Cavities observed in PV modules, induced by the tabbing and stringing process

Eric Pilat[1], **Manuel Hidalgo**[2], **Dominique Thil**[2] & **Marion Vite**[1]
[1]CEA-INES, LMPV (Module Laboratory), Le Bourget du Lac; [2]ARKEMA Sollia Laboratory, LMPV, Le Bourget du Lac, France

ABSTRACT

A major cause of failure in PV modules is related to the penetration of the module by moisture and its retention within. The presence of moisture results in corrosion of metallic contacts or accelerates the molecular degradation of the encapsulant, causing a loss of transparency and in some cases the development of yellowing. The moisture penetration may be intrinsic to the resin itself, but most often it will occur at the interfaces. As a consequence, the adhesion of the resin to glass, metallization, cell and backsheet surfaces may be affected. Engineers involved in the assembly of PV modules used to link adhesion degradation issues to poor conditions for storing polymeric materials, especially the encapsulation resin and the backsheet. In this paper another cause, which has not yet been studied by specialists, is discussed. It is shown that the welding of copper strips can induce residues which prevent the satisfactory adhesion of the resin, resulting in delamination. This phenomenon is identified by 'spots' along the busbars after lamination. The study highlights the possible consequences of these defects for a module's performance, after consecutive thermal cycling, damp-heat and humidity-freeze testing. Recommendations are also given for choosing a suitable solder flux and optimizing the soldering process, in order to maintain satisfactory control over potential delamination problems.

Introduction

The purpose of the encapsulant is to bond or laminate together the multiple layers of a module. Additional encapsulant characteristics must include:

- high optical transmittance
- good adhesion to different module materials
- adequate mechanical compliance to accommodate stresses induced by differences in thermal expansion coefficients between glass and cells, impact and creep protection
- good dielectric properties (electrical insulation)

Over the years, various encapsulant materials have been used in modules, including polyvinyl butyral (PVB), silicone rubber and ethylene vinyl acetate (EVA); more recently, other proprietary encapsulant products have been used.

Module delamination, resulting from the loss of adhesion between the encapsulant and any other module component (glass, cells, metallic contacts, polymeric backsheets), is a failure mechanism that needs to be addressed in order for manufacturers to achieve product lifetimes of 30–40 years [1]. A common observation has been that delamination is more frequent and more severe in hot and humid climates, sometimes occurring after less than five years of exposure. One of the first consequences of delamination is a performance loss due to optical decoupling of the encapsulant from the cells. Of greater concern, from a module lifetime perspective, is the likelihood that the void resulting from the delamination may provide a location of preference for moisture accumulation, greatly increasing the possibility of corrosion failures [2] in metallic contacts.

A chemical analysis of field-aged modules has been conducted, by comparing samples with those from unexposed modules; this analysis provided strong evidence of the dynamic chemical interactions occurring in the module during field exposure. It is clear that sunlight, temperature, oxygen penetration and moisture migration through the encapsulant provided the ingredients required for a variety of chemical reactions, many of which may degrade the integrity of the encapsulant's adhesive bond to the cell. Typical reactive materials found at the cell/encapsulant interface after extended field exposure are phosphorus, titanium, oxygen, solder flux, encapsulant additives and even sodium that has migrated through the encapsulant from the glass.

> "Corrosion is the consequence of interactions between water, ionic species and oxygen."

One of the major concerns for module durability is corrosion, because it can reduce the power output of a module by increasing the resistance at the electrical interconnections. Corrosion is the consequence of interactions between water, ionic species and oxygen. Protection against corrosion involves a combination

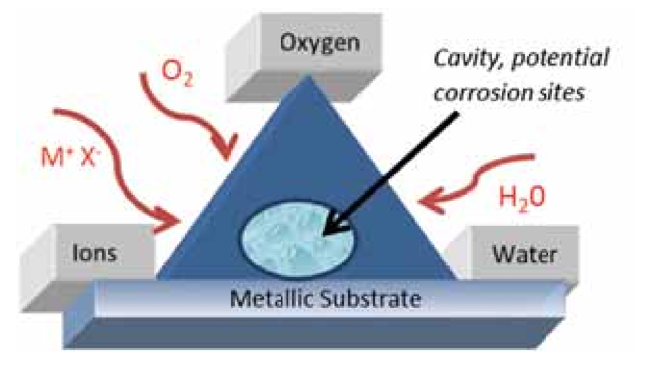


Figure 1. Corrosion triangle (adapted from Ketola & Norris [2]).

