BaR-SPOrt
Thermal qualification test of solar cells in simulated balloon ascension phase environment.

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1. Introduction and aims.

In this report results about thermal test on solar cell are presented. This cell constitutes the module to assembly several photovoltaic panels able to supply power (~ 1 KW) to the BaR-SPOrt experiment (Balloon-borne Radiometers for Sky Polarization Observations) [1, 2].
The assembly of the solar panel will be done by an external industry[i]. It is supported by our group for what about the design and qualification phase of the prototype.
The aim of this test is to study how the efficiency of the cell varies with its physical temperature. Further on, an investigation about its breaking inside an environment as close as possible to the one typical of the thermal inversion layer (~ 15 Km) will be done. For the breaking test two different cooling will be simulated: the first one as slow as the typical ascension speed of a stratospheric balloon, the second one will be very fast to thermally stress the cell.
The cell under test is a POWER MAX® mono-crystalline silicon device. Its size is 10.3 cmx10.3 cm[ii].
Such a cell with the metal strips acting as current leads are shown in Fig. 1.

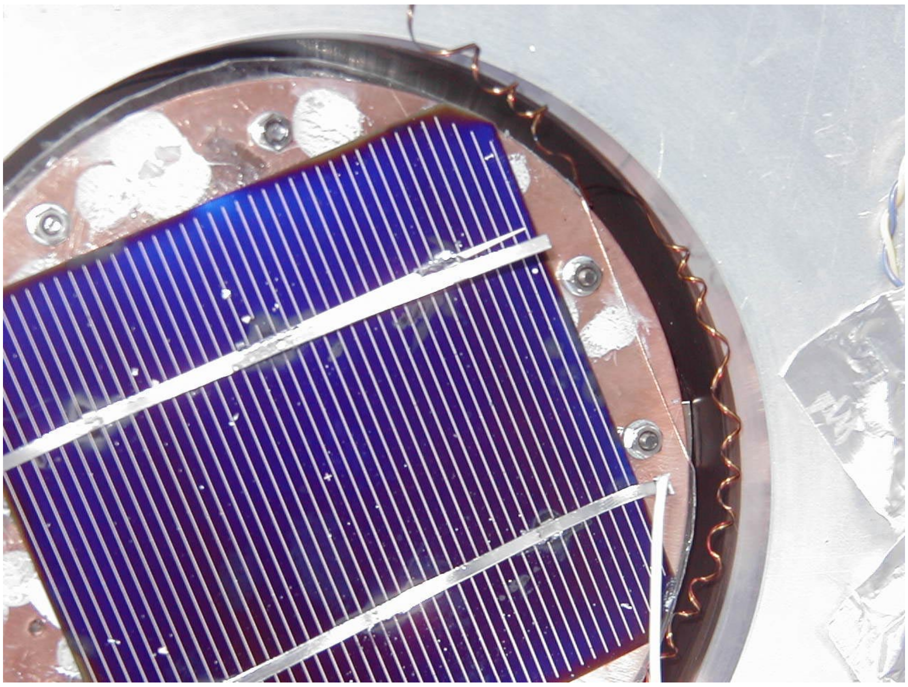

Fig. 1 – Solar cell under test.

[i] LEN s.r.l. Laboratori Elettronici, Internet Maintainer; Chiavari (Ge) Italy; len@len.it.
[ii] http://www.solarcellsales.com/catalog/product-detail.cfm?productid=SM110-12P

2. Generality

The temperature trend of the environment which encloses the payload during its ascension phase must be simulated. Such a temperature follows an exponential profile versus the altitude with the form: $T \propto T_0 e^{-\alpha h}$ (see Fig. 2), at least up to 10-15 km [$\alpha \approx 24\ m^{-1}$, h in m, T_0 ground temperature in K].
The typical temperature and pressure profile, for the USA standard atmosphere, is shown in Fig. 2. It is also highlighted the region of interest for the test.

