Investigation on solar array damage characteristic under millimetre size orbital debris hypervelocity impact

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ABSTRACT

During exposure to space environment solar arrays have high hazard to be impacted by orbital debris, since their large area. The conductors in solar cells would be destroyed by orbital debris impact, which would induce short circuit, open circuit, and a change of output power, and then influence the missions of the spacecraft consequently.

This paper presents the results of hypervelocity impact experiments that were carried out by two-stage light gas gun onto spacecraft solar array, and predicts the solar arrays power loss of a Chinese Shenzhou vehicle based on experiments data.

The solar cells samples were as same materials and facture as the Chinese ShenZhou vehicle. The hypervelocity impact facility was two stage light gas gun of China Aerodynamics Research and Development Center. The impact velocity was ranged from about 3.0 km/s to 6.5 km/s, and aluminium spheres with dimensions about 2-5mm were used. The mechanical damage features were analyzed, and the perforation diameter and maximum damage diameter were measured. According to the experimental data, the function between the perforation diameter and the kinetic energy of the projectile is obtained.

The changes of the solar cell's volt ampere characteristics before and after hypervelocity impact were analyzed, and the short circuit current, open circuit voltage, maximum output power attenuation, and the change of filling factor were obtained.

Finally, according to the solar cell hypervelocity impact test results, combined with the actual parameters of a certain orbit and orbital debris environment model, the power loss of spacecraft solar array was assessed.

1 INTRODUCTION

Solar arrays are the power source for most of spacecraft. As the solar array is exposed to orbital debris environment, and its area is larger than the satellite, the probability of impact by orbital debris may be higher than other positions of satellite. According the data from NASA, in a four-year period of operation, the Hubble Space Telescope solar arrays were estimated to be impacted by approximately 40,000 particles greater than 10microns, of which several hundred will perforate the arrays [1]. After hitting by orbital debris, the conductors within or between solar cells are damaged, resulting in open or short circuit, which affecting the operation of spacecraft. In order to evaluate the damage of solar arrays caused by orbital debris, a large number of investigations were carried out, including post-flight tests and ground simulation tests.

Post-flight impact data was collected from the Hubble Space Telescope, MIR station, EURECA satellite, et al, which was mainly used to study micro-meteoroid and orbital debris environment model [2], composition [3-5], and impact characteristics [6,7].

A variety of hypervelocity launch facility were used to study the solar array damage characteristic, such as two-stage light gas gun, plasma drag accelerator, laser-driven flyer device, and electrostatic accelerator. Since 1990s, the Marshall Space Flight Center, Johnson Space Center and Ernst-Mach-Institut have used two-stage light gas gun to study solar array impact characteristic respectively [8-12].Since 2005,Kyushu Institute of Technology have used two-stage light gas gun to do a series of investigation, in which hypervelocity impact tests and laser irradiation tests were conducted to the solar array under pseudo power generation in order to evaluate possibility of solar array arcing through the plasma created by debris impact, and the result of hypervelocity impact test suggests the possibility of discharge through the plasma created by impact[13-16].

In addition to the use of a two-stage light gas gun, a laser driven flyer method suitable in such a chamber was used to conduct an initial investigation of space debris impact on a new toughened solar cell cover glass material by Air Force Research Laboratory[17]. Damage characteristics, including mechanical damage and contamination generated by impact with a 3mm diameter, 3 micron thick aluminium particle accelerated to 4.5 km/s, were looked at. In order to estimate the

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

probability to detect and identify residue on a crater on any retrieved material exposed to space environment, hypervelocity impact tests used an electrostatic particle accelerator of Max Planck Institute (Heidelberg)were performed on solar arrays. The behavior of metallic targets under impact at various incidence angles is well-known but there are limited data on brittle materials such as the cover glass on the solar cells [18].