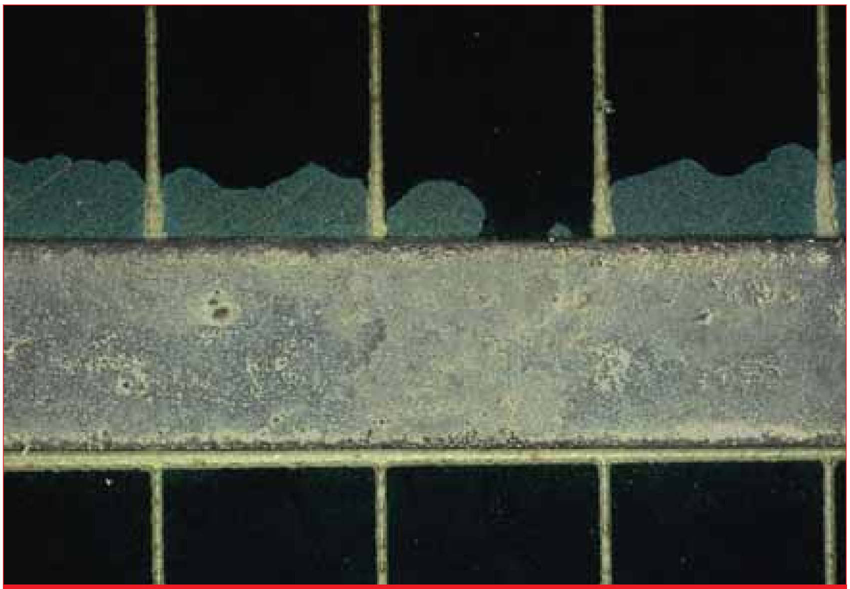


Figure 2. Greenish spots along the tinned-copper ribbon.

Figure 3. Defect observed using 100× magnification.

of effects: low moisture permeation is only one factor that influences this protection. Indeed, moisture permeability – or water vapour transmission rate (WVTR) – should be minimized, but this might not be the only determining factor in corrosion protection, and ultimately in the long-term performance of electronic devices. This fact has been known to the electronics industry for decades and can be related to the corrosion triangle shown in Fig. 1 [3].

Water needs to be in the liquid state to allow the potentially ionic material to ionize into its cathodic and anodic components. Ionic species can be created as a result of contamination or degradation of the encapsulant itself. On the other hand, oxygen is typically present, unless the atmosphere is inert or has been evacuated, and even if this was the case during module manufacturing, oxygen can easily permeate back into the module.

It is known that when EVA is exposed to UV radiation and high temperatures, it may be subject to deacetylation, in accordance with the widely accepted Norrish II mechanism, which results in the formation of acetic acid. Moreover, water and oxygen can increase the chances of this reaction occurring, by (for instance) lowering its activation energy [4]. Thus, damp-heat conditions can very likely lead to an increased release of acetic acid, a product which favours metallic corrosion. Moreover, it should be noted that EVA uses peroxide radical initiators, which lead to the desired EVA cross-linking, and some peroxides can generate acidic by-products. Taking into account all the previously mentioned parameters, any void must therefore be seriously considered to be a potential cause of eventual degradation.

Inspection

Optical

Chapter 10.1 of the IEC 61215 standard specifies that each module should be inspected carefully with illumination greater than or equal to 1000 lux. Only ten criteria are defined, and the last one is rather vague: "Any other condition that may affect performance". On top of that, if the inspection is performed without any magnification, small visual defects that could affect performance may not always be visible.

In the present paper, the focus will be on one defect which can be observed in c-Si modules, although this type of defect is not excluded from also appearing in PV modules using thin-film technologies. The defects have the appearance of small spots along the tinned-copper ribbon (Fig. 2), but very often they cannot be seen when no lens magnification is used.

