The Nature of Negative Potential Arcing: Current and Planned Research at LeRC

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ABSTRACT

Research in progress at LeRC to study the breakdown of negatively biased conductors in an ambient plasma will be described. Possible breakdown mechanisms will be reviewed with an emphasis on applicability to the observed arcing of negatively biased solar arrays. Experiments underway to study the nature of the breakdown process will be described.

INTRODUCTION

For many years the problem of negative potential arcing from surfaces exposed to space plasma has engaged the attention of researchers and spacecraft designers. Despite considerable progress, the fundamental nature of the arcing process remains both controversial and poorly understood. The arcing problem has two separate aspects which must be addressed. The first concerns the breakdown mechanism while the second deals with the nature of the arc discharge itself.

Previous discussions of arcing have usually been in terms of a Paschen discharge process occurring either in background gas or in gases desorbed from the surface. Research now in progress at LeRC is directed at exploring the possibility that negative potential arcing is fundamentally a special case of the classical vacuum arc. As will be discussed below, most breakdown mechanisms previously proposed for arcing can be accommodated within a vacuum arc picture. Furthermore, we will argue that the presence of either background gas or adsorbed gases will only modify the arcing process once it has been initiated. Finally, experiments now underway to support this hypothesis will be described.

THE PHYSICS OF NEGATIVE POTENTIAL ARCING

Despite many years of work by investigators all over the world, the fundamental nature of negative potential arcing in a space plasma environment remains unclear. Experimental work has so far concentrated on characterizing such parameters as breakdown thresholds, arc rates, and voltage or current waveforms ($V(t)$ or $I(t)$). Notably lacking from existing experimental work are measurements of optical spectra and a determination of the volt-ampere characteristic. As a result, several hypotheses are consistent with experimental data and the basic question of "what exactly is discharging" remains controversial.

Most previous treatments of arcs are based on Paschen breakdown processes either in background gas [Thiemann and Bogus] or in desorbed gas [Hastings et. al.]. Research now underway at LeRC is investigating the possibility that the phenomena of interest is really a special case of the vacuum arc.

The term "vacuum arc" is an unfortunate historical misnomer. More correctly called "metal vapor arc in vacuum" the term refers to arcs from cold metal surfaces under conditions of high vacuum. The name derives from the fact that in the early part of this century, when such phenomena first came to be studied, the hardest vacuum that could be achieved under laboratory conditions was of the order 10^{-8} torr. Such arcs have been studied extensively over the past few decades and a number of comprehensive reviews are available [see the books by Lafferty [1980], Latham [1981], and Mesyats [1989] as well as the excellent review article by Farrall [1973]].

A simple picture of the vacuum arc will begin with electric field enhancement at the surface of a negatively biased conductor. Given that this occurs, by possible mechanisms that will be discussed later, the arc erupts explosively with the ejection of a small amount of cathode material. This material forms a plasma jet, sometimes called a cathode flare, with bulk velocities exceeding 10^6 cm/sec. The arc then develops as a breakdown in the ejected metal vapor. Since the vacuum arc is a cold cathode phenomena, it typically undergoes self extinction within a few microseconds [Farrall 1980, pp 184-195] generally terminating quite abruptly. Such an arc has a number of distinguishing signatures which may make identification possible in the laboratory.

First, the optical spectrum of the vacuum arc is characteristic of the metal from which the cathode is made. In the case of solar cell arcing, alternate theories of the nature of the arc would predict a spectrum typical of either background gas or desorbed gases. Experimental measurement of an arc spectrum should therefore unambiguously determine the nature of the arc.

Second, we recall that a well known property of arcs in gases is that the volt-ampere characteristic has a negative slope. A fundamental difference between conventional arcs and the vacuum arc is that the latter is known to have a positive volt-ampere characteristic [see Farrell, 1973 p 1118]. Measurements of the VI curve in the lab will be difficult but are clearly desirable.

Finally, we note that the vacuum arc forms by an eruption from a very small area on the cathode surface. The emission sites are usually on the order of 1 to 5 microns in diameter resulting in power densities greater than 10^5 amps/cm^2. As a result, there is considerable damage to the surface in the immediate vicinity of the arc site. There have been numerous published photographs of such damage [see Harris pp. 137-145 and Mesyats pp. 104-117] and all of them show a strikingly similar pattern. When the arc occurs, it leaves behind a small pit having a bell shaped appearance in the cathode surface. These so called "cathode spots" are always present and may be considered to be a fundamental part of the vacuum arc process. If arcing is heavy, they overlap and cover the entire surface leaving a landscape which often appears to have completely melted and resolidified.

Over the many years that the vacuum arc has been studied numerous models of the initial breakdown have been proposed [see Mesyats et. al. chapter 2, and Farrell, 1980]. The basic problem is that breakdown cannot arise from standard Fowler-Nordheim tunneling because the electric field strength at the surface of the cathode is typically two or three orders of magnitude too small. This is certainly the case for solar cell arcing where fields are on the order of 10^7 V/M rather than the 10^9 V/M [Jongeward et. al. 1985] required for tunneling.

The most commonly invoked mechanism for field enhancement involves the presence of micropoints, sometimes called whiskers, on the cathode surface [Farrall 1980, pp 24-35]. Because of their small size, high ratio of length to width, and generally pointed terminus, these can easily result in the hundred fold increase in field strength needed to initiate breakdown. If present on the surface of the cathode, such structures will almost always be the preferential emission sites.

Perhaps more important for our problem, it has long been recognized that dielectric impurities on the surface of a conductor can provide the necessary emission sites [Mesyats et. al. pp 9-11]. The role of such non-metallic inclusions, as they are commonly referred to in the vacuum arc literature, is to support charge buildup which results in increasing fields in the dielectric and eventually in rupture and breakdown. While not identical, the process is remarkably similar to what is arguably the current leading model of solar cell arcing [Jongeward et. al.] in which the key process is specifically identified as Malter emission [Malter 1936].

