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Fuel and Energy Analysis of a Space Vehicle Aimed at De-orbiting Large-size Objects from Low Orbits Using Thruster De-orbiting Kits

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Abstract: The study focuses on analysis of mass and energy parameters of an advanced SV-collector (SV) designed for fly-pasts between Large-Size Space Debris (LSSD) in low orbits with the aim at their de-orbiting. De-orbiting is supposed to be carried out using Thruster De-orbiting Kits (TDK) installed onboard the SV-collector. The SV and TDKs dry masses are estimated as well as the masses of LSSD objects to be de-orbited with the help of TDKs, the required fuel reserves for TDKs and SV are estimated, the optimal number of TDKs per one SV is evaluated. Earlier the authors of the present study determined 5 compact groups of LSSD in low orbits formed by launch vehicle stages. From the known mass of such objects it is possible to assess the fuel mass required to de-orbit any object of a given group to a disposal orbit. The dry mass of an active SV can be estimated from the mass characteristics of a modern cargo space vehicle. To assess the required fuel reserves of an SV it is necessary to simulate SV's fly-bys between objects of a concrete group of LSSD. Simulation results show that it is expedient to accommodate 8-12 TDKs on one SV, the total initial mass of an SV is estimated to be 7-8 metric tons (at most 10 tons in the limit case).

Key words: Large-size space debris, SV-collector, thruster de-orbiting kit, mass and energy, parameters, disposal orbit

INTRODUCTION

In the present study, we estimate characteristics of an active Space Vehicle (SV) aimed at de-orbiting Large-Size Space Debris (LSSD) from low Earth orbits (altitudes 600-2500 km). By LSSD objects here we mean last stages of Launch Vehicles (LV) and upper stages required to be de-orbited to Disposal Orbits (DO) on which the period of ballistic existence should not be longer than 25 years (Anonymous, 2007).

The 2 versions of LSSD de-orbiting are most frequently considered in the problem of cleaning low Earth orbits. In the first variant, it is assumed that an SV carries jettisonable small modules equipped with engines (a Thruster De-orbiting Kit, TDK). Once an object is gripped such a TDK is fixed in its nozzle or on the surface to secure its de-orbiting to a DO. An SV flies between LSSD objects in succession, until the fuel or TDK are depleted. To resume the mission, it is proposed to inject a special re-fueller vehicle which delivers a new portion of TDKs and refuels the active SV. In the second variant, an active SV de-orbits an object to a DO, stays for some time at this orbit and then travels to the next object. Below we shall specify requirements to an SV to de-orbit LSSD according to the first variant.

Table 1: Compact groups of LSSD in low earth orbits

Group No.	Inclination of orbits of group elements (°)	Semi-major axis range (km)	Eccentricity range	No. of LSSD objects	Typical mass of objects (kg)
1	71	7193-7281	0.0002-0.0036	23	9000
2	74	7122-7152	0.0006-0.0092	11	1435
3	81	7211-7262	0.0031-0.0095	28	1100
4	83	7318-7358	0.0008-0.0081	52	1443
5	97-100	6973-7500	0.0003-0.0099	46	820-9000 (average 2200)

In the previous studies by the researchers of the present study (Baranov *et al*., 2017a, b), 5 groups of LSSD were identified in low Earth orbits (Table 1) and rational fly-past schemes between objects of these groups were proposed based on controlling the natural precession rate of the orbital plane. The required costs of the Total Characteristic Velocity (TCV) of an SV were estimated (for a mission duration up to 10 years), the optimal number of TDKs onboard an SV-collector was estimated. At the same time in the aforementioned papers, no account was made of the mass variation of an active SV during fly-pasts and

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hence the launch mass of an SV-collector cannot be estimated. In the present study, 5 interrelated questions will be considered:

- What is the dry mass of a TDK and the mass of TDK-deorbited LSSDs?
- What are the fuel reserve onboard a TDK?
- What is the dry mass in the first approximation of an SV-collector?
- What are the fuel reserves onboard an SV-collector?
- What is the optimal number of TDK-slots onboard an SV-collector?

