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Evaluating Solar Cell Fracture as a Function of Module Mechanical Loading Conditions

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***Abstract* — Cell cracking presents a serious risk for the long term reliability of c-Si photovoltaic modules. Cracks may not initially result in performance loss, but over time performance may degrade as the module experiences stresses in the field such as temperature cycling and snow/wind loading. This performance loss is due to the formation of new cracks with front side loading, propagation of existing cracks, and the opening of existing cracks in which regions of the cell become more electrically isolated. This work utilizes a new tool, the *LoadSpot*, that allows for I-V performance characterization and electroluminescence imaging of PV modules while under mechanical load. We explore a variety of cell technologies to understand the magnitude of mechanical stress required to induce cell fracture, and assess the impact these cracks have on performance. In addition, we study the use of cyclic loading to open existing cracks. The tests used in this work have potential applications in product development, factory quality control, product evaluations, and optimization of mounting hardware and methods.**

***Index Terms* — cell fracture, cyclic load testing, electroluminescence, mechanical load testing, photovoltaic modules, reliability, silicon.**

I. Introduction

Photovoltaic (PV) modules have an excellent track record of reliability that has been established from numerous studies of the degradation rates of field deployed modules. Degradation rates in the range of 0.5-0.6%/year have been demonstrated for crystalline silicon PV module, with deviations occurring based on variations in the specific module technology, the operational climate, and module mounting configuration [1]. As cell and module technology advance and manufacturing cost decline, it is essential to ensure adequate durability of PV modules in order to reduce the levelized costs of energy for PV systems.

A trend of reducing cell thickness has been established over the years in an effort to reduce manufacturing costs. This has increased the occurrence and susceptibility of cells to mechanical failure through cracking. Basic panel design is vulnerable to cell cracking. Copper wires contract more than silicon during soldering resulting in the formation of microcracks in the silicon underneath the busbars [2]. This may not initially cause performance issues, however forces applied to the cell later can cause these microcracks to propagate into full cracks. The asymmetric design of the standard panel with a thick and stiff glass sheet on the front side and thin polymer backsheet means that front side loads put the cells into tensile stress. If such stresses are high enough, the benign microcracks under the busbars can propagate into full cracks down the length of the cell.

Initially most of these cracks are tightly closed with current transport across the metallization on both sides. Cracks in the closed state do not significantly reduce module performance and are difficult to even detect in electroluminescence (EL) or photoluminescence (PL) imaging. This presents a significant degradation risk as these crack may open up over time, inhibiting current transport across the crack and ultimately reducing overall power generation.

To study cell cracking dynamics, this work utilizes the *LoadSpot* tool developed by BrightSpot Automation. The *LoadSpot* was developed to perform mechanical load testing while leaving the front surface of the module unobstructed to allow for *in-situ* performance characterization [3]. The tool can perform the standard static and cyclic load tests for module design qualification as per IEC-61215 and IEC- DTS-62782, as well as more specialized stress sequences that may be used for product development. Loads are applied to the rear side of the module with vacuum/air-pressure, while a unique seal design allows the module to freely deflect as is depicted in Fig.1. While under load, the module can be characterized using a solar simulator or by EL imaging. In this work, a Sinton FMT-350 is used for I-V measurements and a BrightSpot EL camera system is used for EL imaging.

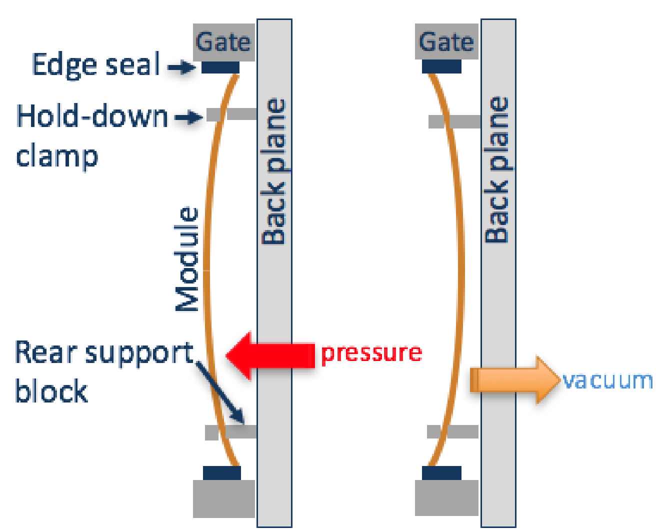

Fig. 1. Diagram showing the operation of the *LoadSpot*.