In 2005, Harbin Institute of Technology described the influence on solar cells by space dust impact[19]. The cumulated impacts of the space micro debris on the solar cells were experimentally simulated on the plasma dynamic accelerator in Center for Space and Applied Research, Chinese Academy of Science, and the damage equation was established. Based on the damage equation, the surface damage ratio of the solar cell due to micro-impacts was calculated, and the associated optical transmittance decrease of the cell was evaluated according to optical measurement and theoretical model [20-21]. In order to evaluate the change of solar cells characteristics after being impacted by micron-sized space debris, single impact and cumulate impact tests had been carried out using the laser-driven flyer system in Beijing Institute of Spacecraft Environment Engineering. The characteristics, including mechanical damage characteristics and volt-ampere characteristics had been measured and compared after tests [22].

In this paper, we present the results of hypervelocity impact experiments that were carried out by two-stage light gas gun onto spacecraft solar array, and predict the solar arrays characteristic change of a certain spacecraft basing on experiments data.

2 IMPACT SURVEY

The solar array samples are as same materials, parameters and processes as the Chinese ShenZhou vehicle, as shown in Fig. 1.

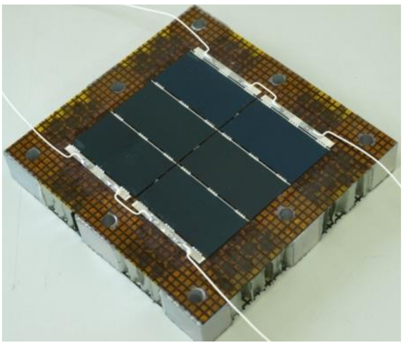
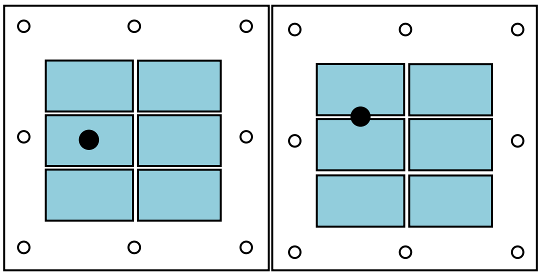


Figure 1 The sample of solar array

Individual solar array samples consist of 6 54mm ×30.5mm pieces InGaP/InGaAs/Ge triple-junction solar cells and a 150mm×150mm piece of substrate with a thickness of 25mm.The substrate is made of M60JB-3K-50B carbon fiber panel and a 3/8-5056-0.0007p Aluminium honeycomb.

The hypervelocity impact tests were carried out on the Φ7.6mm two-stage light gas gun of China Aerodynamics Research and Development Center. The impact velocity ranged from about 3.0 km/s to 6.5 km/s, and the impact angles was 0 °. Aluminium spheres with dimensions about 2-5mm were used. Two different impact locations were selected for testing, which were at the center of a piece of cell and at the cells junction, as shown in Fig. 2.



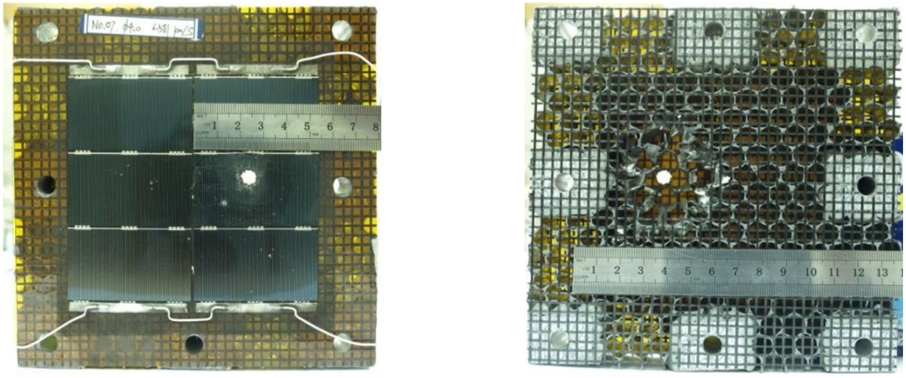
(a)At the center of a cell (b) At the cells junction

Figure 2 Sketch of impact point of solar array

The experimental results are shown in Tab. 1. Fig. 3 and Fig. 4 show impact features on solar array. Fig. 5 is a schematic representation of a ‘at the center of the cell’ impact. The figure demonstrates the different parameters to be measured, such as the perforation diameter D_h, fracture zone diameter D_S, and extended fracture zone diameter D_{CO}, which are nearly circular.

