Analysis of Vacuum Arc Using Solar Array Materials

IEPC-2015-56／ISTS-2015-b-56

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Joel D. Slotten,[1] George Teel.[2] Joseph Lukas,[3] and Michael Keidar[4]
The George Washington University, Washington, DC, 20052, USA

Abstract: This paper examines challenges related to the use of metalloids such as silicon (Si) as the cathode in a vacuum arc thruster. Specifically the low mobility of silicon cathode spots is investigated. Results of experiments using two methods for increasing cathode spot mobility are discussed and show that the location of the cathode spot concentration can be moved either by introducing a magnetic field or by using a second electrical lead to the cathode. Mass consumption was also found to increase using both methods. This could have significant implications for a proposed concept for end-of-life maneuvers for cubesats, in which the satellites' solar arrays are used as the cathode. This paper also includes a description of initial experiments conducted in an attempt to develop a method for generating a self-sustaining arc using actual solar cells.

Nomenclature

B	=	magnetic field
J	=	electric field

I. Introduction

Current debris mitigation standard practices dictate that spacecraft are moved to a disposal orbit at the end of their operational life. For satellites in low Earth orbit (LEO) this generally entails lowering the spacecraft to an altitude that will allow for atmospheric re-entry within twenty-five years. To accomplish this, satellites at higher LEO orbits are typically designed and built with a propulsion system, which they use to perform an end-of-life maneuver. This poses a challenge for cubesats, which due to size, mass and power limitations, do not typically possess a propulsion system. An alternative solution would be for the satellite to use an electric propulsions system such as a vacuum arc thruster. These systems are easily miniaturized and do not require a significant amount of power. In addition, mass and volume savings could be realized if, instead of using a stored propellant for the end-of-life maneuver, the satellite used its own structure as propellant. Vacuum arc thrusters use a solid metallic cathode for their propellant. Therefore, the structural material of the satellite theoretically provides a ready source of propellant. The exteriors of cubesats are generally composed of body-fixed solar arrays, typically composed of silicon (Si) or gallium arsenide (GaAs). However, because these materials are semiconductors they pose unique challenges for generating a vacuum arc. In particular, the cathode spots that are generated generally have very low mobility. This could cause problems with non-uniform erosion of the cathode. Two methods for controlling cathode spot motion are the introduction of a magnetic field and relocating the negative lead on the cathode. Experiments were conducted using both of these methods with a flat plate arc source using a silicon cathode. It was found that the location of the cathode spots could be moved using either of these methods. Mass consumption was also increased

[1] Student, Mechanical & Aerospace Engineering, jslotten@gwmail.gwu.edu.
[2] Student, Mechanical & Aerospace Engineering, gteel@gwmail.gwu.edu.
[3] Student, Mechanical & Aerospace Engineering, jlukas@gwmail.gwu.edu.
[4] Professor, Mechanical & Aerospace Engineering, keidar@gwu.edu.

using either technique. In addition, initial experiments have been conducted using triangular advanced solar cells (TASC) in an attempt to identify techniques for establishing a cell sustaining arc with solar cells.

II. Self-Consuming Satellite

An investigation is underway to gain an understanding of the fundamental principles that would be required to develop a self-consuming satellite, i.e., a satellite that uses its own structure, specifically its solar panels, as propellant to perform an end-of-life maneuver upon completion of its mission. This concept would primarily benefit nanosatellites or cubesats, which have a small mass, and therefore require less total impulse to be de-orbited. These types of satellites would also benefit from this method because they face a number of restrictions and limitations related to the use of installed propulsion systems as described in the paragraphs below.

A. Debris Mitigation Guidelines

The motivation for this work is a new concept for performing end-of-life maneuvers for cubesats. When cubesats are launched they are manifested as secondary or auxiliary payloads. To protect the integrity of the primary payload the use of pressurized systems on cubesats is limited, pyrotechnics are largely restricted, and toxic or corrosive materials such as certain propellants are discouraged. For these reasons, and because of difficulties involved with the miniaturization of propulsion system components, cubesats are normally not built with a propulsion system. Chemical thrusters are too large and heavy for use on a cubesat, and thruster valves require more power than is normally available.

