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Electron Emission for Electrodynamic Tether Systems in Space

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This paper presents the theoretical analysis of three different types of electron emitters and three different system architectures. Thermionic cathodes, field emitter arrays, and hollow cathodes are evaluated for their potential use in various electrodynamic tether system applications. Basic grounded tip, basic grounded gate and series-bias system architectures are considered. It was found that the series-bias grounded gate configuration produced the overall best cases for the electron emitters when de-orbit time was a major factor because they yielded the highest deorbit forces. When power consumption was a major factor the basic grounded gate configurations was the best choice. As far as electron emitters, the spindt type field emitter array technology was always the best choice when comparing it against the thermionic cathode in all of the tether system setups when it involved low power. For many low power systems the field emitter technology is superior.

Nomenclature

A = constant in Richardson Eq. [A/cm^2]
A_e = area of emitter [m^2]
B = constant in Fowler Nordheim equation [A/V^2]
B_{North} = magnetic flux density in north direction [T]
C = constant in Fowler Nordheim equation [V]
D = distance across sheath [m]
dl = unit distance [m]
dF = force per unit distance [N]
e = electric charge [C]
E = energy of a particular state [eV]
E_F = Fermi energy [eV]
ε_o = permittivity constant [F/m]
η = thermionic cathode efficiency (~0.97)
F = electric field in [V/m]
I_{CL} = space charge limited current [A]
I_{end} = current at the end of the tether [A]
I_t = current in the tether [A]
J = current density [A/m^2]
k = Boltzmann's constant in [J/K]
m_e = mass of electron [kg]
N = number of field emitter tips in the array
ϕ = work function of element in [eV]
ρ = perveance [pervs]
r_b = radius of emitter [m]
T = temperature [K]
T_o = energy of emitted electrons [eV]
V = plasma sheath gap potential [V]
V_{emf} = electro motive force [V]
ΔV_{tc} = potential across the thermionic cathode [V]
v_{orb} = orbital velocity with respect to local plasma [m/s]
W = width of the emitter [m]

I. Introduction

Electrodynamic tethers (EDTs) are being considered as a propellantless propulsion technology for spacecraft in low Earth orbit. An orbiting tether system naturally orients along the local vertical due to gravity g. Current flowing along the tether interacts with the Earth's magnetic field to provide thrust by the Lorentz force. To produce this current, electrons must be collected on one end of the tether and emitted at the other. Passive collection of electrons from the ionosphere is relatively efficient but passive emission is not. Therefore, active emission of electrons is required for efficient EDT propulsion. This paper discusses various electron emission methods for this purpose and the relative merits thereof.

There are three electron emission technologies usually considered for this sort of mission: hollow cathode plasma contactors (HCPCs), thermionic cathodes (TCs), and field emitter arrays (FEA's). System level configurations will be presented for each, and the relative costs and benefits discussed.

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II. Electron Emission Theory and Space Charge Limits

A. Thermionic Emission

For the emission of electrons into a vacuum by a heated electronic conductor cathode, the emission current density *J* increases rapidly with increasing temperature; this is illustrated in Eq. (1), Richardson−Dushman, or Richardson equation (ϕ is approximately 4.54 eV and A ~120 A/cm^2 for tungsten).

$$J = AT^2 e^{-\left(\phi/kT\right)} \qquad (1)$$

$$\Delta V_{tc} = \left[\frac{\eta \cdot I_t}{\rho}\right]^{2/3} \qquad (2)$$

TC electron emission will occur in one of two different modes: temperature or space charge limited (SCL) current flow. For temperature limited flow, every electron released from the cathode surface emitted (Eq. 1). If the cathode temperature could be increased additional electrons could be emitted. In SCL electron current flow, there are so many electrons emitted from the cathode that not all could escape the near region of the surface due to the space charge. An external applied bias potential is required to extract charge. This can occur if an accelerated grid is used. Eq. (2) shows what potential needed across the grid in order to emit a certain current entering the device.[2,3]

