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IMPROVEMENT AND EXTENSION OF DATA FROM ATS-6 SOLAR CELL RADIATION DAMAGE EXPERIMENT (SCRDE)

Final Report

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16. Abstract

ATS-6 solar cell radiation damage experiment (SCRDE) data through 2-1/3 years of synchronous orbit operation are presented in this report. Comparisons are made of the performances of the 13 different types of solar cell/cover configurations, including solar cell and cover thickness variations, base resistivity variation, new cover processes and materials, and the COMSAT violet cell. These performances are also compared to 1) the performances of the LES-6 solar cell experiment, the ATS-6 main solar arrays, and the Hughes Aircraft Company solar arrays and 2) laboratory spectrum electron irradiations. It was found that the cells of the ATS-6 experiment generally performed as expected through 6 to 9 months in orbit, but that at 2-1/3 years they were more severely degraded in current than expected. The short circuit current degradation after 2-1/3 years in orbit appears to exhibit an anomalous additional degradation of 5 to 9 percent over what has been experienced in synchronous orbit operation.

Due to malfunctions in the signal processing units, data after 856 days (2-1/3 years) in orbit have become unreliable and data will no longer be retrieved from the ATS-6 SCRDE.

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This final report for the ATS-6 solar cell radiation damage experiment (SCRDE) summarizes the results of the flight data through 856 days (2-1/3 years) of synchronous orbit operation and is submitted for approval to the National Aeronautics and Space Administration, Goddard Space Flight Center. This report contains information prepared by Hughes Aircraft Company under NASA Contract 5-24458. Its contents are not necessarily endorsed by the National Aeronautics and Space Administration.

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1. SUMMARY

ATS-6 solar cell radiation damage experiment (SCRDE) data through 856 days (2-1/3 years) of synchronous orbit operation are presented. Comparisons are made of the performances of the 13 different types of solar cell-cover configurations. Included in these comparisons are solar cell and cover thickness variations, base resistivity variations, new cover processes and materials, and the COMSAT violet cell. These performances are also compared to 1) the performances of the LES-6 solar cell experiment, the ATS-6 main solar arrays, and the Hughes Aircraft Company solar arrays; and 2) laboratory spectrum electron irradiations.

The short circuit current degradation after 2-1/3 years in orbit is greater than expected from other experiences in synchronous orbit. There is strong evidence that there is an anomalous additional degradation of 5 to 9 percent affecting current capability at the solar cells on the SCRDE.

The ATS-6 SCRDE includes a small solar panel holding 16 different solar cell configurations and two identical signal processing units. The panel is mounted to the external surface of the environmental measurements experiment (EME), which is a package of eight scientific experiments, including the SCRDE. The ATS-6 spacecraft was successfully launched into synchronous orbit on 30 May 1974. On 2 June 1974, the first meaningful data were received from the solar cell experiment. Due to the signal processing unit's malfunctioning after 856 days in orbit, rendering the data unreliable, no more data will be extracted from the ATS-6 SCRDE.

2. INTRODUCTION

Since launch (day 150, 1974) of the ATS-6 spacecraft, valuable data have been analyzed and reported on the ATS-6 solar cell radiation damage experiment (SCRDE) (References 1 through 5). The experiment transmits data on 40 solar cells of 16 different configurations. These selected configurations have incorporated some of the state of the art (1974) solar cell technology providing in-flight test results of paramount usefulness. The experiment was designed to study the effects of a synchronous orbit on a number of parameters including cell and cover thickness, base resistivity, new cover processes and materials, and backside irradiation.

The SCRDE consists of a small solar panel and two identical signal processing units (SPU). The panel (Figure 1) contains 65 solar cells on the rigid substrate and 16 solar cells (one cell being inactive) on the flexible substrate. The panel is mounted to the external surface of the environmental measurements experiment (EME), which is a package of eight scientific experiments including the SCRDE. The EME package is located on a structure atop the base of the 9.1 meter parabolic reflector of the ATS-6 spacecraft (Figure 2). The SCRDE package incorporates 80 individual 2 x 2 cm solar cells, with real time telemetry providing 12 current-voltage (I-V) data points for each individual solar cell and five temperature data points for sampling solar cell temperature. With the failure of SPU 2 (Reference 1), data from only 40 solar cells were received. Also, because of combined failures of SPU 2 and the thermistors, solar cell open circuit voltages were used to determine in-flight operating temperatures (Reference 1).

The SCRDE requires 24 seconds for complete data sampling and transmission and is operated at programmed intervals throughout the ATS-6 mission life. Data are retrieved from the SCRDE for approximately 3 minutes, resulting in each cell's being sampled six to eight times each time the experiment is turned on.

The three-axis stabilized ATS-6 spacecraft was successfully launched into synchronous orbit on 30 May 1974. Injection occurred at 19:30:49 GMT into a nearly perfect orbit. On 2 June 1974 at 0:10:14 GMT, the first meaningful data were received from the solar cell experiment. Since then, data were received from the experiment once a day for the first 3 months and once a week thereafter. The solar cell experiment is activated when the sun is normal to the axis vertical to the west face of the spacecraft.

The EME package is rotated 13° about the spacecraft Z-axis in order to align the package with the normal direction of the magnetic field lines at final east longitude. Therefore, when the solar panel is activated, sun angles from $+38^{\circ}$ to -12° are encountered.

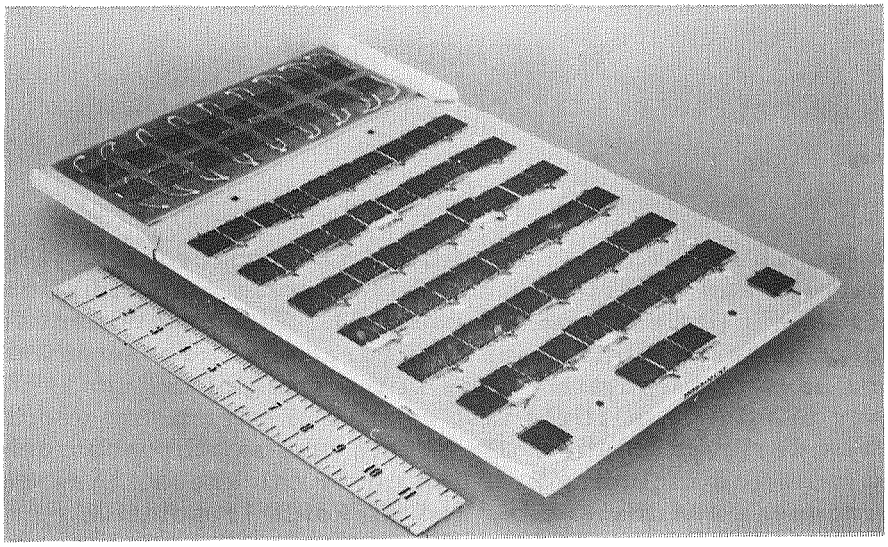

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FIGURE 1. ATS-6 SCRDE SOLAR PANEL (PHOTO 4R32030)

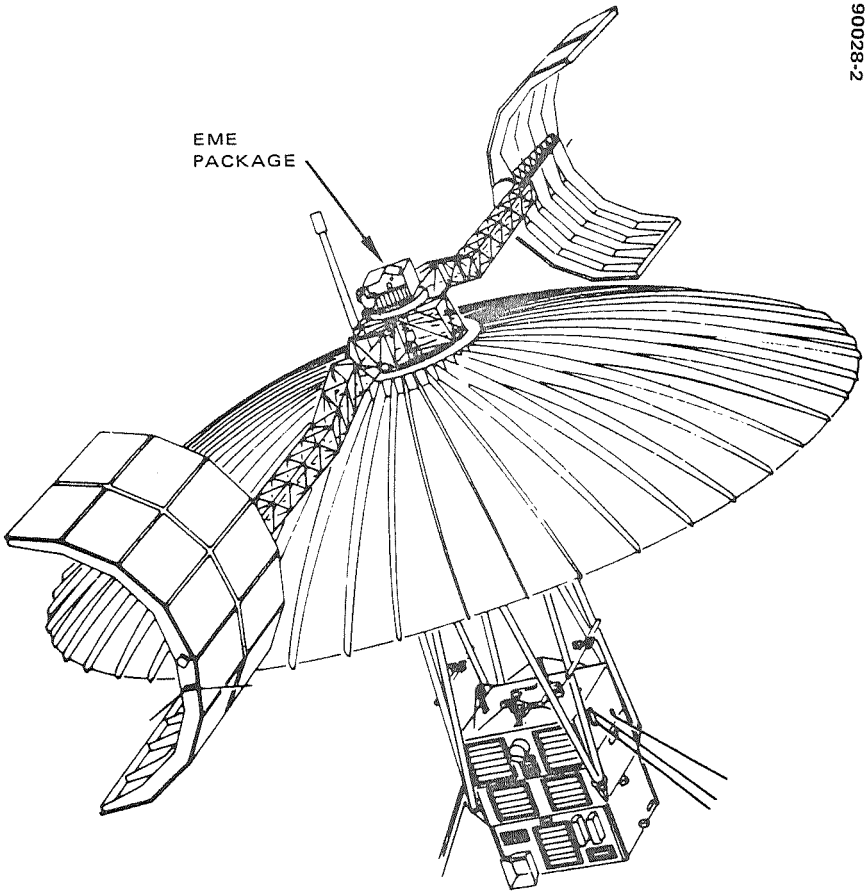

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FIGURE 2. ATS-6 SPACECRAFT

3. FLIGHT HARDWARE DESCRIPTION

A major objective established for the ATS-6 SCRDE was to fly those cell types that would provide the most meaningful data to spacecraft designers. The solar cell sample selection for the flight panel is summarized in Table 1. All cells chosen for the flight experiment are 2 x 2 cm; all of the flight cells were manufactured by Heliotek (Spectrolab), except for a five-cell sample of violet cells made by COMSAT Laboratories. A single lot of Dow Sylgard 182 adhesive was used to bond the solar cell covers, except as indicated in Table 1. Similarly, all cover glasses were formed from Corning 7940 fused silica and had 0.41 μm ultraviolet (UV) cutoff filters, except as shown. Solar cells for configurations 6 and 7 were supplied to ION Physic Corporation to have integral covers applied. Solar cells for configurations 10 and 13 were supplied to NASA Lewis Research Center for fluorinated ethylene propylene, type A (FEP) application.

Each of the 16 configurations listed in Table 1 contains five identical cell assemblies; due to the failure of SPU 2, the sample size was reduced to either two or three. Configurations 1 through 13 are installed on the rigid portion of the panel; configurations 14 through 16 are installed on the flexible portion. In the majority of cases, the selected cells are boron-doped n/p, 10 ohm-cm resistivity, 0.030 cm thick, and have solder-coated silver-titanium (AgTi) contacts. The fused silica covers are bonded to the cells to very tight tolerances. This bond eliminates the presence of any gaps between the contact bars and cover glass edges, thus precluding low energy proton damage because of an exposed cell active area. Ohmic contacts are coated with RADAC, a radiation coating, to prevent low energy proton damage through areas of thin solder coverage.

The SCRDE solar panel dimensions were 25 x 43 cm and the panel was mounted on the west face of the EME package so that the backside of the rigid portion of the solar panel faces the EME package and the flexible portion extends beyond the EME package. The protruding flexible panel allows radiation to impinge on the rear of the cells mounted on the flexible panel.

The SPU is located inside the EME package and is the interface between the solar panels and the ATS encoder. Each SPU measures the I-V characteristics of 40 solar cells using 12 precisely known loads and provides temperature information. In operation, one of the 40 solar cells is connected to one of the 12 load resistors by relays. Thus, only two relays are energized

TABLE 1. ATS-6 SOLAR CELL RADIATION DAMAGE EXPERIMENT CONFIGURATIONS

Configuration	Cell Number	Nominal Resistivity, ohm-cm	Cell Thickness, cm	Cover Glass Thickness, cm	Remarks	Panel Location
1	10, 15, 22	10	0.030	0.0076		Rigid
2	25, 38	10	0.030	0.015		Rigid
3	8, 16	10	0.030	0.030		Rigid
4	19, 35, 37	10	0.030	0.076		Rigid
5	28, 30	10	0.030	0.0076	Plain 7940 fused silica cover; no filter or coatings on cover	Rigid
6	6, 24, 31	10	0.030	0.0038	7940 integral cover	Rigid
7	9, 14	10	0.030	0.0076	7070 integral cover	Rigid
8	11, 23, 27	2	0.030	0.015		Rigid
9	20, 36	2	0.020	0.015		Rigid
10	21, 29, 39	10	0.030	0.015	Cover without UV filter; cover adhesive of 0.005 cm FEP	Rigid
11	7, 17, 32	10	0.020	0.015		Rigid
12	26, 33	1	0.025	0.015	COMSAT violet cell; cerium doped micro-sheet cover without UV filter	Rigid
13	18, 34	10	0.030	0.013	FEP cover without added adhesive	Rigid
14	0, 3, 12	10	0.020	0.015		Flexible
15	1, 4, 13	2	0.020	0.015		Flexible
16	2, 5	2	0.030	0.015		Flexible

within each SPU at any one time. In order to measure cell characteristics, one cell select relay is energized while the unit is sequenced through the load select relays. Each load is connected for 30 ms. During that time, the SPU output is sampled and telemetered once. The encoder then outputs a pulse that is used to increment the load relays. The process is repeated for each of the 40 solar cells. Separate lead wires are provided for voltage and current sensing. The ground return from each cell is connected to a common ground. A more complete description of the experiment operation may be found in the final report of contracts NAS 5-22873 and NAS 5-11677 (References 1 and 2).

