

# PID –1,500V readiness of PV modules: Some solutions and how to assess them in the lab

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## ABSTRACT

Even though it is now more than five years since potential-induced degradation (PID) began to proliferate, and despite the fact that solutions are under development, it is currently still the most discussed mode of degradation associated with cracking in PV modules. This is probably because of the serious consequences that can rapidly be triggered when PV systems are affected. Although test specifications have been established (IEC 62804), there is no pass or fail criterion for identifying a PID-free module. This paper presents several ways of addressing the problem of PID at the module and cell levels, by considering glass, encapsulants, thin-film barriers and ion-implanted cells. The proposed solutions are tested in accordance with a specific test protocol, and an applied voltage of 1,500V is used in order to prepare for the future increase in DC plant voltage. An initial PID test was conducted on mini-modules at room temperature (25°C and Al foil), before proceeding to a more severe test at 70°C (Al foil); this made it possible to clearly differentiate the influences of the different tested materials on PID degradation of the modules. These tests were carried out on 60-cell modules under the following conditions: test duration of 192h, temperature of 75°C, relative humidity of 85% and applied voltage of –1,500V. In contrast to ethylene-vinyl acetate (EVA) and standard glass modules, no evident degradation was observed with thermoplastic polyolefin (TPO), ionomer (ION), and thin chemically tempered glass modules; similarly, no degradation was evident with Al<sub>2</sub>O<sub>3</sub>-layer (deposited under the SiN layer at the cell level) modules or ion-implanted cell modules. The use of one of these components can therefore be a potential solution to the problem of PID.

## Introduction

The development and operation of solar power plants requires a good knowledge of the types of module degradation and their sensitivities to different stresses – temperature (T), relative humidity (RH), bias-voltage frame cells (V), UV, etc.

Potential-induced degradation (PID) is caused by a high negative voltage between module–cell polarities and the ground (the module frame). This type of degradation is highly dependent not only on humidity and temperature, but also on:

- Cell components: junction technology, thin-film materials, etc.
- Module components: EVA, anti-reflection (AR) layer, frame, glass, etc.
- Module ageing and soiling
- System: type and topology of inverters, system voltage, DC and AC grounding system, etc.
- Mounting system: frame grounding, metallic or wood support, fixing plates, dielectric characteristics of rubber, frame-support contact, tightening torque, etc.
- Environment: weather, irradiance, etc.

The topic of PID, which has been very active in terms of international publications since 2010 (see Fig. 1) thanks to the papers of Solon [1,2] and NREL [3], came to light several years ago when PV system voltages increased. The degradation was initially identified in 1978 by Jet Propulsion Labs [4]. At present, no testing standard exists for differentiating ‘PID-prone’ modules from ‘PID-free’ modules. Research into

finding PID-free solutions is currently ongoing, and PID-free modules are appearing on the market. The IEC 62804 test specification was published in 2015, but without any pass or fail criterion for identifying a PID-free module.

The physics that explains the PID phenomenon in c-Si modules, which assumes that sodium ions are responsible for the degradation, was reported in the paper by Naumann [5].

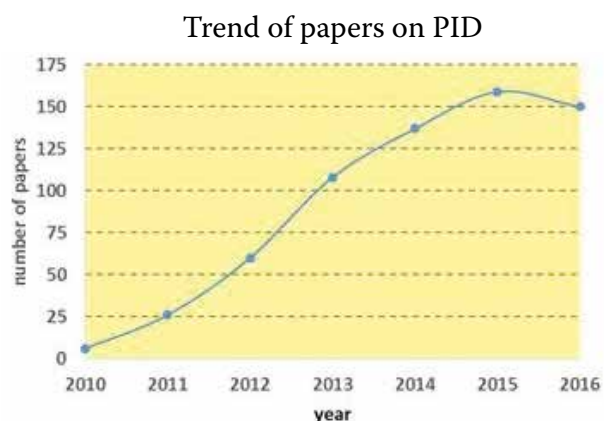


Figure 1. Trend of papers since 2010 that have included a discussion of PID.

According to this paper, the electrical field (between frame and cells) triggers the diffusion of sodium ions from the glass into the encapsulation material and cells; these ions are then released and accumulate at the surface of the silicon nitride (the AR layer). Sodium ions propagate through Si stacking faults in the p-n junction (Fig. 2). In the case of p-type cells, these charges generate local shunts in the p-n junction, which dramatically affects shunt resistance and  $V_{oc}$ .

There are many parameters associated with the module that can mitigate or suppress the consequences of PID – for example, EVA resistivity and glass resistivity [6], intermediate diffusion layer, thickness of the glass and EVA, AR coatings [7], cell and silicon features.

**“The increase in power plant voltage to 1,500V will accentuate PID stresses.”**

Several approaches to solving the PID issue are currently being studied. However, these solutions have not always been authenticated: for example, a module announced by a manufacturer to be insensitive to PID may in actual fact be sensitive in a lab test. The degradation mechanism due to the potential is not entirely understood at the material and microscopic levels. In addition, the increase in power plant voltage to 1,500V will accentuate PID stresses.

The earlier work reported in the previously cited publications has identified possible electrical causes (Fig. 3) of degradation processes at the microscopic level for c-Si and CdTe modules. Moreover, the impacts on PV plants, the testing methods used by laboratories, and a range of solutions at three levels – cell, module and system – have been discussed [8,9].

