# COMPARISON OF PV MODULE PERFORMANCE BEFORE AND AFTER 11 AND 20 YEARS OF FIELD EXPOSURE

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## ABSTRACT

In 1990 the Schatz Energy Research Center (SERC) installed a PV array comprised of 192 ARCO M-75 modules. Prior to installation, SERC measured the performance of each module. For the past 20 years the array has continued to operate in a cool, marine environment. The performance of each module was re-evaluated in 2001 and again last year in 2010.

This paper describes the equipment and procedure used in retesting the modules, and reports module performance results. The average module maximum power production at one full sun and NOCT has progressively decreased from an initial 39.88W in 1990 to 38.13W in 2001 and to 33.43W in 2010. The average module maximum power production fell by an average of 0.4%/yr from 1990 to 2001 and by an average of 1.4%/yr from 2001 to 2010.

## INTRODUCTION

In 1990 SERC installed a nominal 9.2 kWp photovoltaic (PV) array (Figure 1) at Humboldt State University's (HSU) Telonicher Marine Laboratory in Trinidad, CA. The array is situated approximately 150 meters from the ocean in a cool, coastal environment. The PV system is an integral part of an ongoing solar hydrogen demonstration project and its primary function is to power an air compressor for HSU's marine laboratory. Excess power produced by the array is shunted to a Teledyne Energy Altus 20 electrolyzer in order to produce hydrogen fuel for a proton exchange membrane (PEM) fuel cell.

***Figure 1: The SERC 192-module PV array installed at HSU's Telonicher Marine Lab; the Pacific Ocean is in the distance. The photo was taken in 1990 when the array was new.***

The SERC PV array consists of 192 photovoltaic modules configured into 12 independent subarrays facing due south and tilted at 30° from the horizontal. Each subarray consists of 16 modules wired in 8 series pairs for operation at 24 VDC. All modules were originally ARCO M-75s; since installation three have been replaced due to damage. The ARCO M-75 modules utilize single crystal silicon cells, which are laminated to tempered glass with ethylene vinyl acetate (EVA). Each module contains 33 solar cells and two bypass diodes. At standard test conditions (STC) (1000 W/m$^2$ and 25°C) the modules have a nameplate rating of 48 W maximum power ($P_{max,STC}$) and at normal operating cell temperature (NOCT) (1000 W/m$^2$ and 47°C) the modules have a nameplate rating of 46.4 W maximum power ($P_{max,NOCT}$). The nameplate rating for the short circuit current at NOCT ($I_{sc,NOCT}$) is 3.72 A.

In 1990 Zoellick individually tested each of the 192 modules[1]. In 2000 and 2001, Reis and Coleman retested each of the 191 of the original modules [2]. The glazing on one module had shattered and the module was replaced.

In 2010, we have again tested each of the 189 remaining original modules. Two additional modules have been replaced due to damage. The performance parameters investigated in this study are the open circuit voltage (*Voc*), short circuit current (*Isc*), maximum power point (*Pmax*), maximum power point voltage (*Vmp*), and maximum power point current (*Imp*).

## PROCEDURE

We tested the modules in the field at the angle of the array from May through September 2010. Modules were tested within two hours of solar noon with module temperatures ranging from 22.4°C to 56.8°C. The measurements were conducted under clear sky conditions with irradiance values greater than 800 W/m$^2$.

During each I-V curve trace we measured and recorded module voltage, module current, module temperature (via a Type T thermocouple), and solar irradiance (via an Eppley PSP Pyranometer) in the plane of the module. The IV curve response scan was completed in not more than 2s using LabVIEW® software, National Instruments data acquisition hardware, and an electronic load. Voltages were adjusted to 47°C and 1000W/m$^2$ and currents were adjusted to 1000W/m$^2$, following the methods of Zoellick [1] and Reis and Coleman [2].

