RESEARCH INTO NEW TECHNOLOGY PHOTOVOLTAIC MODULES AT TELSTRA RESEARCH LABORATORIES - WHAT WE HAVE LEARNT

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ABSTRACT

The New Energy and Industrial Technology Development Organization (NEDO) of Japan, together with Telstra Corporation of Australia, recently concluded a 15 year project studying photovoltaic module degradation under laboratory and outdoor field trial situations. Crystalline silicon modules have been exposed at outdoor field sites since 1982. Thin film photovoltaic technologies have been studied since 1987. Major conclusions from this project are discussed. Effects of climate, module construction technology and other factors are examined. Relative benefits and disadvantages of using field site exposure and laboratory testing are also discussed. Results are compared with experience gained from studying commercial modules in the Telstra network.

INTRODUCTION

Japan - Australia co-operative agreement

In early years as commercial photovoltaic (PV) modules became more readily available there was relatively little information on how well modules would survive extremes in climate. In 1980 a co-operative agreement was established between the Japanese and Australian governments. Under this agreement a collaborative research program was instigated to determine the factors which affect long term reliability of PV modules, and provide data with which to assist in improving existing technology. Within Australia research in the program was conducted by Telstra Research Laboratories (TRL). As one of the world's largest users of PV for communications use, Telstra has a strong interest in module reliability, with over 2.5MW of installed capacity in some 14,000 systems.

During the project a number of field sites were established in Australia, as shown in Figure One. The sites were chosen to represent a range of environments: marine, cold, temperate, hot/humid, and hot/dry. At each of these sites two modules of every type being studied were exposed, and their individual current-voltage characteristic (IV curve) continually measured. Weather conditions were continuously monitored, and sites visited regularly to observe any physical changes in the modules. Similar modules to those being exposed at the field sites were subject to laboratory testing under standard conditions (AS2915 1987). Several modules were returned regularly to TRL for measurement under standard conditions, to verify field site data.

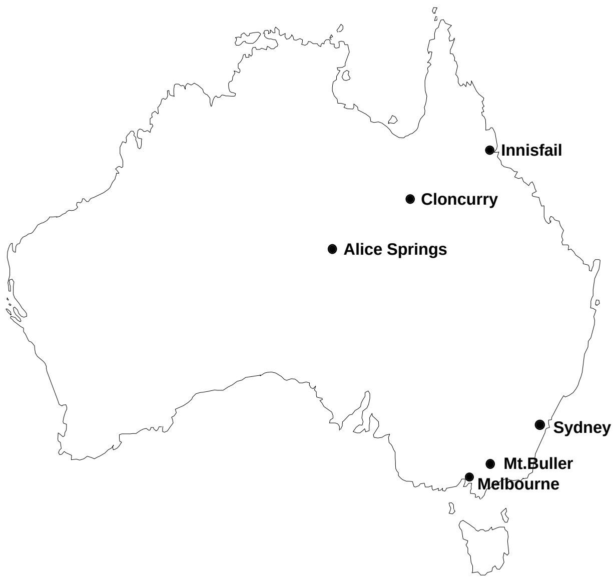


Figure 1 Telstra PV exposure field sites.

Telstra PV research program

Telstra was concurrently active in researching other aspects of PV use, concentrating on potential uses of PV in an evolving network, and identifying problems in modules already in service. In the infancy of commercial module production a variety of construction methods and materials were used, sometimes changing radically from one model to the next. As the technology behind module fabrication has matured, and confidence in the long term reliability of the final product increased, there has been less of a need by Telstra (as a consumer) to rigorously test each type of module.

The majority of modules purchased by Telstra are still in operation, with only one type of module purchased in the early 1980's providing significant problems. However, this is not to say that the use of PV has been without problem. Modules which fail in the field are often returned to TRL for analysis. Materials and semiconductor device analysis, solar simulator measurements, and consultation with manufacturers have generally been able to isolate the cause of problems, though not necessarily the extent.

SIGNIFICANT RESULTS

Crystalline silicon modules

One of the major reasons to study different module technologies is to derive reliable estimates of useful lifetime in a PV system[1]. The determination of service life has been

[1] Modules are deemed by Telstra to have failed when the output has fallen to 80% of rated output.

approached by TRL in three ways: accelerated testing in laboratory environmental chambers, long-term field exposure trials, and examination of commercial modules installed in Telstra applications.

1) Accelerated ageing

Separate groups of different module types manufactured in the 1980's, using different construction technologies, have been subject to 10,000h exposure in dry heat (85^oC, RH <20%) and damp heat (85^oC, 85% RH) environments to simulate long term ageing in the field[2] (Murfett, 1989). For the dry heat test 10,000h is considered to be equivalent to approximately 20-25 years outdoors exposure under Australia's worst conditions. For the damp heat test there is much greater uncertainty but 5,000h is considered equivalent to over 20 years exposure in Australia.