Since the degradation occurs initially to the shunt resistance, measurements taken under standard test conditions (STC) are not adequate for measuring the consequences of PID [10]; the low-light behaviour should be a mandatory criterion for pass/fail results in a PID test. Indeed, the module tested in Braisaz [10], for example, exhibited no degradation at  $1,000\text{W}/\text{m}^2$ , but demonstrated severe degradation at  $200\text{W}/\text{m}^2$ , after 96 hours at  $60^\circ\text{C}/85\%\text{RH}/-1,000\text{V}$  (IEC TS 62804 [11]). It would have passed the requirements of the standard if the only criterion had been  $1,000\text{W}/\text{m}^2$  (because the power loss was below 2%).

In Braisaz [12], a representative, selective and reproducible test protocol with a pass or fail

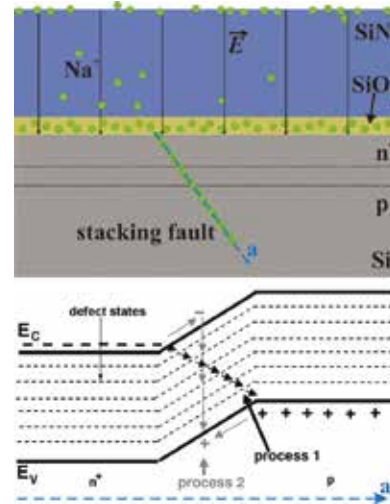


Figure 2. Schematic view of a solar cell cross section: the electrical field causes a drift of  $\text{Na}^+$  ions through the p-n junction [5].

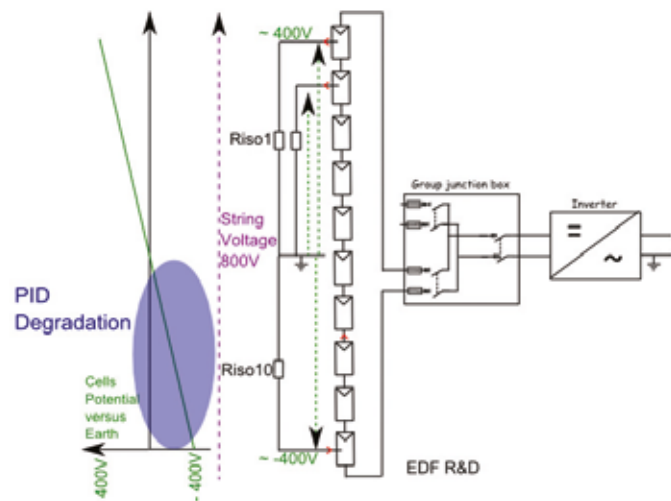


Figure 3. PID in operation in a PV system.

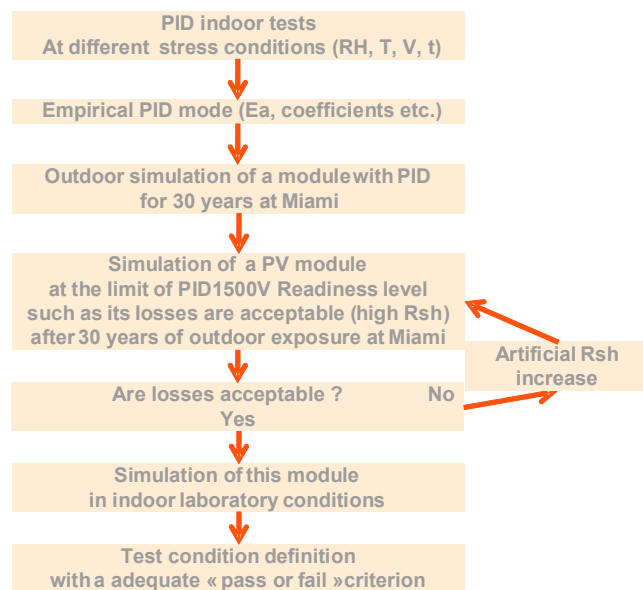


Figure 4. Method for developing a PID test [12].

criterion has been proposed: 192h/75°C/85%RH/-1,500V, with a maximum power loss of 5% at 200W/m<sup>2</sup>. Outdoor degradation has been estimated on the basis of indoor accelerated test results and an empirical PID model. After several iterative simulations, an indoor test protocol with a specific ‘pass or fail’ criterion has been determined: there are limited losses after 30 years’ outdoor exposure in Miami for a module at the end of a 1,500V string. According to this test protocol, all the PID solutions tested and reported by Braisaz [13] appear to be suitable.

### Establishing a test protocol for PV modules

Many tests under various conditions were conducted on several 60-cell c-Si modules from the same manufacturer in order to determine the role that the factors T, RH, V and time play in PID. The approach to creating a test protocol is summarized in Fig. 4.

From these indoor test results, basic laws were deduced by fitting two-diode model parameters to the measurement data (I-V curves and flashes), and a PID behaviour model was formulated. The degradation is considered to satisfy:

- a linear law with respect to time;
- a linear law with respect to voltage;
- a sigmoid law with respect to moisture;
- an Arrhenius law with respect to temperature.