## RESULTS

Based on the testing in 1990, 2001, and 2010, Table 1 provides a statistical comparison of Voc, Isc, Pmax, Vmp, and Imp at NOCT recorded for 189 of the 192 original modules in the array. Most importantly, the mean recorded $P_{max}$ has progressively decreased from 39.88W in 1990 to 38.13W in 2001 and then to 33.43W in 2010. Following the 4.35% drop in their first 11 years of operation, the average maximum power declined an additional 12.32% from 2001 to 2010, totaling a 16.13% drop over the combined 20 years of operation. The overall rate of decay in Pmax is 1.37%/year.

Voc and Vmp show the least changes over the twenty years, suggesting that the power loss in the modules is primarily caused by decay in the modules' production of current. In fact the change in the average Imp is almost the same as the change in Pmax, 16.57% and 16.13% respectively. The mean value of Isc changed less than Imp over each period.

The variation in all of these parameters has steadily increased over the 20 years of service, as can be seen in the increases in their standard deviations. Figure 2 shows the normal cumulative probability plot for Pmax of the modules in each testing year. On this kind of plot the cumulative distribution of a normal distribution would plot as a straight line. For 1990, the distribution of Pmax appears approximately normal. By comparison, the distributions of Pmax for 2001 and 2010 are increasingly skewed to lower values as well as the entire curves seem to be shifted downwards.

## DISCUSSION

Reis and Coleman [2] concluded that the primary cause of the degradation of the ARCO M-75 modules was failure of the EVA encapsulant, which led to discoloration of the encapsulant, electrolytic plating of tin from solder, and severe browning of the EVA above individual cells.

When the modules were originally installed in 1990 the individual cells in these modules ranged in color from a light aqua blue to a deep dark blue (Figures 1 & 3, top). After 11 years of field use, EVA browning was observed to some degree on all of the modules. The discoloration ranged from a light yellow color to a dark brown and occurred directly over the cell surface (Figure 3, center). By 2010 after 20 years of exposure, the discoloration has become even more severe and widespread (Figure 3, bottom). The EVA above the edges of the cells was lighter in color and the diamond shaped areas in between the corners of cells was clear (Figure 4). This pattern of discoloration has been reported by others and attributed to photo-oxidative bleaching (Czanderna and Pern [3]; Dhere and Raravikar [4]). The primary effect of EVA browning is a reduction in the amount of light energy reaching the Si-cell surface, which causes a decrease in current generation, as reported by Czanderna and Pern [3].

***Table 1: Statistical comparison of module parameters at NOCT from 1990, 2001, and 2010.***

| Statistic | Year | Pmax (W) | Isc (A) | Voc (V) | Imp (A) | Vmp (V) |
|---|---|---|---|---|---|---|
| Rating at NOCT | | 46.4 | 3.72 | | | |
| Mean | 1990 | 39.86 | 3.30 | 18.20 | 2.88 | 13.86 |
| | 2001 | 38.13 | 3.15 | 18.15 | 2.69 | 14.16 |
| | 2010 | 33.43 | 2.96 | 18.03 | 2.40 | 13.95 |
| % Change | 1990 v. 2001 | -4.35% | -4.37% | -0.29% | -6.31% | 2.12% |
| | 2001 v. 2010 | -12.32% | -6.04% | -0.66% | -10.94% | -1.46% |
| | 1990 v. 2010 | -16.13% | -10.15% | -0.95% | -16.57% | 0.63% |
| % Change/year | 1990 v. 2001 | -0.395% | -0.398% | -0.027% | -0.574% | 0.192% |
| | 2001 v. 2010 | -1.369% | -0.671% | -0.073% | -1.216% | -0.162% |
| | 1990 v. 2010 | -0.807% | -0.507% | -0.047% | -0.828% | 0.031% |
| Standard Deviation | 1990 | 0.924 | 0.041 | 0.093 | 0.035 | 0.229 |
| | 2001 | 1.665 | 0.119 | 0.108 | 0.110 | 0.326 |
| | 2010 | 2.933 | 0.186 | 0.146 | 0.152 | 1.034 |
| Median | 1990 | 39.91 | 3.30 | 18.20 | 2.88 | 13.91 |
| | 2001 | 38.15 | 3.13 | 18.16 | 2.70 | 14.17 |
| | 2010 | 33.79 | 2.92 | 18.03 | 2.42 | 14.08 |