Finally, we should point out that the vacuum arc is quite often preceded by a series of "microdischarges". This prebreakdown phenomena is attributed variously to such things as the vaporization of submicropoints or to the explosion of local clusters of adsorbed gas atoms [Mesyats, pp 12-14]. It is interesting to note that similar predischarge phenomena have long been observed in studies of solar cell arcing [I. Katz, private communication].

Before proceeding, we should point out that the vacuum arc is normally associated with a low pressure neutral gas while the arcing of interest to the space community involves a process in plasma. This is not as great a difference as it may first seem. In fact, there is a considerable body of work on vacuum arc processes in plasmas for two reasons.

First, much of the work done has been under conditions of alternating current. In this case, the arc extinguishes and reignites every half cycle [Farrall 1980 pp 184-227]. Because of the times scales for the various atomic processes involved, there is usually a plasma present when reignition occurs. Second, a particular variant of the device, known as the triggered vacuum arc [Farrall 1980 pp 107-119], uses an auxiliary electrode arrangement to create a cloud of plasma in the vicinity of the electrodes resulting in immediate breakdown and arc formation.

The general experience has been that the presence of plasma changes breakdown conditions but not the nature of the arc. By this we mean that such commonly measured parameters as breakdown threshold and arc rate will be strongly affected by the presence of plasma. Once breakdown occurs, however, the arc is still characterized by the properties discussed above, e.g. is a metal vapor arc, has a positive VI curve, and operates in spot mode.

EXPERIMENTAL PROGRAM AT LeRC

The experimental program in negative potential arcing at LeRC is closely tied to the upcoming SAMPIE space experiment [D. Ferguson, this volume]. In addition to activities necessary for direct support, it is desirable that as much as possible be done to understand the fundamental nature of the arcing process.

The first step will be to establish unambiguously that the arcing of interest is in fact a case of the vacuum arc. As mentioned above, a key signature can be found in the optical emission spectrum. To record this, we will use an optical multichannel analyzer. Selected solar cells will be placed in one of the vacuum chambers available at LeRc and biased to sufficient negative potential to cause arcing. A fiber optic cable will be used to collect the emitted light and transfer it to a spectrometer. The dispersed light will finally be sent to a linear array of 512 photodetectors. With appropriate triggering and gating we expect to obtain a complete spectrum from a single arcing event. Our earlier prediction that plasma alters only the breakdown threshold will be tested by taking spectra over the full range of plasma densities that we can generate, typically $10^3/cm^3$ - $3 \times 10^5/cm^3$, as well as with the plasma generators turned off.

The second signature that we will look for is evidence of spot mode operation. The procedure here is very straightforward and amounts to doing SEM scans of solar cells subjected to various degrees of arcing. The presence of cathode spots will be a positive indicator that vacuum arcs at least play a role in the overall process.

We will try to do the early measurements with cells that have been carefully cleaned and baked to removed adsorbed gas. Our basic working assumption then predicts that the arcing phenomena can be explained entirely as a vacuum arc. If the cells are allowed to have gases adsorbed onto their surfaces, the arcing process may become much more complicated. We will study this by allowing different gases to be adsorbed on the surface, (e.g. xenon, krypton) while the background gas in the vacuum tank will be kept the same (argon).

When an arc occurs, it may have the effect of blowing off desorbed gas. The metal vapor arc that occurs in the first few microseconds may then undergo a transition to an arc in gas. The first observable consequence of such an event may be a considerable increase in the duration of an arc from a few microseconds to perhaps as long as milliseconds. In addition, the optical spectrum would reflect the changed nature of the arc. It is not clear at this time that we will be able to time resolve various stages of an arc. Even if not, the appearance of strong emission lines characteristic of the desorbed gas in what is otherwise a metal vapor spectrum will allow us to determine at least qualitatively what is going on.

The final breakdown mechanism that we wish to investigate in detail concerns the role of charged particle bombardment. It has long been thought that incoming ions impacting with the surface of a biased cathode play a major role in the initiation of the vacuum arc [Mesyats et. al. pp 31-32]. At the same time, work in the space sciences community has indicated that breakdown on negatively biased conductors in space is caused, or at least strongly influenced, by ion bombardment. The impressive work done in connection with the SPEAR program [Katz, 1989] has shown that a key role is played by ion bombardment of triple points, where conductor, insulator, and plasma meet.

We will study this by two means. First, we will construct solar cell interconnects, or mechanical simulations of them, which have been designed so that electric field lines lead incoming charged particles away from these junctures. The design of such devices will depend heavily on computer modeling and we will use the NASCAP/LEO computer code [Mandell et. al.] to seek optimum geometries. Our effort here will be very similar to what was done by the SPEAR team.

Second, we will investigate various ways of simply insulating the interconnects so that incoming ions cannot strike the critical junctures. Such things as simply extending the cover slides so that the interconnects are shielded or actually providing a separate coating will be looked at.

This part of our program is directly related to the SAMPIE flight experiment. It is our hope to demonstrate in the laboratory that the breakdown threshold for arcing from solar cells can be significantly modified by relatively simple changes to the standard design. If we are successful, variants of these experiments will be flown on SAMPIE.

CONCLUSIONS

The subject of negative potential arcing has been of considerable interest for many years. Two different groups of researchers, the traditional gas discharge community and those whose interests have been in space science, have pursued various aspects of the problem. We believe that we can demonstrate that most negative potential arcing is at least closely related to the classical vacuum arc. In addition to researching the nature of the phenomena, we hope to demonstrate that arc suppression techniques are feasible and to fly such technology on SAMPIE.

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