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THE UoSAT-5 SOLAR CELL EXPERIMENT - FIRST YEAR IN ORBIT

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This paper describes the results for the first year in orbit of the DRA solar cell experiment flying on the Surrey University UoSAT-5 satellite. Several problems have been identified with the measured data, which are discussed along with the techniques used to remove or minimise the effect of the problems.

After 1 year in orbit the majority of the cells flying on the experiment have undergone little or no degradation. The exception to this are all the ITO/InP cells, supplied by two different manufacturers, they are showing more degradation than the GaAs cells. This result is unexpected and currently unexplainable.

It will be necessary to retrieve data from the experiment for several years to obtain the best results due to the relatively benign radiation environment.

1. INTRODUCTION

The solar cell experiment on the UoSAT-5 satellite was launched into a 770 km Sun Synchronous orbit on 16 July 1991 on an Ariane 4 launcher as a secondary payload to ERS-1. UoSAT-5 is a 50 kg microsatellite manufactured and controlled by Surrey University (ref. 1). The satellite is powered by three Spectrolab GaAs/Ge solar panels and a half panel of EEV IMLPE GaAs. The remaining half panel was used for the solar cell experiments.

The experiment consists of various types of silicon, gallium arsenide and indium phosphide solar cells from the UK, Europe and the USA, see Table 1. The purpose of the flight is to compare the performances of these various cell types in the space environment and to determine whether there is any degradation of different types of Pilkington coverglasses and coatings.

2. DATA

The data received back from the satellite are corrected to a temperature of 25°C and to an intensity of 1 solar constant (135.3 mW/cm^2). After processing the first batch of data it quickly became apparent that there were several problems: firstly the I-V curve was measured incorrectly as it approached Voc. It was also found that the temperature resolution was 6° rather than the specified 2° and there was a large scatter in the day to day current, voltage and power values.

Instead of a 2° resolution and a temperature range centred around 0°C, due to a misunderstanding the temperature range was set to cover the maximum and minimum temperatures of the satellite and not the temperatures of the solar cell experiment. When the temperature measurement was checked on the ground the room temperature unfortunately coincided with a temperature at which the bit count changed and so this problem was not noticed. Attempts to improve the resolution by calibrating the temperature sensors of the cells against other temperature sensors on the panel have been made, all of which have proven to be unsatisfactory.

The incorrect I-V curve gives a higher Voc value than is expected. Surrey University, who designed and built the electronics package, undertook some fundamental modelling work on the circuit and its interaction with the solar cells. The conclusion from this was that the difference was due to the slope resistance as one moves down the curve. Due to the measurement speed there is insufficient time for the current to stabilise at a voltage point and hence the measured current is higher than it ought to be. Unfortunately this was not identified in the ground testing.

A large part of the data scatter on Voc and to a lesser extent Pmax can be attributed to the measurement problems discussed above, the scatter on the Voc values is typically 10-20 mV, but the scatter on the Isc values is due to Earth albedo, giving rise to current variations of up to 6-7%.

The position of the satellite relative to the Earth was determined when each measurement was made in order to assess what landmass or ocean was in sunlight and visible to the satellite. The solar cell experiment measurement conditions are met when the satellite is nominally over the North or South Poles ±23° due to time of year, and the stability of the spin axis of the satellite relative to the sun. This showed that in most instances there is the possibility of earth albedo affecting the experiment. However in the early phase of the mission the solar cell experiment was activated and measurements made when the satellite had not been fully stabilised and several measurements were made when the likelihood of albedo was very small.

On the experiment are three cells which are heavily irradiated Mitsubishi GaAs cells (irradiated with 10^{15} 1 MeV e/cm^2) to act as a measurement reference. By taking the average of the Isc values for these cells on the 'no' albedo days it has been possible to establish a baseline current for each of these cells. The % increase in these current values on the measurements days is then assumed to be due to albedo. This value is then subtracted from the measured values to correct the data for the albedo contribution.

3. RESULTS AND DISCUSSION

Figure 1 shows the variation of Isc with time in orbit for cell 22 after correction for the seasonal variation in solar intensity and temperature, figure 2 shows the reduction in scatter after correction for albedo and figure 3 shows the data as a percentage of initial in orbit value (the in orbit value has been taken to be the average of the first 30 days measurement).

