AN ASSESSMENT OF PHOTOVOLTAIC POWER IN THE TELSTRA NETWORK

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Abstract

Generally speaking, the quality of PV modules used in the Telstra network is now quite high. But over the past twenty-one years that PV has been used to power remote communications equipment a number of problems have been observed. Some of these problems have been confined to a small number of modules only; others have been quite significant. Cracks developing in the rear Tedlar layer, browning of EVA encapsulant, corrosion of metal terminal boxes sufficient to destroy the silicon wafer, severe delamination of the encapsulant, failure of blocking and by-pass diodes and the formation of trapped gas between the glass and EVA with sufficient pressure to crack cells are some of the problems observed. The initial design life expected of photovoltaic systems within the Telstra network was 15 years, however it has become evident that in some instances this will not be achieved. This paper presents the results of both research and practical experience resulting from Telstra's experience with PV.

1 INTRODUCTION

Telstra has long had an interest in photovoltaic (PV) power for communications applications, dating back to at least the mid 1950's (Wragge, 1958). In the past 21 years since PV was first deployed in the network the number of installations has grown to more than 14,000, using approximately 50,000 modules of many different types. PV modules supply power to systems ranging in size from small customer radio systems with two modules to large inter-capital optical fibre trunk routes where the peak solar capacity of each repeater is over 4kW.

A highly reliable power system for these systems is critical. It has become obvious that some of the modules currently in use would fail before their initial expected lifetime. Consequently a major study of PV module ageing was conducted by Telstra Research Laboratories (TRL) to provide data on which to base a scheduled maintenance and replacement program. Information was gathered in a number of ways, including laboratory testing and an extensive field visit where both electrical measurements and visual observations were made on approximately 440 modules of 7 different types. This paper presents a general summary of the research.

2 A SURVEY OF TELSTRA SOLAR POWERED SITES

2.1 Research Methodology

Seventeen Telstra sites were visited during September 1994, representing a variety of PV module types, ages between 6 and 13 years, and climates from tropical maritime to hot dry desert. At each site the short circuit current (I_{sc}) and current into a 14V electronic load (I_{14V}) were measured for a number of modules. For practical reasons I_{sc} was chosen as the primary indicator of module degradation, and has the advantage that it is relatively insensitive to temperature. The I_{14V} parameter was used to estimate the current provided by the module into a charging battery, and provided a simple comparison between similar modules of the "quality" of the module Fill Factor (at least at sites where insolation and temperature were similar).

A reference module was taken to each site and was placed at the same angle as the PV array. It was allowed to stabilize in temperature before being measured in the same way as the other modules. Measurements were restricted to within 2 hours of midday to limit variations in I_{sc} caused by changes in Air Mass (which varied between 1.0 and 1.6). The measured I_{SC} of the reference module, corrected for temperature, was normalised against the value of I_{SC} measured in the TRL solar simulator[1]. The mean error of -4% in I_{SC} of the reference module measured in the field was assumed to be a systematic error, presumably dominated by pyranometer calibration and response errors. All data have been corrected for this error. The standard deviation of less than 2% represents the average uncertainty in the individual measurements.

Each of the 440 modules was examined for signs of physical deterioration. Particular attention was given to known potential problems including corrosion, changes to the encapsulant, damage to the rear layer of the module, and breakdown of the terminal box. Wherever possible changes were described in a quantitative as well as qualitative way. For example, browning of the EVA encapsulant was graded according to a colour density card.

2.2 Physical changes to modules

There were a number of different signs of physical degradation, although there was only one model type which consistently suffered several of these problems together. In the majority of cases the degradation had not caused the module to catastrophically fail; rather, it is anticipated that the long term effect will be a somewhat shortened service life.

2.2.1 Terminal box

Some early modules used cast aluminium terminal boxes. These have generally proven to be reliable in all but maritime environments. At one site less than 50m from the sea corrosion on an aluminium terminal box was so severe that the oxide formation had shattered both cells and cover glass. Other early modules used white plastics such as polypropylene, most of which have degraded significantly after prolonged UV exposure. Black plastic terminal boxes with UV inhibitors have been more stable, although some have become brittle after less than

[1]The I_{SC} of a similar module measured at both TRL and Japan Quality Assurance Organisation agreed within 1%.

