated as a method of increasing the drag area. For this hypothetical example, the projected area of the balloon is 1000 m^2, an increase in area by a factor of 250. Assuming the same drag coefficient for the bare spacecraft and for the balloon (a reasonable assumption for the highly rarefied hypersonic flow encountered by spacecraft), the drag force increases by a factor of 250 in direct proportion to the increase in area. This increases the rate of loss of orbital energy, also in direct proportion to the increased area. It follows that the time needed to lower the orbital altitude by the same 2 m is $1/250$th of the original time and, therefore, that the drag ATP is exactly the same in these two cases.

If the risk of a dangerous collision were indeed proportional to the drag ATP, then there would be no value in deploying the large drag device because the overall risk would be unchanged. As will be described, there are a number of reasons why the risk is significantly lower with the large drag device, which is fortunate because they can now be safely included in the arsenal of weapons to combat the growing orbital debris problem.

B. Collision Cross-Sectional Area

Several ATPs refer to different kinds of collisions (collisions that completely disrupt other large objects, collisions that disable space

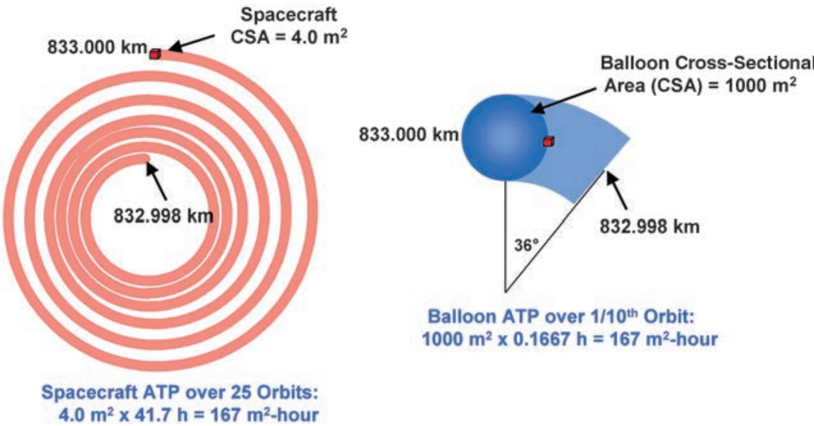

Fig. 11 Drag ATP using a balloon as an example.

systems, but do not disrupt them, collisions that create a lot of new debris, and collisions that do not create significant new debris). In discussions of all of these, the concept of collision CSA is useful. It is somewhat analogous to the collision CSA for particle physics. Particles can interact (or "collide") when they pass within some distance of one another, even though that distance is much larger than the physical size of either particle.

Figure 12 depicts the outline of a spacecraft colliding with a large piece of orbital debris. It is obvious by looking at the figure that a collision can occur even when the center of the orbital debris passes outside the projected (drag) area of the spacecraft. The characteristic length of the orbital debris is shown as 2.0 m. This size corresponds to the peak of the size distribution of all orbital debris when plotted according to the area of the debris [13]. That is, most of the *area* of all orbital debris is concentrated at sizes close to this size. There are many more small objects, but they each have very small area and their aggregate area is still less than that for the larger objects of about 2.0 m in size.

The smooth outline drawn around the spacecraft at a distance of 1.0 m (half the size of the debris) shows the approximate region through which the center of the debris could pass and result in a collision with the spacecraft. The size of this collision CSA depends on both the size of the spacecraft and the size of the debris with which the spacecraft might collide.

The collision CSA is somewhat analogous to the "casualty area" used by NASA [14] in estimating the probability of debris surviving to the ground and seriously injuring people. For "collisions" between debris objects that survive reentry and a standing human, the casualty area is computed as follows:

$$D_A = \sum_{i=1}^{N} (\sqrt{A_H} + \sqrt{A_i})^2$$

where A_i is the area of the ith debris object and A_H, 0.36 m^2, is the area of an average standing human. The summation is over all N debris objects surviving to the ground. This equation is valid for fairly compact objects. However, it is seriously inaccurate for extended objects that survive reentry, such as tethers and booms, where one dimension is significantly greater than the other two. Fortunately, extended objects usually do not survive reentry; hence, the NASA equation works just fine.

For example, for an orbital spacecraft with a 2 m by 2 m square projected area, colliding with a piece of debris with an area A_i of

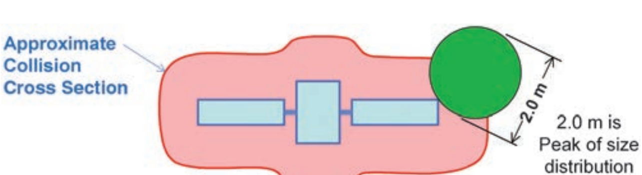

Fig. 12 Collision cross-sectional area.

3.14 m^2 (a spherical object with a characteristic dimension of 2 m), the preceding NASA equation would give an augmented CSA of 14.23 m^2 as illustrated in Fig. 13. Note that in this figure, the dimension of 0.866 m is half the side of a square with the same area as the round debris object with diameter 2 m. Extending the boundary of the spacecraft by 1 m (half the characteristic length of the debris) gives a slightly larger area of 15.12 m^2 than would be calculated from the NASA equation, as shown in Fig. 14. However, the reference spacecraft is not a square and the characteristic debris object is modeled as a 2-m-diam sphere. The reference spacecraft is modeled as a square bus 1 m^2 with a solar panel 2 m by 0.75 m extending from each side, as shown in Fig. 15. Extending the boundary by 1 m (and

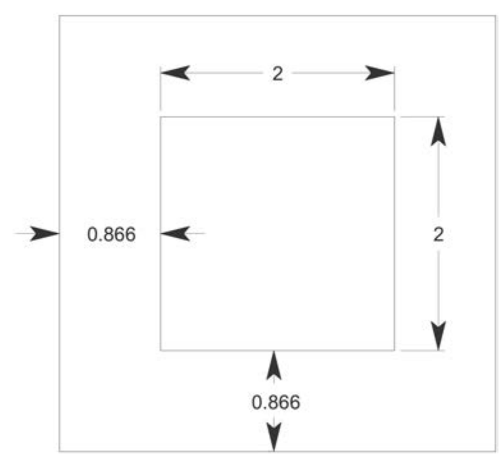

Fig. 13 NASA casualty area.

