THESIS

THERMAL AND OPTICAL PROPERTIES OF EDGE SEALED PHOTOVOLTAIC MODULES

Submitted by

David R Durney

Department of Mechanical Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2025

Master's Committee:

Advisor: Walajabad Sampath

James Sites
Christopher Weinberger

ABSTRACT

THERMAL AND OPTICAL PROPERTIES OF EDGE SEAL PHOTOVOLTAIC MODULES

As the global demand for clean energy accelerates, photovoltaic (PV) technologies must evolve not only to improve performance and reduce cost, but also to address sustainability and end-of-life considerations. Traditional PV modules rely heavily on polymeric encapsulants such as Ethyl Vinyl Acetate (EVA), which contribute to long-term degradation mechanisms including acetic acid formation, potential-induced degradation (PID), and recycling challenges. This study presents the design, fabrication, and evaluation of an encapsulant-free Edge Sealed Module (ESM) architecture developed at Colorado State University. The ESM eliminates vacuum lamination and conventional encapsulants by enclosing photovoltaic cells within an air-filled, edge-sealed glass-glass structure, enhanced with nano-textured surfaces for optical and thermal performance.

The optical performance of ESMs was evaluated by comparing short-circuit current (ISC) to traditional modules under outdoor conditions using a custom-built In-Situ Data Logger. Results indicate that textured ESMs match the optical output of traditional modules within experimental error. Thermal performance was assessed through open-circuit voltage (VOC) measurements, showing that ESMs exhibit similar or improved thermal behavior compared to traditional counterparts, particularly when enhanced with surface textures that promote internal convective cooling. Ultraviolet (UV) stability of PMMA-based nano-textures was also investigated. While encapsulated samples showed minimal degradation, un-encapsulated textures experienced significant transmission loss and delamination, confirming the need for robust edge sealing to ensure durability.

In addition to performance, the ESM design offers a simplified manufacturing process with significant reductions in cycle time, factory floor space, and material costs. Mechanical testing shows

increased structural strength compared to laminated modules. These findings suggest that ESMs provide a viable path forward for next-generation PV module design—balancing efficiency, reliability, and sustainability while supporting the Department of Energy's 50-year module lifetime goal.

ACKNOWLEDGEMENTS

Primarily I would like to thank my committee members for the time they have taken out of their busy schedule to mentor me and make my thesis possible. Their invaluable support cannot go unrecognized.

I would like to thank my adviser Dr. Walajabad Sampath for his guidance and unrelenting support. He has been a joy to work under. His wealth of knowledge including his experience with co-founding Abound Solar and his decades of photovoltaic experience are irreplaceable.

Ryan Ruhle has paved the way for my work. His ingenuity and innovation in ESM technology enables my work. It has been a pleasure to work with him both in the lab and outside of the lab.

Larry Maple's experience and time spent out of his retirement cannot go unmentioned. Much like Dr Sampath, Larry has been a mentor to me both with honing my skills and knowledge in the lab and as I develop as a professional engineer.

I must acknowledge my family and friends for their continuous support out of the lab. Any structure must have a solid foundation, and they are that for me.

I would like to thank Steve Johnston and Dana Kurn at NREL for their assistance in fabricating samples and time in accelerated testing. Their kindness in helping me is truly irreplaceable.

I would also like to acknowledge the support from the National Science foundation under the Industry/University Cooperative Research Center (I/UCRC) for Solar Powered Future SPF 2050 (Award Numbers – 1821526 and 2052735), and the I/UCRC Industrial Advisory board.

Finally, I would like to thank all the students in the photovoltaic lab at CSU, including Marc Tapparo, Lilly Quintana Barrera and others for their support.

AUTOBIOGRAPHY

David Durney is current a graduate student at Colorado State University. He received his undergraduate degree from Colorado State University. David has spent more than a decade in the automotive industry including working in the tire industry, working as a mechanic and is currently employed part time as a auto body technician.

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1.1 Climate Change and the Growing PV Industry

Since the Industrial Revolution, anthropogenic activities have significantly increased global carbon emissions. This rise is driven by the proliferation of internal combustion engines, increased electricity demand, and rapid population growth. As illustrated in Figures 1 and 2, data from NASA demonstrates a consistent upward trend in atmospheric CO_2 concentrations.

Carbon dioxide and other greenhouse gases absorb and re-emit infrared radiation due to their selective interaction with electromagnetic wavelengths. The sun emits as a 6000 K blackbody, while the Earth, at approximately 300 K, emits longer-wavelength infrared radiation. Greenhouse gases are more effective at trapping this terrestrial radiation, leading to a net warming effect commonly referred to as the greenhouse effect.

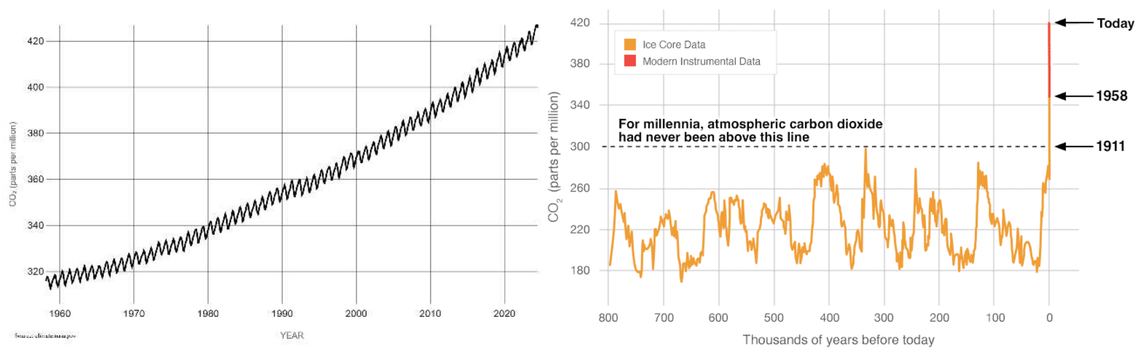

Figure 1: Recent CO2 emissions from climate.nasa.gov/

This phenomenon underscores the urgent need for low-emission, renewable energy technologies. Among these, photovoltaic (PV) systems are rapidly expanding due to their scalability, low operational emissions, and declining costs. The increased deployment of solar energy, illustrated in Figure 2, emphasizes its role in mitigating climate change. However, to further drive adoption, it is imperative to improve PV module reliability, reduce production costs, and develop sustainable end-of-life treatment methods.

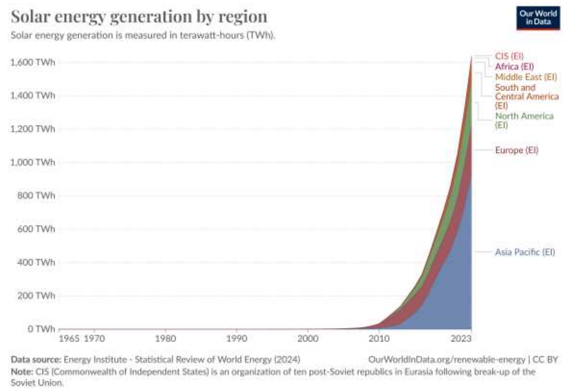

Figure 2: Solar energy generation over time

1.2 Introduction to Photovoltaics and Module Designs

Photovoltaics (PV) is the process by which semiconductors convert sunlight into electricity. Incident photons excite electrons from the valence band to the conduction band across the bandgap, creating electron-hole pairs. These charge carriers can be harvested to generate current (Green, 1998).

