Dielectric Surface Discharges: Effects of Combined Low-Energy and High-Energy Incident Electrons

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ABSTRACT

In simulation of the exposure of spacecraft insulating materials to the energetic-electron environment of synchronous orbit, a study has been made of the effect on dielectric surface discharges of adding high energy electrons at 5 pA/cm^2 to a primary 20 keV, 10 nA/cm^2 electron beam, the high-energy broad spectrum particles having been produced by the β-decay of Strontium-90. Kapton exhibits the most surprising effects, which are significantly increased discharge strength, increased waiting time between discharges, and a decreased number of discharges per specimen before discharge cessation. Mylar exhibits similar but less pronounced effects, while Teflon is relatively unaffected. There is evidence that with Kapton and Mylar the high energy electrons act in some way to delay the instant of discharge ignition so that more charge can be accumulated during charge-up and hence released during arc discharge.

INTRODUCTION

Spacecraft in synchronous orbit are exposed to a natural energetic electron flux with a continuous energy spectrum extending into the MeV range [1]. It has been estimated that this energetic flux could penetrate the outer skin of a spacecraft and accumulate to the point of causing arc discharges to occur in interior dielectrics [2]. It has also been estimated that nuclear β-decay electrons could augment the naturally occurring high-energy electron flux by one to two orders of magnitude, thereby contributing to stronger charging or discharging phenomena [3].

Most laboratory simulations of spacecraft charging have been carried out using metal-backed dielectric sheets exposed to monoenergetic electron beams in the relatively low energy range of 15 to 25 keV. In addition, evidence has been introduced indicating that an electron beam in the relatively high energy range of 200 keV to 1.0 MeV by itself can cause spontaneous discharges [4,5] or can modify discharges caused by a simultaneously applied low-energy beam [6,7]. In particular, it was found [6] that the addition of 200 keV electrons at 100 pA/cm^2 completely prevented the occurrence of discharges due to a 25 keV beam, even when the low energy beam's current density was as high as 13 nA/cm^2. The further investigation of this latter effect of combined high and low energy beams is the objective of the research reported here, with the primary innovation being the use of a broad-spectrum Strontium-90 high-energy β-particle source.

EXPERIMENTAL CONDITIONS

In the planning stage it became clear that the experiments would be extremely time-consuming, so that the number and ranges of the parameters selected would have to be limited. Therefore it was decided to select only one set of fluxes, with the high energy flux lying roughly between the expected natural and nuclear-enhanced values as evaluated in the literature [6], and the low energy flux large enough to permit completion of the experiments in a reasonable time. Thus the selected current densities were 10 nA/cm^2 for monoenergetic 20 keV electrons and 5 pA/cm^2 for the broad-spectrum emission from ^{90}Sr. Theoretical estimation of the emission from a 100 mCi ^{90}Sr source indicated that a current density of 5 pA/cm^2 would exist at a distance of 3 cm from the source, and Faraday cup measurements in a vacuum confirmed this estimate.

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Three materials were tested: FEP Teflon® 50 μm thick, Kapton® H 50 μm thick and Mylar® 75 μm thick. One reason for this choice was the existence of extensive discharge data on these three materials as a function of exposed area [8] and as a function of incident flux [9], the data consisting of discharge peak current, released charge, energy dissipated, and pulse duration. Kapton was selected because of its use in previous high-energy tests, and Teflon and Mylar were chosen to reveal differences among polymers. The specimen area was kept constant at 11.7 cm^2 and the sample surfaces were not touched, cleaned, rubbed or otherwise altered.

It has been mentioned that discharge tests can be time-consuming. One reason for this is specimen fatigue which means that on a particular specimen discharging can suddenly stop and not recommence, or the properties of the discharges can change as the discharges continue. This means that a complete discharge history for each specimen must be recorded and the specimens changed frequently. Furthermore, specimen fatigue is a property which is as important as discharge pulse strength in assessing the effects of high-energy electron exposure.

