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Atmospheric Reentry Disposal for Low-Altitude Spacecraft

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We explored four different options for atmospheric reentry of spacecraft from a circular low Earth orbit, below 2000 km in initial altitude, within 25 years: 1) chemical propulsion maneuvers, 2) low-thrust propulsion transfer, 3) balloon (drag enhancement device) deployment, and 4) a combination of options 1 and 3. This atmospheric reentry approach satisfies the recent set of NASA guidelines on the disposal of space structures. The additional required deorbit weight for each of these options is examined as a function of the initial altitude and ballistic coefficient of the spacecraft. The results of this study show that the additional weight required for deorbit using a low-thrust transfer is significantly less than the additional weight required for the other options. The balloon deployment option is competitive with the chemical propulsion option for low initial altitudes with regard to additional required weight for deorbit. The combined use of chemical propulsion with balloon deployment results in a lower required additional deorbit weight than for either option alone but only for cases with a small ballistic coefficient (area-to-mass ratio below 0.009 m²/kg). The final disposal strategy chosen will also depend on other factors, such as cost, simplicity, reliability, and launch vehicle weight margin. The advantages and disadvantages of each option are discussed.

Nomenclature

A, A_c	=	cross-sectional area of spacecraft in the velocity direction, m^2
C_d	=	drag coefficient
$C_d A/m$	=	ballistic coefficient, m^2/kg
I_{sp}	=	specific impulse, s
M	=	mean anomaly, deg
m	=	mass of spacecraft, kg
P_{coll}	=	probability of collision
v_r	=	relative velocity between the spacecraft and catalog object, m/s
Δt	=	time spent in a given altitude bin, s
ΔV	=	velocity correction, m/s
ρ	=	spatial density or number of space objects per unit volume, number/m^3
ρ_B	=	material density of a balloon, kg/m^2
σ	=	sigma, standard deviation
Ω	=	right ascension of ascending node, deg
ω	=	argument of perigee, deg

Introduction

BECAUSE of an anticipated increase in the number of satellites to be placed in low-altitude orbits in the near future (e.g., Iridium, Globalstar, Orbcomm, Teledesic, and Celestri), there is a growing interest in disposal methods for low Earth orbit (LEO) missions. The recent development of a set of NASA guidelines[1] on postmission disposal of space structures reflects the importance of this issue. NASA studies have examined numerous disposal methods for meeting these guidelines.[2,3] Various organizations are designing, building, and deploying constellations in LEO, each with on the order of a hundred or hundreds of satellites. If the NASA guidelines are to be followed, agencies will likely need to select the method of disposal early in the mission design phase.

According to the NASA guidelines,[1] a spacecraft or upper stage with perigee altitude below 2000 km in its final mission orbit may be disposed of by using an atmospheric reentry option. This NASA guideline for atmospheric reentry is stated as follows:

> Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. 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 of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit.

The focus of this study is on atmospheric reentry for circular orbits with initial altitudes below 2000 km. Most of the large satellite constellations being planned in the next few years will use this category of orbits.[4] One concern of implementing any option that relies on natural decay for atmospheric reentry is the inherent risk that there will be survivable components that could land in populated areas.[5] This concern can be alleviated by adoption of a controllable deorbit, in which the satellite can be deorbited over a broad ocean area and away from populated regions.

Four different options for atmospheric reentry of a LEO spacecraft orbit within 25 years (as outlined in the NASA guidelines) are explored here. These options are 1) chemical propulsion maneuvers, 2) low-thrust propulsion transfer, 3) balloon (drag enhancement device) deployment, and 4) a combination of options 1 and 3. The practicality and usefulness of each of these methods will strongly depend on the initial altitude and ballistic coefficient of the satellite. The tool used to describe orbital decay in this study is called LIFETIME. Previous studies have illustrated the reliability of this program in predicting accurate orbital lifetimes.[6] The risk associated with each of the disposal options in creating further orbital debris (through collisions with other space objects during the 25-year reentry) is also addressed. In addition to presenting quantitative results for the four disposal methods explored in this study, the advantages and disadvantages of each method will be discussed.

