

Improvements in CdTe module reliability and long-term degradation through advances in construction and device innovation

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ABSTRACT

Recent advances in cadmium telluride (CdTe) research and development have improved the long-term power-output degradation and extended reliability test performance of First Solar's thin-film CdTe PV modules. This paper reviews the characterization results of the new First Solar cell structure with improved back-contact design that better manages the fundamental power-output degradation mechanism. First Solar's proprietary 'Black' series module construction significantly enhances the long-term durability and extended test performance of the modules. The accelerated lab-testing methods, field testing and associated analyses are discussed. These advances in the solar cell performance, coupled with upgraded module materials, further substantiate the long-term power-generating capability of First Solar's CdTe PV modules in harsh operating conditions.

Introduction

The rapid expansion of the worldwide PV industry over the last 10 years has been driven by significantly reduced PV module cost trajectories and has resulted in geographical expansion of successful PV markets. These wider geographical applications reinforce the need for PV modules to endure harsh operating conditions for 25+ years. New materials and technical innovations that reduce costs, while ensuring long-term performance and durability, are key to delivering reliable power output over time and competitive PV systems to project owners and investors.

Fundamentally, thin-film PV modules have two primary mechanisms of power loss in the course of time. First, the module construction and materials that encapsulate the semiconductor device can weaken or degrade through harsh environmental exposure,

sometimes enough to allow corrosion of the properly functioning cells, which could result in loss of power. Second, the semiconductor devices themselves experience stress over the lifetime of operation and slowly become less efficient at converting sunlight into DC electricity. This effect, also known as *long-term degradation*, while common to all PV technologies, manifests itself through different mechanisms depending on the construction and characteristics of the semiconductor [1]. First Solar's Series 3 Black (S3 Black) module has been successfully developed to achieve robust long-term package durability via upgraded encapsulating materials. Building on the S3 Black platform, the newest First Solar Series 3 Black Plus (S3 Black Plus) module improves the long-term power output degradation through innovation in device technology.

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Advanced CdTe module packaging technology and performance – material selection

Driven by continuous improvement, the S3 Black module, launched in early 2013, features a durable packaging system that is the result of extensive subscale and product-level testing and development, incorporating innovative and highly capable materials. S3 Black features, between the glass laminates, an upgraded encapsulant that acts as the primary laminate adhesive, and an improved butyl-based edge sealant material that extends around the module perimeter, designed to block water ingress and provide electrical insulation. Fig. 1 shows the cross section of this construction.

Central to the S3 Black module design is a new, high-performance olefinic encapsulant. Compared with most conventional EVA-based thermosetting encapsulants, the S3 Black encapsulant has a water vapour transmission rate (WVTR) that is several times lower. While the edge sealant is designed to be the primary moisture barrier, having an

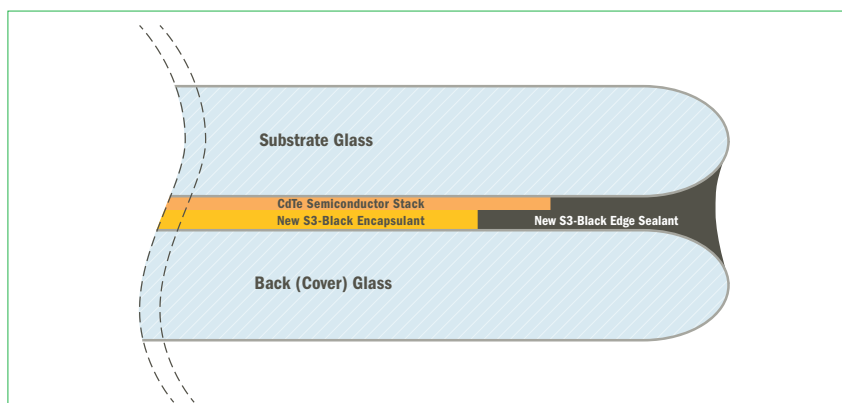


Figure 1. Cross section of First Solar's S3 Black and S3 Black Plus modules.

encapsulant with a low WVTR serves as a secondary barrier against environmental elements. The effect of encapsulant barrier properties on water ingress has been extensively covered in the literature [2]. In addition, the S3 Black encapsulant has a measured volume resistivity of $10^{15}\Omega\text{cm}$, which is two orders of magnitude higher than most conventional EVA-based thermosetting encapsulants. Beyond the moisture barrier and bulk electrical properties, the material selection process was dominated by the excellent adhesion characteristics of the S3 Black encapsulant. Extremely high bond strengths to glass were observed after harsh accelerated cycles, such as 2000 hours of 85°C/85% relative humidity (damp heat), 200 thermal cycles -40 to +85°C, and 85°C hot water immersion. When a relatively wide manufacturing processing window is factored in, the upgraded polyolefin S3 Black encapsulant becomes a strong candidate for PV module packaging material.

The module product name 'S3 Black' is a direct reference to its construction using an upgraded black edge sealant and its carbon-based colorant system. At a low loading level in the edge sealant formulation, carbon does not negatively affect bulk electrical properties, yet provides the benefits of absorbing UV light and acting as a radical scavenger. While selecting a packaging system with an inherent tolerance to extreme environmental conditions was a clear target of the S3 Black development programme, it was also desired to focus on edge sealants that meet component-level requirements for solid insulation, as defined by IEC in DSH 1051 [3]. An integral part of meeting requirements for solid insulation involves achieving a sufficient relative thermal index (RTI), tested per UL 746B [4]. After a test sequence that involved adhesion and dielectric strength measurements before and after long-term thermal exposure, the S3 Black edge sealant was established to have an RTI of 105°C. Such a rating is considered to be a strong indicator of the resilience of the S3 Black module design to hot, arid conditions. In addition, the S3 Black edge sealant was measured to have a volume resistivity of 10^{15} to $10^{16}\Omega\text{cm}$, which is more than two orders of magnitude higher than that of the edge sealant used with the parent S3 module design, and more than ten orders of magnitude higher than that in the technical guidance provided by UL 746C for electrically insulating materials [5]. Coupling the aforementioned technical factors with a higher loading of moisture-absorbing desiccant filler, the S3 Black edge sealant is viewed as an innovative material that provides excellent protection from

environmental conditions throughout the rated service life.

