DESIGN, DEVELOPMENT AND MANUFACTURING OF THE ELECTRICAL PART OF SOLAR ARRAY FOR CHINA-BRAZIL EARTH RESOURCES SATELLITE – CBERS 3&4

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Abstract. *This paper addresses the design, development and manufacturing of the Electrical Part of Solar Array (EPSA) for the China-Brazil Earth Resources Satellite – CBERS 3&4. The EPSA design is based on a chinese triple-junction solar cell and shall generate more than 2.5 kW during three years life in orbit. Laboratory test conditions and in-orbit Begin-Of-Life (BOL) and End-Of-Life (EOL) simulated electrical characterists, as well as, simulated in-orbit thermal behavior are presented. Power analysis results for both standard laboratory environmental and test conditions are compared with test results of a Small Test Panel Section (Test Coupon). An EPSA design representative Test Coupon was manufactured and its environmental qualification tests results are presented. The adjustments of the triple-junction solar cell welding parameters based on destructive test results are discussed. Manufacturing characteristics of the first lot of 10000 Solar Cell Assemblies (SCAs) for the CBERS 3 solar array flight model, including manufacturing electrical and mechanical losses are also discussed.*

Keywords*: Solar array, solar cells, satellite, design, development, manufacturing.*

1. INTRODUCTION

The China-Brazil Earth Resources Satellite - CBERS is a cooperative program between Brazil and China for the development of a series of remote sensing satellites. The CBERS´s Program placed Brazil among the nations that developed the strategic space remote sensing technology for Earth environmental monitoring, applications as maps of forest fires and deforestation of the Amazon region and studies in the urban development in big capitals of the country. As one of the results of the CBERS's Program, Brazil is today one of the biggest distributor of satellite images around the world.

Due to the success of CBERS-1, 2 and 2B Satellites, the two governments have decided in November 2002, to give continuity to the CBERS´s Program entering into a new agreement for the development and launch of two more satellites, CBERS-3 and 4. Satellites CBERS-3 and 4 (see "Fig. 1") represent an evolution of satellites CBERS-1, 2 and 2B, they will have new sensors with improved characteristics.

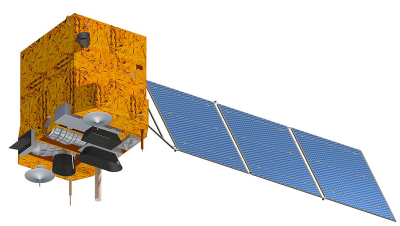

Figure 1. CBERS 3&4 satellites artistic conception. (INPE, 2009)

The power generation equipment within the framework of a power subsystem of a satellite or other space application system that requires electrical power is the photovoltaic solar cell array or, namely, solar array.

The CBERS' 3&4 solar arrays are a deployable single wing type configuration with the following characteristics: three solar panels (inner, center and outer) assembled over a flat composite substrate with aluminum honeycomb core and carbon fiber face sheet structure having 1755 mm x 2581 mm lateral dimensions, 22 mm thickness; one positioning structure (yoke) to support and positioning the solar panels away from the satellite main structure; and a set of holddown and deployment mechanisms.

The design, development and manufacturing of the Electrical Part of Solar Array (EPSA) for the CBERS' 3&4 are being executed by Orbital Engenharia. This represents a hallmark in the Brazilian Space Program, since it consolidates the technological capacity of complete EPSA design and manufacturing in Brazil using technology developed in house by Orbital Engenharia Ltda.

2. THE CBERS 3&4 SOLAR ARRAY DESIGN

The CBERS 3&4 solar array design is based on a chinese triple-junction solar cells ($GaInP_2$/InGaAs/Ge) with integrated diode by-pass, 30.3 mm x 40 mm lateral dimensions, covered with anti-reflecting coating coverglasses, shall generate 2700 W during three years life in orbit.