4. IN-ORBIT OPERATION

When data are acquired from the experiment, the temperature of the rigid solar panel ranges between 56° and 91°C (Figure 3). The solar panel sun angle is obtained from data furnished by the solar aspect sensor of the EME package and varies between +38° and -12°. The sun angle uncertainty is 1°, a value that results in a negligible error at sun-normal conditions and 1.3 percent error at the high sun angles. Some of the scatter observed in the data can be attributed to the uncertainty in the sun angle.

For this report, only data from the cells of the rigid panel will be reported. This is because the exact temperature of the cells on the flexible panel cannot be determined due to malfunction of the thermistors on the flexible panel (see Reference 1 for details). Results of the experiment through 765 days in orbit (day 185, 1976) have been reported in the final report of the NASA/GSFC contract NAS-5-22873 (Reference 1). Since day 185, 1976, 63 magnetic tapes were received from NASA/GSFC containing in-orbit data through day 148, 1978 from the ATS-6 SCRDE. All 63 tapes were processed by the magnetic tape data reduction computer program. Results from the data reduction program showed that the voltage parameter of some cells was failing due to some malfunction of SPU 1. Cells number 7 and 39 had previously failed before day 185, 1976 (Reference 1). Table 2 displays the lost data for each of the tapes received through day 280, 1977 after which time data were lost on all cells.

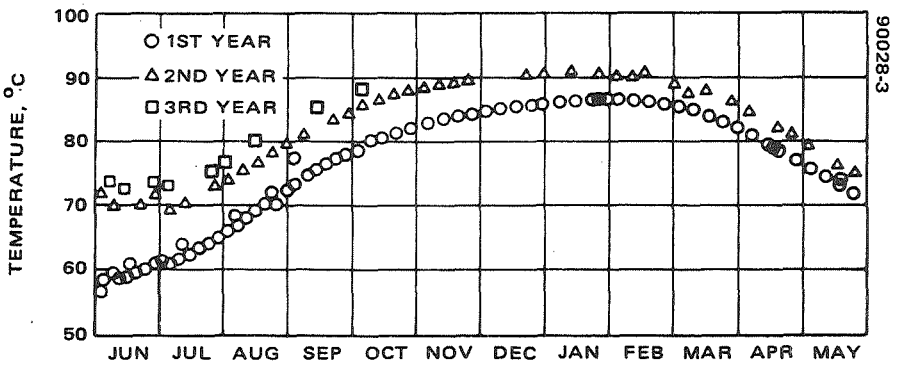


FIGURE 3. RIGID SOLAR PANEL TEMPERATURE FOR ATS-6 SOLAR CELL EXPERIMENT

TABLE 2. IN-ORBIT CELL DATA LOST DUE TO SPU 1 MALFUNCTION

Day/Year	Lost Cell Data	Cells Lost	Comments
185/'76	7, 39	2	765 days in orbit, lost data previously reported (Reference 1)
206/'76	7, 39	2	New data since last report
213/'76	7, 39	2	New data since last report
227/'76	7, 39	2	New data since last report
255/'76	0, 7, 39	3	New data since last report
276/'76	0, 6, 7, 39	4	New data since last report
325/'76	0, 6, 7, 12, 15, 19, 20, 39	8	Data unreliable
58/'77	0, 6-10, 12-20, 31, 33-37, 39	21	Data unreliable
65/'77	0, 6-10, 12-16, 19, 20, 31, 33-37, 39	19	Data unreliable
93/'77	0, 6-10, 12-16, 19, 20, 31, 33-37, 39	19	Data unreliable
280/'77	0-39	40	All cell data lost
148/'78	0-39	40	All cell data lost

Submitting the reduced data from the magnetic tapes to the data analysis computer program revealed that the data were valid only to day 276, 1976 (856 days in orbit). Tables A-1 through A-9 in appendix A display the reduced data for each day since day 185, 1976, as reduced by the data analysis computer program. Data of day 325, 1976 later appear to become quite unreliable and will not be employed in this report. Although data from the ATS-6 SCRDE were received through 4 years in orbit, data only through 856 days in orbit will be reported.

5. IN-ORBIT RESULTS

The additional data (days 206, 213, 227, 255, and 276, 1976) were run through the data analysis program, which is an upgrade of the Hughes solar array prediction program (Reference 6). Results of all photovoltaic characteristics presented herein have been reduced to standard conditions of normal incidence, 25°C and AMO intensity. Displayed in Table 3 are the absolute and normalized values (856 days in orbit) for short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}), and curve factor. Curve factor is defined as the maximum power divided by the product of short circuit current times open circuit voltage, which is a direct indication of the curve shape of the cells' electrical characteristics. Both the absolute and normalized (to the average of the first 5 days) data for 2-1/3 years are also presented.

The beginning of life comparisons with the prelaunch solar simulator cell values are presented in Reference 1. Table 4 presents the short circuit current degradation (UV effects) after 50 days in orbit. Table 4, which is presented for completeness, is explained in detail in Reference 1.

Figure 4 displays the normalized cell degradations through 2-1/3 years in orbit for each cell. Profiles for configurations 1 through 13 are shown. Each point in Figure 4 is an average of 5 days of data, except for the last two data points, where the next to the last point is the average of days 206 and 213, and the last point is the average of days 227, 255 and 276. The performances of I_{sc}, V_{oc}, and P_{max} are plotted through 2-1/3 years of operation.

Table 5 shows the average percentage loss for I_{sc}, V_{oc}, P_{max}. Table 5, for 2-1/3 years in orbit, differs slightly from Table 5 of Reference 1, at 2 years in orbit, but is well within the accuracy of the experiment.

COVER GLASS THICKNESS VARIATION

Configurations 1 to 4 and 6, in which cover glass thickness was varied, display degradation profiles through 2-1/3 years of operation, as shown in Figure 4. The solar cell common to each configuration was a 10 ohm-cm, 0.076 cm (12 mil) thick cell and the cover glasses varied from 0.0038 to 0.076 cm (1-1/2 to 30 mil) thick. Table 6 shows the percentage degradation to I_{sc}, V_{oc}, and P_{max} after 2-1/3 years in orbit for these five configurations: 1 to 4 and 6. As indicated in Table 6, there appears to be a maximum in the

TABLE 3. IN-ORBIT PHOTOVOLTAIC COMPARISONS AT 25°C AND AMO INTENSITY

Configuration	Cell	2 to 7 Days in Orbit				2-1/3 Years in Orbit							
						Absolute				Normalized			
		I_{sc_o} mA	V_{oc_o} mV	P_{max_o} mW	Curve Factor	I_{sc} mA	V_{oc} mV	P_{max} mW	Curve Factor	I_{sc}/I_{sc_o}	V_{oc}/V_{oc_o}	P_{max}/P_{max_o}	CF/CF_o
1	10	149	554	59.1	0.718	127	542	49.2	0.712	0.857	0.980	0.833	0.992
	15	149	550	60.2	0.735	131	542	52.4	0.741	0.877	0.985	0.871	1.008
	22	147	556	60.6	0.744	123	544	50.0	0.745	0.842	0.979	0.825	1.002
2	25	149	549	59.1	0.721	130	540	49.9	0.713	0.870	0.983	0.846	0.989
	38	148	554	60.2	0.731	123	541	48.9	0.733	0.831	0.975	0.814	1.003
3	8	144	544	57.5	0.733	126	537	49.7	0.735	0.872	0.987	0.863	1.003
	16	146	548	59.0	0.738	131	544	52.2	0.734	0.896	0.993	0.885	0.995
4	19	146	552	58.0	0.719	127	546	49.2	0.709	0.872	0.988	0.849	0.985
	35	143	559	59.5	0.742	125	548	50.7	0.738	0.873	0.981	0.852	0.995
	37	146	549	58.4	0.729	130	544	51.9	0.731	0.894	0.991	0.889	1.003
5	28	143	557	59.2	0.741	119	546	48.7	0.747	0.833	0.981	0.823	1.007
	30	145	564	60.5	0.739	121	550	48.7	0.734	0.829	0.976	0.804	0.993
6	6	137	548	54.3	0.727	120	535	46.0	0.718	0.878	0.976	0.846	0.987
	24	136	541	53.7	0.733	120	531	47.1	0.737	0.885	0.983	0.876	1.006
	31	138	554	55.8	0.730	117	541	46.5	0.735	0.849	0.977	0.834	1.006
7	9	141	544	56.4	0.736	121	535	47.8	0.740	0.858	0.982	0.848	1.006
	14	138	540	54.5	0.731	123	532	48.6	0.740	0.894	0.985	0.892	1.013
8	11	141	576	60.1	0.743	117	561	49.1	0.747	0.833	0.974	0.817	1.006
	23	140	589	62.1	0.754	117	573	51.7	0.769	0.839	0.973	0.833	1.021
	27	138	584	60.9	0.757	117	571	51.4	0.767	0.851	0.978	0.843	1.013
9	20	135	569	58.6	0.762	114	556	48.4	0.761	0.845	0.977	0.826	1.000
	36	135	564	58.0	0.759	117	554	48.9	0.754	0.864	0.981	0.843	0.994
10	21	146	556	58.8	0.724	122	546	49.6	0.744	0.836	0.984	0.844	1.028
	29	147	554	60.3	0.739	125	544	50.2	0.740	0.847	0.981	0.832	1.002
	39	146	547	58.0	0.728	—	—	—	—	—	—	—	—
11	7	140	542	56.1	0.741	—	—	—	—	—	—	—	—
	17	141	536	55.6	0.736	125	532	49.0	0.738	0.883	0.993	0.880	1.004
	32	140	544	56.9	0.749	118	534	47.6	0.757	0.841	0.982	0.835	1.011
12	26	176	598	81.8	0.776	142	576	63.4	0.773	0.809	0.962	0.775	0.996
	33	179	598	83.1	0.776	141	573	62.1	0.770	0.786	0.958	0.747	0.992
13	18	151	553	60.1	0.720	121	480	36.2	0.624	0.803	0.867	0.603	0.866
	34	149	560	62.6	0.747	118	475	35.2	0.631	0.786	0.847	0.562	0.844
14	0	144	483	48.2	0.695	125	491	43.0	0.700	0.872	1.016	0.893	1.007
	3	146	494	49.8	0.689	125	495	43.3	0.699	0.856	1.003	0.871	1.015
	12	142	487	48.6	0.703	124	489	43.3	0.713	0.876	1.004	0.891	1.013
15	1	139	512	49.9	0.701	120	510	42.8	0.698	0.866	0.996	0.859	0.995
	4	135	522	51.4	0.729	117	517	44.0	0.725	0.868	0.991	0.855	0.994
	13	137	516	50.8	0.718	121	513	44.2	0.714	0.880	0.995	0.870	0.994
16	2	141	525	52.7	0.715	119	517	44.5	0.723	0.846	0.986	0.845	1.012
	5	142	536	53.8	0.706	122	529	46.3	0.715	0.860	0.987	0.861	1.014

