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4. Investigation of a CTS Solar Cell Test Patch Under Simulated Geomagnetic Substorm Charging Conditions

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Abstract

The CTS solar array technology experiment which consists of a solar cell test patch on the Kapton-substrate solar array and the appertaining electronics unit has been operating in geostationary orbit for nearly 1 year without any malfunction although it is expected to be strongly influenced by charging effects on the array surface.

The results of a past-launch test program show that the experiment would not survive a discharge due to electrostatic charging in the test patch area. In a simulated substorm environment discharges were obtained only below a temperature threshold of about 30°C. With solar illumination, this threshold is reduced below a°C.

1. INTRODUCTION

Spacecraft in geosynchronous orbit and under magnetic substorm conditions are known to be subject to differential charging of different material surfaces leading to high values of electric stress and arc discharges if the threshold for electrical breakdown is surpassed. The highest electric stress is expected on insulating material surfaces which are not sun-illuminated and therefore cannot equilibrate at low potentials by photoemission of electrons.

The Communications Technology Satellite, CTS, which has been in orbit since January 1976 has a sun-oriented 2-wing solar array using a 75 micron thick kapton-glass fibre-compound flexible substrate. The insulating rearside of the array is shaded permanently and therefore constitutes a principal source of discharges.

The CTS flexible solar array is equipped with a solar cell test patch which forms part of the solar array technology experiment provided by ESTEC. The test patch and the appertaining electronics unit are expected to be strongly influenced by discharges on the solar array surface. Therefore, a post-launch test program was initiated in order to study the behaviour of the solar array electronics experiment under simulated substorm conditions. The tests described here were performed in the 2.5 m Space Simulation Chamber of DFVLR in Porzwahn, Germany, in the first quarter of 1976.

2. TEST OBJECTIVES

The data which are presently available on differential charging and arc discharges are not sufficient to predict the behaviour of the CTS solar array experiment in a geomagnetic substorm for two reasons:

(1) Most of the investigations have been done on materials level and the results cannot be applied to more complex structures because there is too little knowledge on structural and size effects.

(2) The investigations on representative samples[1] have not been performed in a representative environment, as far as solar simulation and temperature are concerned.

Therefore a principal goal of the investigation was to analyze the influence of simulated substorm electron plasmas on a representative solar cell test patch under representative environmental conditions.

In detail, the test objectives were as follows:

(1) Measurement of the electron beam induced leakage current through the substrate as a function of electron energy, ambient temperature and solar illumination.

(2) Analysis of the discharge pulse frequency and pulse shape at the output of the solar cell test patch as a function of temperature and solar illumination.

(3) Analysis of the AEE (array experiment electronics) performance in a simulated substorm.

The outcome of these measurements Would allow for direct conclusions in conjunction with actual flight data:

(1) If characteristic anomalies occur at the AEE output during arc discharging, then the AEF could be used as a discharge indicator on CTS. Similarly, if arc discharges turn aut to destroy the AEE, one could determine the time of the first substarm generated discharge pulse from the time of malfunction of the AEE.

(2) If the solar array experiment perfbrmance is not disturbed by discharge pulses, one can have more confidence in the reliability of the flight data.

3. THE SUBSTORM SIMULATION FACILITY

The large 2.5 m space simulation chaniber at DFVLR, Porzwahq Germany, was selected because boundary effects from the wall chambers are kept to a minimum, and because it offers the possibility to mount much larger test samples in a future series of tests.

A cross section through t'ie chamber is shown in Figure 1. The sample is mounted vertically by means of teflon wires. Illumination of the sample front side is provided by a sun simulator of 1 solar constant. The sample rearside can be irradiated homogeneously with electrons, the electron gun being mounted on the center flange of the chamber lid at the rearside. Visual control is possible through a window inclined 15° to the beam axis.