10 years in the field. Plastic clips which relied on some flex in the plastic to secure the terminal box lid broke when the lid was removed.

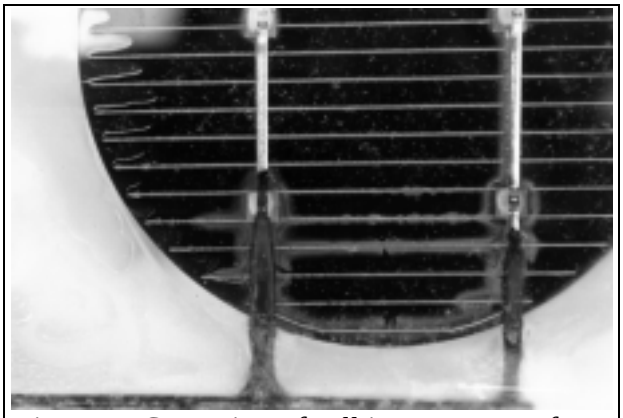

Figure 1. Corrosion of cell interconnects from moisture entering around the terminal box.

A common method of mounting modules on a rack was to have the upper module of a vertical pair inverted, such that the terminal boxes were adjacent. This configuration made the wiring between modules easier. However, such mounting was observed to increase the probability of corrosion in the inverted module, particularly in modules which had inadequate sealing around the point where the wires entered the laminate, under the terminal box. An example of the corrosion found in the most susceptible module is shown in Figure 1.

2.2.2 Encapsulant

The most stable encapsulants in the modules examined were based around silicone resins. The two best performing modules used this material. Although providing a secure encapsulation of the cells, it was an expensive material to use, partly because it was relatively difficult to achieve a satisfactory result.

Severe delamination was observed in only one type of module, where the encapsulant was polyvinyl butyral (PVB) between two sheets of glass[2]. In the worst affected modules delamination exceeded 75% of the front surface area, and contributed substantially to the reduction of almost 25% in rated I_{sc}.

Browning of EVA, which can reduce energy conversion efficiency, was observed in most of the modules which used this material as an encapsulant. However, it was not considered sufficient to severely restrict the performance of the module. Overseas research indicates that browning is not confined to modules from any one manufacturer, nor from a single supplier of EVA encapsulant sheet. It can be attributed to high temperatures and UV radiation experienced by modules using "standard cure" EVA[3] (Holley, Pern).

The pattern of browning varied between types of modules. In some the most intense browning occurred over the cells, where temperatures would be expected to be greatest. In other

[2]Glass/PVB/glass lamination has been successfully used in making laminated automotive windscreens.
[3]Standard cure" EVA uses Lupersol 101 peroxide as a cross-linking agent. "Fast cure" EVA is cross-linked with Lupersol TBEC peroxide. The use of "fast cure" EVA in conjunction with a front cover glass which contains cerium oxide to reduce UV transmission improves colour stability by a factor greater than 15

modules the degree of browning was most pronounced near the edges of the module, perhaps because of a greater availability of oxygen from the air.

In one module type gas released from the EVA encapsulant caused bubbles to form in the laminate. The stretched Tedlar around the bubbles became very thin, although there was no evidence that the material had torn or punctured. In one of the modules examined the radius of curvature was sufficient to crack about 20% of the silicon away from the cell proper. Although this fragment appeared to be still connected electrically via one of the front interconnect strips, it's performance was within the lowest 10% of modules in terms of I_{sc} and 5% in I_{14V}.

Evidence suggests that the formation of bubbles in this type of module should be restricted to the early production modules which employed a Tedlar /aluminium /Tedlar backing, where the aluminium moisture barrier prevented the escape of the gas. The formation of bubbles has also been observed in other types of commercial modules.

2.2.3 Backing material

One of the more common modules in the Telstra network has shown a tendency for the rear Tedlar material to develop linear splits, exposing the EVA encapsulant to the weather. Within about a 3 year production window the proportion of modules which have developed splits seems to increase with age up to 40% of the 41 modules examined, although there are not enough data to make a confident generalization. Outdoor exposure was not a prerequisite for the formation of cracks since a module held in storage for 8 years at TRL had started to develop deep creases in the Tedlar, the precursor to split formation. Consultation with the module manufacturer indicates that the supplier of the Tedlar changed the formulation for a short period. When the problem became evident in 1988 the material composition was altered.