TABLE 4. PERCENTAGE I_{sc} DEGRADATION AFTER 50 DAYS IN ORBIT, ULTRAVIOLET EFFECTS

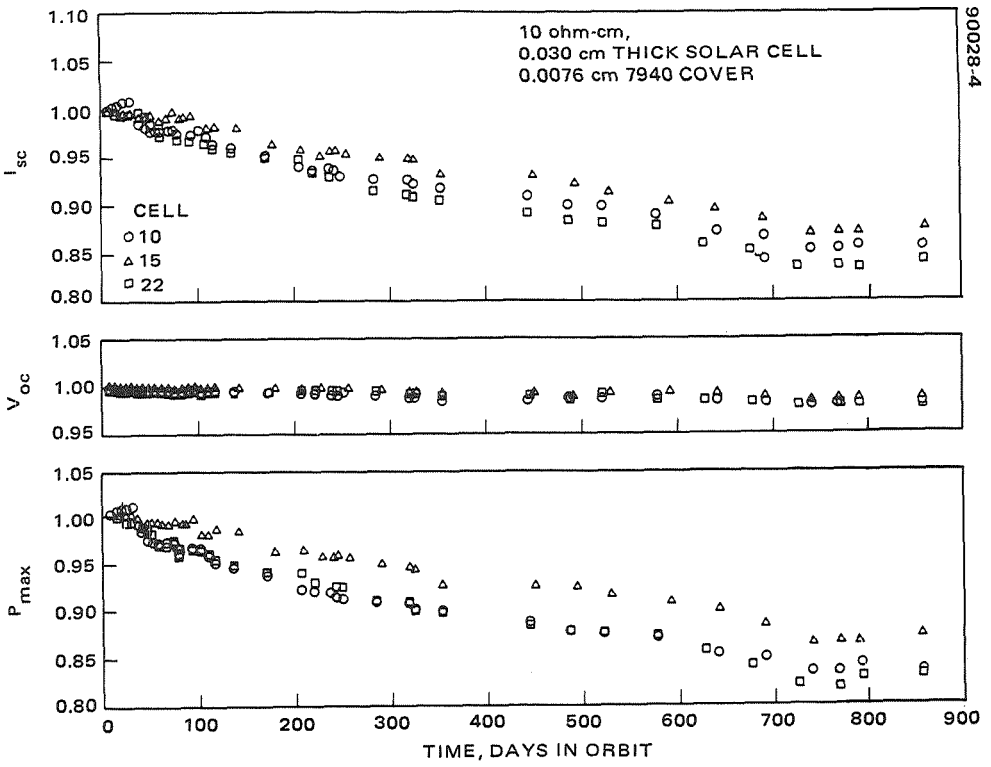
Identification	Average Percentage I_{sc} Loss
Standard UV filter (configurations 1, 2, 3, 4, 8, 9, and 11)	1.6 ± 0.7
Integral covers (configurations 6 and 7)	0.8 ± 1.1
FEP adhesive and covers (configurations 10 and 13)	1.8 ± 0.1
Violet cell (configuration 12)	2.3 ± 0.9
No UV filter (configuration 5)	3.3 ± 0.1

TABLE 5. SOLAR CELL DEGRADATION*

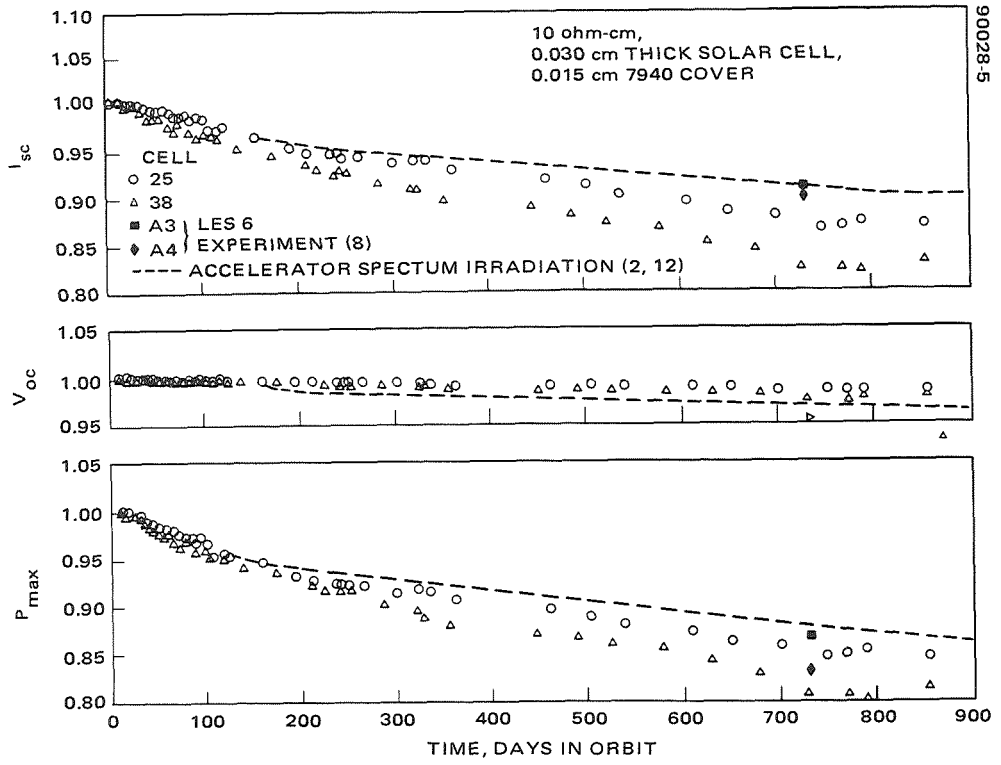
Configuration	Average Percentage Loss			
	I_{sc}	V_{oc}	P_{max}	Curve Factor
1	14.1 ± 2.1	1.9 ± 0.4	15.7 ± 2.7	-0.1
2	14.9 ± 3.4	2.1 ± 0.7	17.0 ± 2.9	0.4
3	11.6 ± 2.2	1.0 ± 0.5	12.6 ± 1.8	0.1
4	12.0 ± 1.3	1.4 ± 0.6	13.7 ± 2.7	0.5
5	16.9 ± 0.3	2.1 ± 0.5	18.7 ± 1.7	0.0
6	12.9 ± 2.1	2.1 ± 0.4	14.8 ± 2.5	0.0
7	12.4 ± 3.2	1.7 ± 0.2	13.0 ± 4.0	-1.0
8	15.9 ± 1.0	2.5 ± 0.3	16.9 ± 1.6	-1.3
9	14.6 ± 1.7	2.1 ± 0.3	16.6 ± 1.5	0.3
10	15.8 ± 1.1	1.8 ± 0.2	16.2 ± 1.1	-1.5
11	13.8 ± 3.7	1.2 ± 1.0	14.2 ± 4.0	-0.8
12	20.2 ± 2.0	4.0 ± 0.4	23.9 ± 2.5	0.6
13	20.6 ± 1.5	14.3 ± 1.8	41.8 ± 3.6	14.5

*2-1/3 years in orbit.

average percentage degradation (mainly maximum power) at 0.015 cm cover thickness. Configuration 6 has an integral cover and does not experience any additional loss to current due to UV effects to the cover adhesive, filter, etc. (see Table 4). However, configurations 1 through 4, with bonded cover glasses, have demonstrated that about 2 percent of the current degradation is due to UV effects (see Table 4). Figure 5 displays the maximum power degradation as a function of cover glass thickness with 2 percent degradation removed from configurations 1 through 4, thus displaying the degradation due to the particulate environment only. The apparent maximum damaged to the cell performance is now obscured but increased damage as a function of decreasing cover glass thickness is more pronounced. There is still less variation than expected at the thicker cover glass thickness. Also plotted in