B. Field Emission

In field emission cathodes, electrons tunnel through a potential barrier, rather than escaping over it as in thermionic emission or photoemission. For a metal at low temperature, the process can be understood in terms of Fig. 1. The metal can be considered a potential box, filled with electrons to the Fermi level, which lies below the vacuum level by several electron volts. The vacuum level represents the potential energy of an electron at rest outside the metal, in the absence of an external field. In the presence of a strong field F. Electrons are extracted from the conduction band with a current density given by the Fowler−Nordheim equation in Eq. (4).[6]

$$J = B \cdot F^2 \cdot e^{-C/F} \qquad (3)$$

In the following analysis, typical constants yielded for Spindt type cathodes include: B = 3.14 x 10^{-7} A/V^2 and C = 771 V. (information c/o Stanford Research Institute). An accelerating structure is typically placed in close proximity with the emitting material as in Fig. 2. To achieve the high surface electric fields required for field emission, the emitting material might consist of a range of materials from semiconductor fabricated molybdenum tips with integrated gates, to a plate of randomly distributed carbon nanotubes with a separate gate structure suspended above. Close (micron scale) proximity between the emitter and gate, combined with natural or artificial focusing structures, efficiently provide the high field strengths required for emission with relatively low applied voltage, and low power.[6]

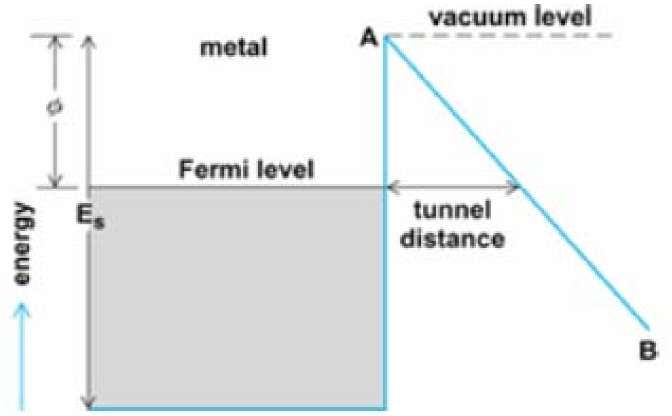

Figure 1: Energy level scheme for field emission from a metal at absolute zero temperature.

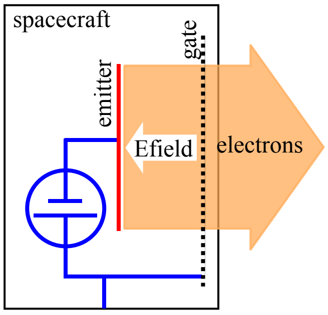

Figure 2: Electrical diagram of the basic field emission concept.

C. Hollow Cathodes

Hollow cathodes emit ions or electrons by ionizing a consumable gas supply to create a high density plasma plume in contact with the surrounding plasma. One type of hollow cathode consists of a metal tube lined with a sintered tungsten insert capped at one end by a plate with a small orifice, as shown in Fig. 4. Electrons are emitted from the barium oxide impregnated insert by thermionic emission. Propellant gas, typically xenon, flows into the tube and exits, partially ionized, out of the orifice. Electrons flow from the insert region, through the orifice plasma to the keeper and other anode surfaces.

In electron emission mode the electrons from the plasma contactor carry the current while the contactor ions neutralize the spacecraft. In the contactor plasma, the electron density is approximately equal to the ion density. The higher energy electrons stream through the slowly expanding ion cloud, while the lower energy electrons are trapped within the cloud by the keeper potential. The high electron velocities lead to electron currents much greater than Xenon ion currents. Below the electron emission saturation limit the contactor acts as a bipolar emissive probe. Each outgoing ion generated by an electron allows a number of electrons, which is approximately equal to the square root of the ratio of the ion mass to the electron mass, to be emitted.

