



# VIPERLAB

FULLY CONNECTED VIRTUAL AND PHYSICAL  
PEROVSKITE PHOTOVOLTAICS LAB

**D9.11**

**Guidelines for the  
assessment of the encapsulation  
materials and whole encapsulation of  
perovskite technology**

**DELIVERABLE  
REPORT**

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**FULLY CONNECTED VIRTUAL AND  
PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB  
VIPERLAB**

**DELIVERABLE**

**D9.11 GUIDELINES FOR THE ASSESSMENT OF THE  
ENCAPSULATION MATERIALS AND WHOLE ENCAPSULATION  
OF PEROVSKITE TECHNOLOGY**

**Project References**

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## DISCLAIMER

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## EXECUTIVE SUMMARY

Perovskite solar cells are highly promising for next-generation photovoltaics but are particularly vulnerable to environmental factors like moisture, oxygen, and temperature changes. Encapsulation is essential to protect the delicate perovskite layers, ensure device longevity, and maintain high efficiency. This report explores various encapsulation methods, focusing on lamination processes and thin-film techniques, which are particularly relevant for industrial applications. Lamination involves using thermo-fusible polymers or UV-curable adhesives to seal protective covers, while thin-film encapsulation employs advanced deposition techniques like ALD and PECVD to create dense barrier layers.

The study also outlines a comprehensive set of assessment methods for encapsulation materials, including gas barrier testing, adhesion evaluation, and thermo-mechanical analysis. Innovative techniques like calcium tests and perovskite tests are discussed for their ability to simulate real-world degradation scenarios. The collaborative efforts within the VIPERLAB project, particularly between HZB and CEA, tested these methods under extreme conditions such as damp heat (85°C, 85% relative humidity) and thermal cycling (-40°C to +85°C). The results highlight the critical role of encapsulant materials in mitigating water and oxygen ingress, as well as maintaining mechanical stability. Practical tips and recommendations are provided to guide manufacturers in choosing and optimizing encapsulation strategies. This report serves as a valuable resource for improving encapsulation designs to enhance the durability and performance of perovskite solar cells.

## 1. ENCAPSULATION METHODS AND MATERIALS

Perovskite solar cells require an encapsulation to protect them from the environment (water ingress, UV) and to provide mechanical support<sup>1</sup>. Different methods exist to encapsulate the devices. The most prominent ones for future industrial use are the lamination of protective covers (glass, back sheet or flexible gas barrier film), the thin film encapsulation (TFE) or the combination of both.

### 1.1 Lamination processes

First, the lamination process relies on the sealing of protective covers, back-sheet and front-sheet<sup>2</sup>. The back-sheet and front-sheets can be sealed thanks to the process of solid thermo-fusible polymers foils (i.e. encapsulants and, if required, edge sealant) or the use of polymerizable liquid glue. The use of each or every process is mostly related to the PV device manufacturing mode.

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<sup>1</sup> E. J. Schneller *et al.*, "Manufacturing metrology for c-Si module reliability and durability Part III: Module manufacturing," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 992–1016, Jun. 2016, doi: 10.1016/j.rser.2015.12.215.

<sup>2</sup> "Lamination process and encapsulation materials for glass-glass PV module design," *PV Tech*, Mar. 10, 2015. Accessed: Jan. 30, 2023. [Online]. Available: <https://www.pv-tech.org/technical-papers/lamination-process-and-encapsulation-materials-for-glassglass-pv-module-design/>



The use of solid encapsulant is predominant in the current silicon industry to make solar panels in a sheet-to-sheet process. The encapsulants can be cross-linkable elastomers (ethylene vinyl elastomer, EVA or polyolefin elastomer, POE for example) or thermoplastics polymers (thermoplastic olefin (TPO) or ionomer for example). The cross-linkable elastomers are clearly the most employed thank to their lower cost. Their use in Perovskite PV encapsulation is still challenging because of relatively high crosslinking temperature ( $\geq 150^{\circ}\text{C}$ ) and the presence of residual crosslinking agent as peroxide which can degrade perovskite layers. On another hand, thermoplastic polymers are more expensive but are more appropriate regarding recycling as it can be molten after processing in contrast to cross-linked polymers. Opaque Butyl rubber materials can be also used as edge sealant to improve the gas barrier protection.

All these materials can be processed in a membrane laminator or a double tray laminator, both presented in Figure 1. The double tray laminator offers a faster heating solution, with a reduced risk of edge compression at the corners<sup>3</sup>. There are also possibilities for cooling stations on such tools. In general, this encapsulation method is simple and low-cost, but there are risks of damage to the perovskite cells due to the high pressure and temperature involved<sup>4</sup>. Each step (duration, vacuum level, temperature control) of processing has to be optimized. The thermal and mechanical sensitivity of the device will be different depending on its constitution (perovskite formulation, choice of the transport layers, etc..). It is generally requested to have a lamination temperature below  $130^{\circ}\text{C}$ . The duration of the process is generally in the range of 10-20 minutes.

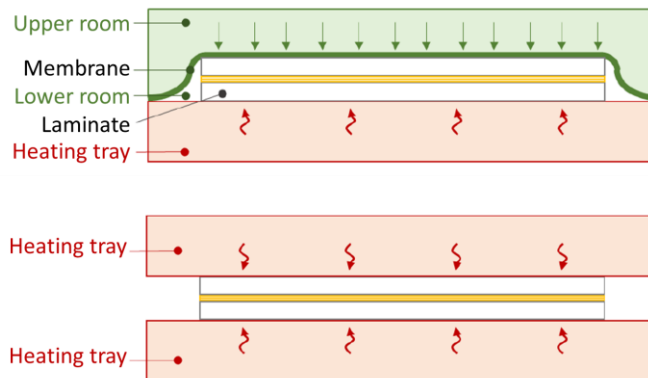


Figure 1: Example of lamination tools with (a) a membrane laminator and (b) a double tray laminator.