Approach

The basic procedure begins with the generation of a 25-year lifetime curve as a function of ballistic coefficient and altitude. The program LIFETIME (4.3) (Ref. 7) is used to propagate a satellite from an initial LEO orbit until impact with the Earth. For various initial altitudes, the ballistic coefficient $C_d A/m$ is adjusted until a 25-year lifetime is predicted.

Next, for various spacecraft ballistic coefficient values with altitudes up to 2000 km, the required fuel or drag enhancement device needed to deorbit within 25 years (lowering the altitude or increasing the ballistic coefficient point until the point lies on the 25-year lifetime curve) is calculated for each of the four atmospheric reentry disposal methods adopted here. By using realistic values for the specific impulse I_{sp} and balloon material density, the additional weight required for deorbit within 25 years is found as a function of initial altitude and ballistic coefficient.

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Finally, by combining the current U.S. Space Command (USSPACECOM) unclassified catalog of tracked objects with a standard growth rate model, the probability of collision during the 25-year deorbit is calculated for each disposal option. On the basis of these results, along with other general considerations, the advantages and disadvantages of each of the considered disposal methods are compared and discussed.

Theory and Assumptions

The program LIFETIME (4.3) (Ref. 7) is used to propagate a satellite from an initial LEO until impact with the Earth's surface. For altitudes larger than 125 km, a semi-analytic propagation method, based on the method of averaging by Liu and Alford,[8] is utilized. The LIFETIME propagation force model includes the J_2 and J_3 zonal harmonic Earth geopotential terms, and an integration step size of 10 revolutions is used in this study. The solar radiation pressure model used in LIFETIME is a flat plate model as developed by Aksnes,[9] with a value of reflection index of 1.3 assumed. Atmospheric drag effects are integrated with the Gaussian quadrature method by using a dynamic atmosphere model. Between altitudes of 125 and 75 km, a Cowell method based on a Runge–Kutta 78 integration scheme is utilized.[10] At 75 km, the chosen altitude in this study for satellite breakup, a vehicle breakup model is adopted, and the resulting debris is numerically integrated to the ground.

The MSIS90E NASA atmospheric model[11] with dynamic solar flux and daily geomagnetic planetary indices was used to obtain orbital lifetime results due to its demonstrated accuracy.[12] These atmospheric model indices were obtained from a linear interpolation of values tabulated from previous 11-year solar cycles.

In this study, the epoch 1 January 2000 was selected as the starting date of the 25-year orbit. This date corresponds to the beginning of the peak of the 11-year solar cycle. The lifetime of a LEO may change significantly, depending on the choice of initial epoch. For example, an orbit predicted to have a 25-year lifetime for the selected epoch year of 2000 has a roughly 10% shorter lifetime than for an epoch year of 2005 because the epoch time is near the peak of the solar cycle. Consequently, the epoch year choice of 2000 used in this study leads to the slightly optimistic prediction of shorter orbital lifetimes. In addition, the solar activity model used in this study tends to be an overestimation: the LIFETIME F10.7 values are based on the outer envelope of the previous four solar cycles; these values are slightly higher than the $+2\sigma$ values of solar flux predictions, as presented in Ref. 2. For these two reasons, a design margin (10–15%) may be needed to account for relatively mild solar peaks.

The orbital lifetime was also found to be slightly dependent on the initial inclination. The choice of $i = 45$ deg represents an inclination that gives roughly an average value of orbital lifetimes. An initial eccentricity of 0.001 was chosen to avoid singularities; the altitudes presented in the results are the average of the perigee and apogee altitudes. All other initial orbital elements (Ω, ω, M) were set to zero.

