Susceptibility of "Ultracapacitors" to Proton and Gamma Irradiation

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Abstract--**Ultracapacitors are promising components for energy storage, power backup and delivery systems. Our study examines the possible effects associated with gamma and proton irradiation in selected samples up to 1200 Farad.**

I. Introduction

THE "Ultracapacitor" is a commercial-of-the-shelf (COTS) energy storage component [1] having low internal effective series resistance and high capacitance. The technology is especially suited for applications where a large amount of power is needed for fractions of a second to several minutes. Ultracapacitor can provide high peak currents to loads while the power source provides steady state power. Using the ultracapacitor in this manner will reduce the power source volume and will prolong the power source life. The ultracapacitor can be charged and discharged indefinitely for the life of the system. They are already in use for military applications, hybrid electric vehicles, power generation plants, commercial electric vehicles and racecars. Ultracapacitors are good candidates for space applications in remote or stand-alone systems where the primary power source is provided by a battery, a fuel cell, or solar cell arrays.

The Technologies Assurance group at JSC conducted performance tests on ultracapacitor samples along with electrical and mechanical screening. These tests included visual inspection, fine leak test, accelerated life test, static burn-in, reverse bias test, self heat test via rapid charge-discharge, over voltage pulse, thermal shock and destructive physical analysis. The tests demonstrated that the device was suitable for the intended applications in the ISS electrical portable systems. However, no data is available on the reliability of the component and its performance in an ionizing radiation environment.

We have conducted a series of electrical tests before, during, and after gamma irradiating these devices with a ^{60}Co source and 60 MeV proton radiation. These tests were performed to characterize the electrical parameters of the ultracapacitors and examine any possible changes in their charge/discharge ability in a radiation environment. This electrolytic capacitor uses an electrolyte consisting of tetraethylammonium tetrafluoroborate, dissolved in acetonitrile solvent. To our knowledge no previously data has been obtained about the interaction of gamma or proton radiation with this electrolyte or individual component.

II. Experimental Procedure

Electrical characteristics testing was conducted to measure the capacitance (C) and equivalent series resistance (ESR) of the devices as specified by the manufacturer. Three different ultracapacitor models: PC10 (10Farad), PC100 (100Farad) and PC1000 (1200Farad) from Maxwell Technologies were selected. Pre- and post-radiation electrical testing were performed on four samples from each category.

The tests were performed according to the manufacturer's recommended procedures [1].

The charging current was monitored on the power supply. Voltage and current were occasionally measured using another multi-meter (shown as voltmeter in Fig.1) to verify power supply parameters.

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We recorded the voltage across the ultracapacitor every 500ms using the "Interactive Characterization Software (ICS)" [2] on a laptop computer. The ICS controls the operation of the semiconductor parameter analyzer hardware, Hewlett Packard model HP4145.

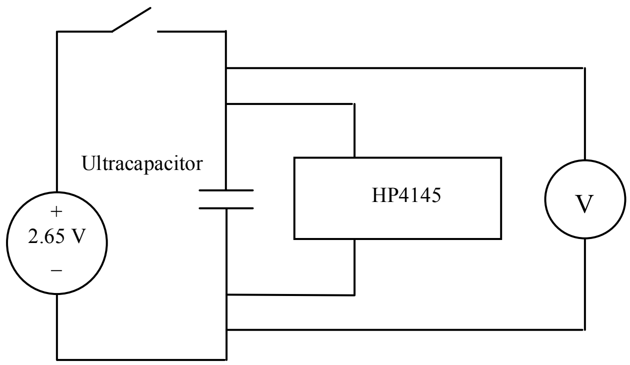

Fig. 1. Schematic of the test circuit

For in situ measurements an HP4142 was used instead. Each ultracapacitor was charged using an Agilent DC power supply model E3632A at constant current. The capacitance and the ESR were calculated using the recorded voltage vs. time data. The switch was opened whenever the specified voltage across the ultracapacitor was reached; this was usually 2.3V or higher (but not more than 2.6V). Each device was tested for 3 charge cycles before and after radiation exposure. For pre-determined intervals, selected samples received up to 200 Krad(Si) accumulated gamma (1Mrad(Si) in one case) and the total of 2 Mrad(Si) of 60MeV proton irradiation. The post irradiation electrical characterization took place approximately 45 days after gamma radiation exposure and 7 days after proton exposure. All measurements were taken at room temperature.

