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CHARACTERIZATION OF FIELD EXPOSED THIN FILM MODULES

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***Abstract* — Test arrays of thin film modules have been deployed at the Solar Energy Centre near New Delhi, India since 2002-2003. Performances of these arrays were reported by O.S. Sastry [1]. This paper reports on NREL efforts to support SEC by performing detailed characterization of selected modules from the array. Modules were selected to demonstrate both average and worst case power loss over the 8 years of outdoor exposure. The modules characterized included CdTe, CIS and three different types of a-Si. All but one of the a-Si types were glass-glass construction. None of the modules had edge seals. Detailed results of these tests are presented along with our conclusions about the causes of the power loss for each technology.**

***Index Terms* — thin film photovoltaics, PV module performance, outdoor field exposure**

I. INTRODUCTION

Test arrays consisting of five types of thin film modules have been deployed outdoors at the Solar Energy Centre near New Delhi, India since 2002-2003. From 2003 until 2009 each type of thin film module was deployed in an individual stand alone system. The 5 thin film arrays charged 5 battery banks which then powered 5 inverters. There was no maximum power point tracking. System voltages were all round 120 volts with no system ground.

After 2009, 4 of the 5 module types were reconfigured into grid connect systems to feed directly into maximum power point tracking inverters at dc voltages between ~ 360 volts and 570 volts depending on the module type. The fifth module type had degraded too much to be usable in the high voltage arrays.

II. MODULE CONSTRUCTION

The five thin film module types were:

- CdTe
- CIGS
- Triple junction a-Si
- Two tandem junction a-Si types from different manufacturers

Both of the tandem junction a-Si module types and the CdTe modules consisted of glass-glass construction with an encapsulant (probably EVA) in-between. In these 3 cases the active cell structure was deposited directly on the underside of the top glass. Each had some kind of edge deletion around the edges but none of them had edge seals.

For the triple junction a-Si module type, the a-Si was deposited on stainless steel substrates. The substrates were then cut into cell size pieces. The pieces are electrically connected together using wires. The cell matrix is then laminated using a metallic substrate, EVA encapsulant and a fluoropolymer front sheet.

The CIGS modules have the active layers deposited onto a glass substrate. The CIGS plate is then laminated using EVA and a front glass plate. These are early generation CIGS modules with unusual construction that includes a second sheet of EVA and then a polymeric (white) backsheet behind the CIGS glass substrate. There are no edge seals in this construction.

III. FIELD PERFORMANCE

The Table 1 shows the percentage degradation in performance of the difference parameters for each of the 5 types of thin film modules over an 8 year exposure period [1].

TABLE 1
AVERAGE PERCENTAGE DEGRADATION OF THE THIN FILM MODULES AFTER 8 YEARS OF DEPLOYMENT IN INDIA AS MEASURED IN INDIA

Technology	Pmax	Isc	Voc	FF
a-Si Tandem A	29%	17%	2%	12%
a-Si Tandem B	16%	0%	3%	18%
a-Si Triple	31%	17%	5%	21%
CdTe	19%	2%	3%	10%
CIGS	36%	9%	2%	25%

A sample set of these modules was sent to NREL in 2011 to better characterize their degradation. Modules were selected to demonstrate both average and worst case power loss over the 8 years of outdoor exposure.

IV. INDIVIDUAL MODULE CHARACTERIZATION

A. Visual Inspection

Each of the 5 types of modules was inspected upon arrival at NREL. All of the a-Si tandem junction modules from the array that were too degraded to continue operation in 2009, showed evidence of large areas of bar graph corrosion [2] where the active layers have peeled off of the glass. For the second type of a-Si tandem, one module had a small amount of bar graph corrosion while the other had no visible degradation at all. None of the Triple junction a-Si modules had any visual evidence of degradation although the cells had a variety of different colors. The CIGS and CdTe modules didn't have major visual problems although several of each had small delaminations.