The basic procedure begins with the generation of a 25-year lifetime curve as a function of ballistic coefficient and altitude. Figure 1 was generated by selecting initial altitudes in 50 km intervals and adjusting the value of the ballistic coefficient at each initial altitude until a 25-year lifetime was obtained. The phase space of ballistic coefficient-initial altitude values to the bottom and right of the curve in Fig. 1 represents orbits that have lifetimes longer than 25 years. It is desired to move these points until they lie on the 25-year lifetime curve. Horizontal movements in Fig. 1 (changes in the altitude) correspond to ΔV maneuvers, and vertical movements (changes in the ballistic coefficient) correspond to deployment of drag enhancement devices.

In this study, the four options considered were 1) a chemical ΔV maneuver ($I_{sp} = 300$ s), 2) a low-thrust ΔV transfer ($I_{sp} = 3000$ s), 3) deployment of a balloon drag enhancement device (balloon density $\rho = 0.132$ kg/m^2), and 4) a hybrid approach consisting of a chemical ΔV transfer to an 800-km-altitude circular orbit ($I_{sp} =$ 300 s), followed by deployment of a balloon ($\rho_B = 0.132$ kg/m^2). The first two options correspond to horizontal movements in Fig. 1, the third option is a vertical movement, and the fourth option is an initial horizontal movement followed by a vertical movement. The reason this particular hybrid approach was chosen will be discussed later.

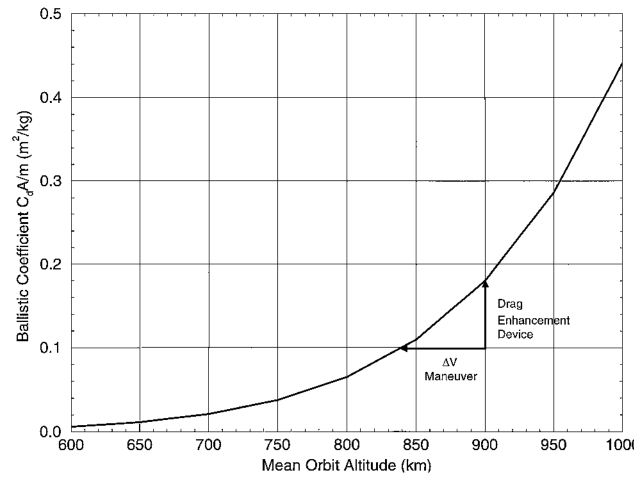

Fig. 1 Ballistic coefficient limits for 25-year orbit life.

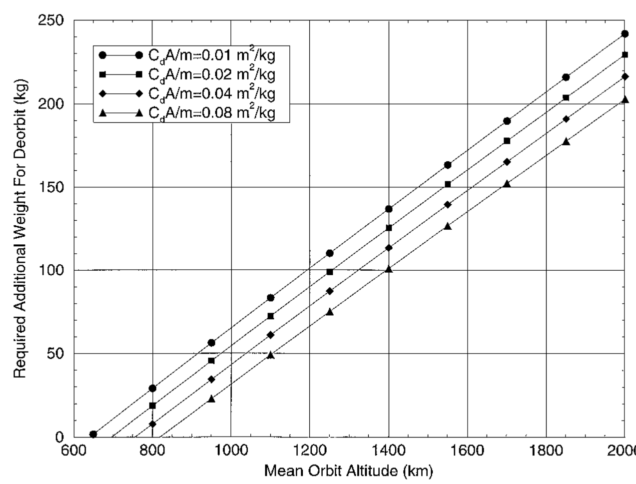

Fig. 2 Required additional fuel weight for deorbit with chemical propulsion within 25 years.

For the deorbit options considered here, the initial orbit is circular, as is the 25-year final lifetime orbit. Use of an elliptical orbit to deorbit requires a lower ΔV. However, this approach would result in the orbit crossing the corridor of manned space flight (the Space Shuttle and International Space Station) over most of the 25-year lifetime, which is assumed in this study to pose an unacceptable risk. For the higher-altitude orbits, it actually requires less ΔV to perform a direct deorbit (in half an orbital period) than to transfer to a lower altitude circular orbit before reentry.[13] This study is focused on the 25-year atmospheric reentry approach with circular orbits; therefore, deorbit via elliptical orbits or direct reentry is not addressed here.