The corrected Isc values for most but not all of the GaAs cells become very similar with little scatter. However on a large number of the Si and InP cells and one or two of the GaAs cells the scatter is reduced but the data splits into two distinct bands as shown in figure 2. The upper band is typically of values measured at the North Pole and the lower band of values measured at the South Pole. The banding is thought to occur due to the difference in the spectral responses of the cells and the reference cells used to estimate the albedo and the albedo having a different spectral content between the North and South Pole.

When cells other than GaAs are used to estimate the albedo level, this banding can be closed up or the data split into bands depending upon which cell is chosen. When silicon cell 18 is used to estimate the albedo for the silicon cells, the bands on cells 14 and 22 are closed up and the scatter on the current values is small. Due to this complication and the fact that the other cells will degrade, all the data remains corrected for albedo using the GaAs reference cells.

Figures 4-9 show typical results for Si, GaAs and InP cells on the experiment, the data has been averaged every four consecutive days to aid clarity and to remove the banding introduced with the albedo correction.

3.1 Comparison with pre-flight data

Table 2 shows the comparison of the in-orbit first 30 day average values with the pre-flight values measured at DRA using a Large Area Pulsed Solar Simulator (LAPSS). All the GaAs cells were calibrated against the same GaAs primary standard solar cell, produced by DRA using a terrestrial global irradiance calibration technique in Cyprus (ref. 2). The silicon cells were calibrated against DRA silicon Cyprus primary standards chosen to match spectral responses as close as possible. Unfortunately no InP primary standard was available and so a calibration value for the LAPSS was assumed.

The in-flight values for the silicon cells are between -0.2 and +1.2% higher than predicted values, *ie.* there is very good agreement with the calibration technique. However the in-flight values for the GaAs cells are all lower than predicted ranging from -0.2% to -3.1%. Given the accuracy of the standard calibration technique, differences in spectral responses between some of the GaAs cells and the standard, and possible errors introduced by the albedo correction this is a reasonable result. The InP cell data are all lower than predicted but this is not unexpected given the lack of a standard.

All the Voc values are higher than predicted, ranging from 1-4.5%. This is to be expected given the measurement and temperature problems. The in-flight Pmax values typically vary from the predicted values by ±3% and is influenced by the difference in the Isc values and by the temperature measurement problem, given this there is a reasonable agreement between flight and predicted. This also shows that the effect of the measurement problem on Pmax is minimal.

3.2 Predicted degradation

The radiation environment has been predicted for the UoSAT-5 orbit with the UNIRAD short orbital flux integration program using the standard NSSDC proton and electron environment models for solar minimum. EQFRUX was then used to calculate the annual equivalent 1 MeV electron fluxes as a function of CMX coverglass thickness using a standard set of silicon damage coefficients. The environment is proton dominated, the equivalent electron fluxes for protons being two orders of magnitude higher. The 1 MeV electron fluences for silicon cells with a 100 micron CMX coverglass has been estimated to be:

ISC	1×10^{13} e cm^{-2} year^{-1}
VOC/PMAX	2×10^{13} e cm^{-2} year^{-1}.

The damage coefficients for Si, GaAs and InP at 10 MeV protons are typically 3000, 1000 and 650 respectively (ref. 3). By taking the appropriate ratio of these it is possible to obtain a first order estimate of the equivalent 1 MeV electron fluences for the GaAs and InP cells. From this it can be seen that the radiation environment is relatively benign for silicon cells and therefore should be even more so for the GaAs and InP cells, we do not expect to see any significant degradation from the InP cells over the life time of the mission.

3.3 Comparison of cell types

The degradation of Isc, Voc and Pmax for all the cell types after 1 year in orbit has been estimated and the results are shown in Table 3. The estimate has been made to the nearest 0.5% and where there is a + this indicates that the performance has increased rather than decreased relative to the in-orbit initial value. It was expected that the unirradiated silicon cells would have degraded the most followed by the GaAs cells and then the InP cells (little or no degradation).

Cell 9 is a typical silicon cell and has degraded by approximately 3% in Pmax, (fig. 4). Most of the GaAs cells have undergone little or no degradation. Cells 15 and 19 show no signs of degradation at all while cells 13 and 17 show only slight degradation of Pmax (100-200 micron coverglass). Cells 3, 6 and 24 are showing signs of Isc and Voc degradation of approximately 0.5% and 1.5% degradation in Pmax (50-80 micron coverglass), see figures 5 and 6.