B. I-V Measurements

I-V measurements of the modules were taken and compared to the original specifications for the module under test. All modules were exposure to about 2 weeks of daily sunlight for a total irradiation level of 65 kWhr/m^2 before being measured in order to minimize any effects of dark storage on performance. The measured power differences are summarized in Table 2.

TABLE II
DIFFERENCE IN POWER OUTPUT OF THIN FILM MODULES AFTER 8 YEARS OF EXPOSURE IN INDIA AS MEASURED AT NREL ON SELECTED SAMPLES

Module Technology	ΔPmax (%)
a-Si Tandem A	**-41%**
a-Si Tandem A	**-38%**
a-Si Tandem B	**-23%**
a-Si Tandem B	**-1%**
a-Si Triple	**+3%**
a-Si Triple	**-5%**
CIGS	**-32%**
CIGS	**-32%**
CdTe	**-16%**
CdTe	**-30%**
CdTe	**-30%**

Some observations and comments about these results:

- The decision not to use Type A a-Si tandem modules in the high voltage arrays was a good one as they have suffered severe power loss.
- In all of the modules besides the ones that suffered bar graph corrosion, power loss was mainly due to degradation in fill factor.
- The a-Si modules that did not suffer bar graph corrosion, are all still within the initial warranty level, with less than 20% reduction.
- The results of measurements on the triple junction modules are not consistent with the reported field degradation in Table 1. This may be due to our comparison to rated power instead of initial power.
- Without edge seals both CdTe and CIGS suffered significant power loss.

C. Performance as a function of irradiance

To better understand their behavior, the performance of the triple junction a-Si, CdTe and CIGS modules were measured as a function of irradiance. The set of irradiance curves is shown for one of each type of module in Figure 1a, 1b and 1c. The first two (a-SI and CdTe) look well behaved. At high irradiances the CIGS module looks like something is impeding the flow of current. Maybe the back contact is no longer fully ohmic, but rather has a reverse junction that impedes the current flow.

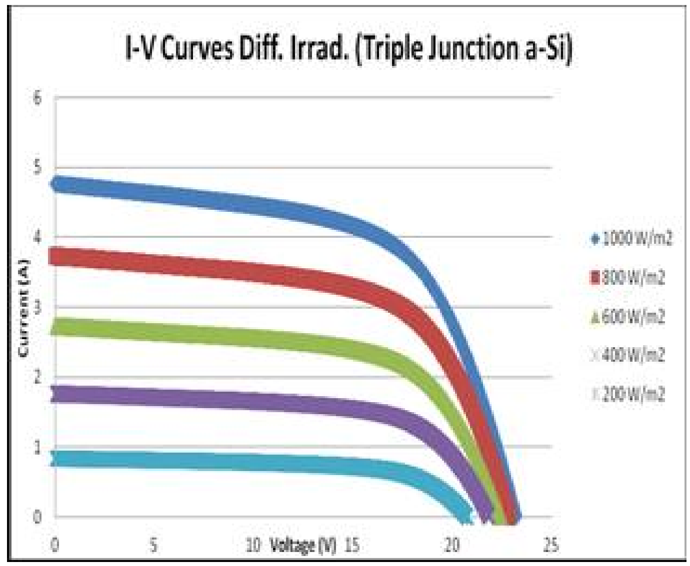

Fig. 1a. I-V curves as a function of irradiance for one of the Triple Junction a-Si module.