Analysis-Additional Deorbit Weight

The four options of disposal are compared by evaluating the required additional weight for deorbit within 25 years. Figures 2 and 3 show the fuel weight as a function of the mean orbit altitude for the chemical ($I_{sp} = 300$ s) and low-thrust ($I_{sp} = 3000$ s) transfers. The four curves shown correspond to the four initial choices of the ballistic coefficient of 0.01, 0.02, 0.04, and 0.08 m^2/kg. A spacecraft mass of 1000 kg is assumed (excluding the mass of the propellant or balloon required for deorbit), and the value 2.2 is used as the spacecraft drag coefficient C_d. The required additional fuel weight for deorbit with a low-thrust transfer is roughly a factor of 10 smaller than that required for deorbit with chemical maneuvers.

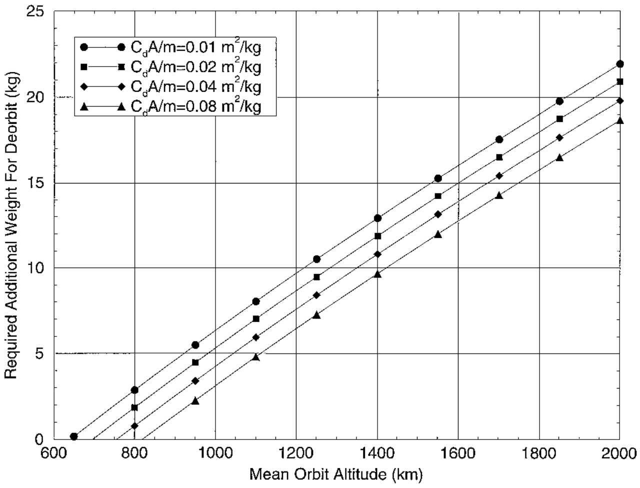

Fig. 3 Required additional fuel weight for deorbit with low thrust transfer within 25 years.

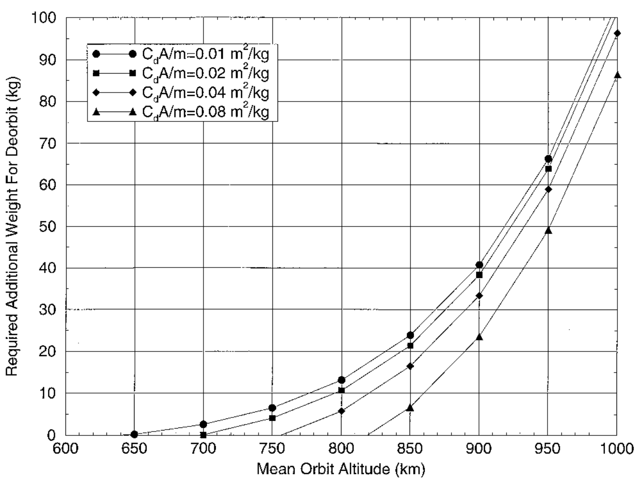

Fig. 4 Required balloon weight for deorbit with balloon deployment within 25 years.

Figure 4 shows the additional deorbit weight for a balloon deployment, assuming the balloon has a material density $\rho_B = 0.132$ kg/m^2 and neglecting the weight of the balloon deployment device. Because the balloon mass (in addition to its area) affects the ballistic coefficient of the spacecraft, an iterative method was adopted to obtain the values in Fig. 4. The information available on balloon densities was found to be quite limited; the value used here was taken from a previous unpublished study. One can easily calculate the required additional deorbit weight for other values of the balloon density, using the results presented here.

In this analysis, the balloon drag enhancement device is assumed to consist of a single spherical balloon; consequently, no attitude control is required during deorbit. An alternative approach of using two or more balloons symmetrically arranged about the spacecraft would have the advantage of using the spacecraft's cross-sectional area in addition to the area of the balloon for deorbit. However, this approach may require active attitude control to ensure proper orientation of the spacecraft during the 25-year deorbit.