The CBERS 3&4 solar array is composed of two main power circuits one to recharge the batteries, named SG1, and another to meet the equipment loads, named SG2. The SG1 was designed to supply a minimum End-Of-Life (EOL) output power of 1300 W at 59.5 V, divided into two similar circuits. The SG2 was designed to supply a minimum EOL output power of 1400 W at 31.5 V, divided into six similar circuits "Baruel *et al.* (2007)". The division of the power circuits into sub-circuits is a functional requirement of the digital shunt type used in the power control unit of CBERS spacecraft. Each power circuit is composed by a number of parallel strings. Each string is composed by a number of serial solar cells and a blocking diode, which is assembled in a diode board to be located in the rear side of the solar panels.

The design for the number of serial solar cells (Ns) and for the number of parallel strings (Np) for the CBERS 3&4 solar array SG1 and SG2 power circuits are: Ns = 35 in SG1 circuit and Ns= 19 in the SG2 circuit. These numbers of serial cells provides a safe design margin between the operation voltage and the maximum power voltage (Vmp).

Due to the dimensional constraints of the solar panel structure, the feasible number of parallel strings for SG1 is Np = 126, being allocated 63 parallel strings in each one of the two SG1 power circuits. For SG2 the number of parallel strings is Np = 264, being allocated 44 parallel strings to compose each one of the six SG2 power circuits (Vaz, 2008d).

2.1. Simulation Model Adjustment and Electrical Characteristics at Laboratory Test Conditions

In order to take into account the solar cell behavior after welding and coverglass bonding, the simulation model was adjusted using the Test Coupon electrical performance test measurements. "Figure 2" shows the results of the model adjustment performed. In "Fig. 2" the continuous line is the simulated curve and the points marked with "*" are the Coupon test measured values after thermal vacuum test.

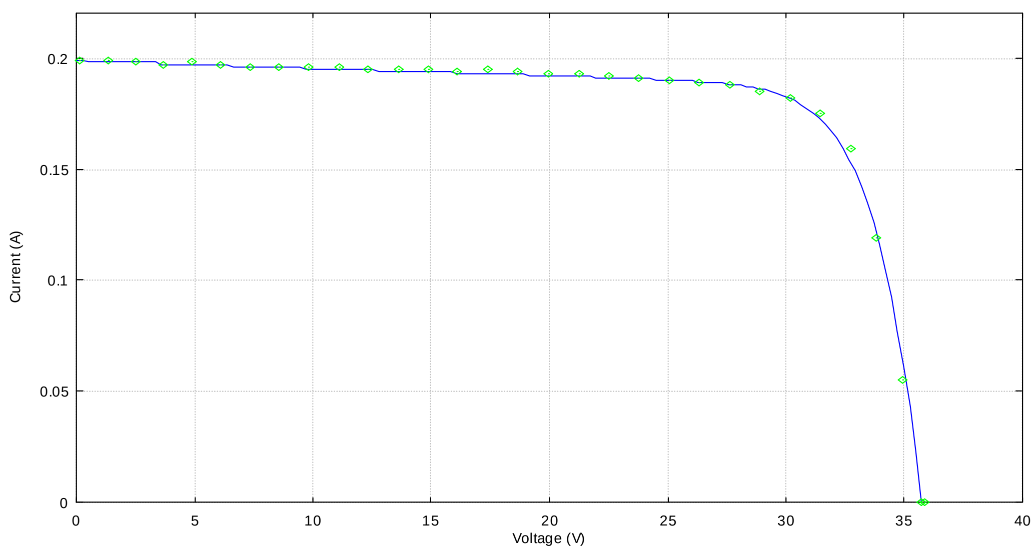

Figure 2. Results of the electrical simulation model adjustment (continuous curve is the simulated curve and points are test coupon measurements)

Both, SG1 and SG2 BOL total electrical characteristics at test condition (AM0, 1323 W/m^2, 25°C) are shown in "Fig. 3" and "Fig.4". The model adjustment based on experimental results is taken into account.