The experimental arrangement is shown in Fig. 1. The radioisotope source was positioned so as to produce minimum blockage of the low energy beam when the low and high energy electrons were incident simultaneously. For low energy incidence alone, the radioisotope source was removed (tests with a dummy radioisotope source showed that its presence or absence in the chamber did not affect the low energy results). Also shown in Fig. 1 is the emission spectrum of the high-energy source, a spectrum which exhibits a lower-energy peak due to the β-decay of ^{90}Sr to ^{90}Y, and a higher-energy peak due to the β-decay of ^{90}Y to stable ^{90}Zr.

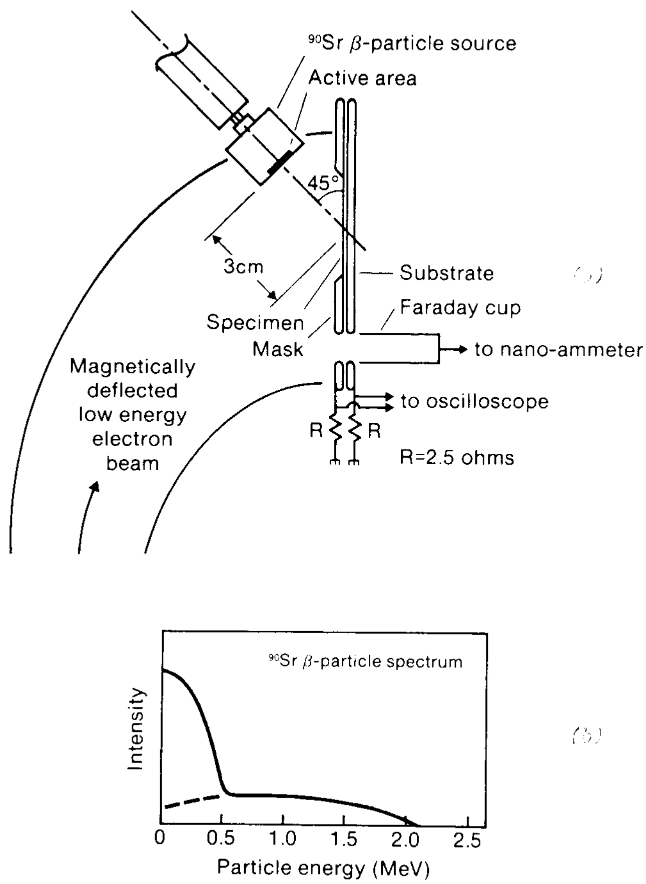

Fig. 1: Experiment arrangement (a), and Strontium-90 β-particle spectrum (b). The spectrum is taken from the CRC Handbook of Radiation Measurement and Protection, p. 354.

SPECIMEN DISCHARGE HISTORY EXAMPLES

Each specimen was found to exhibit a particular kind and degree of fatigue as discharges recurred, and so for each specimen the discharges were assigned serial numbers. The progression of some discharge properties with serial number is shown in Fig. 2 for a single Teflon specimen and low-energy electron incidence. The substrate and mask peak currents both decrease slowly for the first nine discharges, during which the waiting time between discharges increases erratically. Then there is a sudden change to lower peak currents and shorter waiting times. This type of sudden change correlates with the formation of a "punchthrough" or "pinhole" in the specimen and the subsequent arcs tend to concentrate on the punchthrough. It would appear probable that these subsequent discharge arcs are initiated at the punchthrough and then propagate away from it, because of the visual and photographic evidence that the arc is brightest adjacent to the punchthrough and becomes dimmer with distance away from it.

The specimen time histories were organized according to serial number and the discharge properties averaged for each type of material. The example of Kapton exposed to low-energy electrons is shown in Fig. 3, in which the average peak current actually rises slightly as the discharges proceed, a process which is clearly the opposite to fatigue. The vertical bars in Fig. 3 indicate the ranges for all values measured.

As shown in Fig. 3, the waiting time exhibits a great deal of variability, indicating that the slight downward trend in the average may not be significant. It is worth noting that the longest waiting time before a discharge in this sequence was 1.5 hours while the shortest was 20 seconds. Any specimen which did not discharge over a period of 1.5 to 2 hours was deemed to have ceased discharging and was replaced with an unexposed specimen; some specimens did not discharge at all. In this set of experiments Kapton did not develop punchthroughs although in previous experiments on the same type and thickness of material, occasional punchthroughs did occur.