On these assumptions, the degradation rate *Rd* can be expressed as:

$$Rd = A * V * \frac{B}{1 + e^{-C * RH + D}} * e^{-\frac{E_a}{k_B T}} \quad (1)$$

where A, B, C and D are coefficients that are calibrated using the least-squares method on the measurements; V is the voltage; T is the temperature; RH is the relative humidity; k<sub>B</sub> is the Boltzmann constant (1.38 × 10<sup>-23</sup> J.K<sup>-1</sup>); and E<sub>a</sub> is the activation energy of the PID phenomenon. An empirical law can then be established from the evolution of R<sub>sh</sub> during the accelerated PID tests:

$$R_{sh} = \frac{R_{sh0}}{1 + b * Rd * t} \quad (2)$$

where R<sub>sh0</sub> is the initial shunt resistance, b is a coefficient and t is the time (hours). This model is based on a set of empirical parameters.

Up until this point, R<sub>sh</sub>(t) has provided an indication of the level of degradation under steady-state conditions (constant temperature, humidity and voltage); however, outdoor stresses are continually

changing. An incremental algorithm based on previous work [14] calculates iteratively the PID degradation with variable temperature and humidity; the degradation is updated at each time step of 1 hour. The steps for computing the evolution of the outdoor shunt resistance during the module’s lifetime are presented in Fig. 5.

If the temperature at time t, T(t), and the state of the reaction at a time step t-dt, X(t-dt), are known, then it is possible to determine the time t<sub>eq</sub> that would represent the achievement of the same degree of reaction for indoor conditions at a constant temperature T(t). This quantity t<sub>eq</sub> is the reciprocal function of the shunt resistance function.

If the derivative of the function R<sub>sh</sub> at (RH, T, V, X), along with T(t), RH(t) and V(t), is used, the slope of the shunt resistance can be calculated at any point in time, for any module conditions, and for any state of reaction:

$$\dot{R}_{sh}(t_{eq}, RH, T, V) = \left( \frac{dR_{sh}}{dt} \right)_{t_{eq}, RH, T, V} = \frac{-b * Rd * R_{sh0}}{(1 + b * Rd * t)^2} \quad (3)$$

The shunt resistance at time t can then be calculated by numerical integration over the time period from 0 to t:

$$R_{sh_{outdoor}}(t) = \int_0^t \dot{R}_{sh}(t_{eq}(u), RH(u), T(u), V(u)) du \quad (4)$$

With an hourly weather data set consisting of irradiance, temperature and relative humidity, the outdoor-related degradation after 30 years was calculated for a module at the end of a 1,500V string (negative side). In this study, the weather data set is for one full year in Miami, taken from the Meteororm database. Degradation is measured at 1,000W/m<sup>2</sup> and at 200W/m<sup>2</sup>; these will be the PID degradation references. The hypothesis

is that the PV plant operator desires a maximum degradation of less than 1% at STC (1,000W/m<sup>2</sup>) and 6% at 200W/m<sup>2</sup> after 30 years’ outdoor exposure for a module at the end of a 1,500V string (negative side). The characteristics of such a module were therefore determined by calculating an adequate ‘artificially increased’ shunt resistance R<sub>sh</sub>.

The module in question, which is just at the limit of the PID-1,500V readiness level, was simulated in order to check that after 30 years the degradation is less than 1% at 1,000W/m<sup>2</sup> and 6% at 200W/m<sup>2</sup>. This module with a new R<sub>sh</sub> was then simulated in laboratory conditions (constant T, RH, and V stresses). On the basis of what is experimentally possible with test chambers, and in order to accelerate the tests, a protocol was established with an adequate ‘pass or fail’ criterion, specifically 192h/75°C/85%RH/-1,500V, with a maximum power loss of 5% at 200W/m<sup>2</sup>.

### Materials and methods

#### Mini-modules

Two single-cell mini-modules incorporating standard solar cells (p-type monocrystalline silicon with POCl<sub>3</sub>-diffused emitter, SiN<sub>x</sub> AR coating, Al-BSF) were created with:

- Four encapsulants:
  - a classic EVA with a 33% vinyl acetate content
  - a 28% vinyl acetate EVA
  - a thermoplastic polyolefin (TPO)
  - an ionomer (ION)

Two other modules with four cells in series were constructed:

- Two glass backsheet assemblies:
  - standard glass and a Tedlar-polyester-Tedlar (TPT) backsheet
  - special thin chemically tempered glass and a TPT backsheet

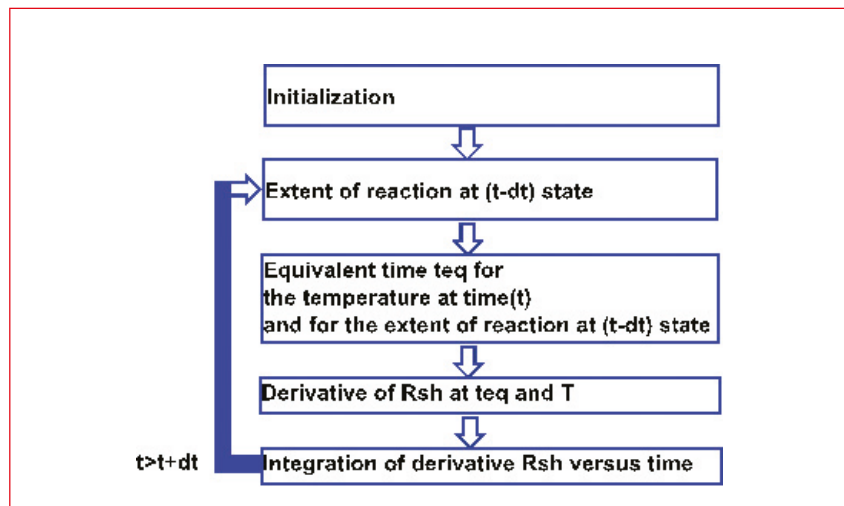


Figure 5. R<sub>sh</sub> degradation method.