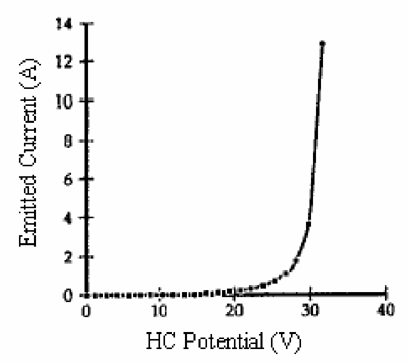

Figure 3: I-V Characteristic curve for a Hollow Cathode

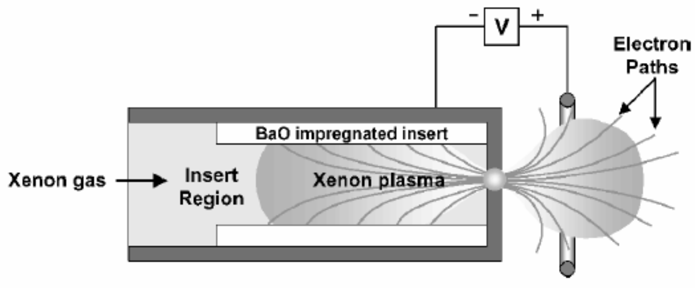

Figure 4: Schematic of a Hollow Cathode System

It can be seen in Fig. 3 what a typical I-V curve looks like for a hollow cathode. Given a certain keeper geometry (the ring in Fig. 6 that the electrons exit through), ion flow rate, and potential, the profile can be determined.[8-10]

D. Space Charge Limit

In any application where electrons are emitted across a vacuum gap there is a maximum allowable current for a given bias due to the self repulsion of the electron beam. Classical space charge limits depend on current density, gap width, gap potentials, geometry, and on initial kinetic energy in the Child–Langmuir Law. Here, the "gap" is an ion-rich plasma sheath transitioning from the background plasma to the spacecraft surface. The presence of ions in the gap (sheath) improves space charge constraints as the ions act to neutralize electron charge. The one-dimensional classical (vacuum gap) Child-Langmuir Law current density limit (in MKS units) is given in Eq. (5) which we multiply by the area of the planar emitter.[11]

$$I_{CL}(1)=\frac{4\varepsilon_o}{9e}\sqrt{\frac{2}{m_e}}\frac{T_o^{3/2}}{D^2}\left[1+\sqrt{1+\frac{eV}{T_o}}\right]^3 A_e \tag{4}$$

Here, we will assume that the plasma sheath gap potential is within a few eV of the local plasma potential, and the sheath width is on the order of a few Debye lengths.. These assumptions are consistent with the situation of an electrically isolated (floating) spacecraft or subsystem. The sheath dimension is in general set by the sheath potential, background plasma density, temperature, and geometry. Representative density and electron temperature values are $5\text{x}10^5$ cm^{-3} and 0.1 eV, for EDT applications in low Earth orbit (LEO).[12] In addition, because of the low electron temperature of ionospheric plasmas in ED tether applications, it is possible to assume $V << T_o$ in Eq. (4).

In going from a 1d to a 2d configuration, Eq. (5) can be increased by a multiplicative term if the beam of electrons can expand laterally (from the direction of beam propagation) into regions of no or less electron charge. The multiplicative term has been determined for when the electrons expand in one direction from a long emitter strip of width, W, and gap, D (see Fig. 7a). This 2-d space charge limit determined by computer simulation can be seen in Eq. (5).[11]

$$\frac{J_{CL}(2)}{J_{CL}(1)}=1+\frac{0.3145}{W/D}-\frac{0.0004}{(W/D)^2} \tag{5}$$

$$\frac{J_{CL}(3)}{J_{CL}(1)}=\frac{\left[r_b^2+(D/2)^2\right]}{r_b^2}=\left[1+(D/2r_b)^2\right] \tag{6}$$

An enhancement over the 1-d classical Child-Langmuir limit ($T_o = 0$) is possible from a narrow pencil beam (i.e., expansion in two lateral directions) generated by an emitter of radius, r_b, and gap, D, according to the 3-d Space charge limit equation in Eq. (6), where it is assumed that $r < D$ (see Fig. 5b).[13] It is also noted that multiple pencil beams can be placed in parallel, with each experiencing the enhancement of Eq. (6), provided that the center to center beam spacing is large with respect to D.

To estimate a threshold for space charge limited current flow, we will use Eq. (4) with the 3-d addition from Eq. (6). This calculation results in the determination of the current emitted after the space charge limit. Table 1 is a plot of possible space charge limits on various emitters.