Another way to laminate protective covers is the use of UV-polymerizable glues. These sealing materials are mostly employed in roll-to-roll process thanks to their rapid

<sup>3</sup> "Lamination process and encapsulation materials for glass-glass PV module design," *PV Tech*, Mar. 10, 2015. Accessed: Jan. 30, 2023. [Online]. Available: <https://www.pv-tech.org/technical-papers/lamination-process-and-encapsulation-materials-for-glassglass-pv-module-design/>

<sup>4</sup> F. Corsini and G. Griffini, "Recent progress in encapsulation strategies to enhance the stability of organometal halide perovskite solar cells," *J. Phys. Energy*, vol. 2, no. 3, p. 031002, Jul. 2020, doi: 10.1088/2515-7655/ab8774.

processing (less than 1 minutes) with flexible gas barrier films as protective covers. These glues need to have good gas barrier properties and then, are often based on epoxy materials with some issues regarding the brittleness and the photo-stability (yellowing). Acrylic materials are promising but suffer of insufficient gas barrier properties and/or thermal resistance. Polyurea two-components materials are also promising and can be processed without UV. The chemical compatibility of the liquid formulation with the perovskite stack needs to be considered carefully. Regarding gas barrier films<sup>5,6</sup>, it is generally PET substrates with inorganic layers deposited by PECVD or ALD to improve gas barrier properties. These films are often laminated with a top fluorinated film to improve the weathering resistance.

### 1.2 Thin film encapsulation

Thin film encapsulation is another promising method. It relies on the deposition of thin and dense layers with high barrier properties<sup>7</sup> on the top of the device using methods such as Chemical or Physical Vapor Deposition (CVD, PVD), Plasma-Enhanced CVD (PECVD) or ALD<sup>4</sup>. ALD offers highly conformable layer deposition, but several studies highlight a risk of performance reduction in the cells due to the excessive temperature<sup>7,8</sup>. The materials used are often oxides or nitrides and can be used either as single layers or in multilayers<sup>4,9</sup>. In the case of single layers, there is an optimal thickness to avoid defect formation and thus obtain the best barrier properties. Multilayers, formed by alternating thin organic layers with dense inorganic layers, can be also employed to reduce the defects density and effectively increases the diffusion path of molecules through the stack. The implementation of thin film encapsulation in perovskite PV technologies will need to be combined with lamination technologies. It could relax the requirements regarding encapsulants gas barrier properties, but the cost/throughput of the deposition techniques is still a challenge.

## 2. ENCAPSULATING MATERIAL ASSESSMENT METHODS

In this section, we will list some methods which looks crucial for the assessment of encapsulating materials to be used in Perovskite Photovoltaic. Some of these techniques

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<sup>5</sup> <https://multimedia.3m.com/mws/media/12854700/3m-ultra-barrier-solar-film-510-f.pdf>

<sup>6</sup> [http://www.i-components.co.kr/pdf/i-Barrier\\_i-Metalish\\_catalogue.pdf](http://www.i-components.co.kr/pdf/i-Barrier_i-Metalish_catalogue.pdf)

<sup>7</sup> Y. I. Lee *et al.*, "A Low-Temperature Thin-Film Encapsulation for Enhanced Stability of a Highly Efficient Perovskite Solar Cell," *Adv. Energy Mater.*, vol. 8, no. 9, p. 1701928, 2018, doi: 10.1002/aenm.201701928.

<sup>8</sup> R. Hosseinian Ahangharnejhad *et al.*, "Protecting Perovskite Solar Cells against Moisture-Induced Degradation with Sputtered Inorganic Barrier Layers," *ACS Appl. Energy Mater.*, vol. 4, no. 8, pp. 7571–7578, Aug. 2021, doi: 10.1021/acsaem.1c00816.

<sup>9</sup> S. Cros and T. Maindron, "Technologies d'encapsulation avancées pour l'électronique organique," *Innov. Technol.*, Feb. 2014, doi: 10.51257/a-v1-in208.



will focus on the measurement of the gas barrier properties, other methods will focus more on thermo-mechanical properties

## 2.1 Gas barrier properties

The gas barrier properties requirement, versus water vapor and oxygen in particular, is stricter as compared to silicon panels because of the numerous degradation mechanisms involving water, oxygen, light and perovskite materials or other layers in the device. We distinguish here the measurement of the gas barrier properties of encapsulant materials and the measurement of the side-permeation from edge of the whole packaging.

### 2.1.1 Gas barrier measurement of encapsulating materials

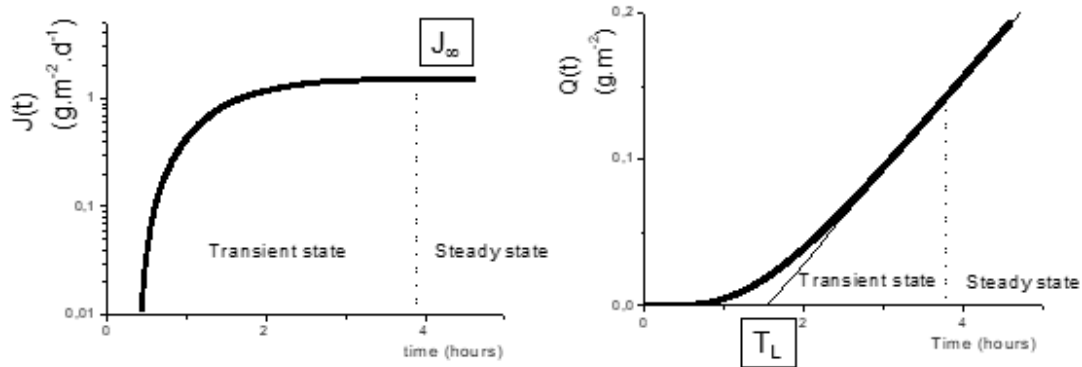
The principle of measurement consists in setting the partial pressure of the target gas (oxygen, water vapor for example) on an upstream face of the sample and to measure the flow, or the cumulated quantity, of target gas transmitted on the downstream side. Depending on the method considered, the measurement signal consists of **transmission flux** and the **cumulative amount** of target gas. Regarding the application for materials employed in PVK photovoltaic encapsulation, we need to distinguish the sealing materials (encapsulant, glue) for which the measured Water Vapor transmission Rates (WVTR) will be in the range  $0.5-100 \text{ g.m}^{-2}.\text{d}^{-1}$  and the gas barrier films covers/ inorganic thin film coating for which the WVTR will be more in the range  $10^{-6}-10^{-2} \text{ g.m}^{-2}.\text{d}^{-1}$ . Considering this aspect, the instrument or the method could be different depending on the material to test.