III. Data Analysis

A. Equivalent Series Resistance

The Equivalent Series Resistance (ESR) was calculated using the data collected from the charge cycle. The ultracapacitor electrical characteristics nominally behave exactly the same when charging or discharging [1] Fig. 2 shows the typical charging cycle for ultracapacitor model PC10 at a charging current (I_{ch}) of 500 mA charged to a maximum voltage of about 2.5V. The maximum reached voltage is designated as V_{max}. After the V_{max} was reached and the switch was opened (no charge current), the HP4145 continued collecting measurements. The measured voltage 5 seconds after disconnecting the charging current was designated as V_f. This voltage drop is due to the lack of charging current passing through the internal resistance of the ultracapacitor. The equivalent series resistance was calculated by using (1).

$$ESR = \frac{V_{max} - V_f}{I_{ch}} \quad (1)$$

Charging currents for PC100 and PC1000 were 2A and 5A respectively.

B. Capacitance

The capacitance values are calculated from voltage vs. time data while charging the device. The charging curve is not absolutely linear; therefore we calculated the capacitance in two different parts of the charging cycle.

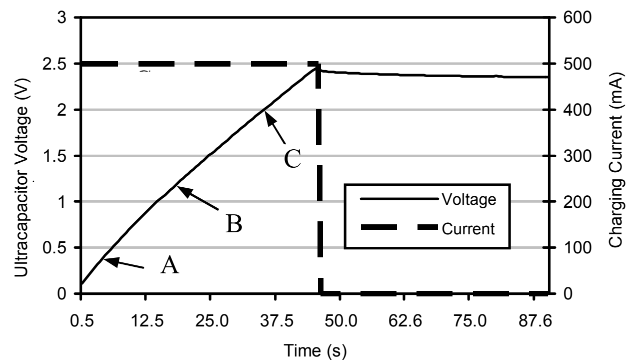

Fig. 2. Typical charging cycle for ultracapacitor model PC10. Similar behavior was observed for all samples of all categories.

Using (2) and (3) we calculated these two capacitance values.

$$C_1 = I_{ch} \frac{t_B - t_A}{V_B - V_A} \quad (2)$$

$$C_2 = I_{ch} \frac{t_C - t_B}{V_C - V_B} \quad (3)$$

For the calculations, three data points were selected A, B, and C (marked on the charge cycle curve) with charged voltages of 0.4V, 1.2V and 2V for each capacitor. All ultracapacitors were charged to the approximately same maximum voltage, so the points A, B and C and relevant times and voltages were reached for all samples. For instance, point A was selected such that the voltage V_A= 0.4 volts (or the recorded voltage closest to 0.4 volts) and time t_A is the corresponding recorded time. The same applies to point B and C at 1.2V and 2.0V respectively.

IV. Results and Discussions

The performance of the ultracapacitor before irradiation and after the irradiation was measured according to the procedures described above. Three sets of measurements were compared and analyzed to observe changes in the electrical parameters; C and ESR. Typical results for PC10 and PC100 are shown in Figs. 3 through 6.

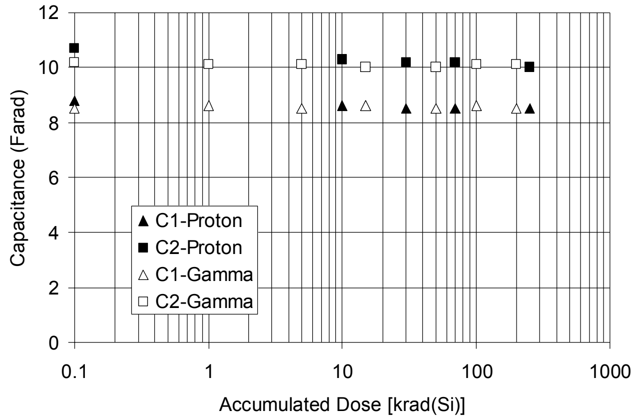

Fig. 3. Capacitance of ultracapacitor PC10 after proton and gamma irradiation, C_1 and C_2 are calculated in two different parts of the charge cycle. (The 0.1 krad on the X axis refers to pre-radiation values).