Spots may be large enough to be seen by the naked eye, as in the photo in Fig. 2, but more often than not one has to look carefully with an optical microscope (Fig. 3) in order to detect them (100× magnification is more than enough).

X-ray probing

X-ray inspection can reveal the presence of some materials such as silver or tin. In

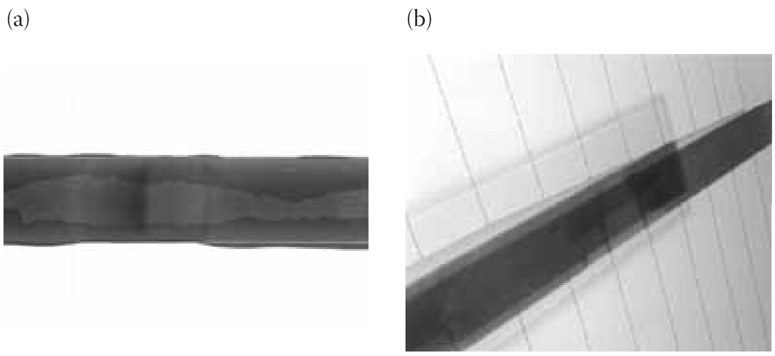


Figure 4. X-ray images: (a) view from above of the copper ribbons soldered to the cell; (b) view of the copper ribbons from an angle.

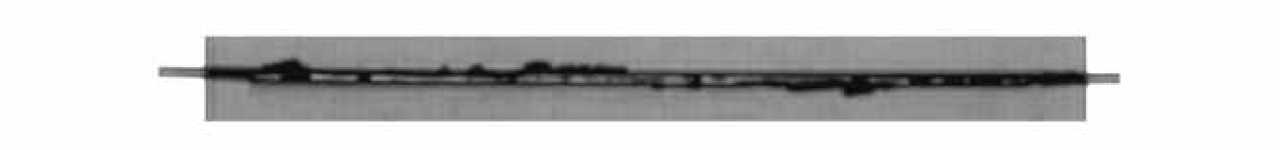


Figure 5. Acoustic image by transmission from the top.

Figure 6. Correlation between the emission C-scan multigate mode and transmission mode.

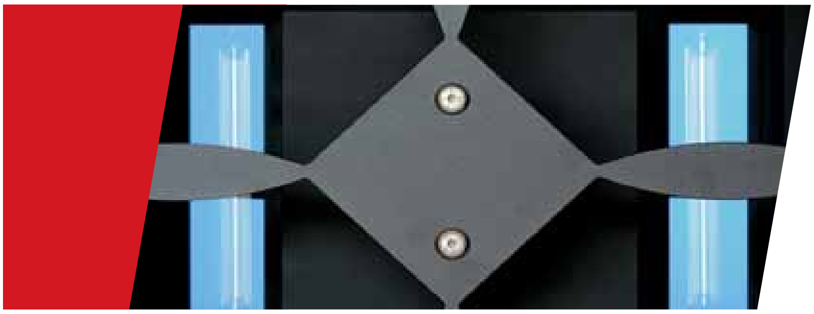
this study, the defect areas were inspected using 10× magnification (Fig. 4). A lack of welding is observed in the centre of the ribbons, but there are no black areas corresponding to the locations of the previously mentioned defects.

> “Acoustic micro-imaging combining emission and transmission modes is a rapid and non-destructive tool for identifying the location of cavities.”

Acoustic micro-imaging

Acoustic micro-imaging combining emission and transmission modes is a rapid and non-destructive tool for identifying the location of cavities. The examination of a cell using this type of microscopy can reveal differences in acoustic impedance of the structure and thus allow the detection of signs of delamination, defects, decrease in adhesion, etc. The approach adopted for examining a cell by acoustic micro-imaging is as follows: an initial assessment of the connectors is conducted in transmission mode (Fig. 5), to examine the most critical part of the cell and to try to detect the optically observed signs; a second series of examinations is then carried out, again in transmission mode, over the entire cell, to verify the presence or absence of such defects elsewhere. If acoustic detection of the optically observed defects is successful, the goal is ultimately to study their location as a function of the thickness of the encapsulant–metal joint, and to analyze the nature of this information. The emission mode of acoustic analysis is then used, employing a multigate method (C-scan comprising a multitude of doors, allowing a layer-by-layer imaging of the structure as a function of thickness). In this way a correlation between the spots – i.e. the ‘suspicious areas’ – visible through optical means and their detection by acoustic emission is established. Finally, transmission acoustics are used to find proof that the defects are caused by delamination (Fig. 6).