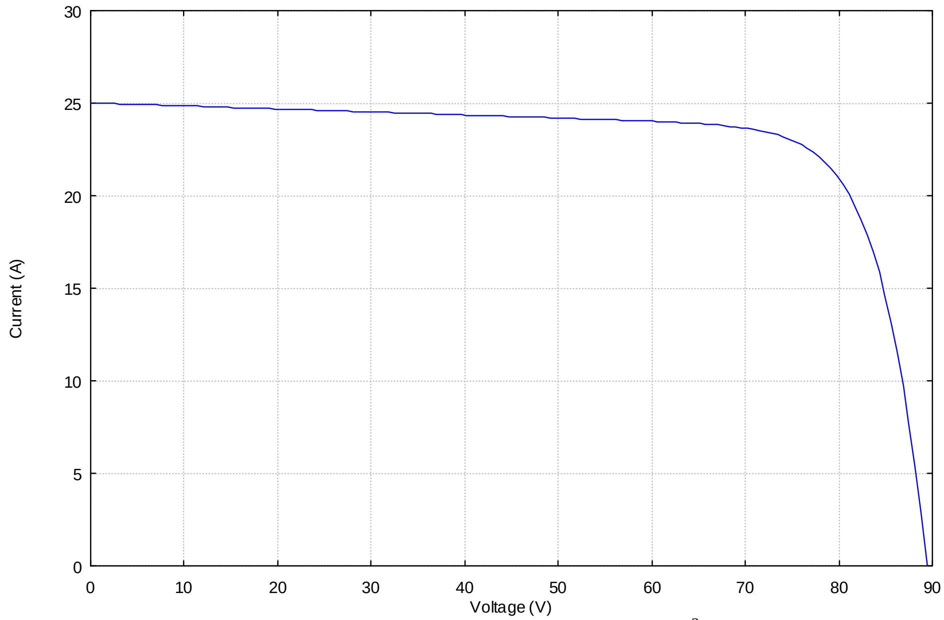

Figure3. SG1 Total I x V (BOL, AM0, 1353 W/m^2, 25^{o}C)

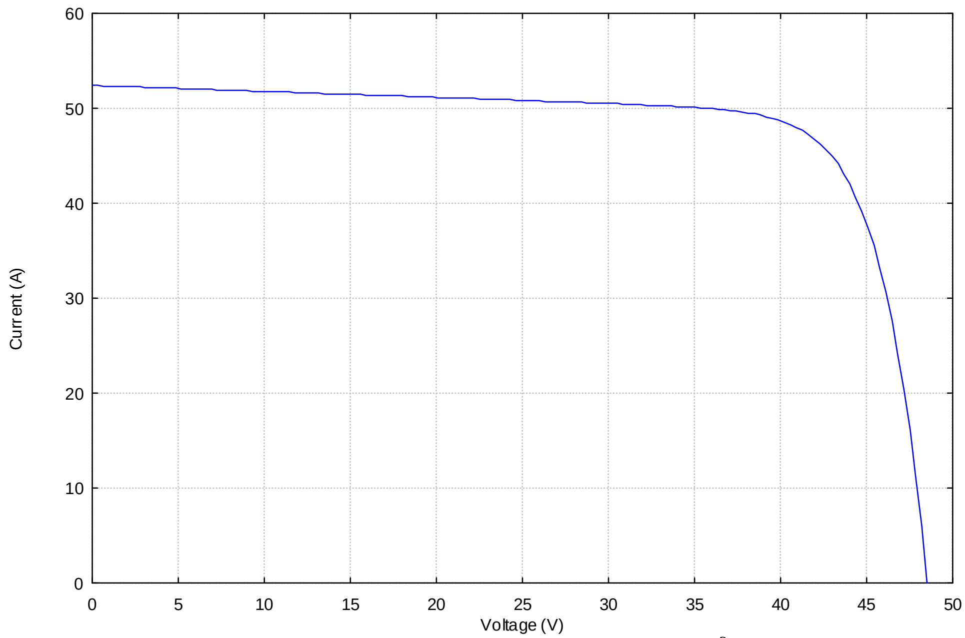

Figure 4. SG2 Total Ix V (BOL, AM0, 1353 W/m^2, 25°C)