The **transmission flux** of the gas  $J$  through the gas barrier film as a function of time, Figure 2 (left).  $J$  increases progressively (transient regime) until a stabilized flux  $J^\infty$  (steady state) is reached.  $J^\infty$  corresponds to the WVTR in the case of the water measurement and to the oxygen transmission rate (OTR) in the case of the oxygen measurement. From the point of view of the measuring instrument this implies that the permeant flow is permanently discharged on the downstream side.

The **cumulative amount** of target gas which has diffused, Figure 2 (right). This is the time integral of the flux measurement. The slope of the straight line in the steady state is equal to the transmission flux  $J^\infty$ . The steady-state regression of the steady state at zero flux gives the characteristic time of the transient regime (or lag time, TL). In the latter case, the downstream detection chamber is closed. A cumulative measurement should ideally "absorb" the permeant (reactive detection). If this is not the case, the partial pressure of the permeant is not maintained at zero, and the boundary conditions are not respected on both sides of the sample.







*Figure 2: (left) Measurement of the transmission flux of the gas  $J$  through the gas barrier film as a function of time. (right) Measurement of the cumulative amount of target gas which has diffused. Here the measurement of PET (175  $\mu\text{m}$ ) at CEA using a mass spectrometer permeameter.*

The transmission flux of the gas  $J$  versus time is measured with a cell permeameter. A given partial pressure of the target gas (flow or static) is maintained on the upstream side of the sample. The target gas concentration depends on standards defined in norms (a hygrometry of 85% and a temperature of 38°C for the water measurement for example (ASTM: D3985-95 and F1249-90)). The downstream side of the of the sample is maintained at a fixed partial pressure by a flow of neutral gas (nitrogen) which transports the gas that has diffused into the sample to a sensor, or by vacuum. The essential differences lie in the means of detection.

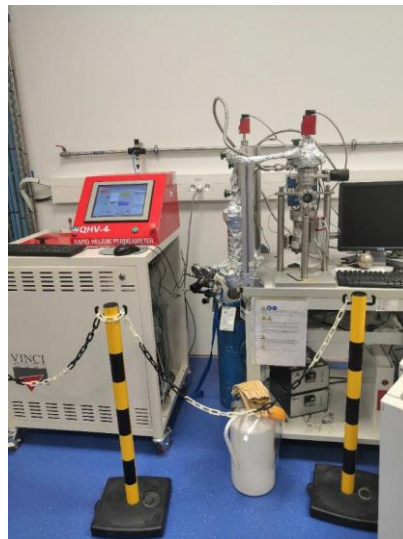
Infrared detectors are commonly used on the instruments currently on the market. These instruments are limited in sensitivity and allow to estimate permeabilities higher than  $10^{-2} \text{ gm}^{-2}\text{d}^{-1}$ . To meet the sensitivity required to qualify high barrier (HB) or ultra-high barrier (UHB) materials, new and more sensitive detectors are used. For example, the coulometric detector of the Mocon Aquatran<sup>10</sup> allows a sensitivity of the order of  $5 \cdot 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$ . Other improved detection technologies have also been developed and are now appearing on the market, such as the one used by the HiBarSens from the company Sempa<sup>11</sup>.

Mass spectrometry allows the detection of the permeant flow in a downstream chamber placed in high vacuum (of the order of  $10^{-8}$  mbar). Today, this technology is emerging at a commercial scale. The detection, especially for water, is limited by the signal to noise ratio in the measurement chamber. It is in the order of  $10^{-3} \text{ gm}^{-2}\text{d}^{-1}$ . However, the use of an isotopic gas (as stable isotope  $\text{D}_2\text{O}$ ) makes it possible to considerably improve the detection limit, up to  $10^{-6} \text{ gm}^{-2}\text{d}^{-1}$ . Vinci technologies, in collaboration with the CEA,

<sup>10</sup><https://www.ametekmocon.fr/products/permeationanalyzers/wvtr-permeation-analyzers/aquatran-340-wvtr-analyzer>

<sup>11</sup><https://sempa.de/en/products/measurement-technology>

developed a permeameter using mass spectrometry and isotope labelling<sup>12</sup>, shown in Figure 3. At another hand, mass spectrometry allows to measure all types of gases, including rapidly diffusing gases such as helium. The use of helium as target gas can be attractive because the measurement is very rapid (roughly 1h versus several days or weeks for water vapor or oxygen) and easy to manage. This gas cannot replace water vapor or oxygen, but it is a complementary method to screen many samples and have statistics. Helium measurements can be very useful to optimize a sample with thin film inorganic coating for which the best with helium will be the best with oxygen or water vapour considering the gas barrier properties are limited by the density of defects in the coating. Helium measurements can be also used to check rapidly the oxygen gas barrier properties as the correlation with helium is pretty good, not only for inorganic coating but also for polymer sheets<sup>13</sup>.



*Figure 3: Vinci technologies QHV-4 in CEA based on mass spectrometry detection for Helium rapid quality control (on the left) and Handmade water vapor or oxygen instrument. (on the right)*

### 2.1.2 Side permeation

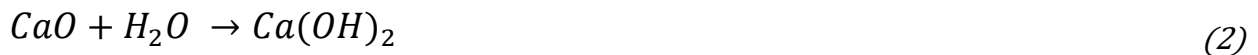
The side permeation means the gas permeation from the edge of the sealed device. As compared to the sole gas barrier measurements of materials, the advantages of these tests are that it additionally accounts for the thermal stress during the processing of the encapsulation, possible chemical degradation during the encapsulation process and the impact of the interfaces of the sealed device (lack of adhesion or other issues). We present here 2 examples based on the optical monitoring of the degradation of coupons of calcium or perovskite layers encapsulated with encapsulants to be tested.