The sensitivity of the modules to PID was evaluated using the following set-up. The modules were stacked together (glass to glass) with an aluminium foil between them. The aluminium foils were connected together to the positive terminal of the voltage generator, while the cell strings were connected together to the negative terminal. The voltage of 1,500V delivered by the generator was thus set between the aluminium foil and the cells. An initial test at 25°C and a relative humidity below 60% was conducted on all modules for 192 hours, i.e. test conditions 192 h / 25 °C / < 60 % RH / - 1,500 V. Subsequently, a more severe test was carried out at a temperature of 70°C for 128 hours, i.e. 128h/70°C/<60%RH/-1,500V.

### 60-cell modules

In the study reported in this paper, the test protocol '192h/75°C/85%RH/-1,500V, with 5% of maximum power loss at 200W/m<sup>2</sup>, was used on 60-cell module prototypes to evaluate various PID solutions that had previously been tested on the mini-modules:

- Three encapsulants (Fig. 6):
  - a classic EVA
  - a TPO
  - an ION
- Three glass backsheet assemblies (Fig. 7):
  - standard glass and a TPT backsheet
  - special thin chemically tempered glass and a TPT backsheet
  - special doubly thin chemically tempered glass module and a TPT backsheet
- One module with an ALD-deposited Al<sub>2</sub>O<sub>3</sub> barrier under the SiN<sub>x</sub> layer of the solar cells (Fig. 8)
- One module with implanted cells (Fig. 9)

The test chamber and the system used are presented in Fig. 10.

### Mini-module test results

#### Encapsulant tests

Fig. 11 presents the maximum power variation of the modules during the tests at 25°C. The maximum power is stable, except in the case of the modules encapsulated with 33% vinyl acetate EVA.

**“The modules with a TPO or ionomer encapsulant showed no degradation.”**

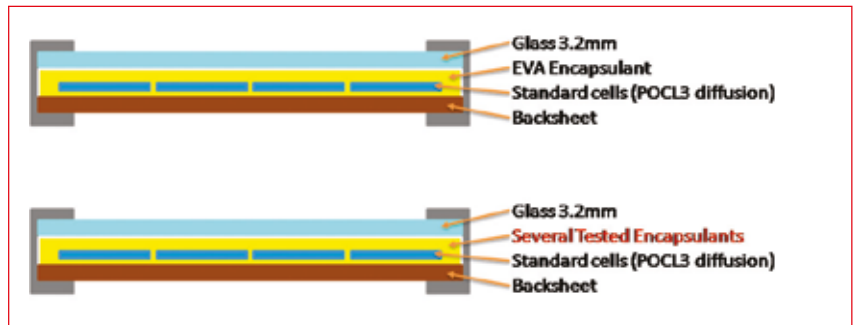


Figure 6. Sectional view of the reference module (top), and the module with the tested encapsulants (bottom).

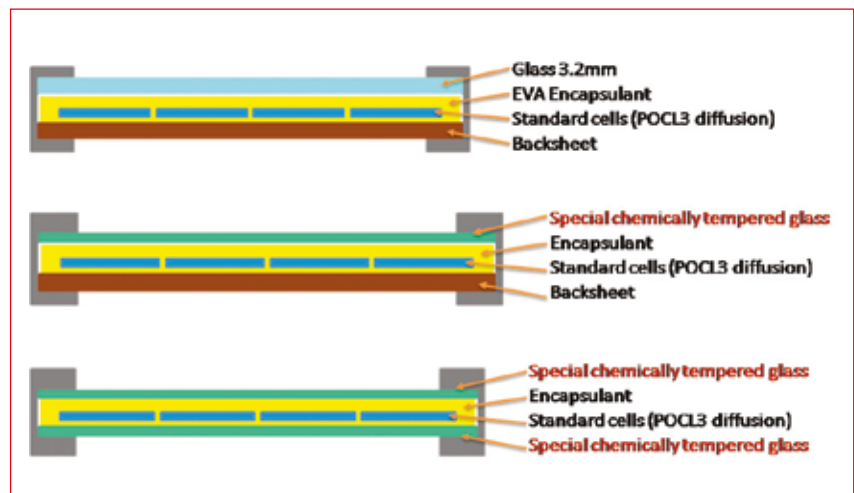


Figure 7. Sectional view of the reference module (top), the tested new glass module (middle), and the tested double-glass module (bottom).

