ELECTRIC PROPULSION: A SOLUTION TO END-OF-LIFE DISPOSAL OF SATELLITES?

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ABSTRACT

The de-orbiting of defunct satellites represents one of the few practical measures which are available in the near term to begin tackling the space debris problem. In this paper the main issues surrounding the de-orbiting of satellites from low, medium and geostationary altitudes are reviewed. Propellant requirements for de-orbiting using electric and chemical propulsion are presented. It is found that, except for small satellites at low altitude, electric propulsion systems (arcjet and ion thrusters) are strong candidates to perform the de-orbit manoeuvres. It is concluded that advanced propulsion could significantly influence the overall feasibility of de-orbiting.

1. INTRODUCTION

After only four decades of the 'space age', the resulting accumulation of debris has now been shown to represent a potentially serious threat to the long term development of near-Earth space. The space industry now recognises the need to avoid the creation of debris during launches and separation events and operators are taking measures to avoid accidental explosions of satellites once their useful lives are over. Furthermore, many organisations are now removing their geostationary satellites to post-mission 'graveyard' orbits to avoid future congestion of valuable orbital slots.

Part of the problem lies in the fact that, thus far, relatively narrow regions of space are found to be most useful and so new satellites are continually being launched into these places. Specifically these regions are: low Earth orbit (LEO) which is below 1,300 km in altitude, medium Earth orbit (MEO), generally exploited at 20,000 km and 10,300 km, and geostationary Earth orbit (GEO) at some 35,800 km altitude. The use of graveyard orbits can go some way to alleviating the near-term hazard from debris for these specific regions, but it must be accepted that graveyards represent only a temporary and partial solution.

Recent work[1] conducted on behalf of the US Office of Science and Technology has examined the probable evolution of the LEO debris environment and has indicated that the 'minimum' set of debris-mitigation measures, including the complete halting of satellite explosions, may not be sufficient to prevent a strong rise in the debris population over the next century.

2. SATELLITE DE-ORBITING AS PART OF DEBRIS CONTROL

Defunct satellites represent a source of future debris due to the possibility of explosions and random collisions. Already non-operational satellites constitute 21% of trackable space objects and constitute a much higher fraction of the total debris mass and cross-sectional area. Since ever more satellites are being launched, either to perform new missions or to replenish failed or exhausted spacecraft, the problem will grow worse. Recognising the potential threat, two major companies, Iridium and Teledesic, have already stated that they intend to de-orbit their LEO satellites after the completion of their missions.

Relatively little work has been performed to determine the requirements on and effects of a general satellite end-of-life disposal policy. However, NASA studies[1] at LEO have concluded that removal of satellites to orbits with lifetimes of less than 25 years should be equivalent to an immediate de-orbit in terms of reducing probability of collision. Quantitative projections using the NASA 'EVOLVE' model at an altitude of 900 km have shown that, by implementing post-mission disposal of satellites to orbits with lifetimes of less than 25 years, debris levels could be maintained at their current state until at least 2070. The result of not de-orbiting at end-of-life was that by the year 2070, debris flux had increased by about a factor of ten.

On the basis that disposal into orbits with lifetimes of around 25 years is a sufficient criterion, it would only be necessary to specifically de-orbit satellites in circular orbits above 600 km altitude[2] assuming a typical

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ballistic ratio (mass/surface area) of approximately 100 kg/m^2.

The purpose of this analysis is simply to present an initial comparison of the propellant mass required for the disposal manoeuvre to see if more advanced forms of propulsion will significantly influence the de-orbiting debate. Of course propellant mass will be only one of the parameters which determine feasibility and cost, but it does reflect directly into launch costs which typically represent a very major fraction of the mission costs.

3. DISPOSAL MANOEUVRES

Only de-orbit manoeuvres are considered in this paper but it is worth noting that from geostationary orbit, escape actually requires less energy. When employing chemical propulsion, impulsive de-orbit manoeuvres to reduce the perigee height are the obvious and simple solution[3]. A perigee height of 400 km has been selected to give a 25 year orbital life or less.

Of the many varieties of electric propulsion available[4], two types shall be considered in this paper: the arcjet, which produces medium to low thrust levels (hundreds to thousands of mN) and the ion thruster which produces low thrust levels (tens to hundreds of mN). The arcjet employs electrical power to greatly accelerate gases, by thermal expansion through a nozzle, to velocities of the order of 6 to 10 km/s. Ion thrusters use electrical power to accelerate ions produced in a gaseous electrical discharge to extremely high velocities, typically 30 to 60 km/s.