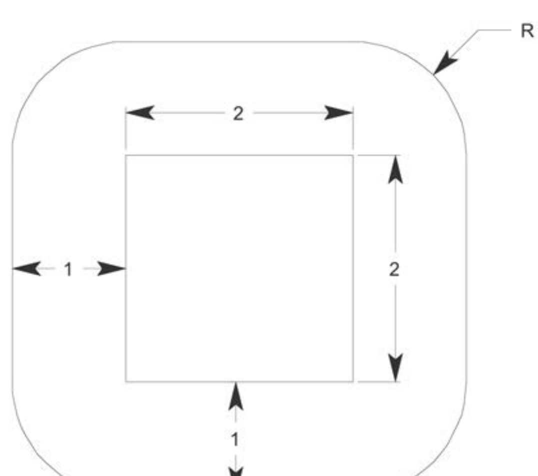

Fig. 14 Area augmentation approach used here.

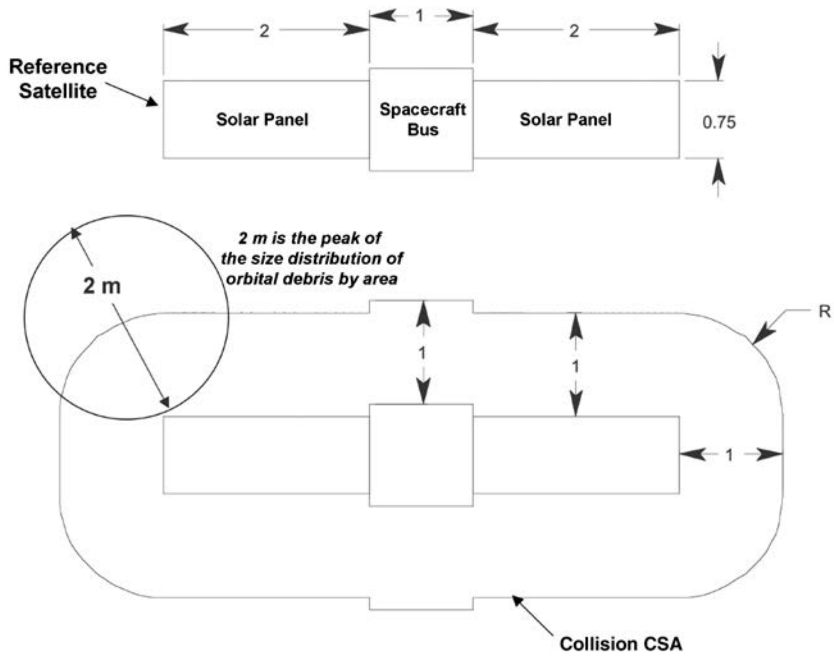

Fig. 15 Bare spacecraft (4 m^2) and augmented collision cross-sectional area (18.6 m^2).

neglecting the small arc that should cover the jog between the spacecraft and the solar panels, and for simplicity in writing equations in Microsoft Excel), the collision CSA is 18.62 m^2. Including the missing arcs, computer-aided design software gives an area of 18.78 m^2. Because this is less than a 1% difference, the simple calculation is used. With these compact objects, the differences between the NASA equation and the approach used here for orbital objects are small. However, for a 1-mm-diam tether with a length of 5 km, the difference is huge. The projected, or drag, CSA of the tether is 5 m^2. For the 2 m debris object, the NASA equation would give a collision area of ~18 m^2. However, if the length, 5000 m, is multiplied by the 2 m dimension of the colliding debris, an area of a little over 10,000 m^2 is computed, which is illustrated in Fig. 16. In this case, the results differ by three orders of magnitude. Because deorbit systems are being compared with extended linear dimensions, this more complex approach is used in computing collision CSA. This is done for all cases for consistency.

An ATP based on collision CSA rather than on drag CSA would more correctly represent collision probability. Collision ATP does not give the actual probability of collision, but allows a proportional comparison between different systems to determine which has a greater probability of collision with debris of a particular size of interest.

Figure 17 compares collision CSA augmentation over the bare object for a space object with a 4 m^2 projected drag CSA (1 m^2 spacecraft bus with two 2 m by 0.75 m solar arrays) and a balloon with a projected drag CSA of 1000 m^2. The ratio of the augmented collision CSA to the drag area is shown in Table 1 for different-sized debris objects for the spacecraft and the balloon.

For 2-m-sized debris objects, the collision CSA for the spacecraft is about 4.66 times the bare drag area, whereas for the balloon, the augmentation in area is only 12%. Even for 10-cm-sized debris objects, the collision CSA for the spacecraft is 15% larger than the drag area. For the balloon, the increase in area for collisions with 10 cm debris objects is less than 1%.

If an ATP is formed using the augmented collision CSA instead of the bare drag CSA, the comparison between the spacecraft and the large drag device no longer comes out the same. This is shown in Fig. 18, which corresponds to the same situation as Fig. 11. Both the spacecraft and the spacecraft with extended drag device have the same drag ATP of 167 $m^2 \cdot h$, but the collision ATP, which more accurately represents the likelihood of colliding with a debris object with a size of 2.0 m, is 776 $m^2 \cdot h$ for the spacecraft, but only 187 $m^2 \cdot h$ for the balloon. Already, it can be seen that using collision CSA instead of drag area gives a significant benefit to a large drag device compared with the spacecraft, with regard to likelihood of colliding with orbital debris. However, as will be seen in the next

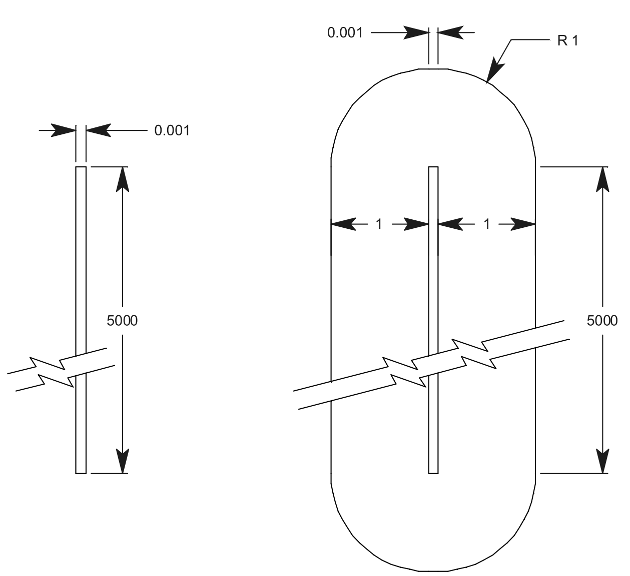

Fig. 16 Bare tether (5 m^2) and augmented collision cross-sectional area (>20,000 m^2).

