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SOLAR CELL INTERCONNECTOR DESIGN OPTIMIZATION FOR SURVIVING HARSH FATIGUE ENVIRONMENTS - EXECUTIVE SUMMARY

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Introduction

Purpose of this document is to present all relevant information encompassing the work, activities performed and results achieved in the frame of ESA GSTP6.1 program. The program has focused on Solar Cell Interconnector design optimization and improvement for surviving harsh fatigue environments.

The activities described in this document are: new interconnector solutions study (improvement with respect to baseline), their “stand-alone” preliminary testing (flex test) and their testing integrated in flight representative DVT (Design Validation Test) configuration against two major mission environments:

1 Very Long Low Earth Environment (LEO)
2 Geostationary Earth Orbit (GEO)

The work performed is presented and subdivided into three main tasks:

1. FE (Finite Elements) Mechanical analysis and design optimization,
2. Manufacturing and preliminary Design verification,
3. Testing and Results.

1 INTERCONNECTOR DESIGN AND THERMO-MECHANICAL ANALYSES

In the first phase of this program, new design and optimization of IC were developed for surviving harsh fatigue environments. The Interconnector configurations, available at Leonardo at the begin of this study, are reported in Table 5-1.

In order to assess goodness of a new proposed design and material, different finite element analyses were performed, to compare old IC design and material. In parallel to the improved geometry, base material was changed from Invar to Rodar, which has higher elastic modulus and yield stress 30% lower than the former.

- The studies started with the FE model of the standard C interconnector, with typical out-of-plane stress relief loop, selecting a new material: Rodar. The evaluations were performed by a structural FE Analysis of a standard C interconnector, two consecutive SCAs, and the substrate, as shown in Figure 5-1;
- The preliminary models provided the indication that new IC designs were desirable in combination with this material

After a shortlist, and further improvements analysis the first proposed improvement design (**Figure 5-2**) was re-submitted to FE analysis, which suggested some improvements in design to lower the stress concentration.

Optimized design final geometry in **Figure 5-3**. Those models are called “Trident triple lead” and “Bifidus”.

Following final geometry selection, new FE analyses were performed considering the different cases for Temperatures (Hot/Cold), Leads (front-rear and rear-rear), Resin presence (resin used to glue cells on the substrate –red adhesive in Figure 5-1, sometimes partially surmounting the IC initial loop part), displacements (none, +70 µm/ -23/+23 µm /100 µm imposed displacement as manufacturing cases simulation).

Results show that, in terms of fatigue strength, the interconnectors, independently on the abovementioned adopted conditioning, can theoretically resist to number of cycles > 10^6. Moreover, the symmetrical alternating stress calculated on Front-Rear I/C, wrt the one calculated on the former interconnector, is about 60-70% lower, confirming the improvement in design. Conclusions coming from FE analyses are:

- The Rodar material shows a higher rigidity with respect to the Invar; this characteristic may improve the process of string manufacturing by a better handling;
- The extended loop permits to better absorb the out of plane stresses and to reach a greater fatigue strength;
- The Triple lead I/C shows a good stress distribution on the loop and in the welding areas;
- The use of the Triple lead I/C would also permit to optimize the welding process, by the reduction of the number of welding points (from 8 to 6);
- The Bifidus I/C shows a good behavior under stress in the loop area, less around the welding points.

2 MANUFACTURING AND PRELIMINARY DESIGN VERIFICATION

Second part of the program consisted of an experimental campaign:

- Mechanical Flex Test preliminary design verification on new I/Cs, to assess performances of simulated thermal-like cycling imposed displacement;
- DVT coupons designed and manufactured to assess performances of integration of newly designed I/C in different configurations (ICs, substrates, Solar cells types) in LEO and GEO thermal cycles representative ambient.

2.1 Flex Test Campaign

A Flex-test was performed, at ambient pressure and temperature, in order to verify the conditions of interconnectors after a defined number of cycles of mechanical stress.

The test consisted in constraining the IC samples over a Piezo Nano Positioning Driven, with a sub-nanometer range motion. The two configuration were ICs setup stand-alone or ICs within two consecutive cells (**Figure 5-4**), IC selected configurations reported in Table 5-2.

