HIGH VOLTAGE SOLAR ARRAY FOR 400V OPERATION IN LEO PLASMA ENVIRONMENT

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Abstract

To realize a MW-class space platform, the power must be delivered at least 400 volts. In order to realize 400 volts operation in LEO, arcing caused by interaction between the spacecraft and the surrounding LEO plasma must be overcome. The purpose of the present paper is to report on the results of laboratory experiment carried out to develop solar array capable of generating electricity at 400V in LEO plasma environment. We tested various types of solar array designs. We biased solar array coupon panels negatively inside a vacuum chamber and measured the arc inception rate for each design. The arc sites were also located to identify the weakness of each design. These data are compared to the characteristics of conventional solar array for 100V bus satellite.

We confirmed that covering array strings by transparent film and by large coverglass is promising. The advanced coverglass coupon is most realistic design

Introduction

The use of high power in future space missions calls for high voltage power generation and transmission to minimize the energy loss during power transmission and the cable mass. In order to promote industrial use of Low Earth Orbit (LEO), such as manufacturing, sightseeing, or power generation, the power of a large LEO platform after the International Space Station (ISS) will soon reach the level of MW. In principle, the transmission voltage scales to the square root of the power to be delivered. Therefore, in order to realize a MW-class space platform, the power must be delivered at 400 volts, at least. In order to realize 400 volts operation in LEO, arcing caused by interaction between the spacecraft and the surrounding LEO plasma must overcome. The development of 400V solar array benefits not only a large space platform but also a satellite with a hall thruster, because the voltage is high enough to directly drive the electric propulsion system without raising the voltage via a DC/DC converter [2]. When a solar array generates electricity in LEO, most of the voltage becomes negative with respect to the surrounding plasma due to mass difference between ions and charge it positively. Then the electric field near triple junction, where interconnector (conductor), adhesive (dielectric) and vacuum meet together is enhanced and an arc occurs [1]. There have been numerous studies on arcing on high voltage solar array in LEO condition. It is now known that an arc occurs once an array has a negative potential as low as –100V with respect to plasma. An arc on solar array surface is usually a pulse of current whose energy is supplied by the electrostatic energy stored on the coverglass surface due to charging via positive ions. Such an arc is often called trigger arc or primary ESD (electrostatic discharge). Repeated arcs lead to surface degradation and electromagnetic interference. Destruction of solar array cell PN junction due to the intense arc current is another concern. Moreover, a single arc might shorten momentary the array circuit and the current flows for a much longer time than a trigger arc by recalled secondary arc. A secondary arc might lead to permanent short-circuit in the array circuit and the arc current keeps flowing until thermal breakdown of insulative layer occurs. Such an arc is called sustained arc and believed to be the cause of the failure of Tempo-2 [4].

The purpose of the present paper is to report the results of laboratory experiment carried out to develop solar array capable of generating electricity at 400V in LEO plasma environment. The development effort is carried out in the two directions; (1) Suppress the inception of arcing completely (2) Minimize the damage caused by each arc. In this paper, we focus on the first items. We tested various types of solar array designs. We biased solar array coupon panels negatively inside a vacuum chamber and measured the arc inception rate for each design. The arc sites were also located to identify the weakness of each design. These data are compared to the characteristics of conventional solar array for 100V bus satellite.

Test Coupons

In the experiments we use various types of solar cell array coupon. Figure 1 shows a picture of base coupon. The base coupon is based on the standard design for a 100V bus satellite and serves as the reference for all the coupons with mitigation techniques. The coupon is made of $7cm * 3.5cm$ Si cell with IBF (integrated bypass function). Four cells are connected in series and three strings are placed in parallel. In order to distinguish each string, the strings are named as *R*, *B* and *G* strings as shown in Fig. 1. Between the strings, RTV-Si rubber is grouted to prevent short-circuit between the adjacent strings. The cells are mounted on the polyimide sheet on top of the aluminum honeycomb / CFRP substrate.

All the new coupons were designed following concepts:

1. Prevent charging the coverglass from ambient ions
2. Prevent interacting between electrons emitted from triple junction and ambient plasmas

Considering these concepts and the results of previous tests, we designed four new coupons. The schematic drawing of coupons tested in this study are shown in Fig. 2 ~ Fig. 5. These coupons are designed with the results of the previous test coupons [6]. There are two types of coupons using large coverglass and using the Teflon film.