MATERIALS AND METHODS

Estimates of TDK dry mass and required onboard fuel reserve: Let us consider the composition of each LSSD group from Table 1. Group 1 is basically, composed of Zenith-2 LV second stages. The second group is formed by Cosmos-3M LV second stages. The third group is made of Vostok-2M LV third stages. The fourth group is basically composed of Cosmos-3M LV second stages and several Tsyklon-3 LV third stages. The objects from the 5th group are located at sun-synchronous orbits and are composed of upper stages of some LVs (including, in particular, Long-March-2, -4, Zenith-2, PSLV, Ariane family and Thor Agena launch vehicles). The most heavy of these objects is the Zenith-2 LV second stage whose mass is about 9000 kg, the length is 11.5 m and the diameter is 3.9 m. The mass of other objects is close to the mean value which is 1500 kg (Table 1).

A description of the concept of an SV-collector with TDKs can be found by Castronuovo (2011): as a TDK one considers a solid-propelled modulus whose dry mass is assumed to be 30 kg. However, under long-time space flights solid fuel is prone to stratification due to the fracture of plasticizers in it. This may result in a dangerous situation in which a TDK engine fails to ignite or operates inadequately. Besides, an emergency shut-off or the thrust neutralization on a TDK may be required with a loss of its attitude control which is hardly realizable for solid-propellant engines. Hence, in the present study we propose to consider a TDK with the propulsion system operating on a single-component liquid fuel (like, for example, derivatives of hydrazine). In the first approximation, the dry mass of a TDK is composed of the mass of fuel tanks, of the corps and of the propulsion system. The required orientation of an object together with a TDK accommodated on it can be achieved prior to de-mating by stabilizing the SV-collector itself, later it will be maintained by employing a flywheel installed inside a TDK along its longitudinal axis. Studies show that a variation of the TDK dry mass by 30-70 kg has practically no effect (1-3 kg) on the mass of fuel required to de-orbit the "LSSD+TDK" stack to a DO. This is explained by the fact that the mass of the de-orbited objects exceeds by approximately 2 orders the TDK dry mass. Hence, as the first approximation, we assume that the TDK dry mass is 30 kg (as was assumed by Castronuovo (2011)) and evaluate the require fuel reserve for each TDK.

The DO parameters were proposed earlier by Braun *et al.* (2013) and refined by Baranov *et al.* (2017a, b) for each of the give groups. By Baranov *et al.* (2017a, b) it was also shown that a transfer of an object to an elliptic disposal orbit requires, approximately 1.5 times smaller TCV costs than for a transfer to a circular DO, even though with this approach (as was noted by Braun *et al.* (2013)) the apogee of the DO of a de-orbited object exceeds 700 km for 10 years.

The variation Δa of the semi-major axis of an elliptic orbit due to a maneuver can be calculated by the equation:

$$\Delta a = \frac{2a^2 v}{\mu} \Delta v_T \qquad (1)$$

Where:

Δv_T = The Tangential component of the velocity impulse
v = The velocity at the point of application of the velocity impulse on the orbit
μ = 398600.44 km^3/sec^2 is the gravitational constant
a = The semi-major axis of the original elliptic orbit

Table 2 summarizes parameters of the elliptic DO corresponding to the semi-major axis range (from Table 1) of elements of each group of LSSD. Equation 1 is used to assess the values of deceleration tangential velocity impulses required to transfer an object to an elliptic DO. A variant was considered for which an impulse was applied at the apocentre of the initial orbit at which the velocity v is minimal.The efficiency of variation of the

Table 2: Transfer characteristics of LSSD objects to elliptic DO

Group No.	Semi-major axis range (km)	Eccentricity range	DO semi-major axis range (km)	Δα (km)	ΔV(m/sec)
1	7193-7281	0.0002-0.0036	7000-7040	193-241	99-122
2	7122-7152	0.0006-0.0092	6970-6982	152-170	80-89
3	7211-7262	0.0031-0.0095	7007-7030	204-232	104-118
4	7318-7358	0.0008-0.0081	7057-7075	261-283	132-142
5	6973-7500	0.0003-0.0099	6938-7090	35-410	19-199

semi-major axis in this case is smallest but only a minimal change in it is required and so, this point is optimal to form the required disposal orbit. Tsiolkovsky's equation can be applied to estimate the TDK wet mass:

$$\Delta V = W_{eff} \cdot \ln \frac{m_1}{m_2} \quad (2)$$

Here:

ΔV = The required velocity increment
W_{eff} = The efficient exhaust velocity of ejected combustion products
m_1 = The full mass of the "fuelled TDK+an LSSD object" stack
m_2 = The mass of the "dry TDK+an LSSD object" stack

Let us estimate the sufficient fuel mass in a TDK under which each object in the LSSD groups can be de-orbited to a DO. The following results were obtained: ~356 kg for Group 1, ~42 kg for Group 2, ~43 kg for Group 3, ~67 kg for Group 4, ~342 kg for Group 5 for diagonal solutions (Baranov *et al*., 2016) and 115 kg for objects not covered by diagonal solutions. These masses of fuel in a TDK are different not only due to different Δa from Table 2 but mostly because of different masses of objects in such groups. This is manifested most heavily in Group 5 which contains a wide variety of various LV stages.

From the above data it is possible to assess the maximal required capacity of the fuel tank of a TDK as the one that corresponds to the fuel mass (unsymmetrical dimethylhydrazine) of 350 kg. In the case of Groups 2 and 3, it suffices to take a tank whose volume is 7 times smaller than the maximal one (50 kg of fuel) and in the case of Group 4, its volume should be 5 times smaller than the maximal one (70 kg of fuel). Such a marked variance with respect to the required fuel mass is responsible for noticeable difference in the mass of fuel tanks. So, given the 3 mm wall thickness of a tank (made of AMg-6 aluminium-magnesium alloy) of 350 kg fuel capacity, its mass is approximately 23 kg while for a tank of capacity 50 kg its mass is about 6 kg. In addition to the fuel tank body, TDK should also involve the control system with all necessary actuators. Hence, in case of full fuel load, the TDK dry mass may exceed with high probability the 30 km limit. At the same time, for TDKs with small fuel margin the value of 30 kg for the dry mass is considered to be realistic.

RESULTS AND DISCUSSION

Estimation of the dry mass of an SV-collector: An SV-collector which fly-pasts and captures LSSD objects, should feature in its construction principal instruments and units to fulfill this task. The total mass of an SV-collector M is composed of its dry mass m_{SV}, the TDK dry mass m_{TDK} (it is assumed that there are n TDKs), the fuel mass $m_{F_{TDK}}$ in each of n TDKs and the fuel mass for the main engine of an active SV m_{fuel}:

$$M = m_{SV} + n \times m_{TDK} + n \times m_{F_{TDK}} + m_{fuel} \quad (3)$$

To estimate the dry mass of an SV-collector, we consider Soyuz-Progress vehicles family (Hall and Shayler, 2003) which is equipped with standard maneuvering and rendezvous systems with space objects (Table 3). The fact that LSSD objects are not cooperative requires installation of additional systems for measuring the distance to the target and its angular motion as well as systems for gripping an LSSD object and its fixation within a TDK in its nozzle. Considering the first variant of de-orbiting these operations should be made using robotic systems dating back to the Canadian Space Station Remote Manipulator System (Canadarm). The mass of this unit was about 450 kg and the length was ~15 m. According to our estimates, the mass of the complex of robotic units of an SV-collector will be ~410 kg. On the other hand, one should exclude from consideration the systems which allow a vehicle to be docked to an orbital station without creating a threat of life for the crew (the systems for gas composition maintenance and oxygen supply) as well as the systems which determine its performance destination (the refueling system). The mass of onboard cables is expected to be slightly lower than in the current version this is because of the fact that an SV-collector has no docking system and has no a transfer door into the space station.

Table 3: Approximate mass budget of a Soyuz-progress type space vehicle and an SV-collector

System type	Mass (kg)	Mass for the SV-collector (kg)
Guidance navigation and control system	150	170
Combined propulsion system	400	400
Onboard radio system	50	40
Onboard measurement system	50	50
TORU microwave devices	10	10
Onboard complex control system	300	300
Thermal control system	100	80
Electric power supply system	300	330
Gas composition provision system	10	0
Docking and transfer system	250	0
Television system with antenna-feeder device	30	30
Refueling systems	650	0
Oxygen supply systems	100	0
Onboard cables	400	380
Structure	1300	1300
Complex of robotic devices	0	410
Total	4100	3500

Table 3 shows that the dry mass of an SV-collector will be about 3500 kg. Hence, for subsequent calculations, one may adopt this constant value which will allow to consider Eq. 3 as a function of the number n of TDKs onboard with known mass of fuelled TDKs.