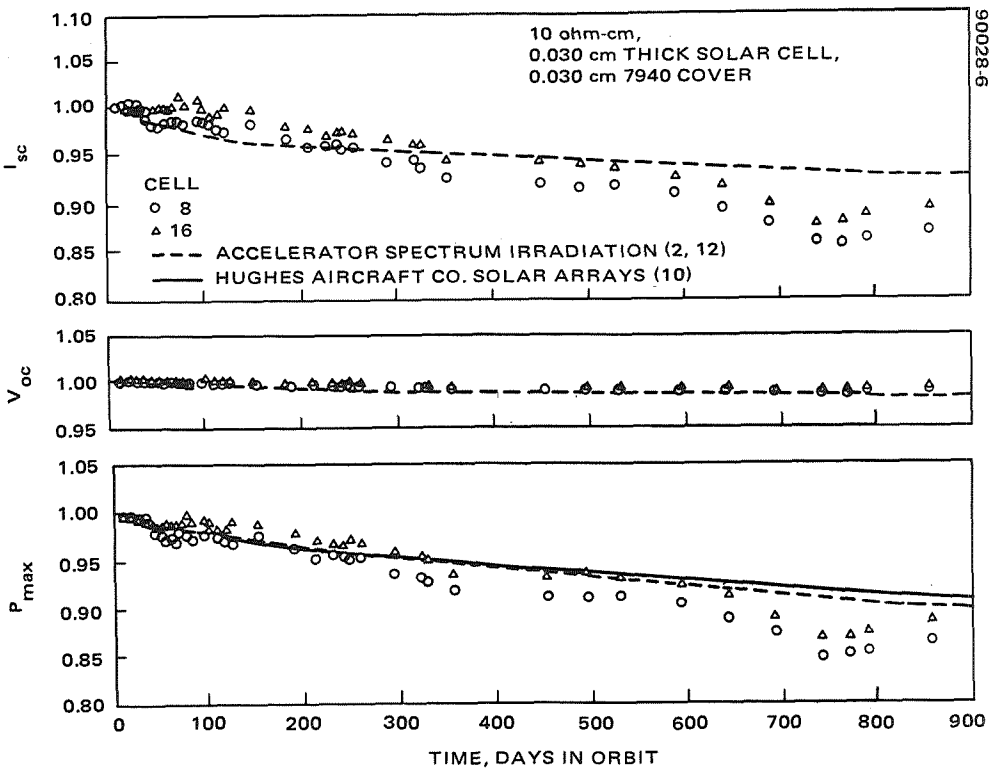


a) CONFIGURATION 1

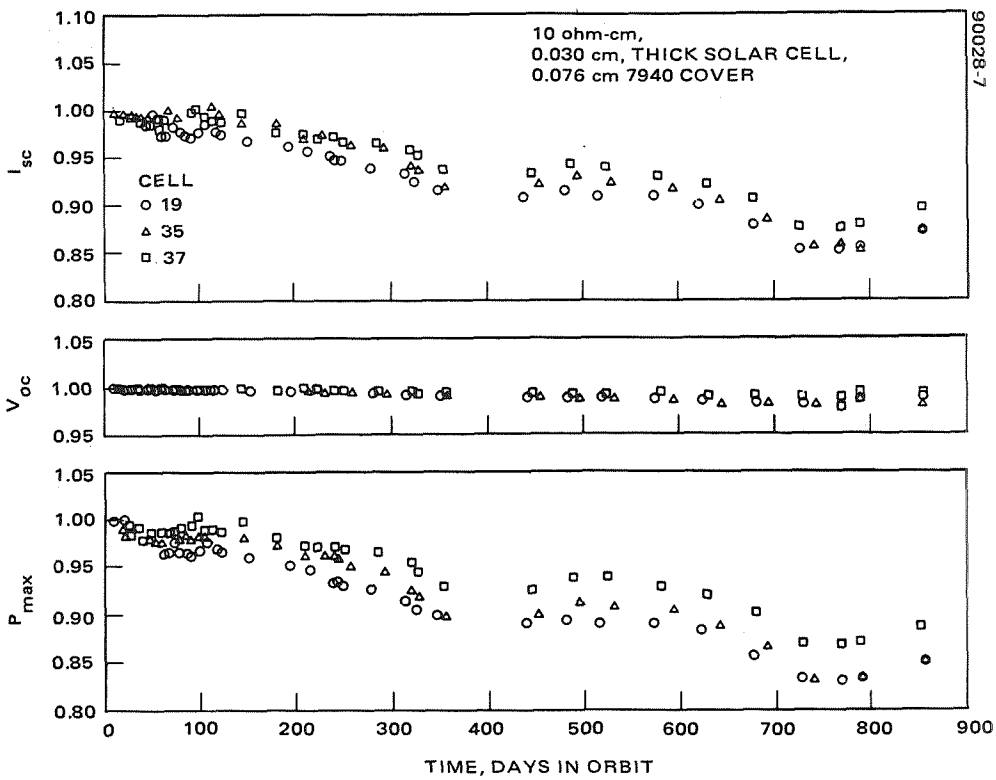


b) CONFIGURATION 2

FIGURE 4. IN-ORBIT NORMALIZED CELL PARAMETERS

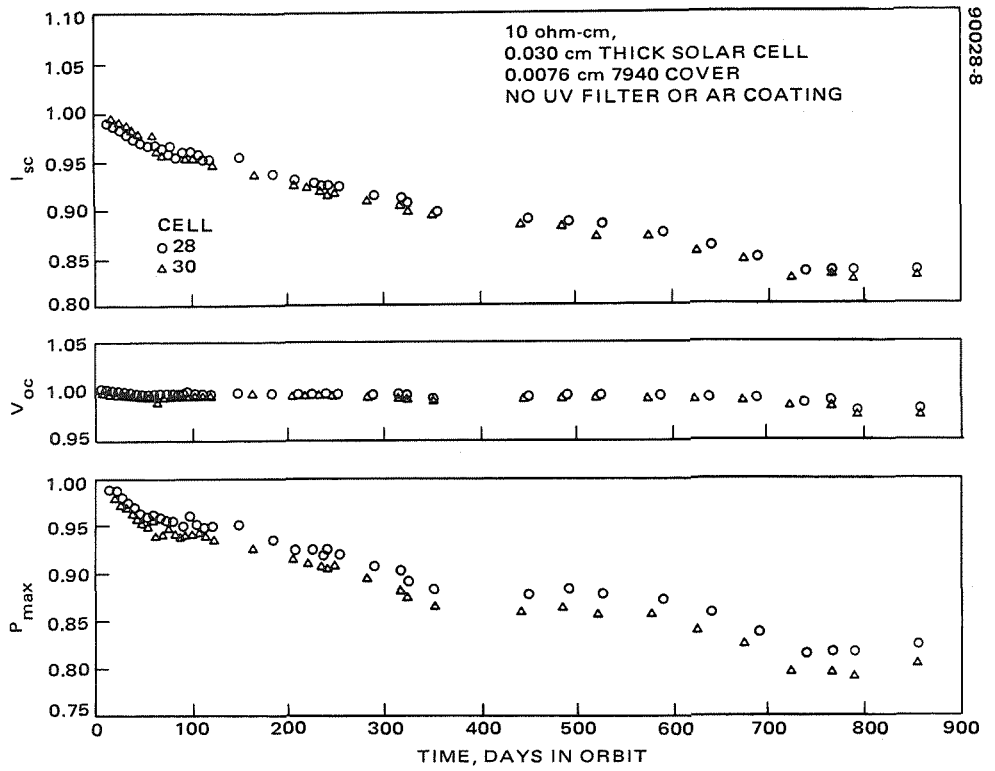


c) CONFIGURATION 3

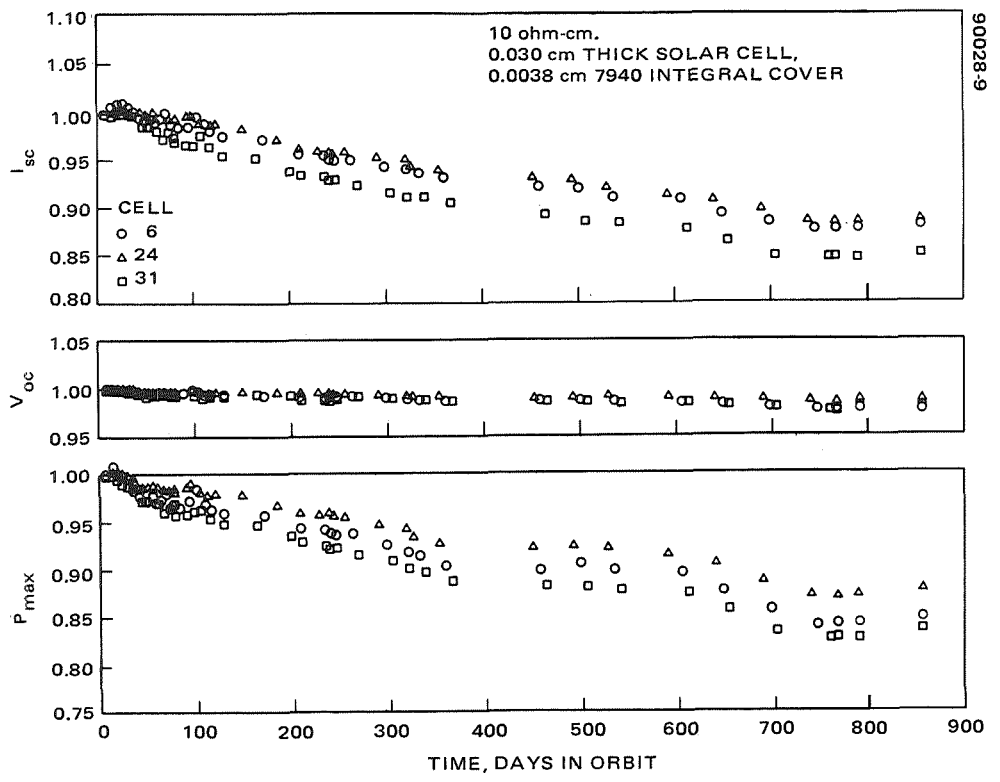


d) CONFIGURATION 4

FIGURE 4 (CONTINUED). IN-ORBIT NORMALIZED CELL PARAMETERS

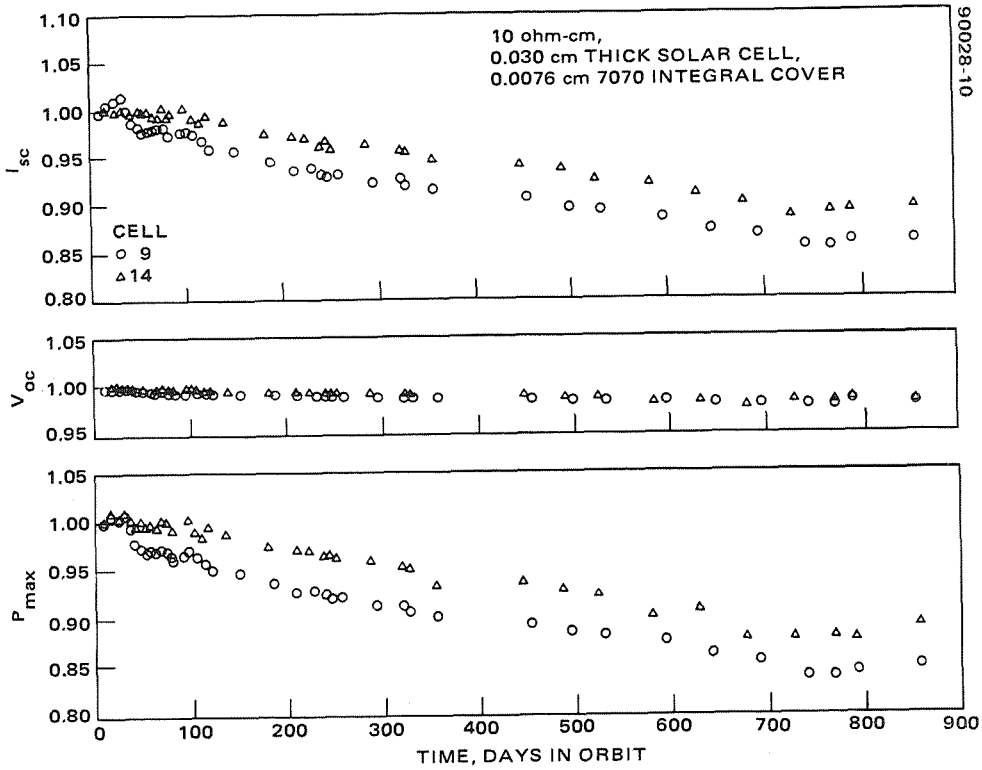


e) CONFIGURATION 5

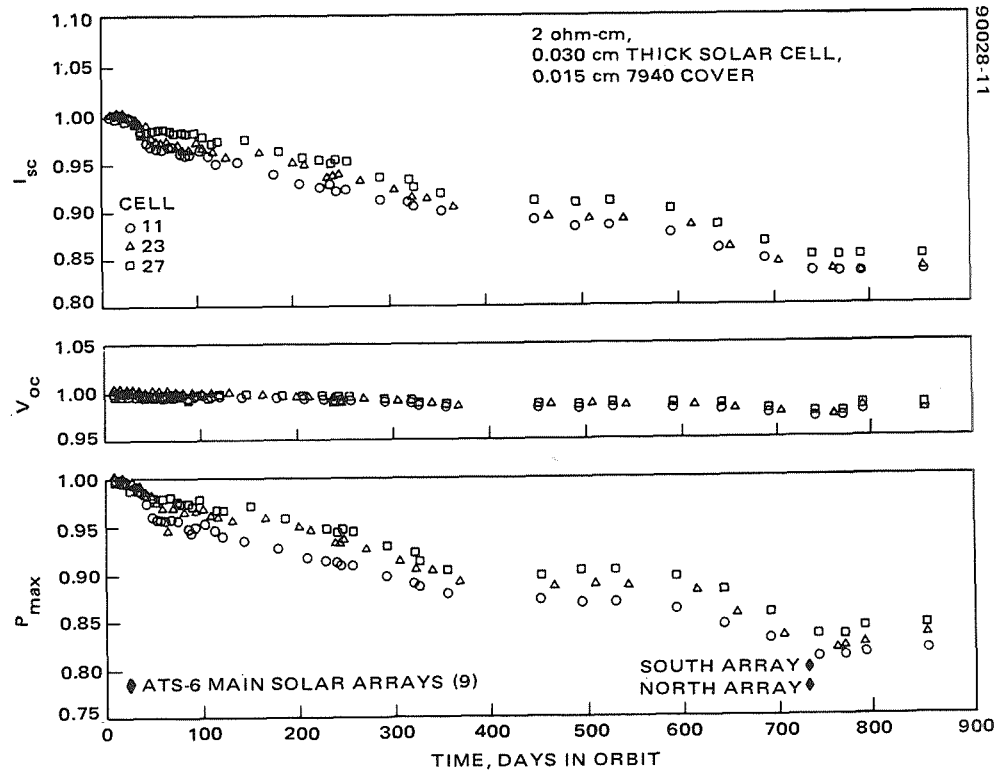


f) CONFIGURATION 6

FIGURE 4 (CONTINUED). IN-ORBIT NORMALIZED CELL PARAMETERS

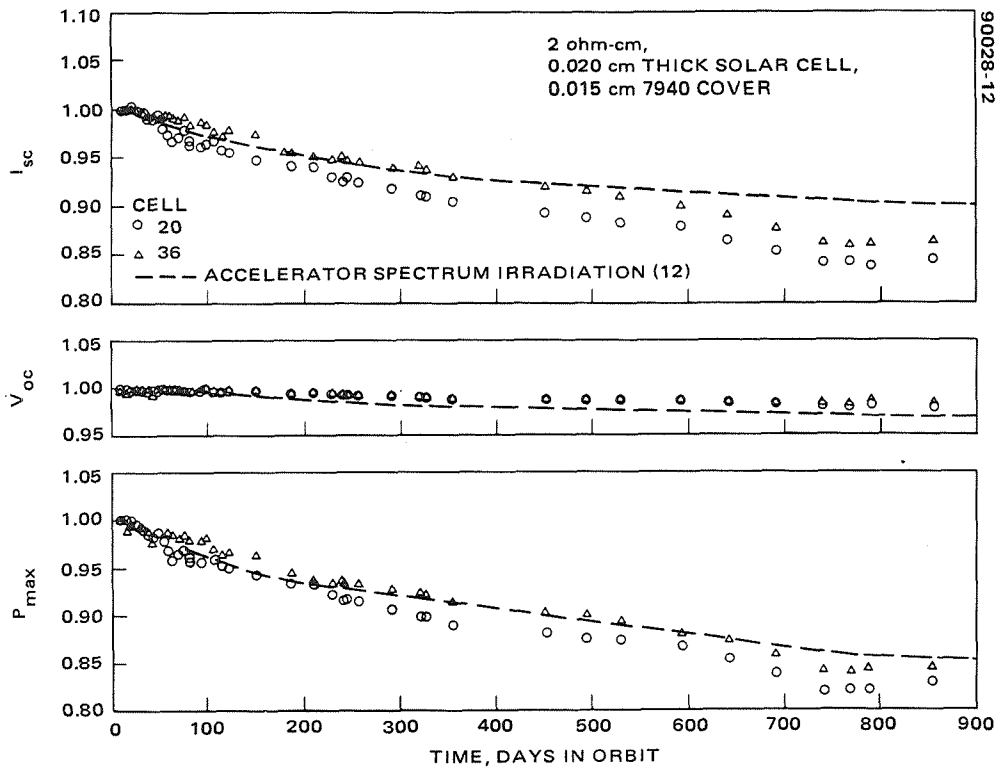


g) CONFIGURATION 7

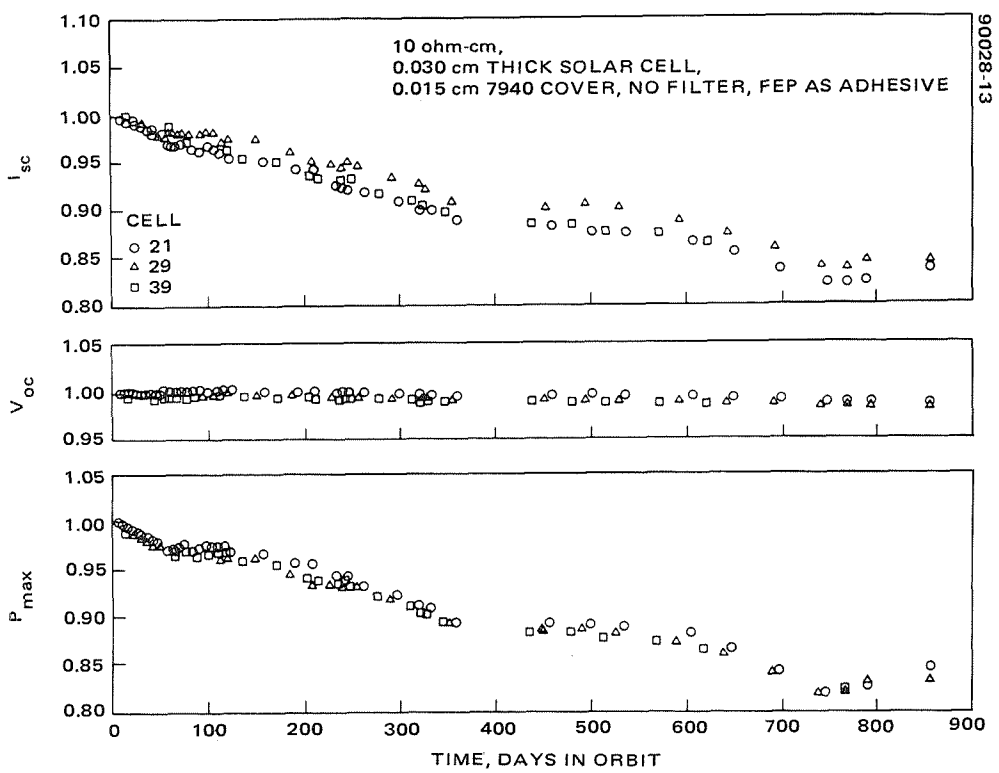


h) CONFIGURATION 8

FIGURE 4 (CONTINUED). IN-ORBIT NORMALIZED CELL PARAMETERS

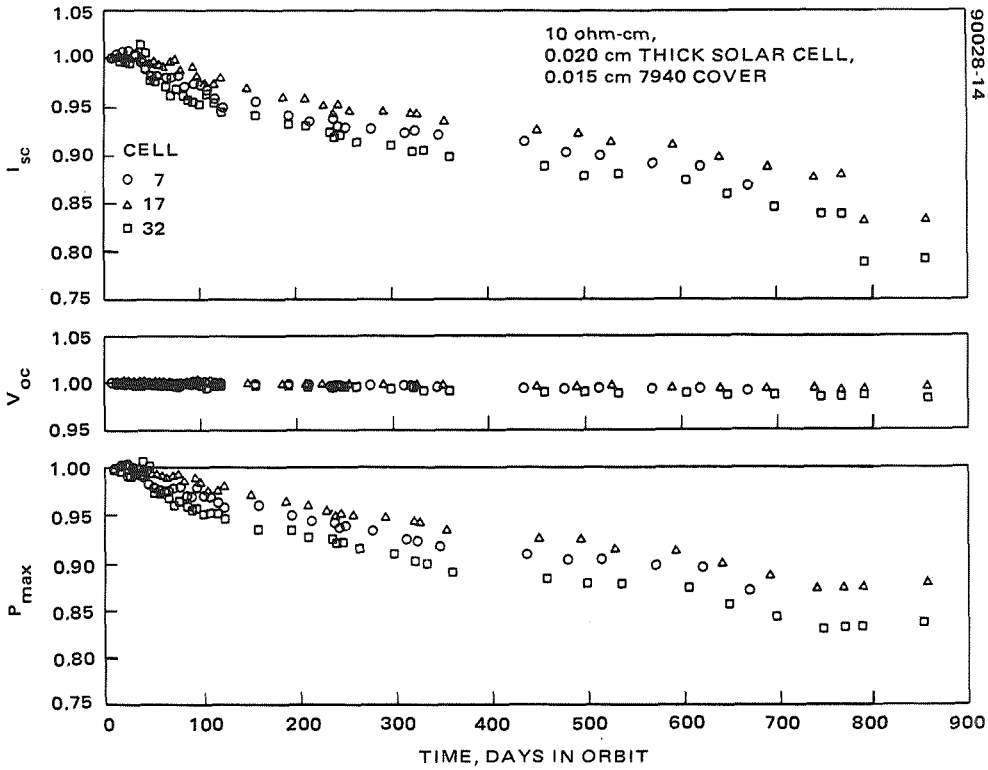


i) CONFIGURATION 9

