Surface Arc Discharges on Spacecraft Dielectrics

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ABSTRACT

Propagating arc discharges are the result of electrical breakdown in electron-beam-charged dielectrics. For incident electron accelerating voltages in the range of *1* to *30* kV, the charge accumulation is primarily within a few μm of the exposed surface, so that the propagating subsurface arc frequently bursts through the surface, ejecting ionized debris and an appreciable fraction of the accumulated electrons. This blowoff current has reached a peak value of *100* to >*1000*A in the laboratory and thus, when it occurs on spacecraft materials, severe interference to control systems could be the result. Such interference on spacecraft has occured many times, correlating with magnetic storm conditions. The present state of understanding of this phenomenon will be reviewed in this paper.

INTRODUCTION

The permanent failure of one satellite, damage to components on several satellites, and hundreds of satellite "operational anomalies" have been blamed on the energetic-electron environment in synchronous orbit. This environment is believed to cause differential charging in the large areas of exposed spacecraft dielectric materials used for thermal control, with the result that occasional arc breakdown occurs and consequent electromagnetic interference disrupts the spacecraft's control or commumications systems. Concern over this phenomenon has been the primary motivation behind two books [1,2], five conference proceedings [3-7], and numerous other conference papers and journal articles. Reviews have been written emphasizing the relationship between the magnetospheric environment and spacecraft performance anomalies [8-13]. Even in Jupiter's magnetosphere, discharges are believed to have caused "power-on resets" on the Voyager spacecraft, necessitating corrective measures for the planned Galileo flight past Jupiter [14].

Magnetospheric investigations began with the observation of whole-satellite charging, reported in 1972 [15]. A satellite intended to study Spacecraft Charging at High Altitude (SCATHA) was launched and the extensive results from it reviewed [16-19], showing evidence of both charge accumulation and arc discharges on samples of various spacecraft materials.

Laboratory simulation of arc discharge phenomena on thin sheets of spacecraft dielectrics over metallic substrates began in earnest around 1972, and this topic will be emphasized in the remainder of this review. Electrons with energies less than *25* keV predominate in the magnetosphere, so monoenergetic incident electron beams in the *15* to *25* keV range were widely used in these simulations, especially in the early years, and both arc discharges and discharge damage were observed. Many of the cases of material damage (to be described later in more detail) turned out to be miniature versions of the large "tree shaped" Lichtenberg figures observed much earlier by Professor Gross [20,21] using *2* MeV electrons. Excellent interpretive reviews of discharge phenomenology have been published by Frederickson [22,23].

ARC APPEARANCE AND MATERIAL DAMAGE

Most dielectric surface discharges have a multiforked, lightning-like appearance and they appear to start at an edge or puncture. The puncture (or punchthrough as it is often called) could be a fault in the material, a hole, or the results of an earlier discharge passing from the charged surface through the material to a metallic substrate. Often, a dielectric film under electron bombardment will produce some strong edge- initiated arcs, followed by a punchthrough, followed by more frequent but weaker arcs initiated at the punchthrough. Whatever may be the initiation point, the arcs on polymers often exhibit a preferred direction which has been shown to correlate with damage tracks, with the slow axis of optical anisotropy, and with the optical axes [25]. A good selection of damage track photographs is available [26], [27]. It is clear that the tracks vary greatly in cross-section, ranging from μm diameter tunnels a few μm below the surface to V-shaped surface grooves. The tracks may be straight or irregular, or may emanate radially from a punchthrough, and damage tunnels often are punctured by surface eruptions. Quartz optical solar reflectors tend to arc only at their edges where they show evidence of edge chipping [28], and (for polymers) there is corresponding theoretical evidence of high -edge concentrations of charge [29]. Even when a dielectric surface has been metallized, penetrating electrons can cause subsurface discharges [30].

AREA, FLUX, AND ENERGY SCALING

Early empirical results showed that the peak substrate replacement current during a dielectric surface discharge was approximately proportional to the square root of the exposed area, ranging from *1000* A at *1* m^2 to *0.1* A at 10^{-8} m^2[31], the latter area being defined by partially focusing the incident electron beam. This result was confirmed by later work [32-34] which demonstrated a similar square-root-area proportionality for the arc duration and an area proportionality for the released charge, all of which are consistent with the existence of a finite arc propagation velocity. Radiated arc spectra up to *4* GHz were measured as functions of frequency and area, and peak substrate replacement current and pulse width were found to be beam-energy-dependent [35,36]. A dependence of peak current on incident electron flux was observed [37,38] and traced to material conductivity effects which predominate at low fluxes [29]. Monoenergetic, low-flux beams in the *200* to *500* keV range were scattered by aluminum foil and still produced discharges, raising the possibility of discharges on spacecraft interior dielectrics [39]. Combined low-energy non-penetrating and high-energy penetrating beams generally reduced arc occurrence and strength on Kapton and Mylar [41]. Dual low and medium energy beams were proved able to produce lower-strength discharges at very low values of surface potential [42,43], and broad-spectrum beams were shown able to produce a wide range of discharge classes [44, 45], the final conclusion being that monoenergetic beams still provide useful worst-case simulations for spectral-energy beams. For all types of incident energy spectrum, discharges emit not only the excess accumulated electrons but also a plasma of ionized gases [46-48].

ARC PROPAGATION VELOCITIES AND MECHANISMS

Early framing-camera photographs of arc evolution in *2*-MeV-charged dielectric blocks [49] revealed velocities in the 10^5 to 10^6 m/s range, along with a velocity dependence on deposited charge density. Similar results were obtained later using a novel "interference" technique involving the propagation of two arcs in opposite directions around an annular dielectric ring [50]. Velocities in the same range were found using segmented-substrate [51] and fiber-optic [52] techniques. Theoretical efforts have involved electron-avalanche models [53] and various models emphasizing both emitted-particle dynamics useful for interference calculations [54-57] and discharge-channel energy considerations [58]: at present, there is no theory that has been validated in comparison with experiment, so the theory of arc discharge propagation can be categorized as a "frontier" area in spacecraft charging research.

NEW DIRECTIONS

To date, only preliminary results are available for arc discharges on negatively biased and illuminated substrates [59-61], for arcs on floating substrates [62] for X-ray triggering [63,64], for barrier effects [65], for ion effects [66], and for transient interference estimates [67]. These preliminary results all raise extremely interesting questions for future research.

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Rep. T.M.

Manuscript was received 23 September 1985.

This paper was presented at the 5th International Symposium on Electrets, Heidelberg, Germany, 4-6 September 1985.