Estimate of the total mass of an SV-collector and the number of TDK slots: The evaluation of the necessary number n of TDK slots onboard of the SV-collector is an important task because it is responsible for both the fuel mass of the main propulsion system and the total mass of the SV itself. There are several approaches to solving this problem. By Castronuovo (2011) it was assumed that n = 7 while by Anonymous (2018) and Sahara (2014) it was assumed that the number n should be equal to n = 25. In all these sources, the number of TDKs onboard an SV-collector was assumed to be fixed and was never justified. At the same time, preliminary data of Baranov *et al*. (2017a, b) and Castronuovo (2011) show that the correct value of n lies within the above range n = 11-12.

We again use Tsiolkovsky's formula and consider separately each group of LSSD. We know the dry mass of the SV-collector and the dry mass of a TDK. The fuel mass in one TDK sufficient for de-orbiting to a DO was determined above for each group. Let us estimate TCV and fuel costs for the SV to fly-past between objects within a group, neglecting the adjustment maneuvers for direct rendez-vous with LSSD.

For each LSSD group, calculation results are given in Fig. 1-5 on fuel and power diagrams. The horizontal axis represents the number n of slots with fuelled TDKs which can be accommodated onboard an SV-collector. Considering the limited power capacities of modern space systems, several re-fuelling of an active SV will be required to fly-past all objects in a group. Hence, on Fig. 1-5 to each value of n there correspond several points describing the parameters of each fuelled active SV. Circular points show the total initial mass of active SVs; rhombic points show the characteristic velocity for maneuvers available at each vehicle. Both parameters are plotted as left vertical coordinates in a unified scale, despite of different units of measurement. The number of plots of each type corresponds to the number of propellant loading operations, including the principal SV-collector. For some values of n, after the last re-fuelling an active SV will have parameters similar to those it had during the injection to the first object in the group (on Fig. 1-5, an approach and even superimposition of points correspond to this case). Such variants of configuration will be the most successful because in this case the last SV-refueller will have no empty slots of TDKs.

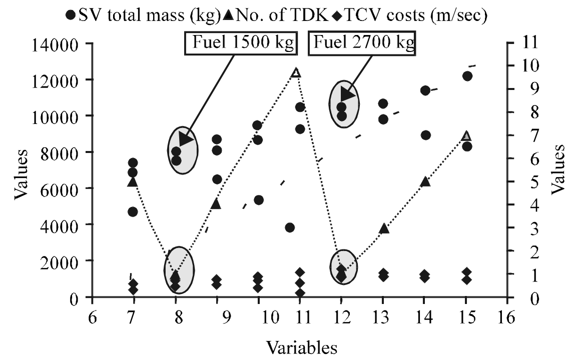

Fig. 1: Fuel and energy diagram for LSSD Group 1 (23 objects)

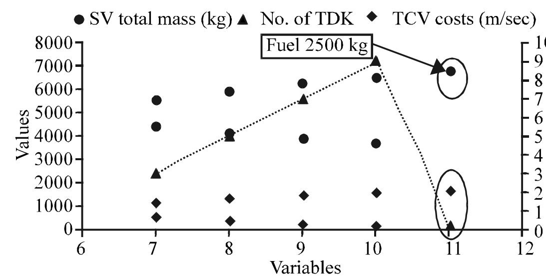

Fig. 2: Fuel and energy diagram for LSSD Group 2 (11 objects)