Previous studies by other groups, including Evergreen Solar, Fraunhofer CSP, SunCycle and ZAE Bayern, have investigated crack opening during module deformation using EL imaging [2, 4, 5]. In this work, we explore how characterization of a module in both the loaded and unloaded state can be used to evaluate a module design for susceptibility to cell fracture.

II. Cell Fracture as a Function of Mechanical Load

Four module types were evaluated for this work that are representative of standard 60-cell module designs with front glass/EVA/backsheet packaging. One representative module of each type is explored in this section. Modules 1-3 were multi-crystalline technology and Module 4 was mono-crystalline technology. Fig. 2 shows the number of fractured cells as the module was exposed to increasing front side load up to a maximum of 5400Pa. A cell was classified as fractured with the presence of any crack, and therefore this data does not attempt to quantify the severity of any specific crack. In many cases cracks became more severe as the loading condition increased. Modules were supported at the manufacturer specified mounting locations so that the loading conditions would be representative of field conditions.

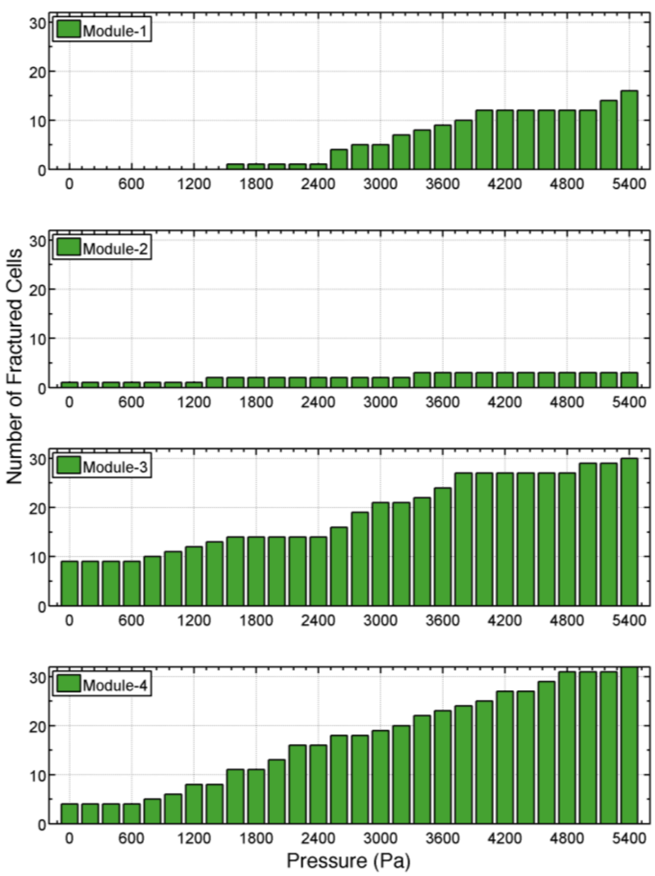

Fig. 2. Histogram showing the number of fractured cells as a function of applied pressure for 4 module types. All modules were of standard size with 60-cells, and 4-point clamping was used.

It is obvious from Fig. 2 that there is a wide range of susceptibility to cell fracture across the various module types. Module 2, for example, has only 2 new cracks formed during the entire testing sequence. In contrast, Module 3 and 4 each have more than 30 fractured cells at 5400Pa. The superior performance of Module 2 is due to the frame design in which there are two cross members, or back rails, that provide extra mechanical support. This data highlights the value that simple mechanical support structures can provide with respect to crack formation. This data also emphasizes that modules with similar electrical performance and upfront cost, may respond quite different when exposed to mechanical stress.

Above 2400Pa, the mono-crystalline cells used in this work appear to fail catastrophically, referring to the dendritic nature of any new cracks formed above this pressure. The shattering of monocrystalline cells also leads to irreversible performance loss once the load is removed. This does not appear to be the case for the multi-crystalline cells. In mono-crystalline cells, cracks can easily propagate along certain crystal planes, whereas the randomized grain structure in multi appears to limit crack propagation. In general, we observed that fracture in multi-crystalline cells was less severe as compared to the fracture observed in mono-crystalline cells. An example of this is in Fig. 3, where the difference in crack patterns that occurred during the test is shown. The dendritic crack in the mono-crystalline cell continues to severely impact performance even after the removal of applied load, whereas the multi-crystalline cell appears to fully recover. If we consider the total crack length for the cells in Fig. 3, the mono-crystalline cell would have an order of magnitude higher total length.