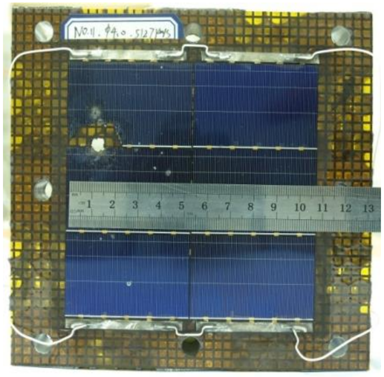
Table 1Tthe results of hypervelocity impact

Test No.	Proj. dia. (mm)	Velocity(km/s)	Impact location	perforation dia. (mm)	fracture zone dia.(mm)	extended fracture zone dia.(mm)	Damage dia. of honeycomb back (mm)
No.01	3.0	3.213	center of a cell	4.5	7.5	30.5	12
No.02	3.0	6.245	cells junction	6.3	9.8	35.0	30
No.03	3.0	6.093	center of a cell	6.0	9.6	35.0	25
No.04	5.0	6.301	center of a cell	7.8	15.2	55.0	40
No.05	5.0	4.097	center of a cell	6.9	12.3	39.0	30
No.06	5.0	5.242	center of a cell	7.45	12.6	42.0	37
No.07	4.0	6.581	center of the cell	6.8	12.0	44.0	40
No.08	5.0	3.247	The corner of a cell	6.6	11.1	37.1	25
No.10	5.0	4.332	cells junction	7.0	13.1	40.0	35
No.11	4.0	5.127	cells junction	6.0	16.2	36.9	30
No.12	5.0	3.205	cells junction	6.55	11.0	34.0	25
No.13	3.0	6.39	cells junction	7.5	27.5	45.8	25
No.14	2.0	6.398	cells junction	4.8	8.8	26.1	25

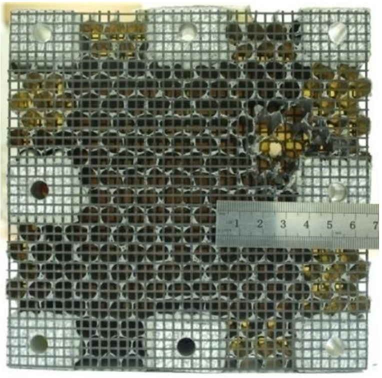


(a) front *(b) back*

Figure 3 Features of No.07 sample after impact



(a) *front*



(b) *back*

Figure 4 Features of No.11 sample after impact.

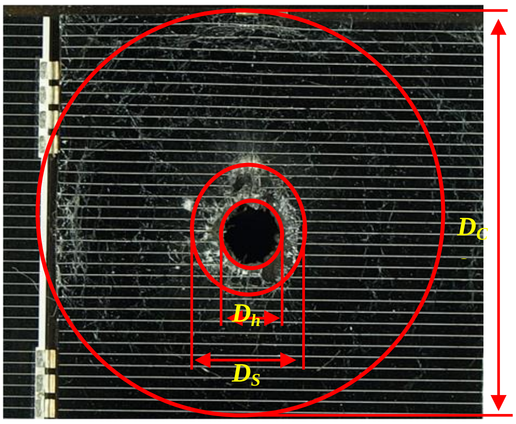


Figure 5 Sketch of damage zone division

3 MECHANICAL DAMAGE CHARACTERISTIC

3.1 Impact Damage Morphology

Fig.6 is the solar cell damage morphology after impact by the diameter of 3mm projectile at 6.093km/s. It can be seen from the figure, there are irregular peeling phenomenon around the perforation, and the solar cell substrate material come out in the peeled area. In addition, at the area where the cover glass is not peeling off, there are cracks spread to a larger area.