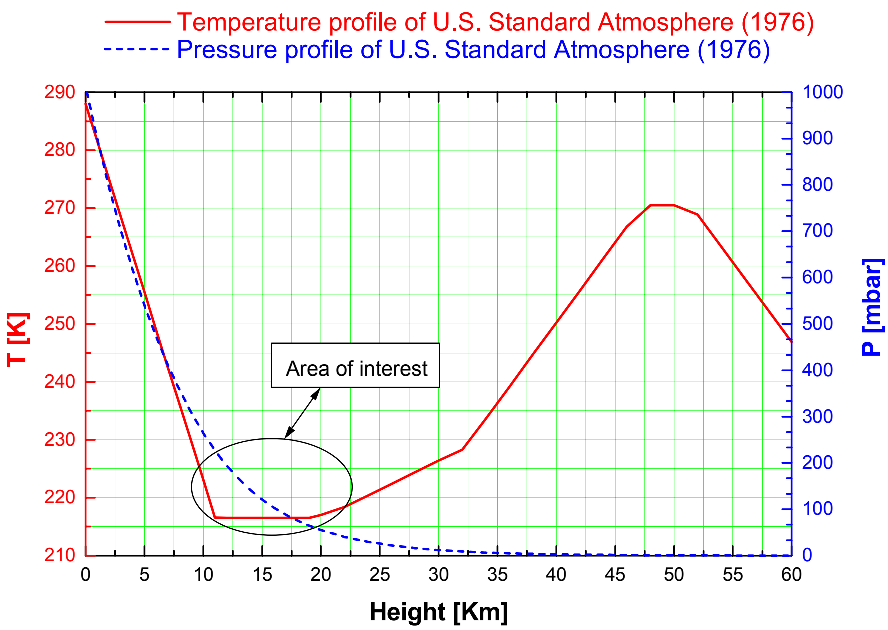

Fig. 2 – Typical temperature and pressure profile for USA standard atmosphere (1976).

The ascension speed is ~ 160-170 m/min. Four hours are necessary to reach the floating-height (38 Km). The balloon ascension will be simulated linearly decreasing the temperature up to [−60 ÷ −70]°C. T(h=0) ≈ 15-25°C, T(h=15km) ≈ −60°C, ΔT ≈ 75°C ⇒ the temperature gradient which well reproduce the ascent is about −75°C/90min ≈ −[0.8÷1]°C/min[iii].
The cell will be housed inside a little vacuum chamber[iv] (see Fig. 2a) in nitrogen atmosphere. The nitrogen is necessary to avoid air condensation or ice around the cell due to the cooling. The pressure will be locked at ~ 200 mbar and controlled by a digital vacuum gauge.

[iii] 90 minutes are necessary to reach the height 15 Km.
[iv] It is usually adopted as a cryostat

In order to illuminate the cell, such a chamber is closed by a Plexiglas vacuum window which is transparent to the visible light.
The fridge to cool the cell is a mechanical refrigerator (CRYOCOOLER Polar SC-7 COM[v], Fig. 2b) which is able to generate on its *cold finger* the temperature set by the user[vi].
By a dedicated controller it is possible to set the cold finger temperature (T_{CF}) and to monitor the electric power absorbed. The temperature is kept constant within ±0.1 K around the T_{CF} by means of the PID control. The higher the thermal input on the cold finger (e.g. LAMP ON) the higher the electric power absorbed by the cooler to guarantee the stabilization of T_{CF}.
Connected to the cold finger there is a copper circular plate (Φ = 14 cm) on which a circular LEXAN sheet is put. The cell is placed on the LEXAN sheet. The LEXAN[vii] has been used because the solar panel will assembled with this material. A good thermal contact among the copper plate, the LEXAN and the solar cell is obtained by means of thin sheets of APIEZON N grease.


Fig. 2a: Vacuum chamber

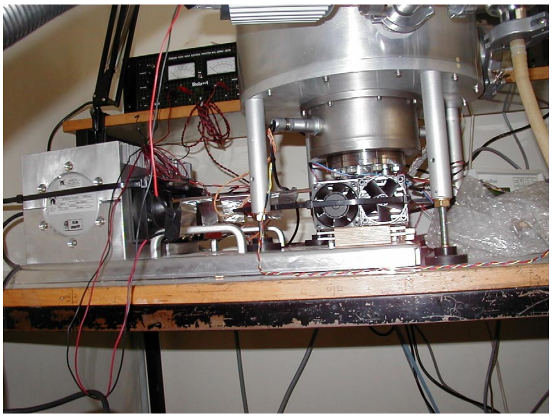
Fig. 2b: The cooler under the chamber

The solar cell is illuminated by a 100 W tungsten lamp, which is at ~ 50 cm away of the cell. Such cell is loaded by an external load $(R_L)_{ext} \approx 2.35\ \Omega$ ($I_L \approx 200$ mA, $V \approx 0.4$-0.6 Volt).
The signals of four temperature sensors[viii] and the cell-voltage have been acquired:

- T7: temperature sensor on the LEXAN clamps which block the cell on the circular LEXAN plate (A, B, C and D in Fig. 3).
- T6: temperature sensor on the LEXAN plate placed under the cell.

[v] http://www.leyboldvac.de/corporate/index.html
[vi] The minimum temperature reached by this model is 35 K when the thermal input is null.
[vii] It is a thermally insulating plastic material.
[viii] Lakeshore controller interfacciato ad un VI di LabVIEW dedicato

- T5: temperature sensor linked to the circular copper plate.
- TCF: temperature sensor directly linked to the cold finger.

The experimental setup, the method used to clamp the cell on the cold plate and the position of the main temperature sensors are shown in figs. 3, 4 and 5, respectively.