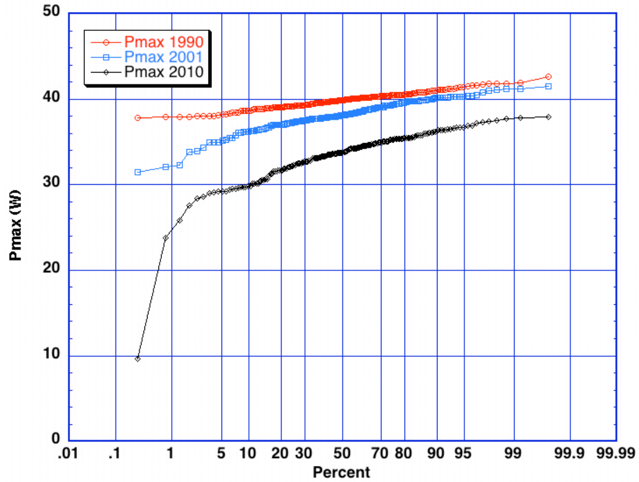


**Figure 2: Comparison of $P_{max}$ cumulative distributions.**

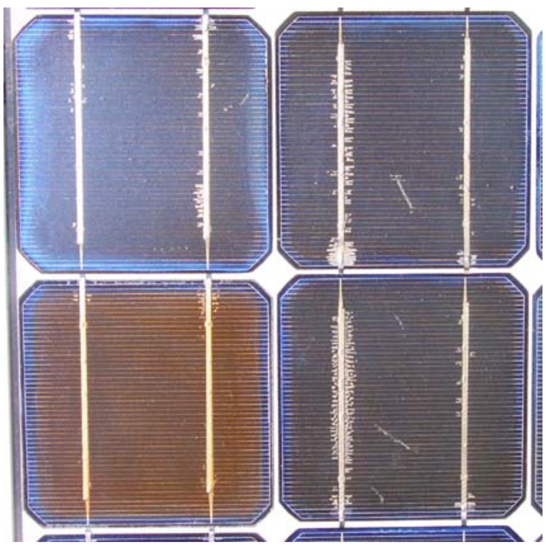

**Figure 4. Four cell section of a module demonstrating varying degrees of EVA browning. The EVA above the lower left cell has undergone severe browning due to elevated operating temperatures.**

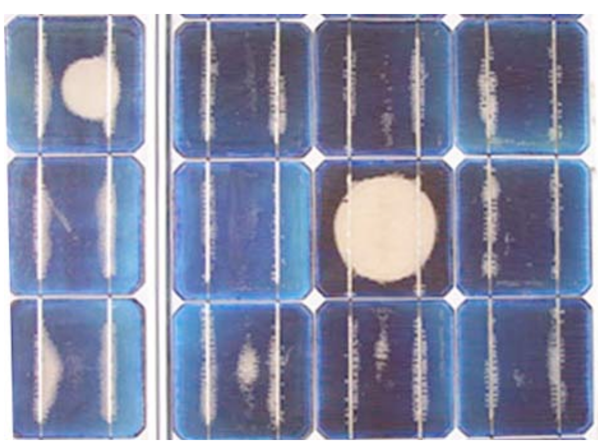

**Figure 5. Module sections demonstrating varying degrees of delamination at the Si-cell/EVA interface. Busline delamination is present on most of the cells in the SERC array.**