Several general observations have been drawn from these tests:

1) The two module types which used cells based around a p^+n construction (p-doped front surface) performed relatively poorly in the damp heat tests. Evidence suggests a rectifying metal-to-silicon contact (ie. Schottky diode) formed on the rear of the cells.

2) With the exception of the p^+n cell type modules, the silicone encapsulated modules all remained within 90% of their respective initial maximum power (P_{max}) values after 10,000h in the damp heat test. With the exception of one module type, the EVA/Tedlar encapsulated modules had generally severely degraded after 5,000h exposure.

3) The reduction in short circuit current (I_{sc}) in some of the modules was found to be due to increased distributed series resistance, presumably caused by corrosion. In other modules an increase in the opacity of the encapsulant was a significant contributor to lower I_{sc}.

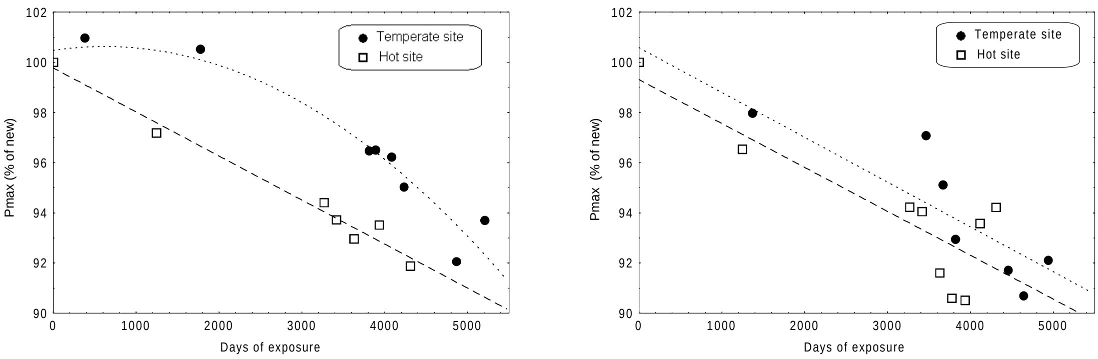
Despite the observed degradation after extended testing, all but one (or possibly two) of the fourteen different types of module passed the IEC 1215 Design Qualification and Type Approval requirements for these two tests.

2) Long term field exposure

Long term exposure testing of several different crystalline silicon module types has been conducted at all sites in Figure 1 except Mt. Buller. Maximum power data measured in the TRL large area pulsed solar simulator for two different module types exposed at the temperate site (Melbourne) and hot site (Alice Springs) are shown in Figure 2. Maximum exposure time is approaching 14 years. Module type **x-A** (Figure 2(a)) is

[2] This length of time was significantly more severe than the 1000h exposure required as a part of the IEC 1215 module test standard.

constructed of single crystal cells, while module type **x-B** (Figure 2(b)) uses poly-crystalline ribbon cells. In both modules the cells are encapsulated in silicone rubber.



(a) (b)

Figure 2 The temporal change in IV parameters of 2 crystalline silicon modules.

Although there is some scatter in data, particularly for the **x-B** module type, the degradation in P_{max} for three of the four modules appears to be approximately linear with time. The data indicate that the difference between climates at the two sites has had negligible effect on the rate of degradation, with a mean loss in P_{max} of approximately 7% over 10 years. The change has occurred primarily through a reduction in module Fill Factor. Detailed results from analysis of another module type of the same vintage, also employing single crystal silicon cells encapsulated between two layers of silicone rubber, have been reported previously (Muirhead & Hawkins, 1995) and support these observations. However, the behaviour of the **x-A** module exposed at the temperate site differs from the other modules shown in Figure 2, with a distinctly non-linear rate of degradation in P_{max}. The reason for this behaviour has not yet been determined. The companion module at the site did not show this unusual behaviour, degrading in a similar manner to the two **x-B** modules at the site.

The silicone encapsulant of both types of modules has shown no noticeable signs of yellowing through exposure to UV radiation. The rear surface of the **x-A** module (of unknown composition) has become brittle and started to split. Splitting of this type has also been observed in a significant number of commercial modules manufactured in the mid-1980's, which used a particular formulation of Tedlar. Both accelerated ageing testing in an $85^{O}C$, 85% relative humidity environment, and measurements on many split modules in the field indicate that these splits do not compromise module electrical performance. The Tedlar backing material of the **x-B** module has shown no sign of deterioration.