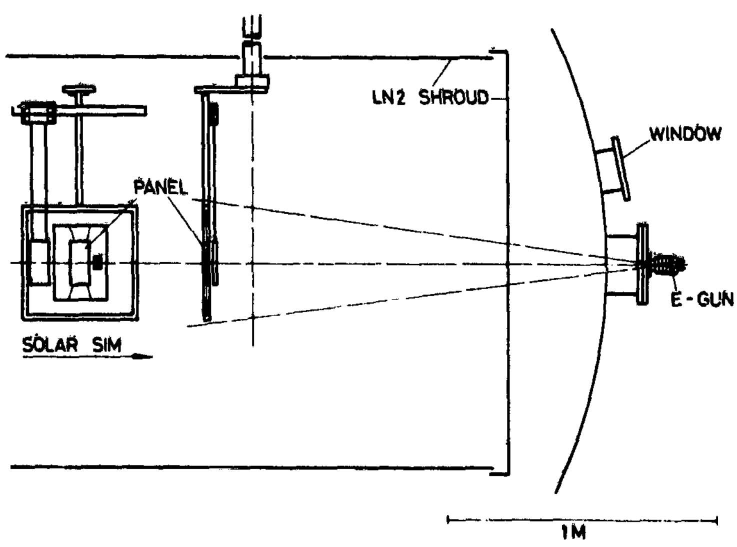

Figure 1. The Geomagnetic Substorm Simulation Facility

Using the liquid nitrogen cold shroud, the residual pressure is below 10^{-6} torr. Without cold shroud, the pressure is between 10^{-4} and 10^{-5} torr.

The electron energy can be continuously varied between 0 and 60 kV. The current density at an electton beam diameter of 1 m^2 in the test plane is between 1 and 100 nA/cm^2.

The uniformity of the electron beam intensity in the test plane cari be checked using a detector with an array of six equally sized receiver plates. A beam uniformity of ±30 percent is achieved without special adjustments.

4. TEST SAMPLE

The test specimen consisted of two parts: the solar cell test patch on a flexible panel-substrate and the AEE engineering unit.

The layout of the test patch is shown in Figure 2. Three solar cells are arranged in parallel and 9 cells in series. On the right hand sideis a representative part of the CTS solar array wiring. At the bottom two PT-temperature sensor are positioned beneath two dummy cells.

The substrate consists of a compound of:

25 μm kapton H film
35 μm glass fibre cloth
5 μm polyester adhesive (Dupont 46971)

The solar cells are mounted on the glass fiber side with RTV 560.

Typical I-V characteristics of the test patch under 1 sblar constant illumination and at various temperatures are shown ih Figure 3.

The AEE has the function to monitor the performance of the test patch in orbit. The parameters tb be monitored are:

(1) the bpen Circuit voltage V_{oc},

(2) the shbrt circuit current I_{sc},

(3) current and voltage at four points of the I-V curve determined by resistors $R_1 - R_4$ (see Figure 3), and

(4) temperatures at the test patch and at four other positions of the panel.