Accelerated testing as a predictor of long-term field performance

PV modules are typically warranted for 25 years of field performance. With rapid innovation cycles in the industry, one cannot simply wait for 25 years of field exposure to validate long-term performance; rather, the PV industry has come to rely upon laboratory accelerated testing protocols to more rapidly assess the suitability and relative eventual performance of modules in the field. To test the reliability of solar modules, a number of internationally accepted accelerated stress-testing methods are used. These tests follow

the general format of an initial test sample measurement, an accelerated environmental exposure, and then final power and safety measurements of the test sample. The three most common stressors for all durable goods, including PV modules, are damp heat (DH: 85°C, 85% relative humidity), thermal cycling (TC: -40 to +85°C), and humidity-freeze (HF: -40 to +85°C, 85% relative humidity) [6]. Additional stressors – such as UV exposure, electrical bias conditions, hail impact and mechanical loads – are also a part of these test protocols.

Damp-heat testing is conducted at 85°C and 85% relative humidity for a standard duration of six weeks (or 1000 hours). Thermal-cycling and humidity-freeze testing both follow a specific profile specified by the IEC standard

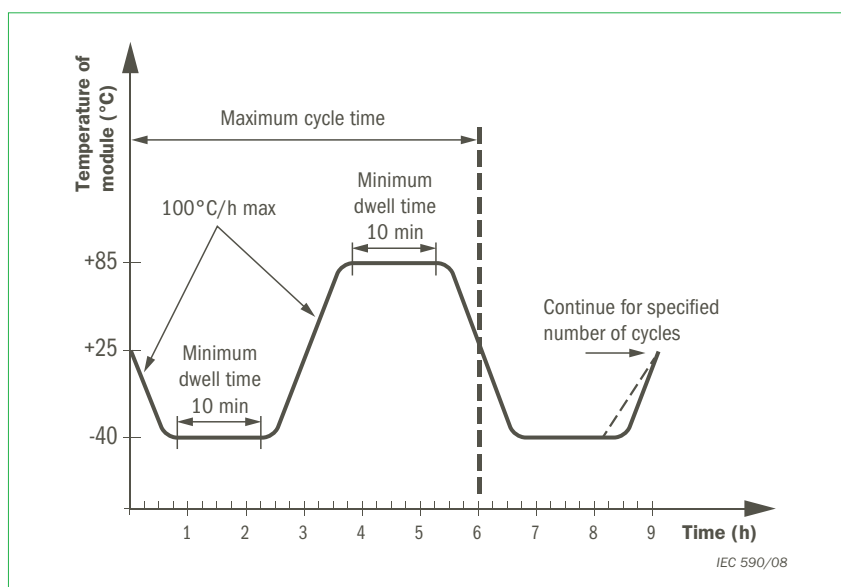


Figure 2. IEC 61646 thermal-cycling profile.

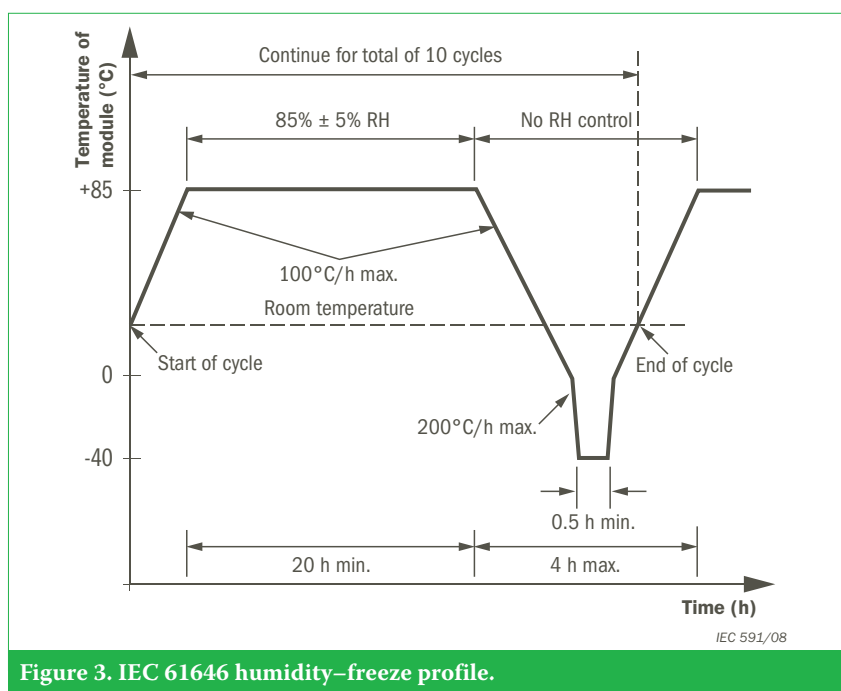


Figure 3. IEC 61646 humidity-freeze profile.

(IEC 61646): a standard TC test consists of 200 cycles, with the profile shown in Fig. 2; for HF testing, 10 cycles are used and a different profile followed, as shown in Fig. 3.