<sup>12</sup><https://www.vinci-technologies.com/vacuum-deposition/products/ultra-high-barrier-permeameters/qhv4-rapid-helium-permeameter/113692/>

<sup>13</sup> S. Shiesl Frontiers in Nutrition, 1 March 2022, Volume 9, Article 790157

### 2.1.2.1 Calcium Test

The calcium is used to study the water barrier properties of thin film inorganic coating in OLEDs industry, by following the progressive degradation of a calcium layer. When calcium is exposed to water, a chemical reaction transforms the metallic calcium into calcium hydroxide [8]:



This degradation can be followed either electrically or optically, sometimes simultaneously<sup>14,15</sup>. In the case of an electrical measurement, the resistance of the layer increases as the degradation occurs. The optical measurement is based on the transmission: the initial layer is opaque, while the degraded one has a higher transmission rate. Images are taken with a setup like the one shown in Figure 4, and their grayscale is then analysed to distinguish degraded and undegraded areas.

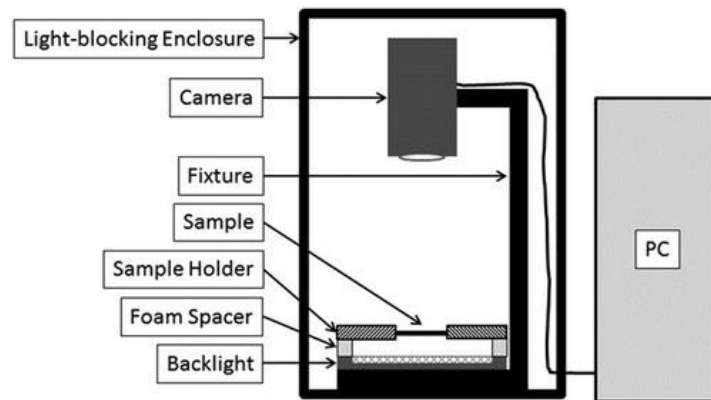


Figure 4: Set-up for the optical calcium test.

<sup>14</sup> R. Paetzold, A. Winnacker, D. Henseler, V. Cesari, and K. Heuser, "Permeation rate measurements by electrical analysis of calcium corrosion," *Rev. Sci. Instrum.*, vol. 74, no. 12, pp. 5147–5150, Dec. 2003, doi: 10.1063/1.1626015.

<sup>15</sup> H. Klumbies, L. Müller-Meskamp, T. Mönch, S. Schubert, and K. Leo, "The influence of laterally inhomogeneous corrosion on electrical and optical calcium moisture barrier characterization," *Rev. Sci. Instrum.*, vol. 84, no. 2, p. 024103, Feb. 2013, doi: 10.1063/1.4791798.

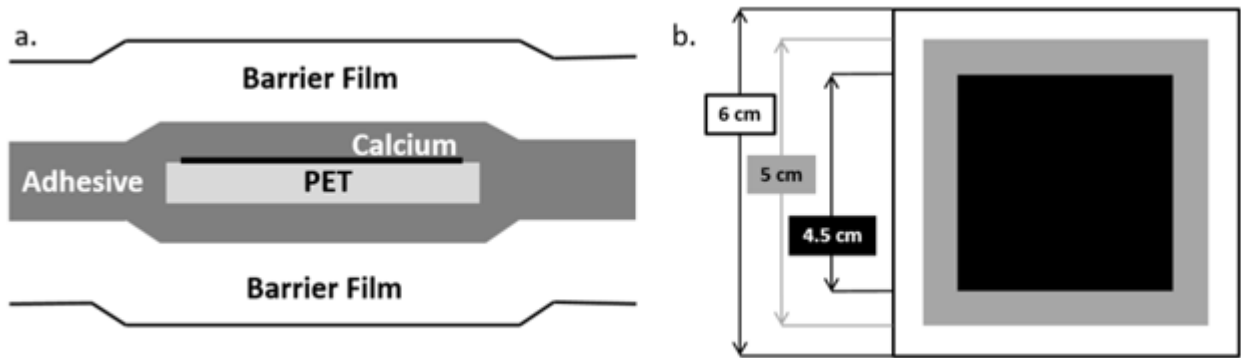


Figure 5: A diagram of the sample geometry<sup>16</sup> for the proposed version of the optical calcium test is shown in (a) cross-sectional view and (b) top view. In the top view, the sample is a square and the marked dimensions are also the same for the horizontal dimensions. Please note that the diagram is not drawn to scale.

Regarding the use of the calcium test for the analysis of the side permeation<sup>16</sup>, the calcium layer can be deposited on PET substrates and then encapsulated as represented in the Figure 5. Then, the sample is put in a chose atmosphere (for example at 85°C/85%RH) and the series of cliché, Figure 6, is analysed.

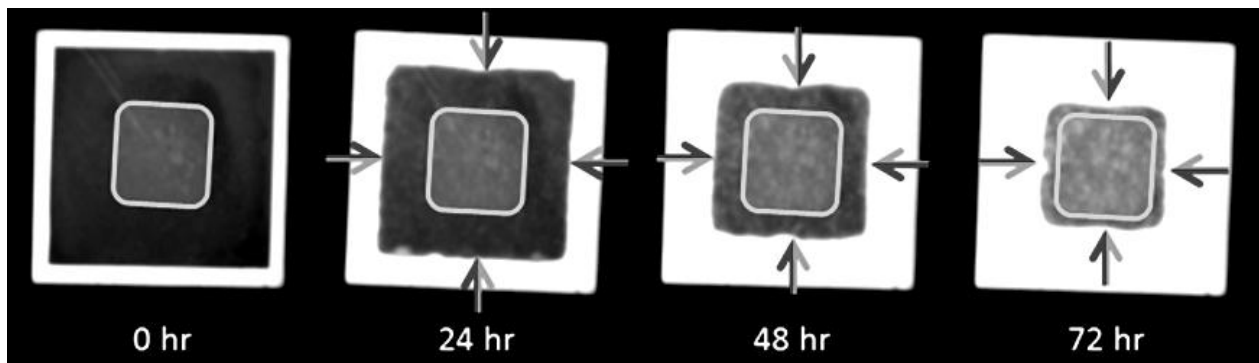


Figure 6: A selection of images<sup>16</sup> from optical calcium test sample is shown after various times of storage at 65°C and 85% relative humidity. The Central Zone remains unaffected by lateral permeation for the duration of the test.