Figure 2 shows the advanced film coupon. This coupon has a transparent Teflon film covering over all the strings. The Teflon film made of ETFE (Ethylene-Tetra Fluoro Ethylene copolymer). It has a transmittance of about 95% between 400*nm* to 1μm wavelength. ETFE has the characteristic of radiation resistance. Because it is hard to adhere the film to substrate, the film is attached by covering the front and back sides by adhesive at edges. To reduce gaps between the film and substrate due to the cables as low as possible, doubled size of film and substrate are utilized. All the bus bars are coated by RTV-Si rubber. Figure 3 shows the advanced film strip coupon. In this coupon, cells are covered only the cell edges by Teflon film strip concerning degradation of film transmittance. At the previous film strip coupon, many arcs occurred through small gaps around the adhesive. Therefore, RTV-Si rubber is grouted between all inter cells and bus bars. Figure 4 shows the large coverglass coupon. A large coverglass is adhered and covers over each cells, so that emitted electrons can't diffuse to ambient plasma. The bus bars and the outer cell edges are covered by the Teflon film strip. No RTV-Si rubber is utilized. Figure 5 shows the roof coverglass coupon. This coupon is similar to the large coverglass coupon. The large coverglass is adhered and supported by one cell which located near its center, and it overhang to other cells. RTV-Si rubber is grouted between all inter cells and bus bars.

Experimental Apparatus

Figure 6 shows a schematic of experimental set-up. The vacuum chamber is 1*m* in length and 1.2*m* in diameter. The chamber can be pumped to a pressure of as low as 10^{-6}*Torr*. In order to simulate the LEO plasma environment, an ECR plasma source generates Xenon plasma with a density of $2 * 10^{12} m^{-3}$ at 3 ~ 7*eV*. The plasma source operates at a flow rate of 0.2*sccm* and the chamber pressure during the operation is 8 ~ 9 $*10^{-5}$*Torr*. In order to keep the coupon temperature constant, halogen IR lamps was utilized. The chamber has also equipped with a metal-halide lamp to simulate the sum light. Using the lamp, we can monitor the cell electrical output without opening the chamber door. During the experiment, a negative bias voltage of –100*V* ~ -800*V* is applied to each coupon. Each bias voltage is applied for 90 minutes considering the orbital period in LEO. The bias voltage is raised from a lower value to a higher (more negative) value. In Fig. 7, we show a schematic picture of external circuit connected to an array coupon. The strings are biased to a negative potential via a DC power supply through a limiting resistance of 100*k*Ω. In order to simulate the arc current supplied by coverglass on the solar array panel as a capacitance [8], we connect an external circuit. The external circuit consists of a capacitance, inductance and resistance. We have attached a capacitance, 5μF, and an inductance, 270μH, and a resistance, 5Ω during the bias voltage from –100*V* to –400*V*. In case of –500*V* ~ -800*V* test, we have unavoidably changed the capacitance to 20*nF* and removed the inductance and resistance due to current limitation of circuit.

The data recorded are the following:

- Arc position
- Arc current waveform
- Fluctuation of the background plasma condition
- Increase of background pressure

We have developed an experimental system that can record all the arc events. A video camera takes the picture of the array coupon during the experiment. The video image is directly recorded via a computer. We have developed a computer program to decompose the video stream into frames, compare each frame, detect the optical flash associated with arcs, record the coordinate of the arc flash and the time of arcing. Using this system, we can identify the position of every arc immediately. We have also developed a high-speed data acquisition system which can acquire 4 channels of current waveform data in 33ms and automatically analyze the waveform data to calculate the peak value and electrical charge flown. The data acquisition speed is fast enough to record all the arc current waveforms. Using the two systems, we can easily know when, where, and what arc occurred on a coupon panel.

Test Results

Figure 8 shows the arc positions observed on the base coupon. All the arc position is plotted on the figure for the bias voltages of –100 ~ -400V. The location of arcing was roughly classified on bus bars, interconnectors and cell edges. Figure 9 shows the relation between bias voltage and the arc number on each location in 90 minutes. The number of arc, especially on the cell edge increased with increasing the bias voltage. In case of –400V, we observed 164 arcs on the strings. Among the arc number of 164, 63 occurred on bus bars, 33 occurred on interconnectors, and 68 occurred on cell edges which not coated by RTV-Si rubber. To estimate cell degradation due to arcs, we measured the electrical output of R-string (see Fig. 10). After the test, the maximum output power dropped to about 70% of the initial value, which means two cells were damaged by arcing [6].