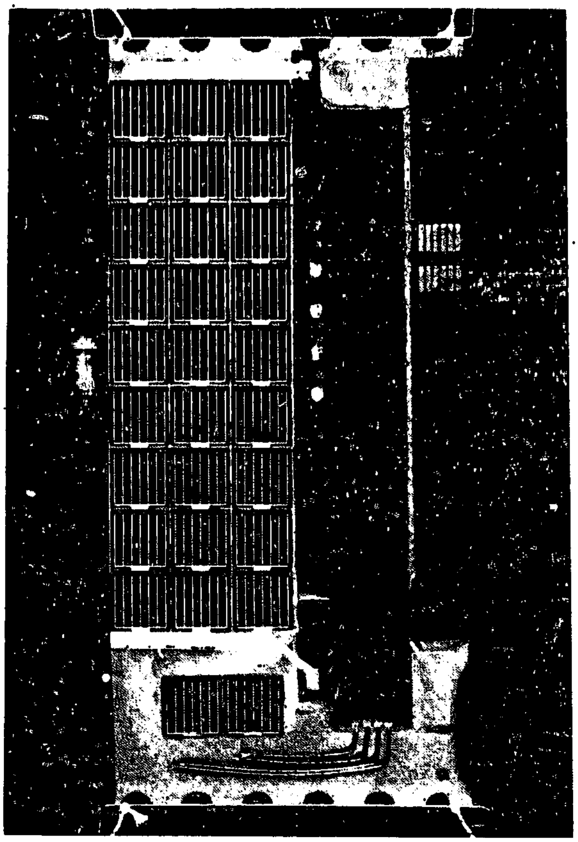

Figure 2. The CTS Solar Cell Test Patch

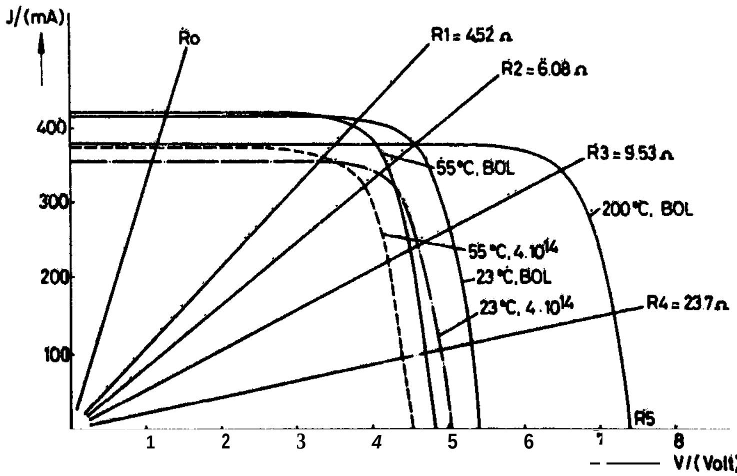

Figure 3. Test Patch I-V Curves

5. CHARACTERISTICS OF DISCHARGE PULSES

With the test patch at room temperature and no illumination, discharges were observed at electron energies above 15 kV.

The discharge frequency was found to be proportional to the electron beam current density. At a beam current of 60 nA/cm^2 a discharge rate of 8 pulses/min was measured, the pulses occurring at rather regular intervals.

Visual observation of the test patch during discharges showed a localized spot of high intensity light emission surrounded by a lower intensity 'Lichtenberg-figure' covering the whole sample rearside. The position of the high intensity spot varied from discharge to discharge and no preferred position could be detected.

To analyze the electrical characteristics of discharges as seen at the test patch terminals, the test patch was connected to an external circuitry as shown in Figure 4. The length of the connecting leads corresponded approximately to the wiring on the spacecraft in order to simulate in-orbit conditions to a certain extent. Nevertheless, considerable deviations in the high frequency properties were anticipated due to different capacitive and inductive components.