<sup>16</sup> P. Boldrighini & al. Rev. Sci. Instrum. 90, 014710 (2019)

### 2.1.2.2 Perovskite Test

A technological challenge for the calcium test is that Ca is highly sensitive to water. That means that the test sample as well as the encapsulation need to be prepared in a dry atmosphere with high precaution to prevent the sample to be exposed to water before the encapsulation process is finished. This restriction is also a bit far of the “real life” considering we generally plan to encapsulate in air regarding cost issues.

The “perovskite test” is an adaptation of the calcium test, where the optical properties of an encapsulated perovskite layer are monitored<sup>17</sup> during aging. The disadvantage of this method is the impossibility to deduct the exact amount of water diffusing through the encapsulating materials considering the reactions of perovskite with water and/or oxygen are complex, can be reversible and then, are non-stoichiometric.

The perovskite test relies on the contrast change in perovskite thin layers as the material degrades<sup>17</sup>. The coupon fabricated in CEA are constituted of a glass/ITO substrate with a double cations (Cs, FA) perovskite and a top ITO layer. The encapsulation of choice can then be added, Figure 7.

The initial coupon is opaque with a dark colour, as shown in Figure 8 at 0h. The progressive degradation leads to the formation of a yellowish and translucent layer, visible in Figure 8 at 685 and 948 hours.

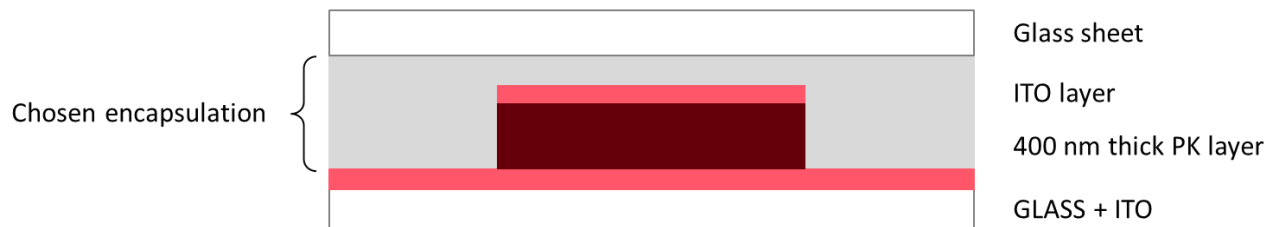


Figure 7: Standardized stack used for the perovskite test.

The images are taken with a setup identical to the one presented in Figure 4, and are then treated with a specific algorithm<sup>18</sup> to extract the equivalent perovskite thickness for each pixel, i.e., what remains non degraded considering a specific threshold. The parameters followed for the comparison of different encapsulation schemes are<sup>17</sup>:

- The surface loss rate: the degradation can start from corners, leading to the formation of a circular pattern.
- The degradation rate in the central area

<sup>17</sup> E. Booker, J.-B. Boutin, C. Roux, M. Manceau, S. Berson, and S. Cros, “Perovskite Test: A High Throughput Method to Screen Ambient Encapsulation Conditions,” *Energy Technol.*, vol. 8, no. 12, p. 2000041, 2020, doi: 10.1002/ente.202000041.

<sup>18</sup> N. Taherimakhsoosi & al; 1,7npj Computational Materials volume 7, Article number: 190 (2021)

The surface loss is mainly related to the kinetic of diffusion of water in the bulk of the sealing material. The degradation rate in the central area is mostly related to issues with interfaces or water included in the sealing material.

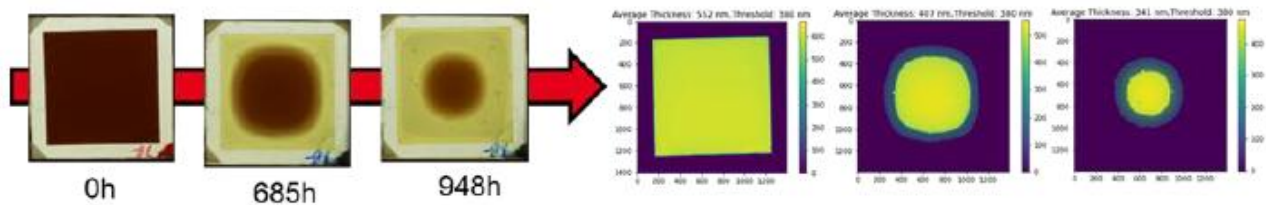


Figure 8. Example of the time evolution of a calcium test and the corresponding effective thickness maps<sup>19</sup>

## 2.2 Adhesion

The thickness and adhesion of the encapsulating material, front-sheet/back-sheet and encapsulant, are relevant parameters, as mentioned in *IEC 61730-2 Edition 2.0 2016-08, Photovoltaic (PV) module safety qualification-Part 2: Requirements for testing*. According to this standard, the adhesion between different layers, a parameter that provides information on the durability of the interlayer bond, is measured through a peel test. In this test based on procedure described in *ISO 813: Rubber, vulcanized or thermoplastic — Determination of adhesion to a rigid substrate — 90 degree peel method*, see Figure 9 below, 10 strips 10 mm wide and at least 100 mm long must be cut from the PV devices and peeled off in a controlled way while measuring the force required to separate these materials to extract the adhesion force. In addition, the thickness of the encapsulation material is measured using the strips obtained in the peeling test.

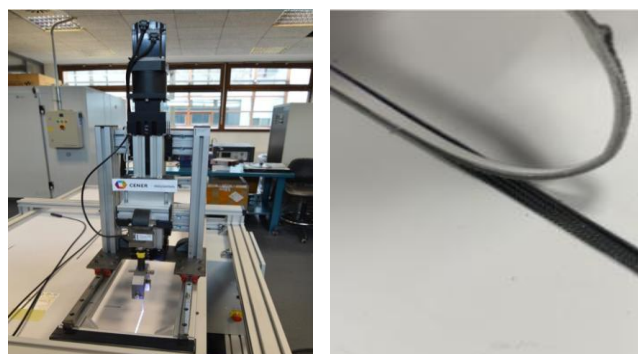


Figure 9: (Left) Peel test set up (CENER) for encapsulant adhesion characterization. (Right) Detail of the strips cut to perform peel test.

