MODELING AND PERSPECTIVES OF LOW-WORK-FUNCTION ELECTRODYNAMIC TETHERS TO DEORBIT SPACE DEBRIS

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ABSTRACT

Low Work-function Tethers (LWTs), i.e. long conductors coated with low work-function materials, can deorbit space debris passively and without using consumable. The coating enables natural thermionic emission of electrons within the cathodic tether segment and avoids the need of active hollow cathodes. Depending on the work function W of the coating and the tether temperature T, photoelectron emission can be also relevant and may improve the cathodic contact with the ambient plasma. Using a typical solar photon spectrum and a Fowler-DuBridge law for the photoelectron yield of the coating, thermionic and photoelectric dominated LWTs are organized within the $W-T$ plane. Key design aspects of the tether, including thermal, electrical, and mechanical considerations, are analyzed and the required theoretical and experimental activities for the development of the concept are identified. A roadmap, which takes into account the state-of-the-art of extra low work function thermionic materials and tether technology in Europe, is proposed.

Key words: Electrodynamic Tethers, Passive Deorbit Technologies .

1. INTRODUCTION

Theoretical studies have shown the unstable character of the space debris population at Low-Earth-Orbit (LEO) [11, 12]. The debris in orbit around the Earth became so dense that the runaway cascade of collisions predicted by Kessler and Cour-Palais in 1978 has been triggered [10]. Several means, like the selection of orbits with less risk, implementation of collision avoidance strategies, and end-of-life passivation, can mitigate the problem. However, in the long term, the development of technologies to bring the deorbit time below 25 years, as stated by the guidelines, will be indispensable. Low cost and simplicity may be the major requirements for these devices.

In principle, passive deorbit technologies, like sails and electrodynamic tethers (EDTs), would be compatible with these two requirements because their underlying physical mechanisms are robust and passive. Being rigid-body motion a definite property of thermodynamic equilibrium of macroscopic systems, a dissipative force (air drag and Lorenz drag), naturally appear upon the sail and the tether due to their relative motions with respect to the neutral air and the ambient conductive plasma in the presence of the geomagnetic field, respectively [20]. However, the lack of efficiency at the altitudes of interest (above 800 km) and the invariance of the area-time-product, are two important physical limitations of sails. EDTs show good performance in deorbit scenarios [3, 2, 23] but, several decades after the pioneer works by Drell et al [7] and Moore [13], EDTs have not been implemented yet as a commercial product by the space industry.

Several reasons explain the delay in the development of EDT technology. First, the presence of a business case that fits perfectly with EDTs, i.e. the deorbit of space debris, is relatively new. Other reasons have been external to tether technology, like the delay of the launch and later cancelation of ProSEDS mission [9] after Shuttle Columbia accident. Successful tether missions like PMG, SEDS1 and TiPS have been shaded by failures in TSS1, TSS1-R, and some low cost missions with cubesats [6]. As a consequence, doubts on tether simplicity and reliability have been raised. However, recent progress on tether technology have simplified EDTs extraordinarily. In particular, the appearance of the Low Work-function Tether (LWT) can contribute to the application of EDT to the deorbit of space debris.

This work is organized as follows. Section 2 makes a short historical review on how the EDT concept has evolved towards the LWT. The present model for the LWT/plasma interaction is briefly revisited in Sec. 3 and Sec. 4 shows some performance in Low-Earth-Orbit scenarios. Section 5 discusses the perspective and roadmap for LWT technology and highlights the key technological progresses that should be overcome. The conclusions of the work are presented in Sec. 6

2. THE EVOLUTION OF THE EDT CONCEPT

In 1965 Drell et al [7] noted that an electric field

$$\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B} \tag{1}$$

at the faraway plasma will be seen by an observer attached to a conductor that moves at velocity $\boldsymbol{v}$ across a magnetic field $\boldsymbol{B}$. In order to use the resultant electromotive force, they proposed a fully passive *flying rigid kite consisting of two 100-meter-long conducting slabs each* $\sim 5 - 10$ *meters across, connected by a conducting rod of 100-meter length* [see panel (a) in Fig. 1]. The authors assumed that the Alfven-waves radiation impedance was the main factor in the tether-plasma current circuit and mentioned the photoemission as a mechanism to release the electrons into the plasma. One year later, Moore noticed that the impedance between the ambient plasma and the solid surfaces would be dominant [13]. He made calculations using the random electron current for current collection and the photoelectric effect for electron emission and found that the results from Drell et al. were not realistic. As a solution, he proposed a conductor equipped with two active plasma contactors at its tips [see panel (b)], which are responsible of the electron collection and emission. However, these devices increase the complexity of the system and, for certain types of contactors, they also involve expellant.