A controlled experiment was undertaken at TRL using accelerated ageing testing in an environmental chamber to determine the long term effect of the splits on module performance. The conclusion from this work was that moisture ingress through splits in the rear of the module would not lead to rapid failure of the modules. However, it is anticipated that there may be some marginal increase in the long term rate of degradation.

One of the early modules purchased by Telstra used round single crystal cells encapsulated in PVB and protected between two sheets of glass. The idea of the transparent glass back was to let insolation incident between cells pass through the module, reducing the NOCT, and thereby improving average power output. A number of these modules were observed to have developed cracks in either the front or rear (or both) glass surfaces. As discussed in Section 2.2.2 this module suffered severe delamination of the PVB/cell/PVB sandwich. One possible explanation for the cracked glass is that since both the front and back surfaces of the module were rigid there was little inherent flex available to allow movement of the encapsulant. As the minute bubbles formed and grew pressure built within the module until the glass cracked.

2.3 Electrical Characterisation

2.3.1 General observations

A number of observations can be drawn from the collected data. However, there are a number of provisos which must be considered beforehand. Included in this list are:

1) Estimation of the rate of degradation in I_{sc} in most cases assumes that the modules were close to rated I_{sc} when new. This assumption becomes less important as the age of the module increases.

2) Only modules manufactured before 1989 are compared. Faults observed in these modules may not necessarily develop in newer modules.

3) In this analysis it is assumed that unless noted the characteristics of the module did not change significantly during the production period.

4) It is assumed that the rate of degradation is constant, primarily because a lack of temporal data does not allow any other comparison. While some degradation processes may be linear with time there was no evidence available to suggest that this will generally apply.

The most stable modules of those examined were the two module types manufactured in the early 1980's which used an encapsulant based on silicone resins (discussed above in Section 2.2.2). Although there were signs of loss in anti-reflection coating around the edges of some cells this did not appear to cause any significant reduction in efficiency. Average loss in I_{sc} was of the order of ½% per annum.

The fastest reduction in I_{sc} was approximately 2½% per annum. This was associated with the module which showed severe delamination, cracking of the front and rear glass surfaces, and corrosion of the cell interconnects (discussed in Sections 2..2.1-3). It was manufactured in the early 1980's. Degradation in several of these modules has been sufficient to force replacement within ten years of service. Ironically, this module was the successor to the most reliable module in the Telstra network.

2.3.2 A Specific example - early 1980's

In the early 1980's TRL received over 70 modules of the same type for testing, with sixty of these being randomly drawn from the modules purchased by Telstra for use in the field. This type of module was manufactured using 100mm diameter single crystal silicon cells encapsulated between two layers of silicone rubber behind a glass front surface. After measurement of initial IV characteristics thirty six modules were sent to a field site in Melbourne where they were installed in an experimental hybrid power system. After 8½ years exposure the modules were removed from the field site and re-measured in the TRL solar simulator. Results are summarized in Figure 2 and Table 1 below.

It is evident from these data that the electrical performance of this type of module did not significantly deteriorated during the 8½ years of exposure in the Melbourne climate. Statistically the P_{max} of only the "aged" module distribution was normally distributed[4]. The values measured for module I_{sc} were normally distributed for the large 60 module sample and before and after exposure of the 35 modules.

[4]Normality was tested using a Shapiro-Wilks' W test and a significance level of $p = 0.02$.