<sup>19</sup> M. Majorel, "Amélioration des propriétés gaz barrière grâce à des matériaux étanche pour l'encapsulation de cellules solaires flexibles (organiques et pérovskites)," Thesis; Jan. 24, 2023. <https://www.theses.fr/s208808>

### 2.3 Crosslinking Degree of encapsulant

To encapsulate cells with cross linkable polymers, prototypes can be processed in a laminating equipment to thermally crosslink the material and complete the encapsulation. The differential scanning calorimetry (DSC) method and a protocol based on the Soxhlet method<sup>20</sup> is used for the measurement of the degree of polymerization of the encapsulating material, see Figure 10. This technique allows to control the degree of crosslinking as the amount of residual crosslinking agent as peroxide.



Figure 10. Multi-column Soxhlet extractor installation at CEA.

### 2.4 Thermic and Thermo-mechanical properties

Differential scanning calorimetry (DSC) is a technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature. Both the sample and reference are maintained at nearly the same temperature throughout the experiment. The basic principle is that when the sample undergoes a phase transitions, less or more heat must flow to the sample depends on whether the process is exothermic or endothermic. This technique is employed to measure the glass transition temperature and the molten temperature for example.

Dynamic mechanical analysis (DMA) is a technique used to study the viscoelastic behavior of polymers. As DSC, this technique can be used to locate the glass transition temperature of the material, as well as to identify transitions corresponding to other molecular motions.

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<sup>20</sup>[https://cea.hal.science/cea-04284516v1/file/Standardized%20crosslinking%20determination\\_full%20paper.pdf](https://cea.hal.science/cea-04284516v1/file/Standardized%20crosslinking%20determination_full%20paper.pdf)

In addition, a sinusoidal stress is applied and the strain in the material is measured, allowing one to determine the complex modulus.

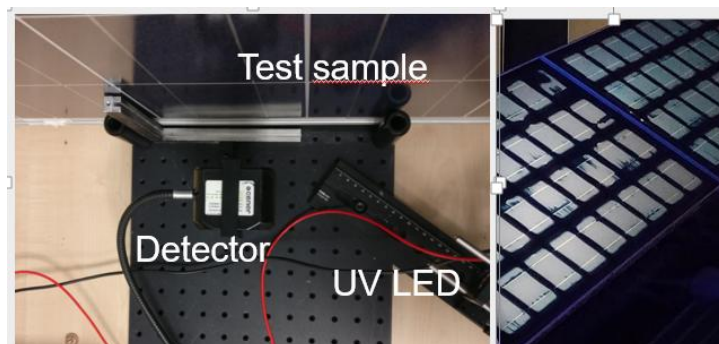
These techniques allow to optimize the lamination process (considering glass transition or molten temperature) as, for DMA, the evolution of the stiffness of the encapsulant with temperature.

## 2.5 Inspection techniques

There are others inspection techniques for polymeric encapsulants currently under development, terahertz frequency spectroscopy and UV fluorescence. Both can be used to extract valuable information on the quality and durability of the encapsulant materials of perovskite PV solar devices such as its thickness, its adhesion and degree of crosslinking (if EVA), directly related to the durability and reliability of the PV modules.

**Terahertz spectroscopy** allows higher resolutions than those provided by microwaves, while maintaining the ability to pass through certain opaque materials at optical frequencies. In the photovoltaic field, the use of terahertz is still limited, although some experiments have been carried out demonstrating the potential for inspection of interconnections and encapsulations.

The **ultraviolet fluorescence spectroscopy technique** is used since 2010 to identify defects in photovoltaic modules based on standard crystalline silicon technology. This technique, based on the fluorescence effect of some encapsulant materials, is used to characterize both its quality and to identify the occurrence of degradation mechanisms in an initial state.



*Figure 11. (Left) Set-up to measure UV spectroscopy and (right) image of a silicon PV module under UV irradiation where some defects could be observed (CENER).*



### 3. USE CASE: TIPS AND TRICKS FOR GOOD ENCAPSULATION FOR PEROVSKITE-BASED SOLAR CELLS

In this study<sup>21</sup>, performed during VIPERLAB project between HZB and CEA, we investigated the important characteristics to consider when choosing an appropriate encapsulation for perovskite solar cells. From physical and mechanical properties of the polymer encapsulants to **damp heat and thermal cycling tests** on full devices. We show how to assess the quality of an encapsulation to maximize the lifespan of perovskite solar cells. Regarding the techniques described in the previous sections, we investigated the gas barrier properties (side permeation) through the use of the perovskite tests, and we characterized encapsulants by Dynamic Mechanical Analysis (DMA).

The description of the stack used to perform the Perovskite test and of the cell architecture are represented in Figure 12, a) and b) respectively. Different combination of encapsulant materials have been tested to seal glass covers, 2 types of encapsulant (POE and Ionomer) combined or not with Butyl edge sealant.

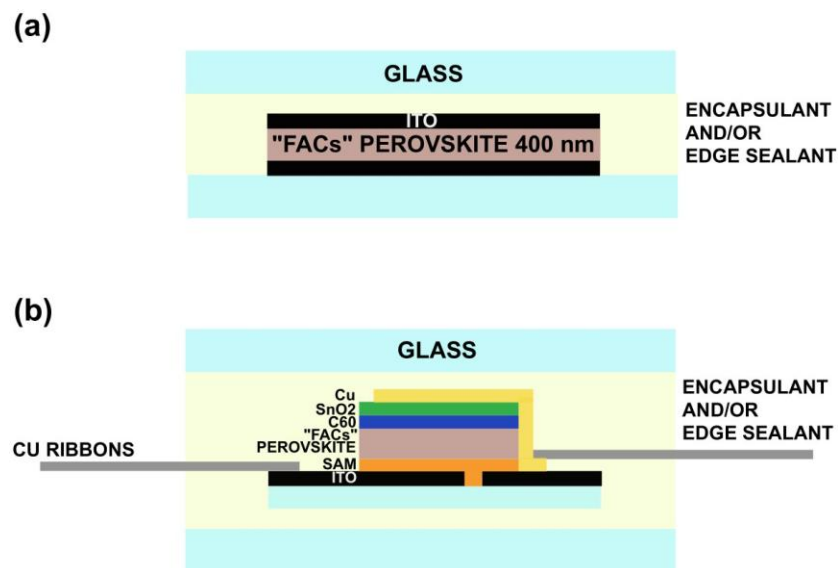


Figure 12. (a) "Perovskite test" stack and (b) encapsulated perovskite solar cell stack.