While various semiconductors are under investigation, crystalline silicon (c-Si) dominates the market, representing approximately 93% of global PV production. Single-crystal c-Si is widely adopted due to its maturity, efficiency, and extensive manufacturing infrastructure.

PV cells are typically packaged in modules to withstand outdoor conditions. A conventional module consists of a front glass layer, an encapsulant such as ethylene-vinyl acetate (EVA), the c-Si cells, and a rear glass or polymer backsheet. EVA performs two primary functions: optical coupling and thermal conduction.

Optically, EVA has an index of refraction (~1.5) similar to glass, minimizing reflection losses at the interface through index matching, as described by Snell's law:

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2 \quad (1)$$

Where R is the reflectance, n1 and n2 are the refractive indices of adjacent materials. In contrast, air has an index of ~1.0, which increases reflectance and reduces light transmission to the cell.

Thermally, EVA exhibits higher conductivity (~0.20-0.30 W/m·K) than air (~0.03 W/m·K), facilitating heat dissipation. Elevated cell temperatures reduce the bandgap and open-circuit voltage (ISC), typically by -2 to -2.5 mV/°C, or approximately -.3% to -.4% per °C (Sharan, 2013).

While EVA supports module performance, its removal without replacement leads to optical and thermal inefficiencies. In a competitive market where even minor losses in efficiency affect commercial viability, any alternative architecture must compensate for these functions.

1.3 Encapsulant-free Modules

Encapsulant-Free Modules (EFM) are solar panels that do not use encapsulants. Instead, they have an airgap between the front glass and the back glass/back sheet. The module is sealed along the edges, typically from poly-isobutylene (PIB) and a silicone sealant. Within this airgap, the photovoltaic devices are placed. Electrical contacts typically exit the rear glass/back sheet in a rear junction box. Though, some designs include a side junction box where the contacts exit. The differences between traditional modules and EFM can be seen in figure 3. Nuances between different designs of EFM will be discussed in chapter 2.

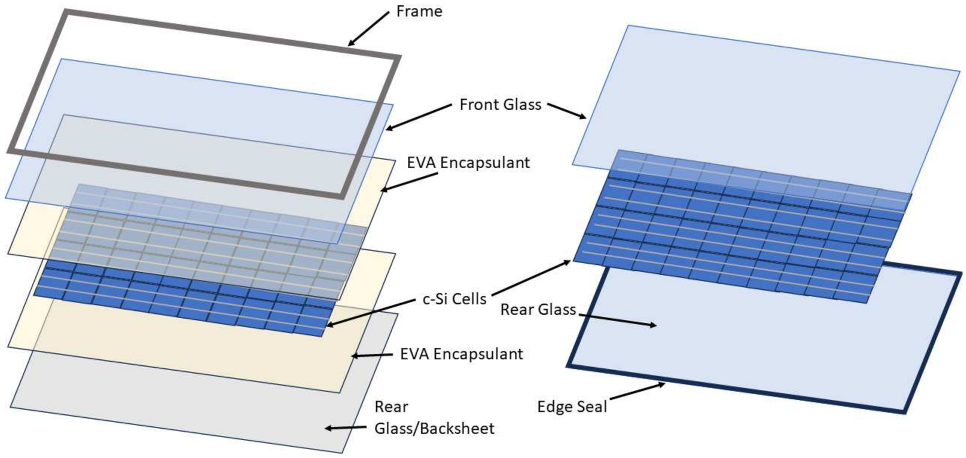

Figure 3: Traditional encapsulation architecture (Left) EFM architecture (Right)

1.4 Vacuum Lamination

The current state-of-the-art method for module encapsulation involves vacuum lamination. This process crosslinks EVA under high heat (~150°C) and vacuum (<1 mbar), forming a cohesive bond that removes air gaps. While effective, this process introduces several limitations.

Tempered glass used in modules introduces surface distortions, and a significant coefficient of thermal expansion (CTE) mismatch exists between c-Si (~2.8×10^{-6} /°C) and EVA (~270×10^{-6} /°C). These mismatches, combined with lamination stresses, can initiate microcracks.

Furthermore, EVA is prone to degradation under UV, heat, and humidity, producing acetic acid, which corrodes cell interconnects and contributes to PID. Delamination is also observed at EVA-glass and EVA-cell interfaces.

Vacuum laminators are capital- and space-intensive, often costing over $400,000 with 15–20 minute cycle times. High-throughput production requires parallelization, expanding the required factory footprint (see Figure 4).

Figure 4: Factory floor of traditionally encapsulated modules. Note the size of people on the right for scale. (Barth, 2018)

1.5 Introduction to Edge Seal Module (ESM) Technology

Edge Seal Module (ESM) technology represents a novel approach to photovoltaic (PV) module design that eliminates the need for traditional encapsulants such as Ethylene-Vinyl Acetate (EVA) and the vacuum lamination process. Instead, ESMs utilize a two-part edge seal, typically composed of polyisobutylene (PIB) and silicone, to create a controlled internal environment without direct contact between the glass layers and the photovoltaic cells. This encapsulant-free architecture reduces thermal and mechanical stress while facilitating easier disassembly for recycling and repair. ESM technology also integrates internal nano-textures to improve optical coupling and thermal dissipation, enhancing performance and durability. Developed and prototyped at the Advanced Module Laboratory (AML), ESMs have demonstrated promising results in accelerated environmental testing and offer significant manufacturing and sustainability advantages over conventional PV modules. Further discussion is in chapter 2.

1.6 Hypotheses

In this section the hypotheses will be introduced. Detailed background information will be given in the literature review section.

1.6.1 Optical Performance

The first hypothesis is that ESMs can achieve optical performance comparable to traditional modules. This requires matching the effective refractive index interface between air and glass to minimize reflectance. Measurements under Xenon illumination, corrected to AM1.5 spectral conditions, suggest that ESMs perform within the experimental margin of error.

1.6.2 Thermal Performance

The second hypothesis posits that ESMs can match the thermal behavior of traditional modules. Since increased cell temperature reduces efficiency, mitigating thermal accumulation is critical. While air is a poorer conductor than EVA, surface nano-textures may promote convective cooling by increasing surface area (Cao, 2011). An increase in surface area on the cell will increase conduction to the encapsulated air in the module. A similar increase in conduction is expected to occur on the front glass to the encapsulated air. Both these effects could increase the internal convection increasing heat transfer from the cell.

1.6.3 Ultraviolet Stability of Nano-Textures

Finally, the third hypothesis investigates whether UV radiation degrades nano-textured materials—primarily polymethyl methacrylate (PMMA). Though manufacturers do not rate these textures for outdoor use, encapsulation may mitigate degradation. This study evaluates UV-induced transmittance loss and structural integrity under combined environmental stressors.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the current state of research related to encapsulation-free module (EFM) architectures, with a focus on existing designs and their limitations. It covers historical efforts in EFM development from various research institutions and companies, including Abound Solar, Apollon Solar, the Fraunhofer Institute, and Colorado State University. Additionally, the advantages and disadvantages of ESM Systems are discussed, alongside material selections and accelerated testing data relevant to their performance.