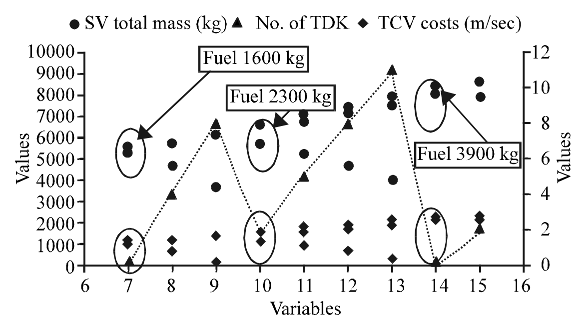

Fig. 3: Fuel and energy diagram for LSSD Group 3 (28 objects)

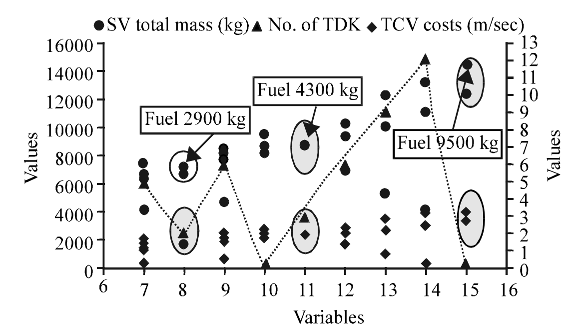

Fig. 4: Fuel and energy diagram for LSSD Group 4 not covered by diagonal solutions (30 objects of 52)

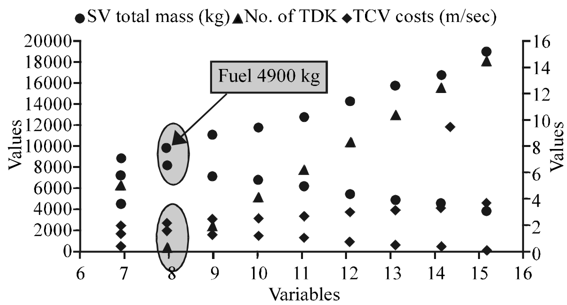

Fig. 5: Fuel and energy diagram for LSSD Group 5 not covered by diagonal solutions (16 objects of 46)

In the general case, the number of fly-past objects within an LSSD group is not a multiple of the number of slots with TDK. As a result, an SV-refueller which is the last to deploy, will not be completely fuelled and will not have the largest number of fuelled TDKs. This should be avoided because additional launches of SV-refuellers are much more expensive than accommodation of TDKs or additional fuel volumes on board of an active SV. On the other hand an SV-collector and SV-refuellers will be launched on available Lvs which imposes additional size and mass restriction for such space vehicles. It is also expedient to have some 1-2 reserve TDKs to fly-past the entire group. In Fig. 1-5, the number of slots with TDKs (marked as triangles) that will be left empty after the last re-fuelling of an SV-collector are plotted as right vertical coordinates. These values, depending on the number n of slots with TDKs are joined by dash lines for illustration purposes.

For group 1 there are two appropriate variants of configuration of an active SV-collector: with 8 or 12 TDKs (Fig. 1). In Group 1, there are 23 LSSD objects and hence with n = 8 de-orbiting of all objects will require three equipped SVs with the initial mass ~8000 kg for each SV (including ~1500 kg for fuel) while for n = 12 two SVs are sufficient with the initial mass ~10500 kg for each SV (including ~2700 kg for fuel). In both cases, one slot with TDK on the last fuelling is on standby, the TCV costs for the SV for maneuvers is at most 1500 m/s. Thus, the above two composition variants differ qualitatively only with the number of launches and capabilities of the required launch vehicle.

In Group 2 (Fig. 2) there are 11 LSSD objects and hence the best configuration variant corresponds to n = 12 (1 slot with TDK is on standby). The SV mass will be about 7000 kg (including ~2500 kg for fuel), the available TCV costs will not exceed 2 km/s.

For Group 3 (consisting of 28 objects) there are three appropriate configuration variants of an active SV-collector: with 7, 10 and 14 TDKs (Fig. 3). For n = 7, de-orbiting of all objects of the group is achieved by four equipped SVs (under this approach there are no standby TDK slots, the mass of one SV is ~5600 kg including ~1600 kg for fuel). For n = 10 three SVs are sufficient of mass at most 6500 kg (including ~2300 kg for fuel); 2 TDK slots are on standby for the last fuelling. In both cases (n = 7 and n = 10), TCV costs for an SV do not exceed 2 km/s. For n = 14 there are no standby TDK slots, an SV should have a TCV reserve exceeding 2 km/s, its full launch mass should be ~8500 kg (including ~3900 kg for fuel).

