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UV TESTING OF SOLAR CELLS: EFFECTS OF ANTIREFLECTIVE COATING, PRIOR IRRADIATION, AND UV SOURCE[1]

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ABSTRACT

Short-circuit current degradation of electron irradiated double-layer antireflective-coated cells after 3000 hours ultraviolet (UV) exposure exceeds 3 percent; extrapolation of the data to 10^5 hours (11.4 yrs.) gives a degradation that exceeds 10 percent. Significant qualitative and quantitative differences in degradation were observed in cells with double- and single-layer antireflective coatings. The effects of UV-source age were observed and corrections were made to the data. An additional degradation mechanism was identified that occurs only in previously electron-irradiated solar cells since identical unirradiated cells degrade to only 6±3 percent when extrapolated 10^5 hours of UV illumination.

INTRODUCTION

Previous testing (1989–1990) of INTELSAT VII preflight cells, performed under contract to MITSUBISHI, had indicated an unexpectedly high degradation to double-layer antireflective (DAR)-coated cells when compared to single-layer antireflective (SAR)-coated cells in the same test. If real, such high degradation would eliminate any advantage of using DAR coatings in space. A second extended ultraviolet (UV) degradation test (>3000 UV sun hours or UVSH)* was therefore conducted on covered, unirradiated and electron irradiated, solar cells provided by INTELSAT.The two tests had identical procedures and equipment, but a few things were changed in the hopes of identifying a possible source of the high degradation observed. First, the cells were limited to a 60°C infrared (IR) soak prior to start of UV exposure. This IR soak was used to aid outgassing of the system and heating the solar cells to prevent deposition of any outgassed contaminants on their surfaces. The earlier test was heated above 80°C since temperature coefficient measurements up to 75°C were to be made of these cells before and after the UV test. One vacuum chamber in the earlier test had produced visible contamination of the quartz window and solar cells when heated to 85°C for an extended period. Second, the UV test was conducted at 40°C rather than the 63°C of the earlier test. This was done to reduce possible contamination from the system over time, and to bring the test temperature closer to that of tests performed during the last 15 years. Third, a small set of unirradiated test cells was included in the UV test along with the electron irradiated cells. The earlier UV test had been conducted using only irradiated test cells from a prior 1 MeV-electron degradation test. Fourth, a larger group of SAR control cells (4 rather than 1) was included in the test to confirm and quantify the observed difference in shape between the DAR and SAR solar cell degradation curves of the earlier test. The DAR-coated cells, which displayed a lower degradation rate up to 2000 hours of UV, degraded more rapidly thereafter and, when the data were extrapolated, they indicated nearly twice the degradation at 10^5 hours.

The similarities in the two test procedures and solar cells allowed a confirmation of the earlier test results and pointed to a failure of the DAR coating to survive a space-UV environment. The differences that were introduced allowed

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[1] Work sponsored by the COMSAT Corporation.

*One UV sun is the UV content of 1 sun air mass zero (AM0). To get proper UV output from the UV source, no filters were used. This results in an excess intensity in the near-infrared region which causes large differences from AM0 in the output spectrum.

identification of several effects that alter extrapolated degradation predications and raised questions about how UV testing should be conducted.

SOLAR CELL DESCRIPTION

The UV test contained three groups of solar cells: Group 1—10-Ω-cm AEG (now Telefunken System Technic [TST]) INTELSAT V cells; Group 2—2 Ω-cm AEG DAR-coated INTELSAT VII primary power cells; and Group 3—10-Ω-cm AEG DAR-coated INTELSAT VII battery charge cells. The INTELSAT V test control cells are of a type used as test controls in other UV tests performed by COMSAT, are well behaved over many years of testing, and were included in a 23,000-hr UV test. These are SAR-coated cells and have always displayed a monotonically decreasing degradation with UV exposure.

Eleven 2-Ω-cm cells were selected from a larger set of 1-MeV-electron irradiated cells and their unirradiated controls. Four 10-Ω-cm cells were all irradiated to 1.2×10^{15} 1-MeV electrons/cm^2. Prior to the UV test, all INTELSAT VII cells had been exposed to at least 24 hours of 60°C annealing under an infrared (IR) lamp and for another 120 hours at 65°C at the beginning of the UV test during a vacuum bake out procedure.

A single AEG INTELSAT V cell was used as an unexposed control (secondary reference) cell. During UV exposure, it was kept covered by a rotatable flap within the vacuum chamber. The flap was moved out of the way while electrical measurements were being made.

DESCRIPTION OF TEST

The UV illumination test was performed in a COMSAT-designed vacuum chamber which incorporates a UV-grade quartz window. The system was rough pumped with a turbomolecular pump system (pressure at 10^{-6} torr) prior to starting the UV system and was operated continuously throughout the test with an ULTEK Model 202-2500 ion pump at a measured pressure of less than 10^{-6} torr and temperature of 40°C ($<2 \times 10^{-6}$ torr at the very start of test).

UV illumination for the test was obtained with a Kratos LH 153 source (1-kW bulb). Intensity levels were checked several times each week using a pyroheliometer covered with a calibrated UV bandpass filter and a quartz cover (to compensate for window reflection in the vacuum system). Intensity adjustments were made when necessary. Beam intensity did not deviate across the test cells by more than ±10 percent.

A Hewlett-Packard computer and data acquisition system was used to monitor test parameters and to measure solar cell current/voltage (I/V) curves. The measured parameters used for comparison during the tests were short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}). These measurements were made while the solar cells were illuminated with a Spectrolab X-25L solar simulator maintained at one sun AM0 using a primary solar cell standard. An internal control cell (mounted inside the test chamber) was shielded from the UV light source and only exposed to direct light while I_{sc} and V_{oc} measurements were being made on the solar cells under test.

After being installed with low-temperature solder on the vacuum chamber baseplate (water heated during the test), each solar cell was measured (without window) at 40°C ± 0.5°C using the X-25L solar simulator (prior to pumpdown). Additional I_{sc} measurements were made under vacuum before and after an infrared bake-out (≥65°C) for 120 hours, prior to exposure to UV. All I_{sc} measurements could be corrected with the internal control cell current (measured within 10 ms) to average out any short-term effects of X-25L light intensity fluctuation with time. Multiple measurements, taken 24 hours after the bake-out and averaged, constitute the initial (1 UVSH) measurement. Vacuum was not broken until after final measurements at the conclusion of the test.

Measurements were performed on cells *soldered* to the test fixture to improve temperature control and electrical reproducibility of the data. Initially, full I/V measurements of each solar cell were made to determine cell fill factors, hence I_{sc} measurement reliability. This technique required 30 seconds per cell measurement and as much as 5 minutes between cell measurements. The normal test measurements were performed automatically by computer, scanning only the V_{oc} and I_{sc} of each solar cell, a process which takes about 20 seconds for the full set of cells. Each cell was measured 10 times, and the results averaged, to create a data point. Cells were in open-circuit condition while under UV illumination.

TEST RESULTS

UV degradation resulting from the test, after 3,340 UVSH, for the three groups of solar cells was: 2 Ω-cm primary power cells, 3.0 ± 0.2 percent; 10-Ω-cm battery charge cells, 3.8 ± 0.2 percent; and 10 Ω-cm AEG SAR-coated test control cells, 3.5 ± 0.2 percent. The error limits represent extremes of statistical error of the mean values for each cell type, but does not include systematic error or variation in the individual cells (typically <±0.5 percent). The degradation of these control cells in other tests (for approximately 2,500 UVSH) was 3.2 ± 0.7 percent (systematic error included). The test-control cell results thus fall well within the range of similar cells in previous tests.