2.2 Abound Solar

Abound Solar, a U.S.-based company founded out of Colorado State University in 2007, pioneered commercial EFM technology using thin-film cadmium telluride (CdTe) deposited directly onto 120 mm × 60 mm tempered glass. This glass-glass construction, with the absorber deposited directly onto the front glass eliminated the reflection losses at the front glass interface and utilized a robust perimeter seal for moisture and vapor protection. The modules featured a rear junction box and obtained IEC certification, with a 25-year performance warranty guaranteeing 80% of rated power (Barth, 2009).

2.3 N.I.C.E. module

Apollon Solar's N.I.C.E. (New Industrial Cell Encapsulation) module represents one of the earliest efforts to adapt EFM architecture to crystalline silicon (c-Si) cells. This design uses a low-pressure internal atmosphere to secure cells and tabbing ribbons. The module incorporates inert gas filling and layered anti-reflective (AR) coatings to address optical losses. While the N.I.C.E. module demonstrated a four-minute production cycle and a two-part moisture barrier, it did not address the thermal limitations associated with air gaps (Dupuis, 2012) (Reinwand 2018).

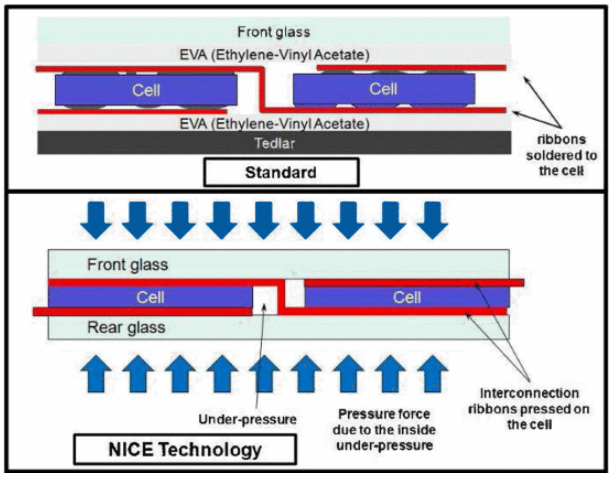

Figure 5: A diagram of the N.I.C.E. module developed by Apollon Solar.

2.4 TPEdge module

The Fraunhofer Institute developed the TPEdge module, another EFM adapted for c-Si technology. The design employs a frameless, glass-air-glass structure, with polymer pins used to mechanically affix cells to the rear glass. A dual-component edge seal comprising PIB and silicone is applied, and AR coatings are used to mitigate reflection losses. The module design was considered ready for IEC certification; however, no improvements in thermal coupling were apparent (Mittag, 2017).

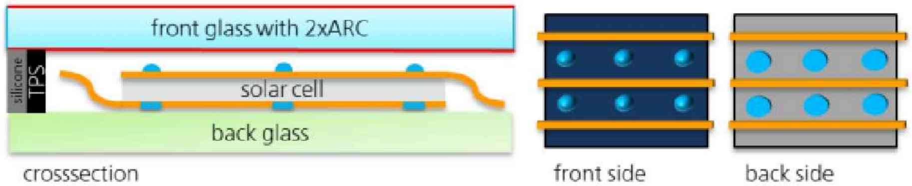

Figure 6: A diagram of the TPEdge module developed by Fraunhofer Institute (Mittag, 2017)

2.5 Edge Seal Module

The Edge Seal Module (ESM) developed at Colorado State University is a unique EFM employing a tempered glass-glass construction with a two-part edge seal. Polymer pins secure cells via the busbar, and electrical leads exit through a side-mounted junction box. To address optical loss, the inner surface of the front glass and the front of the cell are coated with nano-textures designed to minimize internal reflection (Ruhle 2023). These textures may also enhance thermal performance by increasing convective surface area. The ESM demonstrates a rapid 30-second production cycle (Ellis, 2021).

Multiple advantages have been observed in ESMs. Damp heat tests up to 5000 hours—equivalent to 50 years in high-humidity environments—show minimal moisture ingress (Kempe, 2014). Disassembly is straightforward, facilitating recycling and repair. Without EVA, the module avoids degradation mechanisms such as acetic acid formation and PID (Ruhle, 2023).

Two nano-textures are under evaluation: Texture 1 (PMMA-based) and Texture 2 (PET-based). While PMMA is known to degrade under UV, heat, and humidity, preliminary tests indicate acceptable performance when environmental stressors are not combined(Abouelezz, 1978) (Monsores, 2019). These findings are supported by accelerated aging and optical transmission tests (Rainhart, 1974).

Thermal performance could also be improved with nano structure. Researchers found that thermal conductivity increased my two orders of magnitude with nano wire of diameter of 100-200nm (Cao, 2011). Since nano-structure under evaluation is similar in size to this study, thermal conductivity is expected to improve. This increases heat transfer from the cell to internal air in the module, which may promote convection to the front glass, which would also have increased thermal conductivity and dissipate heat outside the module.

Other solar technologies are compatible wit ESM. Technologies like CdTe and Perovskites can be encapsulated in a ESM. Thin films deposited on front glass won't have reflective loss and are directly thermally coupled to the front glass. As such, no nano-texture is needed for these technologies.

Figure 7: CSUs ESM factory floor with ~200MW/yr potential, developed through DOE funded grant (Ruhle, 2023)

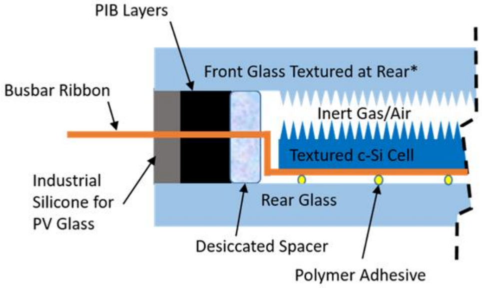

Figure 8: A diagram the ESM module developed at CSU (Ruhle, 2023)

2.6 Benefits of ESM

ESM designs offer numerous advantages. Mechanically, they surpass IEC 61646 static load requirements by a factor of 2–2.5, likely due to reduced internal stress from the absence of vacuum lamination (Ellis,2021). ESMs also pass 5000-hour damp heat tests with negligible moisture ingress (Ruhle, 2023). A 30-second cycle time enables rapid manufacturing, and the factory footprint is significantly smaller (Ellis, 2021). Because EVA is not used, associated degradation mechanisms—such as acetic acid formation and PID—are eliminated. Additionally, ESMs offer material cost reductions of approximately \$0.017/Wp (Barth, 2018).