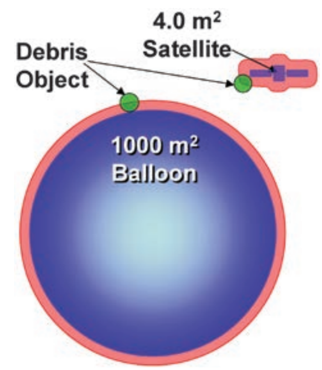

Fig. 17 Collision cross-sectional area augmentation example with a balloon device.

Table 1 Impact CSA augmentation factors

Debris size	10 cm	1.0 m	2.0 m
Spacecraft	1.15	2.63	4.66
Balloon	1.01	1.06	1.12

section, there are additional benefits associated with large, thin drag devices.

C. Debris-Generating Area-Time Product

As discussed in Sec. IV, collisions between a debris object and an ultrathin film does not generate significant new debris. The mass of the film involved in the collision is so small that there is not enough energy to cause disruption of the debris object, despite the very high impact velocity. In contrast, collisions between the high-density spacecraft and a large debris object will produce a very high-energy impact leading to complete disruption of both hard bodies (the spacecraft and the debris) and will typically yield thousands of new large fragments, as was demonstrated by the Chinese antisatellite experiment. The number of fragments from this experiment alone is now over 3000, representing over 22% of all cataloged orbital debris objects in LEO [15]. Thus, there is a significant risk of creating new debris only for the high-energy impact region of the combined spacecraft balloon area versus all of the area for the bare spacecraft with no large drag device. Figure 19 illustrates these two regions (high-energy debris-generating region and low-energy non-debris-generating region). The collision area for generating new debris is now exactly the same in the two cases, but the associated *debris-generating* ATP is hugely different in the two cases. For the bare spacecraft, it is still 776 $m^2 \cdot h$, whereas for the spacecraft attached to the ultrathin balloon, the debris-generating ATP is only 3.10 $m^2 \cdot h$ (a factor of 250 lower). It should, by now, be clear that the original guidelines would inadvertently have eliminated the balloon as a viable orbital debris-mitigation approach, whereas with the correct ATP, it is obvious that there is a tremendous advantage in using it.

Some drag enhancement devices have a significantly greater mass areal density than an ultrathin balloon film. If a collision between the extended drag area and another large object results in significant fragmentation, this drag device cannot take advantage of this significant reduction in debris-generating area, and its entire area must be included in its debris-generating ATP. It will still show a reduction in ATP over the bare spacecraft due to the area augmentation aspect described in the previous section, but it would not be the significant reduction described for the ultrathin-film balloon example used here.

D. Area-Time Product for Disabling Satellites

The preceding section discussed the appropriate ATP to use when concerned with the generation of significant new debris. The debris-generating ATP does not address either damage to other spacecraft or how effective the drag device is after a collision. Naturally, any device that is used to deorbit defunct space systems must take into account the threat caused by its operation to other spacecraft that are still operational. If the operation of a deorbit device interferes with operating satellites, this characteristic is very important in deciding if the deorbit method is really suitable.

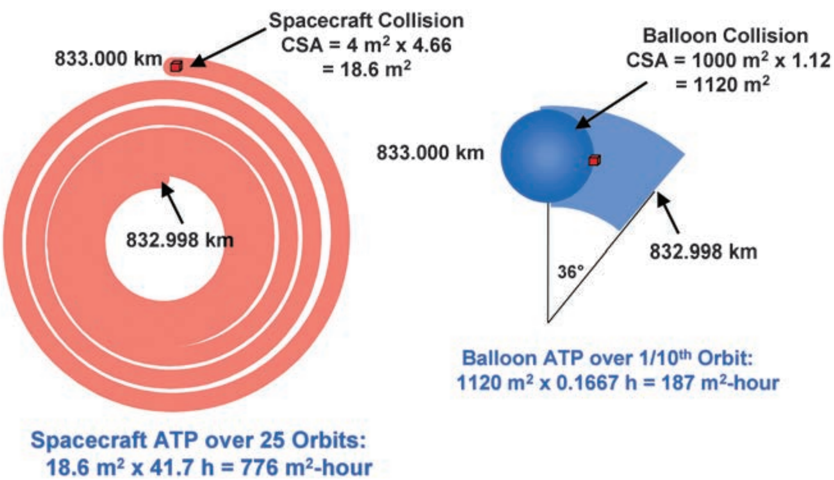

Fig. 18 Augmented area-time product example with a balloon device for 2-m-sized debris.