For the analytical computations the material properties of Carbon fiber skin (panels substrate skin representation), Germanium (solar cells substrate representation), Silver, Rodar and Molybdenum were considered and analyzed, from literatures, and interpolated between the extreme temperatures of -210°C and +135°C. Thermomechanical analysis to asses displacements was performed in temperature cases Cold (-210°C, -190°C, -175°C) and Hot (+135°C), with reference T (+15°C).

The equation used for calculating the expansion/compression of interconnectors has the following form:

$$D=D_0 * (1+CTE*\Delta T)$$

(D0=solar cells distance at 15°C, CTE= coefficient thermal expansion). Cases at abovementioned temperatures were analyzed and results implemented for Flex-test tractions/compressions.

2.1.1 Flex Test Performance and Results

Some pictures are presented in Figure 5-6 and Figure 5-7. At the end of each Run, the interconnectors were inspected under microscope. Results and runs subdivisions are reported in Table 5-3.

At the end of the flex-tests, all interconnectors were in good conditions, without any cracked leg. Also, the interconnectors with intentional cuttings near the loop, have been affected by a very small propagation of cuttings.

The mechanical tests carried out on these interconnectors preliminary proved the goodness and validity of design and the materials used.

2.2 Manufacturing of PVA representative DVT coupons

The new interconnectors were also used in the manufacturing of seven DVT coupons, fully representative of PVA flight models manufacturing, tested at different GEO and LEO environments. DVT coupons main features are summarized into Table 5-4 and the test matrices in Table 5-5.

3 TESTING AND RESULTS

The DVTs were tested differentiated in the thermal cycles between LEO and GEO.

3.1 DVTs campaign results

After the termination of test activity for the DVT1, DVT2, and DVT5 coupons, tested at LEO environments, and DVT3, DVT4, DVT6 and DVT7 coupons, tested at GEO environments, the following results can be derived:

- No anomalies have been highlighted after bake-out, after the 10 TV1 cycles, APTC cycles and after the last 10 TV2 cycles. No cracks or shunts appeared in correspondence of welding points (successfulness of the welding process joint applied to configurations);
- Electrical continuity at string level, both along cells and diodes, was verified during thermal cycling: absence of mechanical discontinuities of interconnectors;
- Magnified visual inspection performed at different steps on the trident and bifidus interconnectors: no remarkable alterations noticed, proving the conformity of their design and manufacturing process;
- Electrical performance measurements with the flasher test have not highlighted relevant variations of main electrical parameters;

- X-rays inspection have not highlighted any damage or cracks on the interconnects
- Ag-sputtered Molybdenum trident shaped and spade, Rodar trident shaped and spade shaped and Ag trident and spade interconnect technologies proved to perform in line with expectations in terms of reliability and fatigue resistance

The applied interconnect technology has been successfully verified in terms of reliability and manufacturing process' suitability on this kind of Solar Cells Assemblies.

4 CONCLUSIONS & FUTURE DEVELOPMENTS

4.1 Mechanical analysis

As result of this iterative thermomechanical design process, 2 kinds of geometries have been identified and analyzed with Rodar (Figure 5-8).

Main advantages:

- Triple leads geometry improves the overall reliability with respect to the previous Leonardo "C" Invar design, and reduces the number of welding joints needed (6 for the triple leads, 8 for the "C" design). Critical for large manufacturing volumes of SCAs. The extended loop configuration allows to have a stress fatigue failure limit well beyond 10^6 cycles.
- Bifidus: it features in-plane loop for stress relief; the welding joints configuration here is as the "C" Invar interconnect design, 2 joints per lead (8 total).The extended loop configuration allows to have a stress fatigue failure limit well beyond 10^6 cycles.