Regarding the study of the side permeation with the different combination of materials, we can see on the figure 13, that the resistance in damp heat conditions of the encapsulated perovskite layer is more important with ionomer materials whatever the processing temperature (I; e; the crosslinking of POE at 150°C doesn't change the water penetration kinetic, it is only useful to avoid mechanical creeping in operation.)

<sup>21</sup> Q. Emery & al., Progress in photovoltaics, in press

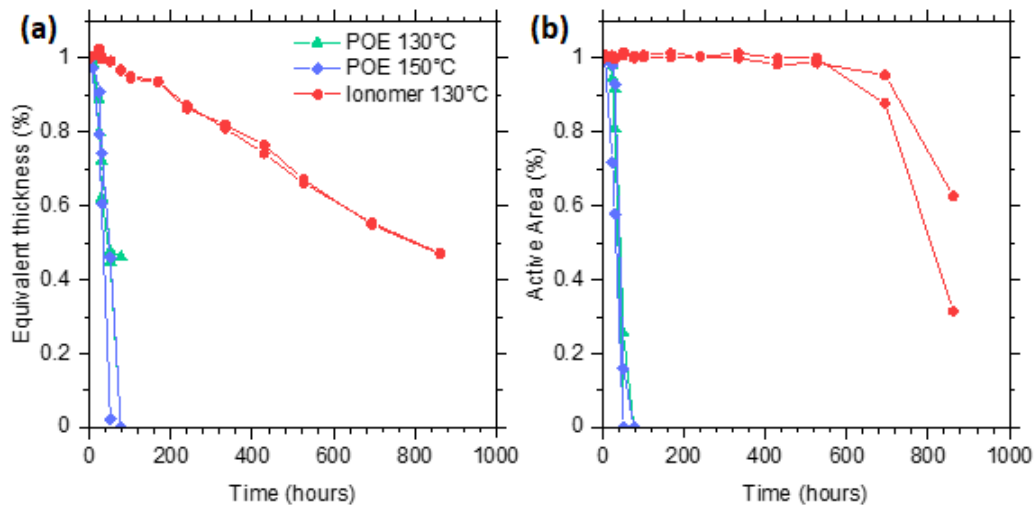


Figure 13: Evolution of the (a) equivalent thickness and (b) active area of perovskite samples encapsulated with ionomer vs. POE and submitted to the PK-test (at 85°C/85%RH)

At another hand, when combined with Butyl edge sealant, first the degradation rates are considerably lower as compared to the use of the sole encapsulant, Figure 14, and there is not any difference between POE and ionomer. It means that the gas barrier protection is provided by the butyl edge sealant. With such encapsulation, the encapsulated devices have similar behaviour in damp heat (85°C, 85%RH) and thermal testing (85°C, low humidity), Figure 15, the observed degradation is not related to water ingress.

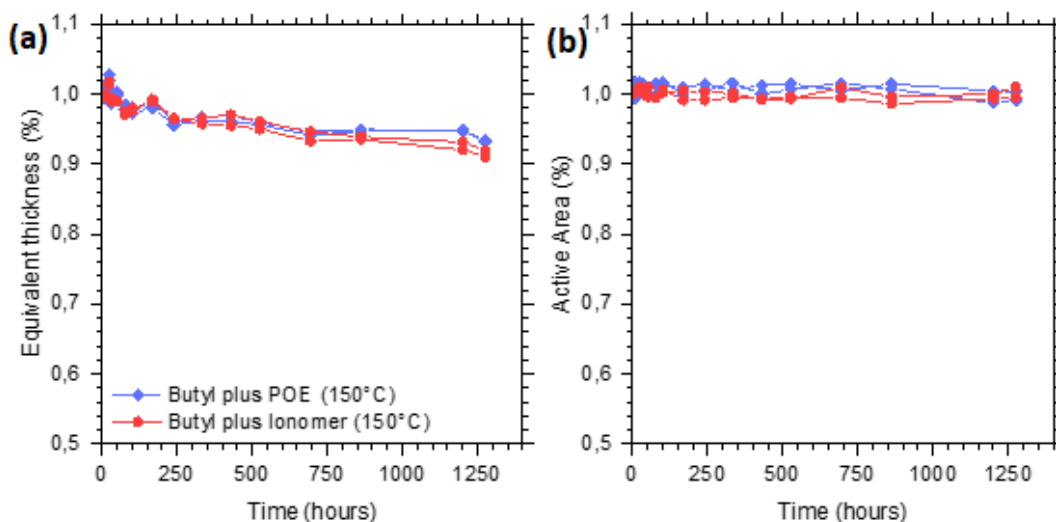
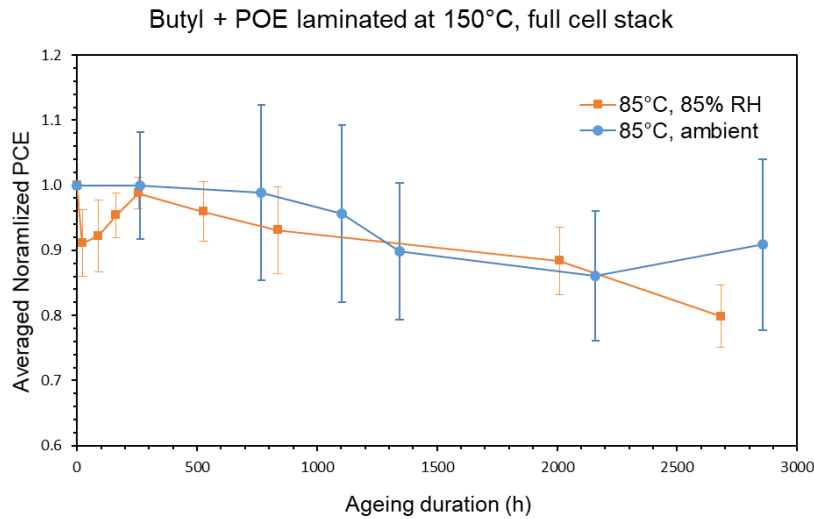