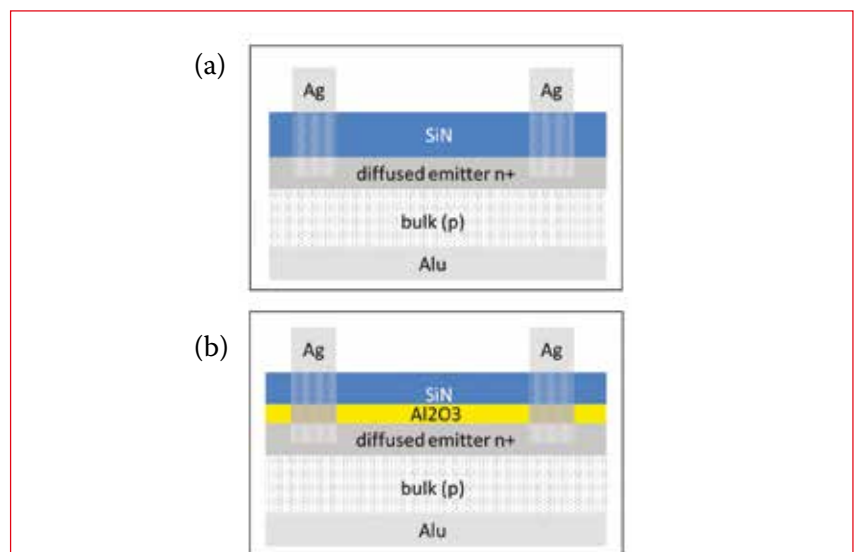


Figure 8. Stack of (a) a standard cell, and (b) a cell with an Al<sub>2</sub>O<sub>3</sub> barrier under the SiN<sub>x</sub> layer of the solar cells.

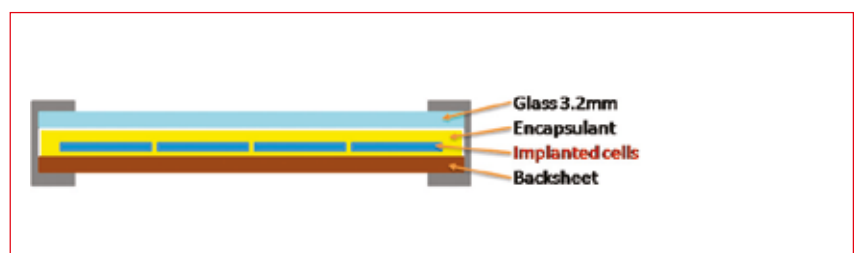
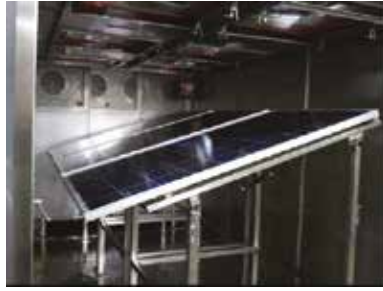
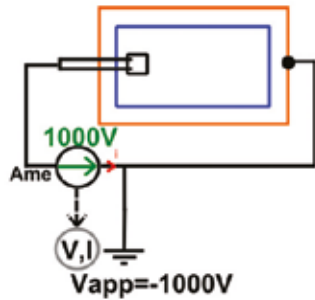


Figure 9. Sectional view of the tested module with implanted cells.





**Figure 10. PID mounting system and picture of the test chamber with the bias voltage applied to the frame.**

To compare the different impacts of the three encapsulants TPO, ION and 28% vinyl acetate EVA on PID, a PID test at 70°C was carried out. The electroluminescence (EL) images of the mini-modules during the test are shown in Fig. 12. A very good cell response before the test was obtained for the modules, all of which remained stable during the test, apart from that with the 33% vinyl acetate EVA, as seen in Fig. 11. Even if the EVA encapsulant is made with 28% vinyl acetate, the material is clearly not suitable for curbing the PID during testing at 70°C (see the  $I-V$

Curves and the EL images in Fig. 12). On the other hand, the modules with a TPO or ionomer encapsulant yielded a very good and stable cell response, as indicated in Fig. 12. Degradation was observed for the module with EVA at 28%, while the modules with a TPO or ionomer encapsulant showed no degradation.

#### Glass tests

The two 4-cell mini-modules with a chemically tempered thin glass (0.85mm thick) were subjected to the PID tests at -1,500V, as was a

4-cell mini-module with a standard solar glass. The results, in terms of the variation in maximum power at 1,000W/m<sup>2</sup> during the tests, are presented in Fig. 13. The degradation rate is limited by the use of the chemically strengthened thin glass, compared with the module with a standard solar glass. Nevertheless, the resistance to PID afforded by the chemically strengthened thin glass is not sufficient to keep the degradation of the initial module power below 5% at higher temperatures.

### Standard-size module results

#### Encapsulant tests

Fig. 14 shows the module efficiency as a function of the irradiance at three stages of a PID test: initially, after 96h and after 192h. No losses at all were observed for polyolefin and ionomer modules, even at low irradiances of 200W/m<sup>2</sup>. These modules showed slight increases in power, as opposed to the EVA module, which lost 66% in STC conditions, and 88% at 200W/m<sup>2</sup> (not visible on the graph in Fig. 14).

EL images of the EVA module are given in Fig. 15; the affected cells are those on the edges, where the electrical field (between the frame and the cells) is stronger. As PID degrades the shunt resistance, the affected cells are visible at low currents.

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### Glass tests

In Fig. 16 no PID is observed on thin chemically tempered glass using a chemically strengthened cover glass. However, the EVA module (created using a different EVA from the one in Fig. 14) lost 15% in STC conditions, and 31% at 200W/m<sup>2</sup>; nevertheless, this EVA performs better than the previous one in terms of PID resistance.