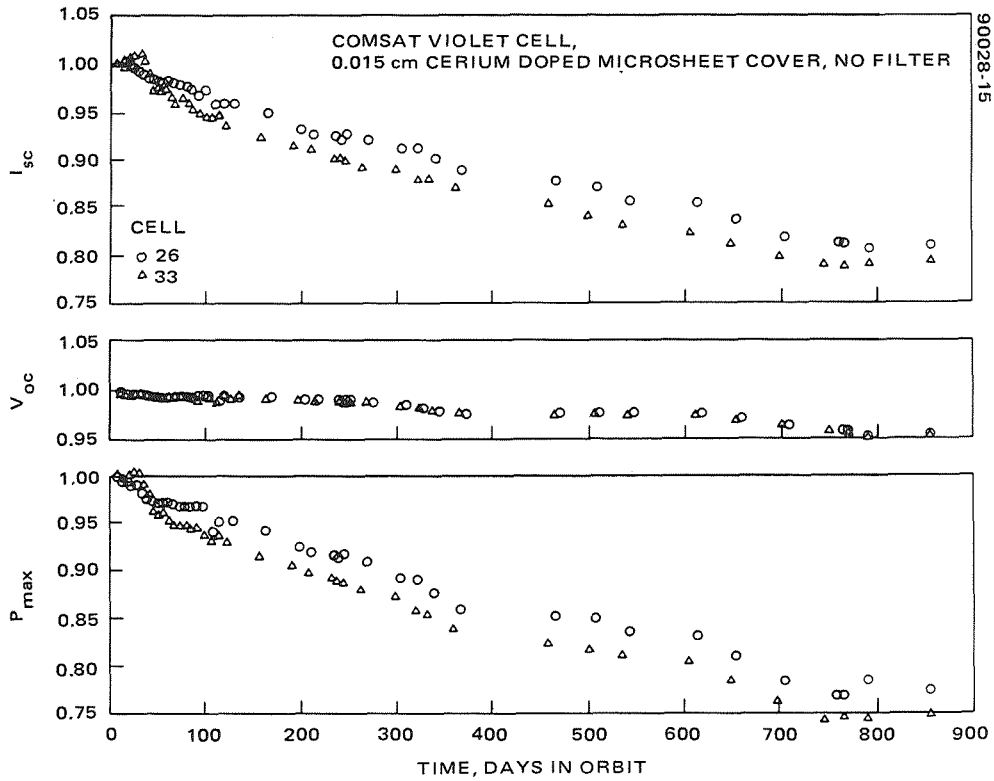


j) CONFIGURATION 10

FIGURE 4 (CONTINUED). IN-ORBIT NORMALIZED CELL PARAMETERS

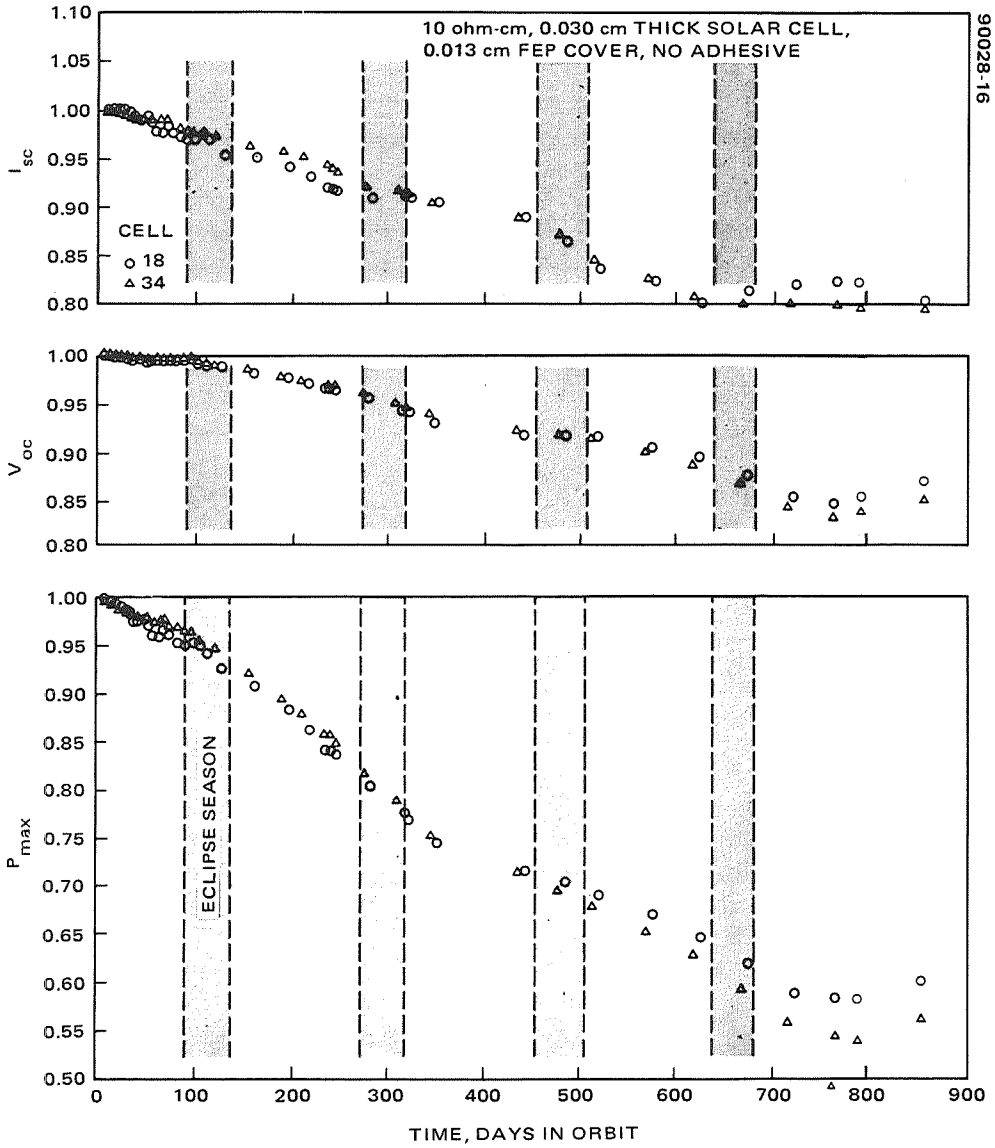


k) CONFIGURATION 11



l) CONFIGURATION 12

FIGURE 4 (CONTINUED). IN-ORBIT NORMALIZED CELL PARAMETERS



m) CONFIGURATION 13

FIGURE 4 (CONTINUED). IN-ORBIT NORMALIZED CELL PARAMETERS

TABLE 6. COVER GLASS THICKNESS VARIATION RESULTS*

Configuration	Base Resistivity, ohm-cm	Cell Thickness, cm	Cover Thickness, cm	Percent Loss		
				I_{sc}	V_{oc}	P_{max}
6	10	0.030	0.0038	12.9 ± 2.1	2.1 ± 0.4	14.8 ± 2.5
1	10	0.030	0.0076	14.1 ± 2.1	1.9 ± 0.4	15.7 ± 2.7
2	10	0.030	0.015	14.9 ± 3.4	2.1 ± 0.7	17.0 ± 2.9
3	10	0.030	0.030	11.6 ± 2.2	1.0 ± 0.5	12.6 ± 1.9
4	10	0.030	0.076	12.0 ± 1.3	1.4 ± 0.6	13.7 ± 2.4

*2-1/3 years in orbit.