Figure 14: Evolution of the (a) equivalent thickness and (b) active area of perovskite samples encapsulated with butyl edge sealant + ionomer vs. POE and submitted to 85°C/85%RH



*Figure 15: Evolution of the normalized efficiency with standard deviation of perovskite solar cells encapsulated with butyl + POE during ageing in the damp heat chamber at **85°C, 85% RH** or in the oven at 85°C, ambient humidity.*

In the Figure 17, the DMA analysis of POE and ionomer encapsulants are reported. On the left, we observe a glass transition temperature at -47°C for POE and +33°C for Ionomer. At another hand, the stiffness of Ionomer is considerably higher, in the range of 30 times more than POE at ambient temperature. For ionomer, this combination of high stiffness and the presence of a glass transition in the range -40°C/+85°C (related to damp heat test), leads to systematic delamination in thermal cycling tests of encapsulated devices, Figure 17. At another hand, devices encapsulated with POE, POE plus Butyl or just Butyl can pass the thermal cycling test.

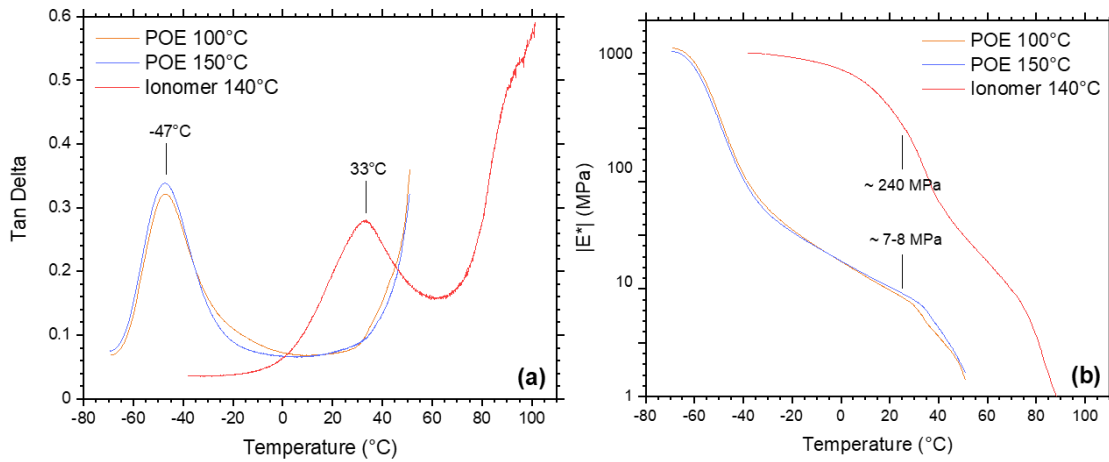


Figure 16: DMA results on POE laminated at 100°C or 150°C, compared with ionomer laminated at 140°C. Graph (a) shows  $\tan \delta$  as a function of temperature, with peaks that correspond to the glass transition. Graph (b) shows the stiffness evolution with temperature.

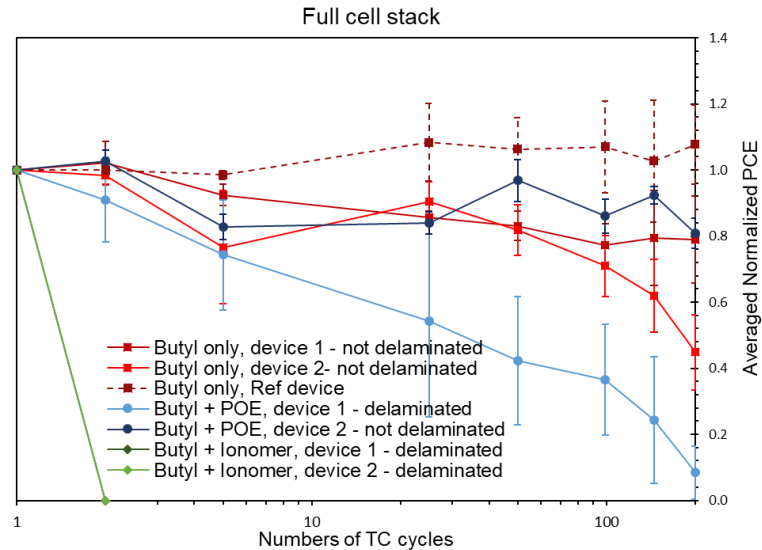


Figure 17: Evolution of the PCE of samples encapsulated with Butyl + Ionomer vs. Butyl + POE vs Butyl only during thermal cycling. Average values over 3 to 6 cells per device are shown with standard deviation

In conclusion of this study, the use of POE can avoid the delamination issue in thermal cycling thanks to its absence of thermal transition in the range of the thermal cycling test and thanks to its low stiffness. At another hand, the combination with butyl edge sealant can counterbalance its poor gas barrier properties.

## 4. CONCLUSIONS

The findings of this study demonstrate that traditional methods for evaluating encapsulation quality, commonly used in the photovoltaic industry, are well-suited for perovskite solar cells, with some additional considerations. Gas barrier properties, both at the material and packaging levels, emerge as a critical factor due to the sensitivity of perovskite layers to water and oxygen. Encapsulation processes must account for side permeation, adhesion strength, and the mechanical behaviour of materials under thermal stress. The study identifies POE as a particularly effective encapsulant due to its low stiffness and absence of thermal transitions in the test range, making it highly resistant to delamination during thermal cycling. When combined with butyl edge sealants, POE further compensates for its limited gas barrier properties, providing comprehensive protection against moisture ingress.

The collaborative experiments also underscore the importance of tailoring encapsulation strategies to the unique needs of perovskite solar cells. For instance, rigid encapsulants like ionomer, despite their superior gas barrier properties, can lead to delamination under thermal cycling due to their stiffness and thermal transitions. Such findings highlight the necessity of balancing gas barrier effectiveness with mechanical flexibility to ensure long-term device stability. Moving forward, encapsulation designs should integrate insights from advanced testing methods, such as perovskite and calcium tests, to develop solutions that withstand environmental challenges. By focusing on material innovation and process optimization, this study paves the way for improving the reliability and commercial viability of perovskite solar cells.

