PV MODULE LAMINATION DURABILITY

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1. Abstract

Lifetime of terrestrial PV modules is determined not by limits of the photovoltaic process but by ingression of moisture into the module laminate. To avoid (or at least to limit) moisture ingression an adequate sealing at the module edges is very helpful, but also a good adhesion of the laminate layers is necessary. This paper addresses the adhesion quality. Adhesion of a standard PV module lamination is consisting of the sequence glass-EVA-cell-EVA-glass or glass-EVA-cell-EVA-backsheet. The adhesion quality depends mainly on:

- 1.1. the cleanliness of the glass sheets
- 1.2. the condition of the EVA (prior to lamination)
- 1.3. the lamination process (process temperature, profile and duration, pressure, homogeneity)

To test lamination quality, three different tests (on the module center as well as close the module edges) have been applied:

2.1. Chemical analysis of samples to determinate the state of "curing" or cross-linking of the co-polymer EVA after lamination

2.2. Peel tests to determine the force to peel-off the layer of the laminate

2.3. Damp-heat treatment (1000 h at a temperature of 85°C and 85% of relative humidity)

It was found out that the chemical analysis of the EVA curing-state (2.1) is good to find out about the accuracy of the lamination process, following the recommended temperature profile and homogeneity (as 1.3), and the initial condition of the EVA used (1.2.). However, this test method may be misleading to allow a statement on the overall quality of the lamination: the surface glass sheet may be treated with oil (e.g., to prevent adhesion of the individual glass sheets during storage) which has not been removed properly before lamination, thus causing low laminate adhesion (especially after the damp heat treatment 2.3), early moisture ingression and a reduced module lifetime. Therefore peel tests (2.2) are essential to determine the overall quality of the lamination. Several results of measurements are presented in the paper.

Keywords: Photovoltaic module; quality; lifetime; reliability, EVA; encapsulate; peel test; lamination; extraction; durability

2. Introduction

Prices of PV-modules became very favourable, but sometimes quality and lifetimes are not meeting the expectations. Lifetime of terrestrial PV modules is determined not by limits of the photovoltaic process but by ingression of moisture into the module laminate. To avoid (or at least to limit) moisture ingression an adequate sealing at the module edges is very helpful, but also a good adhesion of the laminate layers is necessary.

This paper addresses the adhesion quality. Adhesion of a standard PV module lamination is consisting of the sequence glass-EVA-cell-EVA-glass or glass-EVA-cell-EVA-backsheet. The following document intends to give an overview of the different methods for testing of encapsulation and describes the problems which are accompanied by them. The package of a PV-Module is a very complex system with many surfaces involved. Careful selection of the components is required to achieve an optimum result. Just the backsheet itself consists of 2-4 layers (e.g, Tedlar®-Polyester-Tedar®) which are bonded to each other.

To verify overall quality of PV modules the standards IEC 61215 (for modules with crystalline cells) and IEC 61646 (for modules consisting of thin film cells) have been established to ensure performance and lifetime. The quite similar standards IEC 61730 and UL 1703 are both focused on module safety. The test sequence for a combined testing of IEC 61215 and 61730 is shown in Fig.1. In addition to the standards some banks and other financing institutions demand additional tests and proofs which are not covered in the standards. This is for example the proof of sufficient curing of EVA.