Device Emission [eV]	Sheath Potential [V]	Emitter Area [cm^2]	1D Space Charge Limit [mA/cm^2]	Maximum Emitting Current [mA]	Total Power Consumption [W]	3D Space Charge Limit [mA/cm^2]	Max. Emitting Current [mA]	Total 3D SCL Power [W]
100	0.5	1	13	13	1.3	27	27	2.7
100	0.5	10	13	130	12.9	17	174	17.3
100	2	1	2	2	0.2	7	7	0.7
100	2	10	2	17	1.7	3	33	3.3
500	0.5	1	145	145	72.4	299	299	149.4
500	0.5	10	145	1449	723.8	194	1936	967.2
500	2	1	19	19	9.5	75	75	37.4
500	2	10	19	191	95.2	37	368	183.4
1000	0.5	1	410	410	409.5	845	845	845
1000	0.5	10	410	4097	4094.9	547	5475	5472.0
1000	2	1	54	54	53.9	212	212	211.8
1000	2	10	54	540	538.6	104	1040	1037.9

Table 1: Space charge limit effects under varying system attributes

The above analysis does not account for more complicated beam-plasma interactions, but the results remain relatively accurate for the present discussion. Further detailed analysis could cover the following non-idealities: For example, the presence of the emitted electron charge in the sheath could distort local sheath conditions. Besides transit of the electron beam across an ion-rich sheath, its penetration into and accommodation by the plasma must be considered. The larger the density of the electron beam relative to the background plasma density, the stronger the space charge effects will be even in the plasma. Thus, this situation will likely be most acute for ED tether applications where emitted currents are high and background plasma densities are lower.[14]

III. ED Tethers: System Integration

A. Tether Fundamentals

A tether EMF is generated by Eq. (7) as the satellite orbits the Earth. In self powered mode (de-orbit mode) this EMF can be utilized by the tether system to perform various functions: charge batteries, emit electrons at the emitting end, and drive the current through the tether. In boost mode no-board power supplies must overcome this motional EMF to provide bias for current collection, electron emission, and tether resistive losses. These modes are shown in Fig. 6.

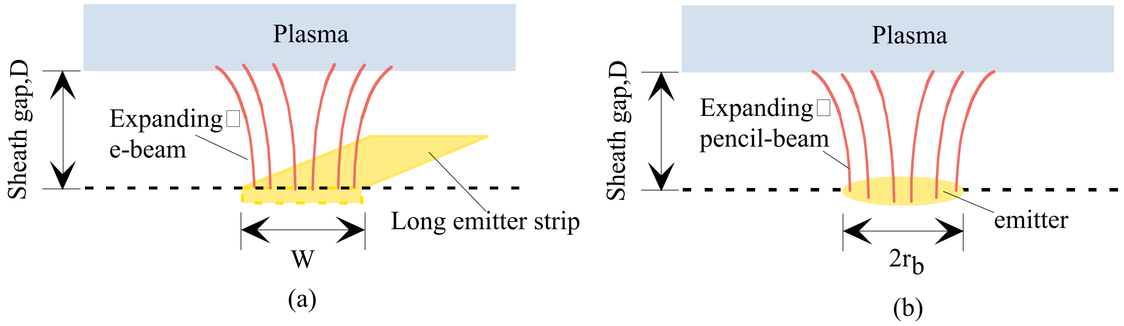

Figure 5: Strip (a) and pencil beam (b) emitters used in Eq's 8 and 9, respectively.