Although electric propulsion has long been advocated for the transfer of satellites into their final orbits in view of the large potential mass savings[5], there have been four major problems:

i) the significant delay (due to low thrust levels) in reaching final orbit

ii) both platform and payload receive substantial additional doses of radiation

iii) electric propulsion technology has not been sufficiently mature

iv) the overall risk, which is necessarily incurred 'up-front', has been seen as unacceptable.

However, for disposal manoeuvres the above issues are far less problematic[6]. Firstly, transfer duration is far from critical since the useful phase of the mission will have already ended. The significance of adding several extra months, or even a year, onto the end of a 10 or 15 year mission life for a disposal phase may be not be great.

Secondly, in those cases where passage through the radiation belts is unavoidable, it is only the platform that needs to be able to withstand the extra dose, the payload having no further purpose.

Thirdly, concerns over the maturity of electric propulsion technology, while still not completely eliminated, are rapidly receding. Already operational applications of electric propulsion to geostationary communications satellites are emerging, primarily for north-south station-keeping (NSSK)[7].

Finally, the use of low thrust manoeuvring for disposal entails only a small fraction of the risk associated with using the same methods for injection. Failure during a disposal manoeuvre would have no financial or operational consequences for the owner/operator of the satellite.

When using the low thrust levels from electric propulsion thrusting must occur in arcs around apogee over many revolutions[8]. Naturally complication is immediately introduced because of the need to employ thrust vectoring around the burn arcs to avoid excessive loss of efficiency.

With electric propulsion, transfer times become rather long (weeks or months). Transfer time is directly related to the thrust level which is, itself, constrained by the power available. However, since the mass of propellant required is not influenced by the time taken, it is not necessary to make any assumptions about transfer duration for this study.

For ion propulsion, a continuous burn to gradually contract the orbit may be advantageous, since maintaining a circular orbit is likely to simplify other aspects of the spacecraft design. This is the method analysed here. De-orbiting down to an altitude of 600 km (circular orbit) is assumed.

Type of propulsion	Manoeuvre	Additional dry mass for disposal hardware (kg)	Exhaust velocity (km/s)
Chemical bipropellant	Single impulsive burn to reduce perigee to 400 km	10	2.9
Arcjet	Multiple burn to reduce perigee 400 km	20 (10 for GEO case)	10
Ion	Continuous spiral orbital contraction to 600 km circular orbit	50 (20 for GEO case)	52

Table 1 Assumptions used for de-orbiting analysis

4. COMPARISON OF PROPULSION SYSTEMS FOR DE-ORBIT MANOEUVRES

The choice of the propulsion system will be constrained not only by mass-efficiency, but also by the necessary additional dry mass, the availability of power and any time limits by which the manoeuvre must be completed.

It is assumed that all satellites will be equipped with a chemical propulsion system (for attitude control at least) as standard. If an electric propulsion system is selected (arcjet or ion) it is assumed that this will be in addition to the basic satellite equipment and so there will be a dry mass penalty. The exception is the geostationary case where it is assumed that electric propulsion is also used for North-South station keeping (NSSK), so a smaller dry mass penalty is incurred.

Table 1 shows summarises the assumptions used in this paper. Fig. 1 shows the results of the analysis of de-orbit manoeuvres from two LEO altitudes for satellite masses up to 5000 kg. For the heavier satellites ion propulsion is the most mass-efficient, this fact being much more noticeable at the higher altitude. The arcjet is the most mass-efficient option only over a very narrow mass range for either altitude. However, the lesser complexity and capital cost of the arcjet may actually make it more attractive than ion propulsion for medium size satellites and it should not be dismissed.

Fig. 2 shows the result of the analysis for two MEO orbits. At neither altitude can ion propulsion be challenged by the alternatives except in the case of the very smallest satellites. Similar results apply at GEO.

5. CONCLUSIONS

Satellites in circular orbits below approximately 600 km altitude are unlikely to require de-orbiting since they will generally re-enter naturally within around 25 years. However, above 600 km, de-orbiting may be needed. The selection of suitable propulsion systems will need to be be based on cost and risk minimisation. Electric propulsion should be specifically considered since few of the disadvantages traditionally associated with low thrust orbital transfers and technologies apply to their use for de-orbiting manoeuvres.

For LEO altitudes the decision will be rather sensitive to satellite orbital altitude and mass. Heavier satellites of approximately tonne or more may benefit significantly from using arcjet or ion propulsion for de-orbiting.