The total cross-sectional area used in Fig. 4 is simply the cross-sectional area of the balloon, and so it is independent of the cross-sectional area (ballistic coefficient) of the spacecraft. However, for low enough initial altitudes, the ballistic coefficient of the satellite is important for determining whether balloon deployment is required to achieve a 25-year deorbit. Table 1 gives ballistic coefficients and corresponding maximum initial altitudes that ensure an orbital lifetime of less than 25 years without any postmission disposal efforts, corresponding to Fig. 1. Additional weight values in Fig. 4 are shown only for initial orbit altitudes up to 1000 km. For higher altitudes, the required size and mass of the balloon becomes too large to be considered for practical application. This is reflected in the roughly quadratic growth of the required additional deorbit weight with initial orbital altitude.

Table 1 Maximum initial altitude values that ensure a 25-year orbital lifetime

Ballistic coefficient, m^2/kg	Maximum initial altitude, km
0.01	640
0.02	696
0.04	756
0.08	820

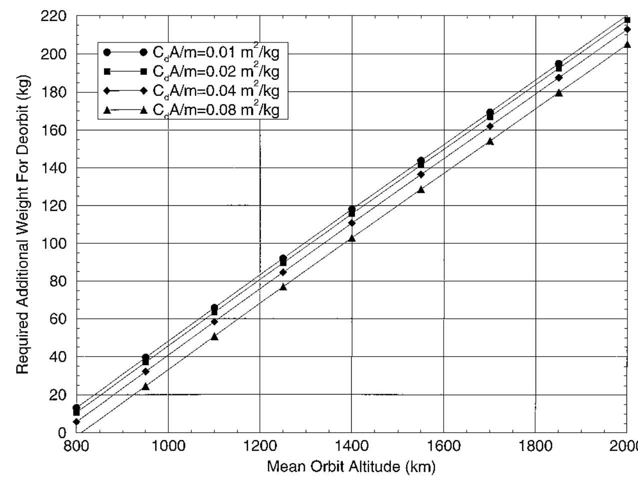

Fig. 5 Required additional deorbit weight for chemical and balloon deployment within 25 years.

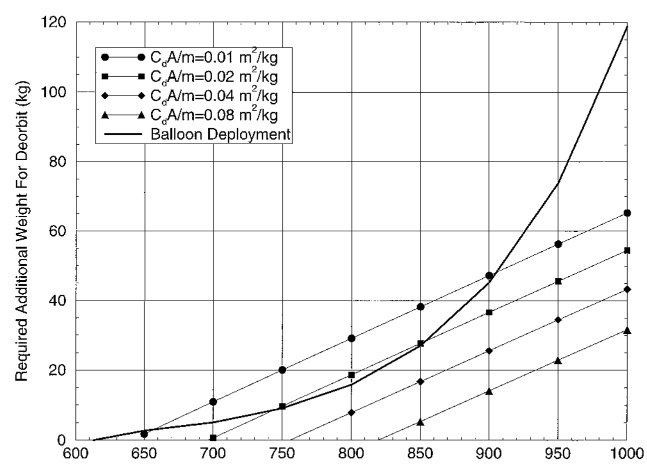

Fig. 6 Comparison of required additional deorbit weight for chemical propulsion and balloon deployment within 25 years.

Figure 5 shows the additional deorbit weight for a combination of chemical propulsion and balloon deployment. The specific hybrid approach chosen was first to apply a set of chemical maneuvers to transfer to an 800-km-altitude circular orbit and then to deploy a balloon at this altitude. Figure 6 is a comparison between the chemical propulsion option (Fig. 2) and the balloon deployment option (Fig. 4). The required additional deorbit weight for the chemical propulsion option varies linearly with initial altitude, whereas the growth is roughly quadratic for the balloon option.

The largest weight savings for the balloon option in comparison to the chemical propulsion option occurs at an initial altitude of about 800 km; consequently, this altitude was chosen as the initial deorbit altitude for the hybrid approach to maximize the weight savings. The savings in required additional deorbit weight when using the hybrid approach in comparison to using chemical maneuvers only is simply the difference in required weights between the balloon and chemical options for an initial altitude of 800 km, as shown in Fig. 6. Because a significant weight savings is achieved only for the value of ballistic coefficient 0.01 m^2/kg in Fig. 6, this was the value used to generate the results shown in Fig. 5.