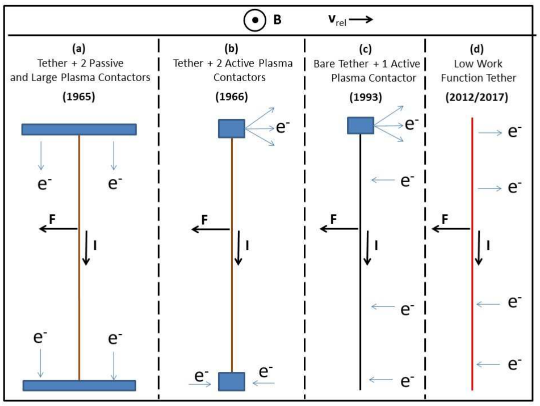

Figure 1. Evolution of electrodynamic tethers

These drawbacks were partially mitigated by the bare tether concept, introduced in 1993 by Sanmartin et al [22]. After calling $\boldsymbol{u}_t$ the tangent unit vector along the tether pointing in the direction of the electric current, the potential V_p of the faraway plasma varies with the coordinate x along the tether direction as $dV_p/dx = \boldsymbol{E} \cdot \boldsymbol{u}_t \equiv E_m$. Concurrently, tether potential V_t satisfies Ohm's law $dV_t/dx = I(x)/\sigma_t A_t$, with $I(x)$ the electrical current, and σ_t and A_t the tether conductivity and cross-section. Therefore, the equation for the local bias $V = V_t - V_p$ is

$$\frac{dV}{dx} = \frac{I(x)}{\sigma_t A_t} - E_m \tag{2}$$

If the tether is left without insulation (bare), the tether operates as a Langmuir probe and the current varies as

$$\frac{dI}{dx} = p_t \times J(V) \tag{3}$$

with p_t the tether perimeter and $J(V)$ the current density, which is provided by probe theory. Electron collection (anodic contact) at tether points with local bias $V > 0$ is given approximately by the Orbital-Motion-Limited (OML) law

$$J(V) = J_{OML} \equiv \frac{eN_\infty}{\pi}\sqrt{\frac{2eV}{m_e}}, \quad V > 0 \tag{4}$$

where N_∞ is the unperturbed plasma density, m_e the electron mass, and e the elementary charge. For typical plasma density values in Low Earth Orbit (LEO), $N_\infty = 10^{11} m^{-3}$, and motional electric field, $E_m = 150V/km$, the electron current collection is about $J_{OML} \approx 3.6 \times 10^{-2} A/m^2$. Ion collection at tether points with $V < 0$ would follow a similar law but with the ion mass m_i replacing m_e in Eq. (4). For O^+ ions the current per unit length for a given bias would be a factor $\sqrt{m_e/m_i} \approx 1/172$ of the one for electrons. Therefore, since cathodic contact is not efficient, Sanmartin et al proposed a bare tether equipped with one active plasma contactor (thermionic emitter or hollow cathode). The electrons are passively capture by the bare tether and ejected back to the plasma by the cathodic contactor [panel (c) in Fig. 1].

The appearance of new thermionic materials with low work functions W, for instance the C12A7 [25] in 2004, triggered the invention of a new type of EDT. In the framework of the FP7/Space project named *BETs* an EDT coated with a thermionic material was proposed [26]. Thanks to the low work-function provided by the coating, a thermionic tether naturally emits electron through thermionic emission [see Panel (d) in Fig. 1]. Recently it was pointed out that the coating also enhances the photoemission [17]. Depending on tether temperature T and W, the relative importance of the photoelectric and thermionic effect varies. The name Low Work function Tether (LWT), which refers to the coating and not to the emission mechanism (thermionic and photoelectric), was proposed. Curiously, the tortuous history of EDTs seems to end up with a concept (the LWT) that operates similarly to the one proposed originally by Drell et al. They are both passive and use the photoelectric effect. However, the LWT does not need big surfaces because the tether itself captures and emits the electrons.