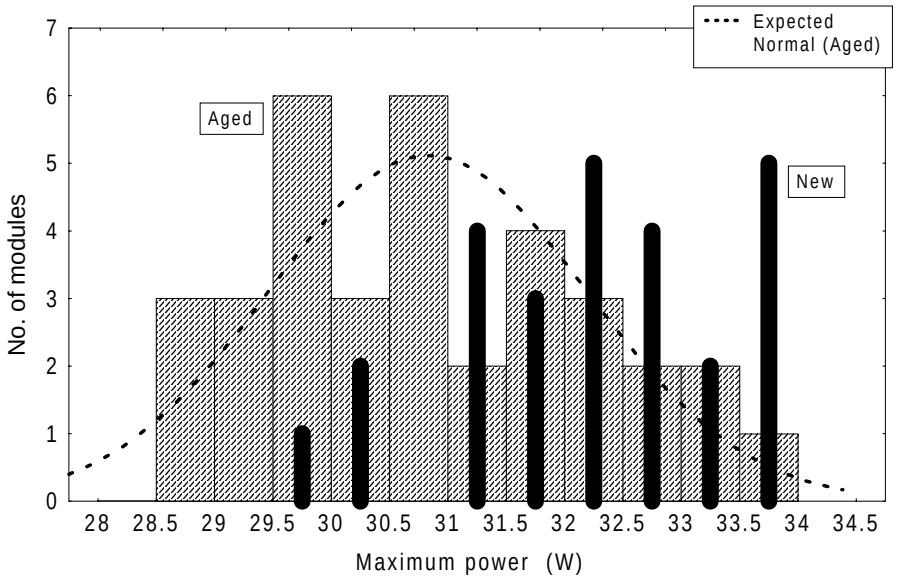

Figure 2 The distribution of P_{max} of commercial early 1980's vintage modules both when new (solid bars) and after 8½ years of exposure in the Melbourne climate (hatched bars).

	μ_{Isc}	σ_{Isc}	μ_{Pmax}	σ_{Pmax}
Initial	2.28A	0.06A	31.8W	1.2W
Final	2.26A	0.08A	30.8W	1.4W

Table 1 The change in I_{sc} and P_{max} of early 1980's vintage modules after 8½ years exposure in the Melbourne climate.

There was no obvious trend visible between P_{max} and date of manufacture. The mean degradation rate is small; approximately 0.4% per annum for P_{max} and 0.1% per annum for $I_{sc.}$ The modules also appear in very good physical condition. These observations are consistent with the data obtained from visiting Telstra installations in the Northern Territory.

2.3.3 Another specific example - mid 1980's

The biggest growth in Telstra PV installations began in the mid 1980's, with approximately 350kW being purchased in 1986/87. Figure 3 summarizes the data obtained from four sites for one of the (several) module types purchased by Telstra around this time. The I_{sc} of this module was nominally 2.7A at an NOCT of around 60ºC. Site A is in the vicinity of Alice Springs N.T., site D near Katherine N.T., while sites B and C are on the coast near Broome, W.A.

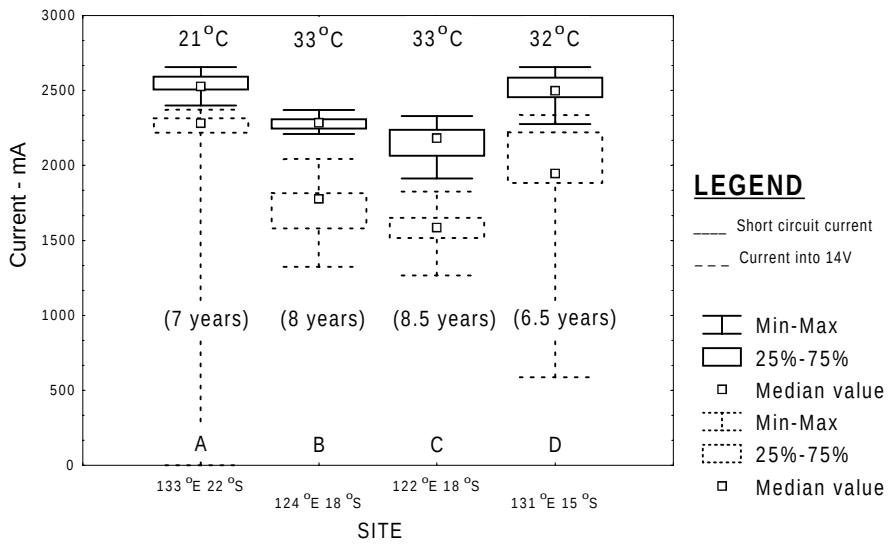

Figure 3 The distribution of I_{sc} and I_{14V} measured for a total of 76 modules at 4 Telstra sites. The whiskers represent the range of values recorded at each site; the box encloses data between the 25% and 75% quartiles; the point locates the median value. Air temperature at the time of measurement is shown at the top.