Comparison of the SAR- and DAR-coated cell test averages (Figure 1) indicate the reason for our concern about DAR-coated cells. The impact on results extrapolated to 100,000 hours (11.4 years) is particularly disturbing if the last few points (>3000 UVSH) are included. Figure 1 also includes a difference curve comparing the 2- and 10-Ω-cm DAR cells (2 minus 10 Ω-cm). The last data point for each cell type is the average of five readings from 3102 to 3342 hours. The error bars indicate the extreme values for the measurements. This format is used here to keep the plot from being cluttered in a region where the data crowd together and overlap. Note that the error limits are on the order of ±0.25 percent.

UV DEGRADATION DATA

Results of the test are plotted along with extrapolations to 100,000 UVSH that encompass two cases. First, the extrapolated degradation based on a simple curve fit to data <3000 UVSH is plotted for each cell type (Figure 2). Second, the extrapolations, including the data >3000 UVSH, are provided (Figure 3). The differences in curve shape between the SAR- and DAR-coated cells are striking. First, the DAR cells appear to increase in I_{sc} during the first 100 hours, whereas the SAR cells degrade during this period. Both type cells degrade at about the same rate during the next 1000 hours, but the DAR-coated cells begin to degrade at a higher rate over the next 2000 hours. While the actual degradation after 3000 UVSH is similar for both cell types, the rate of degradation, which strongly affects extrapolated values, is of greater importance.

DISCUSSION

In a comprehensive and extended (>3000 hour) UV degradation test of DAR-coated silicon solar cells, both systematic and experimental errors were detected. Four sources of error were determined (Appendix A) to warrant correction.

- The greatest source of uncertainty resulted from the use of electron irradiated cells for the UV test. Contrary to expectation, the UV degradation was much more severe for such cells. This effect was identified and found to be extensive (nearly a factor of two), but quantitative evaluation cannot yet be made since only three nonirradiated DAR-coated cells were exposed to UV during this test.
- The second most important correction is related to the age of the UV source bulb. Degradation to the solar cell stack is greatest when the bulb is new. While the actual changes in cell current are not greatly affected by changes in the degradation rate, the extrapolated values can be strongly affected (by as much as a factor of two).
- The third major correction is also associated with prior electron irradiation damage. UV degradation is defined in terms of percent degradation of short circuit current or 100-percent $\Delta I_{sc}/I_{sc}$. Since the irradiated cells averaged 15-percent less I_{sc} than did the unirradiated cells, the percent degradation of these cells is calculated to be 15-percent higher.

- The last correction accounts for contamination and subsequent darkening on this contamination on the cells and vacuum system quartz window during the test. The correction is assumed to be twice the degradation observed by the internal control cell for the window alone.

CONCLUSION

Figure 4 is the corrected average data and fitted curves for the 2- and 10-Ω-cm DAR-coated INTELSAT VII solar cells, along with the unirradiated SAR-coated AEG cells from the INTELSAT V program used as exposure controls. The modifications made to correct the data are: a shift in the time base, a reduction of the electron irradiated cell degradation by 15 percent, and a subtraction of twice the control cell degradation from the test cell data. An unirradiated subset of the 2-Ω-cm DAR-coated cells is shown separately, to indicate the magnitude of the difference between irradiated and unirradiated cells. Being a smaller group, its error limit is percentage-wise greater, but there is little possibility of overlap in the two data sets.

Conclusions of this report are as follows:

- Previously irradiated DAR-coated solar cells made from 2-Ω-cm Wacker silicon degrade more severely than do identical, but unirradiated, cells.
  - Unirradiated 2 Ω-cm 6±3 percent at 10^5 UVSH
  - Irradiated 2 and 10 Ω-cm 11±3 percent at 10^5 UVSH
  - Unirradiated SAR 10 Ω-cm 6±1 percent at 10^5 UVSH
- The use and age of UV source bulbs and optics must be controlled to prevent major errors in extrapolated data.
- The use of linear-linear plots can no longer be condoned in predicting UV degradation for extended missions. Extrapolated results of data plotted with such scales can be an order of magnitude off.
- There appears to be no statistically significant difference in UV degradation between the tested 10- and 2-Ω-cm solar cells. Although such a possibility is suggested by the data in this test, it is not the case in Reference 1. (The 2-Ω-cm DAR-coated cell average data in Figure 4 of this paper includes unirradiated cells.)
- A preference of UV testing for irradiated vs nonirradiated solar cells has not been established. Material type has an effect and crucible-grown silicon may not display any difference.
- Contrary to predictions based on the initial analysis of test data, we can no longer unequivocally claim that DAR coated cells degrade under UV more than do SAR-coated cells when extrapolated to 10^{-5} hours.

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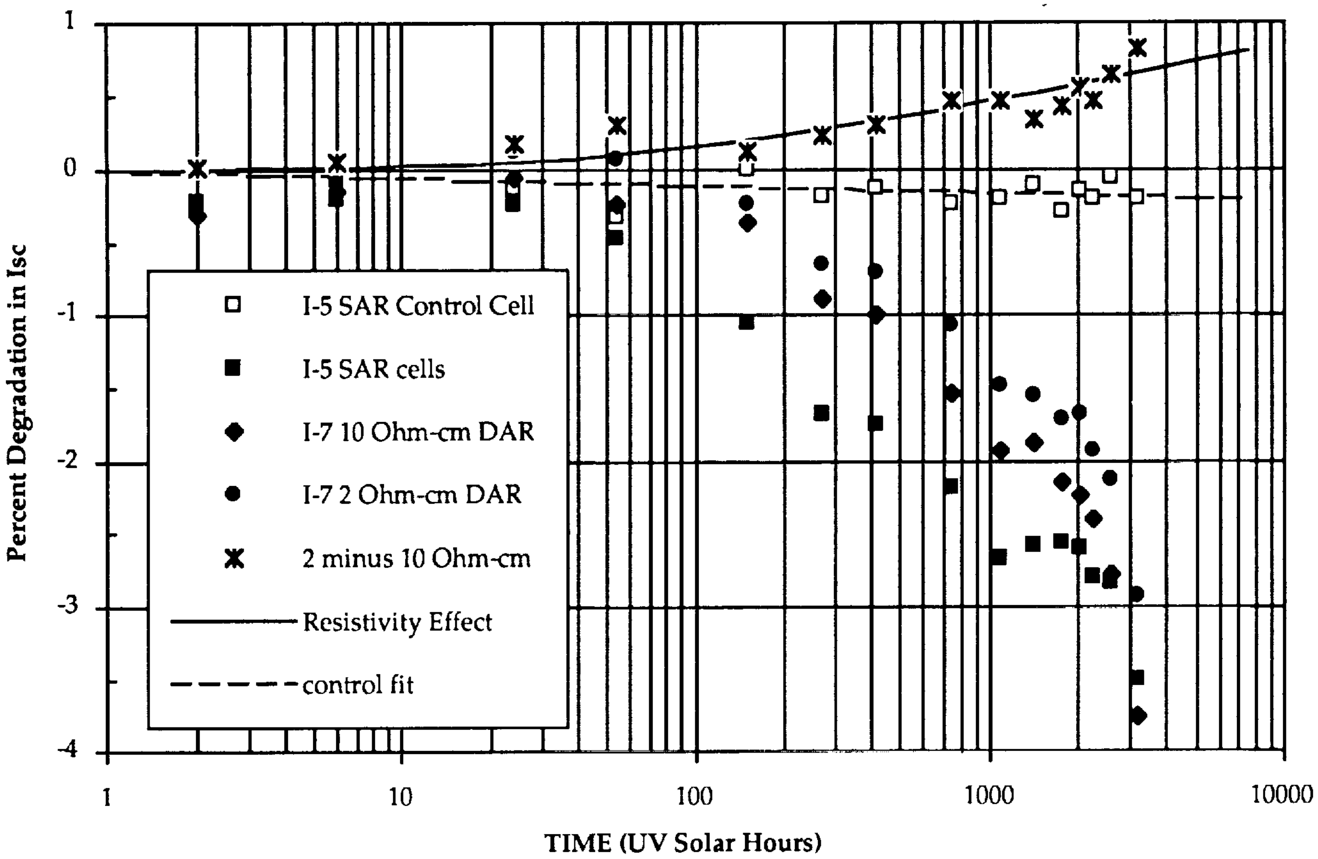