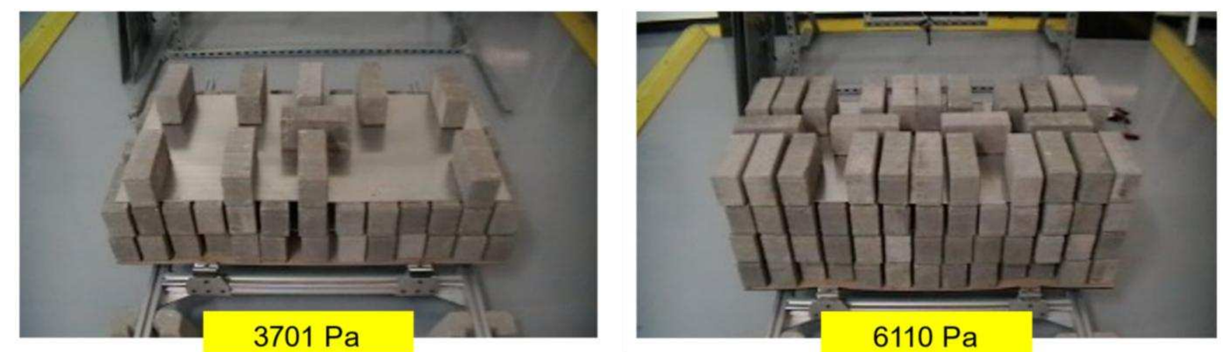

Figure 9: Static loads at break. Traditional modules shown on the left. ESM shown on the right. (Ellis,2021)

2.7 Recent Publications

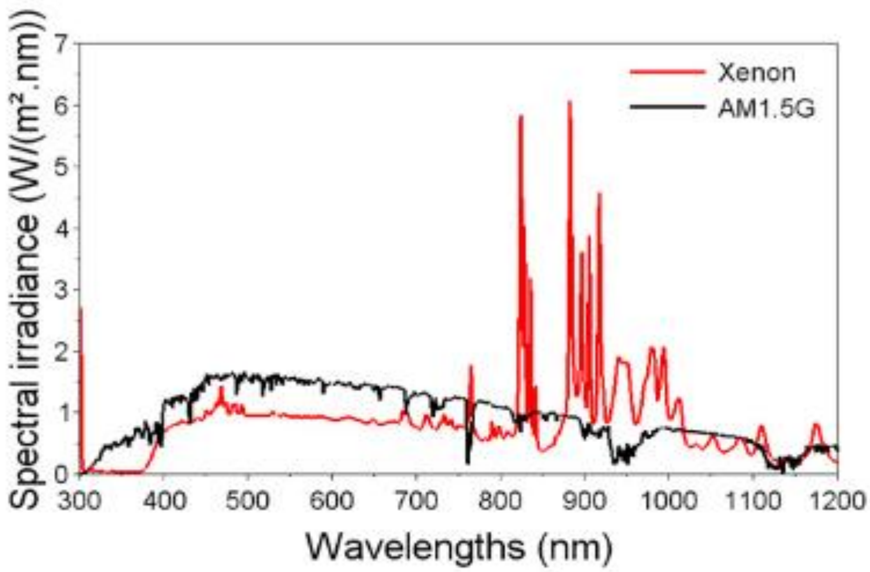

Figure 10: Spectral emission of typical unfiltered Xenon lamp compared directly to AM1.5G as a function of wavelength [Couderc, 2017].

Rhule et al. conducted comparative optical testing on ESM and traditional modules using a xenon light source. As xenon lights emit disproportionately in the infrared (IR) spectrum compared to the standard AM1.5 spectrum, a spectral correction was applied. After correction, ESMs showed performance within the experimental margin of traditional modules. The study confirms the optical viability of ESMs under standardized test conditions (Ruhle, 2023).

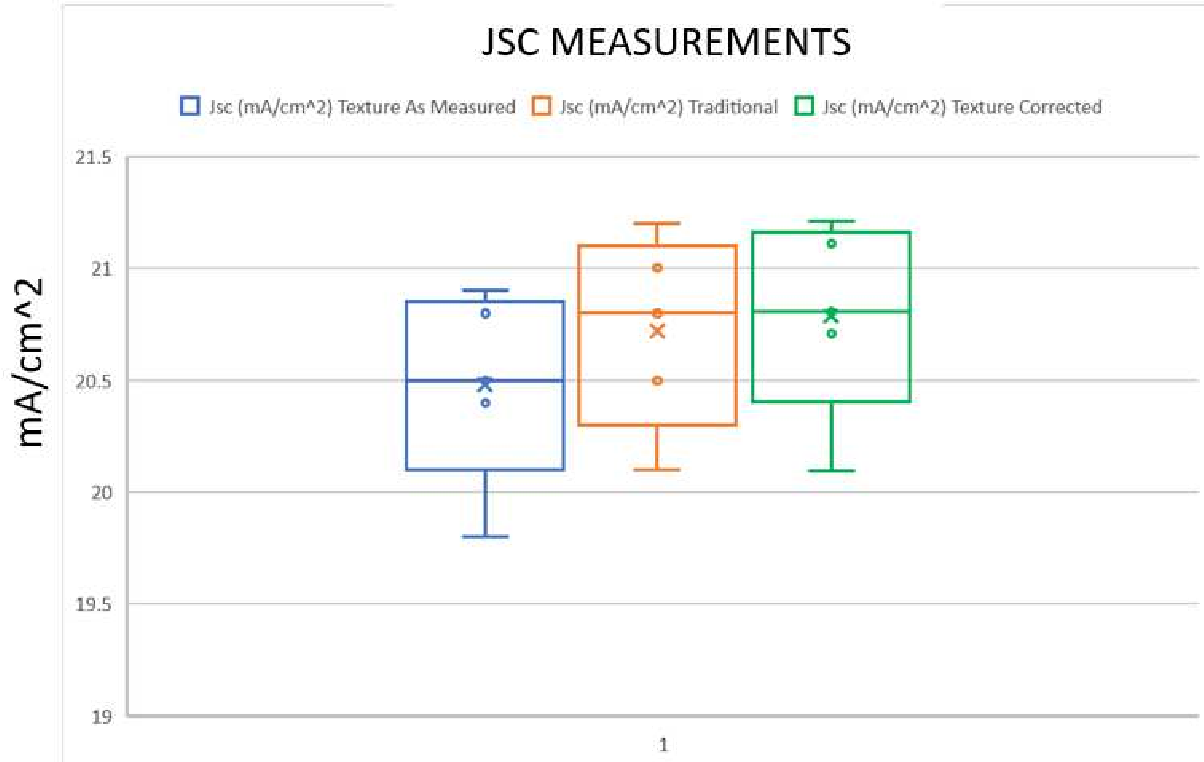

Figure 11: Current density (Jsc) measurements of ESM modules under xenon light for ESM shown in blue. Shown in orange is traditional modules under xenon light, and shown in green is the corrected for AM1.5 ESM data. (Ruhle, 2023)

2.8 PMMA Degradation

Table 1: Coefficients of linear expansion of different formulations of PMMA (Goods, 2003)

Material	Linear Dimensional Change in 150 hr @ 28 °C (%)		
	DI Water	Ni-Sulfamate	Ni-Watts
KCPCQ	0.44	0.28	0.39
OP-1	0.40	0.29	0.37
Sol	0.39	0.28	0.37

PMMA is susceptible to degradation under outdoor conditions, including UV exposure, heat cycling, and moisture ingress. Its swelling rate can reach 0.44% in some formulations. Under NREL's TC50 accelerated temperature cycling protocol (-40°C to 25°C), significant CTE mismatches are observed between PMMA ($50–90 \times 10^{-6}$ K^{-1}), c-Si ($2.5–3.3 \times 10^{-6}$ K^{-1}), and soda-lime glass (~9×10^{-6} K^{-1}). This mismatch can lead to mechanical stress and a 0.57% differential expansion.