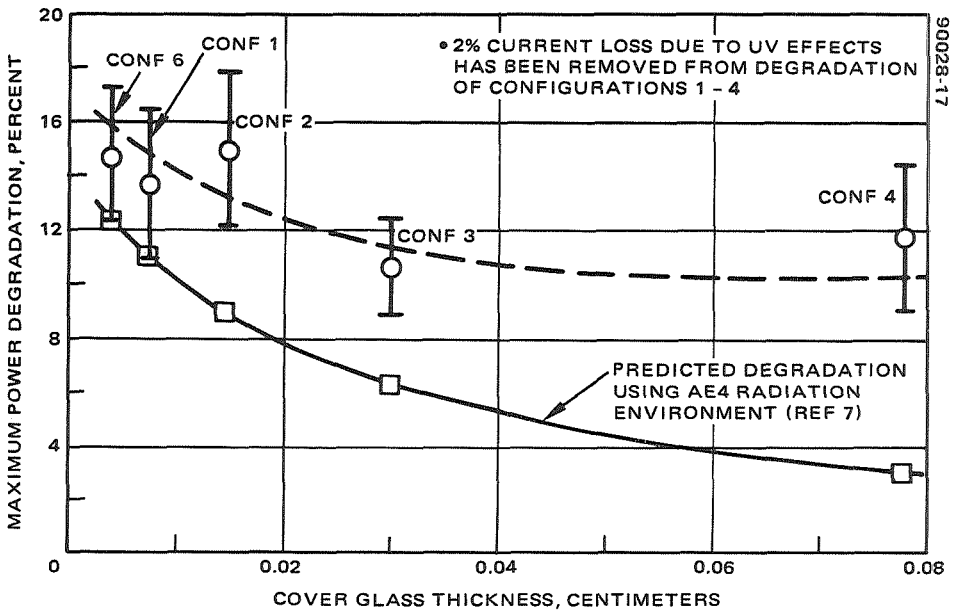


FIGURE 5. MAXIMUM POWER DEGRADATION VERSUS COVER GLASS THICKNESS

Figure 5 is the calculated maximum power degradation as a function of cover glass thickness variation using the NASA's radiation environment model AE4 (Reference 7) for synchronous altitude. As shown in Figure 5, the degradation rate for all of the cover glasses is greater than the calculated degradation, and the divergence is greater for the thicker covers. Since the voltage degradation (Table 6) appears to be reasonably well behaved, the additional degradation over prediction would appear to be due to an additional anomalous degradation to current. An example of an additional degradation would be an external contamination of some sort to the cell covers.

INTEGRAL AND THIN COVERS

Figure 4 (configurations 1, 5, 6, and 7) displays the normalized cell parameters for cells protected with thin covers (0.0038 and 0.0076 cm thick). Again, the same solar cell, 10 ohm-cm, 0.030 cm thick, is used as the common cell. Table 7 displays the percentage degradation to I_{sc}, V_{oc}, and P_{max} after 2-1/3 years in orbit for these four configurations.

Configurations 1 and 5 are cells protected with 0.0076 cm (3 mil) thick 7940 bonded covers. The cover glass of configuration 1 has both the UV filter and antireflective coating. Comparison of the degradation profiles of configurations 1 and 5 (Figure 4) shows that the degradation of the current for configuration 5 (no filter or coating) is slightly steeper than that of configuration 1 (with filter and coating). At 2-1/3 years in orbit, the difference in the average degradation to I_{sc}, reflected in P_{max}, is approximately 3 percent. The additional degradation is most likely due to the additional degradation to the unprotected adhesive.

Configurations 6 and 7 are cells covered with integral covers, 0.0038 cm 7940 and 0.0076 cm 7070, respectively. The average I_{sc} degradation after 2-1/3 years in orbit (Table 7) for configurations 6 and 7 is 12.9 ± 2.1 and 12.4 ± 3.2 percent, respectively. There is considerable dispersion in the data as is displayed by the large standard deviation. This dispersion is not understood. Included later in this section (see SCRDE) is a discussion of this dispersion, which is also seen in other configurations.

No low energy proton type damage was observed on either type of integral cover. Low energy protons produce nonuniform damage, generally around the junction area, resulting in a softening of the knee of the curve, degrading significantly the curve factor of the cell. As shown in Table 7, the curve factor for configurations 6 and 7 has changed negligibly, well within experimental accuracy. These observations indicated that as little as 0.0038 cm (1-1/2 mil) of 7940 covering will protect the cell from the synchronous orbit low energy proton environment. This result is consistent with the results of the LES-6 experiment (Reference 8).

TABLE 7. INTEGRAL AND THIN COVER RESULTS*

Configuration	Base Resistivity, ohm-cm	Cell Thickness, cm	Cover Thickness, cm	Percent Loss				Remarks
				I_{sc}	V_{oc}	P_{max}	Curve Factor	
1	10	0.030	0.0076	14.1 ±2.1	1.9 ±0.4	15.7 ±2.7	-0.1	7940 cover with filter and coatings
5	10	0.030	0.0076	16.9 ±0.3	2.1 ±0.5	18.6 ±1.7	0.0	7940 cover with no filter and coatings
6	10	0.030	0.0038	12.9 ±2.1	2.1 ±0.4	14.8 ±2.5	0.0	7940 integral cover
7	10	0.030	0.0076	12.4 ±3.2	1.7 ±0.2	13.0 ±4.0	-1	7070 integral cover

*2-1/3 years in orbit.

CELL THICKNESS AND BASE RESISTIVITY VARIATION

Configurations 2 and 11 are the 10 ohm-cm cells with cell thicknesses of 0.030 and 0.020 cm (12 and 8 mil), respectively. Configurations 8 and 9 are the 2 ohm-cm cells with the same cell thickness variation. All four configurations have the same cover glass, bonded 0.015 cm (6 mil) 7940 with the UV filter and antireflective coatings. Table 8 displays the cell thickness and base resistivity variation results after 2-1/3 years in orbit. Displayed are the averaged absolute values and percent loss for each configuration. The COMSAT violet cell is included in this section because it is an advanced thin 2 ohm-cm solar cell.

In theory, the 2 ohm-cm cell should perform better than the 10 ohm-cm cell at the beginning of life but degrade faster under the same particulate environment. The initial average cell maximum power for the 2 ohm-cm, 0.030 and 0.020 cm thick cells was 61.0 and 58.3 mW, respectively, and, for the 10 ohm-cm, 0.030 and 0.020 cm thick cells, 59.6 and 56.2 mW, respectively (Reference 1). After 2-1/3 years in synchronous orbit, the average cell maximum power for the 2 ohm-cm, 0.030 and 0.020 cm thick cells was 50.7 and 48.6 mW, respectively, and for the 10 ohm-cm, 0.030 and 0.020 cm thick cells, 49.4 and 48.3 mW, respectively. The 2 ohm-cm cells still have a slight advantage in power after 2-1/3 years in synchronous orbit. The average rate of degradation of the 2 ohm-cm cells compared to the 10 ohm-cm cell is slightly higher.

Configuration 8 (2 ohm-cm, 0.030 cm thick) is very close to the cell type of the ATS-6 main solar arrays. Figure 4 (configuration 8) shows the power degradation to the two main solar arrays of ATS-6 after 2 years in orbit (Reference 9). The ATS-6 main array consists of 2 x 4 cm, 0.034 cm (14 mil) thick, 2 ohm-cm solar cells with 0.015 cm (6 mil), 0211 microsheet covers. The south solar array degraded about 20 percent and the north solar array degraded about 22 percent. Two differences in these cell/cover parameters would account for some additional degradation: 1) the cells were slightly thicker; 2) the covers were 0211 microsheet. Both conditions would cause slightly greater degradation to the ATS-6 main array than to the experiment

TABLE 8. CELL THICKNESS AND BASE RESISTIVITY VARIATION RESULTS*

Configuration	Base Resistivity, ohm-cm	Cell Thickness, cm	Cover Thickness, cm	Absolute			Percent Loss		
				I_{sc}, mA	V_{oc}, mV	P_{max}, mW	I_{sc}	V_{oc}	P_{max}
2	10	0.030	0.015	126	540	49.4	14.9 ± 3.4	2.1 ± 0.7	17.0 ± 2.9
8	2	0.030	0.015	117	568	50.7	15.9 ± 1.0	2.5 ± 0.3	16.9 ± 1.6
9	2	0.020	0.015	116	555	48.6	14.6 ± 1.7	2.1 ± 0.3	16.6 ± 1.5
11	10	0.020	0.015	121	533	48.3	13.8 ± 3.7	1.2 ± 1.0	14.2 ± 4.0
12	1	0.025	0.015	142	574	62.7	20.2 ± 2.0	4.0 ± 0.4	23.9 ± 2.5

*2-1/3 years in orbit.

cells. Cell thickness could account for 1 to 2 percent additional degradation and microsheet covers could account for about 2 percent additional degradation. Taking these differences into account, it can be seen that the amounts of degradation to the ATS-6 main solar arrays and to the ATS-6 solar cell experiment, as shown in configuration 8, appear to be very close. These degradation results, however, are not consistent with degradation observed for the Hughes Aircract Company solar arrays in synchronous orbit (Reference 10). The inconsistency is explained under SCRDE Comparison to Other Data.

Figure 4 displays the COMSAT violet cell degradation (configuration 12). The violet cell not only had the highest beginning of life performance of all cell types, 82.5 ±1.1 mW (Reference 1), but also the highest rate of degradation to all cell parameters, excluding the FEP covered cells (configuration 13). The average percentage degradation to I_{sc}, V_{oc}, and P_{max} after 2-1/3 years in orbit was 20.2 ± 2.0, 4.0 ± 0.4, and 23.9 ± 2.5 percent, respectively. From the published literature (Reference 11), the maximum power degradation to the violet cell is predicted to be 5 percent, much less degradation than observed. Nevertheless, the violet cells, after 2-1/3 years in orbit, are still significantly outperforming all other cells, with a maximum power capability of 62.7 ±1.0 mW.

Configuration 11 is the 0.020 cm (8 mil) thick 10 ohm-cm solar cell; configuration 2 is its counterpart. The maximum power capability (Reference 1) at beginning of life for the 10 ohm-cm, 0.020 cm cell is less than the 0.030 cm thick cell, 56.2 and 59.6 mW, respectively. The rate of degradation (Table 8) for the 0.020 cm cell is slightly less than that of the 0.030 cm cell, 14.2 ± 4.0 and 17.0 ± 2.9 percent, respectively. Again, the cells of these configurations display a large dispersion in the results as is indicated by the large standard deviation.

FEP AS ADHESIVE AND COVER

Table 9 displays the results of the use of FEP as a cover adhesive and as a cover alone, configurations 10 and 13, respectively. Results of configuration 2 are also shown in Table 9 for comparison. Configuration 2 incorporates the "standard" 0.015 cm (6 mil) cover glass with both UV filter and AR coating bonded using Dow Sylgard 182 adhesive.

One of the most interesting results of the ATS-6 experiment is shown in the profile for configuration 10, the solar cell cover glass configuration with FEP as an adhesive. The 7940 cover glass had an antireflecting coating but no UV filter. The degradation rates of this configuration are almost identical to those of configuration 2, its counterpart. There appears no more than the observed early 2 percent loss in I_{sc} due to UV effects, even though the FEP is unprotected from the UV environment. This combination of using FEP as a cover adhesive and a cover without an UV rejection filter could prove to be a very promising cost savings feature for solar array designs.

TABLE 9. FEP AS AN ADHESIVE AND COVER RESULTS*

Configuration	Base Resistivity, ohm-cm	Cell Thickness, cm	Cover Thickness, cm	Percent Loss			Remarks
				I_{sc}	V_{oc}	P_{max}	
2	10	0.030	0.015	14.9 ±3.4	2.1 ±0.7	17.0 ±2.9	7940 cover with filter and coatings
10	10	0.030	0.015	15.8 ±1.1	1.8 ±0.2	16.2 ±1.1	7940 cover without UV filter adhesive of 0.005 cm FEP
13	10	0.030	0.013	20.6 ±1.5	14.3 +1.8	41.8 ±3.6	FEP cover without added adhesive

*2-1/3 years in orbit

Configuration 13 uses FEP as a cover material. These FEP covered cells behaved very similarly to their counterpart, configuration 2, up to the first eclipse season. The eclipse seasons are indicated in Figure 4 for the configuration 13 profile. Shown in this figure are the changes in rate of degradation of V_{oc} and P_{max} during the first eclipse season, indicating that the additional degradations to these cells are related to thermal stresses due to eclipses. Figure 6 displays the individual cell uncorrected I-V characteristics for cells 18 and 34 of configuration 13. Considerable softening of the I-V curve is indicated after 1 and 2 years. The curve factor degradation of 14.5 percent (Table 5) after 2-1/3 years in orbit indicates the amount that the knee of the curve has changed. It appears that shunting is occurring, which could indicate low energy proton damage. Also, it appears that the series resistance has increased as indicated by the large degradations to the voltage parameter.