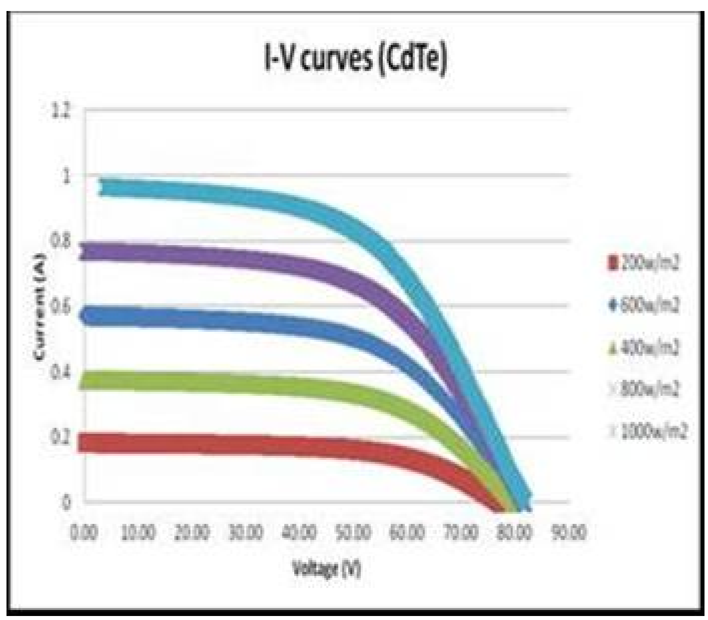

Fig. 1b. I-V curves as a function of irradiance for one of the CdTe module.

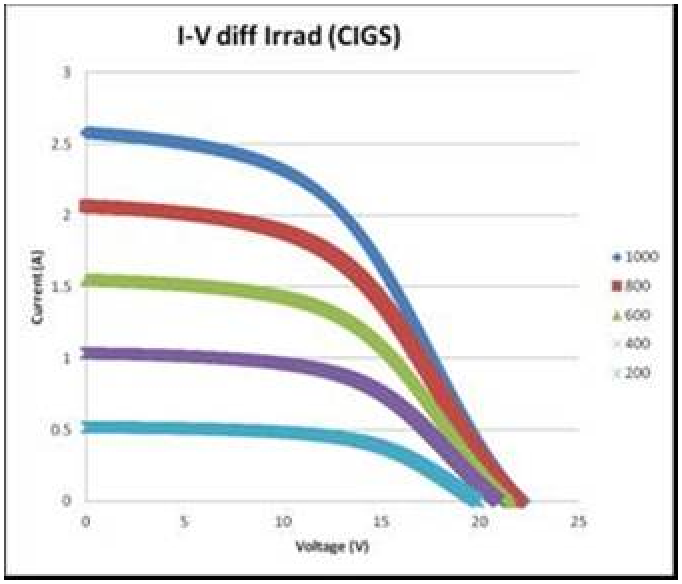

Fig. 1c. I-V curves as a function of irradiance for one of the CIGS module.

Figure 2 shows efficiency versus irradiance for three of the module technologies. As stated above, the CIGS modules have good efficiency at low irradiance, but this degrades at higher irradiance levels probably due to the creation of a bucking back junction. The CdTe modules show little efficiency dependence on irradiance. This is fairly typical of newer generation, non-degraded modules, so it is probably not an indication of why these modules have suffered power loss. Finally the triple junction a-Si modules have their highest efficiency at 1 sun and get worse at lower irradiances. This is contrary to the manufacturer's literature and field experience with similar modules in other systems. We believe that this poor low light level behavior is due to the design of the modules, as the manufacturer has incorporated 22 by-pass diodes into each module. Figure 3 shows a reverse biased Infrared picture of one of the triple junction a-Si modules showing the 22 by-pass diodes. As the irradiance decreases the cells produce less voltage and so more current by-passes through the diodes. Similar poor low light level behavior was observed when a crystalline Si module manufacturer built modules with one by-pass diode for every cell.

D. Electroluminescence

All of the test modules were evaluated using EL. The results for CIGS are shown in Figure 4a. The EL signal is degraded around the edges. Figure 4b is an EL picture of a similar vintage and similarly constructed CIGS module from the same manufacturer that has been deployed outdoors at NREL for a similar time period. There is no evidence of the degradation around the edges in the NREL deployed module. It appears that in the more humid environment around New Delhi, India moisture has penetrated between the sheets of glass and degraded the performance.