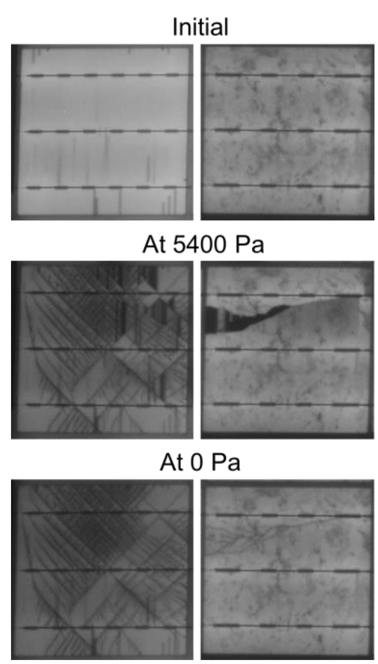

Fig. 3. Example of two cracks formed at 5400Pa, highlighting the differences between fracture in mono-crystalline (left) and multi-crystalline (right) cells.

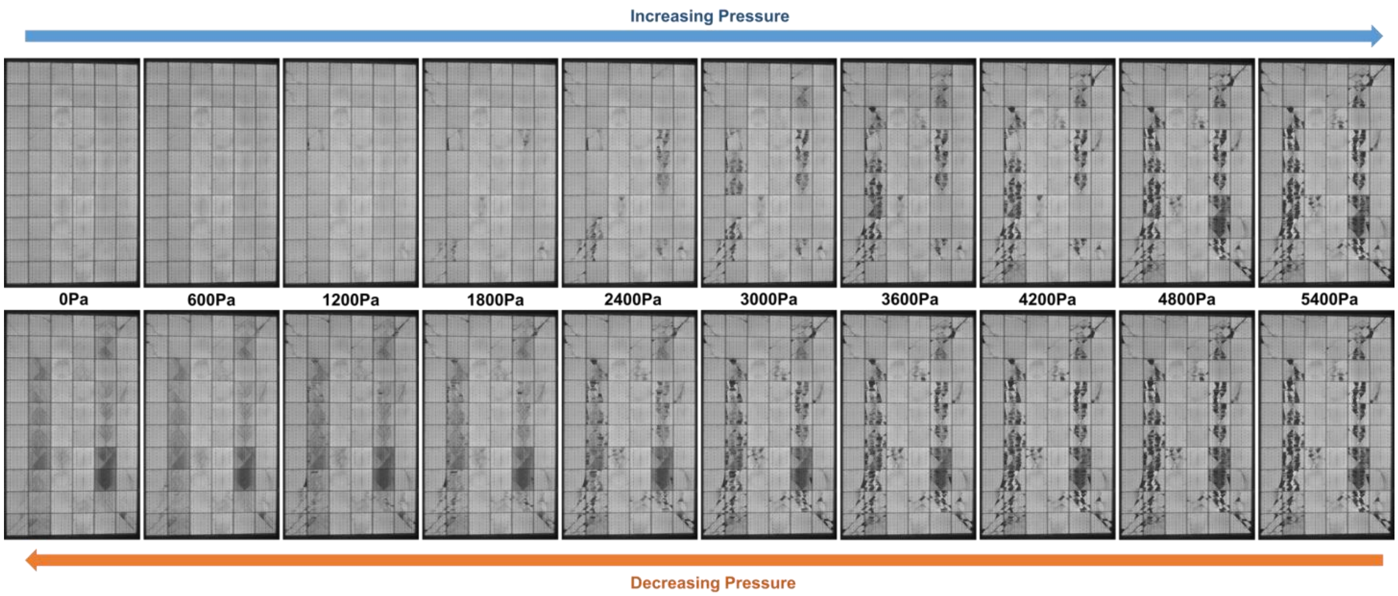

Fig. 4. Electroluminescence images of a mono-crystalline module (Module 4) as a function of applied front side mechanical load.

