SOLID PROPULSION
DE-ORBITING AND RE-ORBITING

R.A.C. Schonenborg(1)**, H. F. R. Schöyer**(2)

(1) Schonenborg Space Engineering B.V., Residence Astrid 23, 2202 BM, Noordwijk, the Netherlands.,
rogier@schonenborg.com
(2)Schöyer Consultancy B.V., van Vrieslandhove 6, 2726 DV Zoetermeer, the Netherlands, hschoeyer@hetnet.nl

ABSTRACT

With many "innovative" de-orbit systems (e.g. tethers, aero breaking, etc.) and with natural de-orbit, the place of impact of unburned spacecraft debris on Earth can not be determined accurately. The idea that satellites burn up completely upon re-entry is a common misunderstanding. To the best of our knowledge only rocket motors are capable of delivering an impulse that is high enough, to conduct a de-orbit procedure swiftly, hence to de-orbit at a specific moment that allows to predict the impact point of unburned spacecraft debris accurately in remote areas. In addition, swift de-orbiting will reduce the on-orbit time of the 'dead' satellite, which reduces the chance of the dead satellite being hit by other dead or active satellites, while spiralling down to Earth during a slow, 25 year, or more, natural de-orbit process. Furthermore the reduced on-orbit time reduces the chance that spacecraft batteries, propellant tanks or other components blow up and also reduces the time that the object requires tracking from Earth.

The use of solid propellant for the de-orbiting of spacecraft is feasible. The main advantages of a solid propellant based system are the relatively high thrust and the facts that the system can be made autonomous quite easily and that the system can be very reliable. The latter is especially desirable when one wants to de-orbit old or 'dead' satellites that might not be able to rely anymore on their primary systems. The disadvantage however, is the addition of an extra system to the spacecraft as well as a (small) mass penalty. [1]

This paper describes the above mentioned system and shows as well, why such a system can also be used to re-orbit spacecraft in GEO, at the end of their life to a graveyard orbit.

Additionally the system is theoretically compared to an existing system, of which performance data is available. A swift market analysis is performed as well.

1. INTRODUCTION

The recent collision on 12 February 2009 of the non-functioning Cosmos 2251 and the Iridium 33 satellite made a number of things very clear:

1. in practice it is presently not possible to timely warn for impact of space debris with live spacecraft. Therefore it is, in practice, not possible to safeguard space assets e.g. the ISS or Hubble Space Telescope.
2. Before this recent collision, the US military had catalogued some 19 000 pieces of space debris [2]. The collision added at least 194 pieces from the Iridium satellite and 505 from the Cosmos 2251 according to the US military [3].
3. As debris will have flown in more or less all directions, some spacecraft above the Iridium orbit, the Iridium spacecraft themselves, and as all debris at this altitude will eventually come down, all spacecraft below the Iridium orbit, are at risk.
4. The debris is expected to have a long life; estimates of thousands to ten thousand years were made by the Russian Chief of Mission Control, Vladimir Solovyov [4]

By the end of February 2009 it became clear that the increased amount of debris also threatens the few remaining shuttle flights [5].

In view of the above, it is obvious that measures must be taken to stop further polluting space, but also the community may start to think of how to clean up space.
For what regards avoiding to further pollution of space, requirements must be implemented and enforced to reach the objective that ensures that non-functioning satellites are being dealt with. For this, three strategies currently have been identified:

1. For satellites at lower altitudes, a safe and controlled return to Earth, de-orbiting, is by far the best solution. This is easily accomplished by transferring a spent satellite to an altitude of ~80 km; atmospheric drag will quickly decelerate the satellite which will, to a large extent, burn up in the atmosphere. More massive pieces may drop onto the Earth. For this reason the reentry position should be chosen above one of the major oceans, outside the shipping areas.

2. Satellites in a Geostationary orbit (GEO) or Geosynchronous orbit (GSO), may be transferred to a slightly higher orbit, a so-called graveyard orbit, a circular orbit usually 300 km or more above the GEO or GSO. This is known as re-orbiting. Satellites will remain at that altitude for very long times, measured in eons, not in years. However, even this cannot be a permanent solution as over

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

time the satellites in the graveyard orbit will move in all kind of directions and mutually collide, creating debris that will also reach lower orbits. For the time being, however, it is the best that can be done.