Under international debris mitigation guidelines[1,2] spacecraft in LEO should be left in an orbit in which natural forces lead to atmospheric reentry within a reasonable time (generally twenty-five years). Consequently, upon completion of their mission cubesats are left in orbits that slowly decay due to the effects of atmospheric drag. This restricts cubesats to circular orbits of approximately 600 km or lower, greatly limiting their utility. If a cubesat were capable of performing an orbit lowering maneuver at the end of its operational life, it could be launched into and perform its mission at a higher altitude, thereby increasing the types of missions it could perform.

B. End-of-Life Maneuver

To add a propulsion system to a cubesat for the purpose of performing an end-of-life maneuver, the challenges identified above (no corrosive propellants or pressurized tanks, etc.) must be addressed. In addition, cubesats are limited to a 10 cm x 10 cm x 10 cm volume and 1.33 kg mass per unit. Adding a propulsion system, including propellant, reduces the mass and volume available to the payload and other subsystems.

Vacuum arc thrusters are an ideal propulsion candidate for cubesats. The propellant is a non-corrosive solid, which does not require pressurized tanks for storage, and which is fed by a spring or other mechanical devise. Therefore high power valves are not required. In addition, very compact vacuum arc thrusters have been developed that require much less power than many other electric propulsion systems.

Mass and volume savings could be realized if the spacecraft structure were used as the propellant. After the completion of the satellite mission the structure could be consumed to provide the necessary thrust to lower the satellite orbit in order to meet debris mitigation guidelines. Vacuum arc thrusters use a metallic cathode as their propellant, and the exterior surfaces of cubesats are typically composed of body-fixed solar arrays. The solar cells in these arrays are normally composed of silicon, gallium arsenide, or another semi-conductor. If a cubesat could be built with a vacuum arc propulsion system that uses the solar cells as the propellant, the satellite could operate at higher than normal altitudes and still meet debris mitigation guidelines by performing an end-of-life maneuver.

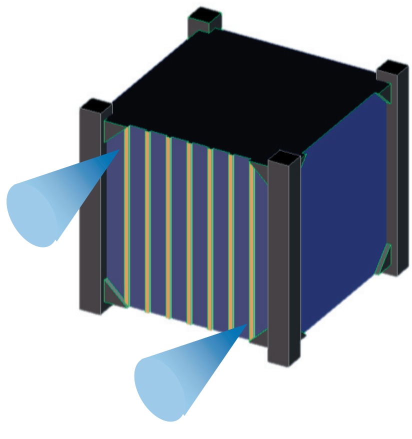


Figure 1. Concept for self-consuming satellite.
Solar cells are used as the cathode in a vacuum arc propulsion system.

Ideally the cells within the solar array could be packed in such a way that the substrate material could be used as the anode in the vacuum arc. Alternatively anode material could be distributed throughout the array. “Thruster” firings would need to be executed in pairs (Fig.1) to prevent the introduction of a rotation moment. A drawback of this approach is that the satellite is consuming the power source needed to generate the arc. Further study is necessary to determine whether sufficient impulse can be generated by this system before power falls below a minimum level.

C. Vacuum Arcs Using Cathodes Composed of Solar Cell Materials

A vacuum arc is an electrical discharge that occurs in the plasma ejected from micron-sized luminous areas on the cathode surface called cathode spots[3]. At high voltage cathode heating and breakdown occur, generating a quasi-neutral plasma that is ejected at high velocity from the cathode spot. It is the ejection of this material that provides the thrust from a vacuum arc thruster.

In most metal materials the cathode spots displace themselves chaotically on the surface of the cathode[4]. However, because silicon and gallium arsenide are metalloids and semiconductors, cathode spots cluster in a small region and do not move across the cathode. This can result in non-uniform erosion of the cathode. To avoid this a magnetic field can be introduced, which will induce spot mobility in a retrograde direction, *B*x*J* [5]. However, this magnetic field might interfere with the attitude control system on the spacecraft if magnetometers and magnetic torquers are used. An alternative method would be to sequentially use multiple electric leads to the cathode to induce motion in the cathode spots. Both methods were investigated using silicon cathodes, and the results reported below.