Figure 1. Raw data for UV degradation test (plus a difference curve)

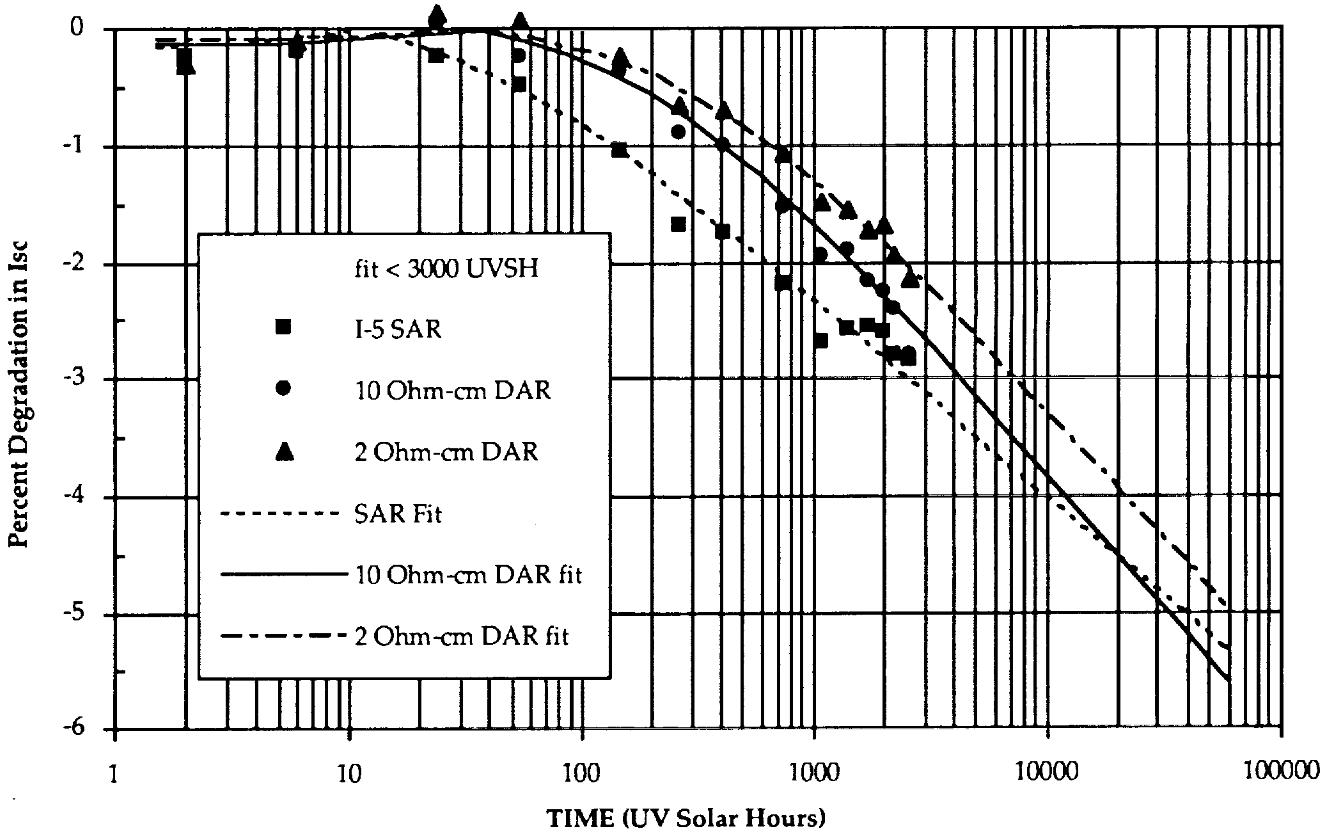

Figure 2. UV degradation for INTELSAT VII and AEG INTELSAT V cells for data <3000 UVSH

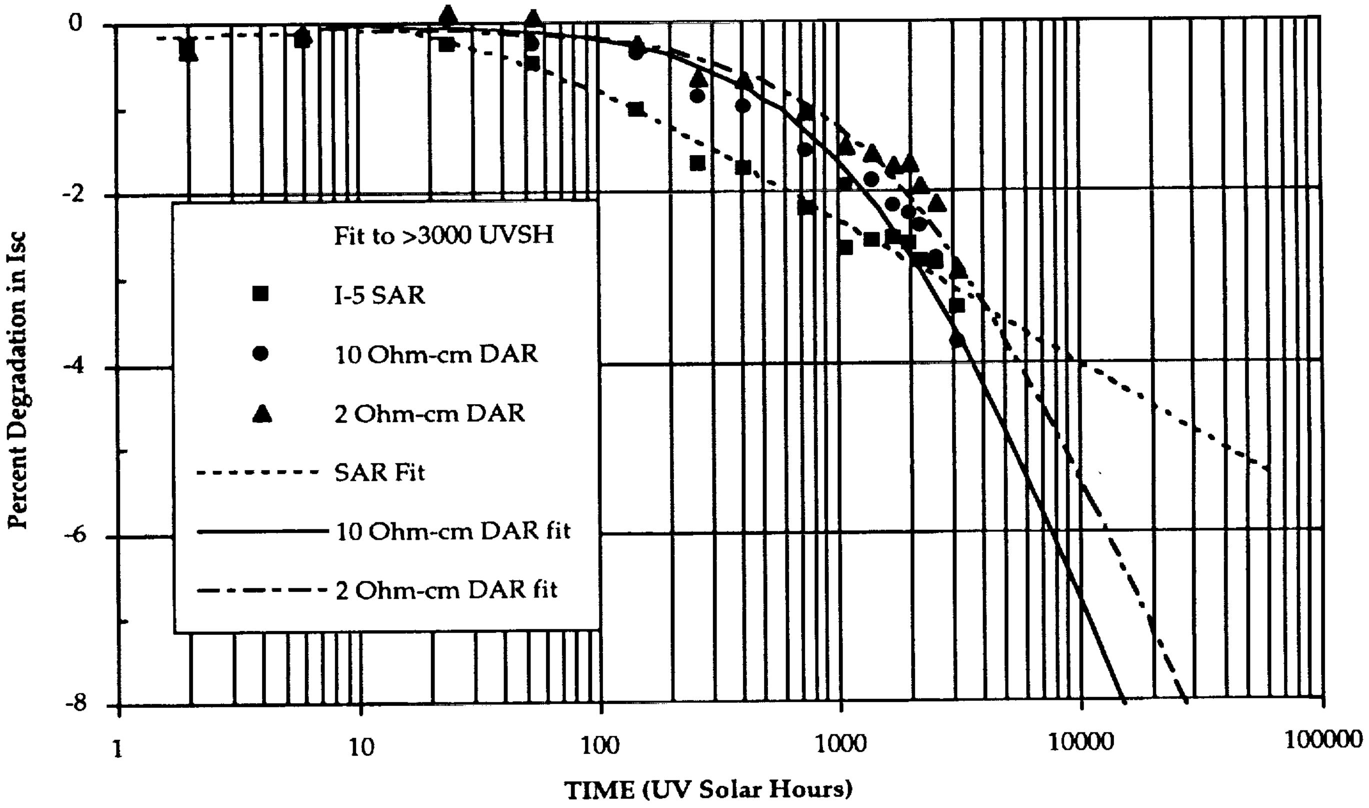

Figure 3. UV degradation for INTELSAT VII and AEG INTELSAT V cells including data >3000 UVSH