In this study, the initial orbits were restricted to be circular. There has been only one proposed constellation consisting of low Earth elliptical orbits: the Ellipso constellation, consisting of eight satellites.[4] Although this particular orbit type was not quantitatively addressed here, some general statements can be made concerning the disposal of spacecraft in these orbits. First, from Ref. 3, third-body perturbation effects become important only for apogee altitudes above ~10,000 km. Therefore, the dominant force for determination of the orbital lifetime will still be drag. Also, the required ΔV for orbital transfer to the 25-year lifetime curve will be significantly less, and the option of direct deorbit becomes more attractive for these orbits than was the case for circular orbits.

Analysis-Collision Probabilities

The risk of collision with other orbiting objects during the 25-year reentry orbit was also evaluated. Using the 25-year orbital trajectories generated with LIFETIME, collision probabilities were calculated for 50-km-altitude bins using the program DENSITY, which is based on equations given in Ref. 14. These probabilities were then summed to obtain the total probability of collision. The probability of collision P_{coll} is given by the formula

$$P_{\text{coll}} \approx \Sigma \rho \cdot A_c \cdot v_r \cdot \Delta t \tag{1}$$

In this study, an average value of 9 km/s was used to represent the relative velocity between the (45-deg inclination) spacecraft and the catalog objects. The set of orbiting objects used consisted of the unclassified USSPACECOM catalog as of 14 January 1998, with an assumed constant uniform growth rate of 250 satellites per year.

Figures 7 and 8 show the collision probabilities for the ΔV maneuvers options (either chemical or low thrust) and the balloon deployment options. This risk was found to be small for most deorbit strategies, on the order of 1 collision per 1000 deorbit events. However, when the largest balloon (corresponding to the highest initial altitude in Fig. 8) required for deorbit in this study is deployed, the collision rate rises to about 1 collision per 50 deorbit events. As seen in Figs. 7 and 8, the probability of collision grows approximately linearly with ballistic coefficient for the chemical or low-thrust options, whereas for the balloon deployment option the probability of collision grows roughly quadratically with the initial altitude.

In this study, only trackable debris was considered in calculating collision probabilities. However, smaller debris fragments and meteoroids may pose further hazards for the disposal methods addressed here, especially concerning the balloon deployment option. Using the data from Refs. 14 and 15, a 10-m^2-cross-section-area balloon can expect to collide with up to on the order of 25 particles of 1-mm diam and 2500 particles of 0.1-mm diam over the course of 25 years. Therefore, if the balloon deorbit option is to be feasible, the material should be designed to survive an impact with a 1-mm-diam particle. Because the flux of debris particles decreases dramatically with increasing particle size,[14] the probability of collision of a 10-m^2 balloon with debris particles much larger than 1 mm over a 25-year period is fairly small.

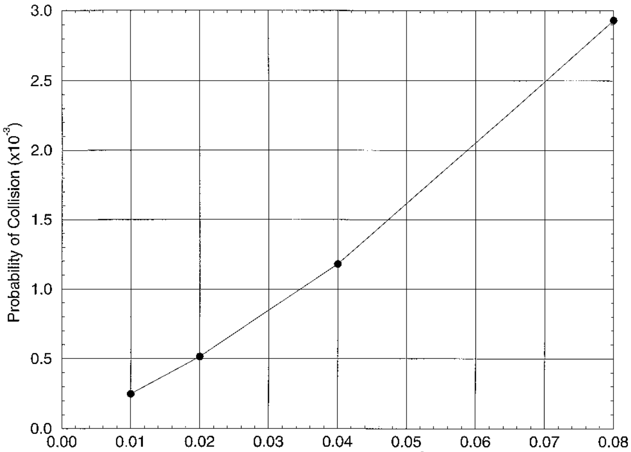

Fig. 7 Collision probabilities for chemical or low thrust during 25-year deorbit.