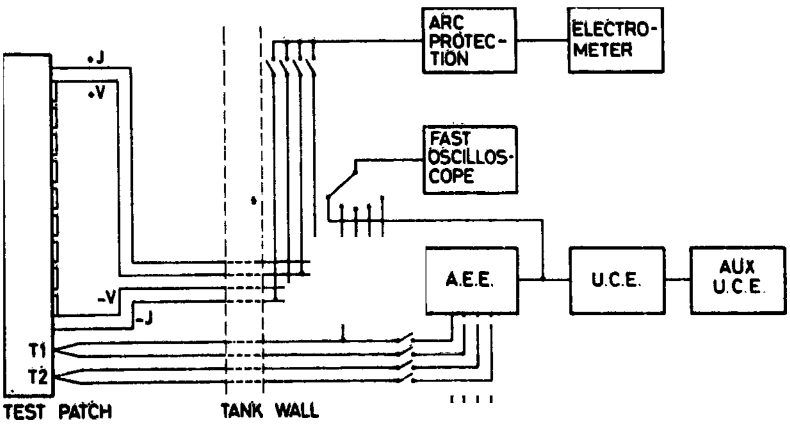

Figure 4. Wiring Diagram

A 20 kΩ terminal resistor, consisting of 20 Ω + 180 Ω + 1800 Ω in series, was connected across the output of the 3 × 9 solar cell module. This corresponds to the input impedance of the AEE when connected to the test patch. Transient signals during discharge were measured at the 0 Ω, 20 Ω, and 200 Ω points of the terminal resistor using a Tektronix 7704-A oscilloscope with a 10:1 attenuator. The peak voltages obtained were:

2 V at 0 Ω (EMI)

10 - 20 V at 20 Ω

100 - 200 V at **200** Ω

From this, the extrapolated peak voltage at 2 KΩ would be 1 - **2 kV.**

l'he transient pulses were rccordcd using a 2048 channel biomation transient recorder with a 50 Ω input impedance and a channel width of 10 μsec. Typical recordings are **shown** in Figure 5. The initial portion of the signal is not displayed in full amplitude due to the voltage limitation of the recorder **to** ±5 volts. **As ran be seen,** the pulses consist of damped oscillations with a typical decay time of 3-5 μsec for a terminal resistor of 50 Ω .

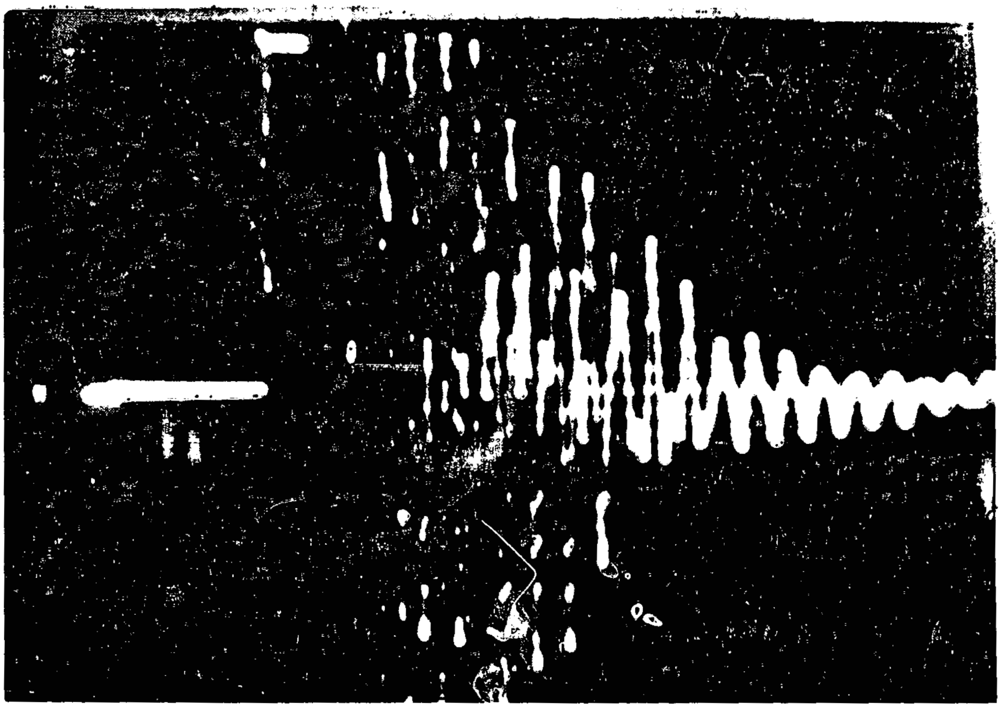

Figure 5. Discharge Transient Pulse (x-axis : 2 μsec/div; y-axis : **1.25** V/div)

The high frequency (3 MHz) oscillations are considered tu bc strongly influenced **by** the external circuitry and **no** dlrcct conclusions ran be drawn which are applicable to in-orbit bchaviour.