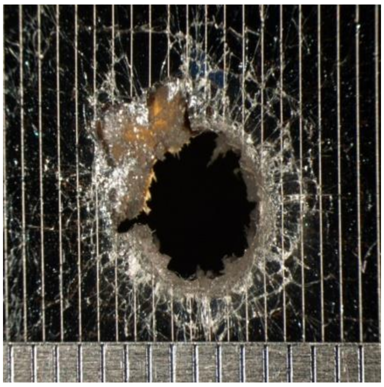


Figure 6 The damage features of solar cell after impact (DP=3.0，V=6.093km/s)

The shock wave generated by the hypervelocity impact will break the brittle material sample boundary and even affect the whole sample. The boundary effect of the solar cell is shown in Fig 7. As the brittle material has brittleness and low tensile strength, the smaller the sample is, the more likely the boundary effect appear, which resulting in greater damage. At the same time, the stronger the impact of the shock wave is, and the more obvious the boundary effect is.

Figure 7 The boundary effect of solar cell after impact

3.2 Impact Damage Equation

According to the experimental data, a through hole diameter prediction equation was developed and is given as Eq. 1, and the relationship of hole diameter D_h and the cube root curve of the kinetic energy of the projectile is shown in Fig.8.

$$\mathrm{Dh} = 1.3\mathrm{En}^{2/9} \qquad (1)$$

Where D_h is the diameter of the through hole (mm) and En is the projectile kinetic energy (J).

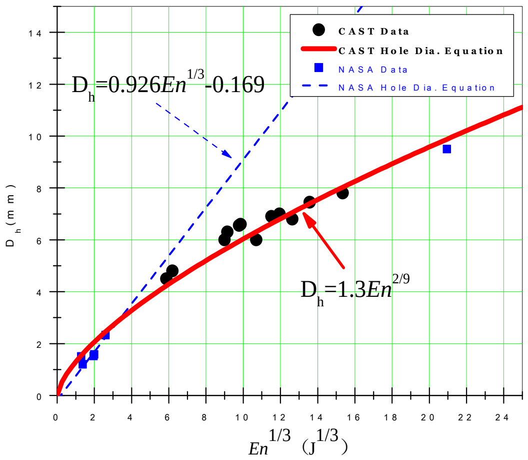


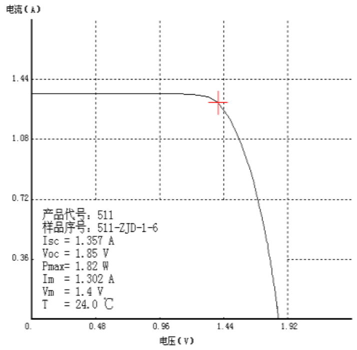
Figure 8 Perforation Diameter VS. cube root of projectile's kinetic energy

The equation developed by NASA is shown in Fig. 8[1]. By comparing the NASA's predictive equation and our work, we can see that NASA equation is a straight-line form, while our equation is not. It is found that the relation between the perforation diameter and the cube root kinetic energy of the projectile is not in a linear but change exponentially. Moreover, the diameter of the hole should be zero when the kinetic energy of the projectile is zero, therefore the curve should pass through the origin, while the NASA equation clearly does not pass the origin.

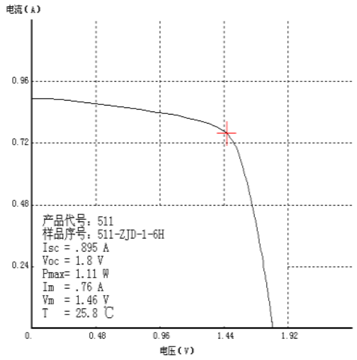
4 VOLT - AMPERE CHARACTERISTICS

The performance of the solar cell is characterized by its voltage-current curve. The main parameters are open-circuit voltage V_{oc}, short-circuit current I_{sc}, maximum output power P_{max} and fill factor FF, and other electrical parameters can also be obtained from the voltage-current curve.

Fig. 9 shows the volt-ampere characteristic curves of the No.7 sample before and after impact, and Tab. 2 shows the test data of the volt-ampere characteristic of the solar array before and after the impact experiments.



(a)Before impact



(b)After impact

Figure 9 The volt-ampere characteristics of No.07 sample

The short-circuit current of the solar cell has a significant decrease after impact, the average attenuation is 32.94%, and the maximum attenuation is 56.61%. The relationship between short-circuit current attenuation and the perforation area is obvious, which is linear, as shown in Fig. 10, the relationship with the area of the fracture region is approximately linear, and the with the extended fracture area is not monotonically increasing.