From the acoustic analysis (supplied by the Predictive Image team) it is known that



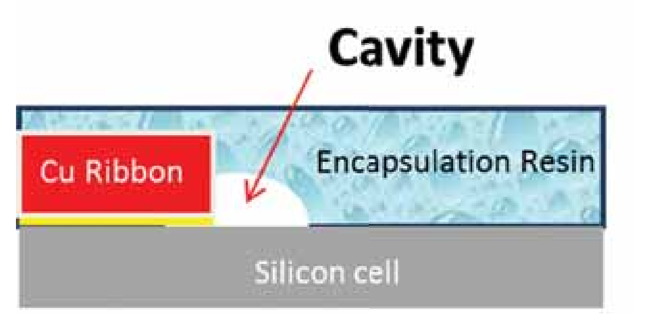


Figure 7. Location of a void, detected by acoustic analysis.

the defect is a cavity, or a void, and that it is located at the base of the connectors, as shown in Fig. 7.

Experimental

The tendency for voids to form inside the resin located at the base of the connectors can be either increased or reduced, depending on different manufacturing practices and conditions. Some of the factors that might influence the presence or absence of these voids will be mentioned here.

In the case of a thermoplastic encapsulant, the influence of the laminator's thermal profile was studied. First of all, the degassing time at the beginning of the lamination cycle, and the actual lamination time at a temperature higher than the melt temperature of the thermoplastic encapsulant, was varied. No resulting correlation with the presence of void defects was identified. Next, the actual lamination temperature was increased; the result was better, but there were still some voids. After the lamination step, the module was heated in an oven at 95°C. When the module was hot, the defects completely disappeared but gradually returned upon cooling.

The same process was then performed on two different cells provided by two different cell manufacturers. Although one of these produced better results than the other, voids occurred in both cases. It is important to note that, as stated earlier, void detection can sometimes be carried out by visual inspection under adequate illumination conditions, but in order to be sure that there are no defects, an optical enhancement must be performed using a microscope.

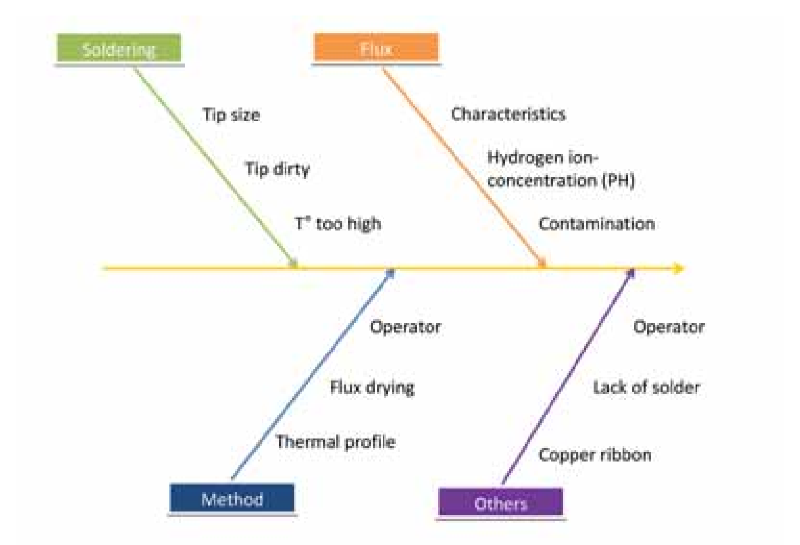


Figure 8. Fault tree analysis.

	No-clean flux remover	Brush-clean	Water 60°C & UL	No-clean
No-clean flux 1	1/1			3/6
No-clean flux 2	0/1			0/3
No-clean tacky flux		1/1		1/3
Water-soluble flux			0/1	

Table 1. Number of busbars with defects vs. total number of busbars with same flux and cleaning process.