The pulse decay time, however, can be correlated with the RC time of the ctrcuit consisting mainly of the sblar cell capacitance of about 70 nF and the terminal resistor of 50 Ω and 2 kΩ, respectively. With the 2 kΩ terminal resistor, the peak voltage was 1000-2000 volt, From $E_s = 1/2\ CU^2$, a pulse energy of abuut 166 mJoule is calculated.

It must be kept in mind that pulses of this energy occur at the solar cell test patch output due tb pick-up from the energy of the discharge pulse at the rearside of the test patch. The maximum energy of the primary discharge pulse can be calculated on the assumptioh that the test patch represents a plate capacitor nsgatively charged over the whole rearside surface with respect to the solar cells on the front side which are on grouhd potential. The total capacitance of this plate capacitor is

$$C = \varepsilon\varepsilon_o\ F/d \simeq 4\ nF \quad .$$

If the entire surface charge is discharged within one discharge pulse, then the total discharge energy would be at maximum

$$E_D = 450\ mJoule \quad .$$

Comparing E_D with E_S and bearing in mind that E_S is only a fraction of E_D because only a fraction of the total energy is picked up by the solar cell module, the two energy figures indicate that, in fact, the charge accumulated over the whble rear surface is discharged in one pulse.

Thid is confirmed by the observed distharge rate of 8 pulses/min at the beam current density of 60 nA/cm^2. From these figures it can be ccncluded that the maximum charge deposited on the whole rear surface of about 100 cm^2 area in between two pulses in about 40 μA sec which at 15 kV represents a maximum stored energy

$$E_c = Q.U \simeq 600\ mJoule \quad .$$

As part of the charge is last by secondary emission and condudtion, E_D has to be somewhat smaller than E_c.

6. INFLUENCE OF AMBIENT TEMPERATURE AND ILLUMINATION OF THE DISCHARGE FREQUENCY

During these tests the discharges were monitored ushg the electron beam detectot as receiver antenna. The beam current density was kept between 20 and

100 nA/cm^2. Discharges on the test patch rearside caused a steep spike on the beam Current recording sufficient for event counting purposes.

Regular discharges at normal rates (Section 5) were Observed in the dark at room temperature. After opening the solar simulator shutter and exposing the front side of the test patch to one solar constant illumination the discharge activity ceased within less than a minute. No discharges were observed under illumination for time periods of more than 20 min and electron energies up to 20 keV. After turning off the illumination, it took about 3 min until the discharges occurred again.

Under illumination the temperature of the test patch as measured with the two temperature sensors rises to about 100°C With an initial slope of 40°C/min. Cool-down to ambient temperature after turn-off of the simulator takes about 5 min with an initial elope of 30°C/min.

The different behavior at turn-on and turn-off indicates that the temperature of the test patch has a strong influence on the discharge frequency. An additional influence of the illumihation can, however, not be precluded.

A more detailed examination of the test patch shbwed that illuminatian of the front side causes also the rearside to be illuminated because light penetrates the gaps between solar cells into the substrate where it is scattered by the light-pipe actibn of the glass fiber over the whole rear surface. Photoemission from rear-side could therefbre prevent excessive Charging of the rear surface. Another potential explanation would be photoconduction through the substrate,

To further investigate the influence of illumination, the tests were repeated with the cell gaps covered by a blackened Teflon mask inhibiting the penetration of light to the substrate. Figure 6 shows the discharge frequency befbre, during, and after solar illumination. The corresponding temperature profile is shown in the upper part. Thd same behavibr as in the test without mask was fouhd, that is, no discharge immediately after turn-bn and delayed reoccurrence of discharges after turn-off of illumination.

These results indicate that the test patch temperature is mainly responsible for the ceasing of discharge under illumination.