**Figure 3: Trinidad Array in 1990 (top), 2001 (center), and 2011 (bottom)**

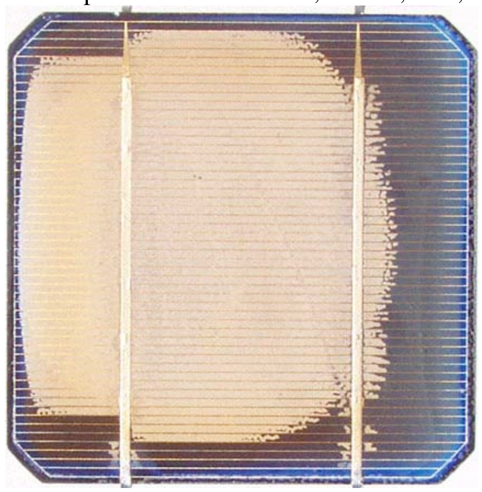

**Figure 6. A single cell that has undergone severe delamination and EVA browning.**

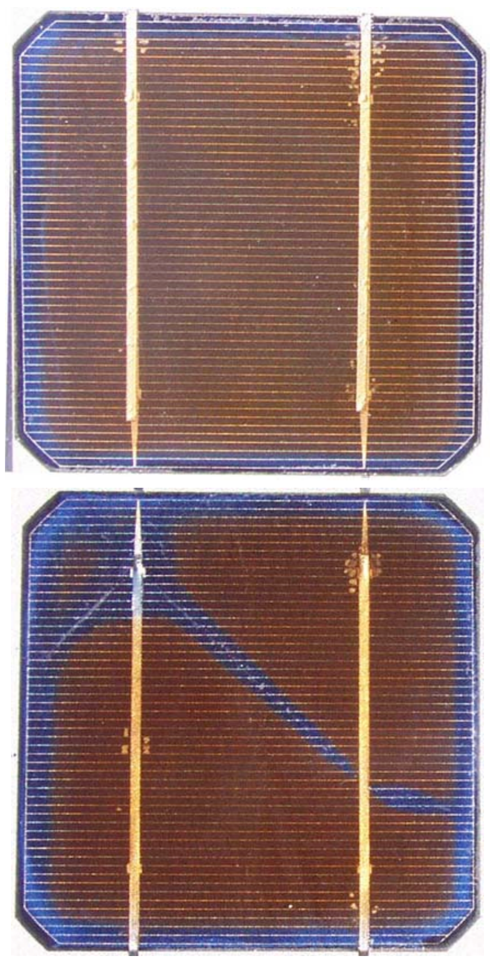

**Figure 7. The severe discoloration in these cells (from different modules) indicates that they have been operating at high temperatures. These cells have become in-line resistors, causing the module bypass diodes to activate. The bottom cell appears to have been cracked during the busline soldering process, which leads to cell overheating and the severe browning.**

Delamination was observed on the majority of the cells in modules located in the array. In all cases, the delamination occurred on the EVA/silicon interface (see Figure 3 and Figure 5). The delamination was present most frequently on and around the buslines and the cells had become completely unbonded from the silicon, buslines and metalization grid. The delamination is assumed to originate along the busline and metallization grid due to the fact that these segments are raised slightly above the silicon cell, providing a preferential location for reduced adhesive strength of the encapsulant. These sites also provide void spaces for moisture accumulation.

Delamination in modules has often been reported to occur in conjunction with EVA discoloration. Together, these two forms of degradation are the types most commonly reported in studies evaluating photovoltaic field use (Figure 6).

Hot spots on individual cells are the most detrimental type of visually observable defect on modules in the SERC array, since the affected cells become in-line resistors in the modules, severely reducing module performance. These defects are indicated by reddish-brown discoloration of the encapsulant over the cell surface, as illustrated in Figure 7. The discoloration of EVA on these cells is much more extreme than the mild discoloration present above the majority of the cells in the PV modules in the array.

Bishop and Ossenbrink [5] reported that the incorporation of bypass diodes in a PV module generally limited hot-spot temperatures to 110˚C - 130˚C. The range of module temperatures recorded during our I-V curve testing ranged from 26.5˚C to 62.5˚C. The reported range of operating temperatures for cells containing hot-spots is therefore much higher than typical average module operating temperatures.