At first, we report on the results of the coupons used the improved cover film. In this experiment, the advanced film coupon has never been suffered arcing during the bias voltage of –800V. Comparing the result of the previous film coupon which suffered 14 arcs at –800V[6], the performance of arc mitigation has been greatly improved. The reason of this improvement is due to reduce the gap between the film and substrate. This coupon is most realistic design from a viewpoint of manufacturing and cost. Figure 11 shows the result of the advanced film strip coupon. The figure shows the relation between bias voltage and arc number on each location. This coupon suffered only 4 arcs at –800V. All the arcs occurred on the bus bar and interconnectors. The electrical output of cells hardly changed. Cell edges that covered by RTV-Si rubber did not experience arcing. As shown in the previous paper [6], the film strip coupon and the interconnector film rap suffered so many arcs in spite of –400V of bias voltage. With respect to electrical output, the maximum power dropped by 20~30%. Therefore, extremely improvement for the arc mitigation using film strip was confirmed.

Next, we report on the results of the coupons which improved the coverglass. Figure 12 shows the result of the large cover glass coupon. This coupon suffered several hundred of arcs at –700 ~ -800V as shown in Fig. 12. However, the arc that was occurred on the outer cell edges came up to as much as 10% of all the arcs. Furthermore, no arc occurred on interconnector and cell edge covered by large coverglass. With respect to the outer cell edges where arcs occurred, there are some gaps between the film and the substrate due to the power cables. Ions probably entered through these gaps and charged the dielectric along the edge. Figure 13 shows the result of the roof coverglass coupon. This coupon suffered about 20 arcs at –800V. Almost all arcs occurred on so-called the stress-relief which is only expose from bas bar with RTV coating to plasma. No arc occurred on the cell edge. The results of arc number at each bias voltage for different coupons are shown in Fig. 14.

The results of cell degradation in each coupon are shown in table 1. The power drops was estimated as shown in Fig. 10. Measured values of power drop contained about 4% of error so that the no degradation of cell electrical output was confirmed almost all the coupons though some coupons suffered many arcs. As the above experiment results show, we obtained satisfactory results for arc mitigation.

Conclusion

(1) Solar array coupons with arc mitigation function have been tested in LEO plasma environment
(2) Covering array strings by transparent film is promising. The advanced film coupon is most realistic design.
(3) Covering array strings by large coverglass is promising

Acknowledgement

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Table 1. Degradations of cell electrical output in each coupon

Coupon	Base coupon	Large coverglass coupon	Roof coverglass coupon	Advanced film coupon	Advanced film strip coupon
Power drop	30%	2%	3%	<1%	1%
Total arc Number	259	312	66	0	13
Total arc number on cell edge	82	26	0	0	0

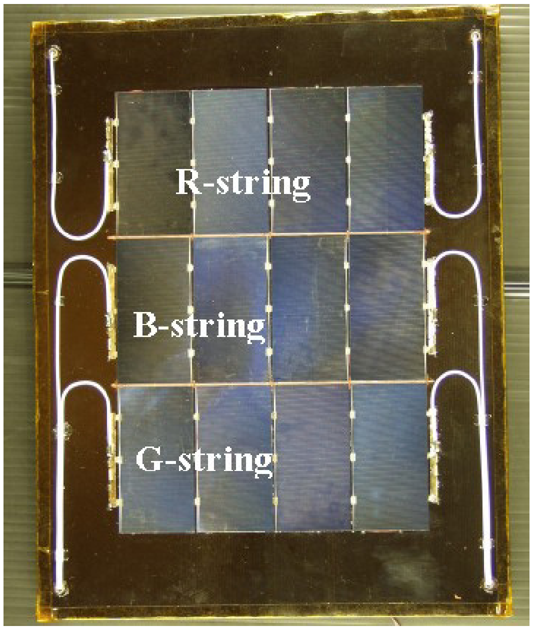

Figure 1. Picture of the base coupon.