To verify these results under representative conditions, the tests were re-peated at liquid nitrogen ambient temperatures. The results are shbwn in Figure 7. In the dark the temperature is below -150°C. With 1 solar constant illumination the ;measured temperature rises to about 50°C. This measured temperature, how-ever, is not tdentical to the solar Cell test patch temperature because the sensors are located beneath twb dummy solar cells at the edge of the test patch, Therefore, there is a tendency for measuring the teniperature low due to the 'fin-effect' at the test patch edge. Thts could account for -5°C to -10°C. On the other hand, there

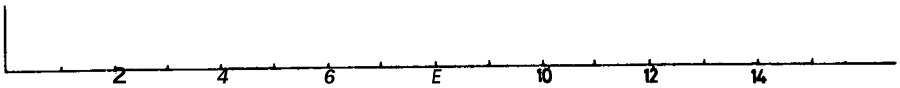

Figure 6. Discharge Rate During Illumination Transient (Without Cooling)

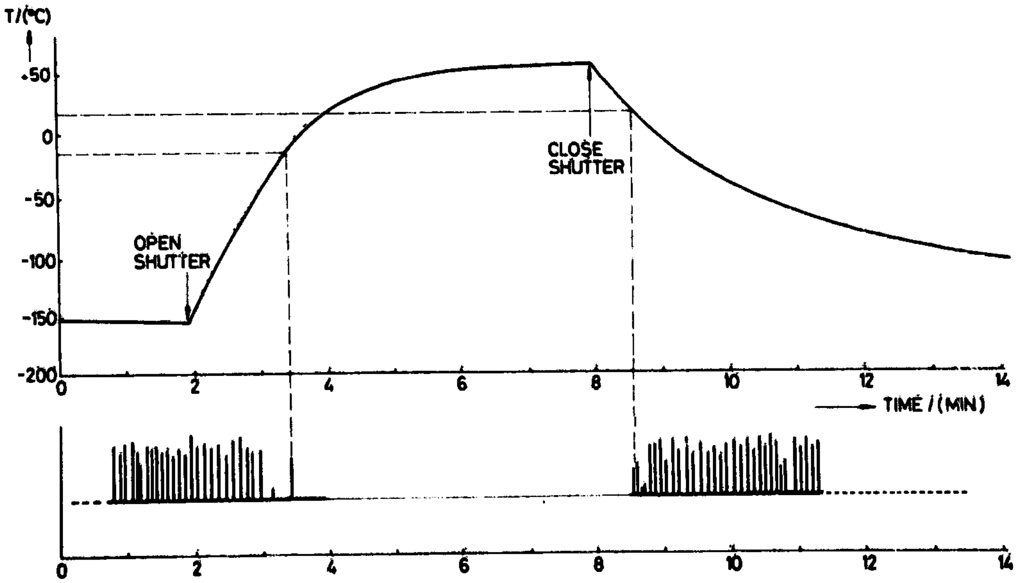

Figure 7. Discharge Rate During Illumination Transient (With LN_2 Cooling)

is a tendency to measure the temperature about 10°C too high because the solar cells of the module were loaded at maximum power in contrast to the cells on top of the sensors which wore in open circuit.

At -150°C the discharge frequency observed at 20 keV and a beam current density of 40 nA/cm² was 15 min⁻¹. After turn-on of illumination the discharges continue for about 2.5 min. This corresponds to a critical temperature of about -30°C. After turn-off of illumination the discharges reoccur at a sample temperature of about +15°C.

This result, although qualitatively showing the expected delay for ceasing of discharge, is quantitatively in contradiction to the results obtained without cooling where the critical temperature for ceasing of discharge had been found to be between 20°C and about 50°C. It appears that in the presence of solar illumihation the critical temperature is reduced by about 60-70°C.

This was confirmed by another test, With the chamber walls again cooled down to liquid nitrogen temperatures, the solar simulator intehsity was reduced step-wise. At 0.5 solar constant still no discharges were observed although the Sample temperature was down to -1°C. At 0.25 solar constant regular discharges occurred again. The sample temperature than was about -45°C.