3. LWT MODELING

In order to understand key design and performance aspects, the LWT/plasma interaction should be explained briefly (find details in Refs. [26] and [17]). Thanks to the coating, the passive emission of electrons through thermionic and photoelectric effects are enhanced. The current densities (A/m^2) emitted due to the former is

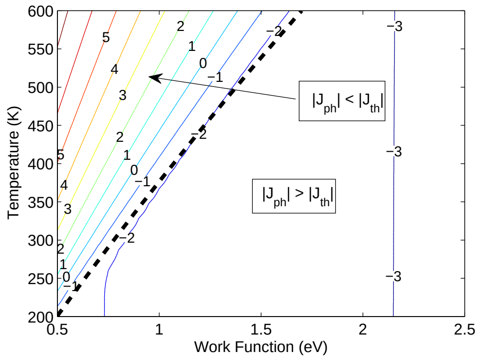

Figure 2. log_{10} ($|$ $J_{ph} + J_{th}$ $|$) versus temperature and work function, with J in A/m^2 (from Ref. [17])

modeled by a Richardson-Dushman (RD) law

$$J_{th} = -A \times T^2 \exp\left(-\frac{W}{k_B T}\right) , \qquad (5)$$

with $A = 4\pi m_e e k_B^2/h_p^3 \approx 1.20 \times 10^6 Am^{-2}K^{-2}$, and h_p the Planck constant. The photocurrent depends on the energy spectrum of the solar photons $S(E)$, the photoelectric yield of the tether $Y(E)$, and the tether reflectivity r_t. It reads

$$J_{ph} = -f \times (1 - r_t)\, e \int_0^{\infty} S(E)Y(E)dE , \qquad (6)$$

with f a factor that takes into account that only a fraction of the total perimeter is illuminated by the Sun.

Figure 2 shows the log_{10} ($|$ $J_{ph} + J_{th}$ $|$), with the current densities in A/m^2 units, versus tether temperature and work function. The calculations were carried out with a Fowler-DuBridge law for the photoelectric yield of the tether and typical parameter values for a LWT in LEO (specific values of the parameters are given in Ref. [17]). The dashed line in Fig. 2 separates the domains of operation dominated by thermionic and photoelectric emissions. For a given temperature, the electron emission is basically controlled by the thermionic (photoelectric) effect for low (high) work function values. For the set of parameters used, both mechanisms are of the same order when the emission level is about $10^{-2}A/m^2$, which is similar to the typical value found for OML current collection. In principle, LWT dominated by thermionic emission will present better performance because they can reach higher emission levels. As shown in Fig. 2, coatings with work functions below 1eV would be necessary to reach such an ideal scenario. However, the state-of-the-art of thermionic materials that are suitable for coatings suggests that LWTs with comparable thermionic and photoelectron emissions are more realistic nowadays.

Equation (5) shows that a key parameter of the LWT is the tether temperature. If Joule heating is ignored, a simple balance between solar absorption and radiative cooling gives the equilibrium temperature

$$T = \left(\frac{\alpha_{abs} S_{Sun}}{\pi \epsilon_{em} \sigma_B}\right)^{1/4} \qquad (7)$$

Therefore, T is basically controlled by the ratio of tether absorptivity and emissivity. For instance, for a ratio $\alpha_{abs}/\epsilon_{em} = 0.5/0.06 \approx 8.3$, and using the solar constant $S_{Sun} \approx 1.37kW/m^2$ and the Stefan-Boltzmann constant $\sigma_B \approx 5.67 \times 10^{-8}W/m^2K^4$, one finds $T \approx 500K$. For such a temperature, electron emission level would be comparable with OML electron collection if the work function of the coating is about $1.4eV$ (see Fig. 2).