### Temperature coefficients

The temperature coefficients were also measured after PID testing (-1,500V/75°C/85%RH/192h) of an EVA module. The power was observed to be very low (a decrease of more than 66%), but now virtually independent of temperature (Fig. 17). Further investigations are necessary in order to assess and explain this phenomenon

(reported by Desharnais [15]). It seems that the shunt resistance is too degraded to be sensitively dependent on temperature in order to have a consequential effect on power.

### Al<sub>2</sub>O<sub>3</sub> thin layer under the SiN

In this 60-cell module, each cell contains an Al<sub>2</sub>O<sub>3</sub> layer deposited under the SiN layer; no degradation was observed after the PID test (Fig. 18).

### Ion-implanted cells

A 60-cell module with ion-implanted cells (p-type monocrystalline silicon with SiO<sub>2</sub>/SiN<sub>x</sub> stack on the front side, ion-implanted emitter, Al-BSF) was subjected to PID testing and compared with a 60-cell module with standard diffused cells (Fig. 19). No degradation for the module with EVA and ion-

implanted cells was observed; it seems that ion-implanted cells are PID resistant. Further investigation needs to be carried out, however, in order to validate this interesting result, probably due to the formation of an oxide layer during the implantation process (reported by Zhu [16], Basame [17] and Han [18]).

“The most promising solution, in terms of cost, is the use of ion-implanted cells.”

### Conclusions

With this new empirical approach for establishing test protocols through modelling and testing, it is possible to assess PID resistance. The PID model developed here is an initial empirical approach that entails validation by additional indoor and outdoor tests, but it could be used for other tests (damp heat, thermal cycling, etc.). The model needs to be supplemented by:

- New tests to refine the parameters, laws and hypothesis.
- A regeneration-effect model, as reported in Lechner [19].
- Tests on other modules with different surface-perimeter ratios.
- A sub-module model of the electrical field at the surface (see Pingel [6]), in order to take into account both the decrease in shunt resistance at the cell level and the mismatch.
- Uncertainty calculations and outdoor validation.

It has been demonstrated that possible solutions offering module

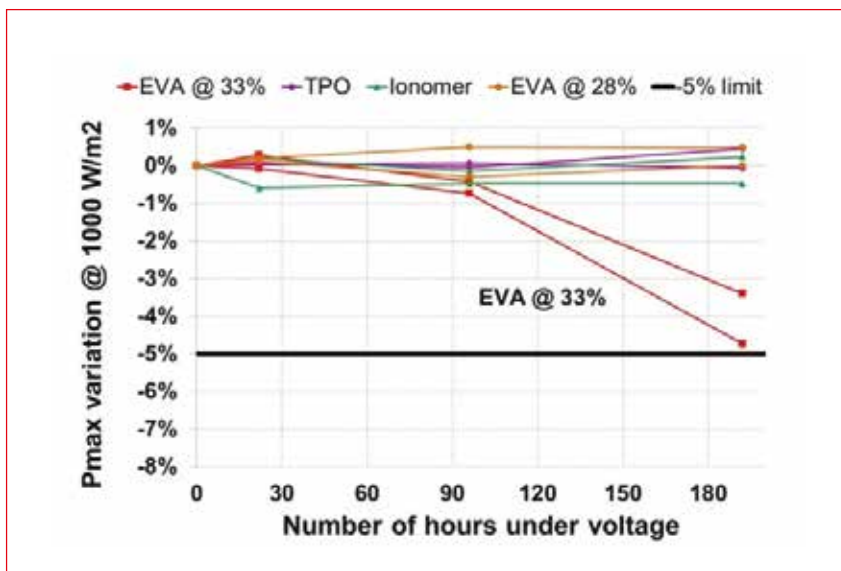


Figure 11. STC relative power evolution for mini-modules with different encapsulants (33%-EVA, 28%-EVA, ionomer and polyolefin) during PID at -1,500V/25°C/with aluminium foil.