Possible causes of the additional degradation are

1) Degradation of the FEP cover, e.g., from cracks, pinholes, flaking, or delaminations at the edges of the cell; this condition could result in low energy proton damage.

2) A thermal mismatch between the silicon, ohmic contact, interconnect, and FEP materials; this condition might result in the interconnect pulling away from the silicon, causing junction damage or an increase in series resistance.

It should be noted that these FEP covered cells represent 1972 technology.

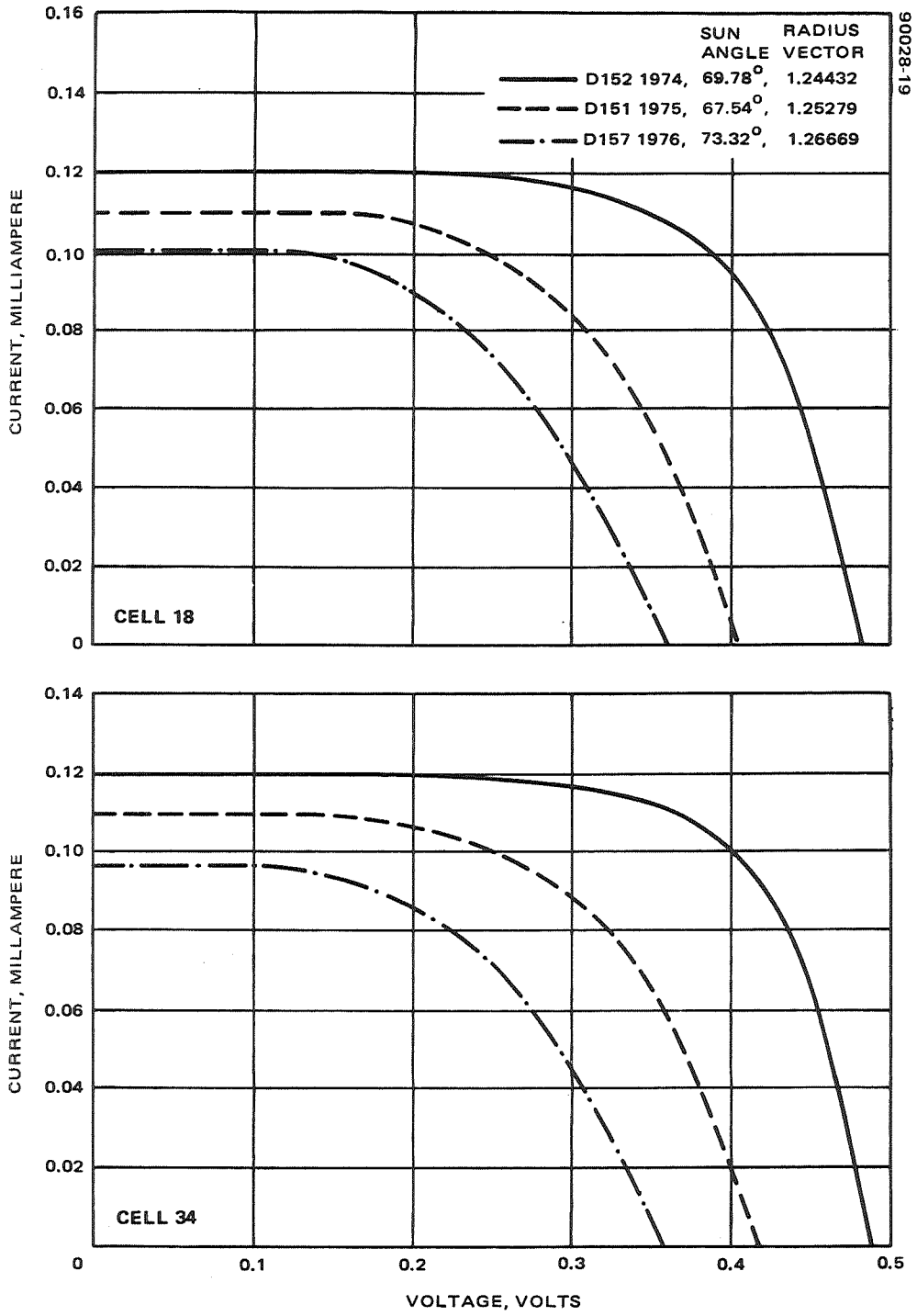


FIGURE 6. UNCORRECTED CURRENT-VOLTAGE CHARACTERISTICS FOR CELLS OF CONFIGURATION 13

SCRDE COMPARISON TO OTHER DATA

The results of the ATS-6 SCRDE are compared with the following ground based and in-orbit data: laboratory spectrum electron irradiation on the ATS-6 ground test cells (References 2 and 12), the LES-6 solar cell flight experiment (Reference 8), the performance of the ATS-6 main solar arrays (Reference 9) presented in Section 4, and the flight performance of solar arrays built by Hughes Aircraft Company (Reference 10).

The results of the 10 ohm-cm, 0.030 cm thick cells with 0.015 and 0.030 cm thick cover glasses irradiated with laboratory spectrum electrons (References 2 and 12) are presented in Figure 4 (configurations 2 and 3). The electron spectrum was an attempt to produce a fluence-energy spectrum closely approximating the model spectrum for synchronous altitude (Reference 7). The cells were mounted on a cylindrical aluminum drum which was rotated during the irradiation, effectively producing a fluence field of cylindrical symmetry. To compare with the degradation in space, 2 percent additional degradation was added to the laboratory results to account for UV effects. The V_{oc} degradations in space of the cells with 0.015 and 0.030 cm thick covers agree within 1 percent of the laboratory irradiations. However, the I_{sc} and P_{max} degradations did not agree well at all with the laboratory results. Degradations were more severe at 2-1/3 years in space. The spectrum irradiation profiles for I_{sc} and P_{max} followed the space degradation for approximately 150 and 300 days in orbit for 0.015 and 0.030 cm thick covers, respectively.

The cells of configuration 2 are quite similar to cells A3 and A4 of the LES-6 SCFE (Reference 8). The 2 year degradations of cells A3 and A4 are indicated in the profile for configuration 2. The I_{sc} degradations are less than those of the ATS-6 cells but very close to the spectrum irradiation results. The P_{max} degradations are both more severe than the spectrum irradiation results and very close to the degradation of the ATS-6 cells. Cell A4 of the LES-6 has no MgF antireflection coating on the cover; however, the I_{sc} current of this cell and cell A3 track within 1 percent, so the MgF coating cannot make the difference. It is interesting to note that the two cells of LES-6 also display the same differences in degradation profile for P_{max} as seen with ATS-6.

Also displayed in Figure 4 for configuration 3 is the maximum power degradation profile as determined from the performance of Hughes Aircraft Company solar arrays in synchronous orbit. The flight performance of the TACSAT, Intelsat IV, Intelsat IVA, Anik, and WESTAR solar arrays was determined for orbital durations over 5 years (Reference 10). Again, the cells of the ATS-6 experiment display more degradation at 2-1/3 years in orbit than has been observed on Hughes solar arrays. It appears that degradations of ATS-6 experiment cells agree only through approximately 300 days in orbit.

Considerable synchronous orbit performance on the 10 ohm-cm, 0.030 cm (12 mil) thick solar cell covered with a standard 0.030 cm thick 7940 cover glass has been gained by the author. Combined with data from particle detectors aboard ATS-6 and the degradation of the Hughes solar arrays (Reference 10), the integral dose to a cell with a 0.030 cm thick cover from the synchronous orbit trapped radiation environment appears to be approximately one-half of the AE4 radiation model. This is in considerable disagreement with the results of I_{sc} and P_{max} degradations of the cells of the ATS-6 SCRDE. Table 10 compares the degradation to the cell parameters of configuration 3 with the calculated degradation to the same cell/cover configuration for 2-1/3 years in orbit using Hughes Aircraft Company experience and the AE4 radiation environment model. The V_{oc} degradation of configuration 3 appears to best agree with the degradation observed by solar arrays built by Hughes Aircraft Company, 1.5 ± 0.5 versus 2.0 percent. The AE4 environment predicts slightly greater degradation to V_{oc} at 3.0 percent. The degradation to I_{sc} for configuration 3 reflects considerably greater degradation than either case for synchronous orbit. The difference between the degradation results for configuration 3 (11.6 ± 2.2) and the calculated I_{sc} degradation based on Hughes' experience (4.6 percent) might indicate an additional loss to current over and above the normal effects due to UV and synchronous electron environment. The mission duration of the ATS-6 SCRDE has been through the solar cycle minimum and no solar proton flares have occurred. Therefore, the anomalously high degradation to I_{sc} and P_{max} is most likely due to an additional loss in the transmittance characteristics of the optical stack. If the solar array degradation experience of Hughes is used as a baseline, the additional loss to I_{sc} would be 7 ±2 percent.

In reviewing the normalized cell parameter results in Table 3, it appears that for most configurations one cell degrades more than others in the group. Figure 7 is the front view of the SCRDE and shows the individual solar cell locations. Only cells of SPU 1 are of concern; SPU 2 had failed

TABLE 10. COMPARISON OF SOLAR CELL DEGRADATION TO CONFIGURATION 3 WITH OTHER RESULTS*

Data Base	Percent Degradation		
	I_{sc}	V_{oc}	P_{max}
Hughes Aircraft Company Experience (Reference 10)	4.6	2.0	6.0
AE 4 Radiation Environment (Reference 7)	6.0	3.0	8.1
ATS-6 SCRDE Configuration 3	11.6 ±2.2	1.0 ±0.5	12.6 ±1.8

*2-1/2 years

at beginning of life (Reference 1). The cells that showed greater degradation to I_{sc} than others in their group have been shaded in. A very interesting effect is demonstrated. Most of the cells that demonstrated the greater I_{sc} losses are located in the lower left corner. The cell numbers are 6, 9, 10, 11, 19, 20, 22, 30, 31, 32, 33, 34, 35, and 38. This result could indicate that possibly some external source has contaminated the SCRDE, especially these cells, adding to the degradation of the cells' current capability.

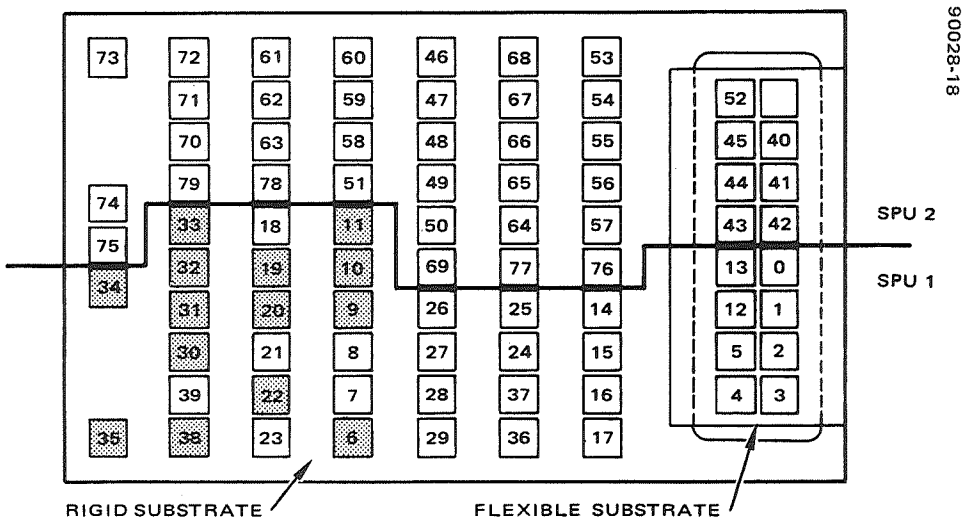


FIGURE 7. ATS-6 SCRDE SOLAR PANEL FRONT VIEW

6. CONCLUSIONS

1. Thicker cover glasses increased the protection to solar cells from the synchronous environment, but with much less effect than predicted. This was demonstrated by the variation of cover thickness on the experiment.

2. Solar cells with integral covers as little as 0.0038 cm (1-1/2 mil) thick were well protected from the synchronous environment. These covers were more than thick enough to shield against the low energy proton complement of this environment.

3. Degradation of cells with integral covers was among the lowest of all configurations. Hence, the need for thicker covers for radiation protection in synchronous orbit is questionable, at least during solar minimum.