<u>3) Evaluation of field faults in commercial modules</u>

Apart from one particular module type which used a polyvinyl butyral (PVB) encapsulant, a recent sample of most of the module types currently in use by Telstra has indicated an estimated service life of at least 15 years (Muirhead & Hawkins, 1995).

However, there have been instances where modules have failed prematurely because of a change in either the quality or specification of materials used in module construction. For example, in the mid 1980's one manufacturer of Tedlar changed formulation unannounced. The new compound subsequently proved to be unsatisfactory for use as the backing material of a PV module. Field testing of a limited sample of modules is likely to be of little benefit in predicting batch-related failures.

Thin film modules

TRL has evaluated amorphous silicon (a-Si) modules using single, tandem, and triple junction cells, as well as modules with cells based on cadmium telluride. In addition to the standard laboratory and outdoor exposure testing undertaken for crystalline modules, there has been some applied research associated with the practical use of a-Si modules. Included have been a study on the benefits of controlled annealing of a-Si modules, methods to enhance field annealing, modelling of long term and seasonal variations in P_{max} , and the estimation of errors associated with correlating solar simulator IV curve measurements with outdoor measurements made under changing spectral conditions.

1) Laboratory studies

In more recent years the laboratory study of thin film modules has concentrated on determining what changes, if any, occur during temperature cycling, dry heat, and humidity testing in an environmental chamber. The majority of modules which went though these tests exhibited some change, but only occasionally were the changes significant enough for the module to fail the relevant test. Delamination within the module, predominantly involving the cell encapsulant, was observed during the testing of several modules. In one such instance delamination detected early during a temperature cycling test was traced by the manufacturer to the curing temperature of EVA being 10^{O}C lower than expected. This fault has not been observed in modules of the same "prototype" batch exposed for more than two years at any of the field sites.

2) Field site testing

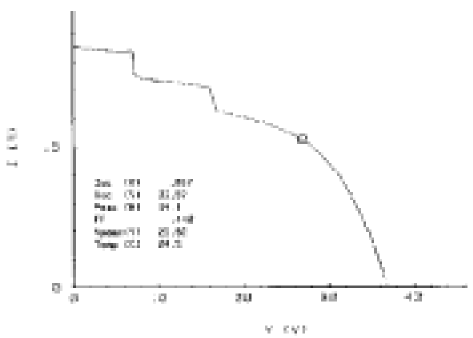


Figure 3 An effect of imperfect soldering.

One of the more unusual faults discovered through field testing of a particular module is illustrated in Figure 3. Poor electrical contacts in the electrode portions of the submodules have caused instability in the I_{sc} of the module. After testing had identified the problem the soldering method was modified by the company in 1990.

Performance degradation in crystalline silicon modules tended to occur because of a deterioration in the physical packaging of the module. On the other hand, a-Si modules have shown significant degradation through changes in the semiconductor material, and less of a change brought about from deterioration in encapsulation. Both types of CdTe based modules have been relatively stable after a drop in P_{max} following initial exposure. However, with data for less than 4 years it is too early to make long term predictions about these modules.

3) Modelling of a-Si module performance

One of the impediments to low cost energy from a-Si modules has been the reduction in power through exposure to light, attributed to the well documented Staebler-Wronski effect[3] (see Figure 4). In order to cost effectively design a PV power system, and obtain high reliability of supply, it is necessary to be able to estimate this change in module efficiency over the life of the power system. For this reason TRL began investigation into performance modelling of a-Si modules, to help assess their suitability for selected telecommunications applications.

Several "generic" descriptors of decay have been used to describe the degradation in a-Si module performance (Muirhead, 1993), including models of the following forms:

$$P_{max} = C_0 - C_1.\log_e(t) \quad \text{(E1)}$$

$$P_{max} = C_0 - C_1.\log_e(t) - C_2.t \quad \text{(E2)}$$

$$P_{max} = C_0 - C_1(1 - e^{-t/\tau_1}) - C_2(1 - e^{-t/\tau_2}) \quad \text{(E3)}$$