In order to determine the temperatures at which cells containing hot-spots operate relative to other non-defective cells in a module, we conducted a separate experiment using multiple Type-T thermocouples placed on the module backing behind cells containing hot spots and cells showing little to no signs of degradation. Temperatures were then recorded under varying load conditions. At an ambient air temperature of approximately 20˚C, the temperatures under cells containing a hot spot reached up to 110˚C when operating at short circuit current while the temperature recorded under the other cells remained fairly constant, ranging from 45˚C to 50˚C.

Because of the action of the bypass diodes, modules that have experienced the greatest degradation in performance of some of their cells begin to exhibit more complex IV test responses. Figure 8 presents the IV curves for a single module as measured in 1990, 2001, and 2010. While the 1990 curve has a single knee, the 2001 curve has developed a second knee at low voltage that becomes more prominent in the 2010 curve. When one of the two bypass diodes becomes active, the 33-cell module is reduced to 11 cells, which reduces both the effective Voc by a factor of three and in some cases removing the cell that has been limiting current, thus resulting in a modest increase in Isc. In the original testing in 1990, no IV curves with two knees were observed; in 2001, about 33% of the modules exhibited two knees and the size of the knees were smaller than in 2010. Two knees are present in 44% of 2010 IV curves, producing increased mismatch loss within the subarrays.

Although the rate of performance degradation reported by Reis and Coleman [2] for 1990 to 2001 was lower than that reported by Machida et al.[6], the rate of degradation from

2001 to 2010 was 3.5 times as high and now almost equals the 1% per year that Machida et al. reported.

We should also note that when power from a subarray was not needed because the electrolyzer was not up to temperature, too much overall PV power was available, or the system was down for maintenance, we chose to short out the subarray. We did this because, for safety reasons, we did not want voltage in the array field. However, it left the subarray with short circuit current flowing through it and over the lifetime of the array, all subarrays spent some considerable time at short circuit. This almost certainly caused some module aging to occur prematurely.

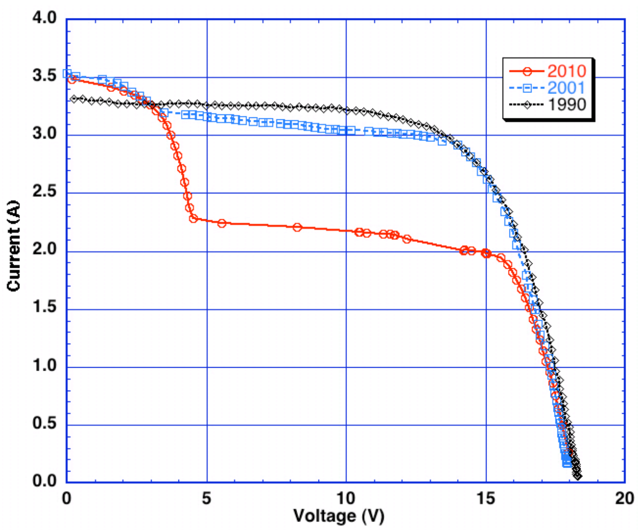


**Figure 8: Comparison of IV curves for module 184**

## CONCLUSION

After twenty years of use adjacent to the Pacific Ocean and continual exposure to that corrosive environment, the average performance of modules in the Schatz Solar Hydrogen Project PV array has decreased by about 16% at an average rate of 0.8% per year, the standard deviation of the distribution has increased by over 300%, and the distribution of the Pmax has become increasingly skewed to lower values. Almost all of this reduction in is due to the decline of module current production as evidence by the 0.8% per year rate of reduction in Imp. In contrast, there has been almost no change in average module Voc and Vmp. The chain of events that follows the browning and delaminating of the EVA provides a reasonable explanation for the decline in current production.

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