Table 2: CTE of different Materials of interest

Material	CTE
PMMA	$(5.0 - 9.0)\mathrm{E} - \mathbf{5}\ \mathrm{K} - 1$
c-Si	$(2.5 - 3.3)\mathrm{E} - \mathbf{6}\ \mathrm{K} - 1$
Soda lime glass	$\sim 9\ \mathrm{E} - \mathbf{6}\ \mathrm{K} - 1$

UV exposure reduces PMMA's elongation at break, tensile strength, and glass transition temperature, indicating bond structure changes. Degradation follows an exponential decay, with the most significant effects occurring early (Abouelezz, 1978) (Monsores, 2019).

Chapter 3: EXPERIMENTAL DESIGN

3.1 Introduction

This chapter outlines the experimental methods used to evaluate the Edge Sealed Module (ESM). It describes the fabrication procedures for both ESM and conventional samples, details the equipment used for performance monitoring, and explains configurations used for ultraviolet (UV) exposure and optical testing.

3.2 Equipment and Sample Manufacturing

The Advanced Module Laboratory (AML) at Colorado State University is equipped for rapid prototyping of photovoltaic module architectures. Its manufacturing line supports module dimensions up to 60 cm × 120 cm and can be adapted to fabricate smaller samples for specific test protocols. In collaboration with the National Renewable Energy Laboratory (NREL), AML has developed prototype ESMs compliant with IEC 61215 accelerated stress testing standards, as well as additional samples for outdoor monitoring.

3.3.1 AFL Manufactoring Equipment

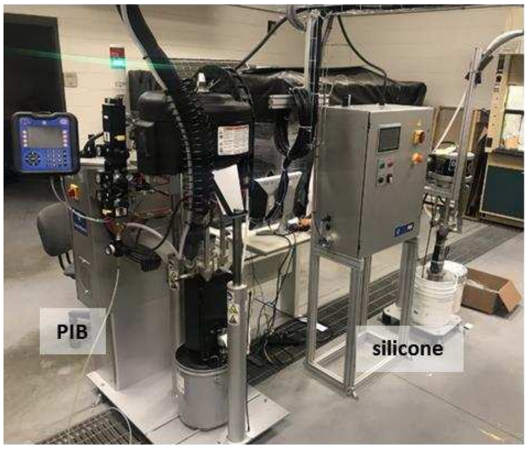

Figure 12: Graco supplied heated PIB pumping system (left) and polymer application tooling shown with 30cm x 30cm adapter plate installed (right).

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3.3.2 ESM Sample Fabrication

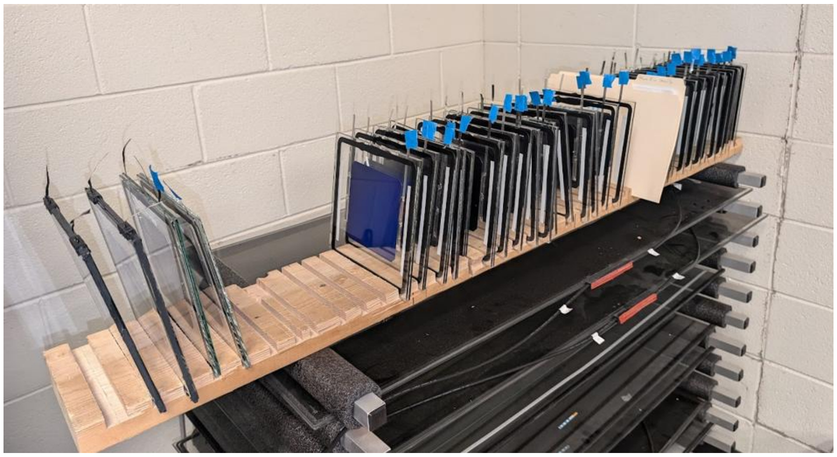

Figure 13: 45 module production run at AML for accelerated testing at NREL and outdoor testing.

The core manufacturing system includes a custom edge-seal dispenser with dual nozzles. This machine eliminates the need for vacuum lamination by applying both the polyisobutylene (PIB) and silicone sealants in under 30 seconds for full-size modules. Originally designed for insulated glass, this equipment was adapted for photovoltaic use through DOE-funded research.

To ensure quality, process parameters were optimized using statistical design of experiments (SDOE). A modified press system with adjustable pressure and customized pistons allows uniform compression for various module geometries. Over 100 modules have been fabricated during optimization trials, with process logs maintained to minimize variability and accelerate future iterations.

The general procedure for ESM sample fabrication includes the following steps:

- Clean front and rear glass layers.
- Apply nano-texture to interior surfaces (if used).
- Place back glass on the encapsulation platform.
- Apply the first PIB layer to the back glass.

- Apply UV-curable adhesive to cell tabbing ribbons.
- Secure cells to the back glass using a UV lamp.
- Apply the second PIB layer to seal lead exits.
- Align and place the front glass.
- Compress the assembly with optimized press settings.
- Inject silicone into the edge using a custom 3D-printed nozzle.
- Inspect modules using electroluminescence (EL) and photoluminescence (PL) imaging.
- Send defect-free modules to testing; document and analyze any failures.