The next step was to produce modules from PV cells that had been previously cleaned with acetone before soldering, or by carefully cleaning the connectors with acetone after soldering. This did not result in any significant improvement in respect of the presence of voids. It was noted that the problem became worse when the cells had been stored for a long time before the soldering process and fabrication of the module.

Taking into account these experimental results, an FMECA approach (failure modes, effects and criticality analysis) was followed. In the fault tree analysis, four families were identified (Fig. 8). From this analysis, and the previous results with the thermoplastic encapsulant, it became clear that the soldering step could be a major contributor to the presence of defects.

> “It became clear that the soldering step could be a major contributor to the presence of defects.”

It was then decided to produce some mini-modules in order to identify the main issue. The first module was made using two cells, comprising two busbars per cell. Different configurations regarding the connector ribbons were considered for each busbar:

- Configuration 1: The soldering flux was applied to the cell's silver bar (busbar), and the connecting copper ribbon was laid upon it without soldering.
- Configuration 2: The soldering flux was applied to the cell's silver bar, and the copper ribbon was also dipped in flux. The ribbon was soldered onto the silver bar.
- Configuration 3: The soldering flux was applied to the cell's silver bar and the hot soldering iron passed over it. This enhanced the temperature effect of the soldering step.
- Configuration 4: The soldering flux was applied to the cell's silver bar, and the ribbon (without flux dipping) was soldered onto the silver bar.

The spots appeared only in the case of configuration 2, clearly showing the influence of the soldering step conditions.

A second module was then produced by placing two cells with three busbars in each of the following configurations:

- Configuration 1: The copper ribbon was dipped in flux and soldered onto the silver bar.

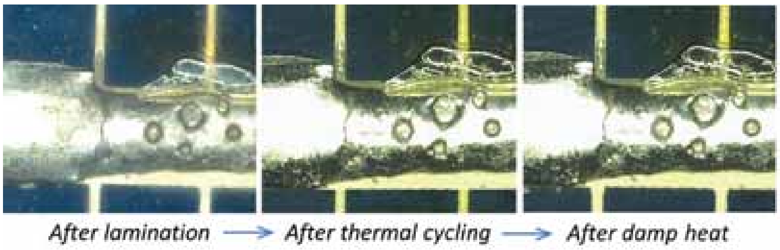


Figure 9. Visual inspection (50× magnification) of the same defect before and after ageing.

	Variation of maximum power after test [%]			
	Reference	Module 1	Module 2	Module 3
TC	1.1	0.1	–0.7	–0.7
TC and DH	1.3	–3.7	–8.8	–3.4
TC, DH and HF	1.6	–9.9	–21.6	–13.4

Table 2. Evolution of maximum power (flash-test measurements) after ageing tests, for the three modules containing defects, compared with the reference module with no defects.

- Configuration 2: The copper ribbon was dipped in flux and heated with the soldering iron. The ribbon was then laid on the cell's fingers without any actual soldering.

- Configuration 3: The copper ribbon was dipped in flux and heated with the soldering iron. The ribbon was then laid on the silver bar of the cell without any actual soldering.

- Configuration 4: The copper ribbon was placed on the silver bar without any flux, heating or soldering.

- Configuration 5: The copper ribbon was simply laid upon the cell's fingers without any flux, heating or soldering.

- Configuration 6: The copper ribbon was dipped in flux and then laid upon the silver bar of the cell without any heating or soldering.

These experiments confirmed that spots appeared when the copper ribbon was dipped in flux and then heat soldered upon the silver busbar of the cell.

Up to this point, it had become apparent that the defects could be created by the soldering step (no defects if the ribbons were not soldered), and that the presence of the soldering flux was necessary to their appearing. The decision was therefore taken to investigate the influence of different types of soldering flux.

Modules were produced with different kinds of soldering flux, with or without a post-soldering cleaning step to evacuate flux residues. The busbars containing defects were identified, with respect to the flux employed and the cleaning process used after soldering, as shown in Table 1.