For over a decade the PV industry has relied on these standard IEC test protocols for basic evaluation of PV modules. IEC 61646 (thin-film) [6] and IEC 61215 (c-Si) [7] type approval standards, along with the IEC 61730 safety standard [8], have provided a framework of certification testing which assures a common minimum level of test performance and which has become de facto in the industry. Conventional IEC 61646/IEC 61215/IEC 61730 standards define a parallel sample test protocol whereby one group of sample modules are exposed to one stressor (i.e. 200 thermal cycles), while a different group of modules are exposed to an alternative stressor (i.e. 10 humidity–freeze cycles).

In recent years, industry stakeholders have recognized the need to further differentiate PV modules by developing extended test durations, sequential testing protocols and application-specific tests which give additional insight into the long-term performance, reliability and durability of PV modules.

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Long-term parallel testing

Long-term parallel testing has been developed in recognition of the need to extend test durations to better differentiate PV modules in long-term field performance. One example is the RETC Thresher Test [9], which builds on the basic parallel test architecture of the conventional IEC tests and defines “a long-term reliability test programme that will not only help in differentiating products, but also in determining the degradation patterns of ... solar modules”. In the Thresher Test the conventional IEC test environmental stress exposure durations are multiplied by a factor of two to four in order to identify those modules with truly differentiated long-term reliability and performance.

Long-term sequential testing

Recognizing that modules in the field

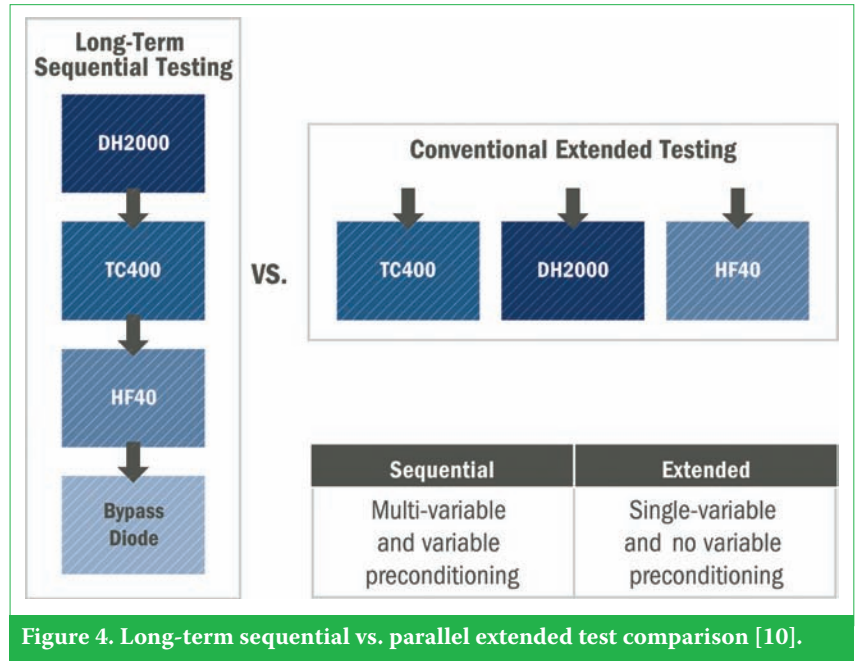


Figure 4. Long-term sequential vs. parallel extended test comparison [10].

are exposed to combinations of stresses over time, long-term sequential testing builds upon the extended durations of extended parallel testing by additionally requiring that the same modules be exposed to the extended environmental stresses in series rather than in parallel. One example of this sequential test protocol is the TÜV Long-Term Sequential Test (TÜV LST). Fig. 4 shows the difference in testing profile of these two extreme durability initiatives.

Application-specific testing

While conventional IEC PV module type approval and safety tests include expected environmental stresses as well as phenomenological tests for wind loads, snow loads, hail impact, etc., there remain some specialized field applications or locations that might warrant additional specialized harsh environment tests. For PV module application in corrosive marine environments, the IEC 61701 Salt Mist Corrosion Test has been developed to ensure that performance and package integrity are maintained: “This testing sequence is more suitable to reflect the corrosion processes that happen in PV modules subjected to permanent or temporary corrosive atmospheres” [11]. Other harsh environment risks include exposure to wind-blown particulate as a result of desert sandstorms. IEC 60068-2-68 is applied to PV modules for evaluating robustness against particulate effects (such as sandblasting) which could reduce incident light capture in the module or otherwise damage its packaging [12]. Manufacturer-specific tests can also be used to supplement standards-based tests, especially when no international

test convention is defined. The evaluation of PV modules on the basis of both of these standardized and non-standardized application-specific tests provides additional confidence in the appropriate and durable application of PV modules in their intended environments.

While the IEC tests are still the industry standard for bringing a product to market, going beyond these tests in terms of both duration and severity is critical to demonstrating the differentiation of those solar modules that are able to handle the harshest climates, demonstrate the lowest long-term degradation, and provide stakeholders with the lowest risks for their long-term investments.

Internal qualification and advanced testing

A combination of the selection of high-quality materials and the innovative construction of the S3 Black and S3 Black Plus modules has been subjected to the aforementioned extended reliability tests to demonstrate their robust performance in extreme conditions for durations far beyond those specified in standard IEC61646 and IEC61730 testing. For example, First Solar subjected the Series 3 Black modules to a test duration of more than six times that of the typical 1000-hour DH test. The results of a sample population of 25 modules are presented in Fig. 5.

It is important to note that because of device metastabilities the modules experience a fully recoverable dark storage state after prolonged exposure in dark environmental chambers. After a few cycles, a light soaking recovery

process is completed to eliminate the dark storage effects and bring P_{mp} (power at the maximum power point) back to normal; this was conducted after 2352 hours and 4368 hours, and at test completion at 6384 hours. Fig. 5 shows that after this extreme testing, P_{mp} of the module population is still within -4 to -10%, which clearly demonstrates the robustness of the S3 Black Plus module's encapsulation and packaging integrity in any of the harshest climates on earth. First Solar also tested the S3 Black modules with a duration five times that of the IEC TC200 test. The test data shown in Fig. 6 also shows no measurable power reduction after this extended duration.