The most surprising results are from the Indium Phosphide cells. Ground based irradiation testing (ref. 4,5,6) has shown that InP is considerably more radiation resistant than either GaAs or silicon and that homojunction (HJ) and ITO cells behave in a similar manner. This is confirmed for the HJ cells: cells 2 and 4 show little sign of degrading and HJ cells 7 and 8 are showing approximately 1% degradation in Pmax, (fig. 2). Both these cells have 50 micron coverglasses and should be compared to GaAs cells 3, 6 and 24.

ITO/InP cells 1, 12 and 16 however are totally different, the cells degrading by 1.5 to 2.5% in Pmax which is worse than the GaAs cells, (fig. 7-8). There appears however to be a difference between the different manufacturers. Cell 1, the NREL cell flown by NASA, has undergone both current and voltage degradation whereas the Newcastle Polytechnic (NP) cells have only undergone voltage degradation, in fact the current on cell 12 appears to have improved slightly. InP cells are susceptible to low energy proton irradiation but as the base material and junction depths are similar to the homojunction cells one would have expected these cells to be showing signs of degradation as well. The ITO/INP cells on LIPS 3 (ref. 7) are showing only 1% degradation after 4 years in a more severe radiation environment, although only the Isc is being measured. The unexpected NP results are currently under investigation and may be due to other factors apart from radiation.

3.4 Comparison of coverglasses

All of the Pilkington coverglasses are mounted on the same type and batch of silicon solar cell. The cells were all irradiated prior to flight with 1 MeV electrons (except cell 9) to ensure that any degradation in performance was due to either the coverglass material darkening or changes to the coating on the coverglass. Cells 9 and 23 both over-ranged on the current values during the middle 6 months data giving rise to either no data points or data subject to a very large amount of scatter.

There are no signs of degradation on the CMX, CMZ and CMX with an ultra violet rejection coating (UVR) cells after the first year, (fig. 3). Cell 23 is showing signs of current and Pmax degradation, both of 0.5%. As the cell was nominally only 1% degraded before launch this is reasonable given that the unirradiated cell 9 has dropped by 1.5% in current. There are two anomalous results, for Teflon bonded cell 20 and directly glassed cell 21. These cells are currently being investigated.

4. CONCLUSIONS

After a successful launch the UoSAT-5 solar cell experiment is returning regular data. After processing the initial data it was found that there are several measurement problems. The temperature range was incorrectly set before flight giving a resolution of 6°C and all efforts to improve this have proven to be unsatisfactory. A fundamental design flaw has been found in the electronics affecting the shape of the I-V curve especially around Voc. The effect is to give a good Isc measurement, a slight error in the Pmax and a large error in Voc. It is not possible to correct the data for this error and so the correct in-orbit Voc values cannot be determined. It is believed however that the relative change in the measured Voc values with time in orbit is still valid although they will need to be used with caution.

The data is subjected to scatter due to variable Earth albedo, estimates of the albedo intensity have been made using 3 GaAs reference cells. When these estimates are used the scatter is considerably reduced.

The ground measured Isc and Pmax values agree reasonably well with the in-flight values. The ground measured Voc values are all considerably lower than the derived in-flight values, due to the temperature resolution and the measurement problems.

When the data is displayed as a percentage of initial value and averaged every four consecutive days the degradation trend in the curve becomes much clearer. From these curves it can be seen that most of the cells are behaving generally as expected. The standard silicon cell has degraded by approximately 3% in Pmax, the GaAs cells by 1.5% in Pmax and the homojunction Indium Phosphide cells by 0-1% in Pmax. Most of the coverglass cells have not degraded as is expected.

The main anomaly however is that all three ITO/InP cells have degraded more than the GaAs cells. All results to date have indicated that they should be far superior to GaAs cells in terms of their radiation resistance and this result is completely unexpected and currently unexplainable.