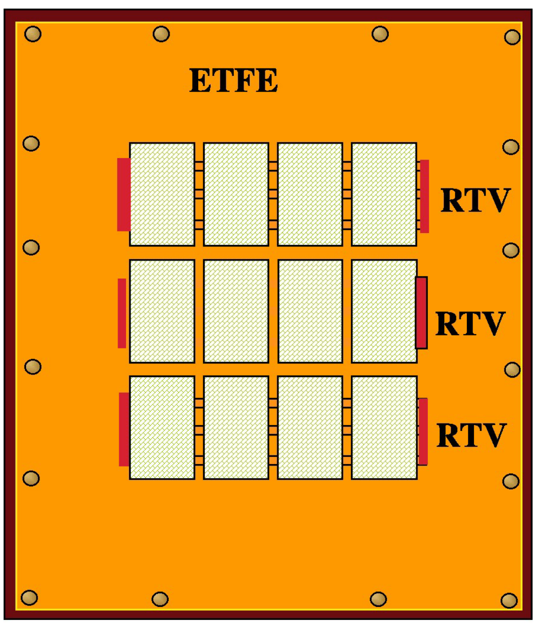

Figure 2. Schematic drawing of the advanced film coupons.

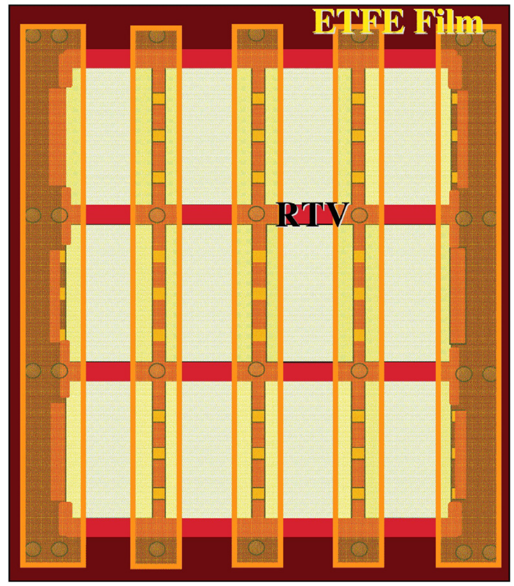

Figure 3. Schematic drawing of the advanced film strip coupons.

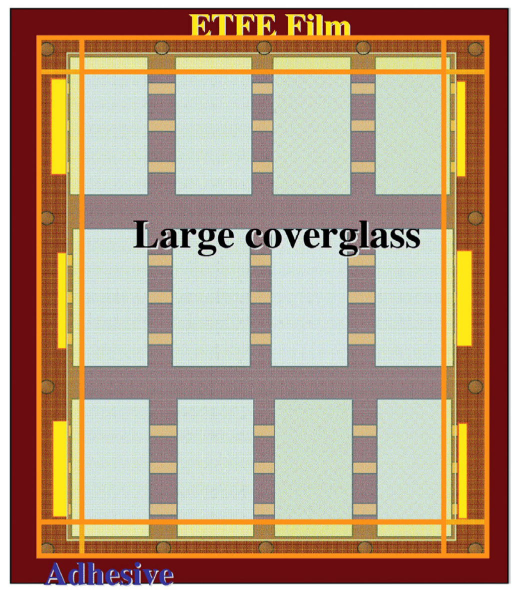

Figure 4. Schematic drawing of the large coverglass coupons.