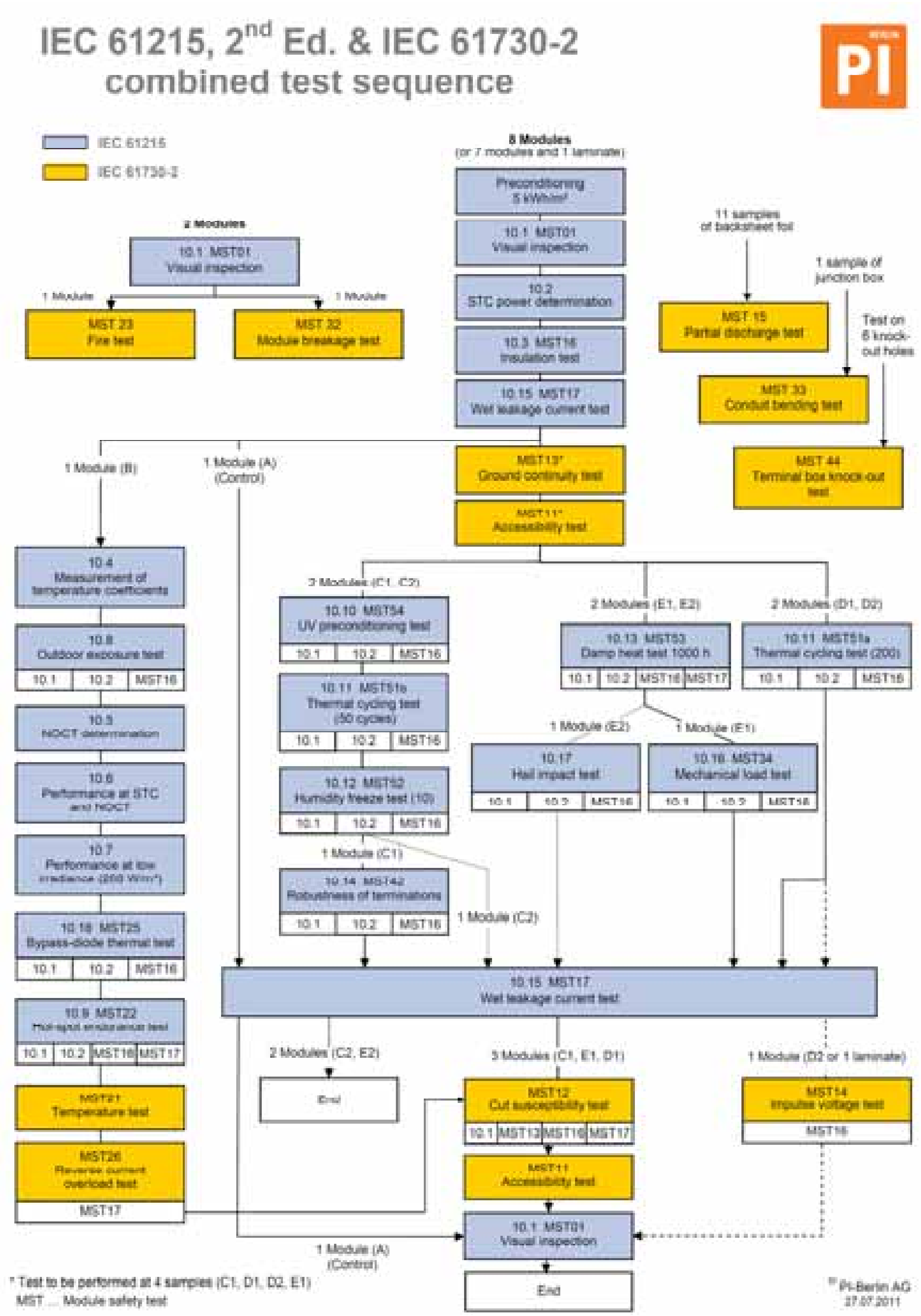

Fig. 1: Full test procedure for module quality, performance, safety as given by IEC 61215, IEC 61730

3. Storing of the material and problems

In most photovoltaic modules an encapsulate material consisting of ethylene-vinyl-acetate (EVA) is used. This encapsulate is produced as a film and is stored and delivered on rolls. The length and the width of the roles may vary. Most of EVA manufacturers recommended a storage temperature below 30°C (optimum at 22°C) and relative humidity below 50%, for a time not exceeding 6 months after the production, no direct sunlight and always wrapped tightly with the original packaging material. A film cut in sheets should be stacked and used within 8 hours (Solutia, 2010). The company STR gives in an overview in the technical manual of Photocap® products: reduction of adhesion of the EVA to other materials by the duration of storage.