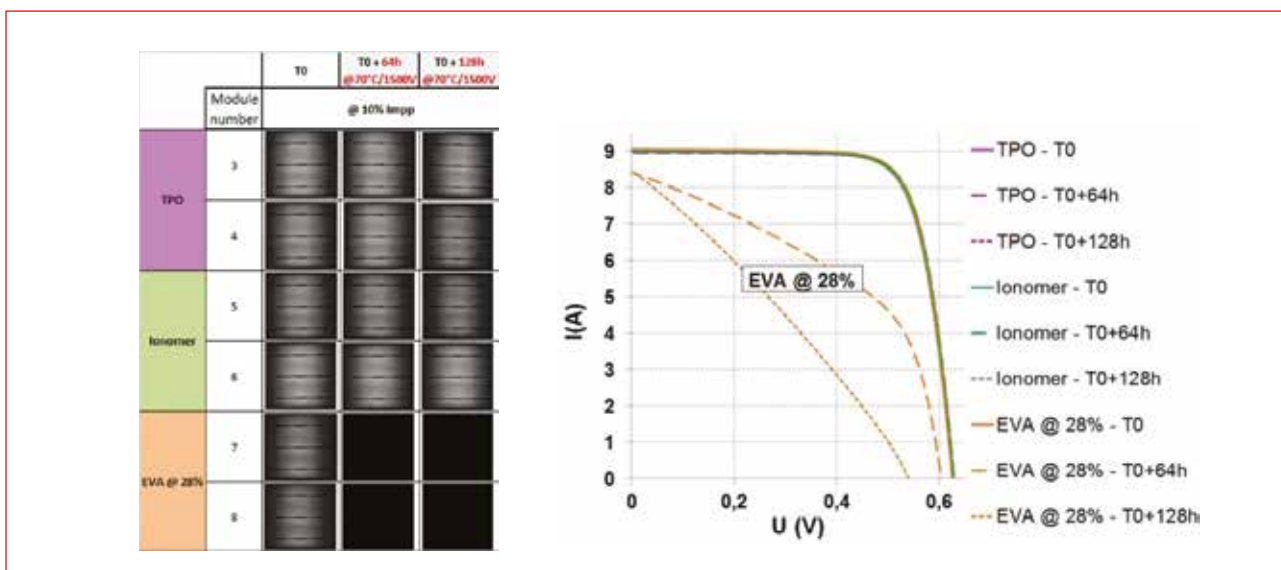


Figure 12. EL images and I-V curves after the PID test (-1,500V/70°C/with aluminium foil).

resistance to PID are: TPO, ionomer, thin PID-free glass with lower Na content (chemically strengthened glass), Al<sub>2</sub>O<sub>3</sub> layer under the SiN, and ion-implanted cells. The most promising solution, in terms of cost, is the use of ion-implanted cells.

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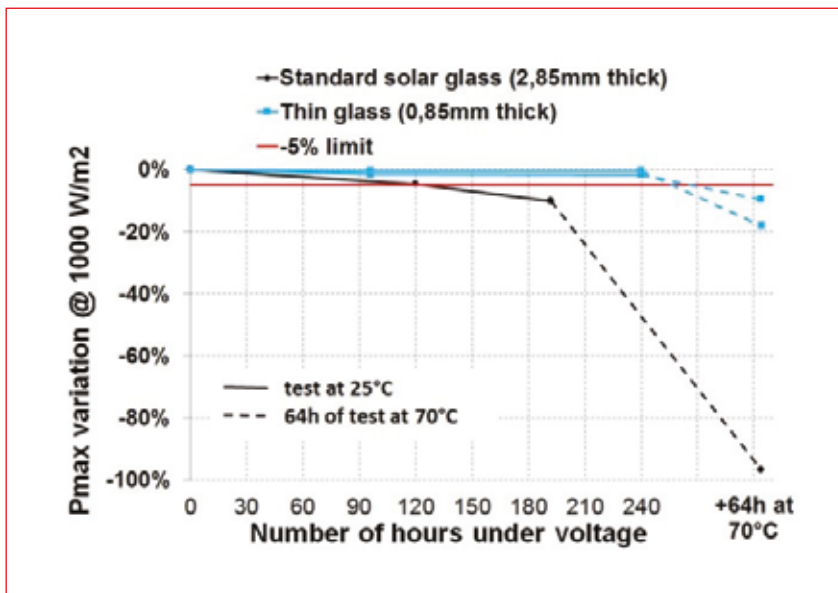


Figure 13. STC relative power evolution for mini-modules with different glass during the PID test (-1,500V/25°C/with aluminium foil).

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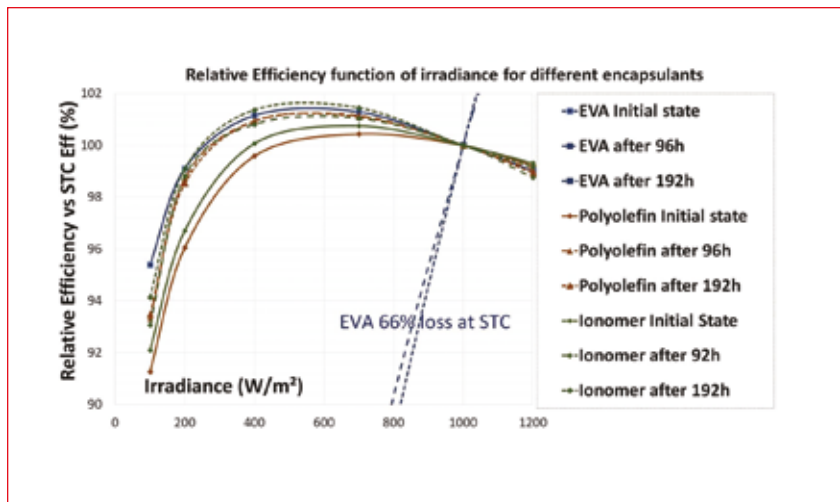


Figure 14. Relative efficiency vs. STC efficiency as function of irradiance for different module encapsulants (PID conditions:  $-1,500\text{V}/75^\circ\text{C}/85\%RH$ ).