3. Do nothing.

Unfortunately, although it is the worse solution, strategy 3 is more or less the one that is being applied most.

Requiring the safe return to Earth or the safe parking of spent satellites in a graveyard orbit is one thing; the (technical) implementation is a different matter. The presented paper discusses a technical approach to safely and quickly return spent satellites to Earth or to safely and quickly park spent satellites in a graveyard orbit.

2. CHARACTERISTICS OF A DE-/RE-ORBIT SYSTEM

A de-/re-orbit system should have specific characteristics. The most important ones are listed below:

1. Reliability
   The de-/re-obit system must be extremely reliable. It is up to the space community to set reliability levels for the system, but the expectancy of the system not to function shall be substantially smaller than just leaving the spent satellite in orbit.
2. Independence / autonomous
   The de-/re-orbit system must be as independent as possible from the satellite system itself. I.e. even if the satellite fails, the system must have power for its operation and be able to have simple communications with the satellite operating centre. This centre can then uplink commands that allows the satellite to further carry out an autonomous de-/re-orbit manoeuvre
3. Applicability
   It must be possible to apply the de-/re-orbit system to any new satellite. This implies that no particular system has to be developed for a satellite as a standard system will be available. This does imply that the system is scalable to meet the different requirements with respect to ΔV and satellite shape and size.
4. Storability
   As the useful life of satellites can easily exceed 15 years, the system should be able to remain fully operable after 15 years or more of inactive storage in space. A 15 years storage in space is neither for solid nor for liquid propulsion systems problematic. The system being inactive for 15 years or more, may put a severe requirement on systems with moving parts (valves, actuators, pressure regulators) such as found in liquid and hybrid propulsion systems. In this respect, solid propulsion systems that do not need moving parts may be advantageous.
5. Performance
   The performance of the propellant shall be good. In general, the propellant mass for de- and re-orbiting will be small in comparison to the satellite mass at the end of mission. For these cases, it is not the specific impulse, but the density impulse that determines the performance [6].

3. PROPELLANT CHOICE

When reviewing the characteristics of a de-/ re-orbit system described in 2, the choice for solid propellant over liquid propellant becomes obvious. Reasons are; the simplicity versus complexity, that is not having any moving parts versus having a series of valves and pressure regulators; having a large military production experience versus small production experience for space applications; a solid rocket motor operates until all propellant has been consumed, which is favourable for de/re-orbit manoeuvres since the motor does not require any further control after having been ignited; a solid rocket motor requires little energy to be ignited, which is favourable if a limited amount of power is available; the thrust of a solid rocket motor can be high and therefore the burn time, hence de-orbit procedure short, which also makes spin stabilisation an attractive option for thrust misalignment compensation; due to their simplicity, solid rocket motors can easily be produced in large quantities, so different clusters of standardized motors can be applied to different spacecraft sizes for as well de-orbiting as re-orbiting; the specific impulse is good and the density impulse is the highest of all chemical propellants, leading to low propellant mass and a compact system.

Solid propellant rocket motors can be stored over longer periods of time. This is important since storage on board the spacecraft might be required for up to about 15 years before the motor is used.

Since a solid propellant system is inherently very reliable its' probability of a successful de/re-orbiting of a satellite is substantially higher than for the much more complex liquid system. Where 'dead' satellites cannot be de-orbited or re-orbited anymore by a liquid propellant system, de- or re-orbit manoeuvres remain possible with an autonomous solid propellant system. An autonomous liquid subsystem would be too complex, heavy and costly, since this would basically involve the installation of a separate copy of the liquid propulsion system that is already on board.

For the de-/re-orbit manoeuvres, a low acceleration is required preventing parts of the spacecraft to break off, thereby creating debris. Solid motors are apt to have a relatively high thrust, however, there are many solutions to obtain a low enough thrust e.g. by limiting the burning surface area by using a cigarette burning grain or by using a slow burning propellant.