2.2. SAG Electrical Characteristics at BOL and EOL

The CBERS 3&4 SAG power at the operation voltage (Vop), the short circuit current (Isc), the power at Vop (Pop) and the power at maximum power voltage (Pmp) for the power circuits SG1 and SG2, at BOL and EOL conditions, for minimum effective solar irradiation, SOLMIN, with operational temperature -80°C, and for maximum effective solar irradiance, SOLMAX, with operational temperature up to 95°C, to reach the maximum temperature found in the conservative thermal analysis, are summarized in "Tab. 1".

Table 1. The CBERS 3&4 SAG electrical characteristics for each SAG power circuit SG1 and SG2 respectively.

BOL		**SG1 Total**		**SG2 Total**		**SAG TOTAL**	
CASE	**Insolation (W/m^2)**	**Pop**	**Isc**	**Pop**	**Isc**	**Pop**	**Isc**
SOLMAX +95°C	**1253**	1312.0	24.0	1480.2	49.8	2792.2	69.4
	1287	1350.0	24.6	1521.0	51.6	2871.0	76.2
	1316	1384.0	25.2	1557.0	52.8	2941.0	78.0
EOL		**SG1 Total**		**SG2 Total**		**SAG TOTAL**	
CASE	**Insolation (W/m^2)**	**Pop**	**Isc**	**Pop**	**Isc**	**Pop**	**Isc**
SOLMIN -80°C	**1184**	1114.0	19.6	1242.0	40.8	**2356.0**	60.4
	1227	1158.0	20.4	1290.0	42.6	2448.0	63.0
	1265	1196.6	21.0	1332.0	43.8	2528.6	64.8
SOLMIN +95°C	**1184**	1118	21.66	1278	45.36	**2396**	67,02
	1227	1162	22.40	1329	47,04	2491	69,44
	1265	1202	23.14	1374	48,48	2576	71,62
SOLMAX +95°C	**1253**	1188.0	22.8	1360.2	48.0	2548.2	70.8
	1287	1227.8	23.4	1400.4	49.2	2628.2	72.6
	1316	1257.0	24.0	1434.6	50.4	2691.6	74.4

The presented electrical configuration design solution for CBERS 3&4 solar array is certainly among the best feasible solutions that one may find, taken into consideration the severe system and thermal constraints imposed over the SAG electrical design, just to mention two of them:

- Solar panel dimensions (available photoconversion area);
- SG1 and SG2 subcircuits electrical characteristics (different number of circuits and operational voltages).

Some advantages of the presented solar array electrical design configuration are highlighted in the following items:

- The requirements for both SG1 and SG2 are met.
- Good Vop to Vmp design margin at EOL for both SG1 and SG2 circuits. The equipment was originally designed to meet the operational range of -80°C to +80°C and is being demonstrated its functionality until 95°C;
- The three solar panels have identical electrical configuration, making easy their manufacturing and testing;
- Only 6 different solar module length (module number of serial cells);
- Good electrical configuration symmetry at panel level;
- Good packing factor.

2.3. SAG Thermal behavior in-orbit simulation

The in-orbit transient temperatures to be experienced by the CBERS 3&4 solar array BOL and at EOL conditions was performed considering the external thermal loads in accordance to the thermal cases: when in orbital condition the main external thermal loads interfering in the energy balance of the CBERS 3&4 solar array are the direct solar irradiation, albedo irradiation and Earth infrared irradiation. The albedo irradiation was considered to be in the same spectrum as solar irradiation. Earth emitted irradiation was considered as diffuse long wave infrared, equivalent to a black surface of about 250 K (average value of 214±12 W/m^2). “Figure 5” shows the solar cell temperature is the upper curve and lower curve is the rear side carbon fiber face sheet temperature.