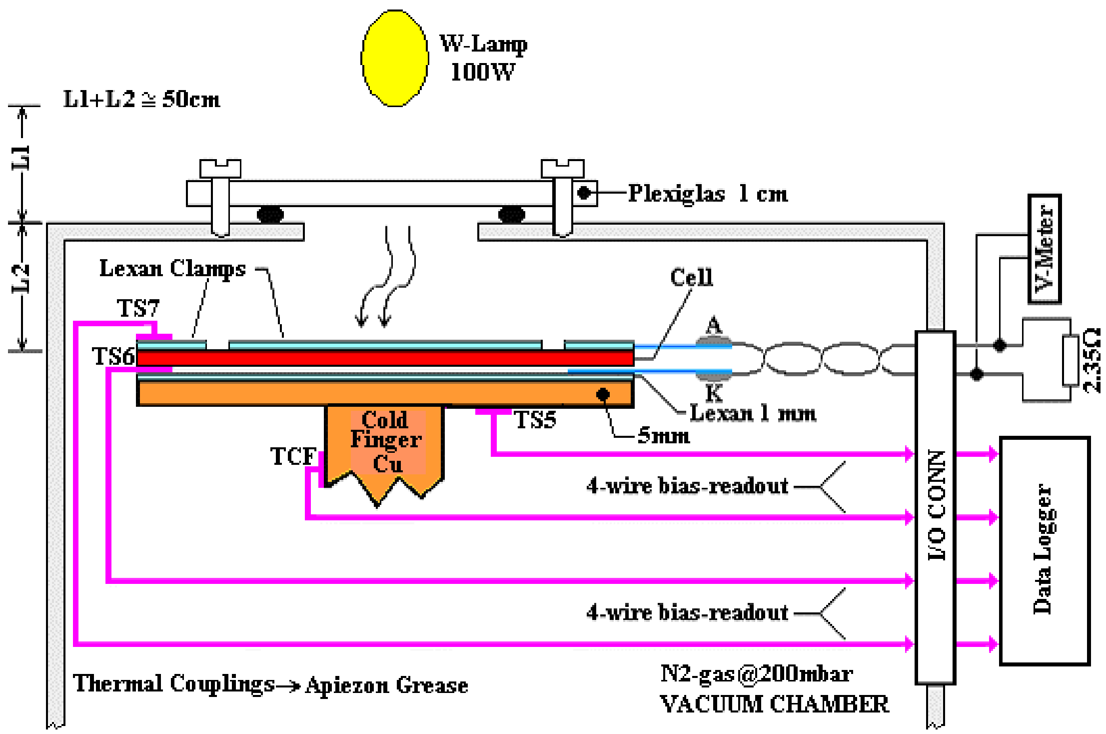

Fig. 3 – Experimental setup.

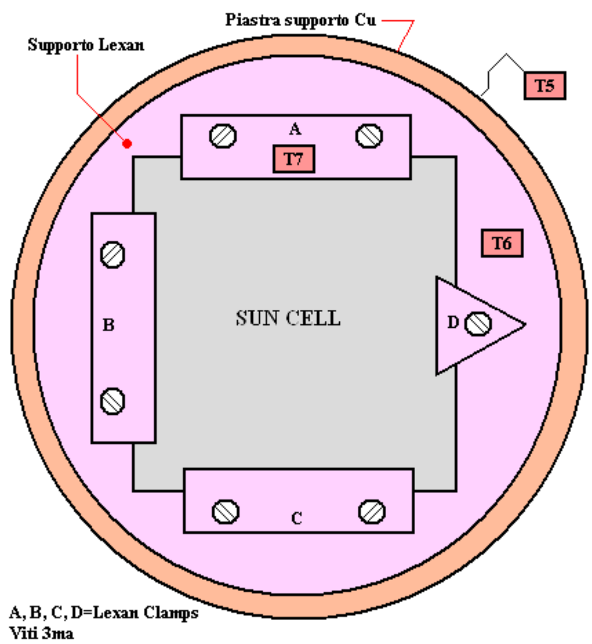

Fig. 4 – Cell-clamping on the cold plate.

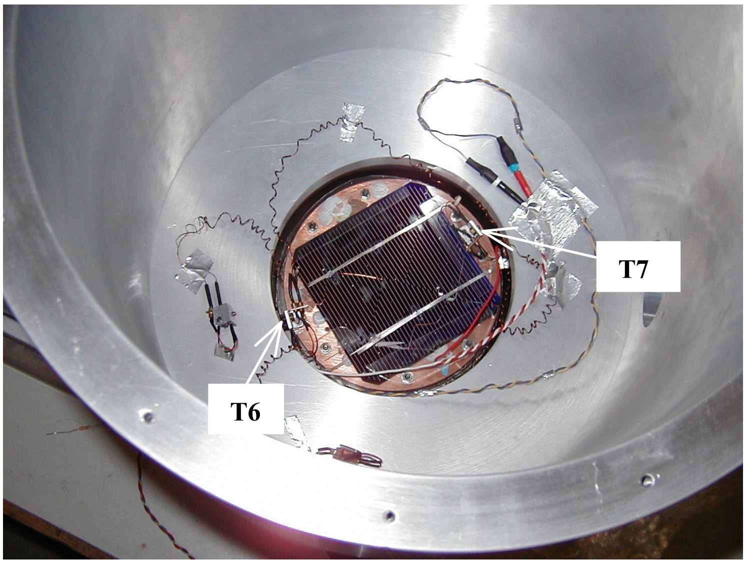

Fig. 5 – Disposizione dei principali sensori temperatura.