III. Experiment

A. Setup

Three experiments were performed using flat plate arc sources in a vacuum chamber. All three arc sources used a silicon cathode and steel anode separated by a boron nitride insulator of approximately 1 mm and coated with carbon paint. The cathode in the first experiment had a single electric lead. Photographs were taken before and after. Mass loss was measured and erosion rate calculated. In the second experiment two leads were used on the cathode, as shown in Fig. 2. In the second experiment the arc was initiated in one lead, then switched to the other lead for the duration of the experiment. Photographs, mass loss and erosion rate were again taken and calculated as in the first experiment. Both experiments were run for approximately 130 minutes at 38 pulses per minute. This resulted in approximately 5,000 pulses in each experiment. For the third experiment, a magnetic coil was added around the arc source with a field strength of up to 160 mT. Photographs, mass loss and erosion rate were again taken and calculated. This experiment was run for a shorter period of time, but at a high pulse repetition rate, resulting in approximately 4,800 pulses.

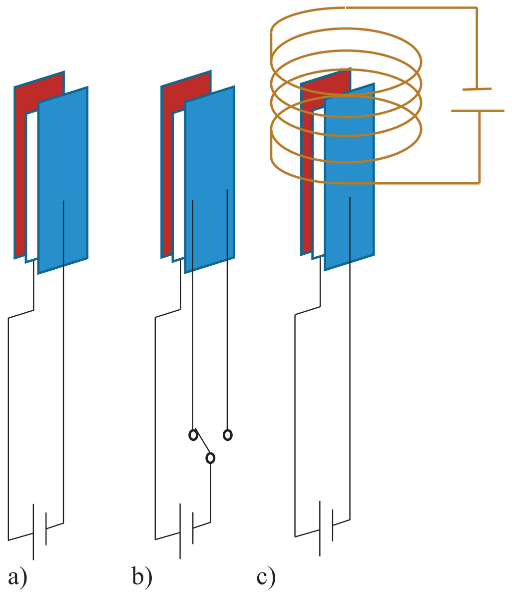
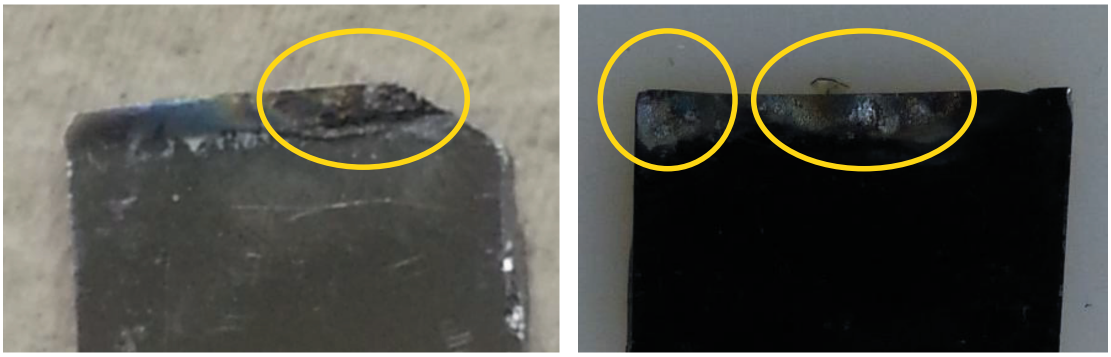


Figure 2. Arc source configuration.
A single lead a) was used in the first experiment, a second lead b) was added in the second, and a magnetic field c) was added in the third experiment.