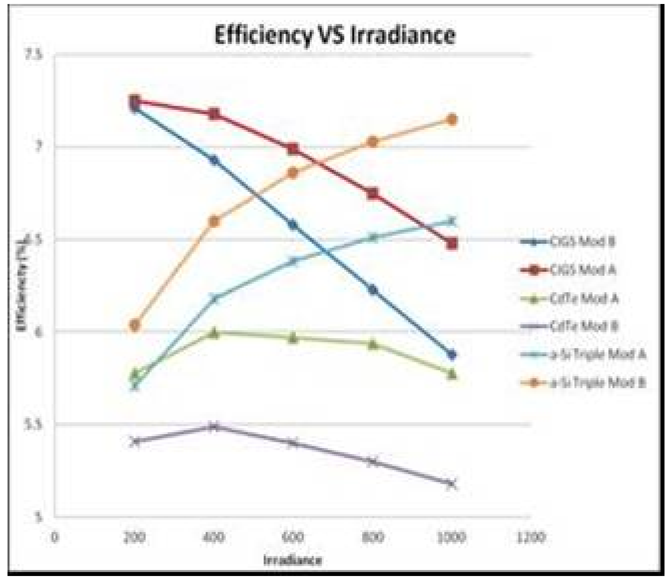

Fig. 2. Efficiency as a function of irradiance for CIGS, CdTe and a-Si Triple Junction.

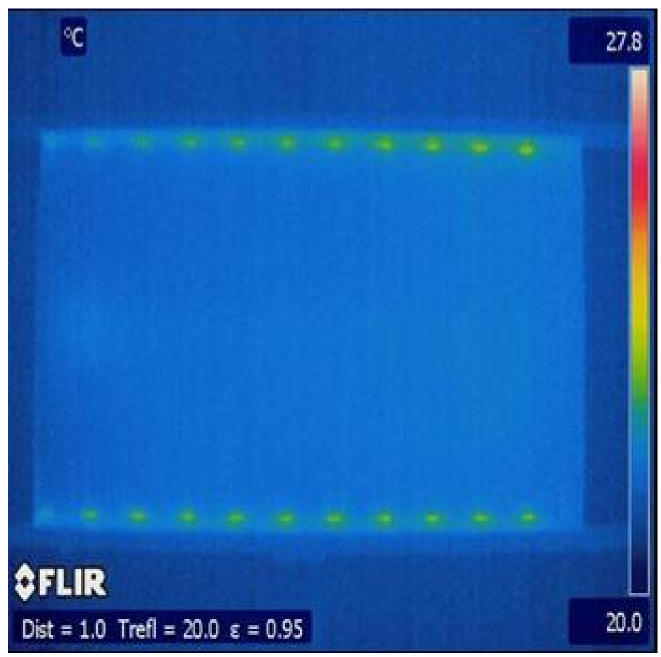

Fig. 3. Reverse Biased IR Image of Triple Junction a-Si Module

V. COMPARISON OF DEGRADATION (INDIA VS NREL)

NREL has measured outdoor degradation rates for three of the technologies represented in the modules from India. The results for the three groups are compared below.

CIGS: A CIGS array with modules from the same manufacturer as the Indian CIGS modules was deployed at NREL from 1999 to 2004. The average degradation rate of peak power for this array was 3.5%/year. The modules from India suffered a peak power loss of 25 to 32% over 8 years or 3 to 4%/year. So the two degradation rates are similar.

Triple Junction a-Si: Three triple junction a-Si modules of similar vintage from the same manufacturer were deployed at NREL from 1998 to 2006. The average degradation rate of peak power for this array was 0.7%/year. The modules from India suffered a peak power loss of 4 to 8% over 8 years or 0.5 to 1%/year. So the two degradation rates are similar.

CdTe: A system consisting of CdTe modules of similar construction from the same manufacturer was installed at NREL about the same time that the CdTe array was installed in India. The modules from India have suffered about twice as much power loss (from 2 to 4% per year) as those deployed at NREL (0 to 3.5% per year). The additional power loss for the India modules was almost all in fill factor.

VI. ASSESEMENT OF DEGRADATION MECHANISMS

Summarizing the observed module degradation and discussing why the different technologies performed as observed:

Double junction a-Si: In the two types of glass-glass a-Si modules, degradation occurred via the bar graph corrosion process. If the packaging can keep the bar graph corrosion from occurring, the modules do quite well.