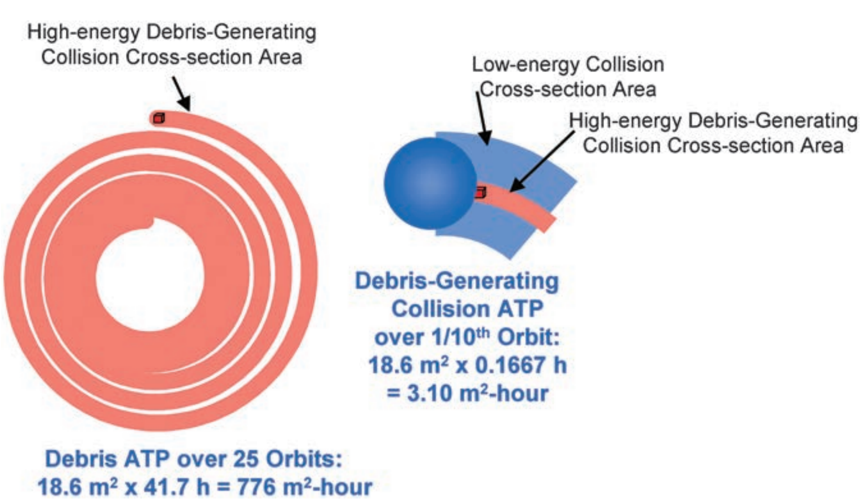

Fig. 19 Orbital debris-generating ATP example using a balloon device.

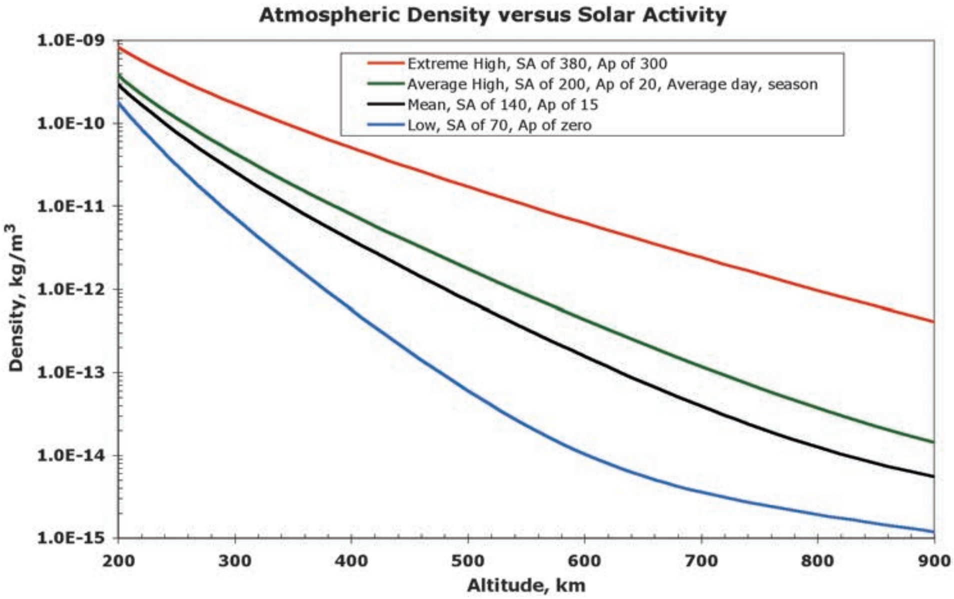

Fig. 20 Atmospheric density as a function of altitude and SA levels.

Continuing with the balloon example, if the balloon film inadvertently collides with an operational spacecraft, even though that is not likely to cause complete disintegration of that spacecraft into debris, it may well cause damage to the spacecraft, preventing it from completing its intended mission. All known objects larger than about 10 cm are currently tracked and their trajectories extrapolated to predict potential close encounters or conjunctions with other objects. When an operating spacecraft with a propulsion system is expected to pass close to another object (either debris or another operating spacecraft), and analysis shows that a significant risk of a collision exists, the operational spacecraft can adjust its orbit to avoid the potential collision. Therefore, no deorbit device poses a credible threat to operating spacecraft with propulsion capability because they can maneuver out of the way.

For potential collisions with nonmaneuverable operating spacecraft, the threat should be based on the collision CSA for the full deorbit device (augmented based on the size of the operating satellite with which it might collide). Such a threat comparison will still show a favorable reduction in the total risk compared with the threat due to the bare spacecraft whose collision ATP is relatively low.

E. Effects of Solar Activity on Area-Time Product

Figure 20 displays the mass spectrometer and incoherent scatter experiment model (MSISE-90)[¶] atmospheric density for four solar activity (SA) levels, namely, low, mean, average-high, and extreme-high solar activity levels. The MSISE model describes the neutral temperature and densities in Earth's atmosphere from the ground to thermospheric heights. Note that, for a mission altitude of 800 km, the density can vary by almost three orders of magnitude, depending on solar activity. The average-high MSISE atmosphere model is approximately representative of the average solar activity ± 1 year about high sun periods.

One can see that, for the range of altitudes (500–800 km) at which the deorbit systems can spend a majority of time, the atmospheric density can vary by a factor of 1000 depending on solar activity, geomagnetic index, etc. Very clearly, deorbit time can vary considerably, depending on solar activity level, and needs to be considered in designing and using drag-augmentation deorbit systems.

The debris-mitigation policies have incorporated a guideline to remove space assets within 25 years. They implicitly accept the risk of allowing a dead spacecraft to continue carving out a threat volume through space for 25 years. The solar cycle is about 11 years, so during the 25 years allotted to remove an object from orbit, there will be at least two solar maxima. It is known that during a period of a couple of years centered on solar maximum, the density of the Earth's atmosphere in LEO, up to an altitude of around 900 km, increases by several factors over the average density over the full solar cycle. Between around 600 and 900 km, the air density at solar maximum is about three orders of magnitude greater than at solar minimum. Although this is significant, it should be noted that this extremely high case rarely occurs and, when it does, it is for a very short time, on the order of months. Except at very low altitudes where the bare spacecraft will naturally deorbit on its own without any drag augmentation within a few years, the time part of the ATP for a bare spacecraft effectively averages out the drag variations throughout the solar cycle. But if a large drag enhancement device is deployed and is large enough to complete deorbit in less than about three years, then it makes more sense to wait to deploy the device until a year or so before solar maximum. In this way, it will complete its entire deorbit when the air density, and therefore the drag, is enhanced by a few factors. With the assumption that the device will be operated near solar maximum, then the ATP with the large area can be further reduced by this factor when compared with the bare spacecraft averaged over many solar cycles.