$$V_{emf} = (v_{orb} \times B_{North}) \cdot dl \tag{7}$$

$$dF = dl \cdot I_t \times B_{North} \tag{8}$$

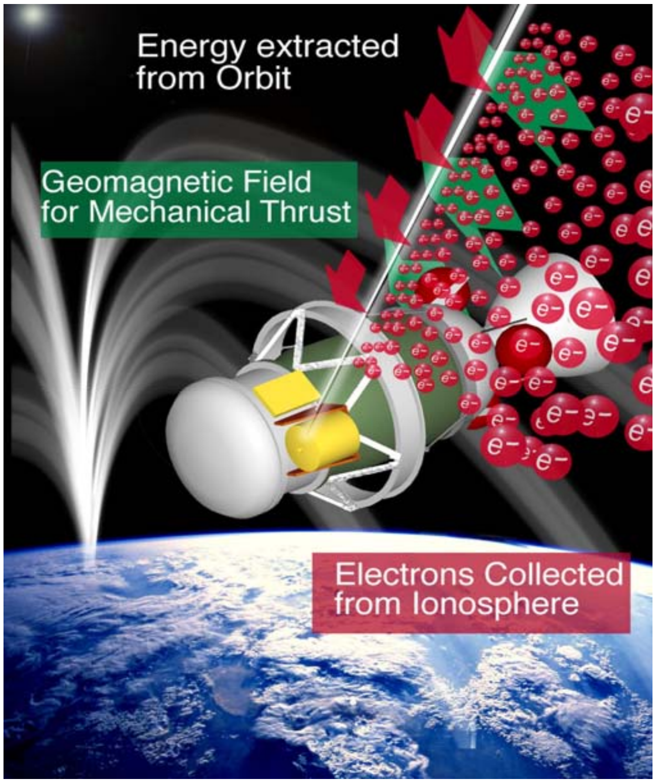

Figure 6: Illustration of the EDT concept

Take, for example, the ProSEDS mission. The Earth's magnetic field is approximately 0.18 – 0.32 gauss in LEO, and the orbital velocity with respect to the local plasma is about 7500 m/s at 300-km altitude. Assuming a tether 5000 m, this results in a V_{emf} of a range of 35 – 250 V/km along the length of the tether. This established emf dictates the potential difference across the bare tether which controls where electrons are collected and or repelled. Here a de-boost tether has a setup that allows for electrons to be collected on the positively biased upper section of the bare tether, and returned to the ionosphere at the lower end. This flow of electrons through the length of the tether moving across the Earth's magnetic field creates a force that produces a drag thrust that helps de-orbit the system as given by the Eq: (8)

B. System Requirements

In every ED tether mission there will be a number of conditions that will be encountered. These ED tether system requirements deal with the pressure environment, emission currents, electron emission energy, leakage current, and lifetime.

The electron emitter must be able to operate with the expected ambient environment pressure and species plus outgassing from the spacecraft ($<10^{-7}$ Torr). Some systems must be able to survive pressure exposures to 10^{-3} Torr (e.g. due to attitude control thrusters such as hydrazine and other spacecraft effluents).

Arrays of electron emitters will need to emit peak current that can range from 1 to 10 A depending on the specific application (1 to 6 A, typical). For example, atmospheric drag make-up of a large spacecraft could require less than 1 A while rapid de-orbit of a spent stage or drag make-up of the space station may benefit from currents as much as 10 A. Emission of this level of current requires special consideration of space charge effects which will limit maximum allowed current densities while spacecraft surface area utilization will place a lower limit. For example, for a small satellite de-boost application emission area might need to be constrained to some number at or below 100 cm^2 while a large spacecraft boost system may be able to accept current emission areas many times larger. For these emission areas, operation should be below space charge limited current flow levels (See space charge limit section for further discussion).

In order to assure minimal bias requirements which directly affects system efficiency, extraction potentials (gate-to-tip plus anode-to-gate for field emitter arrays) less than 50-100 V or smaller are desired. The electron emission will occur into space plasma that will have densities ranging from as low as 10^9 m^{-3} to $5x10^{12}$ m^{-3}. A low-potential plasma sheath will exist between the spacecraft and the ambient plasma which the electrons must cross.

Low leakage current of the electron emitters is required to ensure efficient cathode operation and since ED tethers use similar systems the requirements here are identical to that described above (e.g. FEAC gate current must be less than 1% is best for conservative operation).

Finally, a typical ED tether system is expected to operate for durations ranging from a few weeks of continuous operation to several years at a 50% duty cycle. Typical lifetimes requirements are between 1,000 hours and 13,000 hours depending on the application. For some applications the unit would be expected to remain dormant on the spacecraft for some 5 to 7 years before operation.[14]

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C. Configurations

There are three configurations considered for connecting the electron emitter to the tether circuit as shown in Fig. 9. They are identified as: (a) basic grounded emitter, (b) basic grounded gate, and (c) series bias - grounded gate. The grounded emitter (Fig. 7a) configuration effectively isolates the tether and high-voltage power supply (HVPS) circuit from the electron emitter. The electron emitter bias is exclusively set by the 'emitter bias' supply. However, the gate is at a positive potential with respect to the surrounding space plasma that can attract electrons from the plasma drawing current through the power supply.[16] A grounded gate configuration is shown in both Fig's 7b and 7c. The grounded gate configuration allows all external structures, including the field emission gate itself, to be held at the floating potential of the spacecraft, which should minimize the disturbance in the surrounding plasma when the electron emitter is providing all of the tether current. The Fig. 9b configuration has the draw back that if the electron emitter can not provide all of the tether current, then the spacecraft potential will be pulled negative and possibly substantially negative through the electron 'emitter bias' supply; a technical challenge to adequately protect the field emitters in that situation. Our initial assessment, therefore, is that the series bias - grounded gate configuration in Fig. 7c will be the best, most robust option to be utilized for most EDT systems. The drawback to this configuration is that the emitter bias supply now must source power although there is a corresponding reduction in the power provided by the HVPS and overall power requirements remain unchanged. A more complete system diagram is shown in Fig. 8, which shows how the ED tether system passes current to and from the space plasma and must account for spacecraft charging and anomalous currents to the spacecraft and through the field emitter power supply while satisfying Kirchoff's current and voltage laws.