3. Balloon ascension phase test

The cell will be cooled following the time-profile of the balloon ascension phase.
The control panel of the cooler, during this test, is shown in Fig. 6.

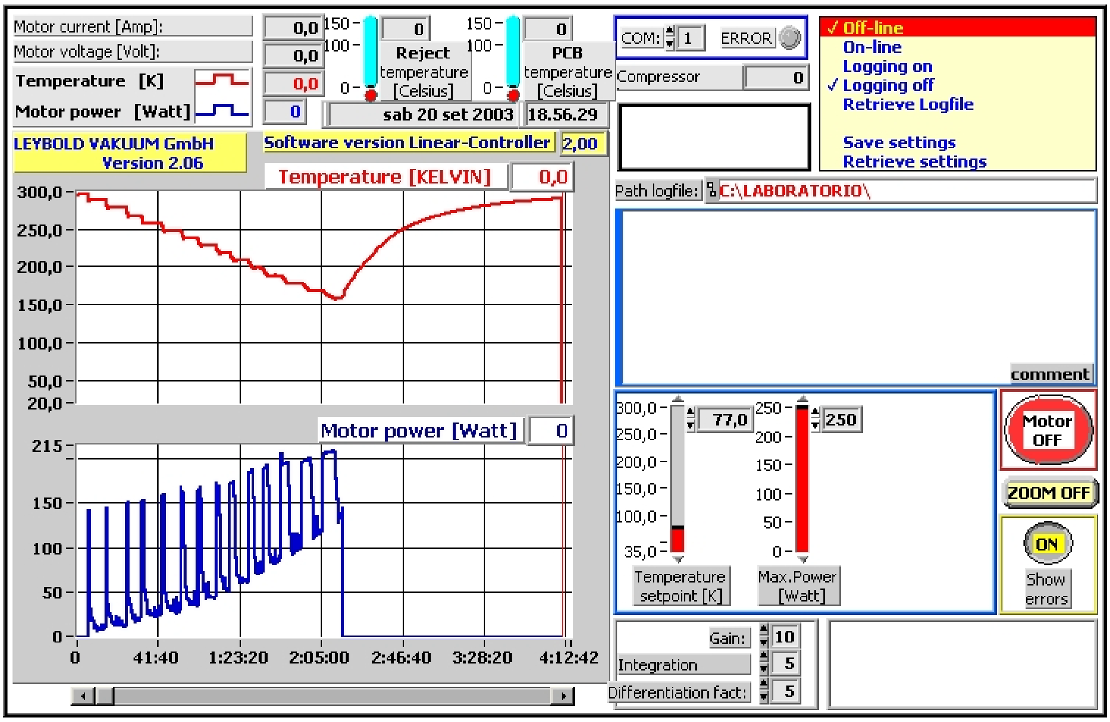

Fig. 6 – Cryocooler control panel: Simulation of the balloon ascension phase with the light source switched on (LAMP ON).

Since the light intensity is fixed, the same is for the thermal input to the cell. By lowering the T_{CF}, the cooling efficiency of the cooler diminishes, so increasing the electric power demand.

The temperatures and voltage acquired are shown in Fig. 7 e 8. Such values have been recorded on regime after the transient phase.