Via customer reply and own investigations, PI Berlin compiled a list of possible reasons for partial failure or complete failure of the laminate. Some of the problems are a direct result of not following the storing parameters as mentioned above (PI Berlin, 2011):

- Unclean glass or other parts

Dirt or process chemicals might stick on a surface of one the components of the compound. This prevents adhesion of the EVA or the backsheet or the glass.

- Evaporation of the curing agent before curing.

Due to wrong storage or mistakes on producer-side there is not enough curing agent left for the curing process.

- Curing time too short

In order to increase production numbers, insufficient curing time may be applied by the process engineers. The result might be inhomogeneous curing within a module, or only partial curing at all.

- Wrong curing parameters.

The temperature for curing is selected too high or too low. In combination (or not) with inappropriate curing duration partial curing might result or the material can be irreversibly damaged.

- Not uniformly cured.

Since the development ultra-fast, fast, or similar curing formulas in combination with increasing module sizes the curing process might not be completed across the whole range of the module. We found that the curing level could deviate up to 20% between the positions. The problem is the time difference when curing temperature is reached at the central part of the module and at the edge or corner of the module. In addition, thermal stress might result in a bending of the module, which lifts parts of the module from the surface of the laminator and reduces heat flow considerably. During the testing at PI Berlin gel-content rates for different positions were obtained which deviated more than 30% from each other.

- Error by the supplier

It could happen that the supplier does not put enough peroxide in the EVA, stores it too long or just mixes good EVA with bad EVA. In contact with customers PI Berlin was told that it was a single batch of EVA, yet in the lab it proved to have different curing properties.

- Process problems on the supplier side

Non-uniformly distributed curing agents and other chemicals in the films cause local different properties. In highly optimized process it might lead to localized curing. (Schulze) has shown that for a standard EVA there is already a noticeable local variation of the peroxide in the sheet.

- Chemicals in the EVA are damaging the backsheet.

In contact with suppliers of back-sheets it was told that a too high remaining peroxide level can damage the bonding. Results at PI Berlin seem to proof it, yet this is still under investigation.

4. Lamination process and preparation of the parts

On the market there is a broad selection of different EVA-films from a wide selection of manufactures (Solutia, STR, Mitsui, DuPont, Bridgestone and many others). Each of the manufacturers offers different films with different curing properties and different recommended curing levels. These recommended curing-levels range from about 70% to 90%. Depending on the type of EVA and backsheet used, the producer of the cells has to wash and/or prime the components to ensure a good adhesion.

In their datasheets the manufacturers of EVA-films state mechanical, chemical and optical properties which are valid for their recommended curing level. With different curing levels these properties might deviate from the data sheet.

An optimization as well a total control of the lamination process (process temperature, profile and duration, pressure, homogeneity) is essential to obtain the best properties of each component of the laminate. But searching for an ultimate optimization can be risky. As every material, the components used in the laminate have their own limit in term of temperature resistance for example.

In a term of aging of the PV module, a good lamination can prevent or at least slow down delamination and solar cell aging, ensuring a durability of the PV module performances year after year.

5. Testing Methods

5.1 Chemical analysis of the EVA

5.1.1 System of crosslinking

The film is composed of a standard co-polymer EVA which is produced for example by DuPont™ under the name of Elvax®. The bulk material of the EVA is a thermoplastic. The manufacturer of the film adds a curing agent and other chemicals. The curing agent is a peroxide (Klemchuka, 1997) which decomposes with the increase of the temperature and starts the reaction in the film. That should be the curing process in the laminator. When the curing process is finished the former thermoplastic becomes an elastomere and cannot be melted anymore. The material is irreversibly cured.

5.1.1 Discussion of the Methods

There are several methods on the market to measure the cross linking of a polymer A comparison of the extraction process and the differential scanning calometriy (DSC) was made by (Xia et al, 2009). In addition there is dynamic mechanical (DMA) analysis which is common for rubber polymers e.g shown by (Schulze 2011). Also swelling (Zang et al., 1989), relaxation with and without heat can be used to determine the grade cross-linking.