B. Results

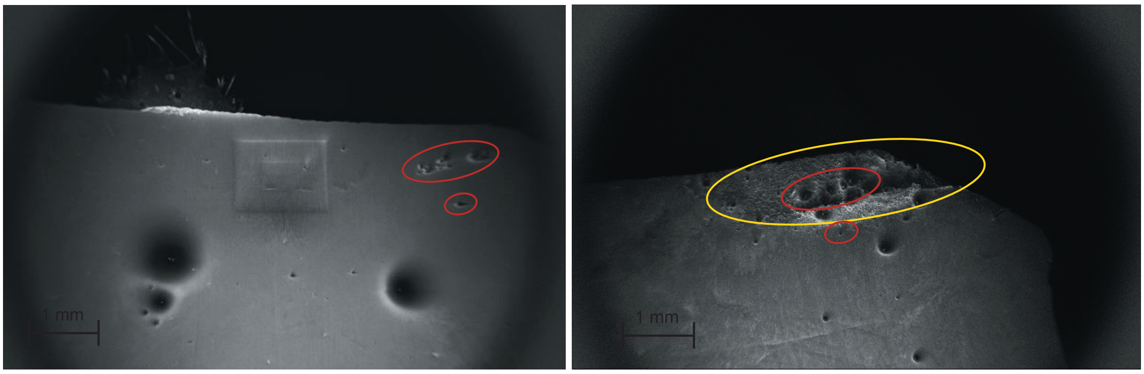
Figure 3 shows photographs of the two silicon cathodes used after the first two experiments were run. A single region of cathode spot erosion is evident in the cathode used in the first experiment using a single cathode. Two cathode spot regions can be seen in the cathode used in the second experiment where two negative leads were used. The region in the upper left corner is where the arc originated when the first lead was used, and the second, larger region in the middle of the upper edge of the cathode is where the arc appeared when the second lead was used instead. The color differences between the two cathodes is a result of lighting conditions.



a) b)

Figure 3. Photographs of silicon cathodes following experiments one and two.
The cathode used in the first experiment a) shows a single isolated region of erosion, whereas the cathode used in the second experiment b) shows two separate spot regions.

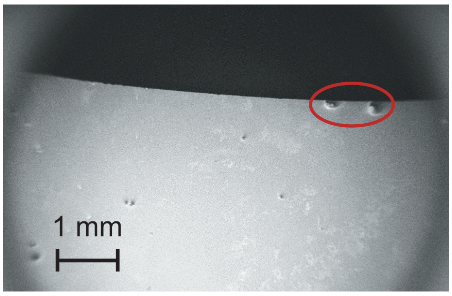
Figure 4 shows before and after images of the cathode used in the first experiment taken using a scanning electron microscope. Features seen in both images are circled in red, and the region of erosion is circled in yellow. The arc appears to have initially been generated at the location of some impurities in the material.



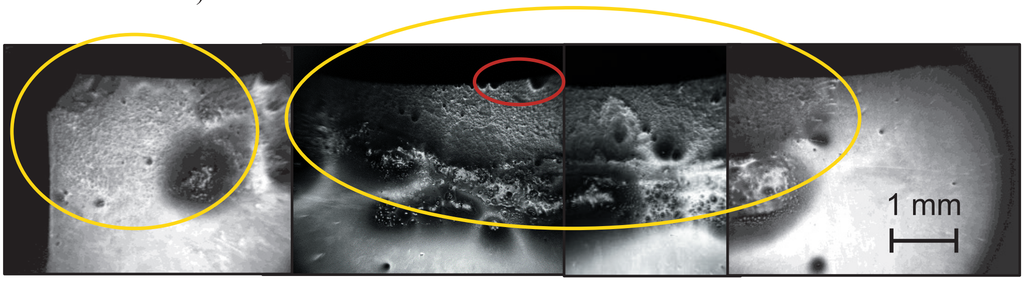
a) b)

Figure 4. Silicon cathode from single lead experiment.
Images of the single lead silicon cathode from the first experiment taken a) before and b) after the experiment using a scanning electron microscope. Common features are circled in red, and the cathode spot region is circled in yellow.