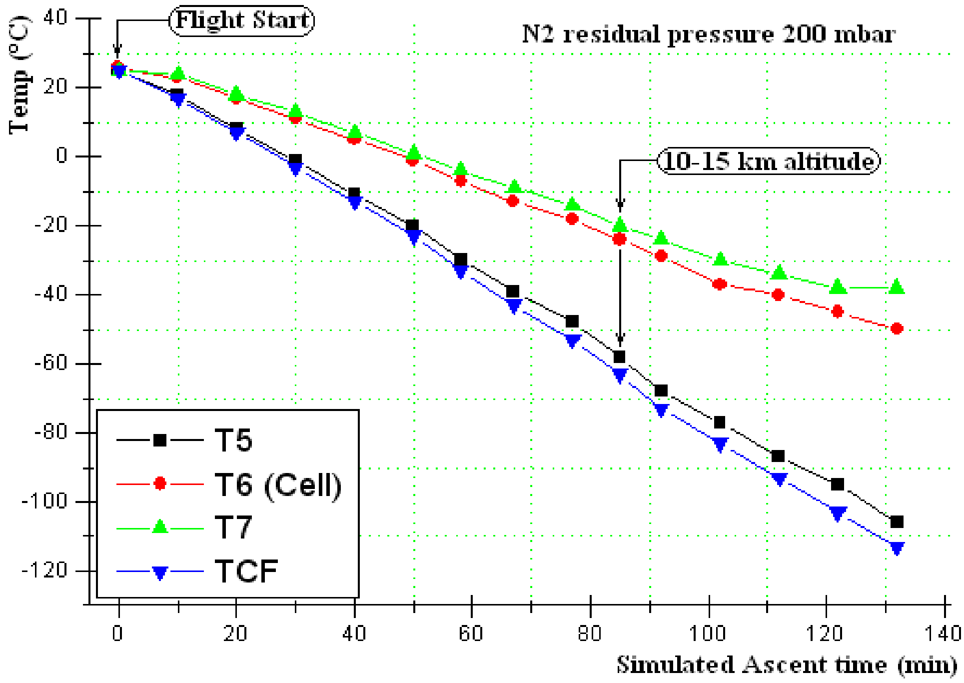

Fig. 7 – Temperatures during the simulated ascension phase

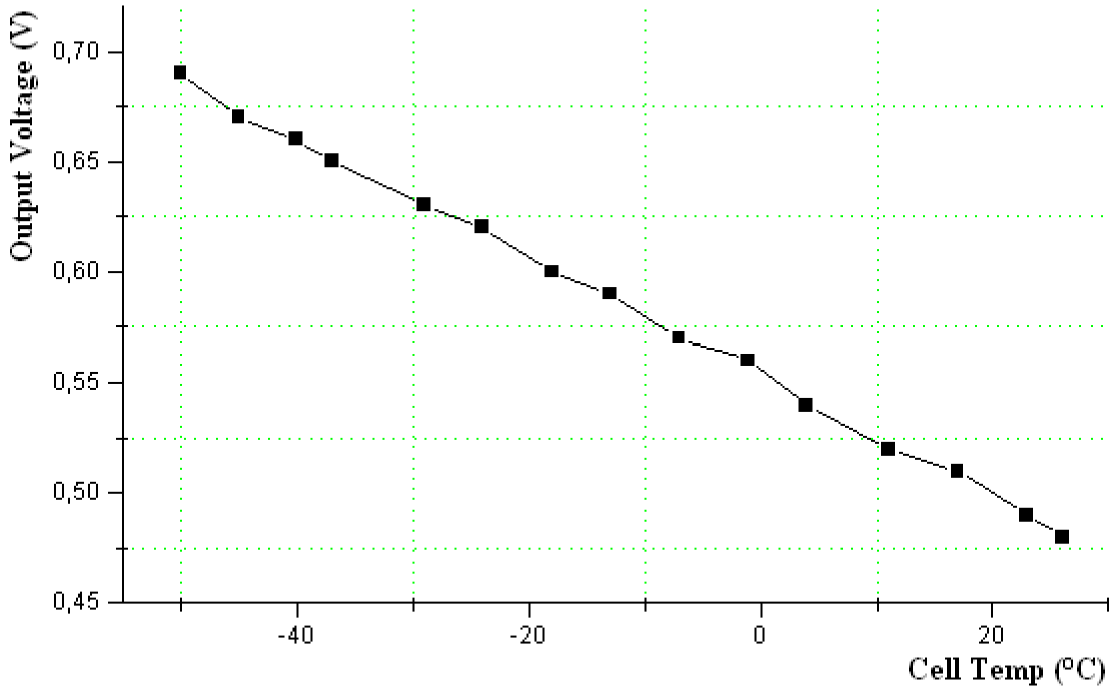

Fig. 8 – The voltage-cell versus its physical temperature (T6).

The Figure 8 shows that the voltage increases as the cell physical temperature decreases: an efficiency increase greater than 40% has been produced due to cell temperature decrease of about ~ 80 °C from the ambient temperature.
In the following figure a linear fit performed on the cell temperature and voltage measurements is shown (V_{load} is the voltage at the external load of 2.35 Ω). As reference cell temperature the average temperature between T6 and T7 has been adopted in this fit.