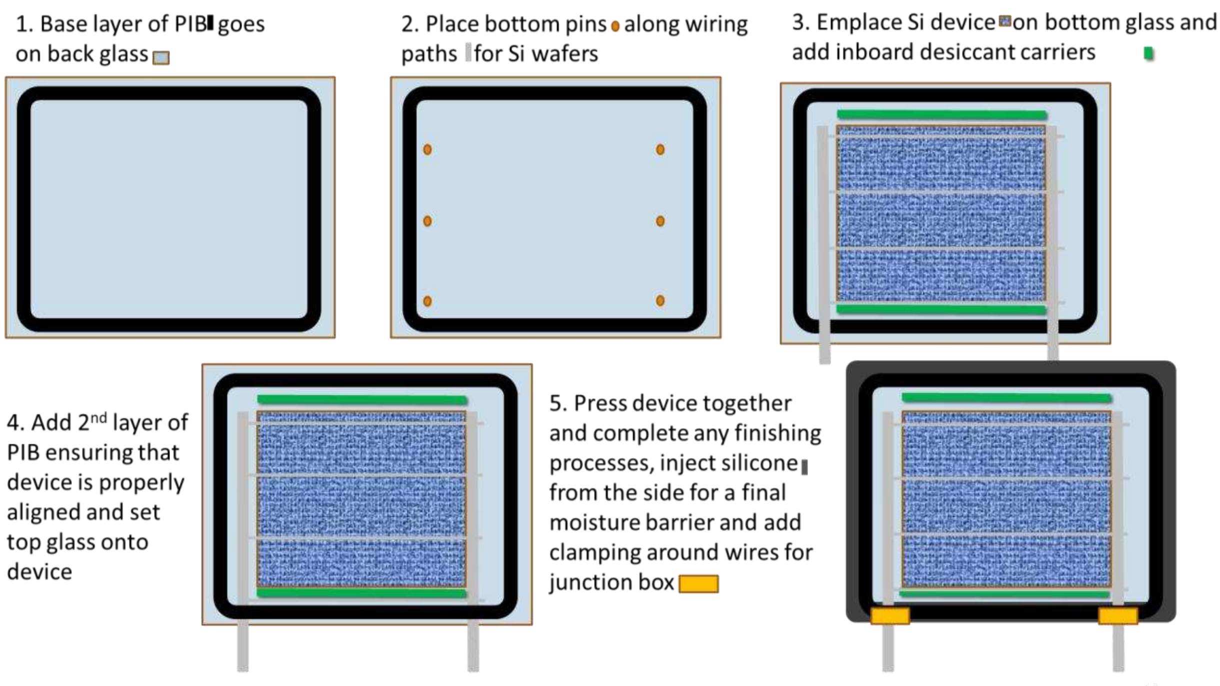

Figure 14: ESM assembly process for c-Si

3.3.3 Traditional Sample Fabrication

To replicate conventional module designs, samples were fabricated using optical silicone as a surrogate for EVA. The fabrication steps mirror those of the ESM process, with the following differences:

- Optical silicone is applied to the front glass.
- Cells are embedded in the silicone and covered with an additional silicone layer.
- The silicone is allowed to flash cure before final assembly.

Optical silicone approximates the optical and thermal properties of EVA, with a refractive index of ~1.41–1.46 and thermal conductivity of ~0.15–0.25 W/m·K.

3.3.4 In-Situ Data Logger

Figure 15: In-Situ data logger test plate shown with 8 single cell test samples at the CSU test field. A 3 x 3 cell module powers the measuring circuitry.

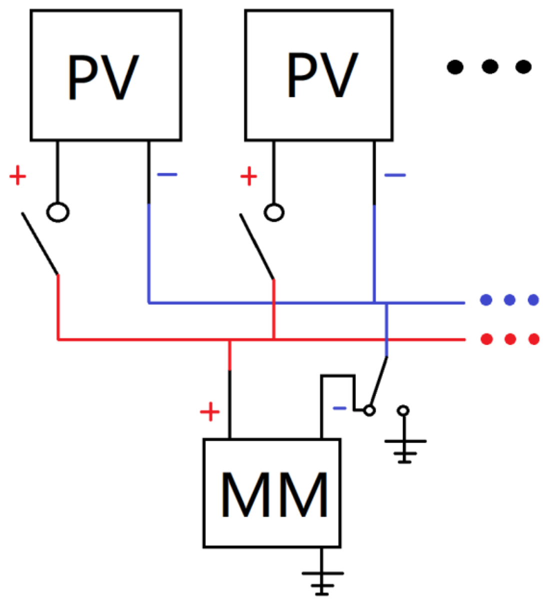

Figure 16: In-Situ data logger test circuit. Two PVs shown with relays to connect individually to multimeter (MM) chip. Relay to switch between open circuit and short circuit also shown.

Outdoor testing was conducted using the In-Situ Data Logger (ISDL), developed at AML and controlled by a Raspberry Pi Zero. The system measures the open-circuit voltage (VOC) and short-circuit current (ISC) of up to 18 modules mounted on a fixed-angle platform (~42°) at CSU's solar field (see figures 15 and 16). The ISDL will be used in hypotheses 1 and 2.

Single cells are difficult to measure. This is due to the low characteristic voltage (Green, 1998). Test cells have a VOC of .713V and an ISC of 6.11A. This yields a characteristic resistance of 116mΩ. A series resistance greater than this will reduce measured ISC. To reduce series resistance, 12guage wire is used entirely in the test circuit, run in parallel where possible and all possible connections are soldered. Using these configurations, 68mΩ resistance is measured using a 4-wire resistance test.

3.3.5 Static Weathering Station

Figure 17: Static Weathering Station shown with 6 encapsulated samples and 4 un-encapsulated samples

The Static Weathering Station (SWS) is placed in the CSU test field in the fixed mount configuration at approximately 42 degrees. It consists of a weather rated approximately .375 x 24 x 48 inch polymer plate. Supporting the plate on the back is a .25 x 2 x 48 inch stainless steel beam, to reduce flexing or distortion from weathering effects. On top of the plate are brackets to support samples placed for weathering testing. The SWS will be used for Hypothesis 3.

3.3.6 Transmission Measuring Equipment

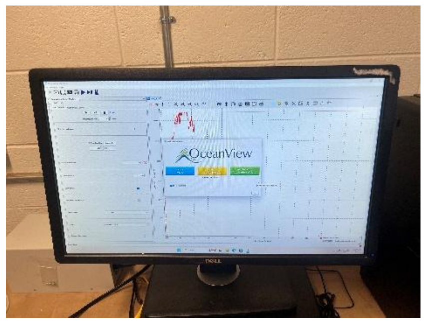

Figure 18: OceanView software used for transmittance measurements

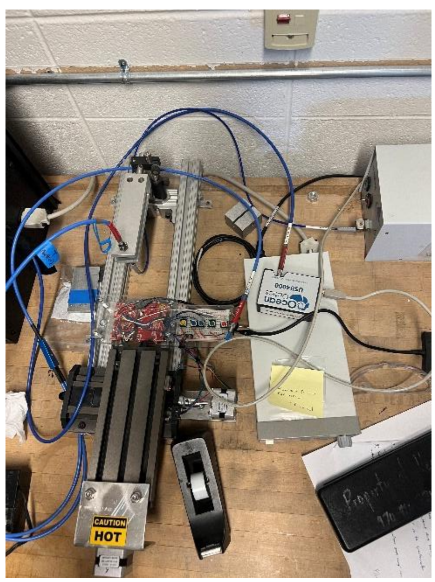

Figure 19: Hardware set up for transmittance measurements used.

Transmission testing is conducted using a calibrated light source and detector setup. The sample is placed between the source and the detector, and transmission is measured relative to the unfiltered beam. Measurements span wavelengths from ~300 nm to 1100 nm using Oceanview 1.67 software.

3.3 Hypothesis 1: ESMs match optical performance to traditional modules

To assess optical performance, ISC was monitored over time for eight modules, including:

- Two ESMs with PMMA-based texture
- Two ESMs with PET-based texture
- Two traditional samples
- Two untextured ESMs

Testing was conducted on October 4, 2024—a cloudless day—to reduce variability. As ISC correlates with light collection, comparable performance between traditional and textured ESMs supports the hypothesis that ESMs match conventional modules optically.