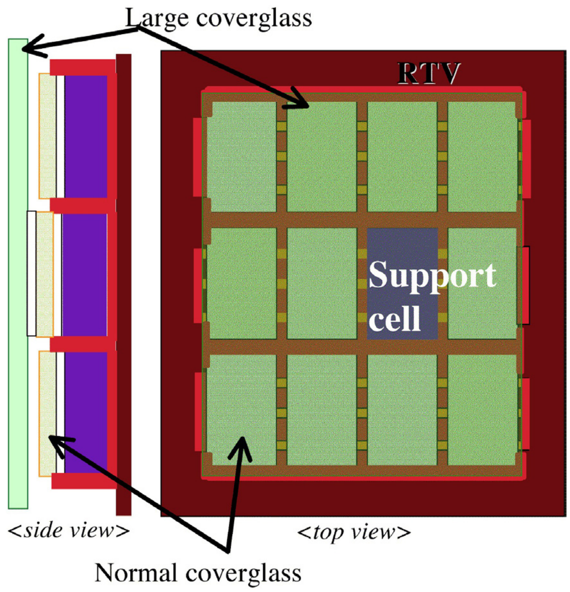

Figure 5. **Schematic drawing of the roof coverglass coupons.**

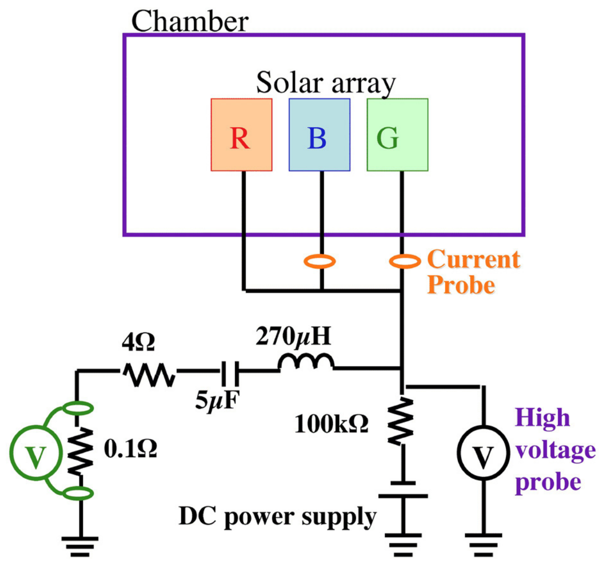

Figure 7. **Schematic illustration of experimental circuit from –100V to –400V**

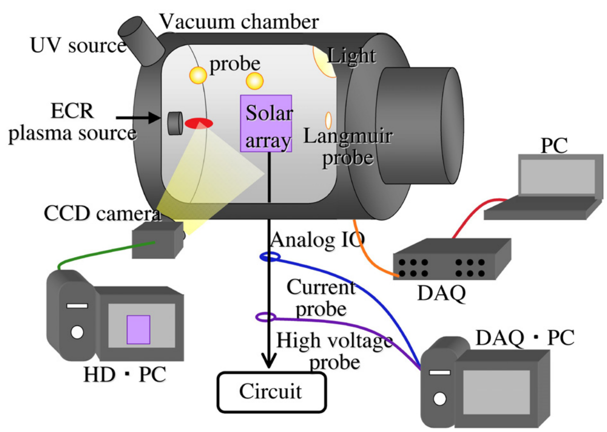

Figure 6. **Schematic illustration of experimental apparatus.**

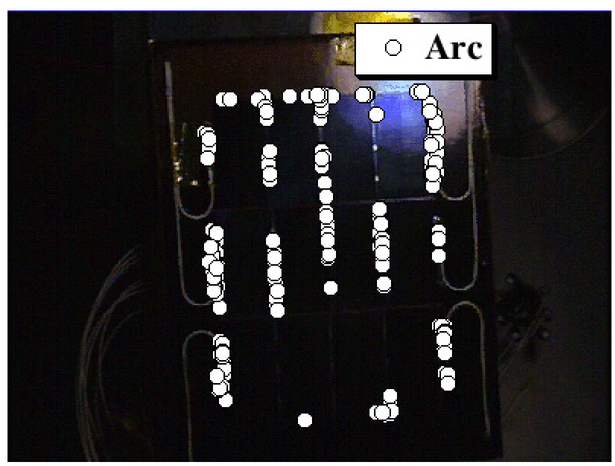

Figure 8. **All the arc positions observed on the base coupon from –100V to –400V**

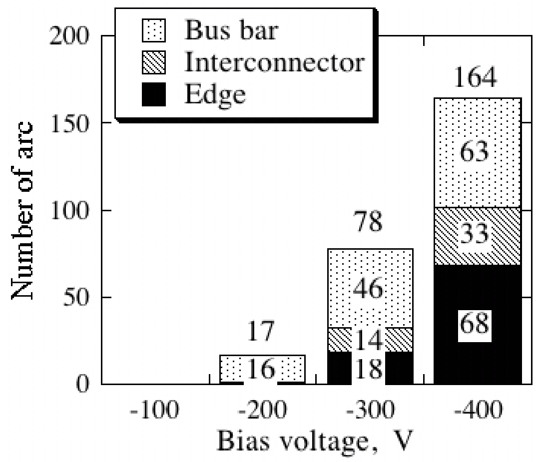

Figure 9. The arc positions observed on the base coupon

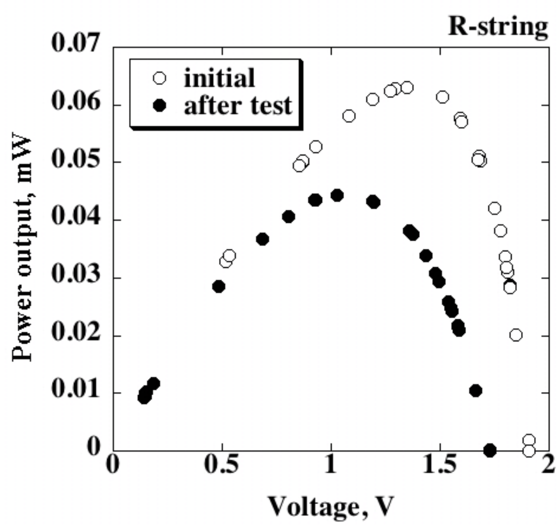

Figure 10. Degradation of cell electrical output. Result of R-string of a base coupon.