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Table 1

List of Cells Flying on the Experiment

1	NASA Lewis ITO/InP (NREL cell)
2	NASA Lewis HJ InP (Spire/NRL cell)
3	NASA Lewis cleft GaAs (Kopin cell)
4	Wright Lab. (USAF) InP (Spire cell)
5	Wright Lab. (USAF) GaAs (ASEC LPE cell)
6	Wright Lab. (USAF) GaAs (ASEC LPE cell replaced by DRA)
7	NASA Lewis HJ InP (Spire/NRL cell)
8	Link HJ Inp
9	PST - CMX unirradiated Si
10	Irradiated reference GaAs
11	Irradiated reference GaAs
12	Newcastle Polytechnic ITO/InP
13	EEV IMLPE GaAs - 100 micron CMG
14	PST - CMZ irradiated Si
15	EEV IMLPE GaAs - Teflon bonded CMG
16	Newcastle Polytechnic ITO/InP
17	EEV IMLPE GaAs - 200 micron CMG
18	PST - CMX irradiated Si
19	EEV IMLPE GaAs - 0.5 micron junction depth
20	PST - CMZ Teflon bonded irradiated Si
21	PST - CMZ directly glassed irradiated Si
22	PST - CMX UVR2 coated CMX irradiated Si
23	PST - CMX high emissivity coated CMX irradiated Si
24	NASA Lewis GaAs/Ge (Spectrolab cell)
25	Ex-Cyprus standard GaAs reference
26	EML/BAe/TST MOVPE GaAs
27	TST high ETA silicon

Table 2

Comparison of the In-Flight Initial Isc Values with the Pre-Flight Values Measured at DRA

Cell No.		Pre-Flight	In-Flight	% Difference
1	INP	123.0	119.6	-2.7
2	INP	129.6	128.8	-0.6
3	GAAS	128.9	126.2	-2.1
4	INP	136.3	134.3	-1.5
5	GAAS	120.6	117.9	-2.2
6	GAAS	122.9	119.6	-2.6
7	INP	113.5	110.4	-2.7
8	INP	125.3	121.9	-2.7
9	SI	164.6	165.9	+0.8
10	GAAS	86.3	84.4	-2.2
11	GAAS	85.6	83.2	-2.8
12	INP	110.4	107.8	-2.3
13	GAAS	245.3	236.7	-3.5
14	SI	137.9	137.6	-0.2
15	GAAS	210.6	210.1	-0.2
16	INP	108.9	106.1	-2.6
17	GAAS	236.2	232.0	-1.8
18	SI	144.7	144.3	-0.2
19	GAAS	210.6	209.8	-0.3
20	SI	148.5	149.6	+0.7
21	SI	150.7	152.5	+1.2
22	SI	145.5	147.2	+1.2
23	SI	162.9	164.5	+0.9
24	GAAS/GE	259.1	250.8	-3.2
25	GAAS	166.1	163.4	-1.6

Table 3

Estimated Degradation of Isc, Voc and Pmax after 1 year in orbit

Estimated to the nearest 0.5%, a '+' indicates performance has increased over the initial value rather than degraded

	Isc	Voc	Pmax
ITO/INP cells:			
1	1.5	1.0	2.5
12	+0.5	1.0	2.5
16	0.0	1.0	1.5
HJ INP cells:			
2	0.0	0.0	0.0
4	0.0	0.0	0.0
7	0.0	0.0	1.0
8	0.5	0.0	1.0
GaAs cells:			
6	0.5	0.0	1.5
13	0.0	0.0	0.5
17	0.0	0.0	0.5
24	0.0	0.5	1.0
Coverglass SI cells (pre-irradiated):			
14	+0.5	0.0	0.0
18	0.0	+1.0	0.0
22	0.0	+0.5	0.0
23	0.5	0.0	0.5
Silicon cells:			
9	1.5	0.0	3.0