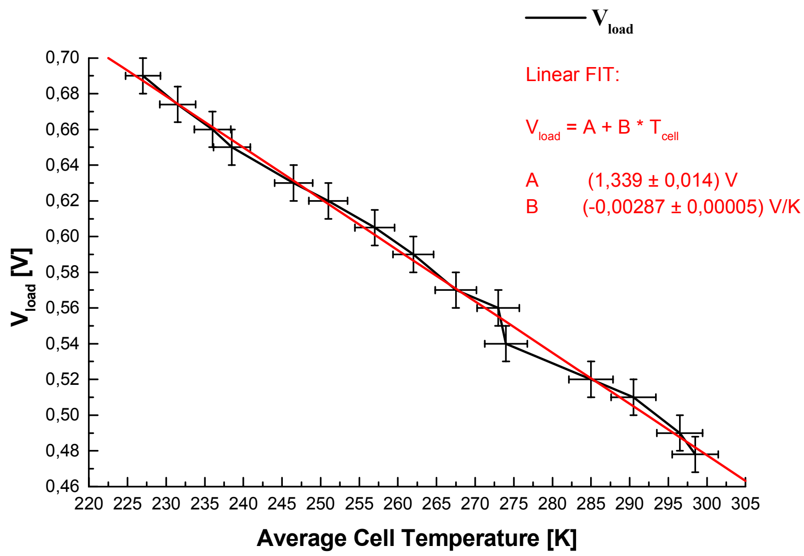

Fig. 9 – Linear fit of the acquired data. The temperature errors are 1% of the read values while for the voltage, the error is the last digit.

The trend highlighted by the fit in the range [220 ÷ 300] K is the following:

$$\mathbf{V_{load}(2.35\ \Omega) = 1.339 - 0.00287 \cdot T_{cell}}$$

where T_{cell} is the cell temperature in Kelvin.

4. Thermal shock test

In order to induce the braking of the cell, a test has been done cooling it fast (loss-kind test). The following plots show how fast was the cooling with respect to the ascension phase test and the cryocooler electric power demand (see for comparison Fig. 6).

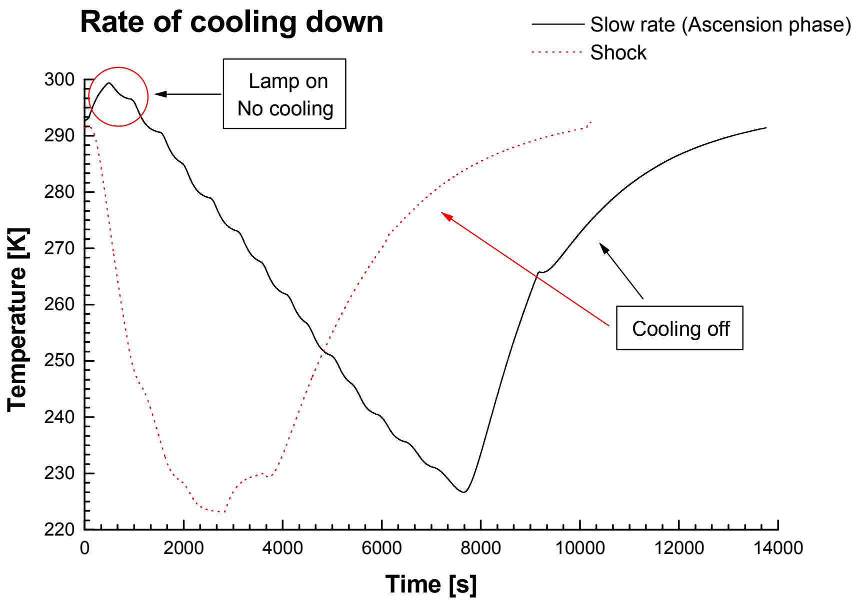

Fig. 10 – Time-comparison between the two kind of cooling. During the ascension phase the temperature increase for time t < 1000 s, is due to the fact that the lamp is switched on but the cooler is switched off.

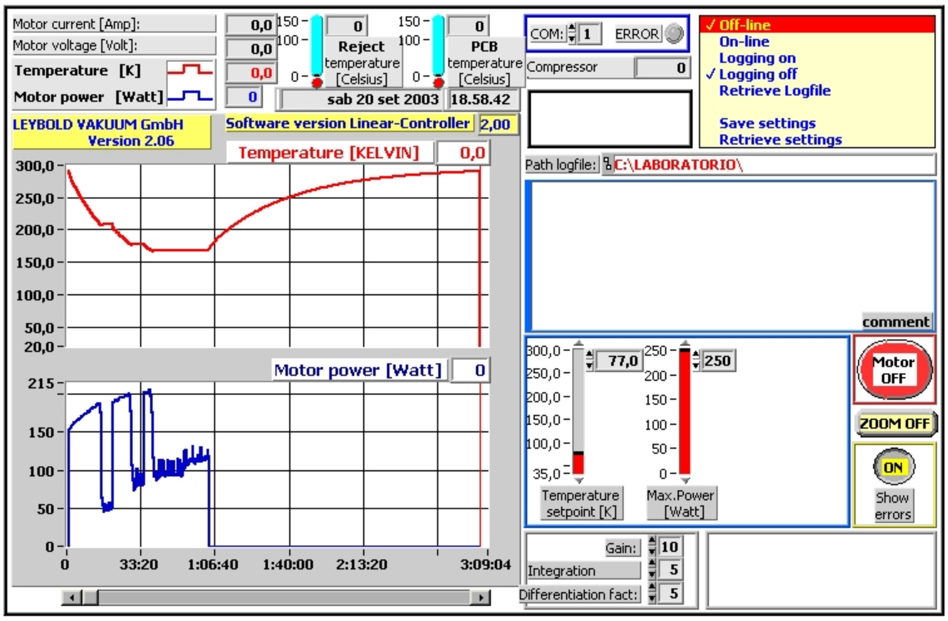

Fig. 11 – Cryocooler control panel: thermal shock phase. The cold finger temperature trend is shown.