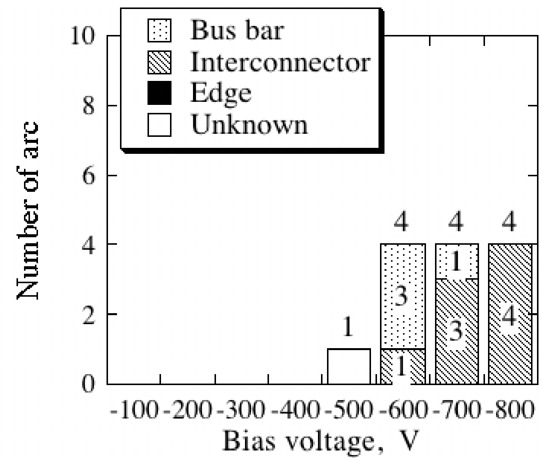

Figure 11. The arc positions observed on the advanced film strip coupon.

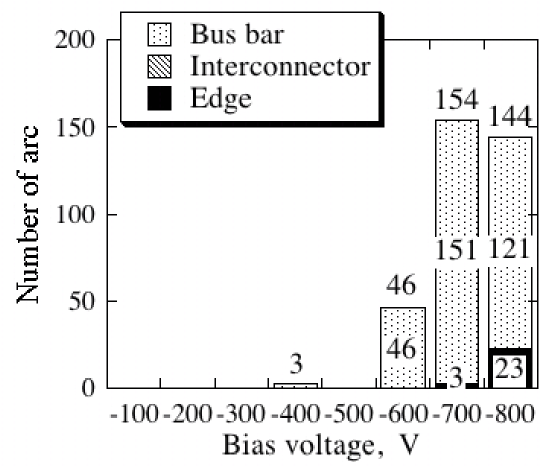

Figure 12. The arc positions observed on the large coverglass coupon.

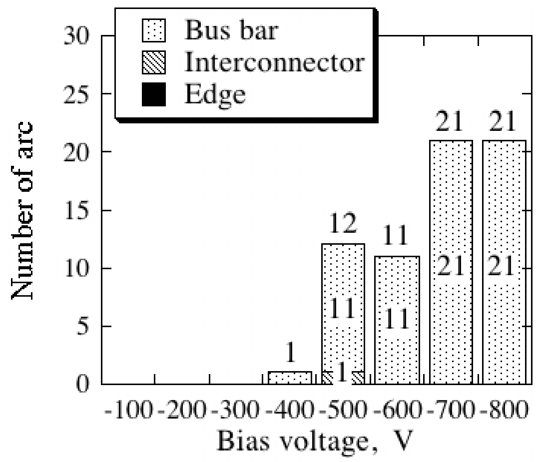

Figure 13. The arc positions observed on the roof coverglass coupon.

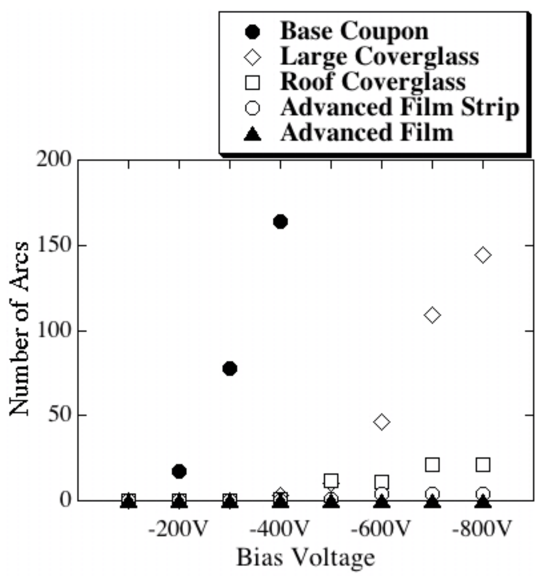

Figure 14. Number of arcs in 90 minutes at each bias voltage for different coupons.

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