DISCHARGE OCCURRENCE

The horizontal lines in Fig. 4 depict the number of discharge occurrences before discharge cessation. For Teflon, punchthrough-type discharge occurrence is designated by dashed lines. In the Figure the vertical bar following each 6th discharge is a reminder that the computed averages (shown later) of the discharge properties include only the first six discharges, and furthermore it should be added that these averages exclude punchthrough-type discharges.

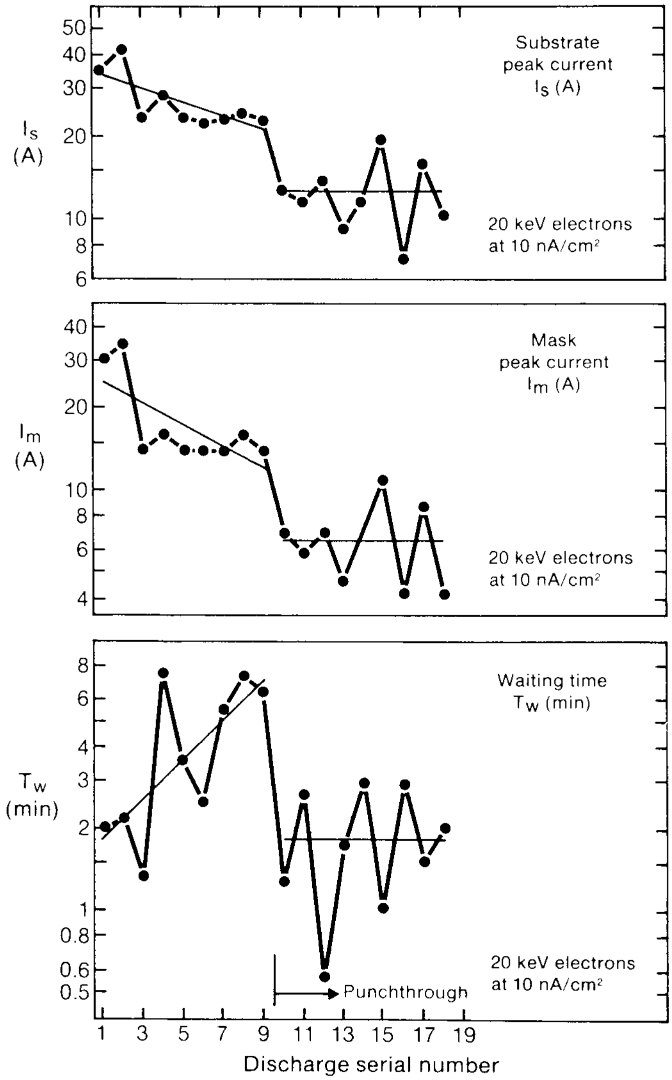

Fig. 2: Discharge history of a single Teflon specimen, illustrating effects of punchthrough formation.

For Teflon, the effect of adding high-energy broad spectrum electrons was to increase the number of instances of punchthrough occurrence by 50%; however, the number of normal discharges per specimen remained essentially constant at about 6. For Kapton, the number of discharges per specimen declined from 10 to 4.5 upon addition of the high-energy electrons. For Mylar the corresponding change was from 4 to 3 discharges per specimen. Clearly, Kapton was the only one of the three materials to exhibit significantly fewer discharges per specimen upon addition of high-energy electrons from the ^{90}Sr source.

AVERAGE DISCHARGE PROPERTIES

The discharge current pulse properties were averaged over up to the first six normal discharges and the results depicted as bar graphs in Figs. 5 to 8. The measures of the discharge strength depicted in Fig. 5, show that for Teflon the addition of high-energy electrons causes the peak current and released charge to decrease slightly, but has the opposite and much stronger effect on Kapton and Mylar. Indeed, for Kapton the released charge is tripled and the energy dissipated (shown in Fig. 6) is multiplied by a factor of seven.

The pulse durations shown in Fig. 6 are relatively unaffected by the high-energy electrons. It is significant that the values for Mylar are about half the values for either Teflon or Kapton. If pulse duration is associated with arc propagation velocity [9], one is led to the conclusion that the arc velocity on Mylar is greater by a factor of two.