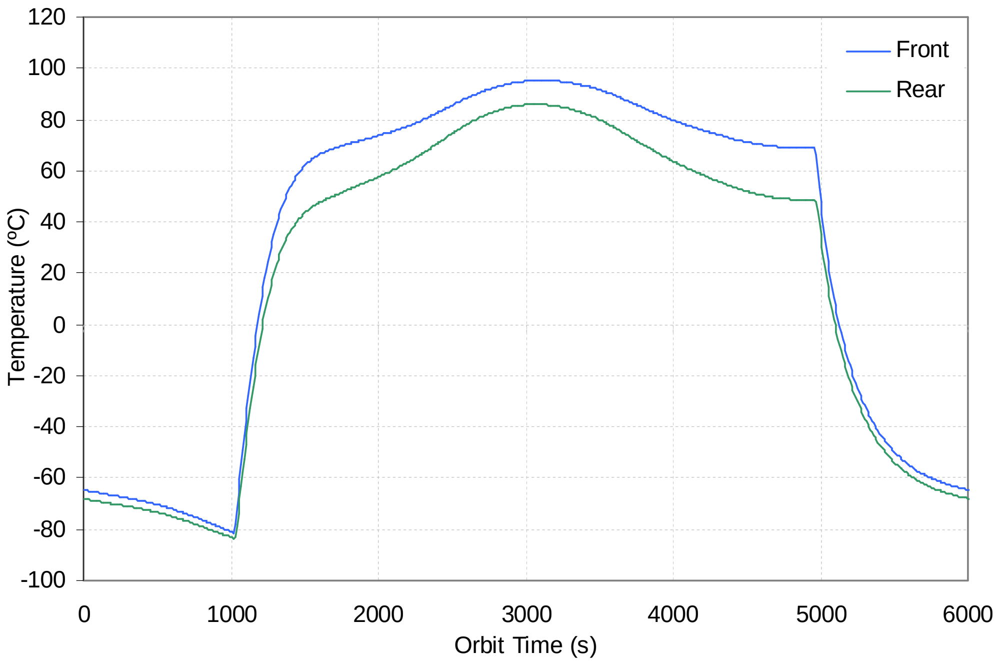

Figure 5. In orbit solar panel temperature for the thermal case HOT 1045 (Solar Cell: Tmax = 95.4°C. - Tmin = -83.3°C).

The solar panels temperatures meets the specified requirement (-80°C to 80°C) (Vaz, 2008c).

3. TEST COUPON

To verify that the process and the solutions design meet the electrical performance requirements after being submitted an environment qualification tests, a Small Test Panel Section, usually named Test Coupon (see "Figs 6 and 7"), that is an representative of a full size solar panel with 400 mm x 300 mm lateral dimensions, consisting of three solar modules, which one has 4 SCAs and the others two has 5 SCAs, all electrically connected in series (384 welding points) was designed and manufactured.

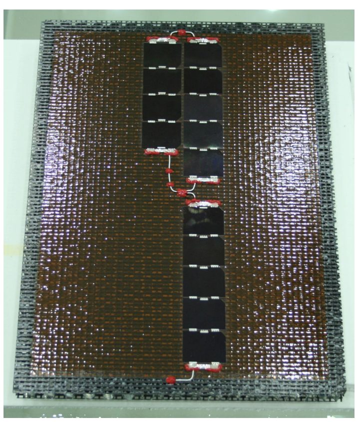

Figure 6. Test Coupon front side:14 SCAs electrically connected (solar modules)

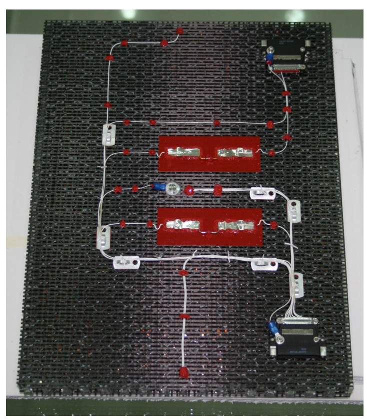

Figure 7. Test Coupon rear side: cabling, diode and resistor boards

3.1. Test Coupon Environmental Qualification Test Results

The Test Coupon was submitted to the following inspection, electrical and qualification tests and it was performed at the Integration and Tests Laboratory (LIT) at National Institute for Space Research (INPE):