Depending on the motor design, the solid propellant itself can act as thermal protection preventing the motor case being exposed to hot combustion gases. This concept would work best for short burning high thrust motors such as spin up thrusters. If one can't rely anymore on the on-board liquid propulsion system for attitude control, these thrusters can initiate spacecraft rotation, which compensates for thrust misalignment of the de/re-orbit motor cluster.

Solid propellants can be made without aluminium, still producing a high specific impulse. Deposition of aluminium oxide in Earth orbit is thereby avoided. Also the propellant composition can be such that particles in the exhaust plume do not pose a threat to other objects in Earth orbit.

The above illustrates that solid propellant motors are very suitable for de/re-orbiting.

Since all other propulsion system alternatives are liquid or combine liquid with solid (hybrid), these systems all have the disadvantages of a liquid propulsion system. Tab. 1 [1] provides some values and characteristics to compare different types of propellant, showing sometimes marginal advantages with respect to specific impulse for non-solid propellant systems, but showing the large disadvantages of liquid propellant with respect to reliability, complexity, and density specific impulse.

Table 1: Performance data of various propellants

		Mono propellant N_2H_4	EHT-Mono propellant N_2H_4	Storable Bi-propellant N_2O_4 $+CH_6N_2$
I_{sp}	[m/s]	2205	2890	2940
I_{sp}	[s]	225	295	300
I_δ	[kg·s/m^3]	$232\cdot10^3$	$309\cdot10^3$	$369\cdot10^3$
T		mN-N	µN-mN	N-MN
R*		+ + +	+ +	+
C*		+ +	+ + +	+ + + +
		Hybrid propellant	Solid propellant	
I_{sp}	[m/s]	3000	2885	
I_{sp}	[s]	306	294	
I_δ	[kg·s/m^3]	$428\cdot10^3$	$500\cdot10^3$	
T		N-MN	mN-MN	
R*		+ +	+ + + +	
C*		+ + +	+	

* = The more + signs, the higher the Reliability (R) / the more Complex (C) the system.

4. TECHNICAL APPROACH FOR DE-ORBITING AND RE-ORBITING

De-orbiting and re-orbiting spacecraft requires (a) velocity increment(s) at (a) certain point(s) in the spacecraft's orbit. Fig. 1, Fig. 2 and the text below clarify where the velocity increment(s) or burns of the solid rocket motors shall take place. The velocity increments in apogee, ΔV_a and perigee, ΔV_p, follow from orbital mechanics calculations. The amount of required propellant follows from Tsiolkowski's equation.

De-orbit

To de-orbit a satellite, one may consider a circular orbit, see fig. 1.

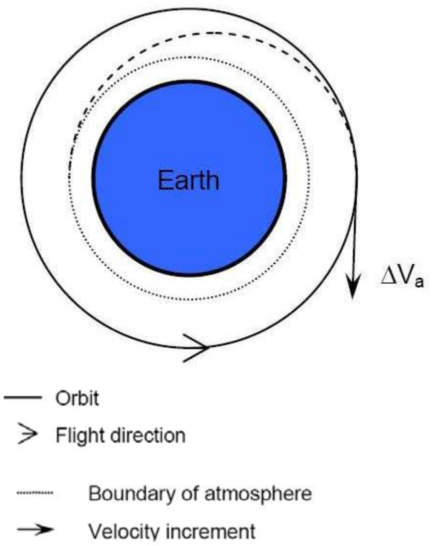

Figure 1: De-orbit procedure

The velocity in the apogee of an elliptical orbit is always lower that that of a circular orbit at the apogee altitude of the elliptical orbit. Therefore the values presented here are upper limits.

The strategy is to decrease the apogee velocity such that an orbit results with its perigee at 80 km altitude. Atmospheric drag then will rapidly decelerate and heat the satellite. As said before, most of the satellite will burn up in the atmosphere. In case one could expect heavy and heat resistant parts to impact the Earth' surface, one first may have to wait till the satellite is in a proper position, so the impact would be on a safe location (e.g. ocean). The required ΔV's in relation to the altitude of the circular orbit are given in Tab. 2

Table 2: Velocity increments for de-orbiting from various orbits to 80 km altitude [1]

De-orbit from: [km]	ΔV to 80 km [m/s]
500	121
1000	249
1500	362
2000	462
10000	1224
20000	1450

Re-orbit

The strategy for a graveyard orbit transfer is simple. At a certain instant a perigee velocity increase ΔV_p is given to the satellite, see Fig. 2. This will put the satellite in an elliptical transfer orbit. At the apogee of this transfer orbit, another velocity increment, ΔV_a, is given to the satellite to circularize the orbit to the final graveyard orbit.