External qualification

S3 Black modules, as the predecessor of the S3 Black Plus modules, were the first and only thin-film modules to date to pass two of the most difficult and strenuous independent tests of module durability, reliability and long-term degradation: the Thresher Test (long-term parallel) and the, even harsher, Long-Term Sequential Test (long-term sequential), both evaluated by TÜV Rheinland.

“S3 Black modules were the first and only thin-film modules to date to pass two of the most difficult and strenuous independent tests.”

First Solar modules were shown to exhibit power output degradation of less than 5% after completion of the Thresher Test, providing a high level of confidence in the long-term degradation rates of First Solar modules, and outperforming warranted degradation rates over time. First Solar's success in the Long-Term Sequential Test results for its modules places it on an exclusive list with only five other module manufacturers who have demonstrated this capability at the time of publication [13–17]. In addition, First Solar S3 Black and S3 Black Plus modules have passed the application-specific IEC 61701 Salt Mist Corrosion Test with the highest level of exposure. Moreover, both module types have successfully passed the IEC 60068-2-68 Desert Sand Resistance Test, demonstrating robustness against sandstorms and providing performance confidence in harsh operating environments.

First Solar's S3 Black Plus modules are built on the core S3 Black construction, maintaining the highest levels of extended reliability and performance achieved via extended parallel, sequential and application-specific testing. S3 Black Plus modules further contain an improved device structure, which will be discussed next.

CdTe device degradation and performance

Literature and degradation mechanism review/new back contact and device structure

Research in CdTe PV has been ongoing for over 40 years, but not until recently have such significant achievements been made in demonstrating its

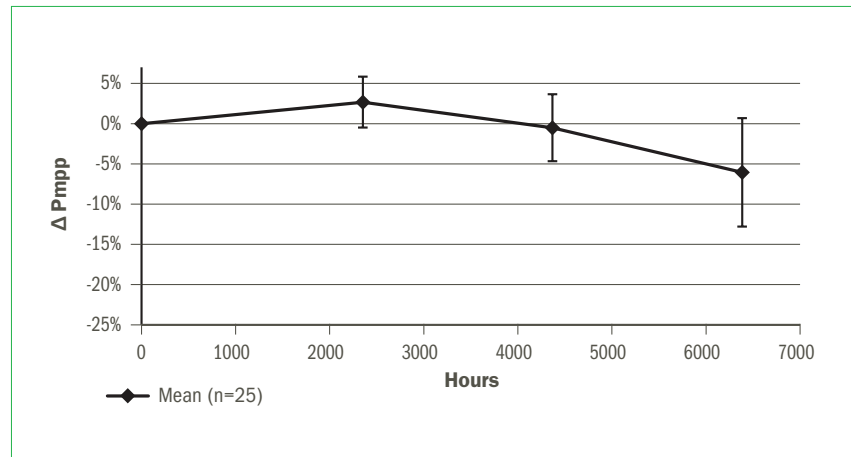


Figure 5. Results of extended damp-heat testing.

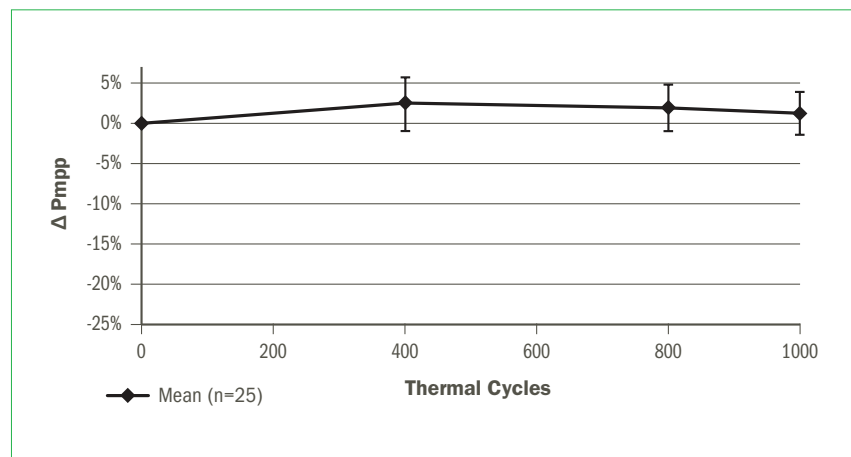


Figure 6. Results of extended thermal cycling.

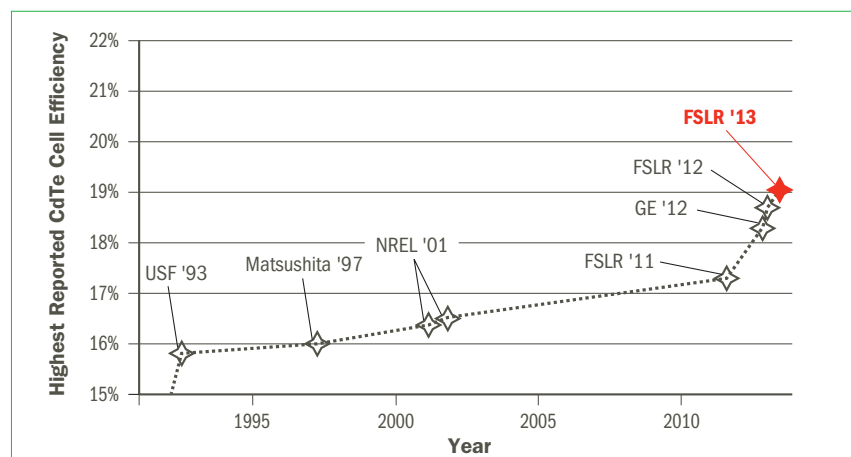


Figure 7. World-record CdTe cell efficiency (reproduced from Gloeckler et al. [18]).

efficiency potential [18]. Fig. 7 shows the recent trends in CdTe device world-record performance.