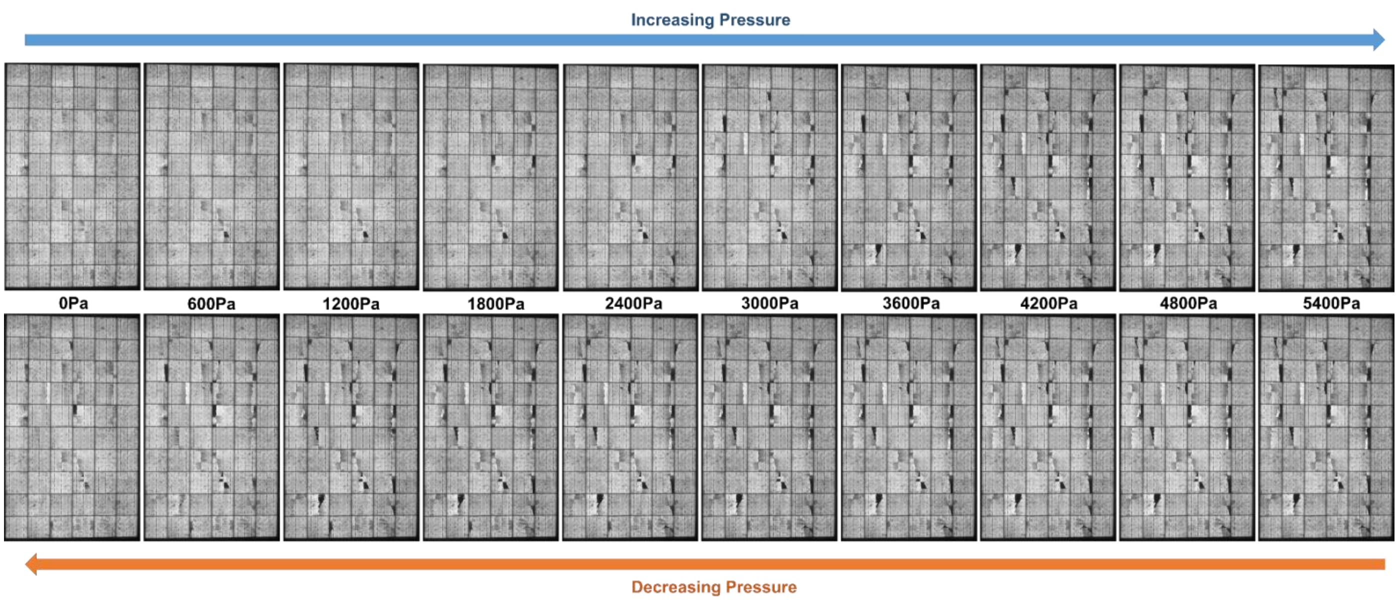

Fig. 5. Electroluminescence images of a multi-crystalline module (Module 3) as a function of applied front side mechanical load.

Fig. 4 and Fig. 5 show the complete progression of the testing sequence used in this work for both a mono-crystalline and multi-crystalline module. One can visually see that many of the cracks are formed at or above 2400Pa for both modules. There is a clear difference in the type of cracks that occur and how these cracks behave upon removal of the load between the two modules. For the mono-crystalline module we see a pattern that matches the first principle stress that is predicted from simulations. The multi-crystalline module shows a different trend where many of the cracks form parallel to the busbars.

While the cells are under tensile stress (i.e. applied front side load), cracks have a tendency to open, which can affect the electrical conductivity between the contacts on either side of the crack. This can lead to certain regions of the cell being electrically isolated. These regions appear dark in the EL images. As the tensile stress is removed, the cracks close and conduction across the cracks may increase. We see this effect in the EL images as the area fraction of these dark regions reduces dramatically from 5400Pa to 0Pa. This so called crack "healing" has been reported in other work [6]. Although the trend is clear that as one reduces front side pressure more cracks close, some portion of this effect is random.

III. IMPACT OF MECHANICAL STRESS ON PERFORMANCE

As cracks form within a module, the power of the module will degrade. The magnitude of that power loss, however, is dependent on several factors including the directionality of the crack, the electrical resistance across the crack, and the total number of cracks [7, 8]. With the ability to measure performance while under load, we can start to quantify these different influences. In this work we focus specifically on two metrics. The first metric is the maximum power loss which is measured at 5400 Pa. A large fraction of this loss is recoverable upon removal of the load. The second metric is the irreversible power loss measured as the difference in power between the initial state and the final unloaded state. Fig. 6 and Fig. 7 show the change in maximum power (P_{mp}) as a function of applied load for the modules shown in Fig. 4 and Fig. 5 respectively. Although both modules had a similar number of fractured cells, the mono-crystalline module had a maximum power loss above 20% whereas the multi-crystalline module only had a maximum power loss of 5.3%.