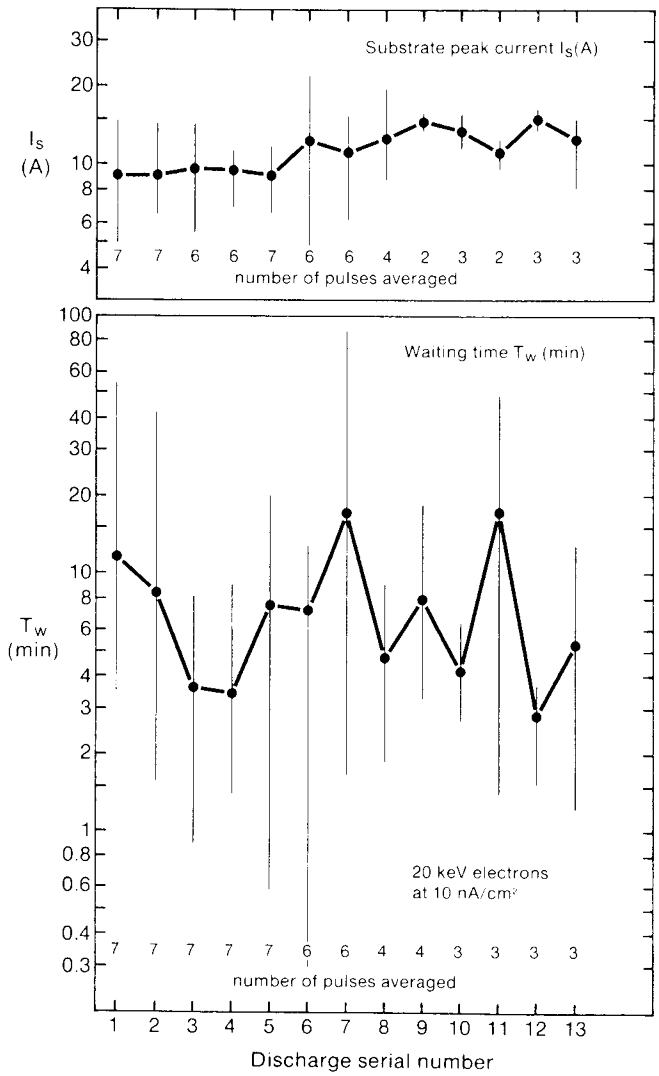

Fig. 3: Average discharge history for seven Kapton specimens. Some specimens stopped discharging after 5 to 10 discharges. A few peak current values are missing due to failures in the photographic pulse recording system.

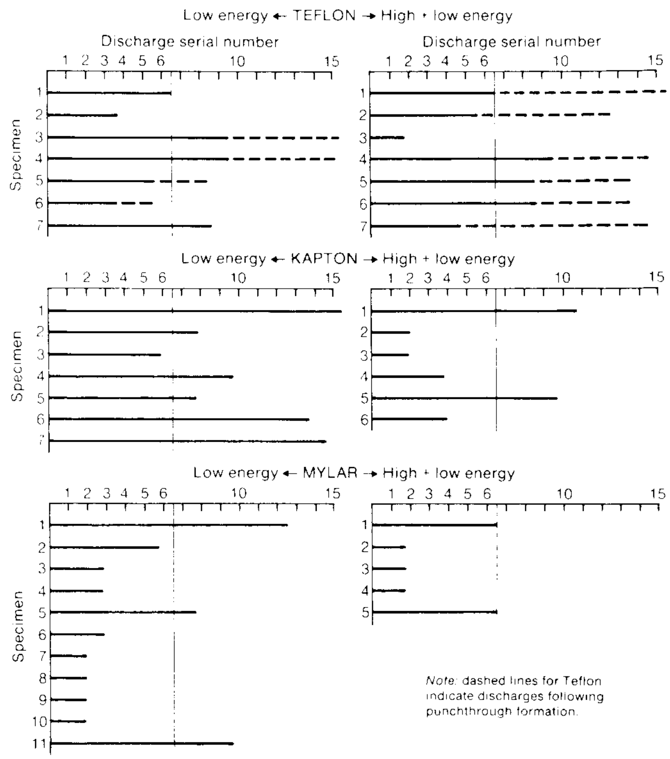

Fig. 4: Discharge occurrence on individual specimens, showing effects of adding high energy electrons from Strontium-90 to a monoenergetic 20 keV beam.