- **Visual inspection:** was performed to verify the conformance of assembled parts and components to the design and manufacturing requirements and to identify eventual assembling discrepancies or defects caused by workmanship or equipment mishandling. Non-conformances were not found.
- **Electrical continuity:** was performed to verify the circuits' electrical continuity before and after the environmental tests (thermal vacuum and thermal shock). The electrical continuity test results showed that all electrical connections were done in accordance to the designed electrical circuits' diagrams without non-conformances.
- **Electrical insulation:** was performed in the photovoltaic circuits to verify its conformance to the electrical insulation requirements. The electrical insulation requirement is insulation resistance higher than 10 MΩ at 250 Vdc. The electrical insulation test results shows that all measured values are typically higher than 1 GΩ, thus meeting the minimum required value.
- **Electrical grounding:** was performed in the grounded parts and circuits to verify its conformance to the electrical grounding requirements. The electrical grounding requirement is that all metallic parts or components with 1 square cm or higher shall be grounded. The ground resistance shall be lower than or equal to 100 **Ω**. The electrical grounding test results shows that all measured values are typically 0 **Ω**, thus meeting the minimum required value.
- **Thermal Vacuum:** the objective was to submit the Test Coupon to thermal-vacuum environment that the CBERS 3&4 will experiment in orbit, to demonstrate conformance to specification and to act as quality control screens to detect manufacturing defects, workmanship errors, the start of failures and other performance anomalies, which are not readily detectable by normal inspection techniques. The test was conducted according the following specification "Marino *et al.*(2008)":
  - Chamber pressure: $\leq 1.33 \times 10^{-3}$ Pa;
  - Number of cycles: 03;
  - Hot soak temperature specified: 90°C
  - Hot soak temperature tested: 105°C
  - Cold soak temperature specified: - 90°C
  - Cold soak temperature tested: -93°C
  - Duration in each soak: 12 hours.
- **Thermal Shock:** was executed to demonstrate the capability of the spacecraft materials of resisting to in-orbit temperature variations. The test was conducted according the following specification:
  - Chamber pressure: ambient;
  - Temperature specified: -80°C to +80°C;
  - Temperature tested: -65°C to +95°C
  - Number of shocks: 1650;
  - Temperature range of change: 3°C / minute.
- **Electrical performance:** was executed to verify if there was no electrical degradation after being submitted to the environmental tests. "Figure 8" shows a typical electrical performance test results before and after the environmental tests.

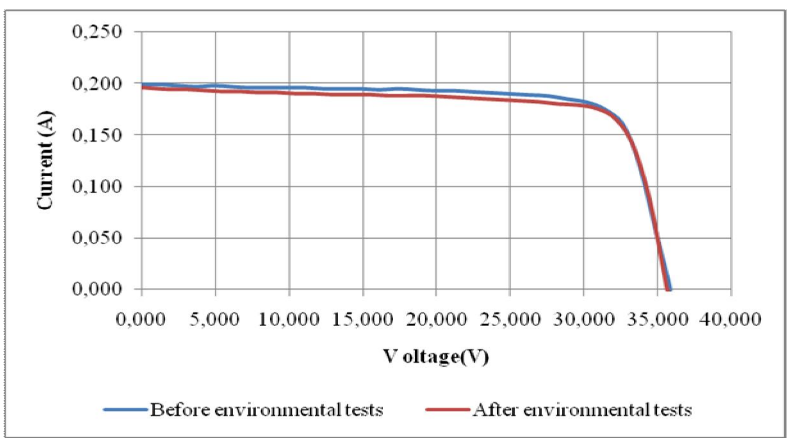

Figure 8. Electrical performance test results

Afther the thermal vacuum and thermal shock tests the results was that the electrical interconnection components showed no open circuit failure, the solar cells showed no cracks, the cable holders, solar modules, diode boards showed no detachments, the connectors, cabling supports were not loosen. The test was carried out within the conditions specified and the degradation was negligible. This results were verified by electrical functional tests and visual inspections described previously (Melo, 2008a).