For both front-rear and rear-rear design, FE analysis was performed with Rodar as core material for these items:

- Extended loop permits to better absorb the out of plane stresses and increase fatigue strength. The number of cycles to reach fatigue failure are analytically demonstrated to be $N_f > 10^6$ cycles,
- The Triple lead I/C shows a good stress distribution on the loop and in the welding areas.
- The Bifidus I/C shows a good behavior under stress in the loop area, while higher stress concentration can be found around welding joints.
- In general, symmetrical alternating stresses were analysed to be, on both trident and bifidus designs, 60% lower with respect to those simulated on C-type Invar interconnects

4.2 Manufacturing and preliminary design verification

Leonardo has managed the manufacturing and procurement of interconnects realized using Rodar, Molybdenum and Silver as core material; after flex test it was observed that:

- All samples (Rodar, Molybdenum and Silver triple leads) samples successfully survived to cycles (>10^6) without showing cracks at magnified inspection (or with minor enlargements in artificially procured cracks).

4.3 Testing and results

During DVTs testing electrical continuity across cells and diodes interconnects was continuously monitored during APTC and thermal vacuum tests, so that intactness of interconnects and welding joints was verified during each testing phase.

The following conclusions regarding interconnects geometries and materials can be derived:

- RODAR:
  - Triple leads Rodar interconnects ensured reliability in temperature excursions (GEO) and extended cycling in LEO: no discontinuities were measured.
  - Bifidus Rodar interconnects have proven to ensure reliability as well, in case of extended cycling in LEO: no discontinuities measured. Bifidus design demonstrated at DVT level the effectiveness of in-plane stress relief.
  - Thanks to the satisfactory weldability of Rodar on cells, no shunts were caused on strings (no power degradation)
  - Visual inspection confirmed the absence of thermal cycling-induced deformations on loops.
- Triple leads Molybdenum interconnects proved reliability for both LEO and GEO cycling: no discontinuities detected on DVT 2 and 3. Rigidity of Molybdenum prevented the out-of-plane loops to deform during testing

phases. It has to be remarked that a not-negligible sensitivity of welding parameters was observed, in response to process variables.

- Triple leads Silver interconnects have been installed on DVT6 (extended stress relief loop) and DVT7 (reduced stress relief loop). These two designs proved reliability for GEO cycling, no discontinuities have been detected during tests and no anomalies were found on visual inspection. On both coupons, no power degradations were measured. Handling of soft silver interconnects demonstrated to be easier for the geometry adopted on DVT7