7. CONDUCTIVITY THROUGH THE SUBSTRATE AT HIGH ELECTRIC STRESS LEVELS

The leakage current to the solar cell module through the substrate under electron irradiatibn of the rearside was measured by connecting the solar cell module terminal leads in parallel to the input of ah electrometer. The measurements were made at room temperature at a beam curredt density of 90 mA/cm². The beam energy was increased in 2 keV steps up to 16 keV. The results obtained in the dark are shown in Table 1, giving the equilibrium current after decay of the displacement current component. Between 1 add 5 keV positive current values were obtained indicating a secondary emission coefficient of more than 1. At higher voltages the leakage current increases supralinearly which shows that the conductivity increases with voltage!.

Illumination has a considerable influence on the leakage current, At 16 keV the Current increases from -2.25 μA to -5.8 μA after turn-on of the solar simulator. (The cell gaps were not covered by a mesh during these measurements but still the light intensity at the rearside is odly a small fraction of 1. S.C.) These results are qualitatively in agreement with the results recently obtained at Stanford Research Institute, SRI[2] on pure kaptoii samples. At SRI a conductivity increase of 10^5 was observed when illuminating kapton-H-film wtth 2.3 suns of Xenon illumination.

Table 1. Current Through Sample versus Beam Voltage

U - 0 kV	j = 0 nA
2 kV	+40 ... +20 nA
(Maximum bel ctwa 3 kV)	
4 kV	+25 ... +15 nA
6 kV	-30 nA
8 kV	-120 nA
10 kV	-260 nA
12 kV	-560 nA
14 kV	-1, 12 μA
16 kV	-2, 25 μA

8. IMPACT OF ELECTROSTATIC DISCHARGES ON THE ARRAY EXPERIMENT ELECTRONICS UNIT

In normal operation the array experiment electronics unit (AEE) is used to monitor the I-V curve of the test patch at six points and the array temperature at five ldcations on the solar array. Details of the design, canstruction, add performance of the AEE can be found in Ansorge and Pischel.[3]

The AEE telemetry sample sequence is shown in Table 2.

For the purpbse of the test, only the current and voltage sensing terminals of the AEE engineering unit and the wiring for two temperature sensors were connected to the test sample in the simulation chamber. The remaining input terminals were connected to the check-out unit which also provided the power supply and the clotk signal.

A print-out of AEE/test patch data is shown in Figure 8 indicating an open circuit voltage of 4.75 volts and a short circuit current of 263 mA with the test patch under 1 S.C. illumination. With the AEE running continuously, the electrbn beam voltage was increased in steps bf 1 kV starting at zero.

Up to 17 kV no discharges and no anomalies of the AEE performance were observed. Slightly above 17 kV still no discharges were observed, either visually or with the detecting antenna, but the AEE output showed loss of clock synchronization. The AEE swttched to the next channel at random rate.

In order to obtain discharges, the solar simulation was turned off with the electrbn beam being kept at 1? kV. After 25 discharges, the solar simulation was turned on again and the elkctron beam was switched off. The AEE output at this stage is shown In Figure 9. The AEE samples only open circuit voltage values and zero current Instead of the actual pairs of I/V values on the curve. This indicates

Table 2. AEE Sample Sequence

NO.	Nomenclature	
	Chanhel A	Channel B
1	V_{oc}*	T1
2	I_{sc}	T1
3	V_3	T1
4	I_3	T1
5	V_2	TL
6	I_1	T1
7	V_1	T1
8	I_1	T1
9	V_4	T1
10	I_4	T1
11	V_{ref}	<100 mV
12	T_1	<100 mV
13	T_2	<100 mV
14	T_3	<100 mV
15	T_4	<100 mV
16	T_5	<100 mV

*V_{oc} = open circuit voltage
I_{sc} = snort circuit current

that the input transistor(s) which load(s) the test patch according to the sample sequence has an open circuit fatlure.