4. CBERS 3 MANUFACTURING

The CBERS 3 solar array is currently being manufactured. Until the date of preparation of this paper, a 10000 triple-junction solar cells were welded, it means 120000 welding points were executed. The total manufacturing loss (solar cells cracks) due to the welding process was 0.17%, what is considered excellent if compared with other projects manufacturing losses, in general about to 2% loss.

Figure 9 shows a bare triple-junction solar cell. The electrical contact between two adjacent serial solar cells is performed using an electrical conductor component named Interconnector. The interconnector is welded to the solar cell front side bus bar, and afterwards to the solar cell rear side. Figure 10 shows an interconnector welded to a solar cell front side bus bar.

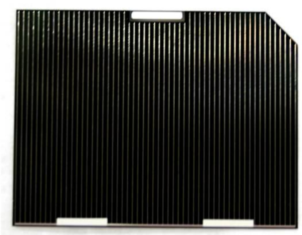

Figure 9. Bare triple-junction solar cell

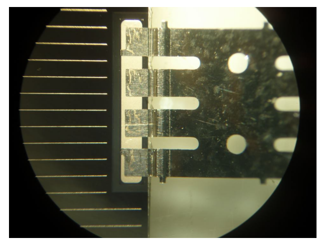

Figure 10. Interconnector welded to a solar cell front side bus bar (50x magnification)

The coverglass bonding is currently in process and shall meet severe quality assurance criteria in order to avoid defects in the adhesive bonding layer, like bubbles for example, coverglass cracks, coverglass mispositioning, lateral protruding adhesive, adhesive opacity and other related mechanical defects.

4.1. Experimental Welding Parameters Determination

Foreseen the minimization or, whenever possible, the elimination of defects that could contribute to early on orbit degradation, mal function or failure of components or parts of the solar arrays, the set of requirements, related to the welding process, are generally imposed by users of low earth orbit satellite applications. For CBERS 3 solar array these requirements were verified through a set of test specimens, named CIC N and CIC P: they consists of a triple-junction solar cell with a interconnector welded in its front and rear sides electrical contacts respectively (12 welding points per test specimen):

a) Strength - The solar cell welded interconnector shall withstand 1.5 N pull strength per interconnector finger, applied at 180^o to the terminal direction. This was verified by a destructive pull test;
b) Solar Cell Degradation – the welding process shall not degrade the solar cell short circuit current more than 2%. This was verified by electrical performance test;
c) Appearance - The welding shall not present evidences of cracks, crunches or burned areas, solar cell metallization delaminating, nor deformation due to excess electrode pressure (indentation higher than 50% of the interconnector thickness). This was verified by visual inspection;

"Table 2" shows a representative sample of the destructive pull test results performed in the CIC P test specimen type. As it can be observed from "Tab 2", the results meet the specified requirements. Based on these test results the selected welding parameters for the flight model manufacturing were determined (Melo, 2008b).

"Table 2". Tests results performed in the specimen CIC-P

Solar cell ID	**Welding**			**Destructive pull test**	**Electrical performance**		
	Interc.	**Finger**	**Charge (A.s)**	**Force (N)**	**Itest Bare solar cell**	**Itest CIC-P**	**Degradation (%)**
T35312	1	1	63,95	2.48	189,3	188,1	0,63
		2	62,14	1.89			
		3	67,67	1.80			
		4	63,58	1.50			
	2	1	60,47	1.92			
		2	58,51	1.73			
		3	55,74	1.76			
		4	59,48	1.69			
	3	1	64,00	2.02			
		2	62,14	1.82			
		3	65,02	1.97			
		4	60,42	1.84			

3. REFERENCES

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