5 FIGURES & TABLES

5.1 Figures

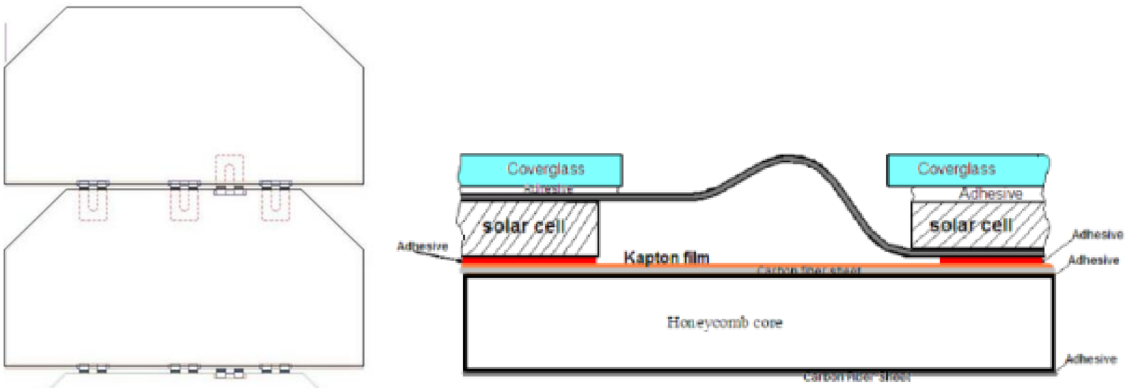


Figure 5-1 – IC connecting two consecutive Solar Cells – top &lateral view

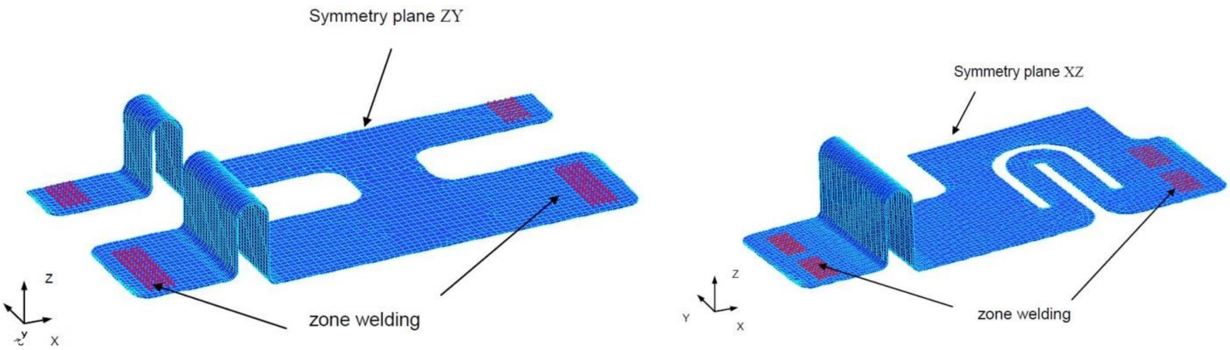


Figure 5-2 – Triple Lead (left) and Bifidus (right) preliminar design – half solution for symmetry

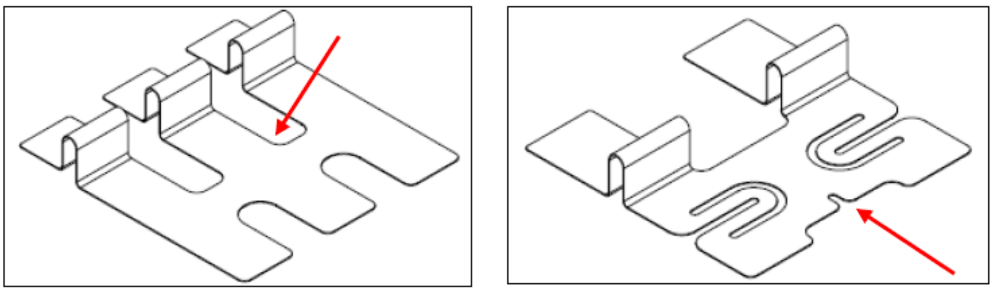


Figure 5-3 – Final Design: improvement on Triple lead (left) and on bifidus (right) I/Cs