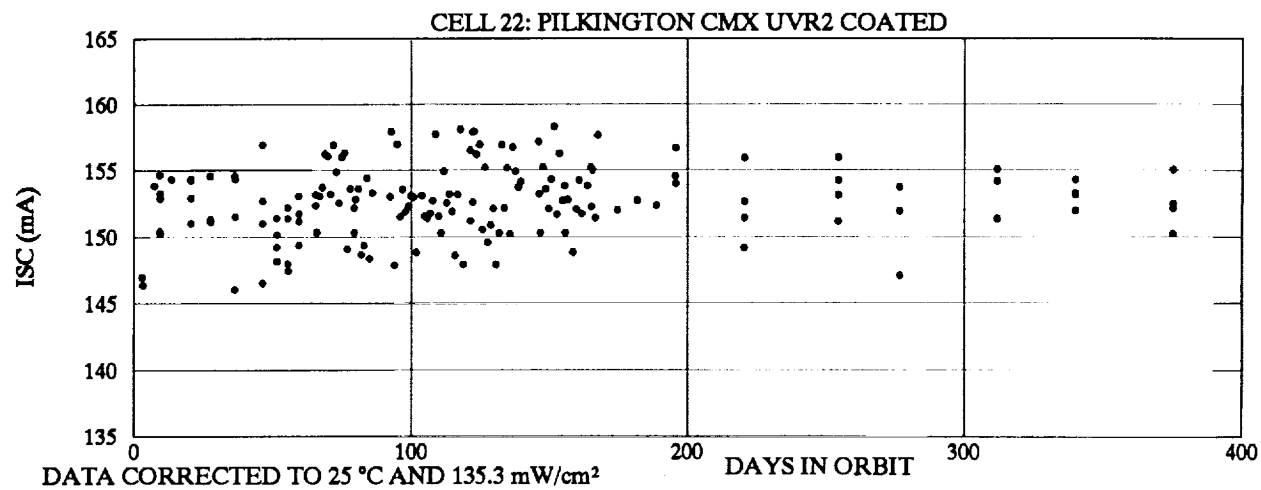


FIGURE 1.

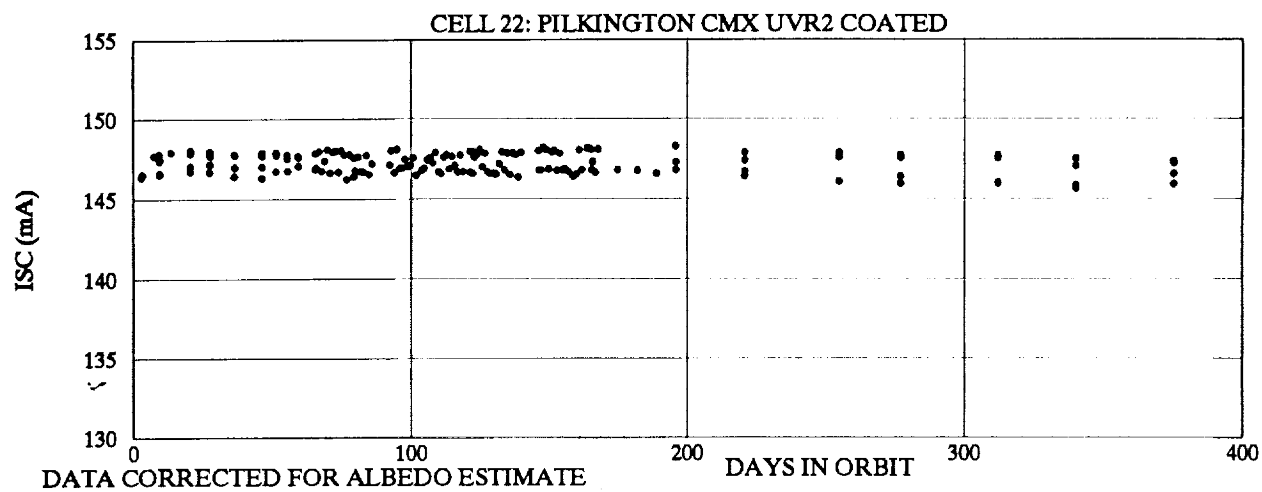
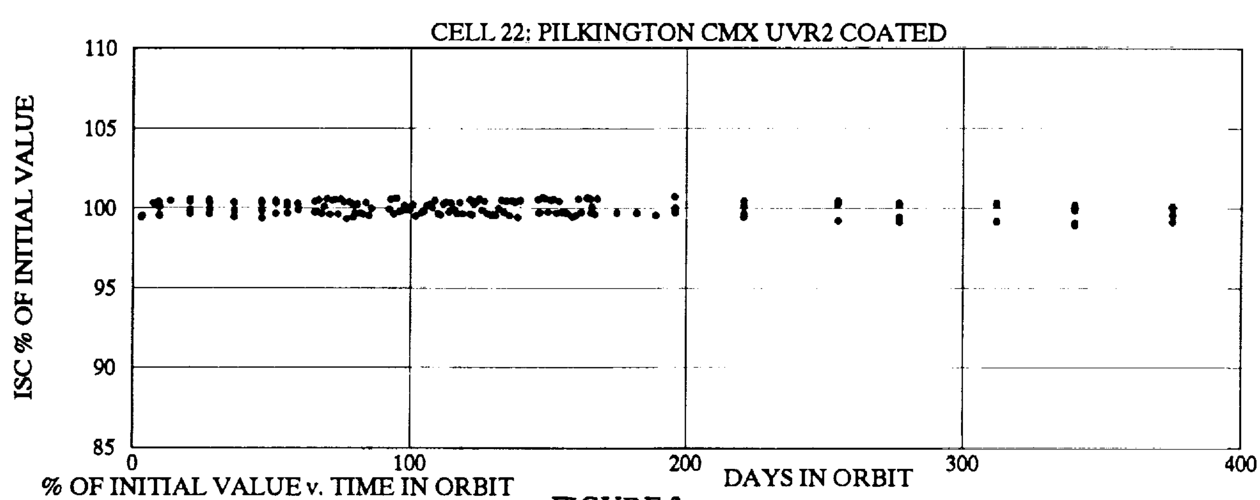