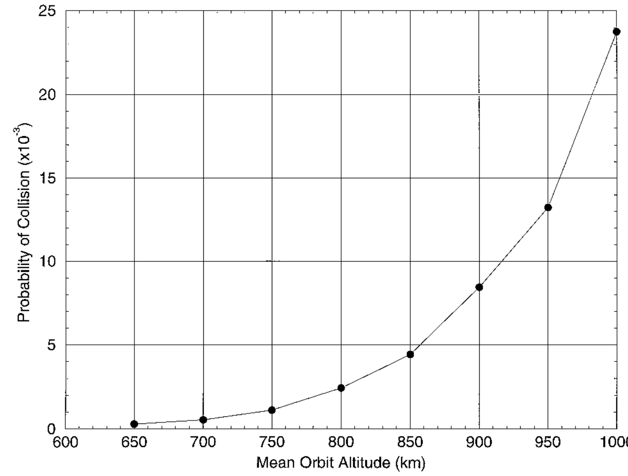

Fig. 8 Collision probabilities for balloon deployment during 25-year deorbit.

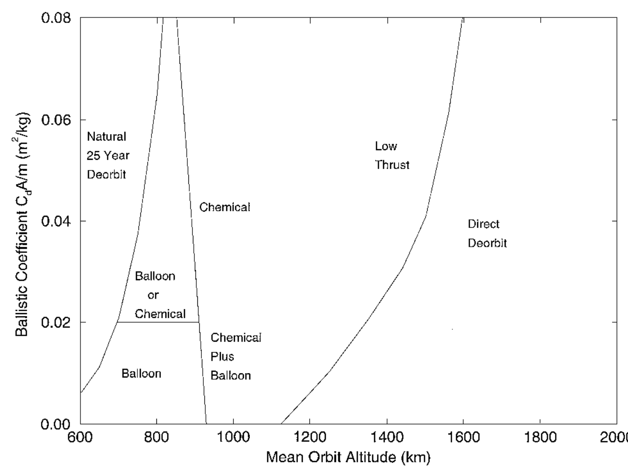

Fig. 9 Regions where explored disposal methods are the most weight efficient.

Discussion: Advantages and Disadvantages of Options

The four options of disposal are compared by evaluating the required additional weight for deorbit within 25 years. Figure 9 illustrates the regions (as functions of initial altitude and ballistic coefficient) in which each option of disposal is the most attractive based on the additional weight that must be carried. The boundaries separating a preferred disposal method from other methods are not always clear; the diagram in Fig. 9 is an attempt to show general trends. At the highest altitudes (2000 km), a direct deorbit (deorbit within half of the orbital period) requires less ΔV than transfer to a lower-altitude circular orbit with a 25-year lifetime. At the lowest altitudes (600 km), the NASA 25-year lifetime guideline is satisfied, and any further action concerning deorbit is unnecessary.

The use of a balloon by itself for deorbit is practical only for altitudes below about 1000 km. However, when combined with chemical maneuvers, the use of balloons for deorbit can be extended to higher initial altitudes. The required additional weight for deorbit with chemical maneuvers also becomes expensive at higher initial altitudes but is less expensive than the balloon-only approach at these altitudes (see Fig. 6). The low-thrust option requires less additional weight (consideration of propellant weight only) than the other options over the range of ballistic coefficients and altitudes addressed here. Consequently, the low-thrust option, if available, is a very attractive approach when reduction of additional fuel weight for deorbit is a primary objective.

Although this study has focused on the required additional deorbit weight for the various disposal options explored, other factors such as cost, simplicity, and reliability may also play an important role in the final disposal strategy chosen. A knowledge of the specific details of a given mission will ultimately be required in the selection of the most feasible deorbit option. However, a general survey of the advantages and disadvantages of the disposal methods explored here will be undertaken.