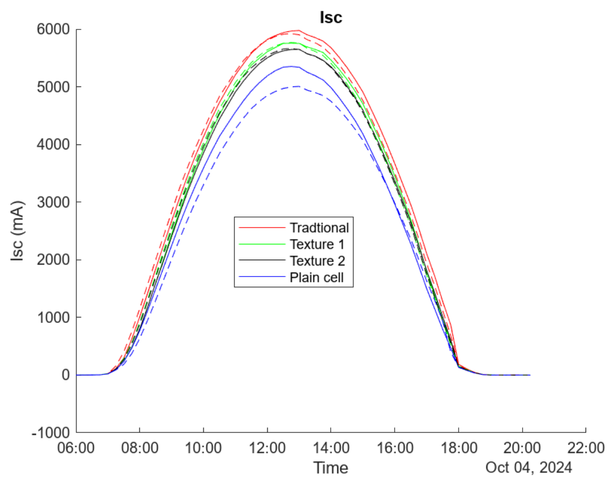

Figure 20: ISC measurement taken on October 4th, 2024. Dotted lines represent separate cells of the same architecture.

Sample sizes are limited to two in this study. Electroluminesnce and photoluminesnce were not available before measurements are performed. It is observed that from post imaging that the quality of samples are poor. Theses measurements should be repeated with higher quantity sample count with pre-screening samples to ensure tighter distribution and valid statistics. Electroluminesnce photographs of some samples used in this study are shown in figure 21.

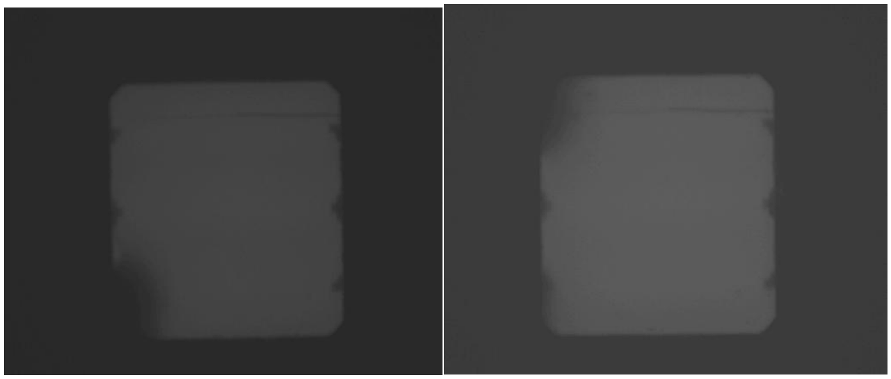

Figure 21: Electroluminescence photographs of samples used in hypothesis 1 and 2. Shadowing and cracks line defects are shown.

3.4 Hypothesis 2: ESMs match thermal performance of traditional cells

VOC measurements were used to evaluate thermal behavior, as VOC decreases with increasing cell temperature. Again, eight modules were tested outdoors on October 4, 2024. The results demonstrate that both textured ESMs, especially the PMMA-based variant, outperform untextured ESMs thermally and are comparable to traditional modules.

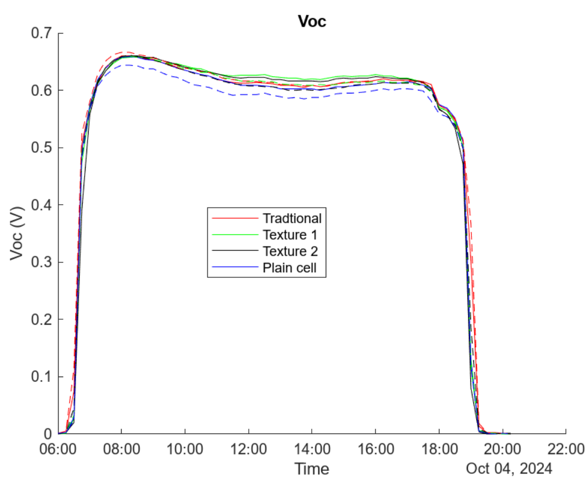

Figure 22: VOC measurement taken on October 4th, 2024. Dotted lines represent separate cells of the same architecture.

The same problem with statistics as seen in hypothesis 1 persists in this hypothesis.

3.5 Hypothesis 3: Ultraviolet Stability of Nano-Textures

Four unencapsulated and six encapsulated PMMA-based textured samples were exposed to natural outdoor conditions from January 15 to May 19, 2025. Transmission was measured through regions with intact and peeled nano-textures and compared to unweathered control samples.

Unencapsulated samples exhibited delamination and significant transmission loss, especially in the 350–450 nm range. Encapsulated samples showed smaller losses within acceptable limits. These

Figure 23: Right: markings observed on un-encapsulated samples exposed outdoors 124 days. Center: additional films remain under peeled regions. Right: cracks observed through 60x magnification

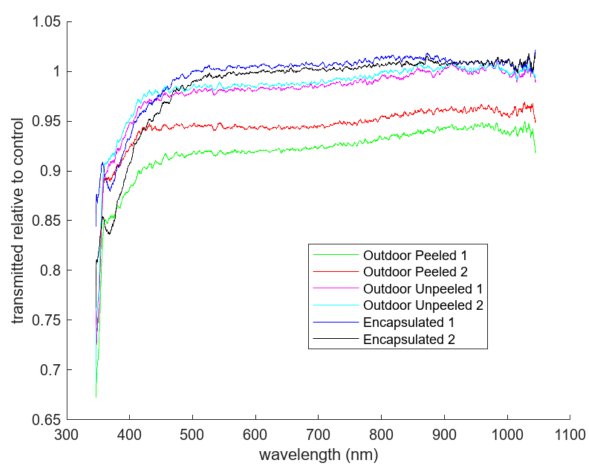

Figure 24: Transmission relative to the control sample. Outdoor samples are un-encapsulated samples.

findings confirm that PMMA-based textures degrade under combined UV, heat, and moisture exposure, but remain stable when properly encapsulated.

Chapter 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter analyzes the results from the experiments described in Chapter 3. The data is evaluated in relation to the three hypotheses: optical performance, thermal performance, and UV durability of nano-textures. Each hypothesis is addressed in its own section with a discussion of results and supporting evidence.

4.2 Hypothesis 1: ESMs match optical performance to traditional modules

Short-circuit current (ISC) was measured to assess the optical performance of ESMs compared to traditional modules. As shown in Figure 21, ISC values from all samples followed a sinusoidal pattern throughout the day, consistent with expected solar irradiance profiles.

Among the tested samples, the two traditional modules and the two textured ESMs (one with PMMA texture, one with PET texture) exhibited similar ISC values. The differences between the textured ESMs and traditional samples fell within the margin of experimental error, which was estimated based on the observed variance between the untextured ESM samples. These findings indicate that the nano-textured ESMs are optically comparable to traditional laminated modules under real-world conditions.

4.3 Hypothesis 2: ESMs match thermal performance of traditional cells

Thermal performance was evaluated by monitoring open-circuit voltage (VOC), which inversely correlates with cell temperature. Maxeon Gen 3 cells, like those used in this study, typically show a VOC reduction of approximately -2.2 mV/°C.

Results from Figure 22 reveal that VOC values of the textured ESMs were higher than those of the untextured ESMs, suggesting reduced operating temperatures. Notably, the PMMA-textured samples demonstrated the best thermal performance, likely due to enhanced internal convection from the increased surface area of the nano-texture.