For Groups 4 and 5, the authors of the present study proposed earlier the so-called "diagonal" solutions to the problem of fly-past of LSSD objects (Baranov *et al*., 2017; Baranov *et al*., 2016). Without going into the details about the method of their derivation, we note that for Group 4 there are two such solutions: they enable to fly-past, respectively, 12 and 10 objects of 52. For each of such fly-pasts much fewer amount of fuel is required than for a successive fly-past scheme. Hence, n = 12 is believed to be the most appropriate number of TDKs onboard.

For the portion of Group 4 not covered by diagonal solutions (30 objects in total), there are three appropriate variants (Fig. 4) for configuration of an active SV-collector (8, 11 and 15 TDKs, respectively). For n = 8, de-orbiting of all objects in the group is achieved by 4 equipped SVs with TCV costs smaller than 2 km/s (2 TDK slots are on standby for the last fuelling, the mass of one SV is ~7100 kg, including ~2900 kg for fuel). For n = 11, it suffices to have 3 SVps with launch mass 8800 kg (including ~4300 kg for fuel) and 2.5 km/s for TCV costs. The 2 TDK slots are on standby for the last fuelling. For n = 15 there are no standby TDKs, the SV is ~14500 kg. The most optimal is the value n = 11 for which fewer number of re-fuelling is required and when the SV launch mass is sensible.

In Group 5, there are at least 2 diagonal solutions to fly-past 18 and 12 objects, respectively. To fly-past the first 18 objects, even for n = 18 one re-fuelling is required in any case. So, without giving the fuel and energy diagram for this separate solution, we take n = 9. The value n = 12 is optimal to fly-past 12 objects from the second diagonal solution.

For the portion of Group 5 not covered by diagonal solutions (16 objects in total) there is only one appropriate variant of composition of an active SV-collector (Fig. 5): 8 TDKs. With n = 8, all objects of the group can be de-orbited using 2 equipped SVs with TCV reserve 2.5 km/s there are not standby TDK slots on the last fuelling, the mass of one SV is ~9500 kg, including ~4900 kg for fuel).

Analysis of diagrams in Fig. 1-5 shows that the optimal number n of slots with TDKs on board of an active SV-collector is 12. On the other hand in Groups 3, 4 and 5 by taking n slightly smaller than 12, it is possible to homogenize the launch mass of the SV-collector and save its fuel costs with the same number of re-fuelling. Hence, the design of an SV-collector should have an option to transform the capacity of a "cluster" with TDKs in the range n = 8-12.

The total launch mass of an SV-collector to fly-past all 5 LSSD groups is at most 10 metric tons. Besides, for Groups 2, 3 and 4, the launch mass of an SV will be at most 7-8 tons. For a properly chosen number of TDK slots, the launch SV mass is not greater than that of a modern "progress" supply vehicle and hence, the creation and launch of such an SV-collector is a technically, feasible problem at present.

CONCLUSION

The dry mass of an SV-collector equipped by 2 robotic arms for gripping an LSSD object and fixation of a TDK in its nozzle is approximately 3500 kg.

By analyzing the composition of LSSD groups in low orbits (various LV stages and upper stages), the upper estimate of 350 kg for the required fuel mass limit (UDMH) for one TDK is obtained. In Groups 2 and 3, the sufficient fuel mass in one TDK is 50 kg and in Group 4, 70 kg.

The mass of an active fully equipped SV is at most 10 tons (mainly 7-8 tons), the TCV reserve for maneuvers is at most 2.5 km/s. Depending on the type of de-orbiting objects, the required fuel mass on board of an SV-collector may vary from 1.5-5 tons.

The optimal number of TDKs on board of an active SV is estimated to be 12. The configuration of TDKs on an SV-collector should be of modular-type which enables one to reduce the number of TDKs onboard when working with a concrete group of LSSD.

By varying n in the range from 8-12 with the same number of re-fuelling it can be achieved that after each re-fuelling the SV will have the smallest possible total mass.

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