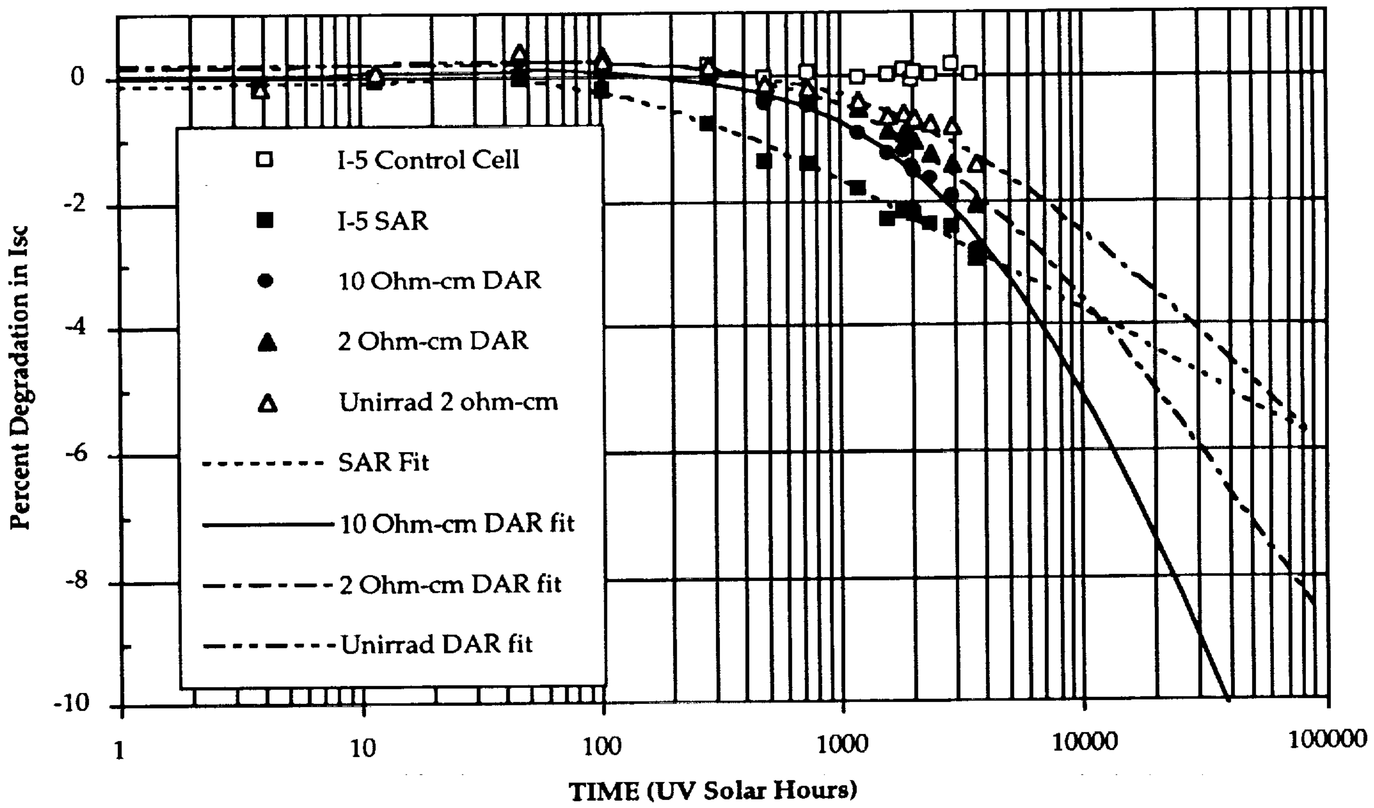

Figure 4. UV degradation (with modifications) for INTELSAT VII DAR and INTELSAT V SAR cells

APPENDIX A

CORRECTIONS TO DATA

Before analyzing the differences in results for the two cell types, it is important to examine the similarities (to determine systematic errors) and to determine the statistical fluctuation to be expected in the data. The fluctuation in results for the single AEG unirradiated internal control cell is less than ±0.2 percent (Figure 1). If this is purely statistical, then the average of *n* cells should be 0.2 percent/$n^{1/2}$. Thus the four SAR and four 10-Ω-cm DAR cell averages should fluctuate about the best fit by about 0.1 percent and the average of eleven 2-Ω-cm DAR-coated cells by 0.06 percent. It is clear from Figures 2 and 3 that the larger cell samples do not have smaller fluctuations about the fitted curves as drawn. Therefore, a combination of statistical and systematic errors must be present. If systematic errors from the solar simulator strongly dominated, then the data could be safely normalized to the control cell. However, the other data sets would then display the statistical uncertainty of a single cell. A fitted curve through the internal control cell data reduces the apparent statistical error and indicates at least one component of systematic error. Temperature stability over the test period and during measurement is within ±0.25°C; hence neither statistical nor systematic error can be attributed to this source.

CONTAMINATION

The systematic error displayed by the non-zero degradation of the internal control cell is less than 10 percent of the degradation observed in the test cells. If the source of this control cell degradation is contamination buildup inside the quartz window, then a similar layer is probably building up over all of the window and all of the cells. Since the control cell does not see UV light (except for the brief periods during electrical measurement), the contamination on its surface will not darken as much as that on the window and other cells would. Therefore, the degradation measured for the control cell is about only one-half that likely to be observed from this source on the other cells.

Correction for this systematic error would affect both SAR- and DAR-coated cells. A realistic correction would be to fit the internal control cell data with the same degradation function as used for the test cells (since it fits many different types of cells) and then subtract twice this value from the test cell results. Such a correction is made in the Conclusion.

SOLAR SIMULATOR SPECTRUM

Other systematic errors must be examined. A change in solar simulator spectral output with time could cause only the test cell outputs to decrease during the test, but this is unlikely since the test cells, the control cell and primary reference cell all have different, but similar, spectral responses. A feature in both SAR- and DAR-coated cells is the unusual curve shape beyond 1000 hours. Elimination of the data point at 1100 hours reduces the anomaly to some extent but does not resolve it. Therefore, a number of nonstatistical error sources have been examined in detail to better determine the true shape of the curves (and their extrapolated values) as well as to identify sources of the difference between SAR- and DAR-coated cell degradation.

RADIATION DAMAGE

The INTELSAT VII test cells, experiencing UV exposure, displayed a loss of voltage with time (2.5 mV average). The expected loss in V_{oc} for a 5-percent loss in I_{sc} is $\simeq$1.3 mV, which is confirmed by the changes in voltage of $\simeq$1.5 mV observed when the quartz window is removed and replaced ($\Delta I_{sc} \simeq 5$ percent) at the end of the test. However, the change in I_{sc} of 3–4 percent for the cells under test resulted in an average change in V_{oc} of over 2 mV for the INTELSAT VII cells and less than 0.4 mV for the INTELSAT V cells. In examining the data, a pattern was observed. The INTELSAT VII cells had been irradiated with a few exceptions. These exceptions (some of the 2-Ω-cm cells) were degraded in I_{sc} like the irradiated cells; but, they displayed the same low drop in V_{oc} as did the INTELSAT V cells which also were not irradiated.