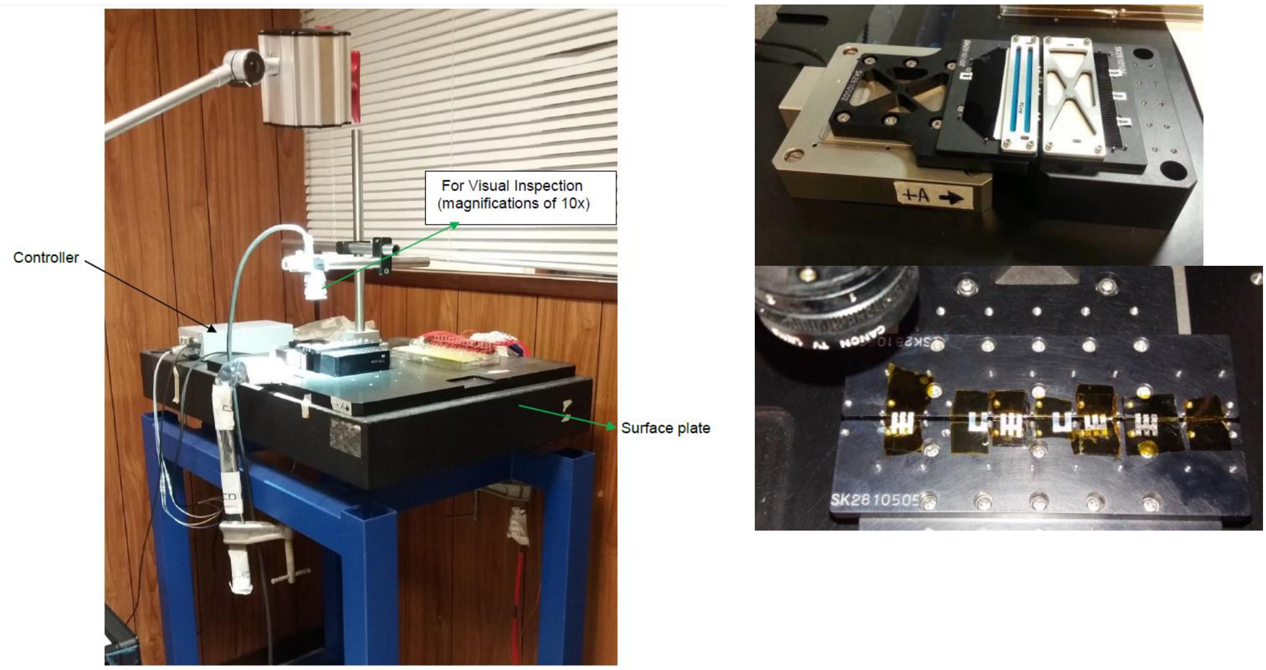


Figure 5-4 – Flex-test setup (left), equipment for interconnectors (top) and cell+interconnectors (bottom)

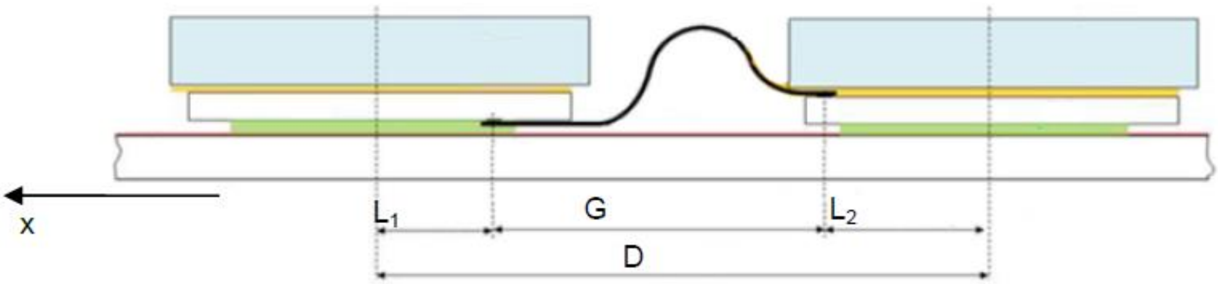


Figure 5-5 – Schematic of interconnector welded between two cells (front/rear)

Figure 5-6 – Rodar interconnector after test- (edge bending induced by set-up fixing system)

Figure 5-7 – Run3 test setup

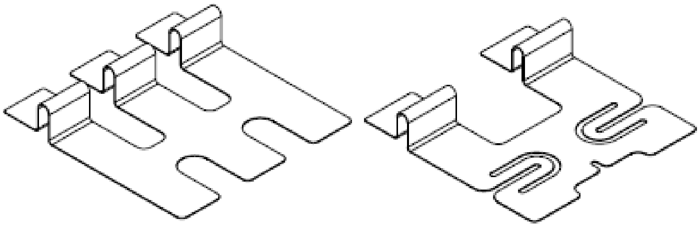


Figure 5-8 – "Triple leads" and "Bifidus" design

5.2 Tables

Table 5-1: Leonardo interconnector heritage

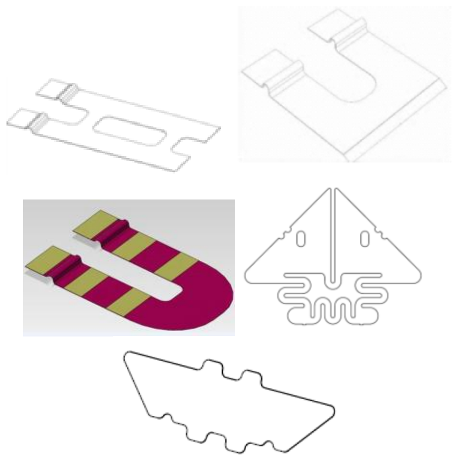
I/C TYPEs	SHAPEs	MATERIAL/SURFACE FINISH	REPRESENTATIVE PICTUREs
Front/rear – rear/BB Front/rear Rear/rear	U; C; 2H Spade Bat	Materials: (Ag,Invar, Au, Molybdenum); Surface (Ag plating, Au)	