The problems discussed in (Xia et al. 2009) also apply for quality control by a third party. In contradiction to Xia et al. it was found that extraction based on gel-content analysis works best. Most modules and EVA samples received by PI Berlin have been a type of “black box” - little or nothing was known about the EVA used and the thermal history of the module. Therefore it is not possible to assume that the rest of 30% (Ezrin et al, 1995) which is needed for the DSC is still present. DMA and other methods are also not practicable due to either problems in sample preparation or lack of reference samples.

Extraction methods are well known for cross-linking determination see e.g (Xia et al, 2009),(Schulze, 2011), ASTM D7567-9, EN 579, in addition many producers of EVA propose a quality control by some sort of extraction in their manuals e.g. (STR-Photocap), (Etimex Solar GmbH, 2010).

5.1.2 Soxhlet Extraction at the PI Berlin

The extraction method at the PI Berlin is based on an extraction according to soxhlet. The apparatus used by the PI Berlin has proven to give the most reliable results due to good controlling of the extraction cycle and an active flushing of the specimen at the end of the cycle. Further information can be found in the Information sheet about the extraction at the PI Berlin (PI Berlin, 2011) Fig. 2 shows the setup of the extraction equipment.

Fig. 2: Picture of the setup of the extraction apparatus

5.1.2.1 Removing of the EVA

The removing of the EVA is a difficult part of the analysis. At defined or from customer requested positions the backsheet is removed and the EVA taken out. This takes a lot of time and practice many modules have completely different adhesion qualities. After taking the EVA the samples have to be cleaned. In this process it is also possible to determine if a filled EVA (fiberglass or otherwise supported) is used which results in correctional parameters for the extraction. In fig. 3 the process of the EVA removing for the extraction is shown. In the Fig. 3 it is possible to see the different adhesion qualities to the different parts of the module, a weak connection to the cell and metallization paste and a good connection to the busbar and glass.

Fig. 3: Picture of EVA sampling.

5.1.2.1 Extraction process

PI Berlin elaborated a useful set of parameters to achieve satisfying results. Different EVAs with different curing times are behaving very different in the extraction process. Typically, 45 and 75 cycles are run. If the deviation of 45 and 75 is too high, the measurements are repeated doing 150 cycles. Extended extraction may be required to reach the stability on the gel content determination. It is essential to provide the most accurate result. As shown in Fig.4, stability is reached after specific extraction times or extraction cycles - depending on the tested module (and so lamination process and material). For different scenarios different sets of filters have been used: cellulose (low level) and stainless steel (medium and high level gel content). For solving EVA, PI-Berlin uses stabilized tetrahydrofuran (THF). This solvent avoids further curing during the extraction process and minimizes the melting and softening of the polymer due to a high extraction temperature.

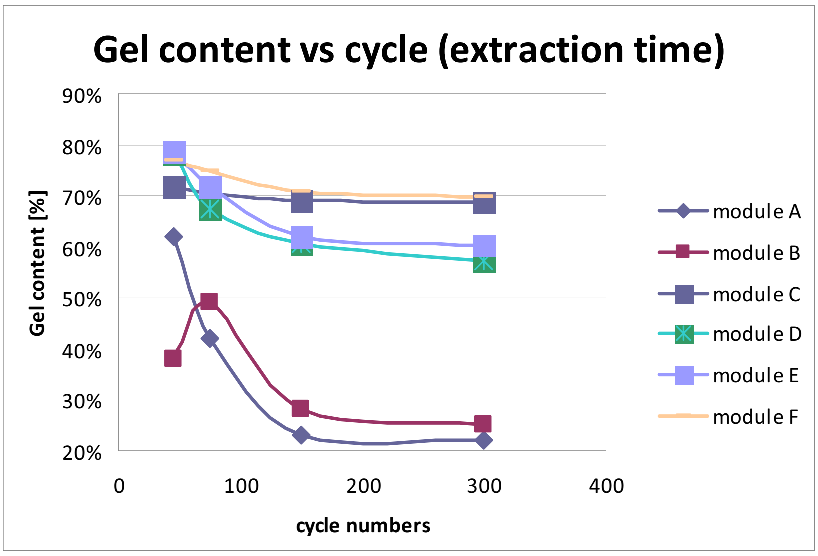

Fig.4: Gel content vs. number of extraction cycles

5.1.3 Results

As shown in Fig. 5, the majority of samples tested do not have a problem with insufficient curing. However, 35% of the samples show insufficient curing.