With this distinction, a clear separation in the extent of UV degradation to I_{sc} between the irradiated and unirradiated cells is possible. If no distinction is made, the maximum cell-to-cell variation in I_{sc} of the 2-Ω-cm cells at 2000 and 3300 UVSH is ±1.5 percent. However, after separating the groups (Figure A-1), the difference between the groups at 3300 hours is 1.4 percent (~1.9-percent degradation for the unirradiated group VS ~3.3 percent for the irradiated) and the unirradiated group (three 2-Ω-cm cells) group has a maximum internal variation of ±0.5 percent. While one irradiated cell has less UV degradation than the average of the three unirradiated cells (data not shown), the difference between the groups is clear.

The four 10-Ω-cm INTELSAT VII cells (which were all irradiated to $1.2 \times 10^{15} e^-/cm^2$) had a spread in UV degradation of only ±0.5 percent and the four unirradiated INTELSAT V cells had a spread of less than ±0.3 percent. The larger set of 2-Ω-cm cells has a larger spread in degradation, as expected. Since the numbers of cells in any group is too small for statistical analysis, no standard deviation for cell variance can be calculated. The 2-Ω-cm set contains four levels of irradiation ($0, 8, 10, 12 \times 10^{14}\ e^-/cm^2$) but, other than with the unirradiated cells, no correlation can be made between UV degradation and electron dose. However, there is a strong correlation between the change in open-circuit voltage and the change in short-circuit current under UV exposure. This implies that the internal radiation damage to the solar cell itself is affected by extended UV exposure. Since the UV does not penetrate to the cell junction, the change in cell output would be dominated by the n^+ surface layer and its interface with the AR coating. However, the dominant term affecting V_{oc} in 10-Ω-cm cells is from the base, or p-layer. Therefore, a change in surface layer is not likely to strongly affect V_{oc} in 10-Ω-cm cells as it would affect 2-Ω-cm cells which are less base dominated. (The 2-Ω-cm cells are affected by both base and emitter, or surface regions.) Since the 10-Ω-cm cells show an effect as strongly as the 2-Ω-cm cells, the possibility of influence from the longer wavelength (more penetrating) component of the UV source must be considered.

Such photon redegradation was first reported in 1972 [1] for 10-Ω-cm float zone silicon solar cells and shown to be related to the bulk minority carrier lifetime. Crabb later reported [2] that dopant type (and levels) and dislocation density of the starting material was important and that the effect (up to 8-percent change in I_{sc}) saturates within 24 hours at 60°C. Space data indicated the need to produce such photon redegradation during electron irradiation tests to best predict array degradation. Fisher and Pschunder [3] confirmed the effect in 1-Ω-cm crucible-grown material (but to a lesser extent) and noted a reversible effect in this material prior to irradiation. In addition, they [4] found a correlation between carbon and oxygen content and photon stability in float-zone solar cells. This material difference showed up in our 1989 test where Shinetsu-supplied silicon was compared to Wacker silicon when made into solar cells by AEG and then electron irradiated and exposed to UV light.

Figure A-2 demonstrates the correlation between degradation in I_{sc} and in V_{oc} with UV exposure. Two groupings are observed. The data with least change in V_{oc} consists of the unirradiated 2-Ω-cm DAR and INTELSAT V (SAR) cells. A second group consists of the electron irradiated 10-Ω-cm DAR cells and most of the irradiated 2-Ω-cm DAR cells.

The major change in V_{oc} occurs between 200 and 1000 hours. At 270 hours (Xs in Figure A-2) the groups are already beginning to separate. The four cells in this set with highest change in I_{sc} are the SAR-coated cells. The three cells with lowest change in V_{oc} are the three unirradiated DAR cells.

UV SOURCE AGE

In examining the data to determine why the UV degradation appears to increase strongly beyond 2000 UVSH, one source of systematic error stood out. This was the fact that the quartz-xenon bulbs, used to provide ultraviolet light, normally last about 2000 hours. As they age, the UV output decreases and the source input power must be turned up. The bulb manufacturer feels that the worst degradation (from tungsten electrode sputtering) occurs in the region near 0.35 μm; just the region where the coverslide adhesives, and perhaps the AR coatings, are most sensitive to degradation. Since the simulator UV output is set with a filtered detector (~0.30 to 0.47μm), adjustments to maintain a constant solar UV level are, in fact, not valid for the short wavelength region which has lower power than the upper portion of the filter passband.

To correct for this effect, a first order adjustment was made to the UVSH values which were originally considered linear with time of exposure. The algorithm used is to multiply any increment of UV bulb use by (1.9–0.9t/1000) UVSH/bulb hours, where *t* is the average number of hours on the bulb during that increment. This means that a new bulb will provide 1.9 UVSH for each hour of use. UV solar hours from a bulb at 1000 hours will have a 1 to 1 relationship with exposure hours and at 2000 hours a 0.1 to 1 relationship. Figure A-3 displays four models of UV source degradation with age of the bulb. The 1:1 curve assumes that the UV detector used to establish the UV source intensity properly reflects the damaging component of the output spectrum. Consequently, adjustments in UV source input power, to maintain a fixed UV level on the cell surfaces, would be correct. The other curves assume that, despite the increases in source power made as the bulb ages, the damaging UV light output decreases with bulb age. The abrupt rise in these curves at 2100 hours results from a change of bulbs. The nonuniformity in the curves is a consequence of the approximation made in calculating the effective bulb age between measurement points. The 1.9:1, and 3:1 initial value curves fit the test data best. This implies that little or no damaging UV remains to a bulb by 2,000 hours.

Figure A-4 shows the combined DAR cell average plotted against hours exposure (A) and against corrected UVSH (B and C). It is possible to fit the corrected data with a single function (B or C), but the uncorrected data deviates greatly (± 0.5 percent) from such a fitted curve (A). While the algorithm for the effects of bulb degradation is crude (a linear fit for B) and the actual values selected are somewhat arbitrary, the model provides some insight into expectations for most UV testing. A nonlinear relationship (C) is included to provide a greater initial ratio (3:1) while still permitting some effect beyond 2000 hours (0.2:1). [UVSH /exposure time = $3 - 2(t/1000)^{1/2}$]. In comparing the latter two relationships, it is seen in Figure A-3 that they really are not that different beyond the first 500 hours of bulb life.

EXTRAPOLATION

In most UV testing, the exposure is limited to 1000 UVSH and the results are plotted against a linear time scale. The UV lamp is generally changed prior to the test so that degradation rates are higher at the beginning. Figure A-5 is the first 2000 UVSH of the SAR and DAR cell percent degradation plotted against the time on a linear scale. Looking at these data allows one to understand the reported claims that UV degradation is saturated by 1000 UVSH and that DAR-coated cells display less degradation than do SAR-coated cells. Figure A-6 compares the fitted curves for these cell types, corrected for statistical fluctuation and the slight degradation in the control cell and plotted against corrected UVSH. While the SAR cells still appear saturated near 2000 UVSH, a claim for saturation of the DAR cells now becomes untenable.