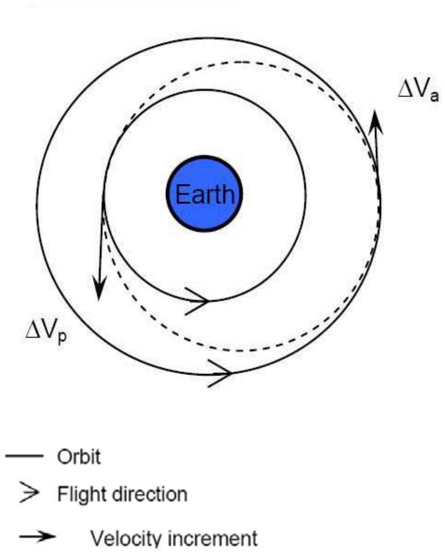

Figure 2: re-orbit procedure

Although the velocity increment in the apogee is a fraction smaller than the one in the perigee, in practice the differences are negligible and the total velocity increment $\Delta V_{tot} = \Delta V_p + \Delta V_a \approx 2 \bullet \Delta V_p$.

The total velocity increment, necessary to place a satellite in a graveyard orbit, h km above the Geostationary or Geosynchronous orbit is shown in Tab.3.

Table 3: Velocity increments for re-orbiting to various orbits above GEO / GSO.

Re-orbit to h above GEO / GSO [km]	ΔV [m/s]
100	3.61
200	7.21
300	10.8
400	14.4
500	17.9
1000	35.6

The ΔV's for de-orbiting are one to two orders of magnitude larger that those for transfer to a graveyard orbit. On the other hand, most of the low-orbit satellites are substantially smaller and lighter than the GEO satellites (BOL masses 1500 kg vs. 6000 kg). Therefore, the amount of propellant required to de-orbit a low orbit satellite remains quite acceptable!

Motor conceptual design and applicability

The thrust of a solid propellant de- or re-orbit motor, is limited by the maximum acceleration that the spacecraft can bear. This restricts the propellant consumption. With a cigarette burning propellant, the burning surface area is small as is the resulting acceleration. However, the motor becomes quite long with a long burn time and hence a large mass of thermal protection necessary to protect the motor case from the hot combustion gasses. Reference [1] shows that a cluster of motors that are fired as well sequentially as parallel, has a lower overall mass than one single dedicated de-orbit motor. This is due to the reduction in thermal protection material when a cluster is applied. An additional advantage is that a cluster of smaller motors can easier be implemented and integrated in the design than one single large motor. Also the same single small motor could be used in different clusters in order to de-orbit different satellites (different mass and altitude). Another advantage is that these motors can also be used to re-orbit GEO and GSO satellites. This way the commercially dominant GEO market is coupled to the more institutionally driven LEO market. Although the ΔV and hence amount of propellant is substantially larger, solid propellant motors may be applied as well for de-orbiting MEO satellites, such as e.g. satellites of navigation constellations at ~20000 km altitude. Since constellations are divided in slots and since each slot should house an active satellite, replacement satellites might be hit by spent satellites as these remain in their slot in the constellation. It is therefore in the interest of the constellation owner to de-orbit spent satellites since this reduces collision risks and promotes the constellation's operability. This applies likewise for LEO constellations.

Fig. 3 shows a solid propellant de-orbit motor from a 9/3 cluster (Cigarette burning propellant grain not shown). Length: 542 mm, case and nozzle diameter 124 mm [1].