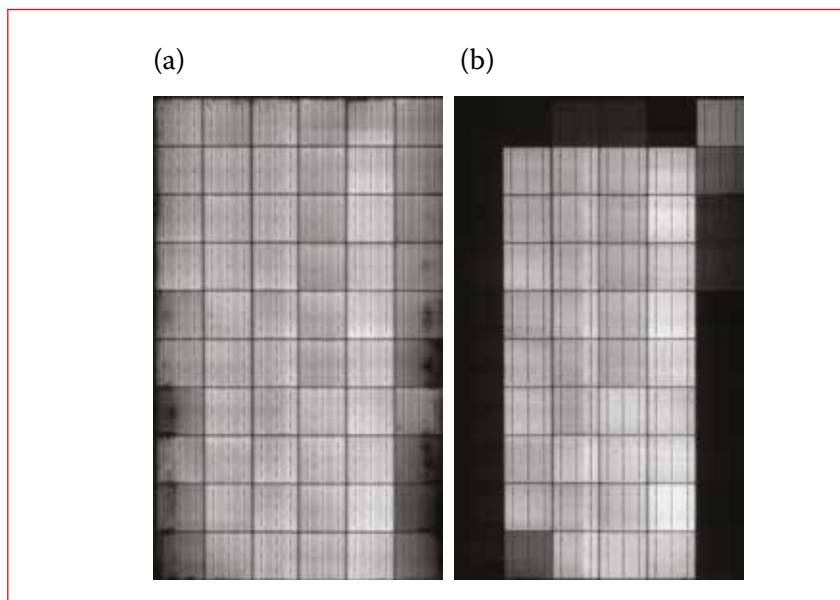


Figure 15. EL images after the PID test ( $-1,500\text{V}/75^\circ\text{C}/85\%RH/96\text{h}$ ): (a) 9A; (b) 0.9A.

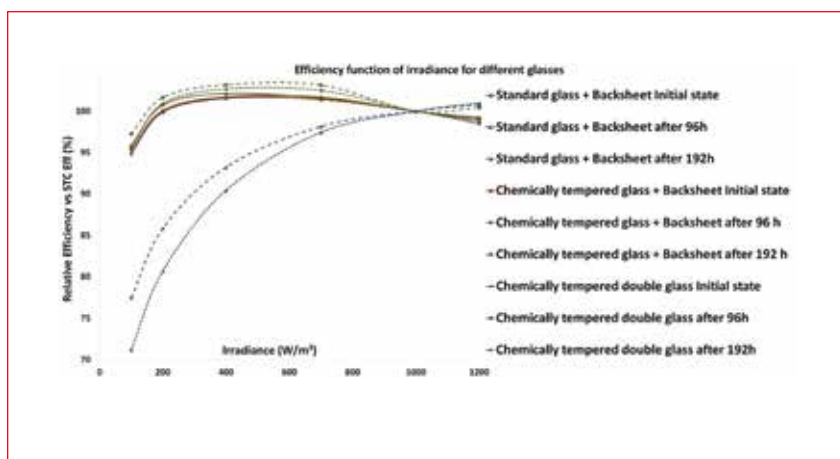


Figure 16. Relative efficiency vs. STC efficiency as a function of irradiance for different module glass (PID conditions:  $-1,500\text{V}/75^\circ\text{C}/85\%RH$ ).



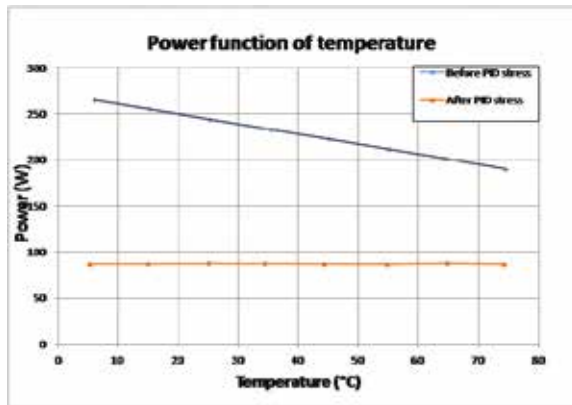


Figure 17. Power as a function of temperature, before and after PID stress testing. After the test there is virtually no temperature dependency.

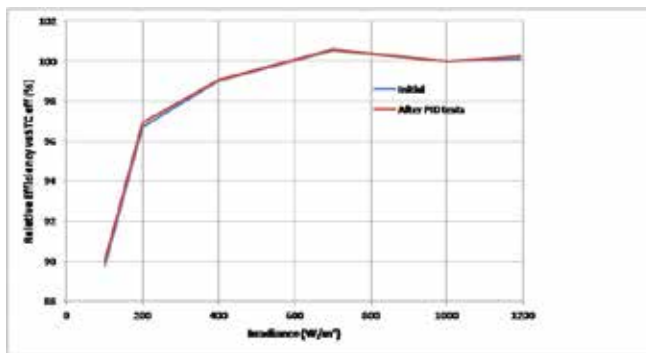


Figure 18. Relative efficiency vs. STC efficiency as a function of irradiance for a module with diffused cells and an Al<sub>2</sub>O<sub>3</sub> layer, before and after the PID test (PID conditions: -1,500V/75°C/85%RH/192h).

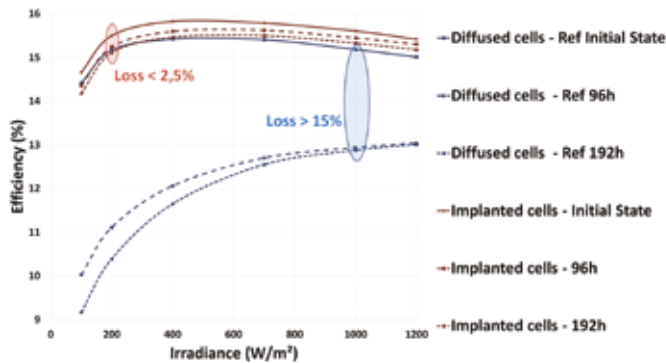


Figure 19. Efficiency as a function of irradiance for a module with implanted cells and for a module with diffused cells (PID conditions: -1,500V/75°C/85%RH).



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