With no-clean flux 1, defects appeared even when the soldered ribbon was cleaned with the alcohol-based no-clean flux remover. With no-clean flux 2, no defects were detected, even without cleaning; with the no-clean tacky flux, defects appeared. In the case of the water-soluble flux combined with cleaning in a heated ultrasonic bath, no defects were observed. The defects were caused by the presence of flux residues, which can be generated even when the so-called 'no-clean' fluxes are employed. The nature of the flux is an important factor.

> "The defects were caused by the presence of flux residues, which can be generated even when the so-called 'no-clean' fluxes are employed."

The voids seem to be caused by encapsulant delamination at places where the presence of flux residues hampers adhesion. One assumption is that flux is burned during the soldering process and that the soldering iron sweeps and pushes the solid residues. These residues concentrate in one location and prevent good adhesion of the encapsulant to the cell or to the silver metallization. The nature of the flux seems to be an important factor, as no-clean flux 2 did not produce any defects.

The authors' latest experimental work has revealed that voids may also be created in EVA-encapsulated modules, and that the soldering step – including the soldering flux influence – may be at the heart of these defects. The possible consequences of these voids for reliability issues of EVA-encapsulated modules will be discussed in the next section.

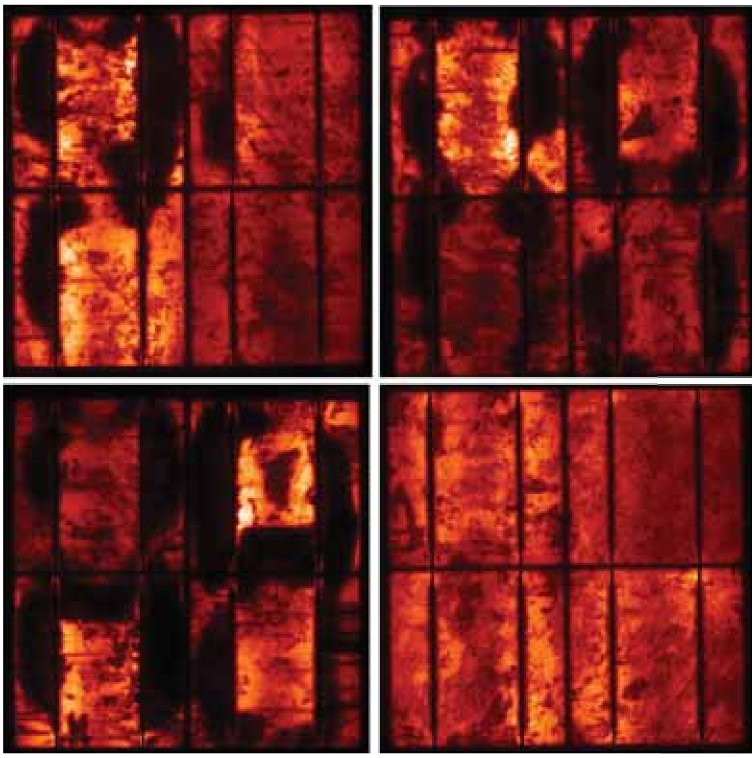


Figure 10. EL imaging of three different modules after ageing (TC, DH and HF), compared with the reference module at bottom right.

Impact on module reliability

Consecutive thermal cycling (TC), damp-heat (DH) and humidity-freeze (HF) tests were conducted on a series of three modules in which the defects described here were abundant. (In fact, once the origin of the problem became clear, an emphasis was placed on the conditions leading to the manifestation of defects, mainly flux type and quality, but also volume of flux dispensed and soldering temperature.) For each test, the conditions described in the IEC 61215 standard were followed, and the tests were conducted consecutively in the order given above (TC, DH, HF). For comparison, a module containing no such defects was included in the test panel.

Fig. 9 shows photographs (from optical microscopy at 50× magnification) of such defects (i) after lamination, (ii) after TC testing (> 200 cycles), and (iii) after DH testing (> 1000 hours). As can be seen from these images, there is no apparent evolution of the voids as a result of the TC and DH ageing tests. Inspections were carried out at different locations where the voids were present.

However, there was a clear performance decline (as measured by the maximum power of the modules tested at STC with a flash-type solar simulator from PASAN) after each ageing test, with respect to the reference module containing no defects (see Table 2).