Not only is CdTe one of the lowest-cost technologies to manufacture [19], but it also has a band gap in the optimum range for single-junction semiconductors [20]. One factor for the increased laboratory efficiency has been advancements in the CdTe back contact. For a high-efficiency cell it is imperative to have an ideal semiconductor–metal interface and minimize the losses from the back contact. For p-type CdTe these losses or non-idealities can result from a combination of high-resistance layers and unfavourable valence energy-band alignment.

It is well established that using zinc telluride (ZnTe) as an interlayer improves the valence band offset to p-type CdTe and, with the optimized work function, enables a more ohmic and stable back contact [21,22]. First Solar's initial development of this improved ZnTe back contact was first demonstrated by an NREL-verified record 17.3% cell efficiency in 2012 (see Fig. 7). Following the established path of prior cell-to-module integration successes, First Solar has now migrated this cell-level advancement into a proprietary high-volume module-manufacturing process with an improved redesigned back contact incorporating the ZnTe layer into the full-scale module. The full-scale module production process demonstrates a nameplate efficiency improvement of approximately two to three power bin classes, or 5–8Wp. The current production device stack and the new product with the ZnTe interlayer are shown in Fig. 8.

The cell-level improvement is observed by the increase in open-circuit voltage (V_{oc}) and fill factor (FF). The improvement in the back-contact electrical behaviour is evident if the solar cell is subjected to a forward bias in the dark. Fig. 9 shows the I - V curve of the ZnTe-based back contact, which behaves like an ideal p-n diode with a sharp turn-on voltage that progressively increases with lower temperature.

The non-ZnTe device stack has a substantial amount of current 'roll-over' [23], and the electrical conduction suffers further at lower temperatures, where the carriers are less energetic and the impact of the interface barrier becomes more pronounced. The improvement in back-contact electrical behaviour results in a nearly linear V_{oc} vs. temperature profile, with even higher values of V_{oc} observed at lower temperatures, as shown in Fig. 10.

Hence there is a higher and linear relative increase in efficiency with lower operating temperatures, which naturally results in an increased magnitude of the efficiency temperature coefficient. For the S3 Black Plus product with a ZnTe-based back contact, the efficiency temperature coefficient will nominally

be $-0.29\%/^{\circ}\text{C}$ compared with the standard value of $-0.25\%/^{\circ}\text{C}$ [24]. While this will slightly reduce specific annual energy yield, the increased initial efficiency will outweigh this effect, and the result will be that more total energy is produced per module. Note that the S3 Black Plus temperature

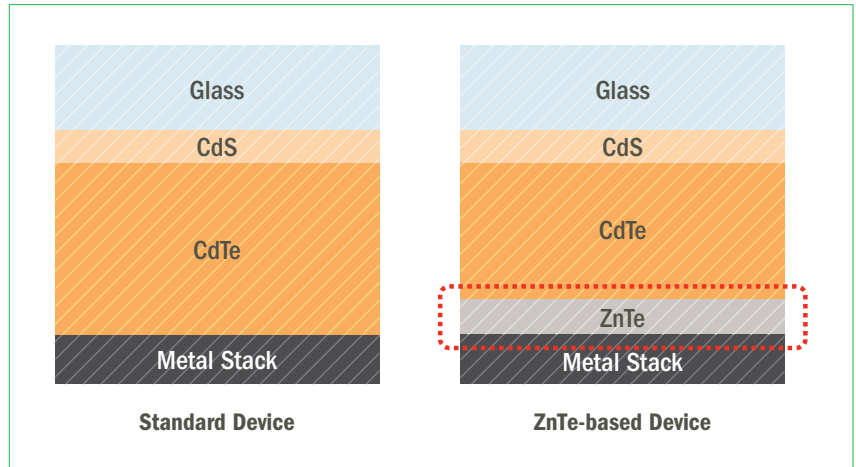


Figure 8. S3 Black (standard) and S3 Black Plus (ZnTe-based) device stack comparison.

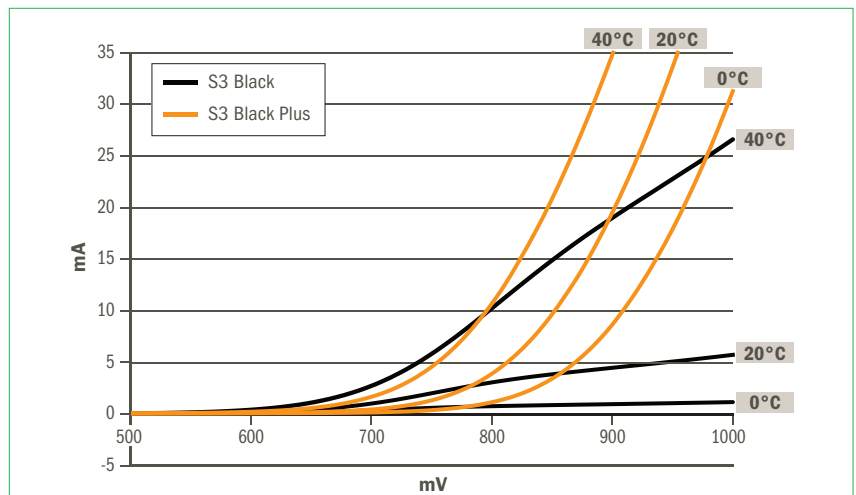


Figure 9. Comparison of the I - V curves of S3 Black (standard) and S3 Black Plus (ZnTe).