Table 5-2 – Interconnector Configuration

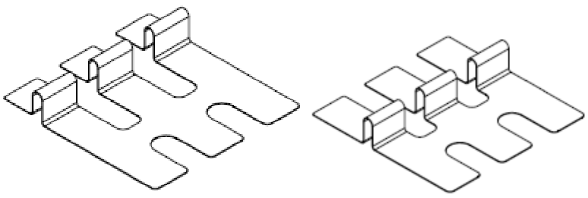
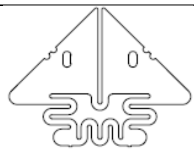
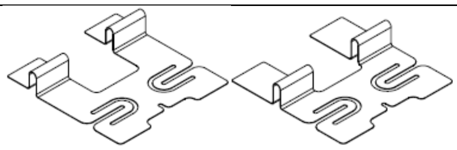
Type	Shape	Material	Drawing
Front/rear (left) Rear/BB (right)	Triple lead	Molybdenum	
		Silver	
		Rodar	
		Silver	
		Rodar	
Rear/rear	Spade	Molybdenum	
		Silver	
Front/rear (left) Rear/BB (right)	Bifidus	Rodar	

Table 5-3 – Flex text Runs configurations

Run	Number of Samples	Shape	Material	Displacement	# of cycles	Notes/results
1	2	Triple leads	Ag-plated Rodar	Compression: +15.5µm; Traction: -12.5 µm	375’290	Dry Run for configuration; Some connector pre-deformed to simulate handling
	2	Triple leads	Silver			
	2	C-shape (reference only)	Ag-plated Invar			
2	2	F/R Triple leads	Rodar	Compression: +24.4µm; Traction: -29µm	1’769’617	At the end of flex-test, the interconnectors did not present any sign of crack.
	2	F/R Triple leads	Silver			
	2	F/R C-shape	Ag-plated Invar			
3	4	F/R Triple leads	Silver	Compression: +31µm; Traction: -45µm	999’999	Some connector pre-deformed to simulate handling Both the interconnectors types did not present any sign of crack
	2	R/R Triple leads	Silver			
	2	F/R Triple leads	Ag-sputtered Molybdenum			
	2	R/R Triple leads	Ag-sputtered Molybdenum			
4	4	F/R Triple leads	Silver	Compression: +31µm; Traction: -45µm	999’999	Cuts made on installed interconnectors, as suggested by ESA. At the end of flex-test, both interconnector types did not present any sign of crack
	2	R/R Triple leads	Silver			
	2	F/R Triple leads	Ag-sputtered Molybdenum			
	2	R/R Triple leads	Ag-sputtered Molybdenum			