Emission velocity depends upon the field strength required to pull electrons from the emitter material at sufficient current densities. For some emitters the voltage required is high enough that the beam escapes into the plasma freely. For the higher technology emitters, with more efficient extraction methods, this extraction energy can be low enough that the beam immediately beyond the emitter will be affected by space charge limits and electrons will be reflected back to the spacecraft. This effect can be countered by increasing emission voltage or adding an additional accelerating grid, but this costs additional power. Other solutions exist such as adding a secondary gate outside the emitter to defocus the departing beam or pulsing the emitting beam at certain frequencies to avoid space charge limitations.[7,17]

The boost (also referred to as thruster) mode is similar to the de-orbit mode except for the fact that the HVPS is on and is creating a potential difference greater than the V_{emf}. This drives the current the opposite direction, which in turn causes the upper end to be negatively charged, while the lower end is now positively charged. The setup in Fig. 7 will be the same in the upper end as it is in the lower end with the exception of the HVPS. An example of this can be seen in Fig. 8. When the EDT system is in boost mode the electron emitter in the cathode will be turned off by having the V_{emit} switched to an open circuit. The cathode will use its surface area as an electron collector. When the EDT system is in de-orbit (also known as generator) mode then the HVPS will be off and the opposite configuration will occur.

When FEA's and TC's are used they have to emit the electrons as close to floating potential as possible in order to be the most efficient.[17] The grounded gate configurations allow this to occur. The spacecraft surface is at the floating potential in these cases, provided all the current from the tether is being emitted through the emitter without any coming back from space charge limits. The hollow cathode has a phenomenon called a double sheath which makes the emitted electrons cross two boundary layers, the emitted xenon and the normal plasma sheath. The most accurate way to model this is through (9a). Here the spacecraft body is forced negative by the positively charged xenon released from the hollow cathode.

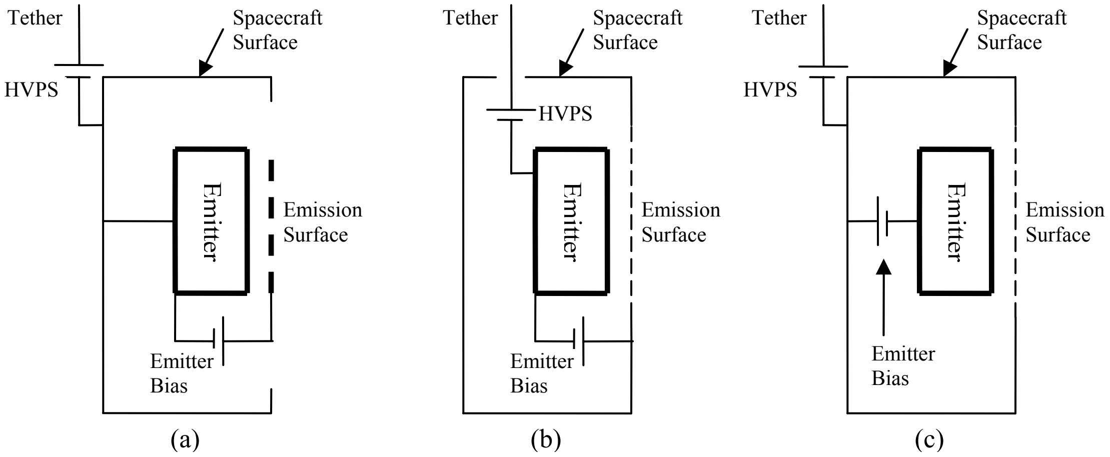

Figure 7: Possible electrical configurations of the electron emitter with the tether and high voltage power supply (HVPS): Grounded tip/emitter (a), grounded gate (b) and grounded gate, isolated tether (c) configurations.