Although deploying the large drag device earlier, rather than waiting for solar maximum, would get the defunct spacecraft out of orbit sooner, it would actually incur greater total integrated risk of collision with other operational spacecraft. Deploying the drag device earlier when the air density is lower means the deorbit time spent with the large drag device deployed would be longer. The extra time would contribute relatively more to the collision ATP. Instead, while waiting for the air density to be higher near solar maximum, one accumulates collision ATP based on just the area of the bare spacecraft. Also, with premature deployment, the drag device itself would experience more collisions with small MOD objects because it would be extended for a longer period of time. Taking these various considerations into account, it is better to wait for higher air density near solar maximum.

To support these claims numerically, NASA's Debris Assessment Software (DAS) [16] was run, assuming a satellite with bare cross-sectional area of 4 m^2, an area-to-mass ratio of 1.0 m^2/kg (1000 m^2 drag area, 1000 kg satellite), and an initial orbit of 833 km altitude and 98.2 deg inclination, for a number of starting times over a period of about three solar cycles. Figure 21 shows the resulting total deorbit time versus deployment date, and Fig. 22 shows the date of entry versus deployment date. These two figures give an indication that it is beneficial to wait until just before solar maximum to deploy the large drag device, however, to provide a more quantitative comparison, the

[¶]Data available online at http://uap-www.nrl.navy.mil/uap/?content=article1;code=7643 [retrieved 21 July 2011].

collision ATP was computed in Fig. 23 for three scenarios, namely, 1) immediate drag area deployment (black line), 2) waiting for solar maximum 25 (red line), and 3) waiting for solar maximum 26 (blue line). This figure presents the solar maximum regions, as used in DAS, as roughly two-year-long periods centered about the ramped plateau near the peak of the predicted F10.7 solar flux index. These solar maximum regions also correspond roughly to the minima seen in Fig. 21. These data show that it is more favorable to wait to deploy the drag area between about eight months before a solar maximum period start and eight months before the end of a solar maximum period, than to deploy a drag area immediately. There can be a significant penalty (extra risk of collision) for deploying immediately; therefore, one should wait until solar maximum activity has increased the atmospheric density before deploying to reduce collision risk. In fact, if the mission ends near the end of a solar maximum period, it is already too late for immediate deployment, as indicated by the steep upward slope there. It is better to wait about nine years and then deploy about eight months before the subsequent solar maximum period.

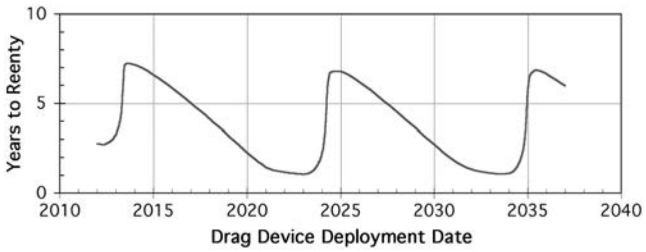

Fig. 21 Reentry delay for different start dates.

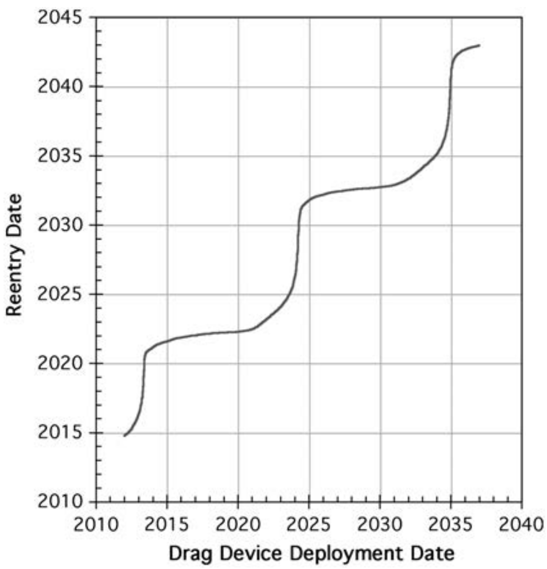

Fig. 22 Drag device performance.

VI. Comparison of Collision Area-Time Product for Several Deorbit Concepts

This section compares the risk associated with various methods of removing defunct spacecraft from orbit to reduce the risk of creating new debris, as well as reducing the danger of incapacitating operational space assets. Because the focus is on avoiding the creation of new debris, the 2 m characteristic size of debris has been used in computing collision CSA and ATP. However, potential collisions with operational spacecraft are discussed, and it is tacitly assumed that they also have a 2 m characteristic size. Of course, some spacecraft will be larger than this and others will be smaller. But, for simplicity, they are being treated as having the same size as the characteristic size of debris. Spacecraft are probably a little larger on average than this size, and the collision area augmentation would then show even greater risk for the defunct bare spacecraft in comparison with the deorbit systems discussed.

First, assumptions are defined that will allow a comparison of deorbit concepts. From the preceding discussion, it is very clear that deorbit devices that rely on atmospheric drag should initiate deorbit around the time of solar maximum to reduce the decay time to the minimum, thus keeping ATP low. And so, with the exception of propulsion systems, it is assumed that all of these concepts begin deorbit within about one year from solar maximum, which occurs about every 11 years. Second, it is assumed that the satellite or derelict object to be deorbited weighs 1000 kg and is in a sun-synchronous orbit at an altitude and inclination of 833 km and 98.2 deg, respectively. In this fashion, all of the atmospheric drag enhancement devices have almost exactly the same CSA. The electromagnetic tether will have a tether length approximately sized for a one year decay period (i.e., about 5 km). Third, it is assumed that the debris size under consideration has a characteristic length of 2 m because this is close to the peak in the distribution of aggregate area of debris versus debris size.