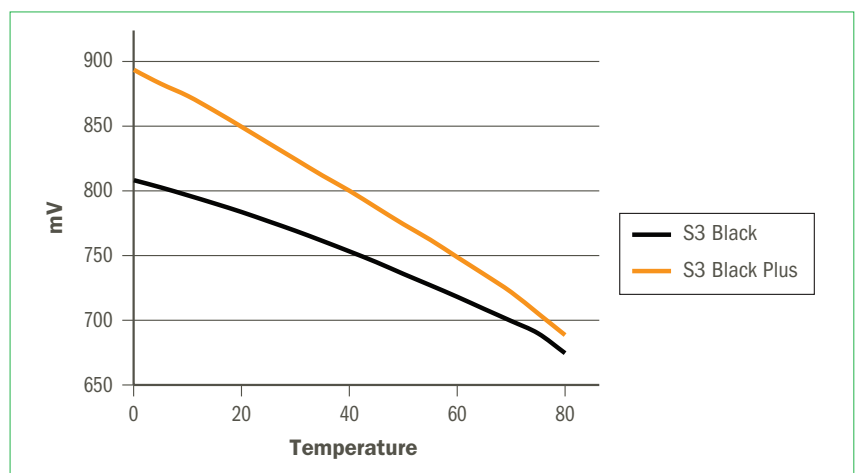


Figure 10. Comparison of back-contact V_{oc} behaviour vs. temperature.

coefficient remains demonstrably better than that of crystalline silicon solar modules, which preserves the high-temperature performance advantage that is characteristic of CdTe modules, resulting in higher specific annual energy yields [25].

Extended testing of the ZnTe back contact

First Solar has a rigorous qualification programme that encompasses accelerated stress testing, independent validation of key tests in reputable external laboratories, and validation through field testing. A detailed characterization of the module performance – including temperature coefficient, spectral response and initial stabilization – is a key input to the energy prediction model. In conjunction, the stress tests and characterization are performed on the standard non-ZnTe-based product for comparative purposes. The existing First Solar device platform already has a proven track record, with more than 18 years of field data [25,26], along with more than 8GW of field deployment history. Based on extensive prior history, an established benchmark correlating existing field performance with lab stress testing is available for evaluating the relative

long-term performance improvement, and uniquely enables First Solar to substantiate its conclusions from the qualification process.

“A detailed characterization of the module performance is a key input to the energy prediction model.”

CdTe cell reliability has historically been linked to back-contact stability and the migration of Cu from the Cu-rich back contact, along the CdTe grain boundaries, to the main CdTe/CdS heterojunction [23,24]. During the operating life of the module in the field, higher levels of Cu accumulate at the CdTe/CdS interface and this contributes to progressively lower cell efficiency or power output. For its existing standard product, First Solar has developed processing techniques that substantially reduce the sensitivity of the CdTe/CdS heterojunction to the presence of Cu [24]. As will become evident in the subsequent discussion, the ZnTe-based back contact builds on this established platform and substantially improves the long-term cell reliability of the CdTe device.

The long-term power degradation of a cell can be assessed through accelerated tests in the lab by using elevated temperature and bias conditions [27,28]. In Fig. 11 the power loss with time is shown for the current standard product and compared with that for the ZnTe-based module.

The devices are stressed under accelerated conditions incorporating high-bias conditions, extreme temperatures and full-spectrum light of power density greater than 1000W/m². At the 300-day accelerated exposure point, the ZnTe device has a power loss of less than 10% compared with 17% for the standard device. The aforementioned First Solar benchmarks indicate that this 300-day accelerated exposure is representative of the relative long-term field performance of modules with the ZnTe back-contact and prior-generation products. This result shows a significant improvement in the long-term stability and device performance of the ZnTe-based contact. The improvement over plant lifetimes in long-term degradation rate afforded by the ZnTe-based back contact enables First Solar’s long-term degradation guidance to be improved to –0.5% per annum for all climates.

It has been reported that the presence of a ZnTe layer in the back

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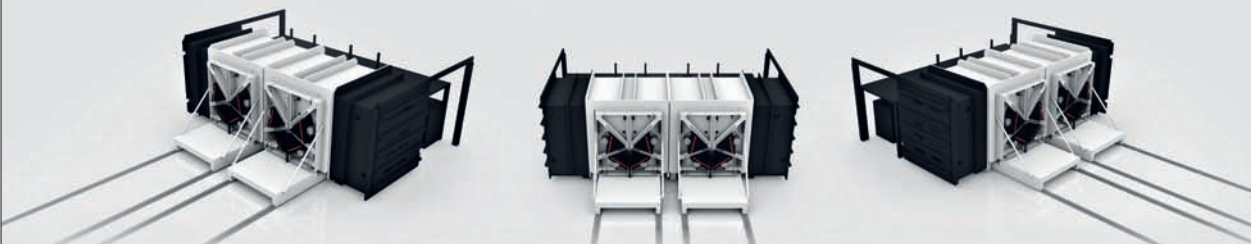
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contact retards Cu diffusion and maintains a Cu-rich back contact [29]. While these assessments are typically based on Cu migration due to thermal diffusion, the curtailment of the same underlying phenomenon is also responsible for the improvement in long-term cell stability. This aspect further manifests itself with much-improved robustness of performance against temperature under accelerated light soak testing. Fig. 12 shows a comparison of power loss after modules were exposed to three different temperature stress levels for equivalent test durations.