Figure 5 shows before and after images of the cathode used in the second experiment taken using a scanning electron microscope. Features seen in both images are again circled in red, and the regions of erosion are circled in yellow. As stated previously, the region in the upper left corner is where the arc originated when the first lead was used, and the second, larger region in the middle of the upper edge of the cathode is where the arc appeared when the second lead was used instead. Significant melting is evident at the edges of this region.



a)



b)

Figure 5. Silicon cathode from dual lead experiment.
Images of the dual lead silicon cathode from the second experiment taken a) before and b) after the experiment using a scanning electron microscope. Common features are circled in red, and the cathode spot regions are circled in yellow.

Figure 6 shows a composite image a) combining several images taken after the third experiment using a scanning electron microscope, as well as a photograph b) of the same cathode. A magnetic coil was used in this experiment to create a magnetic field in the vicinity of the arc, thereby inducing cathode spot motion in the BxJ direction as shown. A large cathode spot region can be seen circled in yellow.

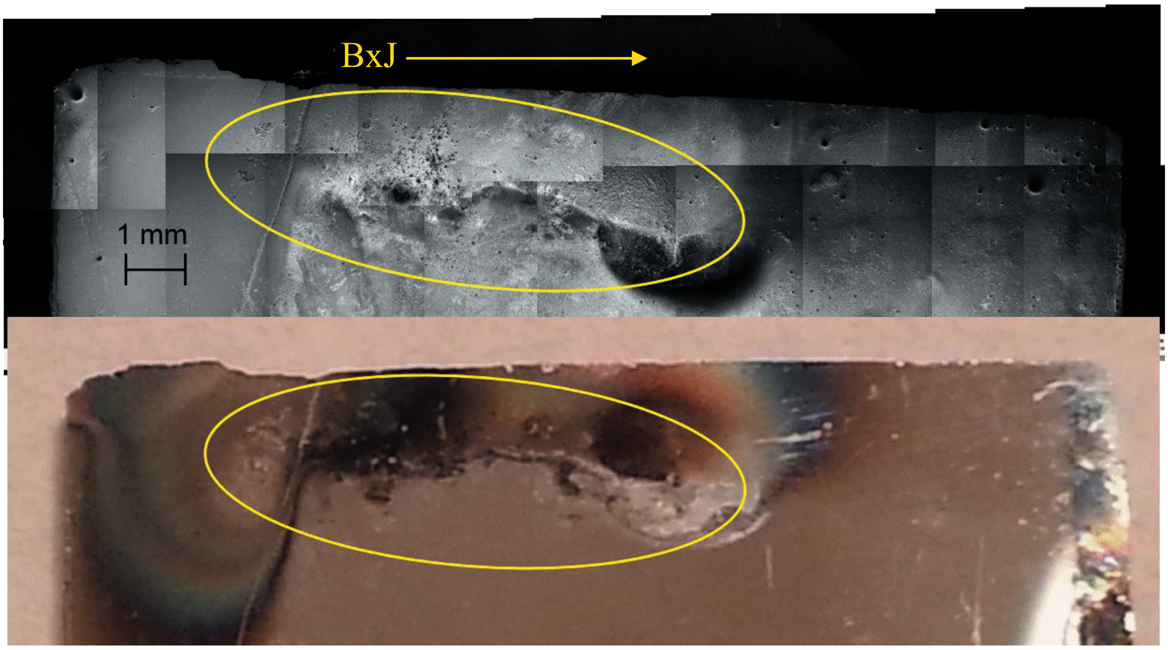


Figure 6. Silicon cathode from magnetic coil experiment.
Images of the magnetic coil experiment taken after the experiment with a scanning electron microscope a) and with a camera b) showing the large cathode spot region in the middle of the cathode.

C. Erosion Rates

The mass of the cathodes was determined before and after each experiment, and mass loss calculated. The mass loss during the first experiment using a single lead was 100 µg, and the mass loss during the second experiment using two leads was 180 µg, an 80% increase. Arc current readings were taken during the experiment as shown in Fig. 6, and used to calculate a transported electric charge of 1500 µC per pulse. Since there were approximately 5,000 pulses each experiment this results in 7.5 C in each experiment, and an erosion rate of 13.3 µg/C in the first experiment and 24 µg/C in the second. Erosion rates depend on the cathode material used and are more typically in the 50-500 µg/C range[6]. Nevertheless, a significant increase in the erosion rate was seen when the cathode spot region was moved using two leads on the cathode. An even greater increase was seen when the magnetic coil was used. In that experiment the mass loss was 830 µg, and the transported electric charge was 4,400 µC per pulse. The approximately 4,800 pulses during the experiment therefore resulted in a total of 21.1 C and an erosion rate of 39.2 µg/C. Table 1 is a summary of the erosion rates calculated in the three experiments.