D. System Response / Precautions

Numerous environmental conditions will cause the dynamics of the EDT system to fluctuate dramatically. As a result the potentials and currents will be constantly changing. Each electron emitter will behave differently under such varying conditions, and as a result the system must be understood and controlled for all such cases. Since the EDT system is almost symmetrical (with the exception of the HVPS) only the de-boost case will be evaluated. This particular case assumes a grounded gate configuration (Fig. 7c). Fig. 8 is a more elaborate circuit diagram detailing the entire EDT system.

Outputs from instruments that measure return current and the spacecraft's floating potential could be used by the electron emitter to make decisions about emission current. This feedback loop, which balances incoming and outgoing current, controls the spacecraft potential and keeps it near neutral. Thus the electron emitter operates at optimum efficiency for whatever current level the tether power system is able to provide. The electron emitter will need to automatically and stably respond in different ways for conditions when there is too much current and too little current.

When there is too much current (I_{emit}), the spacecraft's potential (V_c) will drift positive some amount and electron current will flow back to the spacecrafts surface (I_{scl}) and electron emitter. The electron emitter will detect the electron return current and/or spacecraft positive potential shift and reduce the emission current until neutrality is regained again. It will do this by limiting the amount of potential across the emitter as defined by Eq's (2), (3), or Fig. (3) depending on the emitter.

If there is too little current then the spacecraft potential will charge negative by some amount and the ion current (I_{col}) will flow to the spacecraft surfaces and electron emitter. The electron emitter must detect the ion return current and/or spacecraft negative potential shift and increase the emission current by increasing the potential across the emitter until neutrality is regained again.[7]

These precautionary measures need to be in place not only to ensure the system runs efficiently, but to prevent damaging the electron emission devices. The TC is only meant to run up to a maximum potential and maximum current depending on its design parameters, however these are often relatively high conditions. Similar things could happen to the FEA. Above approximately 120 volts for a spindt type emitter the array may be damaged. Finally, the hollow cathode is able to emit a much higher current without being damaged.

IV. Emitter Comparisons

A. Different Missions

There are numerous mission objectives and environmental conditions that would each call for different EDT system configurations. Some of these adjustable system variables that must be predetermined include: tether length, geometry, bare versus insulated tethers, boost versus de-boost cases, orbital parameters, extra power sources, current or potential monitors, load resistances, surface collecting areas, and especially electron emission device choice. As a result of there being so many variables and cases possible for an EDT system this paper will discuss a couple of the more dominant cases. The important question that will be addressed is to determine which technology and configuration is the most energy efficient.

A test case was conducted with the goal of the mission to de-orbit the satellite where time is not a major concern, but power efficiency is. The results can be seen in Table 2. The constraints of the EDT dynamic analysis were: The tether is 5000m long and the first 200 m is insulated; The electron density is $5x10^{11}$ ions / m^3; The electron temperature is 0.1 eV; The Debye length is 3.94 mm; The sheath is set at 3 Debye lengths; The magnetic flux density, B, is 0.25 gauss; The floating potential is 1 eV; The de-boost condition is considered and all cases take into consideration the space charge limit.

It turns out that the basic grounded gate figure (7b) is the best configuration while using field emitter arrays. The grounded gate setup basically ensures that zero power is required by the system. Since the potential from the EMF drives everything, no more power is needed. The asterisk in the chart is given because those particular cases require no additional power and run by themselves. Since there is a condition where all three electron emitter technologies operate at zero power, additional factors must be compared. The HC has the greatest de-orbiting force, however it consumes fuel, which is a major negative attribute. The FEA is the best choice because it has a relatively high de-orbiting force and it consumes nothing.

Another case that must be evaluated is the fastest de-orbiting time. The series bias grounded gate configuration, figure (7c) is the best choice. Greater current flows through this setup and as a result the de-orbiting force is the greatest. The only consequence is the power that must be put into the system. It is clear that the FEA requires much less power to emit the 3.41 amps needed to keep the system at floating potential. This would be the best emitter to use in configuration c. An important note is that the surface area for the field emitter was allowed to float because the maximum potential that a Spindt FEA can have is 120 V. The TC, on the other hand, was not allowed to float because of the complexities involved in designing an abnormally large electron gun and the effects on the system were not understood enough as of yet. The perveance of the TC was set to 7.2 micropervs because that was a representative value used on a previous Tethered Space Satellite mission[3]. It was not known how the perveance changes with the overall emitter size and thus nothing larger could be analyzed effectively.