The results illustrate a reduced impact of temperature on cell power degradation for the ZnTe-based back-contact device. The maximum power point voltage (V_{mp}) degrades by only 6% and stabilizes more quickly, as shown in Fig. 13. This stability helps system-level design, where additional considerations for minimizing the drift in V_{mp} can be taken into account.

The new device stack is also subjected to special durability testing in which the module construction

is intentionally compromised to expose the active semiconductor cell to harsh environmental conditions. This approach far exceeds the IEC standards but conforms to the internal qualification programme and to the stringent benchmarking exercise against the standard product. Combining the new back contact with the superior S3 Black construction leads to a field-durable S3 Black Plus module that has robust lifetime performance in the harshest of operating conditions, with a clear performance advantage in hot and humid climates.

Field testing and predictability

As part of First Solar's standard product launch and qualification process, extensive multi-climate (hot/arid, hot/humid, temperate) field testing is conducted to ensure reliable field performance and that energy predictability remains accurate and within expectations. Of particular interest, for a hot climate evaluation, six ~100kW pre-production systems were fielded in April 2013 at a

commercially operating power plant in Arizona, USA, to assess their real-world initial performance and for comparison with the benchmark of First Solar's monitored fleet using a non-ZnTe back contact. All arrays were matched in their configurations. This test location is considered an ideal environment for evaluating the impact of high temperatures on outdoor performance, where module cell temperatures are routinely elevated to high-stress conditions and can reach up to 75°C. This data is illustrated in Fig. 14.

The orange dots in Fig. 14 highlight the six S3 Black Plus arrays among the fleet of over 415MW (AC) of commercially operating First Solar PV projects. In this test the S3 Black Plus arrays, incorporating the ZnTe back contact, demonstrated a 5–8% increase in total DC energy produced, confirming the respective nameplate power improvement over existing non-ZnTe products. All the systems are measured by their predicted energy ratio (PER), which is the lifetime ratio of actual energy produced and energy predicted. The PER substantiates First Solar's field performance record and validates First Solar's accuracy in predicting field performance. For product generations prior to S3 Black Plus, a degradation guidance of –0.5%/year in temperate climates and –0.7%/year in high-temperature climates is modelled into predictions.

As shown in Fig. 14, the performance of utility-scale systems monitored over their lifetimes is consistently tracking near 100% of the P50 prediction energy [30,31] inclusive of prior multi-year degradation rate guidance. When this field performance history of older product generations is linked to the aforementioned lab light soak testing (Fig. 13), and the relative improvement of S3 Black Plus in lab light soak testing is observed, the basis of the 0.2% per annum improvement in P50 degradation guidance of S3 Black is established, despite limited long-term field performance history. (P50 degradation guidance is the average expected annual system power loss.) While the field performance data for the new S3 Black Plus system is limited, the performance to date indicates that the operation of these systems is consistent with First Solar's energy prediction model; this supports the conclusion that the S3 Black Plus module performance can be predicted accurately and consistently.

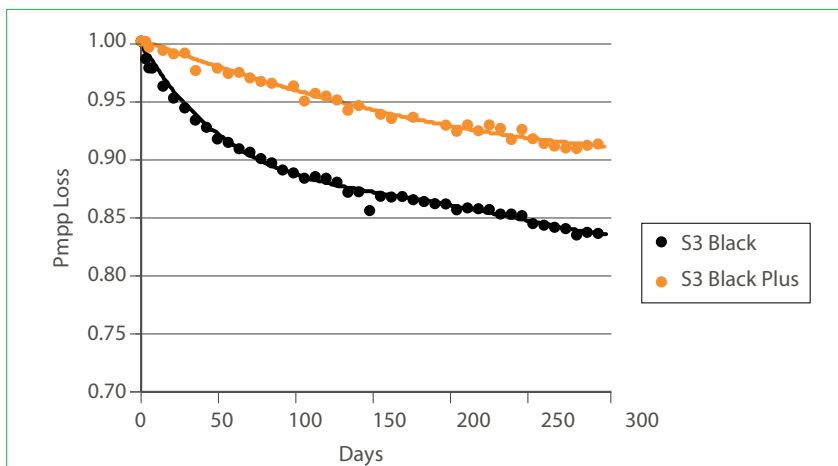


Figure 11. Power loss after accelerated light soak exposure.

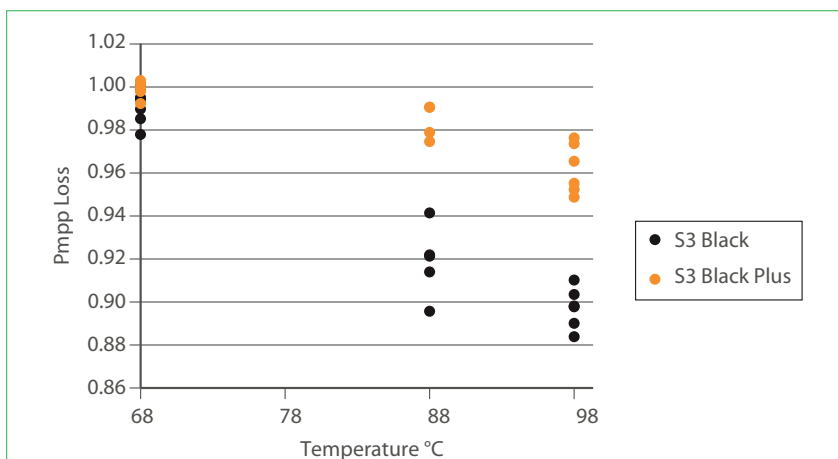


Figure 12. Comparative power loss vs. accelerated temperature stresses.

“First Solar’s S3 Black modules provide numerous enhancements to long-term extended reliability test performance compared with previous First Solar products.”