AVERAGE WAITING TIME

The increased discharge strength for Kapton and Mylar as referred to above correlates fairly well with the increased waiting time shown in Fig. 7. This correlation is better for the released charge than for the other discharge properties as can be seen in Table 1. Presumably, the added high-energy electrons act in some way to permit charge to build up for a longer period before discharge occurs. It is conceivable that the beam-induced conductivity allows enough charge redistribution to prevent early formation of charge concentrations and resultant breakdown-level fields. Whatever the reason may be, the factor of four increase in waiting time is particularly significant because it allows time for a much larger charge to accumulate. The longer waiting time also greatly extends the time required to perform the experiments.

The average mask-to-substrate ratios of Fig. 8 indicate that the addition of high-energy electrons has little effect. Because these ratios and the pulse durations are little affected, it seems reasonable to conclude that the addition of high-energy incident electrons does not affect discharge dynamics.

TRENDS DURING FIRST SIX DISCHARGES

It is reasonable to ask whether or not the averages presented as bar graphs in Figs. 5 through 8 mask any significant variations during the first six discharges. The average discharge histories plotted in Fig. 9 address this question by showing that the peak current does not change greatly with discharge serial number, and even increases slightly in the case of Kapton for both the low energy and the combined high and low energy exposure. For specific serial numbers, the peak currents varied typically over a 2:1 range. The other discharge properties (released charge, energy, pulse duration) exhibited similar variations, indicating that the average discharge properties are indeed representative of all the discharges.

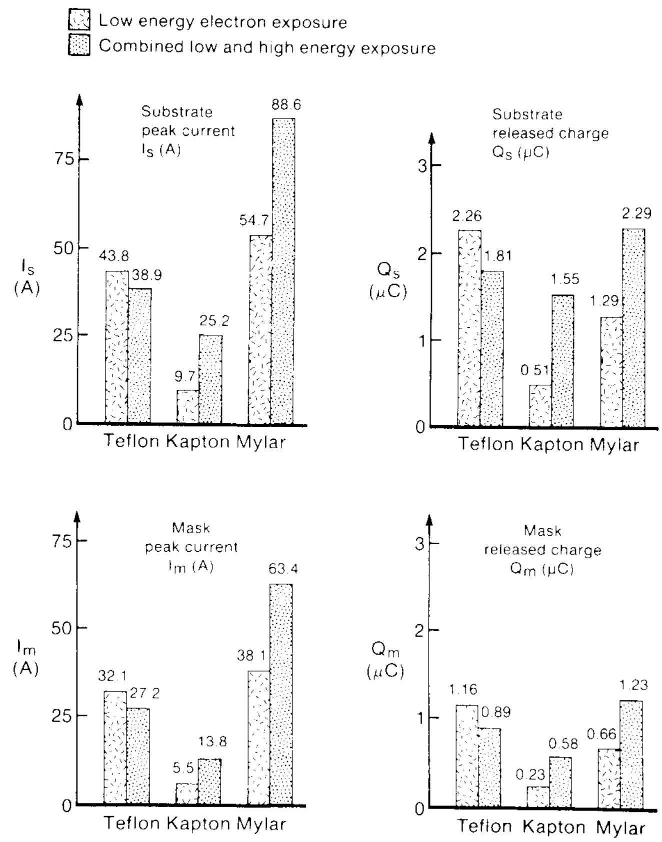

Fig. 5: Average peak current and average released charge for substrate and mask as measured over first 6 discharges.

The waiting times as shown in Fig. 9 vary appreciably, with the rapid increase for Teflon exposed to low-energy electrons being especially noticeable. If the range bars were shown in Fig. 9 (not shown because of complexity), one would see that these waiting times for Teflon for a given serial number varied typically over only a 4:1 range while the averages varied over a 10:1 range, which supports the significance of the 10:1 variation; however, no explanation is apparent. For Mylar, the variation with serial number is less pronounced and probably not significant in view of the 4:1 range at a given serial number. For Kapton, the situation is quite different because the variations at a given serial number were typically over a 15:1 range. In addition, for the high-energy case the 6th Kapton discharge waiting time was derived from only two specimens. All these factors suggest that the Kapton waiting time decrease over the first six discharges probably is not significant.