Figure 24 shows a schematic representation of the various concepts being compared. These concepts include, for reference, the bare spacecraft with no deorbit device, a large inflation-maintained ultrathin envelope (balloon), a large thin-film drag area supported by booms, a long, thin tape oriented vertically using gravity gradient

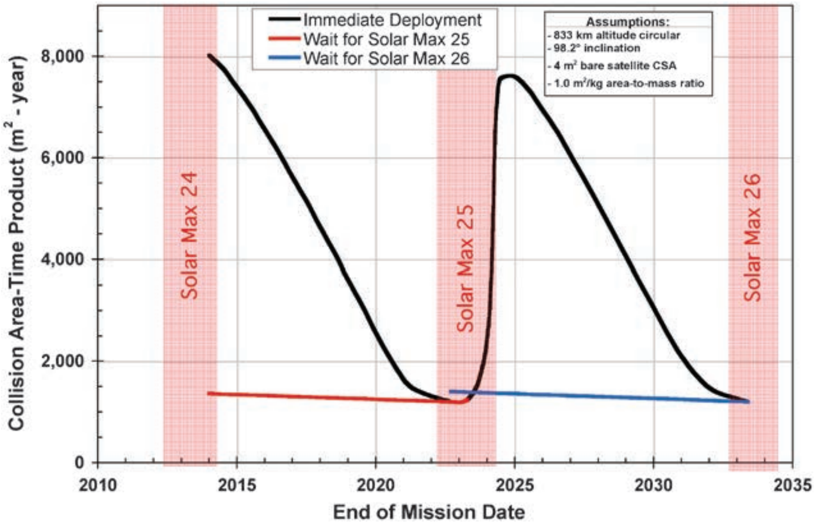

Fig. 23 Comparison of immediate deployment versus waiting for solar maximum.

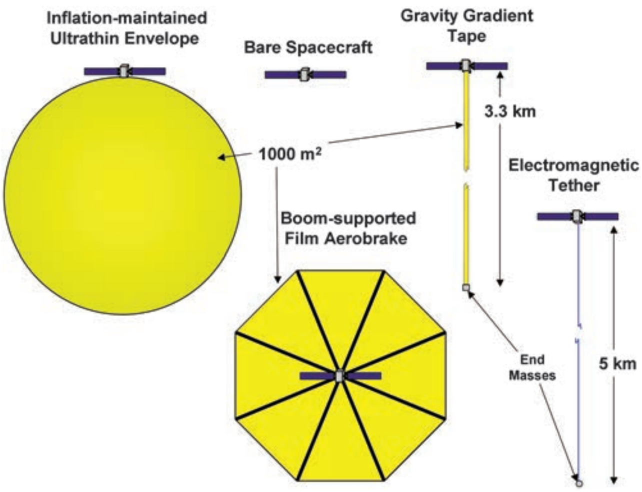

Fig. 24 Schematic comparison of deorbit systems.

torque, and an electromagnetic tether, also oriented vertically using gravity gradient torque.

Figure 25 highlights schematically in red the augmented area that will cause many large new debris fragments (or disrupt another spacecraft) during a collision. Here, it is assumed that the booms supporting the film have sufficient mass per unit length that they would cause significant damage and create much new debris on impact with a large debris object or spacecraft. It is assumed that the tape and the tether are sufficiently thin that they would not create new large debris.

Finally, Fig. 26 depicts in green the portion of the area that will not create large new debris fragments upon collision with a large debris object or spacecraft, although it would still represent a serious threat for disabling an operating spacecraft in the unlikely event of a collision. If a large balloon-like device were chosen that had to be rigidized rather than inflated, then the areal density would be high enough that the entire area would cause significant large debris on impact. This would still have a benefit compared with the bare spacecraft, but would be significantly worse than other deorbit devices.

Figure 27 compares the collision ATP for several methods of deorbiting space hardware following end of mission. The collision ATP for deorbit methods in the figure are shown as horizontal bars in order of decreasing threat of creating many new, large debris objects by "high-energy" collisions. The red portion of the bars indicate the high-energy collisions contribution of ATP that is computed for collisions between debris objects with a typical dimension of 2 m and

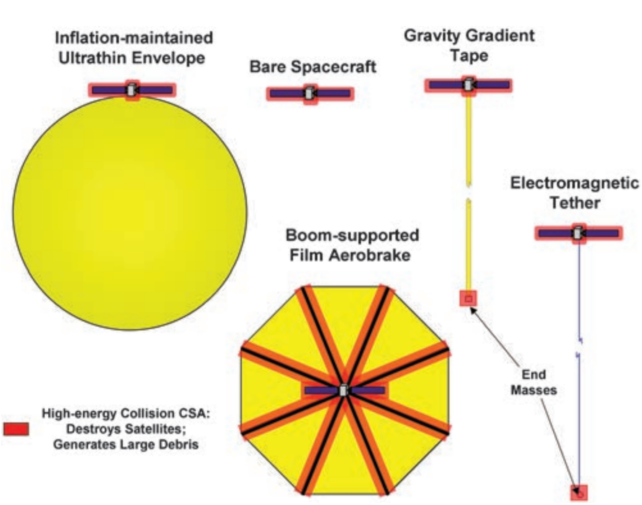

Fig. 25 Comparison of deorbit systems highlighting high-energy collision regions.

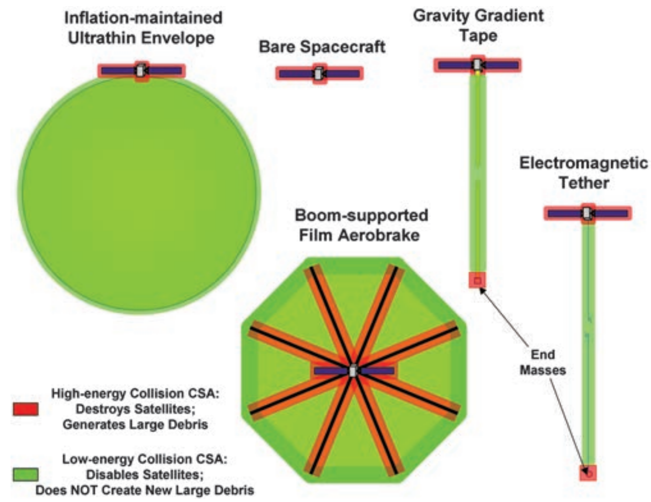

Fig. 26 Comparison of deorbit systems contrasting high- and low-energy collision regions.

high areal density portions of the deorbiting system, including the satellite being deorbited. High-energy collisions are those that generate many new large debris objects (greater than 10 cm in size). Low-energy collisions are those collisions that do not generate a significant number of new large debris objects. The ATP for low-energy collisions are shown as the green portion of the bars. In all cases, the example spacecraft is the one used earlier: a 1000 kg spacecraft with a cross-sectional area of 4 m^2 starting at an altitude of 833 km (a typical polar sun-synchronous orbit). In addition, the orbit decay period is one year near solar maximum. The bare spacecraft, with essentially no deorbit method, takes about 700 years to deorbit, according to NASA's DAS, and all collisions are high-energy because all collisions are with the hard body (spacecraft). Because it may not be appropriate to compare a risk that occurs over one year with one that occurs over seven centuries, the collision ATP for the bare spacecraft is calculated for only 100 years, which is a short enough time to be considered a more relevant risk for comparing against deorbit systems. Because there are no assumed extended thin areas for the bare spacecraft, the low-energy collisions portion of the bar is zero.