Conclusions

First Solar’s S3 Black modules have been rigorously tested by leading external laboratories as part of a commercial launch, and provide numerous enhancements to long-term extended reliability test performance compared with previous First Solar products. Via the Long-Term Sequential Test, superior results have been demonstrated compared with most competitor modules in the PV marketplace, regardless of technology type. The new ZnTe back contact incorporated within the S3 Black Plus module platform improves initial module efficiency and increases robustness against thermal and bias-driven power degradation, resulting in a reduction in long-term power degradation rate guidance. By incorporating all of these characteristics, the S3 Black Plus module demonstrates increased energy production over the life of the power plant, as well as increased

confidence in predictability, long-term performance and durability of power plants containing First Solar module technology.

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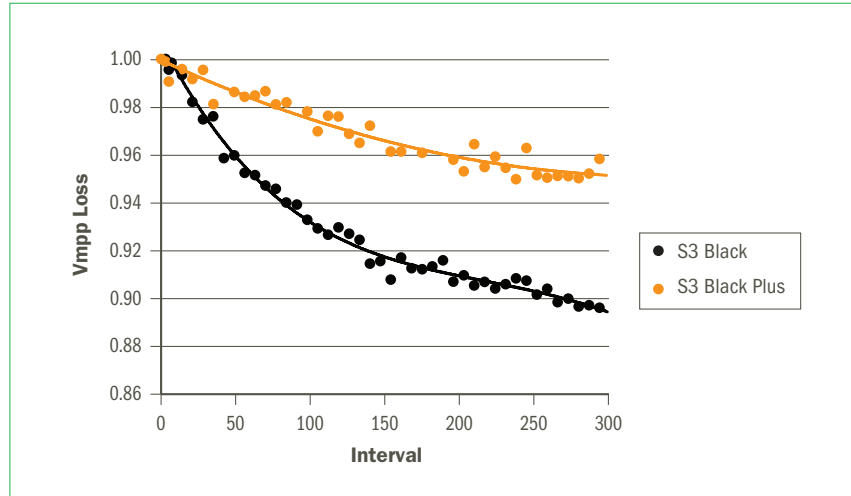


Figure 13. Voltage loss after accelerated MPP (maximum power point) light soak exposure.

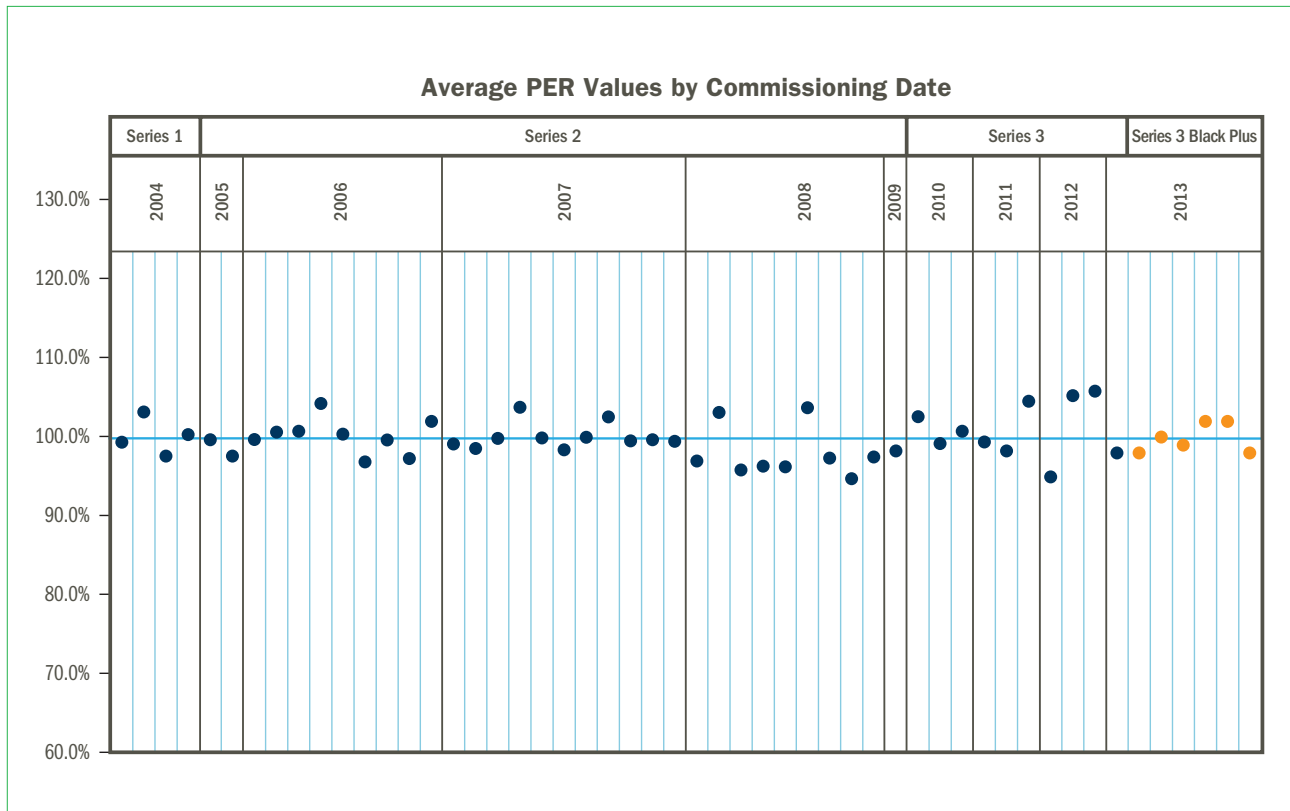


Figure 14. Performance predictability of ZnTe back-contact modules.

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