While the DAR-coated cell data (beyond 2500 hours) indicate degradation to be less than the linear fit provided in Figure A-6, a somewhat less severe linear degradation does fit (within ±0.3 percent) the modified-time-base data out to 4000 hours. Linear extrapolation of these data to 10^5 hours would indicate above 50-percent degradation at 10 years. While the linear fit-to-data is better than that of a saturated model, the extrapolation based on either assumption is unacceptable. The simple function, used in our best estimate of extrapolated UV degradation, has been found to fit results of nearly all our tests, even those of a 23,000 hour test; therefore, we feel comfortable using it here.

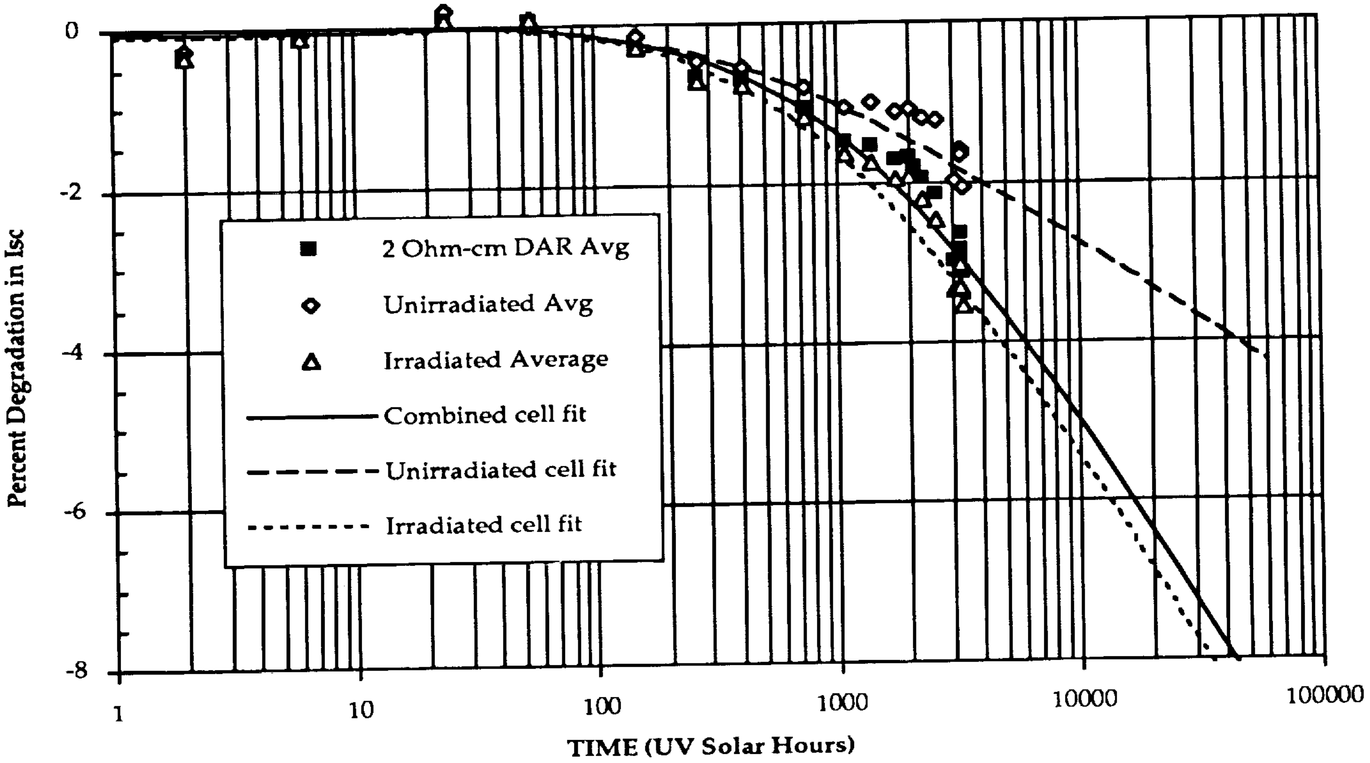

Figure A-1. UV degradation of electron irradiated and nonirradiated cells

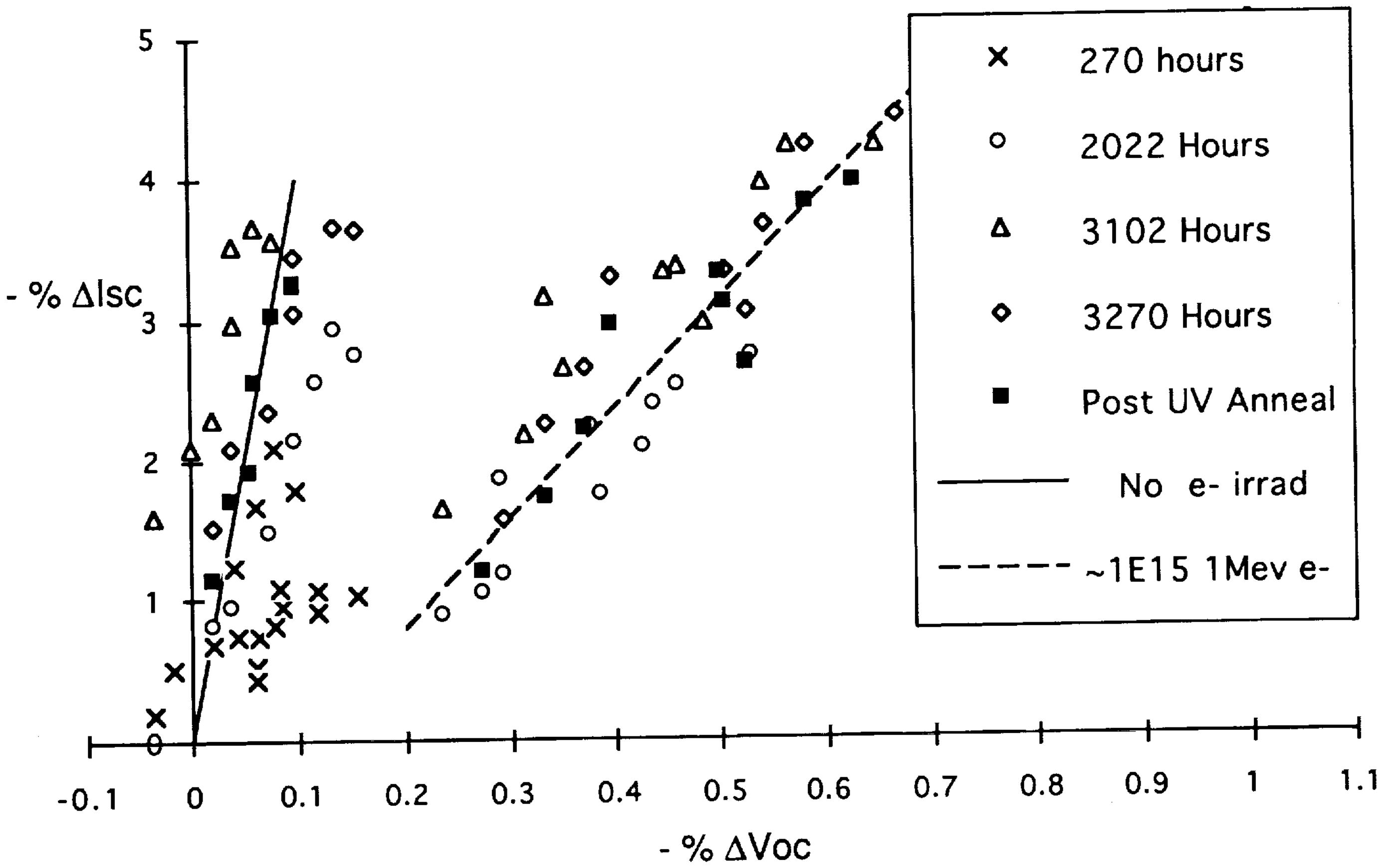

Figure A-2. ΔV_{oc} vs ΔI_{sc} during UV test and anneal