The sum $J_{th} + J_{ph}$, given by Eqs. (5) and (6), corresponds with the total current emitted by the tether surface but do not coincide, in general, with the function $J(V)$ that should be inserted in Eq. (3) for $V < 0$. Depending on V and the emission level, space charge effects can lead to an outward radial electric field that reflects the emitted electron back to the tether. The tether segment under this effect, BB^*, is said to operate in the space-charge-limited (SCL) regime [26]. Recently, an Orbital Motion Theory (OMT) for long cylindrical emitters have been presented [5]. Such a theory, which gives the law $J(V)$ that should be used in Eq. (3), fully incorporates SCL effects and also the possible operation of the cylinder beyond the OML regime, i.e. when the typical length of its cross-section is above certain threshold [21]. Alternatively to such a theory, one may use the approximate model[4]

$$J(V) = \begin{cases} J_{OML} & 0 < x < x_B \\ \frac{8\pi\epsilon_0 V}{R}\sqrt{\frac{2kT_e}{m_e}} & x_B < x < x_{B^*} \\ J_{RD} & x_{B^*} < x < L \end{cases} \qquad (8)$$

with constant $\sigma_1 \approx 0.24$, R and L the tether radius and length, ϵ_0 the vacuum permittivity, x_B the zero bias point $[V(x_B) = 0]$, and x_{B^*} the SCL-RD transition point. The tether current profile $I(x)$ is found by solving Eqs. (2)-(3) with the boundary condition $I(x = 0) = I(x = L) = 0$ and $J(V)$ provided by the OMT theory or Eq. (8). Once $I(x)$ is known, the Lorentz force is found from

$$\boldsymbol{F}_L \approx \boldsymbol{u}_t \times \boldsymbol{B} \int_0^L I(x)dx \qquad (9)$$

4. LWT PERFORMANCE IN LOW-EARTH-ORBIT

To the best of our knowledge, a flight simulator of LWTs with $J(V)$ computed at each time-step with the OMT of Ref. [5] and including photoelectric and thermionic effects has not been developed yet. However, the simulator named BETsMA [18] can compute deorbit performance by using Eqs. (8) and ignoring the photoelectric effect. Such a tool has been used to study the deorbit performance of LWTs in geostationary transfer orbits[19].

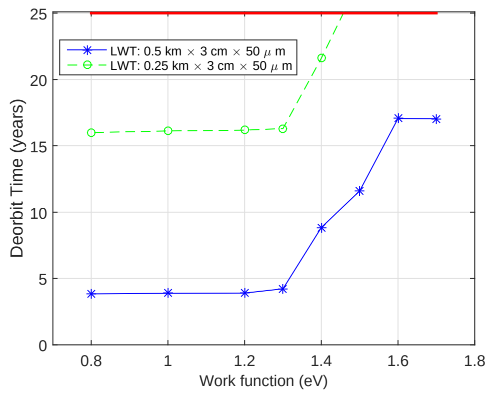

Figure 3. Deorbit Time versus work function of the LWT without photoelectric effect and $J(V)$ computed from Eq. 8. Epoch 1988

For the simulations we considered a spacecraft of mass $200kg$ and flying at a circular orbit of altitude 800 km and $98°$ of inclination. The LWT is a tape of Aluminum with conductivity $\sigma_t = 3.546 \times 10^7 \Omega^{-1} m^{-1}$, absorptivity $\alpha_{abs} = 0.5$, emissivity $\epsilon_{em} = 0.06$, width $3cm$, and thickness $50\mu m$. Two set of simulations were carried out for tether lengths 0.5 and 0.25 km, respectively. The drag coefficient of the spacecraft and the tether was $C_D = 2.2$ and the area-to-mass ratio of the spacecraft $0.01m^2/kg$. The simulator includes the Lorentz drag and air drag perturbations. Plasma densities, geomagnetic field, and air densities were computed with the 2012 International Reference Ionosphere (IRI), International Geomagnetic Reference Field, and the COSPAR International Reference Atmosphere (CIRA) model under moderate solar activity. The starting date of the deorbit manoeuver was 1/1/1988.

Figure 3 shows the deorbit time versus the work function of the LWT for the two selected tether lengths. For convenience, it also displays the deorbit time (25 years) of the guidelines. From BETsMA, we found that the natural deorbit time of the 200-kg spacecraft without the tether is about one century. In order to assess the effect of the air drag alone, we first considered the same spacecraft equipped with a tether of dimensions $L = 0.25km \times 3cm \times 50\mu m$ but without Lorentz force. The action of the air drag upon the spacecraft and the tether yielded a deorbit time of 29 years. If tether length is doubled, i.e. $L = 0.5km \times 3cm \times 50\mu m$, then the spacecraft deorbit time is almost halved (17.1 years).