FIGURE 2.



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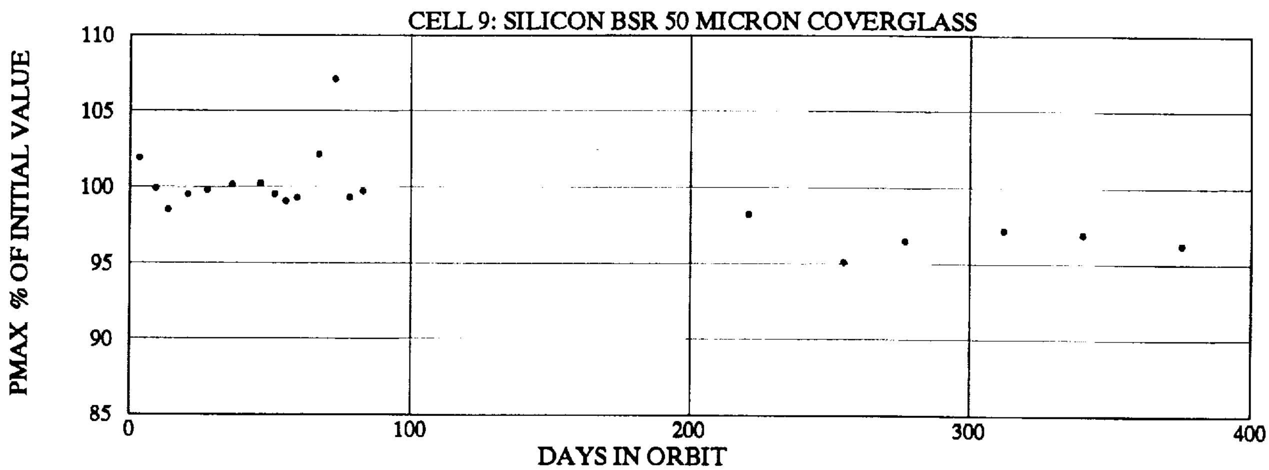

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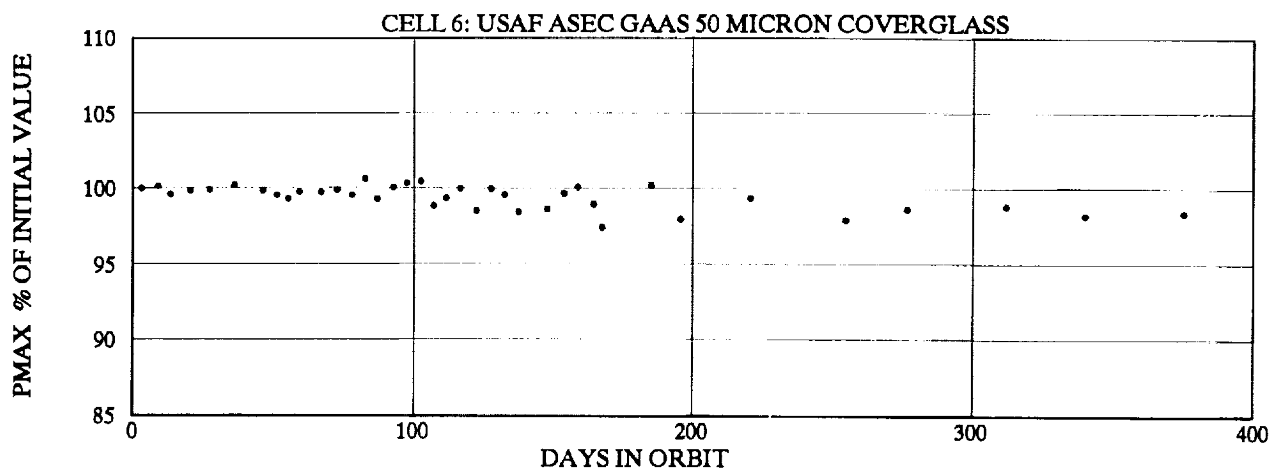