Table 5-4 – DVTs manufacturing front side elements

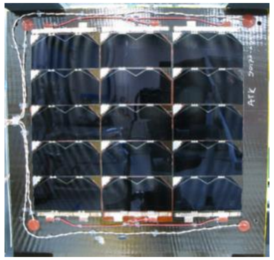
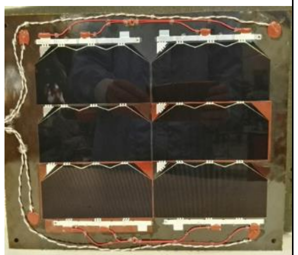
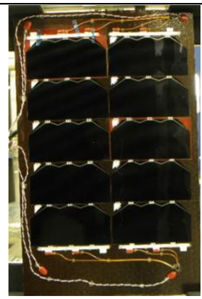
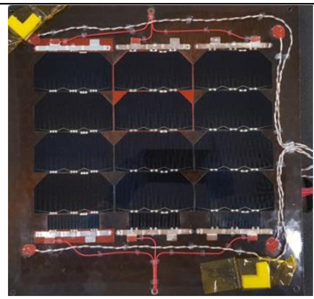
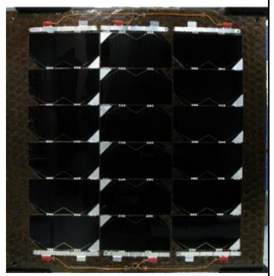
Description	**Items FRONT SIDE DVTs**										
	DVT1		**DVT2**		**DVT3**	**DVT4**		**DVT5**		**DVT6**	**DVT7**
Environment	Extended LEO		Extended LEO		GEO	GEO		Extended LEO		GEO	GEO
Coupon Size	25x30cm		25x30cm		30x30cm	35x35cm		25x30cm		30x30cm	15x40cm
Substrate supplier	Airborne		Airborne		Airborne	Thales		Thales		Thales	Airborne
Layout	5s3p		3s2p		6s3p	5s2p		4s3p		6s3p	8s1p
Bare Cell	15x3G30C 40x80 mm², 150µm		3G30C 120x60 mm², 230µm		3G28C 40x80 mm², 100µm	3G30C 120x60 mm², 230µm		3G30C 40x80 mm², 150µm		3G30C 40x80 mm², 150µm	3G28 LILT 40x80 mm²
Cell Coverglass	10xCMG100 AR	5xCMG100 AR	CMG150AR		CMG100AR	CMG150AR		CMG100AR		CMG100AR	CMG 300ITO
Front Interconnector	Rodar three leads	Rodar bifidus	Molybdenum three leads		Molybdenum three leads	Rodar three leads		Rodar three leads	Rodar bifidus	Ag three leads	Ag three leads
Bypass Diode (& coverglass)	External SIBPD diode (10,9 x 10,9) CMG125		Ext. SIBI (12,8x12,8)	Ext. SIBPD (10,9x10,9) CMG125	External. Si diode 100 µm (12,9 x 12,9)	Ext. SIBPD (10,9x10,9) CMG125	Ext. SIBI (12,8x12, 8)	Integrated bypass diode		External SIBI diode (12,8 x 12,8)	Ext. SIBPD (12.8x12.8)
Bypass diode front I/C	Rodar three leads	Rodar bifidus	Molybdenum three leads		Molybdenum three leads	Rodar three leads		Rodar three leads	Rodar bifidus	Ag three leads	Ag three leads
Bypass diode rear I/C	Rodar three leads	Rodar bifidus	Molybdenum spade	Molybdenum three leads	Molybdenum spade	Rodar three leads	Rodar spade	-		Ag spade	Ag spade
Rear Interconnector	Rodar three leads	Rodar bifidus	Molybdenum three leads		Molybdenum three leads	Rodar three leads		Rodar three leads	Rodar bifidus	Ag three leads	Ag three leads
Bus Bar	Ag Invar		Molybdenum		Molybdenum	Ag Invar		Ag Invar		Ag	Ag Invar
											

Table 5-5 – DVTs Test Matrix

Step #	Test Sequence/Condition	
1	**Incoming Inspection – substrates and components**	
2	**Manufacturing Phase**	
	Solar Cells, Strings, Laydown and cabling	DVTs manufacturing
3	**Test at PVA level**	
	Mass, visual inspection, Electrical checks, continuity, electrical performance	
4	**Bake-Out + tests**	
	24h @ +95 °C + 24h @ +125 °C; p<2E-5 mbar @ end of dwell	Full visual inspection
6	**Mandatory repairing**	
7	**GEO cycling**	**LEO cycling**
	10 cycles @ avg. T_{front} = • -175°C/+135°C • p < 2E-5mbar 2h dwell,	10 cycles @ avg. T_{front} = • –110°C/+110°C • p < 2E-5mbar 2h dwell
	GEO cycling	**LEO cycling**
	2100 cycles @ avg. T_{front} = • -175 °C/ +135 °C no dwell,	100000 cycles @ avg. T_{front} = • –110 °C / +110 °C No dwell, checks every 20k cycles.
	GEO cycling	**LEO cycling**
	10 cycles @ avg. T_{front} = • -175°C/ +135°C • p < 2E-5mbar 2h dwell	10 cycles @ avg. T_{front} = • –110°C / +110°C • p < 2E-5mbar 2h dwell
	Electrical checks during thermal test INS:ECC, ECD & ECTH	
8	**Tests after thermal cycling**	
	Full visual inspection: (optical+ELM+xrays)	
	Electrical health checks	
	Electrical performance measurement	