Let us now discuss the deorbit performance of a LWT, i.e. when a conductive tether is coated with a thermionic material of work function W and there is Lorentz drag. As the work function increases, the deorbit times approach to the ones obtained without the Lorentz drag (29 and 17 years). This effect is explained by the low emission capability of LWTs with large W, which yields to low currents and Lorentz forces. Adding the photoelectric effect would improve the deorbit performance for this domain of the diagram. On the opposite side, as W decreases, the deorbit time also approach to constant values (16 and 3.8 years for tether lengths 0.25 and 0.5 km, respectively). For very low W, the tether current is almost invariant with the work function because it operates under the SCL regime. For low W, adding the photoelectric effect to the simulator would not modify the deorbit performance. These two deorbit times are not far from 11.9 and 2.45 years, which are the one provided by bare tethers with active plasma contactor (not shown in Fig. 3). For moderate W values, i.e. between 1.2 and 1.5 eV, the performance is very sensitive with W.

An important issue related with short tethers (below 1 km) is the sensitivity of the performance with the plasma density. For this reason, the deorbit time provided by the simulations may present certain degree of dispersion as a function of the epoch and the plasma density model implemented in the code. In any case, Fig. 3 shows that a LWT can easily fulfill the guidelines if the work function of the coating is below about 1.5 eV. The low masses of the LWTs, about 1 and 2 kg for tethers with lengths equal to 0.25 and 0.5 km, show that a deorbit kit based on this technology would represent a little penalty for the satellite.

5. PERSPECTIVES OF LWTS IN DEORBIT APPLICATIONS

The major challenge for LWT technology is related with material science due to the unprecedented set of of optical, mechanical, and electrical properties. The substrate should be a conductor with a low density-to-conductivity ratio (ρ_t/σ_t) and a high melting temperature (T_m). The latter is key for the electron thermionic emission due to the factor W/T inside the exponential of Eq. (5). Two good candidates for the substrate are $1100 - H19$ Al alloys ($\rho_t/\sigma_t = 7.62 \times 10^{-5} kg\Omega/m^2$ and $T_m = 920K$) and BeCu alloys ($\rho_t/\sigma_t = 3.3 \times 10^{-4} kg\Omega/m^2$ and $T_m = 1300K$).

Unlike the substrate, a suitable coating for LWT applications has not been developed yet. The work functions of conventional thermionic materials used in electric propulsion, such as $LaB6$ ($W = 2.7eV$), $CeB6$ ($W = 2.5eV$) and $BaO - W$ (W = 2.1 eV), are too high for LWTs. A promising material is the C12A7 [25] because it exhibits high stability properties and its work function is extremely low. Since several research groups measured different values ($0.6eV$ [1], $0.76eV$ [16] and $2.1eV$ [24]), the intrinsic value of the work function of the C12A7 is now unclear. Moreover, this material has been used successfully for the manufacturing of hollow-cathode inserts [16, 1], but a coating process is not available yet. LWTs could also benefit from the progress in other applications like photocathodes. For instance, materials coated with Cs/O can reach a work function between $1.1eV$ and $1.4eV$ and an ultra low work function graphene, with $W \approx 1eV$, has been also achieved by combining electrostatic gating with a Cs/O surface coating (see Ref. [27] and references therein).

In addition to the work function, there are two properties that should be also considered. First, the lifetime of the materials should be long. The lightest LWT would correspond to the one designed for completing the deorbiting manoeuver exactly in 25 years. If the coating degrades, then LWT geometry should be selected to give a shorter deorbit time, thus penalizing the mass budget. Second, the absorption-to-emissivity ratio of the LWT should reach the typical values presented in Sec. 3, in order to keep the tether hot enough and stimulate the electron thermionic emission.