Comparison with traditional modules indicates that textured ESMs achieve similar thermal behavior. This supports the hypothesis that, when designed appropriately, ESMs can thermally perform on par with traditional encapsulated modules.

4.4 Hypothesis 3: Nano texture does not degrade in UV

To evaluate the UV durability of PMMA-based nano-textures, both encapsulated and unencapsulated samples were exposed to outdoor weathering for 124 days. Transmission spectra were collected post-exposure and normalized to control samples that had not been weathered.

Unencapsulated samples showed significant delamination and decreased transmission, particularly in the 350–450 nm range, with total transmission losses reaching 6–8.1%. In contrast, encapsulated samples exhibited transmission losses of only 1.3–1.9%, which falls within an acceptable range for outdoor applications. The PET-based texture, while not the primary focus, showed less pronounced degradation under similar conditions.

Given that ESM architecture has demonstrated effective moisture exclusion in damp-heat tests, the encapsulated samples were primarily subjected to UV and thermal cycling. The data suggests that PMMA degradation is largely driven by the combined effects of UV exposure and moisture ingress, with UV being a secondary concern when proper encapsulation is in place.

These results support the hypothesis that nano-textures can remain functional in ESMs when adequately protected, though unencapsulated use remains impractical for long-term deployment.

Table 3: Reported transmission loss of PMMA-based nano textures

Un-encapsulated outdoor delaminated regions	**Un-encapsulated outdoor un-delaminated regions**	**Encapsulated outdoor**
6.00-8.11% loss	2.66-3.53% loss	1.34-1.91% loss

Chapter 5: CONCLUSIONS

5.1 Conclusions

This study addresses the need for innovative photovoltaic module architectures in the face of increasing global energy demands and the urgent transition to low-carbon technologies. As outlined in Chapter 1, the limitations of traditional encapsulated photovoltaic modules—including performance degradation, manufacturing complexity, and recyclability issues—highlight the importance of alternative designs like Encapsulant-Free Modules (EFMs). Among these, the Edge Seal Module (ESM), developed at Colorado State University, represents a promising approach to achieving high reliability, manufacturability, and sustainability.

Through experimental evaluation and comparison with conventional modules, it has been demonstrated that ESMs can match the optical and thermal performance of traditional encapsulated modules. Outdoor testing confirms that the short-circuit current (ISC) and open-circuit voltage (VOC) of ESMs are within experimental margins of traditional designs, validating Hypotheses 1 and 2. These results affirm the feasibility of using air as an optical and thermal interface, particularly when enhanced with nano-textures that reduce reflection and potentially improve convective cooling.

However, durability of the nano-textures—particularly those based on PMMA—remains a concern. As shown in Chapter 4, UV exposure and environmental stressors can degrade these textures, especially in un-encapsulated samples, leading to delamination and unacceptable transmission losses. Encapsulation of the textures within the ESM architecture mitigates this degradation to an acceptable level, aligning with Hypothesis 3 and emphasizing the importance of edge sealing for long-term stability.

The ESM platform offers notable manufacturing advantages: simplified processing, elimination of vacuum lamination, material cost reductions, and a significantly smaller factory footprint. With demonstrated moisture resistance, mechanical robustness, and simplified disassembly for end-of-life recycling, the ESM architecture represents a compelling pathway toward more sustainable and economically viable photovoltaic manufacturing.

In conclusion, the Edge Seal Module successfully challenges many of the longstanding assumptions of solar module design. With further refinement—particularly in the durability of internal optical structures—ESMs could become a next-generation standard in PV technology, supporting longer lifespans, lower costs, and improved recyclability, all while maintaining high energy output.

5.2 Future work and recommendations

While the findings of this study support the viability of ESM technology, several areas warrant further investigation:

1. **Long-Term Outdoor Exposure**: Additional long-duration field testing should be conducted to validate performance stability over multiple seasons and years. This includes performance under snow load, hail, and extended UV exposure across various climates.

2. **Nano-Texture Optimization**: Further research into alternative nano-texture materials with improved UV resistance and minimal CTE mismatch with glass and silicon is necessary. Materials like PET, or hybrid coatings could provide improved durability.

3. **Recycling and Reuse**: Developing scalable disassembly and recycling protocols specific to ESM architecture would support circular economy goals. Future studies should explore cell reuse, and glass reclaim pathways.

4. **Manufacturing Scalability**: Further validation of manufacturing throughput, cost modeling, and automation potential will help establish commercial readiness. Pilot-line demonstrations are recommended to assess process reliability and yield.

5. **Electromechanical Interface Testing**: Investigation into the robustness of the electrical interconnects and side junction box under real-world stress, including thermal cycling and vibration, would complete the mechanical reliability profile.

By addressing these areas, the ESM platform can continue evolving toward becoming a commercially viable, durable, and sustainable alternative to traditional photovoltaic module technology.

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APPENDIX A- PUBLICATIONS

1. Ruhle, R. J. E., Maple, L., Durney, D., Johnston, S., Kern, D., & Sampath, W. S. (2024). *Developments for novel module architecture for lower CapEx and improved recyclability for c-Si PV modules*. Paper presented at the 52nd annual IEEE PVSC conference.

2. Ruhle, R. J. E., Maple, L., Durney, D., Johnston, S., Kern, D., & Sampath, W. S. (2024). Advanced solar module design and development for crystalline silicon panels. PCT Application No. PCT/US2024/012345. Retrieved from https://csustrata.org/technology-transfer/available-technology/advanced-solar-module-design-and-development-for-crystalline-silicon-panels/

3. R. Ruhle, D. Durney, D. McDougal, L. Laxmi, V. Chityala, D. Kabra and W. Sampath (2025). *Edge Sealed Modules for Improved Perovskite Stability in 1000 Hours of Damp Heat Testing.* Poster presented in NREL PVRW 2025

4. D. Durney, R. Ruhle, L. Maple, S. Johnston, D. Kern, and W. Sampath (2025). *Edge Sealed Photovoltaic Modules: Matching Thermal and Optical Properties and UV Degradation* . Poster presented in NREL PVRW 2025. Won best poster for Area 7

LIST OF ABREVIATIONS

AM1.5	Air Mass 1.5 (Standard Solar Spectrum)
AML	Advanced Module Laboratory
CTE	Coefficient of Thermal Expansion
DOE	Department of Energy
EFM	Encapsulant-Free Module
EL	Electroluminescence
ESM	Edge Seal Module
EVA	Ethylene-Vinyl Acetate
IEC	International Electrotechnical Commission
IG	Insulated Glass
IR	Infrared
ISDL	In-Situ Data Logger
LED	Light-Emitting Diode
NREL	National Renewable Energy Laboratory
PET	Polyethylene Terephthalate
PIB	Polyisobutylene
PID	Potential-Induced Degradation
PL	Photoluminescence
PMMA	Polymethyl Methacrylate
PV	Photovoltaic
SDOE	Statistical Design of Experiments
SWS	Static Weathering Station
VOC	Open-Circuit Voltage

ISC	Short-Circuit Current