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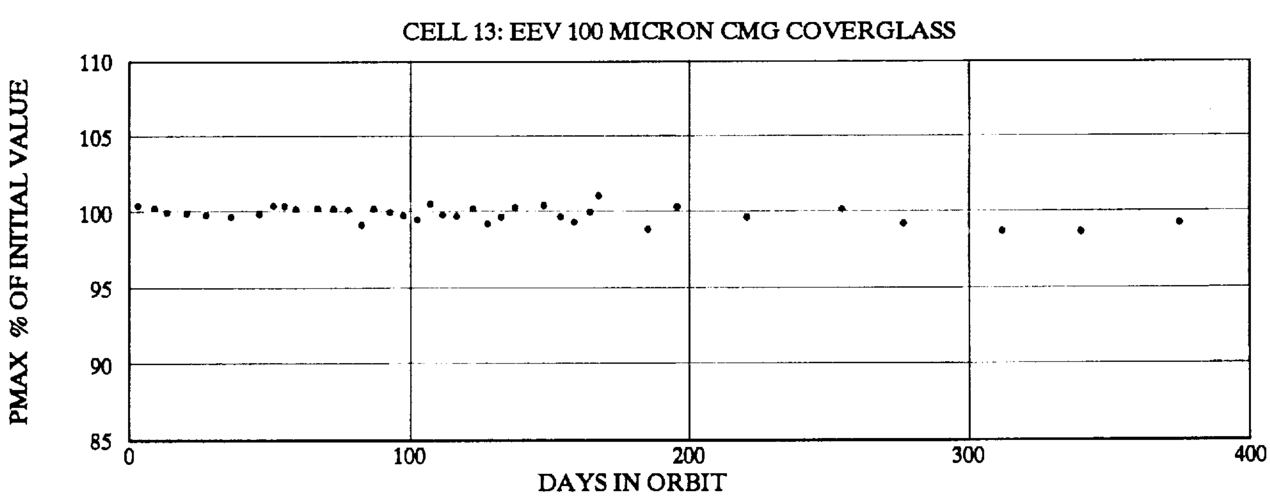

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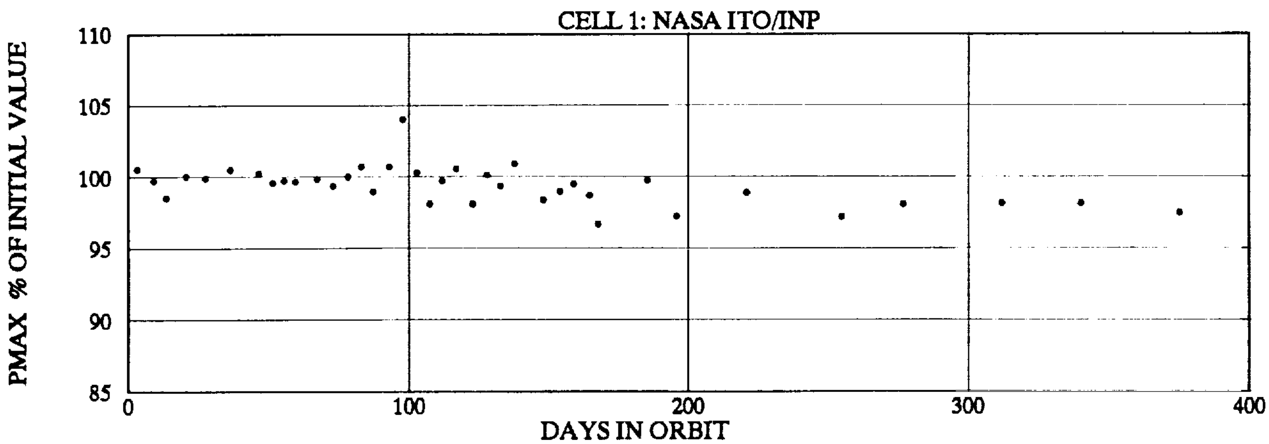