Of those compared, the worst deorbit method is a rigidizable space inflatable sphere. For the rigidizable space inflatable sphere, the areal density is assumed to be high enough that all collisions will produce many new large debris fragments. Thus, all the ATP is in the high-energy collisions portion of the bar. Even this worst deorbit method is better than the bare spacecraft over 100 years in terms of total integrated risk over the entire deorbit period. This difference is entirely due to the use of augmented collision CSA rather than bare drag CSA. However, this threat is all accumulated during a one year period, rather than over several centuries. This may be considered worse than leaving the spacecraft in orbit for a while.

The next worst concept is any method that just meets the 25 year rule without changing the area of the bare spacecraft. For example, this would include the use of residual propellant to lower the orbit of the spacecraft to the point at which it will subsequently decay in 25 years due to drag on the bare spacecraft. This approach is much better than leaving the space junk to decay over centuries, but still poses a significant threat of creating new debris.

The boom-supported film aerobrake deorbit system concept is better than the 25 year rule. For this method, the same projected drag area is assumed for the rigidized sphere. However, the augmented area associated with the booms (their length multiplied by the assumed 2 m dimension of the debris) added to the bare spacecraft area (augmented by collision with 2 m debris) is used in computing the high-energy collision ATP. The thin film between booms contributes only to low-energy collisions and makes up the bulk of the collision ATP. This leads to a sizable reduction in high-energy collisions compared with the rigidizable sphere, because a large

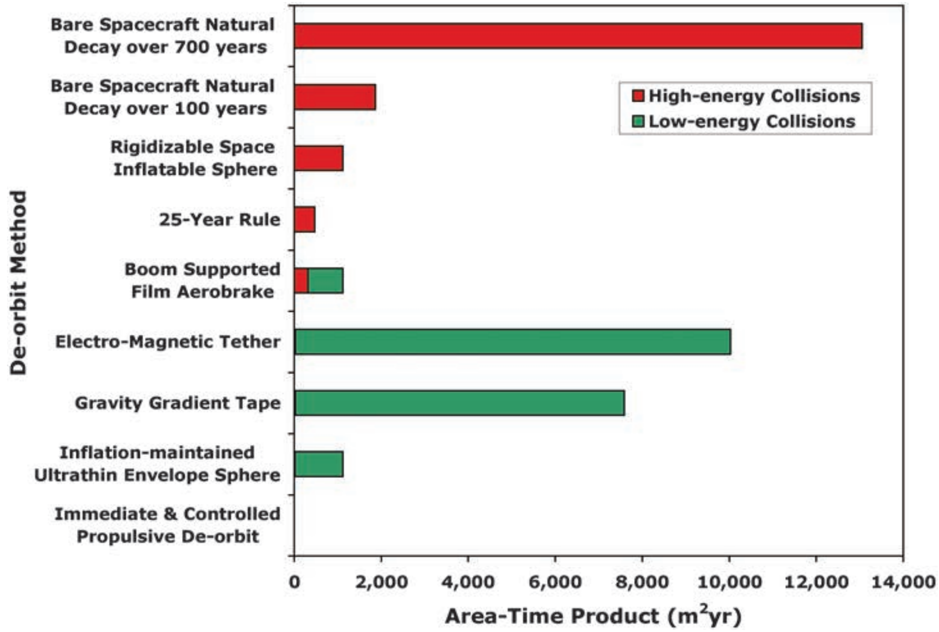

Fig. 27 Area-time product summary comparison.

fraction of the area is thin film whose areal density is too low to cause large debris particles in collisions with other objects.

The electromagnetic tether and gravity gradient tape deorbit methods are a further improvement for high-energy collisions. Both concepts have relatively small ATP for high-energy collisions, but they both have very high ATP for low-energy collisions (nearly an order of magnitude higher than other concepts) that could disable operating satellites. For both of these methods, a dense mass is assumed at the end of the tether or tape at the end away from the spacecraft. This counterweight is needed to allow sufficient gravity gradient torque to prevent the tether or tape from swinging backward and upward due to the very force they are using to deorbit the system. It is assumed that this counterweight has a radius of 0.3 m. The collision CSA of this counterweight is equal to the area of a circle with a radius of 0.3 m plus half the characteristic size of the colliding debris object. Because of their very long extent vertically, their low-energy collision CSA is augmented greatly by multiplying their length by the characteristic size of debris objects. Even with a very lightweight tether or tape, the very large collision CSA swept out constitutes a very significant risk of disabling operating spacecraft that cannot maneuver out of the way. It is possible that an electromagnetic tether could have some maneuverability, but would require a very complex dynamic and operational system to react in a predictable manner when trying to avoid operating spacecraft.

The relatively simple analysis of the collision ATP of electromagnetic tethers used here is consistent with previous research on the probability of impact of tethers with large space objects like satellites. For example, Cooke et al. found that, for a 20-km-long tether in an 800 km altitude, 51.6 deg inclination orbit, the probability of collisions with operational satellites, assumed to have a 10 m characteristic size, is ~0.11 per year [17]. Later, Anselmo and Pardini calculated the collision probability for tethers with all cataloged objects (including operational satellites) at 800 km altitude and in a 50 deg inclination orbit [18]. Their results indicate that a 20-km-long tether and a 10-m-sized object will have a collision probability of 0.24 per year, which is consistent with Cooke et al. [17]. Reducing the tether length by a factor of 4, to 5 km, only reduces the probabilities by a similar factor, which makes the collision probability still unacceptably high. In addition, Patera's numerical analysis [19] indicates that the collision probability associated with a 20-km-long space tether is 400 times higher than with a large, 6 m radius, spherical space object when colliding with a 2-m-diam space object, where most of the area of all debris is concentrated. It is clear that tethers are a very high risk to operational satellites due to their large collision CSA.