The average attenuation of the maximum output power of solar cells is 34.91%, the maximum value of 59.78%. Fig. 11 illustrates the relation between the attenuation of the maximum output power and the perforation area, which is linear.

We can see form the test results that the short-circuit current and the maximum output power are related to perforation area directly, because cover glass and the battery internal semiconductor materials are destroyed after perforation; and are related to extended fracture zone area lightly, because there is no damage to the semiconductor material, and the cracks in cover glass resulted in decrease of its optical transmittance, which can only change the current, but not the series and parallel resistance and load voltage.

In the analysis of the short-circuit current and the maximum output power, the test data which the impact point is located at the junction of two cells is not used, for these data did not show the any rules, and it will be analyzed farther.

Although the perforation area of Test No.2 is not the maximum among all of the tests, its short-circuit current and maximum output power attenuation are maximum, for the impact point is located in the junction of the two cells, and the impact speed is the highest.

Table 2 Volt-ampere characteristics of solar array

Test No.	V_{oc}			I_{sc}			$P_{\max}$			FF		
	Before impact /V	After impact /V	Descent /%	Before impact /A	After impact /A	Descent /%	Before impact /W	After impact /W	Descent /%	Before impact	After impact	Descent /%
No.01	1.85	1.80	2.70	1.381	1.154	16.44	1.80	1.53	15.00	0.703	0.740	-5.16
No.02	1.85	1.74	5.95	1.369	0.594	56.61	1.79	0.72	59.78	0.708	0.694	2.05
No.03	1.84	1.79	2.72	1.365	0.975	28.57	1.82	1.21	33.52	0.724	0.696	3.82
No.04	1.83	1.77	3.28	1.382	0.867	37.26	1.80	1.07	40.56	0.710	0.699	1.53
No.05	1.85	1.81	2.16	1.386	0.886	36.08	1.79	1.16	35.20	0.696	0.723	-3.84
No.06	1.85	1.81	2.16	1.389	0.907	34.70	1.82	1.11	39.01	0.706	0.676	4.15
No.07	1.85	1.80	2.70	1.357	0.895	34.05	1.82	1.11	39.01	0.726	0.689	5.14
No.08	1.83	1.79	2.19	1.364	1.008	26.10	1.80	1.37	23.89	0.721	0.756	-4.90
No.10	1.84	1.79	2.72	1.371	1.025	25.24	1.80	1.34	25.56	0.714	0.730	-2.21
No.13	1.85	1.81	2.16	1.369	0.898	34.40	1.81	1.13	37.57	0.715	0.696	2.60

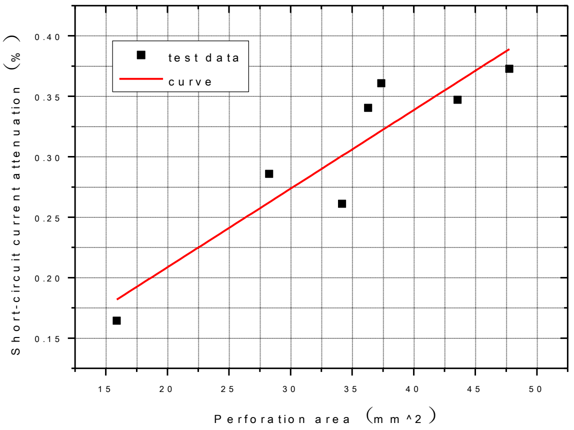


Figure 10 Short-circuit current attenuation VS. Perforation area

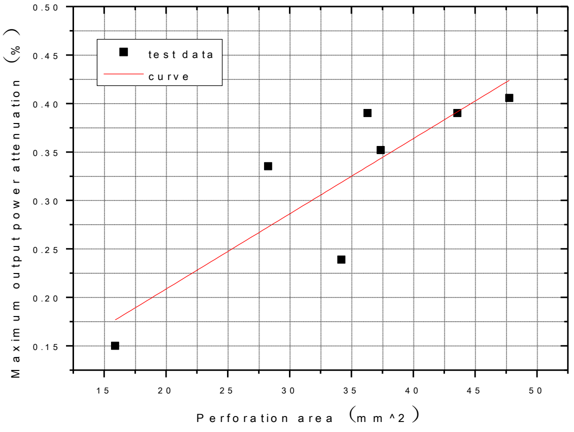


Figure 11 Maximum output power attenuation VS. Perforation area

The open circuit voltage of the solar cells is decrease after impact. The average attenuation and maximum attenuation are 2.87% and 5.95%respectively. It is considered that the impact of millimetre space debris has little effect on the open circuit voltage of the solar cells, and there is no directly relationship between the area of damaged region and attenuation.