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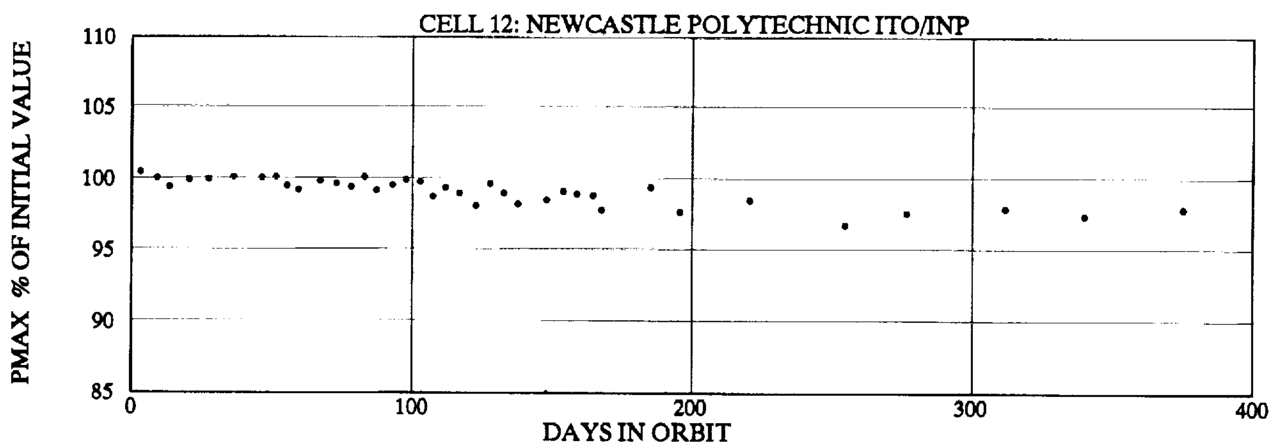

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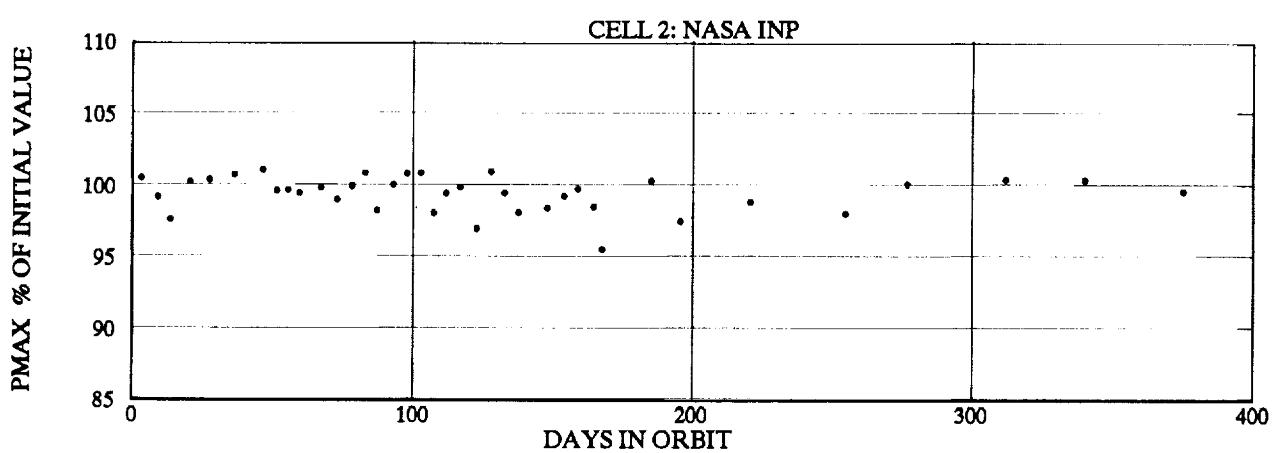

FIGURE 9.