CIGS: The formation of a reverse junction and some degradation of all parameters around the edges are the likely cause of power loss for the CIGS modules. These may both be the result of moisture ingress around the edges, which is why most CIGS products today use glass-glass with an edge seal.

Triple junction a-Si: The triple junction a-Si modules we evaluated did not show any significant degradation when compared with the original power rating. The outdoor measurements at the Solar Energy Centre in India must have compared the measurements before and after field exposure, so have measured the light induced degradation.

CdTe: While the CdTe modules lost significant power mostly attributed to fill factor loss, there is little physical evidence to indicate why they have lost so much efficiency. Further analysis is required to identify a cause, although we can speculate that the loss may be due to moisture ingress and/or copper diffusion driven by the higher temperature in India and the higher bias voltage per module [3] occurring during the time period when the modules were used for battery charging. Today most CdTe modules have edge seals and are used in systems with peak power tracking so neither of these mechanisms should be an issue.

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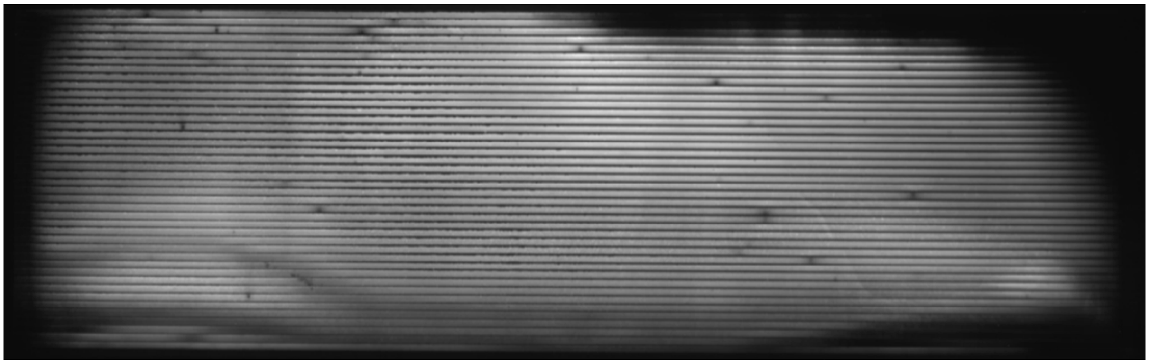

Fig. 4a. EL picture of CIGS module after 8 years of deployment in New Delhi, India

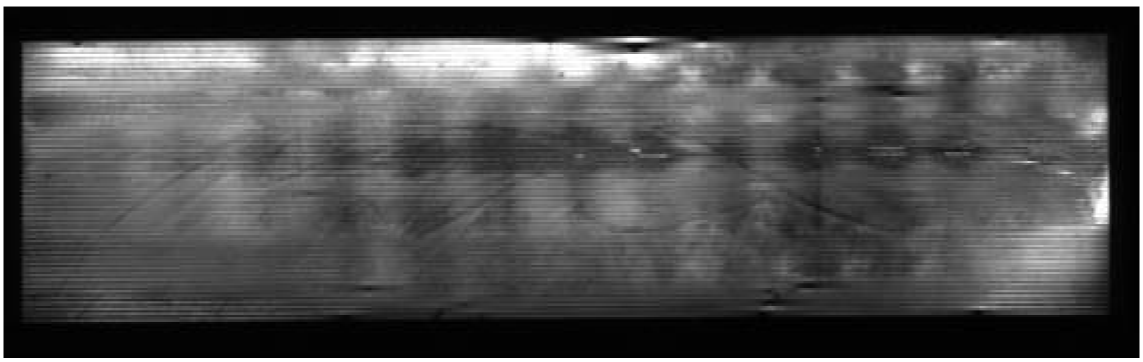

Fig. 4b. EL picture of CIGS module after deployment at NREL