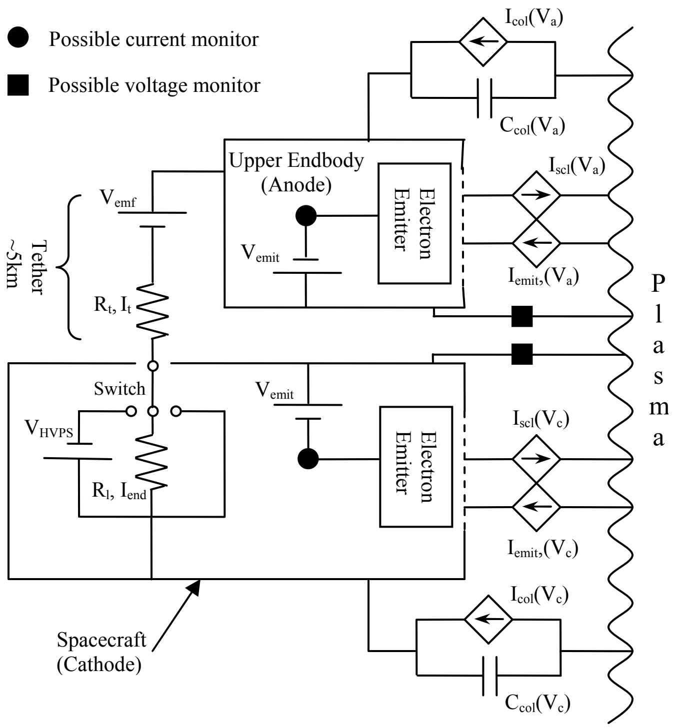

Figure 8: Equivalent EDT system circuit model showing the series bias grounded gate configuration (9c).

B. Pros and Cons

	Emitter	Current [A]	Potential [V]	Power [W]	Force [N]	Other
Config. A	HC	2.6	30	79*	0.22	4.1 sccm Fuel, Heater
Config. B	FEA	2.1	120	246*	0.19	114 cm^2 Area
	TC	0.15	739	110*	0.02	
Config. C	FEA	3.4	120	415	0.31	89.5 cm^2 Area
	TC	3.4	5980	20520	0.31	

Table 2: System test for the emitter technology for various configurations

Overall there are a few major positive and negative attributes associated with each technology. When designing a mission these tradeoffs must be weighed carefully. TC's are a well established and reliable technology, which have been proven for many applications. As a result of this fact they are also relatively inexpensive and fairly common. They are also capable of functioning at relatively high potentials before they go off nominal emission. However, as shown earlier, TC's also require considerable power to operate and are often not economically feasible for emission of higher currents (above ~1 A). They also require two parts in their setup. The TC actually just boils the electrons off with little to no emission energy. As a result an electron gun is needed to emit the electrons at an energy great enough so the electrons escape the space charge limit. This significantly increases the power requirements of the system.

FEA's have somewhat opposing statistics compared to thermionic cathodes. They require a fraction of the potential needed to emit the same current as a TC. There is also no fuel required to operate the device. A major negative aspect of FEA's is that they are easy to damage. Too much current through or potential across the individual emitter and it could be ruined. Also, as of right now the devices are relatively new and have not been tested enough to be reliable. There are currently many experiments and tests that are being conducted to remedy this. One of the greatest attribute of this device is that it uses no propellant.[7]

Like TC's, HCPC's also have the luxury of being a relatively established and reliable technology. They have been used for many space applications and are very robust. HCPC's are capable of emitting a great deal of current with only a small amount of potential, and as a result do not consume a great deal of power. The greatest disadvantage of this device is that it consumes fuel in order to operate. This one fact can often be the deciding factor in a mission.

V. Conclusion

Many aspects of each mission play a major role when deciding how to design the proper EDT system. One of the greatest factors is the proper electron emission device to use. It is clear that if FEA's prove reliable they will most likely be utilized into most of the future missions involving electron emission, especially EDT missions. While HCPC's are still a very efficient and useful technology the fact that they use propellant may deter many missions from using it when other technologies exist that do not use propellant. Future work will be done analyzing more aspects of EDT missions and cases where various configurations will be used. Particular aspects or interest will be looking at the boost conditions of EDT's as well as momentum transfer technologies.

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