In absence of illumination, the thermal shock (time: 14.20, T6=25°C; time: 15.00, T6 = −53°C) induced the braking of the cell along its diagonals (see Fig. 12). By switching on the lamp, the load-voltage is about 44 mV, an order of magnitude lower than the voltage when the cell was entire.

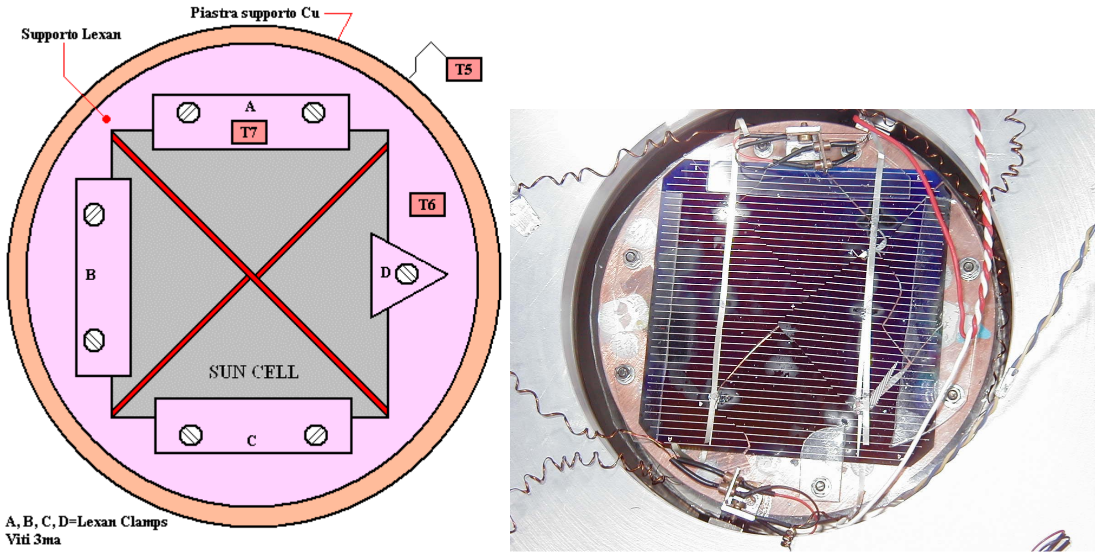

Fig. 12 – Mechanical braking of the cell.

In our opinion the braking during the shock phase is due to the cell anchorage above the LEXAN plate. It has been done by LEXAN clamps (A, B, C, and D in Fig. 12). The mechanical stress of the cell due to the fast cooling has been released to the clamps. The cell-failure is due to the mechanical rigidity of such clamps. In spite of this fail, we continued to illuminate the cell. The temperature profile from the minimal temperature to the laboratory one is shown in Fig. 13.

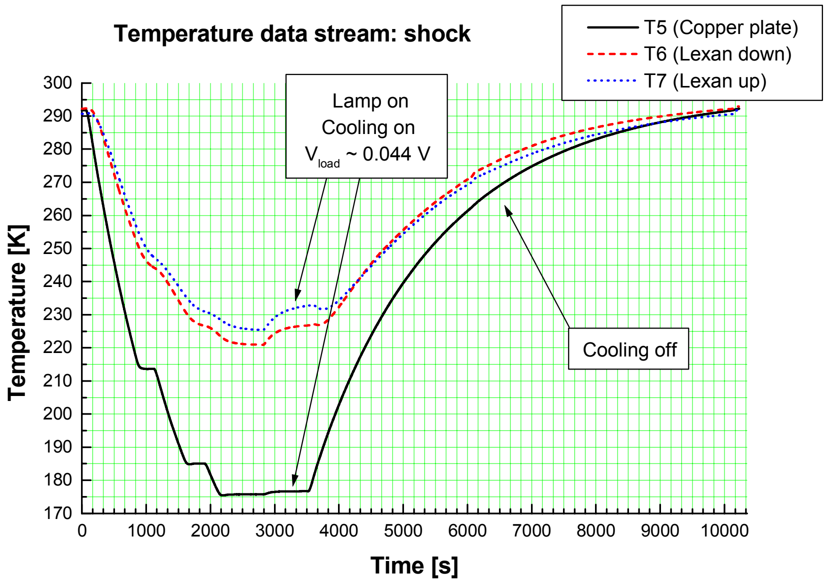

Fig. 13 – Temperature profile during the shock phase.