Although the modules at site A are slightly older than those at site D, the mean value of I_{sc} is 2% higher[5]. A statistical comparison of the two sample populations indicates that there is a greater than 95% probability that the modules have aged at a different rate. This reinforces the general observation that the climatic environment in which the modules are exposed will affect the rate of ageing. Similarly as expected, from the data it is evident that the longer the modules have been exposed outdoors, the greater the loss in I_{sc}. Based on these data the lifetime of the modules (to 80% of rated I_{sc}) is approximately 15 years, although there is a relatively large estimated uncertainty of ± 3 years.

The currents measured for each module into the 14V load are interesting[6]. Because I_{14V} is a function of more parameters than I_{sc}, each of which will add to the scatter, it was expected that the variation in I_{14V} within samples would be larger than that of I_{sc}, and this was observed. However, while the behaviour of one module at site A, providing normal I_{sc} but zero current into 14V can be explained, the reason behind the low value of I_{14V} for one module at site D cannot positively be identified based on the simple field measurements.

The I_{14V} = 0 datum at site A is symptomatic of by-pass diode failure. This module employed two by-pass diodes protecting each of the two (nominal) 6V strings. A diode normally fails in a short circuit condition (Thornton). In such a state the module will still provide a normal value for I_{sc} (voltage independent) but because V_{oc} has been reduced by half, to between 9 and 10 volts, there is not sufficient potential to drive the 14V load. Hence zero current. In a 12V system failure of one of the two by-pass diodes will make the module inoperable; in a 48V system typically used by Telstra the effect will be similar to severe performance

[5]The mean I_{sc} at site A can be expected to be of the order of 1% lower than it would have been at the other sites because of the temperature difference of approximately 12ºC.

[6]Comparisons between sites should exclude site A since the data have not been corrected for temperature.

degradation, especially at higher temperatures. Fortunately, the most severe reduction in battery charging current will usually occur under full sun conditions when the array output is at its highest.

-Field exposure in Melbourne

Four modules of this type were installed for seven years at the outdoor field site at TRL. Unfortunately, the modules were not measured when new. However, measurements in the TRL solar simulator after exposure indicate an average loss in I_{sc} per year of approximately 0.7%, compared with generic specification, and an average loss in P_{max} of 1.3% per year. The loss in I_{sc} is about half the average rate determined for the four sites discussed above, but this is not unexpected since Melbourne has a less severe climate in terms of module degradation.

3 CONCLUSION

Based on the collected data the mean estimated lifetime of the modules in the Telstra network is around 15 years. The data collected at each site were generally normally distributed, as observed elsewhere (Berman). Estimates of the mean loss in I_{sc} range between ½% and 2½% per annum. The loss is strongly dependent on the type of module, with the stability of the encapsulant a key factor. Data support the general observations that the degradation of a module is both a function of duration of outdoor exposure and climatic environment. Most modules exhibited at least some signs of physical degradation, but in only one early module type has this lead to consistent catastrophic failure.

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5 REFERENCES

Berman, D., Biryukov, S., and Faiman, D., EVA Laminate Browning After 5 Years in a Grid-Connected, Mirror-Assisted, Photovoltaic System in the Negev Desert: Effect on Module Efficiency, Solar Energy Materials and Solar Cells, 36, 1995, pp421-432

Holley, W.H.Jnr., Agro, S.C., Galica, J.P., Thoma, L.A., Yorgensen, R.S., Ezrin, M., Klemchuk, P., Lavigne, G., & Thomas, H., Investigation into the Causes of Browning in EVA Encapsulated Flat Plate PV Modules., 1st WCPEC, Hawaii, 1994

Pern, F.J., Factors that Affect the EVA Encapsulant Discoloration Rate upon Accelerated Exposure, 1st WCPEC, Hawaii, 1994

Thornton, Richard, Telstra Research Laboratories, Private Communication, 1995