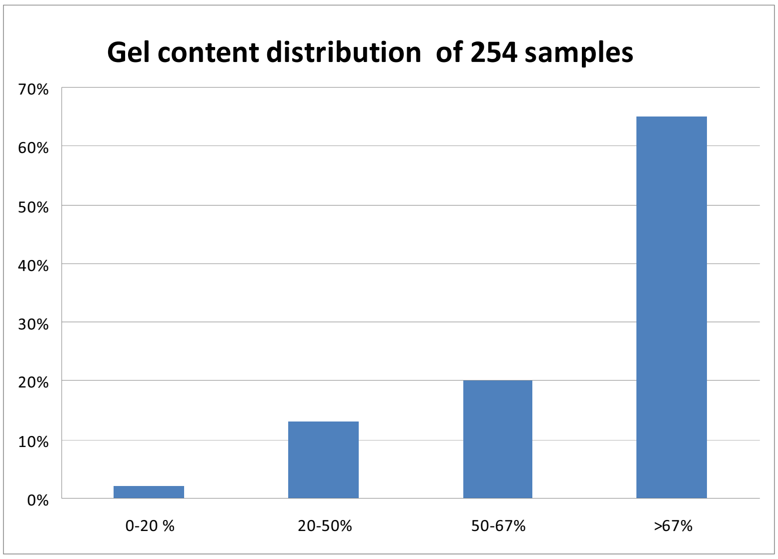

Fig.5: Gel content distribution of 254 samples
(254 samples from 120 modules analyzed from several manufacturers)

5.1.4 Problems

In addition to the problems described above, extraction adds some more problems. The main problem is the lack of standardization and the large number of different EVA-films on the market and their differing properties. When the customer receives the datasheet he has to check if the test result is within acceptable limits which guarantees for the properties he has been promised by the manufacturer. The test only shows if the curing happened and gives a fairly good approximation of the cross-linking level.

5.2 Peel Test

5.2.1 Principle of the peel test

Similar to extraction there is no definitive standard for the peel-off test in the PV industry. The peel test origins from the field of adhesives and is described internationally in many standards e.g. EN 1895, EN 28510. The principle of the peel test is the pulling of a thin flexible film from a rigid substrate (see Fig. 6). The angle for pulling at PI Berlin is 90°.

The peel-off test also includes the surface condition in the test procedure. In some cases the curing sate of EVA may be satisfying, but the adhesion (and consequently the lifetime) of the module may be poor, due to the low adhesion caused by unclean surfaces at the glass, backsheet or cells. Therefore, the Peel-Off-Test is giving more comprehensive information about the durability of the lamination, but the EVA-gel-content tests helps to find details. In figure 6 the setup of the test at the PI Berlin is shown. The peel-off procedure is carries out by cutting off stripes partly form the backsheet laminate and apply an increasing pull-force to them (see Fig.7). For the test the speed of the peel is constant and the force is recorded. At a specific force the rest of the stripe starts to dismantle from the module laminate. That specific pull-off force is recorded. The test is carried out for 20 times at different locations of the module (center, corner, edge, busbar, cell and glass) in addition if it is possible the different layers (backsheet, EVA or parts of the backsheet) are separated and pulled off. During the peeling the module moves in the opposite direction to the peel to keep the peeling angle at 90°.