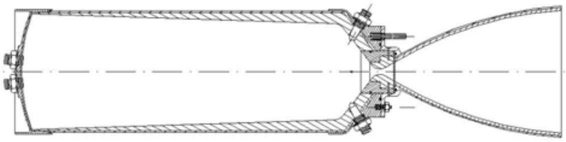

Figure 3: Solid propellant de-orbit motor

Spin stabilisation, pointing and motor placement

If the system must function autonomously, it might be necessary to spin the spacecraft prior to firing the main de- / re-orbit motors in order to cancel out thrust misalignment effects. One cannot rely on the available liquid propellant thrusters because these might not be available if control over the spacecraft has been lost. Therefore solid propellant thrusters could be implemented. Next to that, a small box with de- / re-orbit electronics has to be added to the satellite. Fig. 4 shows a solid propellant spin-up thruster with star burning propellant grain. Length: 272 mm, nozzle diameter 53 mm (motor and thrusters are not depicted at the same scale) [1].

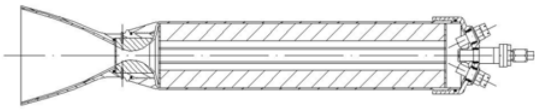

Figure 4: Solid propellant spin up thruster

Pointing and placement

Pointing the thrust vector of the de-orbit / re-orbit motors in the desired direction must occur prior to firing the spin-up thrusters and de-orbit / re-orbit motor.

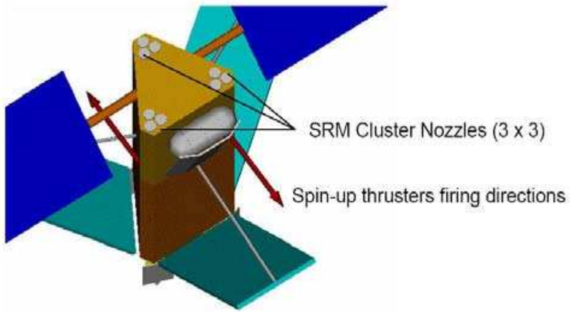

Figure 5: Example of placement of solid rocket motor and spin-up thrusters.

There are several locations on a spacecraft where a de-orbit motor could be mounted. Each of the possible locations requires a specific spin rotation. Spinning around a specific axis is not always feasible due to the inertia characteristics of the satellite (stable spin-axis or not), movements of Centre of Mass of the spacecraft due to depletion of propellant over the lifetime of the satellite, issues related to reaction wheels, the location of other subsystems and available space.

In some cases [1] inertia of reaction wheels may be used to achieve an eventual favourable spinning motion of a satellite. This in combination with corresponding placement of the de-orbit motor and spin-up thrusters can lead to a feasible de-orbit concept.

Placement of the de-orbit or re-orbit motor in combination with associated spinning, might be considered as the biggest challenge of the concept of autonomous solid propellant de-orbiting and re-orbiting, since bringing the thrust vector for a long enough duration into the desired direction for firing, is easy only in some specific cases. In other cases clever engineering will be required and perhaps a change of spacecraft design philosophy. Fig. 5 gives an example of possible location of de-orbit motor and spin-up thruster placement.

5. SOME NUMERICAL VALUES

Tables 4,5 and 6 give some numerical values for de-orbiting and re-orbiting. Tab. 4 gives some typical values for de-orbiting to 80 km. Tab. 6 gives detailed numbers of a de-orbit system with a de-orbit motor cluster of 9 motors and 2 spin up thrusters. The data in tables 4 and 6 comes from [1], a study in which solid propulsion de-orbiting was considered and not re-orbiting. Tab. 5 shows numerical data for re-orbiting a typical GEO satellite of 3000 kg. For each of the two ΔV manoeuvres 5.6 kg of solid propellant is required. This amount of propellant does just not fit in a single motor as displayed in tab. 6, which means that 2 partly filled motors would be required for each ΔV manoeuvre if the motor in tab. 6 would be the 'standard' for de- and re- orbiting. This has the disadvantage that the motors are not optimally filled with propellant. On the other hand it has the advantage that 2 x 2 motors are required (two ΔV manoeuvres), which can be positioned around the centre of mass of the to be re-orbited spacecraft. This example actually illustrates nicely the compromise between standardizing the de- / re-orbit system to save costs and not making optimal use of it versus producing a dedicated and expensive system.