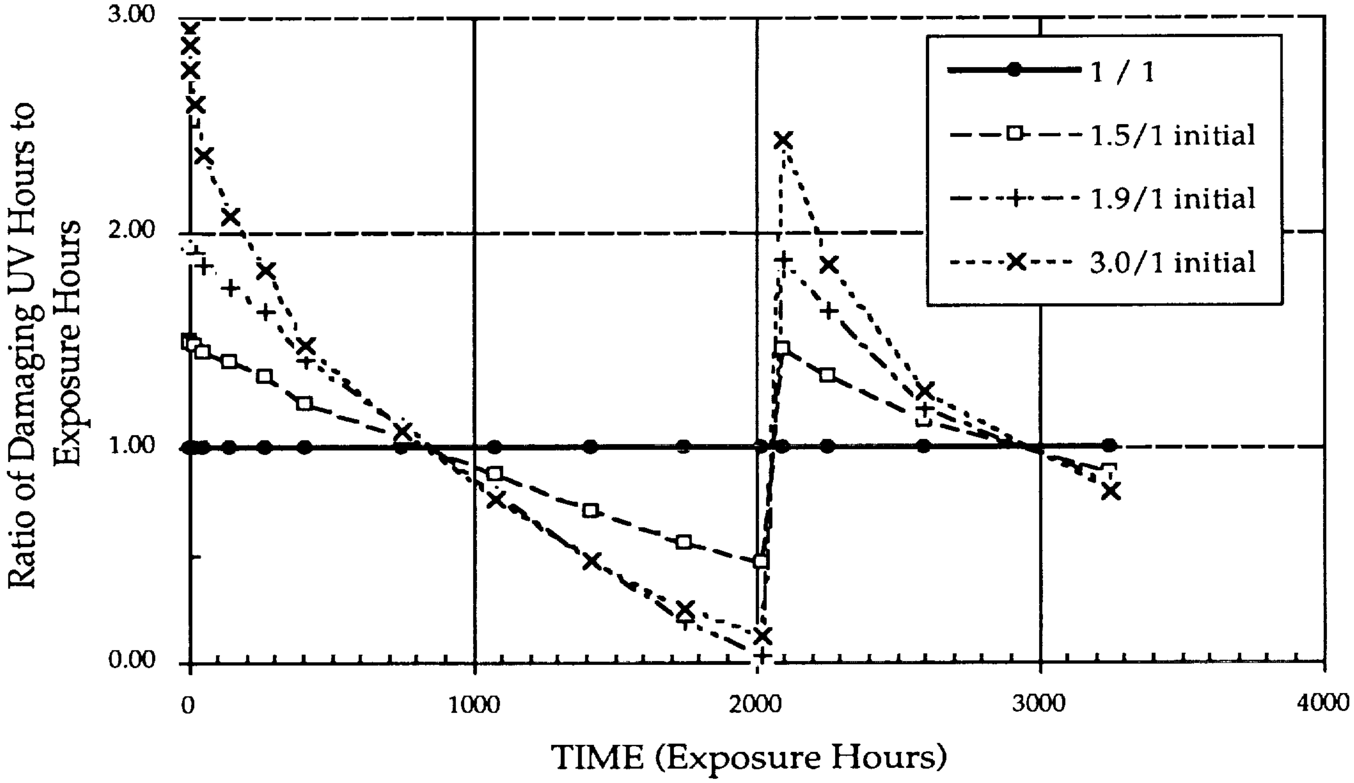

Figure A-3. Four models of UV simulator damaging radiation as a function of time

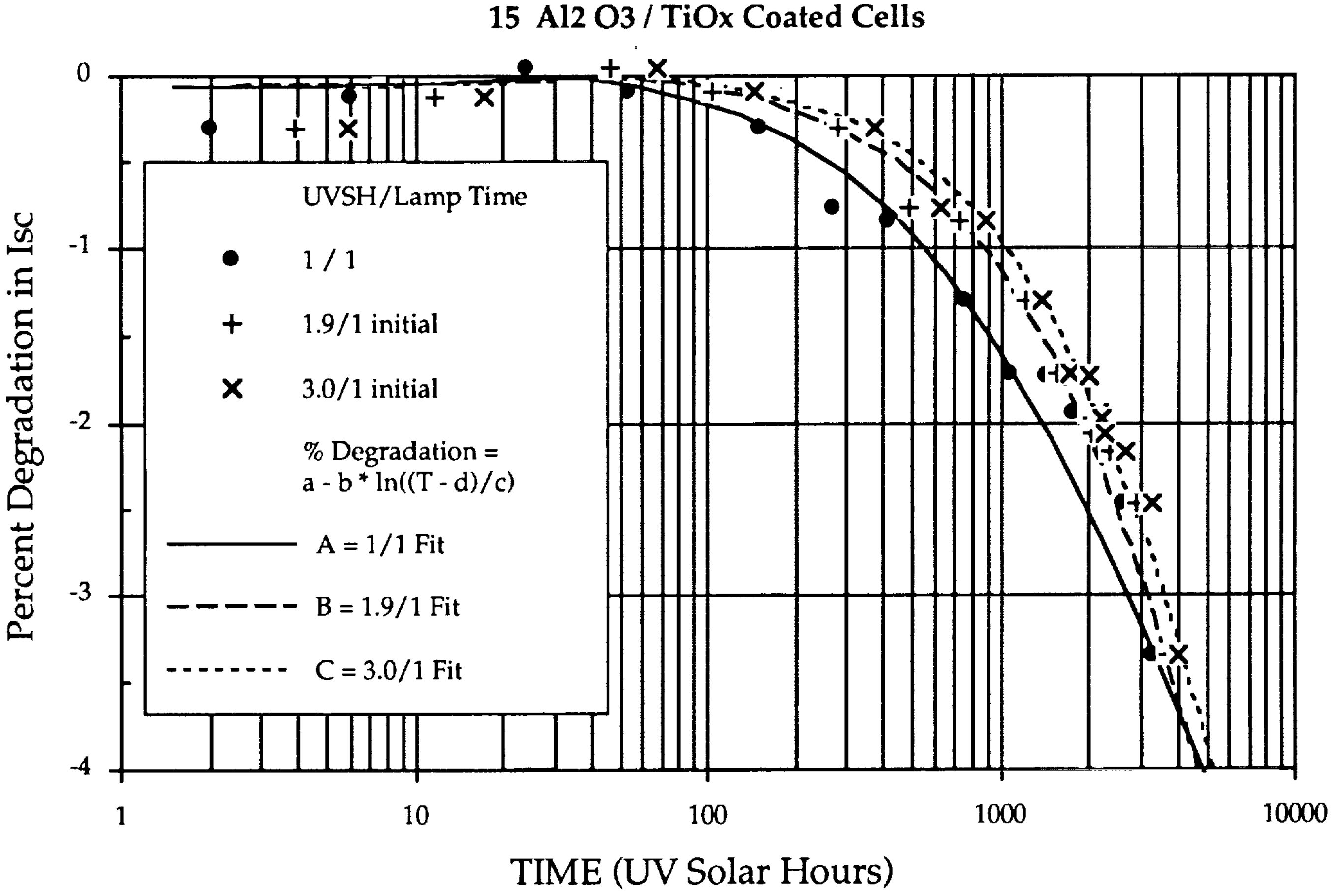

Figure A-4. DAR-coated solar cell data with corrected time bases

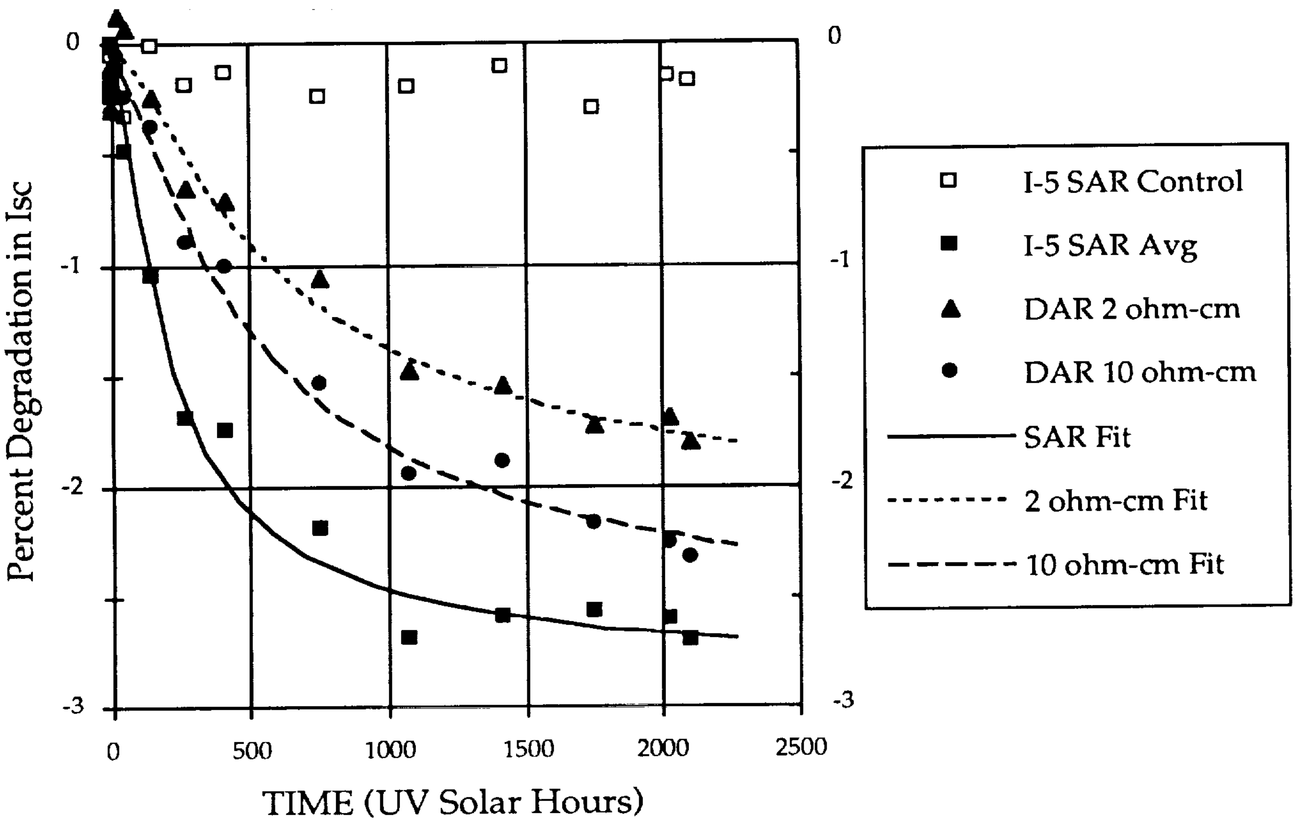

Figure A-5. Degradation from first UV lamp, on a linear scale

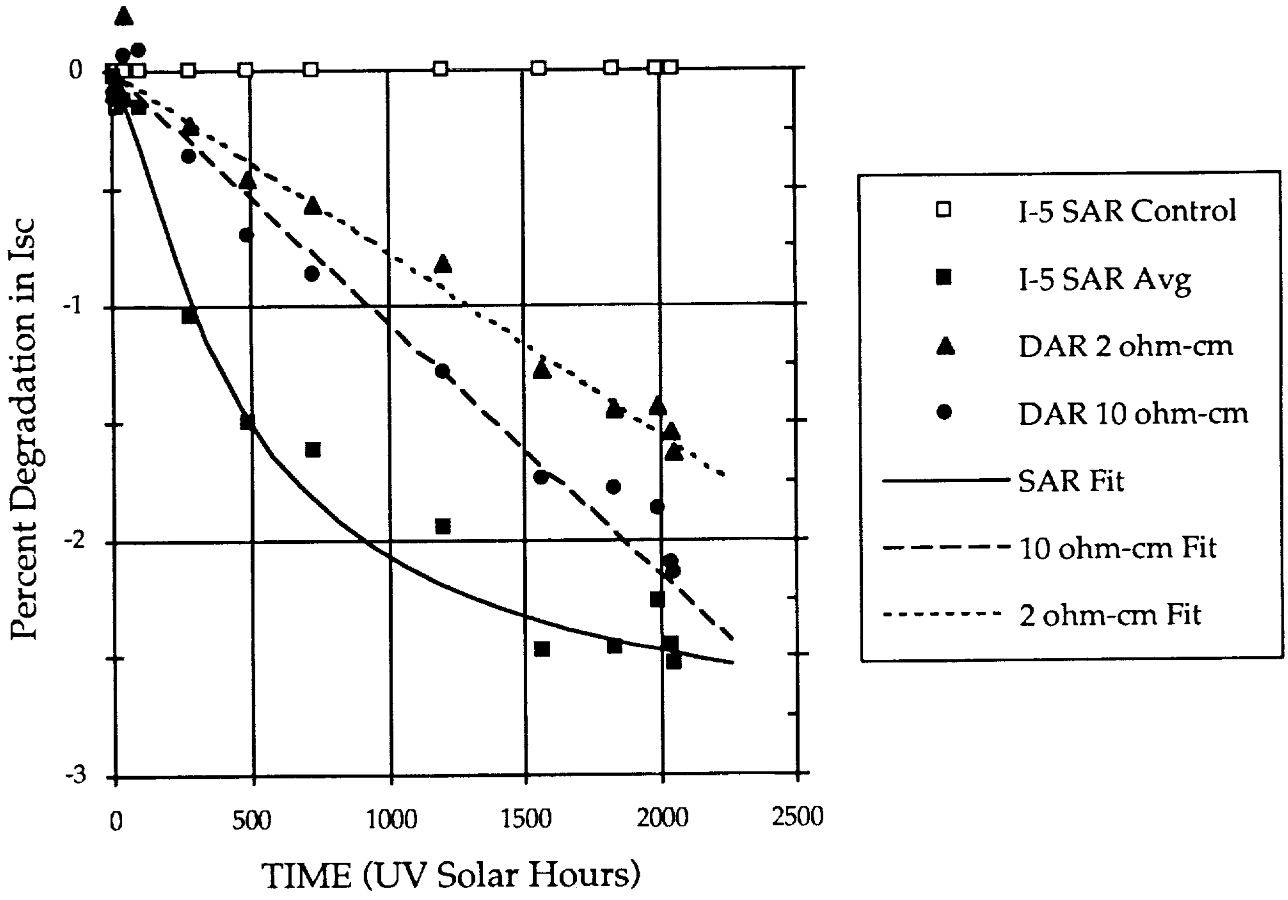

Figure A-6. Normalized and time base corrected degradation from first UV lamp, on linear scale