The chemical propulsion option has wider applicability due to the more frequent availability of chemical thrusters aboard the spacecraft. Deorbit via chemical maneuvers is fast, reliable, and controllable. Multiple-burn strategies can be adopted to minimize the impact of unforeseen errors. The required additional propellant weight is modest (less than 100 kg below 1200-km altitudes) for lower altitudes but does become appreciable ($\sim$200 kg) for higher altitudes. This option does rely on an operational attitude control system, which may not always be available near end of life.

The low-thrust deorbit option offers a significant reduction (by about a factor of 10) in required additional deorbit weight. As indicated in Fig. 9, for fairly high initial altitudes and fairly large ballistic coefficients, a low-thrust deorbit option is the only reentry option available that will not result in a significant deorbit mass penalty. However, the low-thrust transfer occurs over a much longer time than the chemical transfer, requiring an operational attitude control system during the entire transfer. Therefore, this option may be considered a greater risk than the chemical maneuver option.

A potential advantage of the balloon deployment option is that it should be relatively simple to implement. However, the need to develop a balloon that can withstand the possibility of puncturing by small debris particles may reduce the atrractiveness of this option. This balloon option does provide a weight savings over the chemical maneuver option at low altitudes for small values of the ballistic coefficient. The balloon option does not require additional fuel, a working propulsion system, or a working attitude control system. However, there has been little experience in the use of this system. Because of the larger cross-sectional area of the balloon, this option presents a greater orbital debris hazard than deorbit with ΔV maneuvers. The use of an alternative drag enhancement device, such as a parachute, may overcome some of the disadvantages of the balloon option (no concern of puncturing, possible lower weight). However, these methods will probably compromise the simplicity of deployment and operation of the balloon option. For example, any methods using drag enhancement devices that require an active attitude control system during part of the 25-year deorbit will be of much greater complexity.

For the case of a small ballistic coefficient, the combination of chemical maneuvers with a balloon allows for a greater weight savings than using either system separately. The cost of this gain in weight savings is the combined complexity of these two systems. In addition, the balloon will still pose an orbital debris hazard due to its large cross-sectional area.

Cost may be the determining factor as to which disposal method is ultimately chosen. In this study, a spacecraft mass of 1000 kg was chosen. The additional wet mass required for deorbit may be upward to 10–20% of the dry mass. The wet mass of a system is typically not as strong a driver of cost as the dry mass. However, in deployment of constellations of satellites, multiple satellites (up to seven for Iridium, using the Proton) will be launched on a single launch vehicle. Therefore, the additional required deorbit weight per satellite will be multiplied by the number of satellites being launched. The total additional deorbit weight may then become very significant. If this increase in additional weight leads to a change in launch vehicle, the cost penalty for satellite deorbit can be substantial. Consequently, launch vehicle weight margins may limit the availability of cost-effective deorbit options. For a single-spacecraft launch, the additional cost required to deorbit is expected to be relatively small for most cases.

Conclusions

In this study, four different options for using atmospheric reentry to deorbit spacecraft from a circular LEO within 25 years are explored. The additional weight required for deorbit using a low-thrust transfer is significantly less than the additional weight required for the other options explored here. The balloon deployment option is competitive with deorbit via chemical propulsion maneuvers for low initial altitudes with regard to additional required weight for deorbit. However, the practical use of balloon deployment for deorbit is limited to low initial altitudes (less than 1000 km). In addition, the balloon deployment option presents a greater orbital debris hazard than deorbit with ΔV maneuvers, due to its larger area. The combined use of chemical propulsion maneuvers with balloon deployment results in a lower required additional deorbit weight than for either option alone but only for cases with a small ballistic coefficient (area to mass ratio below 0.009 m^2/kg).

The final disposal strategy chosen will also depend on factors other than required additional deorbit weight, such as cost, simplicity, reliability, and launch vehicle weight margin. Rather than recommend a particular method, the advantages and disadvantages of each method are discussed, with the final choice left up to the mission planner. However, if an atmospheric reentry disposal is desired and minimization of required additional deorbit weight is a primary consideration, deorbit using a low-thrust transfer is the most viable option.

Acknowledgments

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