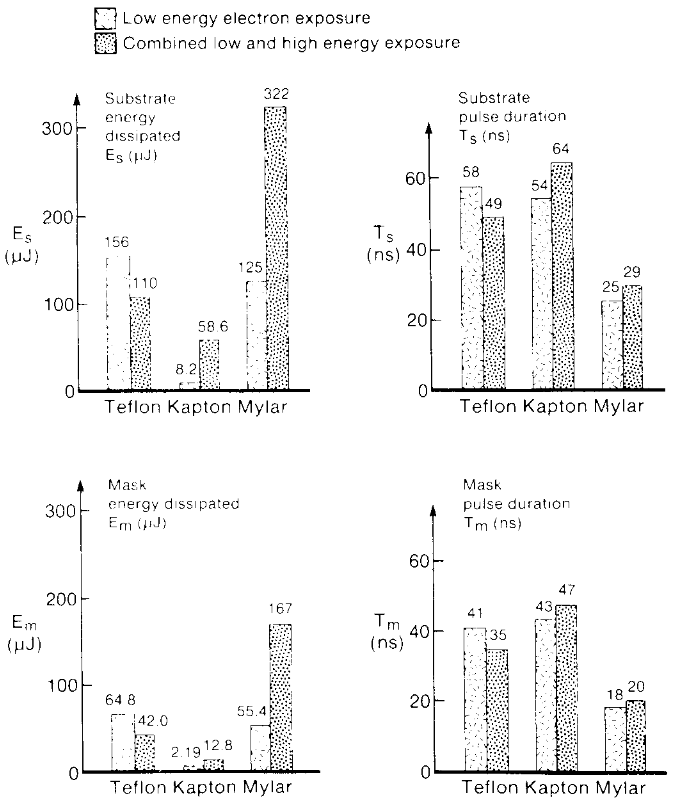

Fig. 6: Average energy dissipated in a 2.5 ohm load resistor and average pulse duration for both substrate and mask as measured over first 6 discharges.

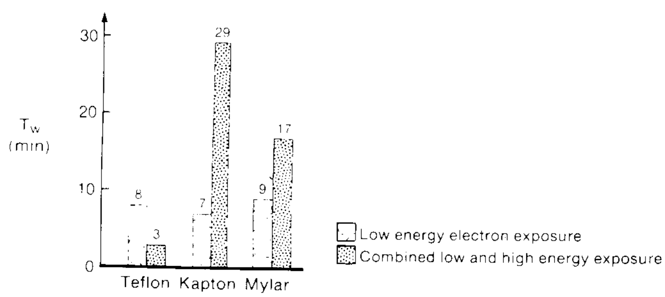

Fig. 7: Average waiting time between discharges as measured over first 6 discharges.

CONCLUSIONS

It is necessary to consider a detailed discharge history for each specimen tested in order to characterize properly each material with respect to both fatigue and average discharge properties. Such discharge histories show, for example, that the formation of a punchthrough is characterized by an abrupt change to weaker and more frequent discharges.

Table 1. Ratio of High+Low to Low Energy Average Discharge Properties

	I_s	Q_s	E_s	T_s	T_w
Kapton	2.6	3.0	7.1	1.2	4.1
Mylar	1.6	1.8	2.6	1.2	1.9
Teflon	0.9	0.8	0.7	0.8	0.4

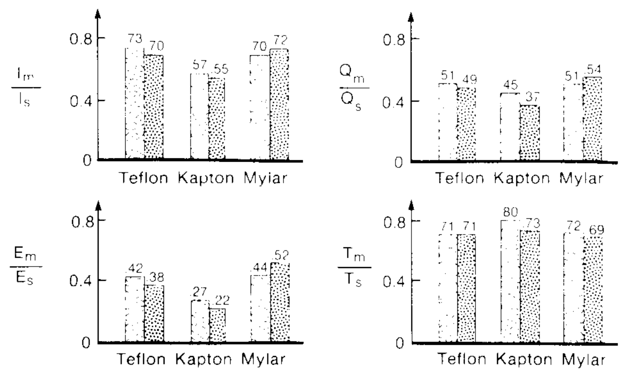

Fig. 8: Average mask-to-substrate ratios over first 6 discharges for peak current, released charge, energy dissipated in a 2.5 ohm load resistor, and pulse duration.