LWTs have a drawback that does not affect to bare EDTs with active emitters. During eclipses the LWT will not produce significant drag because a lack of electron emission. In the absence of sun illumination, the photoelectron mechanism will be inactive and, since tether temperature will drop, the thermionic emission will be also negligible. This issue is mitigated for Sun-synchronous orbits, where an important population of space debris exists. By contrast, the LWTs have several advantages as compared with other EDT technologies:

1. One of the constraints of bare EDTs equipped with hollow cathodes (HC) is the need of expellant. As a consequence, tether dimensions have to be selected to guarantee a deorbit time compatible with the amount of expellant of the deorbit kit. Since a HC needs about 1 liter of expellant to operate during 6 months, the tether is typically oversized with respect to the actual legal framework (25 years). This constraint does not affect to LWTs because they do not need consumable. As a consequence, if the emission efficiency of the coating does not decay and tether width is selected to avoid a fatal impact by small space debris, then an optimal tether length can be designed to make the deorbit time equal to 25 years.

2. Once a LWT is deployed, its operation does not involve any active element and power, thus enhancing simplicity, robustness, autonomy, and cost.

3. For a conventional bare EDT, the active plasma contactor should be placed at the correct tip of the tether, which depends on the direction of the motional electric field. Such a requirement affects the tether deployment and would increase the complexity of the deorbit kit. An entirely coated LWT does not present this constraint because the cathodic and anodic tether segments are naturally adjusted by the motional electric field. Note that most of the electrons emitted at tether points with positive local biases will be reflected back to the tether. For spinning tethers, this feature also increases the efficiency of a LWT with respect to an EDT equipped with one active plasma contactor. The latter does only produce Lorentz drag during a fraction of each revolution.

4. The active emitter of a conventional EDT is normally placed close to the mother spacecraft. Such a configuration is beneficial, although not definitive, to mitigate a well-known dynamic instability [14]. For LWTs, tether segments could be deployed in opposite directions (butterfly configuration) and their lengths could be calculated to yield a self-balanced configuration [15].

Collision avoidance maneuvers are possible, in principle, with an EDT equipped with an active emitter by switching on/off the emitter. A LWT in a butterfly configuration could also carry out such a maneuver if a battery is interposed between the two tether segments at the mother spacecraft. Such a battery would be outside the tether/plasma circuit during the normal operation of the LWT and it would be used during a collision avoidance maneuver. Since the battery would change the tether bias, it gives control on the tether current and the Lorentz force.

6. CONCLUSIONS

LWTs are a promising technology for deorbit space debris from Low-Earth-Orbit. As a consequence of its fully passive character and the strength of the Lorentz drag, the concept potentially gathers the desired set of properties for a future deorbit kit, including simplicity, autonomy, and efficiency. However, the feasibility of LWTs and their performance in key deorbit scenarios are still open questions that need effort on three different areas, which define the roadmap for the technology development.

The manufacturing of LWTs with the required optical, mechanical, and electrical properties is currently the main obstacle. Momentarily, the development of a coating process for the C12A7 is promising and, besides LWTs, it may impact to other space and terrestrial applications, such us electric propulsion, thermionic converters, photon-enhanced thermionic emission devices, light emitting devices, and cold cathode fluorescent lamps [8]. A manufacturing and testing campaign, involving several substrates and coatings, together with tradeoff analysis can shed light on the feasibility of LWTs.

A flight simulator incorporating an accurate model for the LWT/plasma interaction is needed. The Orbital-Motion-Theory (OMT) presented in Ref. [5] provides a solid framework but it has not been coupled yet with with a tether flight simulator and it only applies to round tethers (and not tapes). The challenge is mostly related with the computational cost because finding the $J(V)$ characteristic at each time step with OMT would overload the simulator. Making a fitting by using a previously computed database, i.e. $J(V)$ versus the key dimensionless parameters, seems to be more efficient. Such a database would also benefit plasma community because it could be applied to emissive probes in plasma diagnostics.

After being prepared the theoretical simulators and a testing campaign with realistic values for the properties of the LWT, tradeoff analysis and simulations of spacecraft equipped with a LWT kit could be carried out. The preliminary results of this work and the study of Ref. [17] shows that, if the work function of the thermionic material is below 1.5 eV, the device is effective in deorbiting scenarios from Low-Earth-Orbit and Geostationary Transfer Orbits. These are two interesting cases with commercial applications for satellites and payload adapters.

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