Another significant difference between the two modules is how the power loss recovers as the pressure is reduced. The mono-crystalline module recovers almost completely by 1200Pa, whereas the multi-crystalline module only starts to recover at that pressure. This is likely due to the differences in the type of cracks that are present in the two modules.

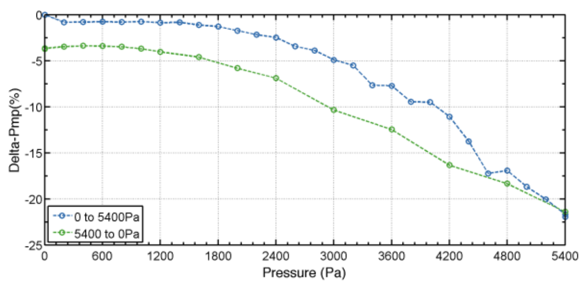

Fig. 6. Change in Maximum Power as a function of front side load for the mono-crystalline module depicted in Fig. 4.

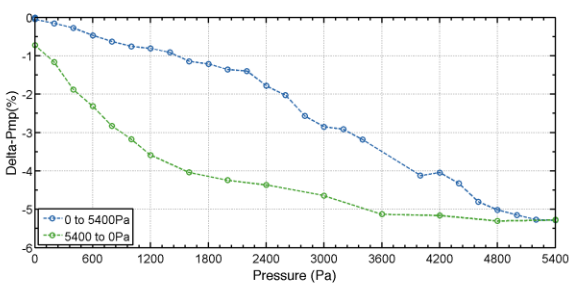

Fig. 7. Change in Maximum Power as a function of front side load for the multi-crystalline module depicted in Fig. 5.

To explore the reproducibility of these results, we performed the same test sequence on five modules of the same make and model as the mono-crystalline module. The results are shown in Fig. 8. All five modules behave in a similar manner. The irreversible damage is just under 5% for each of the modules. There is greater variability in the maximum damage measured for each module, highlighting the somewhat random nature of crack formation.

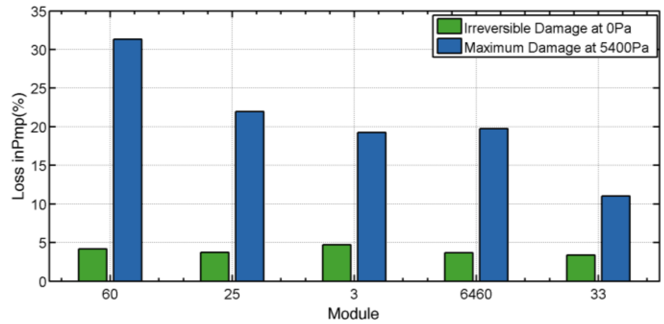

Fig. 8. Power loss for 5 mono-crystalline modules, from the same manufacturer, at an applied pressure of 5400Pa (maximum damage) and with pressure removed (irreversible damage).

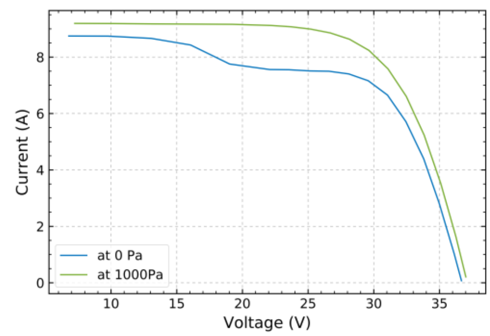

Fig. 9. Variation observed in I-V characteristics for the same module in the both the loaded (at 1000Pa) and the unloaded state (at 0Pa).

There is a significant difference in the I-V curves measured in the loaded and the unloaded state. This difference is shown in Fig. 9 for a module that underwent static and cyclic loading. The curve under load shows a step, that is the result of cell mismatch. Cell mismatch is known to cause hot-spots when the module is deployed in the field [9, 10]. These hot-spots can cause secondary degradation modes to occur, such as back sheet delamination, further impacting module performance.