Table 4: Typical values for End Of Life satellite de-orbiting to 80 km. [1]

Name	Unit	Satellite to 80 km at 0.04 g
Orbit altitude	[km]	780
Satellite mass (BOL)	[kg]	689
Satellite mass (EOL)	[kg]	574
Propellant mass	[kg]	115
Liquid propellant		Hydrazine
Solid propellant		AP-HTPB O/F = 9.3, $\varepsilon \approx 400$
Specific impulse	[s]	294
Density	[kg/m^3]	1825
Velocity increment	[m/s]	194.3
Required solid propellant	[kg]	44.9
Burn time with solid propellant	[s]	479

Table 5: Typical values for satellite re-orbiting to 300 km above GEO

Name	Unit	Satellite to Graveyard orbit 300 km above GEO at 0.04 g
Orbit altitude at GEO	[km]	35870
Satellite mass (EOL)	[kg]	3000
Solid propellant		AP-HTPB O/F = 9.3, $\varepsilon \approx 400$
Specific impulse	[s]	294
Density	[kg/m^3]	1825
Velocity increment 1	[m/s]	5.3
Required solid propellant	[kg]	5.6
Burn time with solid propellant	[s]	14
Velocity increment 2	[m/s]	5.4
Required solid propellant	[kg]	5.6
Burn time with solid propellant	[s]	14

Table 6: Data of a solid propellant de-orbit motor and spin-up thruster [1]

		De-orbit motor	Thruster
ΔV	[m/s]	194.3 m/s (9 motors)	
De-orbit altitude	[km]	80	N/A
Satellite mass	[kg]	574	
Type of cluster		9/3 (9 motors of which 3 fire simultaneously)	2 thrusters generating a pure couple
Thrust for motor	[N]	77	192
Burn time	[s]	480	1.7
Dry mass	[kg]	1.85	0.4
Propellant load	[kg]	4.72	0.18
Maximum acceleration	[-]	0.04 g	0.42 rad/s^2
Minimum angular velocity to be stable	[rad/s]	N/A	0.7
Propellant AP-HTPB	[-], [s], [-],[-]	O/F = 9.3, I_{sp} = 294 and $\varepsilon \approx 400$ Cigarette burning	O/F = 9.3, I_{sp} = 276 and $\varepsilon = 100$ Star shape

De-orbit or re-orbit electronics

The de- or re-orbit system is autonomous if it can rely on its own power source and electronics. Therefore the system needs to be equipped with small batteries; the capability to cut power to reaction wheels; means to determine the spacecraft's attitude; means to communicate with the Earth; means to operate the de- or re-orbit electronics and to ignite the motors.

An electronics box controls the different tasks to de- or re-orbit the spacecraft. To save electric power, information concerning the attitude of the spacecraft shall be send to the Earth at certain time intervals. For LEO spacecraft, data concerning the attitude may come from several GPS antennas mounted on the spacecraft. According to [7], four GPS antennas allowed determination of the attitude of the Globalstar satellite with an accuracy of 0.2°.

On-ground, computers process the data and determine attitude and its change over time (spin rate) of the spacecraft. With this information an initiating signal, if necessary with a time delay, may be sent to the spacecraft. The mass of the de-orbit electronics is estimated to be 1.5 kg [1]. For re-orbit this value might increase due to the consequences of the increased distance between satellite and Earth. Tab. 7 lists the overall masses of a complete de-orbit system [1].

Table 7: Mass estimate of an autonomous de-orbit system [1]

Part	Mass [kg]	Nr.	Total mass [kg]
Cluster of de-orbit motors (9/3)	6.57	9	59.13
Spin-up thruster	0.58	2	1.16
De-orbit / re-orbit electronics	1.5	1	1.5
Total mass of de-orbit system			62

6. ADDITIONAL ADVANTAGES

Due to the relatively high thrust of the solid rocket motor, the de- orbit procedure takes little time and will be realised within half a revolution (Hohmann transfer with perigee at 80 km). The relatively high thrust minimises therefore the in-orbit time of ‘spent’ satellites and reduces the chance of collisions with other satellites, reduces the chance of explosions of e.g. batteries, allows determination of the impact point of unburned debris, eliminates the need to track the satellite during e.g. a 25 years natural de-orbit process during which avoidance manoeuvres of other satellites or ISS, might be necessary.