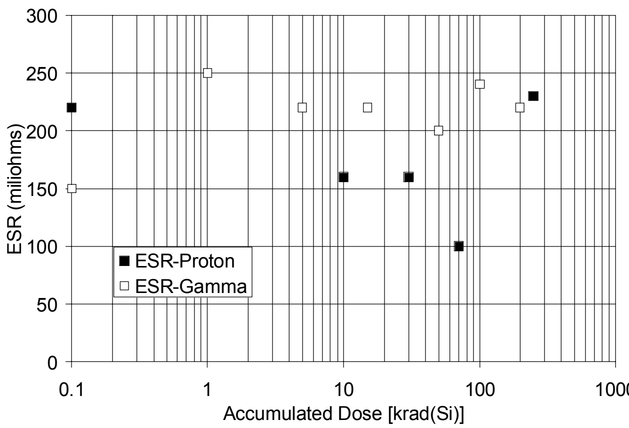

Fig. 4. Equivalent series resistance (ESR) of the ultracapacitor PC10 after proton and gamma irradiation. (The 0.1 krad on the X axis refers to pre-radiation values).

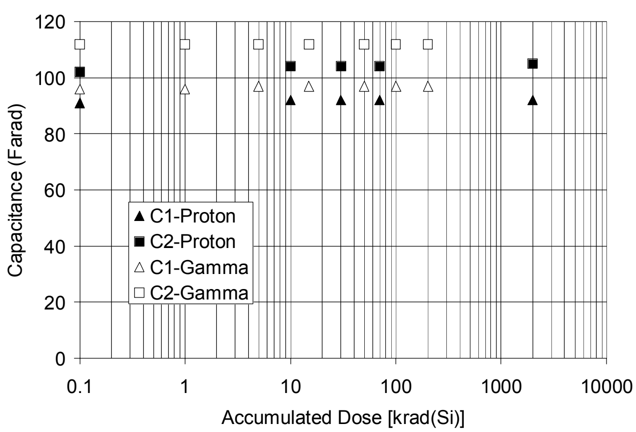

Fig. 5. Capacitance of ultracapacitor PC100 after proton and gamma irradiation, C_1 and C_2 are calculated in two different parts of the charge cycle. (The 0.1 krad on the X axis refers to pre-radiation values).

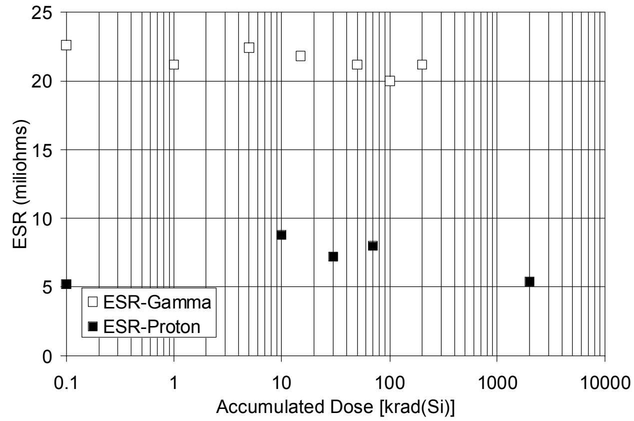

Fig. 6. Equivalent series resistance (ESR) of the ultracapacitor PC100 after proton and gamma irradiation. (The 0.1 krad on the X axis refers to pre-radiation values).

We did not observe any significant changes in C or ESR of the tested samples for gamma doses up to 200 Krad(Si) and even higher doses of proton irradiation up to 2 Mrad(Si). We believe the fluctuation shown for ESR is not a result of irradiation but from measurement artifacts. This problem might be solved using permanent connections and eliminating any possible contact resistance in the circuit. One gamma irradiated PC10 did show a significant change, this was the only unit that was exposed to a higher gamma dose level for 13 hours and received the maximum absorbed dose of 1 Mrad(Si). This unit became completely discharged while the leads were floating open and could not hold any charge for more than 60 seconds.

V. Conclusions

Except for the one unit exposed to 1Mrad(Si) gamma radiation, the devices tested showed no significant effects due to gamma and proton doses given. These observations indicate that these devices may be good candidates for low earth orbit applications. The results also suggest that applications for interplanetary exploration may be possible, but further work with high total ionizing doses should be performed.

VI. Acknowledgment

We would like to thank Mr. Mark Cohen from Maxwell Technologies for his valuable advices during our test and measurements on these devices.

VII. References

[1] Ultracapacitor Application Note, Maxwell Technologies, 9244Balboa Ave., San Diego CA 92123.
[2] Metrics Technology Inc., 3830Commons Ave., NE, Albuquerque NM 87109.