The thermal-shock test has been repeated by placing a new cell on the LEXAN plate without any clamps. Since there are not mechanical clamps, in order to increase the thermal coupling between the cell and the cold plate, the quantity of thermal grease has been increased.
The cooling time has been about 45 minutes, following the previous time profile (see Fig. 14). The LEXAN plate has been cooled down to 210K (~ – 63 °C). At ambient temperature the load voltage is: $V_{load} = 0.33 \pm 0.01$ V. By illuminating the cell the following signal has been observed: $V_{load} = 0.56 \pm 0.01$ V.
The signal variation with respect to the voltage supplied in ambient temperature is greater than 40% as in the ascension balloon test (§ 3).

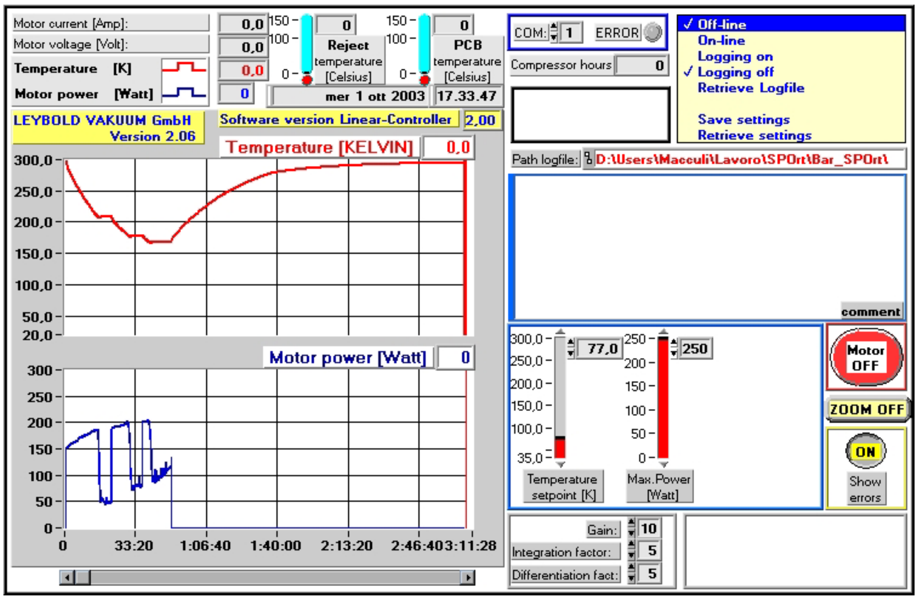

Fig. 14 – Cryocooler control panel: thermal shock phase.
The cold finger temperature trend is shown.

Since the cell adopted is different to the one used during the ascension phase test and the thermal coupling is also different, it isn't possible to compare the value of the load-voltage acquired in this test with the ones shown in Fig. 9.
The aim of this test is a mechanical check and not a optical efficiency one.
This test provides a positive result: no cell failure has been observed.
However the braking into two points of the weld of current leads has been observed near the temperature of 217 K. This failure highlights the criticality of the weld phase.

5. Conclusions

The POWER MAX® solar cell has been thermally qualified. The result is that such cells are good candidates to assembly a solar panel to supply electric power to a balloon-borne experiment.
Two kinds of test have been done by stressing the cell in the typical ambient expected near the atmospheric thermal inversion layer.
They are:

1) Verification of the efficiency variation in the light-current conversion versus the cell physical temperature
2) Mechanical rigidity

Both the tests provided interesting information.
The first one highlighted the cell efficiency increase as its physical temperature decreases.
The second one highlighted that to avoid failure, it is necessary to place the cell in a housing where it is free to differentially contract with respect the frame; the weld of the current leads are critical too.

6. Bibliography:

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[2] *Zannoni M., Cortiglioni S., Bernardi G., Carretti E., Cecchini S., Macculi C., Morelli E., Sbarra C., Ventura G., Nicastro L., Monari J.,Poloni M., Poppi S., Natale V., Baralis M., Peverini O.A., Tascone R.,Virone G., Boscaleri A., Pascale E., Boella G., Bonometto S., Gervasi M., Sironi G., Tucci M., Nesti R., Fabbri R., de Bernardis P., De Petris M., Masi S., Sazhin M.V., Vinyajkin E.N., The BaR-SPOrt Experiment, in Polarimetry in Astronomy, SPIE Symposium 2002 on Astronomical Telescopes and Instrumentation, August 22-28th 2002, Waikoloa, Hawaii, SPIE Proc., 4843 (2003).*