The ratio of the maximum output power ($Imp \bullet Vmp$) to the product of short circuit current and open circuit voltage ($Isc \bullet Voc$) is called the battery fill factor (FF), which represents the "squareness" or "hardness" of the volt-ampere characteristic curve. The larger the FF is, the higher the corresponding conversion efficiency is. According to the test results, the FF changes little before and after the impact, which changes in the range of -5.16% ~ 5.14%, and the average change is 0.32%.

5 EVALUATION OF SOLAR ARRAYPERFORMANCE

Based on the experiment results of the solar array, and the actual parameters of the orbit and the orbital debris environment model, the performance of a spacecraft solar array is evaluated.

The orbital parameters of the Chinese ShenZhou vehicle are as follows, the altitude of orbit is 400km, the inclination is 51.6 °, the time in orbit is 3 years, and the total area of two solar arrays is 12.24m^2. In the period from 2016 to 2018, the number of particles impacted on the solar arrays is shown in Tab. 3, which is calculated by NASA orbital debris engineering model ORDEM2000. According to Tab. 3, the number of particles which diameters are larger than 1 cm, 1 mm, 100 µm, and 10 µm, is 1.49E-4, 1.7, 812, and 32400, respectively. According to NASA data, Hubble Space Telescope was hit by 40,000 pieces of debris larger than 10µm during the four-year operation, and the perforation caused by impact was several hundred times, which indicated that the calculation of this paper is reasonable.

We assume that the size of orbital debris diameter is 5mm, 500µm and 50µm, According to the test results above, the evaluation result of solar array performance is shown in Tab. 4. We can calculate the sum of the perforation area of all sizes is 0.05% of the total area of the solar array by using the impact damage equation. The 0.36% area loss caused by the perforation result in34.91% loss of the output power, therefore the solar arrays power will be loss of 4.85% during the three-year operation.

Table 3Orbital debris impact number in 2016-2018

Particle number	>10µm	>100µm	>1mm	>1cm
Average flux（/m^2/ year）	8.83E+02	2.21E+01	4.60E-02	4.06E-06
Total flux in 3 years	3.24E+04	8.12E+02	1.69E+00	1.49E-04

Table 4 Evaluation result of solar array performance

Particle size	50µm	500µm	5mm
total flux in 3 years	32400	812	1.7
perforation diameter of single particle(mm)	0.3904	1.8121	8.4112
perforation area of single particle(mm^2)	0.1197	2.5790	55.5656
perforation area of single particle ×Total flux in 3 years(mm^2)	3878.28	2094.15	94.46
total area of perforation(m^2)	6.0669×10^{-3}		
perforation area percent	0.05％		
power loss percent	4.85％		

6 CONCLUSIONS

In this paper, the hypervelocity impact characteristics of spacecraft solar arrays were studied on two-stage light gas gun. The relationship between the perforation diameter and the cube root of the kinetic energy of the projectile was obtained, which is not linear, but exponentially.

The changes of the solar cell's volt ampere characteristics before and after the hypervelocity impact were analyzed. The short-circuit current and the maximum output power are related to perforation area directly, and open-circuit voltage and the filling factor have little change after impact.

Finally, according to the solar cell hypervelocity impact test results, combined with the actual parameters of a certain orbit and orbital debris environment model, the power loss of spacecraft solar array was assessed. According to the space debris impact risk assessment of the spacecraft in 400 km orbit with solar arrays of a total area of 12.24m^2, it showed that the solar cell array power loss is 4.85% in 2016-2018. Therefore, the space debris environment has little effect on the life of the solar array, after hit by the millimetre-level space debris, without the whole solar array being short-circuited.

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