Furthermore the common practice to re-orbit GEO satellites to a graveyard orbit, using the on-board propulsion system is prone to non-optimal-use, since propellant gauging is difficult and therefore the satellite is often re-orbited with too much left-over propellant with loss of valuable operational transponder time as a consequence, or too little propellant, leading to an incomplete re-orbit procedure, i.e. not reaching the required graveyard orbit or remaining in an elliptical orbit touching GEO. A solid propellant re-orbit system allows utilization of all the satellite's liquid propellant for station keeping and attitude control. After depletion of the liquid propellant, the solid propulsion system can move the satellite into its graveyard orbit. Even if a satellite were to die completely before the predicted End Of Life, a solid propulsion system can still move it to a graveyard orbit. Due to the mass of left over liquid propellant in the 'dead' satellite, the desired graveyard orbital altitude might not be reached, but with only a liquid propulsion system, a 'dead' satellite cannot be moved at all!

Mild shielded detonating cord may initiate the next motor in the cluster once the previous motor is burned out. In this way, a light and flexible system is created fitting more easily in a spacecraft than one large single motor.

By developing a standard motor, this motor may be used in different numbers in clusters to de- or re-orbit satellites with varying masses and orbital parameters. The larger production volume reduces cost. The same applies for the spin-up thrusters. Combined with standardized electronics, the whole contributes to the realisation of a cost effective system.

Combining the re- and de-orbiting market and using a standard system, the development costs are spread over a large market (both institutional and commercial), again leading to an affordable system.

7. COMPARISON OF LIQUID PROPULSION AND SOLID PROPULSION DE-ORBITING AND THE ACTUAL SITUATION

In [1] a comparison was made between liquid propulsion de-orbiting and solid propulsion de-orbiting. This was possible since the solid propellant de-orbit system study used an Iridium satellite as a reference satellite that is already equipped with a liquid propulsion de-orbit system. By the time of publication of this paper, data was available on a number of failing Iridium satellites as well as several failures of the de-orbit procedures, using the liquid propulsion system.

According to [8], 21 satellites of the Iridium constellation had failed until 9 March 2009. Of these 21 satellites, only 5 decayed. The remaining 'dead' satellites have not been de-orbited, most likely due to e.g. loss of control of the satellite, a failing propulsion system or uncontrollable tumbling (the source highlights that 13 of the 16 faulty satellites are tumbling) of the satellite probably due to a failing momentum bias wheel.

An autonomous solid propulsion de-orbit system, quite likely would have had a higher success rate. Especially because the solid propulsion system, in [1] actually made use of a specific failure, seen in [8], namely, a failing momentum bias wheel that leads to tumbling of the satellite. The de-orbit procedure with a low thrust engine like the EHT takes about 2 weeks during which control over the satellite is required. The solid propulsion system would de-orbit the satellite in only 480 seconds!

8. MARKET SIZE

Analysis of [9] reveals that over a 2 year period from 28-2-2006 until 23-02-2008, approximately 145 larger (mass > 100 kg) spacecraft have been launched in the following orbits:

LEO:	61
MEO:	10
GEO:	52
Escape:	4
ISS:	18

If one does not take ISS and escape mission related launches into account, still a significant amount of satellites remain, that could incorporate the proposed system for either de-orbiting or re-orbiting.

9. CONCLUSIONS

Autonomous solid propulsion de-orbiting and re-orbiting is feasible and is quite likely more reliable than utilising a non-autonomous liquid propulsion system.

Solid propulsion de-orbiting is much faster that de-orbit with an e.g. an EHT or other resistojet (for a specific study: 480 seconds instead of 2 weeks). Similar conclusions apply if the normal on-board thrusters were utilised.

Due to the faster de-orbit process, the 'dead' satellite spends less time in orbit, compared to the current 25 years natural de-orbit requirement, with the additional advantages that: the impact point of unburned debris can be chosen over a remote area, chances of collisions are lower, chances of in orbit explosions are lower, the number of avoidance manoeuvres carried out by other

satellites is lower and the satellite does not need to be tracked for 25 years.
Solid propulsion re-orbiting allows more optimal use of the on board liquid propellant for commercial operations since all liquid propellant can be used for operations and no liquid propellant will remain in the tanks due to gauging errors. Neither will there be too little propellant to re-orbit the satellite.