Fig. 6: Picture of the peel test

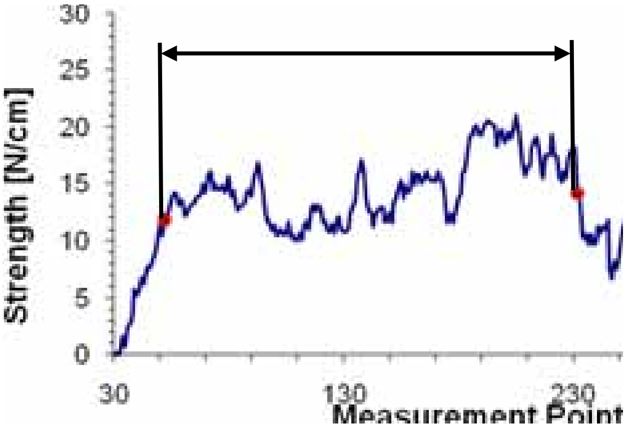

Fig.7: Picture a measured sample and the interval used for the end result

5.2.2 Data

As well as the curing rate of the EVA, the adhesion EVA to the glass or to any other component of the laminate is essential to ensure a long lifetime of the PV module. In terms of adhesion of EVA to glass, a peel strength from 75 N/cm to 125 N/cm can be expected (Fig.8), this range should be a reference value for quality control. A lower value can be critical for the PV module durability. It has been shown already that the adhesion can decrease by the time. A diminution of 50% (up to complete delamination) of the adhesion can be recorded after aging of the PV module in the damp-heat chamber.

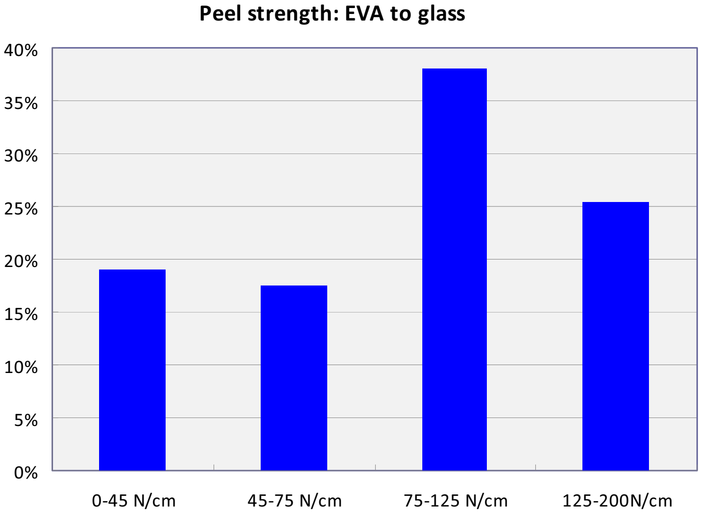

Fig.8: Peel strength distribution, adhesion between EVA and Glass

5.3 Damp heat test

The damp-heat test is a standardized procedure as described in IEC 61215/61646 (85°C, 85% relative humidity for 1000 h). This test is quite helpful to determine module durability, but while it takes at least 42 days to be performed, it is not the main focus of this paper.

5.4 Other methods

In any other test stress applies on the encapsulation system e.g., ammonia chamber (for modules applied on farm roofs with livestock), UV (especially for module made without glass), humidity freeze tests increase the possibility of failure of the encapsulation.

6. Discussion

None of the tests can me applied as the only measure to describe module durability. For example, it is possible to have an almost perfect cured EVA (extraction) and still poor adhesion, on the other hand it also possible that the EVA sticks (peel test) quite well to backsheet and EVA yet most of the peroxide has been remaining in the EVA. In addition, a non-durable encapsulation might also be visible via the standard tests of IEC 61215/61646. Close attention has to be paid to the results which indicate discoloration, delaminating or moisture ingression. Due to the lack of standardization and the complex system of the encapsulation problems might be indicated by small hint rather than the failure in one of the standard tests of IEC 61215/61646.

For the producer of the module the extraction test and the peel-off test can be easily applied in their production facilities to constantly monitor the quality of the production process. The suppliers of the components usually will provide them with the information necessary and different test equipment is available on the market.
For testing labs the challenge is to address the constantly changing properties of the EVA and backsheet materials and sometimes the unwillingness of the encapsulation manufacturers to pass technical documentation to third parties. Many of the tests are made for banks and resellers. Before testing, the only information these groups have is the number plate on the module. Sometimes, the encapsulation process changes without giving notice to the customer nor the testing lab, nor to the certification body. A steady control and supervision of the production process seems to be necessary in several cases.

7. Acknowledgements

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