The addition of high-energy, broad-spectrum electrons to a 10 nA/cm^2, 20 keV electron beam has the following effects:

1. For Kapton, the number of discharges per specimen is cut in half.

2. For Kapton and Mylar, the discharges that do occur are much stronger.

3. The waiting time between discharges for Kapton and Mylar increases greatly, in approximate proportion to the charge released during discharge.

4. The pulse durations and mask-to-substrate ratios remain essentially unchanged for Teflon, Kapton, and Mylar.

5. For Teflon, the steadily increasing waiting times for low-energy electrons become appreciably smaller and constant upon addition of high-energy electrons.

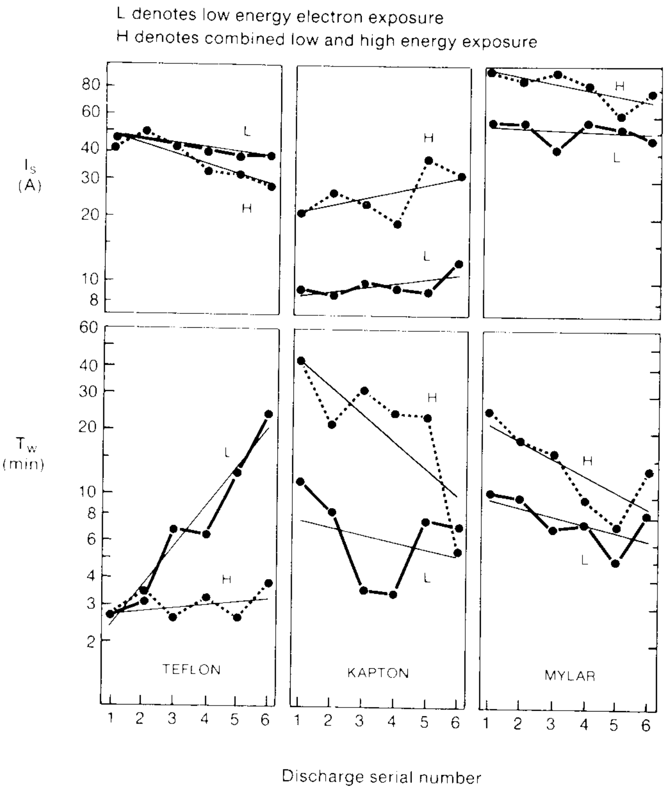

Fig. 9: Average discharge histories for all specimens tested for up to the first 6 discharges.

Thus, for Kapton in particular, and to a lesser degree for Mylar, the effect of adding broad-spectrum high-energy incident electrons is to cause discharges which are stronger but fewer in number and less frequent. However, the fact that the pulse durations and mask-to-substrate ratios are unchanged suggests that the physics of the discharge process is unaffected by the high-energy electrons (the discharge physics also determines the arc propagation velocity which for Mylar appears to be a factor of two higher than for Teflon and Kapton, for the particular specimens tested). The correlation between the waiting time and released charge suggests that the high-energy electrons influence strongly the charge accumulation process. It is postulated that additional beam-induced and nonlinear conductivity during the charge-up process acts to delay the formation of charge concentrations and resultant high-field regions which are strong enough to trigger discharges.

The low-energy flux levels employed are somewhat higher than the values expected in synchronous orbit, and the ratio of low-energy to high-energy fluxes is 2000 which is also high with respect to synchronous orbit. Nevertheless, conditions have been found such that discharges are made stronger by the addition of energetic electrons rather than being eliminated completely as found in earlier work done at lower low-energy fluxes [6,7]. Although further study is required, it is clear at this stage that the spacecraft charging threat to satellites cannot be dismissed easily because of the presence of high-energy electrons in synchronous orbit.

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