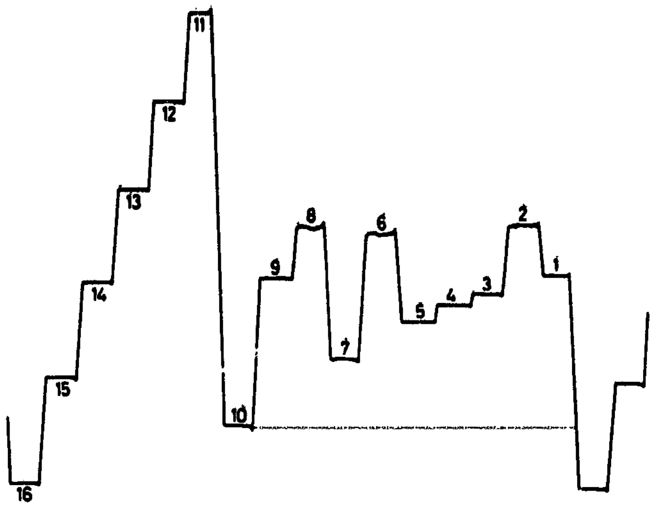

Figure 8. AEE Sample Sequence before Discharge

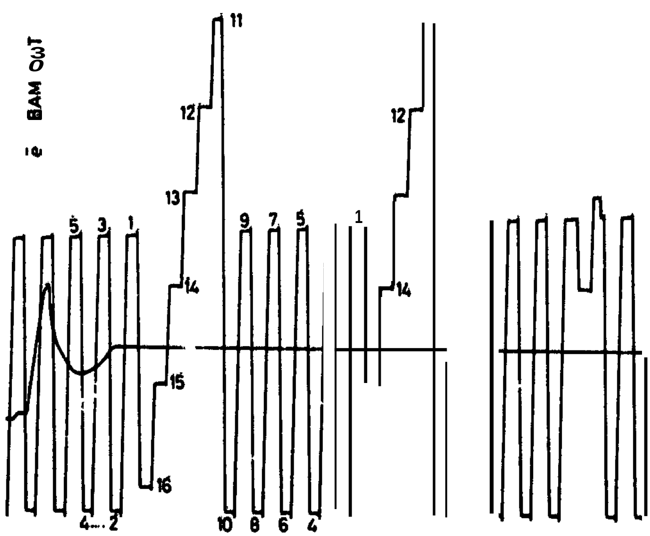

Figure 9. AEE Sample Sequence after Discharge

9. CONCLUSIONS

Several new phenomena have been observed in this series of substorm charging tests that may lead to a better understanding of the in-flight behavior of the CTS solar array experiment. Moreover, the test results may be of general importance for other solar arrays of similar design.

Discharges due to electrostatic charging of the solar cell test patch rearside occur at energies above 15 keV when the frontside of the test patch is not dun-illuminated. After turn-on of solar simulation, the discharge frequency decreases to zero within a short time. It could be shown that the test patch temperature is an important parameter for the discharge frequency. Above 30°-40°C no discharges are obtained. Moreover, the illumination level on the front side was shown to have an influence on the temperature limit below which discharges are obtained.

Finally it was shown that the experiments electronics will not survive discharges in the test patch area. As the solar array experiment is still operating in space, it can be concluded that up to now no severe discharges have occurred in the test patch area. The conclusion is made plausible by the observed discharge frequency dependence on temperature and illumination.

The phenomenological nature of the tests does not allow more quantitative conclusions to be drawn. More detailed data, however, are needed for the design and the specification of future solar arrays. Therefore it is planned to continue the tests as soon as possible and to obtain quantitative results in the following areas:

(1) Dependence of discharge energy, spectrum and frequency on the sample size.

(2) Investigation of the temperature and illumination intensity dependence of charging/discharging phenomena,

(3) Investigation of the behavior of new solar array substrate materials (for example, carbon-fiber-kapton compound) in a substorm environment.

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