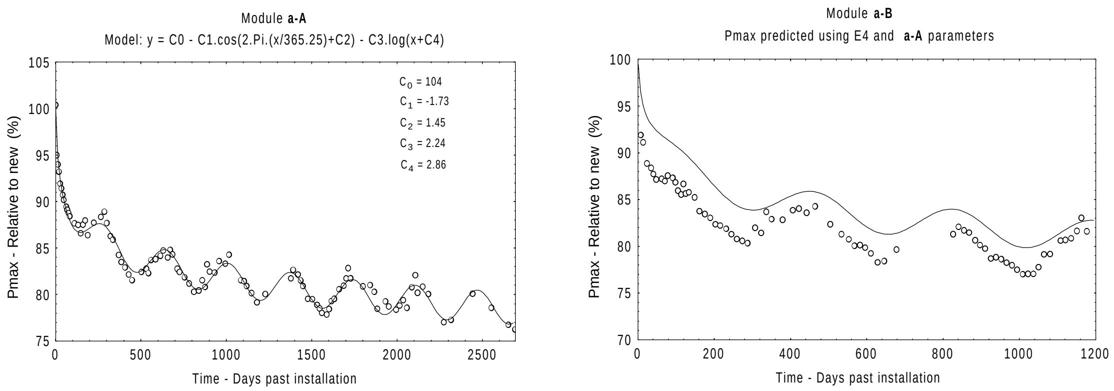
$$P_{max} = C_0 - C_1.\cos(2.\pi.(t/365.25)+C_2) - C_3.\log_e(t+C_4) \quad \text{(E4)}$$

The time variable **t** is the cumulative exposure time in days. Models **E1**-**E3** were used to predict the underlying rate of degradation of single, tandem, and triple junction cell a-Si modules, ignoring any seasonal improvement through annealing (Gibbs&Kuhn 1990, Muirhead 1993). In general, the simple model **E1** has been capable of providing a good estimate of the degradation in single junction modules, but was less capable for the triple junction module studied.

The model described by equation **E1** was used as a basis for developing **E4**, which incorporates seasonal variations in P_{max} caused by the annealing-degrading cycle. Although this seasonal variation is not completely symmetric it is described using a cosine function of the form $\mathbf{\cos(2.\pi.(t/365.25) + \theta)}$, where θ is a phase angle to allow for the time of the year when the modules were installed. The seasonal variation was observed to be approximately constant for any one module at a given site, which simplified the final model with little sacrifice in predictive power. The fit of the model to the data, illustrated in Figure 4(a) for module **a-A** which utilizes single junction cells, is generally very good. Regression parameters of **E4** for **a-A** are provided in Figure 4(a).

[3] Considerable research into a-Si has managed to improve material stability significantly in recent years

The degree of seasonal improvement in P_{max} caused by thermal annealing is given by $2.|C_1|$. Although sufficient data were not available to draw general conclusions, it was found that the amount of annealing was smaller for the triple junction module compared to the single junction module of the same vintage, and was smaller still for the more recent tandem cell module. In model **E4** the peak in annealing will occur when the cosine function is at a maximum; that is, when $\cos(2.\pi.(t/365.25)+C_2) = 0$. The mean value of the phase shift C_2 of both the single junction and triple junction cell modules was 1.4, which corresponds to 80 days ($365 \times 1.4/2\pi$). Since both modules were installed on 25 May, the maximum value of the P_{max} cycle brought about through thermal annealing is predicted to (and does) occur 80 days earlier than this date each year, around the end of summer in Melbourne where the modules were exposed. Since annealing of the a-Si structure is caused by heating of the cell material, the end of summer is the time when annealing would intuitively be expected to start to decline.



(a) (b)

*Figure 4 Measured and predicted values of P_{max} for the **a-A** and **a-B** modules.*

A key requirement of any model is the ability to predict the values of independent data. Module **a-B** is of the same type as **a-A** but was installed at the Melbourne site 18 months later (Nov 1989). Figure 4(b) compares the estimated and measured P_{max} data for **a-B**, using the parameters derived for **a-A** and the appropriate change in phase angle C_2. The Figure shows that the model predicts the behaviour of **a-B** well except at the very beginning of exposure. It is possible that the longer hours of sunlight during summer caused a more rapid initial degradation in P_{max} of **a-B** than occurred for **a-A** which was initially exposed in winter (fewer hours of sunshine), despite the higher average temperatures which in subsequent years of exposure aid the annealing process. It is evident that the phase shift C_2 alone is not sufficient to fully account for the time of year when a module is installed, and an improved version of **E4** is required. Further conclusions to this work will be reported more fully elsewhere (Muirhead & Hawkins, 1996).

CONCLUSION

The research program described in this paper has provided significant data on the mechanisms by which PV modules fail, from which substantial improvements in module reliability have been made. Telstra's experience suggests that results from laboratory and field testing are mutually supportive, but neither should be considered sufficient alone. Results suggest that lifetimes of at least 15-20 years can be confidently expected for the majority of commercial crystalline silicon modules. The seasonal and long term degradation in amorphous silicon can be modelled with good accuracy, facilitating reliable cost-benefit analyses of potential a-Si PV projects.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the many people and organizations from Japan, Telstra, and the Australian PV industry who have contributed to the project. The permission of the Director of Research, Telstra Research Laboratories to publish this paper is also acknowledged.

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