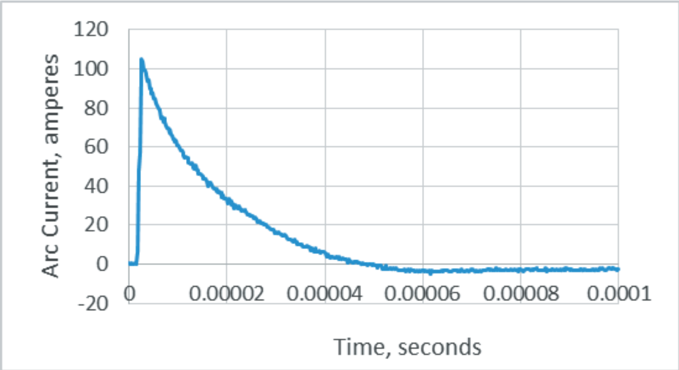


Figure 7. Arc current over one pulse.
Arc current was uses to calculate transported electric current and erosion rate

Table 1. Erosion rates of silicon cathode experiments.

Experiment	Transported Electric Charge	Pulses	Total Charge	Mass Loss	Erosion Rate
1. Control	1500 µC / pulse	5000	7.5 C	100 µg	13.3 µg/C
2. Two Leads	1500 µC /pulse	5000	7.5 C	180 µg	24.0 µg/C
3. Magnetic Field	4400 µC / pulse	4800	21.1 C	830 µg	39.2 µg/C

D. Work with Solar Cells

An initial investigation is underway examining methods for initiating an arc on the surface of a solar cell. Spectrolab's Triangular Advanced Solar Cells (TASC) are being used for these experiments. These are triple-junction gallium arsenide cells. This work has focused on identifying an efficient setup to generate a self-sustaining arc, as well as the necessary current, voltage, and spacing between the solar cell surface and the anode material. Copper wiring has been used for the anode, and geometries have included placing the wire both parallel and normal to the solar cell surface. This investigation is still in the preliminary phases, and results are not yet available for publication.

IV. Conclusion

The cathode spots on a silicone cathode were found to be immobile, clustering around a single region on the cathode material. By using two negative leads to relocate the source of the electric current it was found that the location of the spot region could be moved. In addition, creating a new spot region in this manner resulted in an increased erosion rate. Placing the arc source within a magnetic field also resulted in an increased erosion rate. This could have important implications in a propulsion system such as the one described in this paper that uses a satellite's solar cells as the cathode material to generate a vacuum arc.

References

[1]"UN Space Debris Mitigation Guidelines," United Nations Office for Outer Space Affairs, 2010.

[2] "IADC Space Debris Mitigation Guidelines," Inter-Agency Space Debris Coordinating Committee, IADC-02-01, Sep 2007.

[3] Keidar, M., and Beilis, I., *Plasma Engineering: Applications from Aerospace to Bio and Nanotechnology*, Elsevier, Waltham, MA, p. 113.

[4] Boxman, R. L., Martin, P. J. and Sanders, D., eds. *Handbook of Vacuum Arc Science & Technology: Fundamentals and Applications*, Noyes Publications, Park Ridge, NJ, p. 74

[5] Boxman, R. L., Martin, P. J. and Sanders, D., eds. *Handbook of Vacuum Arc Science & Technology: Fundamentals and Applications*, Noyes Publications, Park Ridge, NJ, p. 87

[6] Boxman, R. L., Martin, P. J. and Sanders, D., eds. *Handbook of Vacuum Arc Science & Technology: Fundamentals and Applications*, Noyes Publications, Park Ridge, NJ, p. 124