For MEO and GEO altitudes, ion propulsion is probably the only viable mechanism of achieving complete disposal. The mass penalties for so doing are not unrealistic, a fact which should inform future debates on end-of-life disposal policies.

6. FURTHER WORK

Since de-orbiting is one of the few practical options available to tackle the debris problem, further study would be beneficial. A detailed analysis of the costs of implementing de-orbiting is needed together with an investigation of the technology requirements which might emerge. Confirmation that the 25 year criterion is sufficient would also be desirable since this will affect de-orbiting costs and the ultimate effectiveness of the policy. The desirability of de-orbiting from high altitude orbits should be assessed in view of increasing use of MEO altitudes. Another requirement is to investigate how the disposal propulsion system can complement other functions e.g. NSSK on GEO satellites, or the initial orbit insertion and manoeuvring, in order to see how to minimise the 'effective' cost of de-orbiting.

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7. REFERENCES

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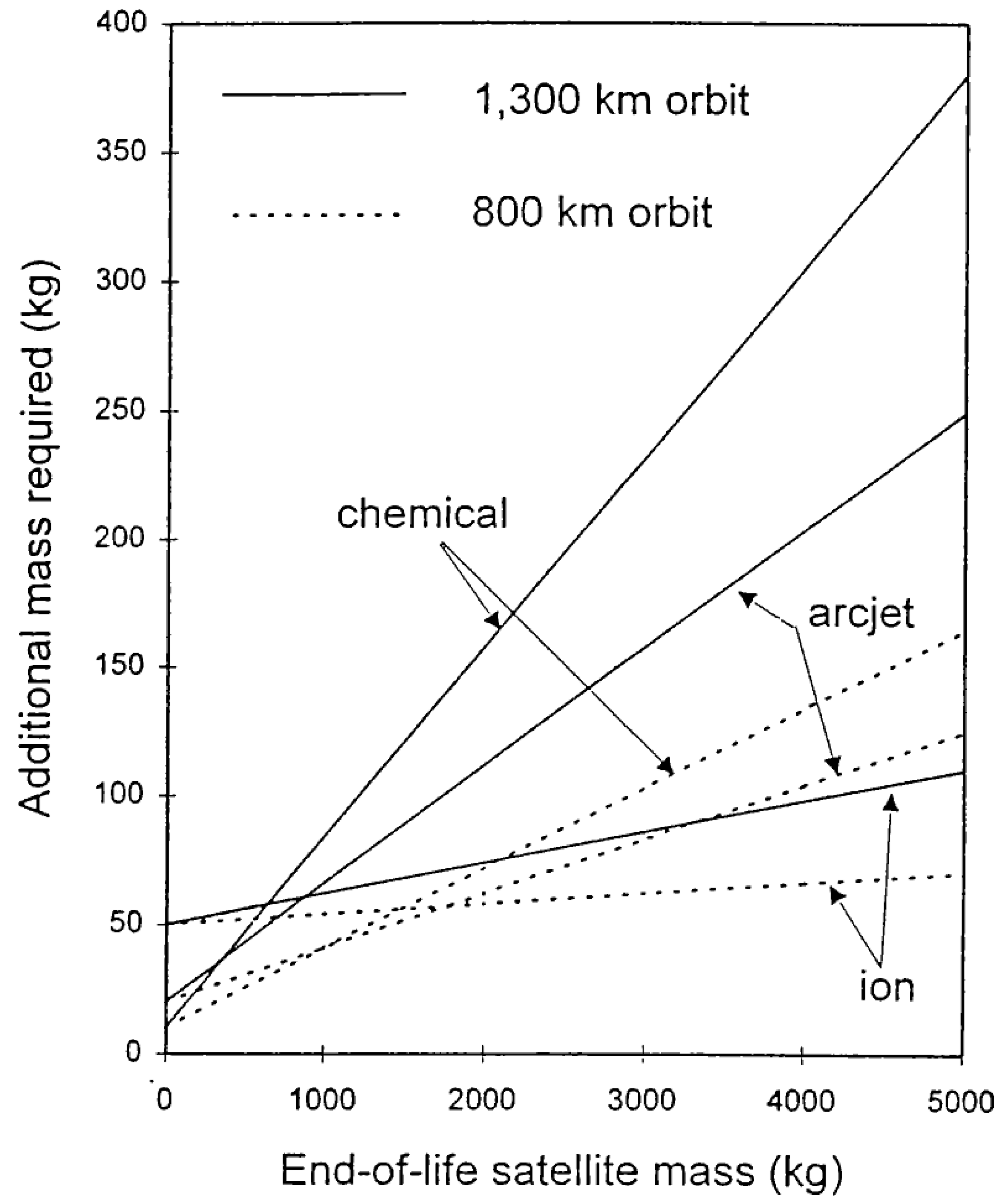