It is unclear if the module will transition from the performance in the unload condition to the performance in the loaded condition while deployed in the field. This transition may occur slowly as the number of thermo-mechanical cycles continues to increase and the cracks begin to permanently open up. There is also the possibility that during particularly windy conditions the module could rapidly change from one state to the other. This rapid switching, particularly when there is severe cell mismatch, could stress the bypass diodes in the module. This cycling of the diode may lead to failure over time, presenting a serious safety hazard. If a bypass diode quickly switches from forward to reverse bias, there is also a concern that a thermal runaway type of failure may occur [11].

The use of the performance of a module during application of a front side load may be a useful indicator of long term module performance. Further testing is underway to validate the predictive nature of this type of test [12]. The strong power loss signal produced from the module while underload can be used to evaluate module designs in terms of their susceptibility to cell fracture and maximum power loss.

IV. IMPACT OF CYCLIC LOADING ON CRACKS

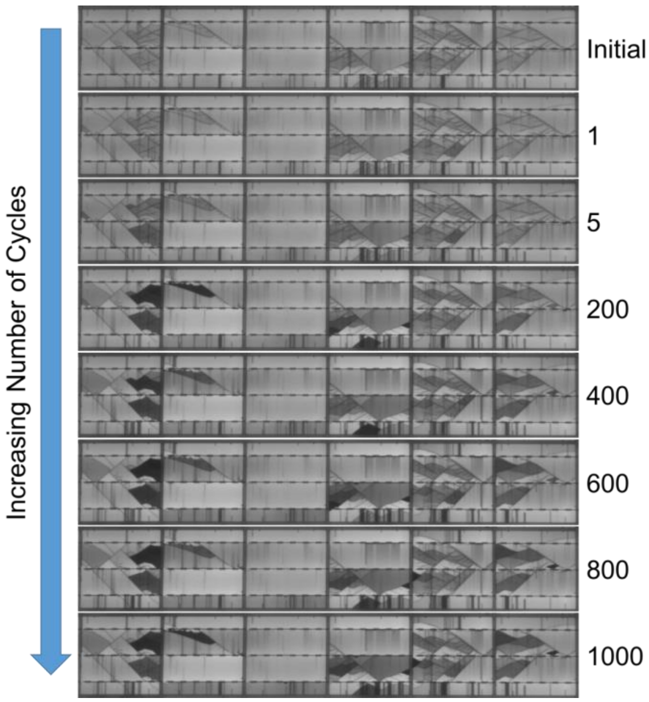

Fig. 10. Progression of cell opening, witnessed through electroluminescence imaging, as a function of loading cycles (+1000Pa to -1000Pa).

Cyclic loading is a widely used testing protocol for the purpose of qualification testing and accelerated aging. After the static loading performed in the initial section of this work, select modules where then taken through the standard IEC protocol for cyclic loading: 1000 cycles of +1000Pa to -1000Pa at a rate of 7 cycles per minute. The motivation was to explore how cracks respond to the high number of opening and closing cycles. The results for a region of one module are shown in Fig. 10. The initial state exhibited very few open cracks. There is very little change after only 5 cycles, however, significant change is observed after the first 200 cycles. The extent of permanent crack opening continues to progress as more and more cycles accumulate. This result indicates that cracks have a tendency to remain open after being exposed to a high number of loading cycles.

IV. CONCLUSIONS

To ensure adequate reliability of PV modules, the influence that cell fracture has on the long term performance of PV modules must be understood and quantified. Current IEC test specifications, including static and cyclic loading, are effective in creating cracks but may not capture the latent power loss induced from these defects once the module is deployed. We investigate the use of module performance characterization while under load as a critical indicator for module reliability and durability. This indicator could provide value throughout the PV supply chain for module R&D, within production, and also for module sellers and module buyers. The ability to quantify performance of the module with and without crack opening provides an avenue to predict the maximum potential power loss that may occur over time in the field. This type of test could be used in module design qualification, quality control, and product evaluations

We use the proposed testing sequence to evaluate several module technologies. Modules that had additional mechanical support in the form of back-rails, performed superior to those without such support. We also identified a substantial difference between the performance of mono-crystalline and multi-crystalline modules. In this somewhat limited investigation, we identified that damage was more severe in mono-crystalline modules at similar load levels. These test cases were used to highlight the breadth of knowledge that could be obtained through performance characterization of modules while under load.

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