A standardized solid rocket motor can be used in different clusters to de-orbit and re-orbit different spacecraft in respectively low Earth Orbit and possible Medium Earth Orbit as well as GEO and GSO.

There seems to be a significant market for which the system is suitable.

Allowing higher acceleration loads on the satellite e.g. by installing stronger antennas and solar panel hinge mechanisms, allows applying an even higher thrust which leads to even shorter burn times of the de- / re-orbit motors and increases the likelihood of a successful de- / re-orbiting.

Pointing the thrust vector in desired direction to carry out the de- / re-orbit procedure seemed possible in a specific case. This area requires more investigation in order to see possibilities for other satellites. Such an investigation, together with the tolerance to higher acceleration loads, might lead to recommendations for spacecraft design if autonomous solid propulsion de- / re-orbit is foreseen.

10. RECOMMENDATIONS FOR FURTHER STUDY

The biggest technical hurdle to overcome in the realization of autonomous solid propellant de- and re-orbiting is pointing of the thrust vector into the required direction with a sufficient degree of accuracy. In some cases, the stored energy of the satellite reaction wheels may be used to generate a spinning motion during which the thrust vector is pointed into the correct direction. Subsequent spinning around the thrust axis, to average out thrust misalignment, as well as ignition for the de- or re-orbit burn, completes the first part of the de / re-orbit manoeuvre. It is underlined again that this is only possible in specific cases. Additional investigation will therefore be necessary. This may lead to recommendations for satellite design if solid propulsion de- or re-orbiting is to be implemented.
Possibly this has to be done in parallel to the investigation for higher tolerable acceleration levels on the spacecraft. Higher allowable acceleration levels allow an even faster de- / re-orbit burn, in which case satellite residual spin is even less problematic and in which case the motors can be lighter due to reduction of thermal protection material.

11. REFERENCES

1. Schonenborg, R.A.C., '*Solid propellant de-orbiting for constellation satellites', 4th International Spacecraft Propulsion Conference, Chia Laguna, Italy, May 2004*

2. Washington Post, 2/14, A3, Achenblog
http://links.mkt751.com/ctt?kn=17&m=3912910&r=MTU4OTU3MTUwMgS2&b=0&j=MTA5ODMyMjM3S0&mt=1&rt=0

3. Washington Post, 2/14, A3, Achenblog
http://links.mkt751.com/ctt?kn=17&m=3912910&r=MTU4OTU3MTUwMgS2&b=0&j=MTA5ODMyMjM3S0&mt=1&rt=0

4. AIAA Daily Launch 27 February 2009
http://links.mkt751.com/ctt?kn=38&m=3912910&r=MTU4OTU3MTUwMgS2&b=0&j=MTA5ODMyMjM3S0&mt=1&rt=05

5. Wall Street Journal (2/27, A14, Hotz)
http://links.mkt751.com/ctt?kn=15&m=3939486&r=MTU4OTU3MTUwMgS2&b=0&j=MTEwMjcxODY1S0&mt=1&rt=0

6. Cornelisse, J. W., Schöyer, H. F. R. and Wakker, K. F. "Rocket Propulslsion and Spaceflight Dynamics", Pitman, London – San Francisco 1979, pp 115, 116.

7. Dietrich, F.J., Systems Engineer at Globalstar, *Personal communication (e-mail)*, December 1998, January 1999

8. Web page on Iridium constellation and failures, http://www.rod.sladen.org.uk/iridium.htm, downloaded in 31 March 2009 (last update 9 March, 2009)

9. 'Launch log', http://www.spaceflightnow.com/tracking/launchlog.htm 25/02/2008

12. ACKNOWLEDGEMENTS

The authors would like to thank the following people for their support and their time for discussions.
Mr. R. Brandt ESA/ESTEC
Dr M. Ford ESA/ESTEC
Dr H. Klinkrad ESA/ESOC
Mr. C. Bonnal CNES