The best deorbit method (lowest risk) that does not use propulsion for immediate deorbit is the inflation-maintained ultrathin envelope (i.e., balloon). It reduces the time to deorbit from centuries to months, and the only high-energy portion of the area is the hard-body spacecraft. Thus, the associated ATP is quite low. Almost all of the area is the very thin film, which does not produce large new debris upon impact, and so the bulk of the area-time product is in the low-energy collision portion of the bar. This value is still lower than for the original bare spacecraft, even for 100 years, due to the area augmentation effect described earlier.

Immediate propulsive deorbit poses the lowest risk because it assumes complete and immediate deorbit at the end of life. The time from the assumed delta-velocity (delta-V) is on the order of an hour, and so the integrated area-time product is negligible in terms of meters squared years. Although having the lowest risk of collision with debris, propulsive deorbit is expensive with respect to mass and cost, especially if the mission does not already require propulsive maneuver capability. Even when a satellite already includes a propulsion system, the mass of extra propellant needed for immediate deorbit is often higher than the mass of some of these other deorbit systems. This is because all the needed delta-V comes from the propellant, whereas these other methods get their "propellant" from the environment, either in the form of momentum from molecules, ions, and atoms, or from electromagnetic interaction with the Earth's magnetic field. Another consideration is that the use of a propulsion system usually requires a cooperative satellite with attitude determination and control, as well as computational capability and power. A dedicated independent deorbit system, focusing on surviving and deploying with very high reliability, may well be able to operate despite a defunct satellite. Another consideration on the use of propulsion is the pressure to continue using propellant to extend the spacecraft mission. As long as a satellite functions, operators will tend to keep using propellant, arguing that the economic or national interest value of the satellite is greater than the long-term risk, even if the satellite is not ultimately deorbited. When pressed to meet the regulations, operators frequently seek waivers to continue operating the spacecraft for as long as possible, meaning there often is not enough propellant to get into an orbit that will decay in 25 years, never mind immediate deorbit.

VII. Conclusions

The 2009 collision in low Earth orbit (LEO) of an operational Iridium satellite and a defunct Russian satellite highlights the critical need for the ability to deorbit large objects from popular, congested orbital regions. The altitude band from about 750 to 900 km is a highly used portion of space, due largely to the sun-synchronous missions executed there. As a result, the spatial density (i.e., number of objects per volume) is greater there than in any other region in Earth orbit. This region is just several hundred kilometers above the sensible atmosphere, and so the use of a drag-augmentation device would have the greatest impact, both operationally (making a very useful orbit still available) and physically (be the most likely altitude where drag-augmentation devices would be useful). It is also a region where removing spent satellites and launch vehicle stages safely without creating more orbital debris is critical to the future of safe operations in this altitude band.

The physics of hypervelocity impacts between various density objects in space has been discussed and the implications of the resulting energy deposited in each colliding object (or energy to mass ratio) has been made clear with respect to the possibility of catastrophic debris generation events. A key point is that collisions between large objects and low areal density films and tethers, in common with several deorbit concepts, will not result in catastrophic fragmentation and breakup of the colliding object; however, these collisions will likely disable operating satellites. Another key point is that collisions by large debris objects with booms and rigidized structures, also in common with some deorbit concepts, will result in catastrophic fragmentations that will increase the population of orbital debris objects.

The extra energy dumped into the Earth's upper atmosphere during solar maximum causes the Earth's atmosphere to bloom outward as compared with solar minimum. This effect increases the density in LEO by a factor of 1–3 orders of magnitude, depending on altitude, and about a factor of 3 compared with the long-time average. As a result, atmospheric drag deorbit devices are much more efficient during solar maximum, pose a lower risk to operating satellites, and have a lower chance of creating new, large debris objects. Permitting a satellite to use a smaller drag device over 25 years, which will average about two solar cycles, means it will incur about three times the risk compared with a larger device selectively operated near solar maximum (including the time taken waiting for solar maximum). As a result, it is recommended that drag-augmentation devices be sized and timed to complete their deorbit function only during solar maximum to further reduce the risk of creating new debris.

The concept of area-time product (ATP) has been further developed and refined by defining a drag ATP, which is just the cross-sectional area of an object, and an augmented collision ATP, which takes into account the size of both colliding objects. The collision ATP is larger than the drag ATP and more accurately characterizes the potential risk of having collisions with extended bodies, like tethers. This new information, and the insights on risk it affords, will assist regulators in recognizing that collision ATP, rather than the simple drag ATP, should be used to analyze the potential risk of orbital collisions and in comparing the risk of deorbit systems. In addition, it is hoped that the two important benefits of operating drag-augmentation devices during periods of high solar activity are well recognized, namely, reduced deorbit time or drag area and reduced risk of collisions.

Results of an analysis of the collision ATP and hypervelocity impacts with components of several deorbit methods indicate that a rigidizable space inflatable sphere has the highest risk of creating new, large debris by high-energy collisions with other orbital debris objects. Surprisingly, the next highest risk is using residual propellant to lower the orbit to an altitude from which it will decay in 25 years. Electromagnetic tether, gravity gradient tape, and inflated-maintained ultrathin envelope deorbit methods have the lowest risk, besides immediate propulsive deorbit, of creating new, large debris due to their small ATP for high-energy collisions. However, tethers and tapes have a very high risk of disabling operating spacecraft due to their large ATP for low-energy collisions. Other than immediate propulsive deorbit, ultrathin inflation-maintained drag envelopes pose the lowest risk of disabling nonmaneuverable operational spacecraft, and they also have the lowest risk of creating new debris during the short deorbit period.

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