Moreover, after the HF tests on the modules (which had already undergone TC and DH testing), a massive degradation, mostly detectable through electroluminescence imaging (using GREAT EYES EL equipment), became evident in all the modules exhibiting voids (see Fig. 10). This was definitely not the case for the reference module without the void defects. Further investigations need to be conducted in order to find out if there is indeed a link between this massive degradation and the void defects discussed in this paper.

Possible solutions

Once the problem had become apparent and its origin had been identified (see previous sections), possible solutions were explored. The soldering flux, having been identified as the main factor, was investigated further. Experiments were conducted while carefully monitoring the flux quality, and especially its concentration as measured by the pH method, which reflects the actual concentration of the product. It was found that fluxes for which the concentration has become too high during production may lead to a higher number of defects. Nonetheless, with some fluxes kept at the right concentration, there were still some defects, although clearly not as many.

A thorough screening of fluxes of different natures was then carried out, which seemed to be the most robust solution to the problem. It was discovered that the choice of flux is the most important preventive action against the creation of voids in modules with different encapsulants.

> "The choice of flux is the most important preventive action against the creation of voids in modules with different encapsulants."

Summary

To avoid the issue of bad adhesion due to flux residues, the soldering process must be carefully controlled, especially with regard to the nature of the flux and its quality (concentration), as well as the volume dispensed. In the case of small-volume production, or if the process is not automated, it is highly recommended to either use water-soluble fluxes and clean the cells after soldering the copper band before encapsulation, or to carefully choose the no-clean flux to be employed, by checking, with the help of an optical microscope, the absence of voids due to delamination.

Acknowledgements

The authors are grateful to H. Robin, D. Carite and B. Novel for their help in manufacturing the modules, and I. Richard and the Predictive Image team for x-ray and ultrasonic images.

References

[1] Coello, J., Cornacchia, F. & Muñoz, J. 2010, "Analysis of the degradation of 735 commercial crystalline silicon modules after first operation year", *Proc. IEEE 5th World Conf. PV Energy Conver.*, Valencia, Spain.

[2] Ketola, B. & Norris, A. 2010, "The role of encapsulant moisture permeability in the durability of solar photovoltaic modules", *Proc. IEEE 5th World Conf. PV Energy Conver.*, Valencia, Spain.

[3] Quintana, M.A. et al. 2002, "Commonly observed degradation in field-aged photovoltaic modules", *Proc. 29th IEEE PVSC*, New Orleans, Louisiana, USA, pp. 1436–1439.

[4] Czanderna, A.W. & Pern, F.J. 1996, "Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review", *Solar Energy Mater. & Solar Cells*, Vol. 43, pp. 101–181.

About the Authors

Eric Pilat graduated as an engineer from INSA of Lyon in 1984. He has more than 12 years' experience in the packaging of microelectronic components, MEM and CCD devices. In 1997 he founded a company for developing an innovative process for manufacturing connections for high-density electronics. Eric joined CEA in 2008 to begin development of the platform for PV modules.

Manuel Hidalgo earned his Ph.D. degree in macromolecular materials from the University of Lyon 1. He is a senior research scientist for Arkema and currently a co-project leader at Sollia, a joint laboratory with the French Institute for Solar Energy (INES). Dr. Hidalgo holds more than 50 patents and has published almost 30 papers in the polymer field.

Dominique Thil has been working in R&D since 1990, mainly in the chemical process industry. At present, he works at the Sollia joint laboratory within INES. Dominique has two years' experience in the manufacturing of PV modules, including soldering and lamination.

Marion Vite received her Ph.D. degree from the University of Savoie in the field of polymers and composite materials. She currently works at INES on encapsulation and packaging of solar cells, as well as on European R&D projects concerning patterned injection-moulded PV modules. Dr. Vite is an INES co-project leader for the Sollia joint laboratory with Arkema.

Enquiries

Eric Pilat
CEA-INES INES – LMPV
50 Avenue du Lac Léman
BP 332
73377 Le Bourget du Lac CEDEX
France

Tel: +33 4 79 44 46 42
Email: eric.pilat@cea.fr