Fig. 1 Additional mass (propellant + equipment) required for de-orbit from two LEO circular orbits

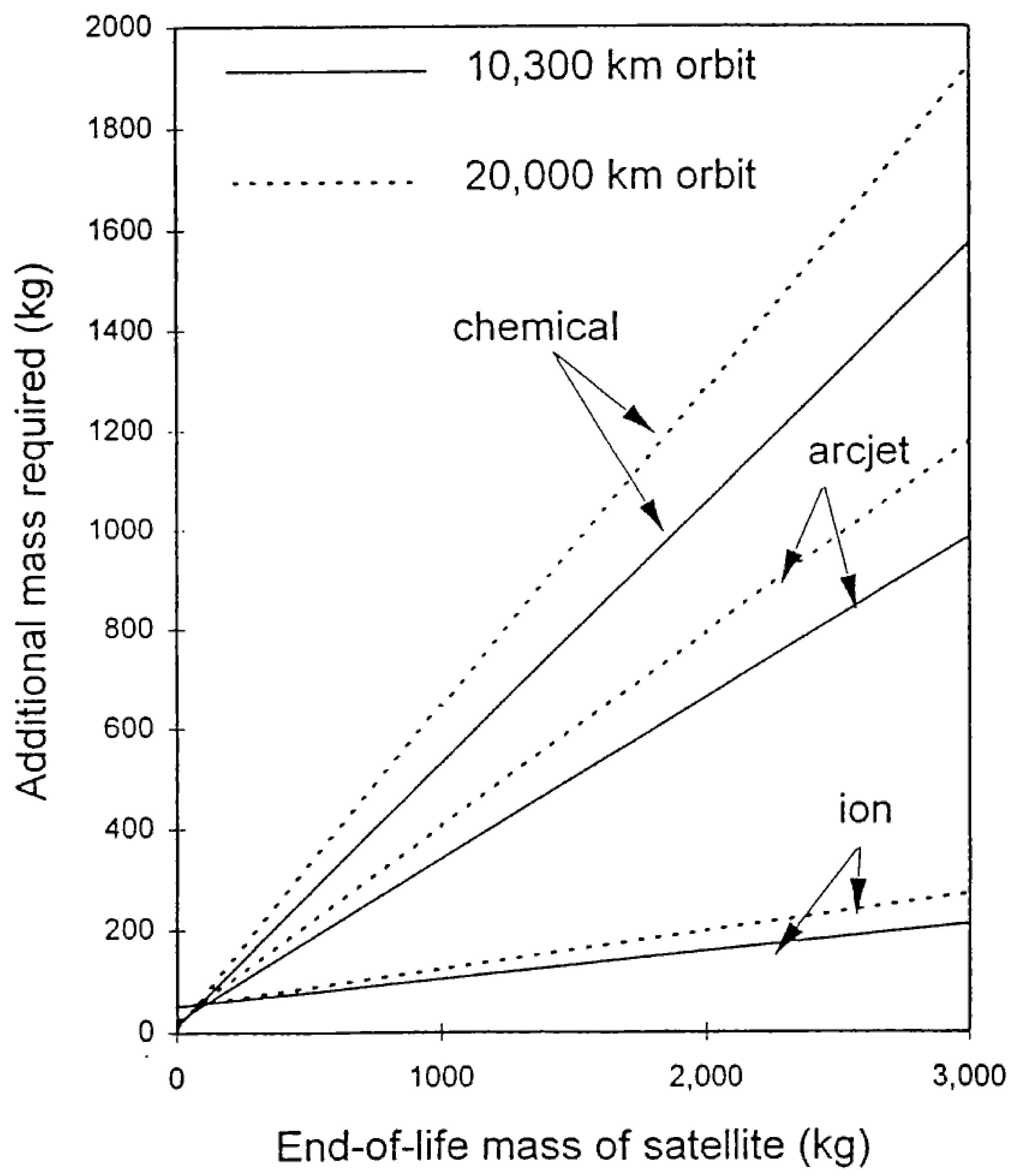

Fig. 2 Additional mass (propellant + equipment) required for deorbit from two MEO circular orbits