4. For the conventional cells after 2-1/3 years in orbit, the 2 ohm-cm, 0.030 cm thick cell performed 2.6 percent (3.0 percent at beginning of life) better than the 10 ohm-cm cell of the same thickness, 4.3 percent (4.6 percent at beginning of life) better than the 2 ohm-cm, 0.020 cm thick cell, and 5.0 percent (8.3 percent at beginning of life) better than the 10 ohm-cm, 0.020 thick cell.

5) The maximum power capability of the COMSAT violet cell was 35 percent greater than that of the conventional 2 ohm-cm cell at beginning of life and 25 percent higher after 2-1/3 years in orbit, even though degradation was more rapid.

6) After 2-1/3 years in orbit, the COMSAT violet cell has the highest performance (63 mW) of all configurations tested. This configuration also experienced the greatest rate of degradation (configuration 13, FEP covered cell, excluded). The 2 ohm-cm conventional cells still exhibit a slight maximum power advantage over the 10 ohm-cm cells.

7) The FEP covered cells (configuration 13) performed as well as their counterparts until the first eclipse season, when the rate of degradation increased. Forty-two percent power degradation has been experienced in 2-1/3 years of synchronous operation.

8) FEP type A, as a cover adhesive with no UV protection, performs as well as its counterpart through 2-1/3 years in synchronous orbit.

9) Dow Sylgard 182 adhesive without the protection of the UV filter on the cover glass degrades an additional 3 percent over the protected adhesive.

10) The short circuit current degradations after 2-1/3 years in orbit are greater than expected compared with laboratory electron spectrum irradiation and Hughes experience with solar arrays in orbit. There is strong evidence that on some cells more than others on the SCRDE there is an anomalous additional 5 to 9 percent degradation affecting the current capability.

11) The remaining SPU of the ATS-6 SCRDE has malfunctioned after 856 days (2-1/3 years) in orbit. Data from SCRDE is no longer reliable; thus, this report represents the final data from the experiment.

7. NEW TECHNOLOGY

This report does not contain items of new technology developed by Hughes Aircraft Company under this contract.

8. REFERENCES

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APPENDIX

Detailed in-orbit results for each cell are displayed for I_{sc}, V_{oc}, and P_{max}, for days 206, 213, 227, 255, 276, and 325 of 1976 and days 58, 65, and 93 of 1977.

TABLE A-1. ATS-6 DATA FOR DAY 206 OF 1976

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10	127.8	541.9	49.3	9	20	113.4	557.6	48.0
	15	130.5	542.4	52.1		36	116.8	554.3	49.0
	22	122.8	544.2	49.5	10	21	120.1	547.1	48.6
2	25	129.8	541.6	50.5		29	124.5	543.5	49.9
	38	122.0	540.5	48.3		39			
3	8	124.3	536.7	49.1	11	7			
	16	129.8	542.7	51.6		17	125.0	531.3	48.7
4	19	124.3	544.3	48.1		32	117.1	535.9	47.4
	35	122.3	549.8	49.6	12	26	143.0	573.3	63.0
	37	128.5	545.3	50.9		33	140.0	574.3	62.0
5	28	119.8	545.1	48.2	13	18	125.1	470.6	35.0
	30	119.9	549.1	47.8		34	118.8	468.8	34.0
6	6	120.2	534.7	45.6	14	0	124.2	494.0	43.2
	24	120.3	531.5	46.9		3	127.5	500.5	44.4
	31	116.8	540.6	46.0		12	124.7	497.1	44.1
7	9	120.4	535.9	47.6	15	1	120.9	516.5	43.4
	14	123.2	532.2	48.2		4	116.0	523.6	44.4
8	11	117.3	559.5	48.7		13	119.3	520.7	44.5
	23	116.7	573.0	50.9	16	2	118.4	523.9	44.9
	27	117.1	570.0	50.9		5	121.6	533.2	46.4

TABLE A-2. ATS-6 DATA FOR DAY 213 OF 1976

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10	127.0	541.5	49.1	9	20	113.0	557.7	48.0
	15	129.7	543.8	52.1		36	116.5	555.0	48.7
	22	121.9	544.5	49.5	10	21	120.7	547.3	48.7
2	25	130.2	540.7	50.3		29	125.1	543.7	50.1
	38	122.1	540.8	48.2		39			
3	8	125.1	535.8	49.1	11	7			
	16	129.5	542.6	51.5		17	124.2	532.0	48.6
4	19	125.1	544.5	48.2		32	117.6	536.0	47.3
	35	122.2	549.9	49.6	12	26	143.0	574.8	63.4
	37	127.9	544.3	51.0		33	140.1	574.5	61.7
5	28	119.4	546.0	48.4	13	18	124.0	471.9	35.1
	30	119.1	549.9	47.9		34	118.8	469.2	34.0
6	6	119.3	534.6	45.7	14	0	124.6	493.4	43.1
	24	120.3	532.0	46.7		3	126.4	500.9	44.3
	31	116.0	541.4	45.9		12	124.7	497.4	44.1
7	9	120.8	533.8	47.4	15	1	121.3	515.4	43.6
	14	122.4	534.1	48.3		4	116.8	521.3	44.2
8	11	116.9	558.7	48.6		13	119.9	520.5	44.5
	23	116.4	573.3	51.1	16	2	118.8	522.8	44.9
	27	117.6	570.1	51.2		5	121.8	532.9	46.3

TABLE A-3. ATS-6 DATA FOR DAY 227 OF 1976

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10	127.4	542.9	49.3	9	20	113.9	558.3	48.3
	15	132.0	542.8	52.8		36	116.9	554.3	48.8
	22	123.2	545.6	50.0	10	21	121.1	548.5	49.3
2	25	130.2	541.3	50.2		29	124.3	544.1	50.1
	38	123.9	540.4	48.9		39			
3	8	125.5	537.5	49.5	11	7			
	16	131.5	543.2	52.2		17	125.8	531.2	49.1
4	19	126.0	545.0	48.7		32	118.4	535.3	47.8
	35	124.7	548.8	50.3	12	26	142.7	575.4	63.4
	37	128.9	543.7	51.3		33	142.0	572.8	62.4
5	28	119.3	546.0	48.4	13	18	124.0	474.7	35.7
	30	120.9	549.7	48.4		34	120.1	471.4	34.8
6	6	119.7	534.9	45.8	14	0	125.3	490.6	43.0
	24	119.6	532.7	46.9		3	126.8	500.2	44.2
	31	117.5	541.5	46.5		12	125.3	494.2	44.0
7	9	121.1	535.0	47.6	15	1	120.9	514.1	43.5
	14	124.1	533.3	48.8		4	117.3	520.0	44.1
8	11	117.2	561.6	49.0		13	121.9	517.0	44.9
	23	117.0	574.4	51.6	16	2	119.3	522.2	45.1
	27	117.1	571.8	51.1		5	122.3	531.7	46.5

TABLE A-4. ATS-6 DATA FOR DAY 255 OF 1976

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10	128.5	541.4	49.3	9	20	114.9	555.5	48.7
	15	129.4	541.2	52.0		36	116.6	553.1	48.7
	22	124.1	543.0	50.2	10	21	123.1	544.9	50.0
2	25	129.5	539.9	49.8		29	125.2	542.3	50.1
	38	123.3	540.0	49.0		39			
3	8	126.0	536.1	49.8	11	7			
	16	129.9	544.5	51.8		17	123.2	532.7	48.6
4	19	127.9	546.5	49.4		32	117.6	534.2	47.5
	35	125.1	547.9	50.7	12	26	142.8	576.0	63.6
	37	130.5	543.4	51.9		33	140.0	573.6	62.0
5	28	120.0	545.1	48.8	13	18	120.9	481.1	36.3
	30	120.1	549.3	48.6		34	116.8	475.2	35.1
6	6	120.1	534.3	46.1	14	0			
	24	120.2	531.3	47.1		3	125.5	491.5	43.1
	31	117.1	539.2	46.3		12	124.0	489.0	43.1
7	9	121.6	533.6	48.1	15	1	119.9	506.8	42.5
	14	123.0	531.4	48.3		4	116.9	516.7	43.8
8	11	117.8	558.9	49.1		13	119.6	513.3	43.8
	23	118.2	572.2	51.9	16	2	118.6	514.0	44.1
	27	117.6	570.9	51.5		5	121.5	527.9	46.0

TABLE A-5. ATS-6 DATA FOR DAY 276 OF 1976

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10	126.2	543.2	49.0	9	20	114.2	554.1	48.1
	15	130.8	540.7	52.5		36	117.4	554.2	49.1
	22	122.8	542.8	49.9	10	21	121.9	545.8	49.6
2	25	129.2	539.9	49.8		29	125.0	544.3	50.4
	38	123.2	541.4	48.9		39			
3	8	125.8	537.4	49.6	11	7			
	16	131.0	544.3	52.6		17	124.9	532.2	49.2
4	19	127.8	545.3	49.5		32	117.0	532.3	47.4
	35	126.1	546.7	51.0	12	26	141.8	575.7	63.1
	37	131.6	545.0	52.4		33	140.3	571.9	62.0
5	28	119.1	547.7	49.0	13	18	118.5	483.9	36.7
	30	120.5	551.3	49.0		34	115.6	477.9	35.7
6	6				14	0			
	24	120.5	530.4	47.1		3	123.4	493.5	42.7
	31	116.5	541.9	46.7		12	123.3	484.9	42.8
7	9	119.4	535.3	47.6	15	1	120.5	508.7	42.6
	14	123.1	530.7	48.6		4	117.8	515.7	44.1
8	11	116.4	561.6	49.1		13	120.3	510.0	43.9
	23	117.0	571.3	51.6	16	2	119.0	515.8	44.3
	27	117.0	571.1	51.5		5	123.0	527.9	46.3

TABLE A-6. ATS-6 DATA FOR DAY 325 OF 1976

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10	105.1	545.0	41.8	9	20			
	15					36	97.7	550.7	40.8
	22	101.0	556.0	42.8	10	21	99.8	558.9	41.9
2	25	107.8	537.2	42.3		29	102.8	540.8	41.9
	38	101.2	539.9	40.7		39			
3	8	104.9	541.1	42.3	11	7			
	16	108.4	540.5	43.9		17	102.8	528.7	41.0
4	19					32	97.7	546.6	40.8
	35	104.0	561.0	43.7	12	26	117.2	569.7	52.1
	37	110.0	543.1	44.1		33	114.8	584.6	52.4
5	28	98.0	544.0	40.3	13	18	100.7	475.9	29.8
	30	97.9	547.9	40.0		34	96.7	482.7	29.4
6	6				14	0			
	24	99.2	527.6	39.2		3	108.7	494.0	35.5
	31	95.5	539.6	38.6		12			
7	9	99.5	538.3	40.1	15	1	99.8	507.7	35.8
	14	101.8	535.9	40.7		4	97.0	520.2	37.0
8	11	96.7	562.5	41.2		13	99.3	516.7	37.1
	23	96.3	584.4	43.7	16	2	98.6	513.0	36.7
	27	96.6	566.3	42.7		5	101.0	530.2	38.8

TABLE A-7. ATS-6 DATA FOR DAY 58 OF 1977

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10				9	20			
	15					36			
	22	124.5	419.7	35.0	10	21	123.5	422.4	34.7
2	25	132.6	415.2	34.8		29	128.7	417.4	35.2
	38	125.0	415.1	33.8		39			
3	8				11	7			
	16					17			
4	19					32	120.2	407.5	32.6
	35				12	26	150.0	458.3	48.7
	37					33			
5	28	123.3	420.6	34.4	13	18			
	30	122.1	424.8	34.1		34			
6	6				14	0			
	24	124.4	405.9	33.2		3	123.5	366.4	27.9
	31					12			
7	9				15	1	120.9	389.6	29.3
	14					4	120.4	396.7	30.7
8	11	121.1	442.7	35.8		13			
	23	120.7	455.3	38.1	16	2	121.6	397.6	30.5
	27	122.2	452.7	38.6		5	125.4	409.4	32.8

TABLE A-8. ATS-6 DATA FOR DAY 65 OF 1977

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10				9	20			
	15					36			
	22	124.4	424.9	35.5	10	21	123.2	428.7	35.3
2	25	132.5	419.5	35.1		29	128.2	422.3	35.6
	38	120.4	531.0	47.1		39			
3	8				11	7			
	16					17	126.5	408.1	33.8
4	19					32	121.3	417.6	33.7
	35				12	26	148.9	462.4	48.8
	37					33			
5	28	122.7	425.3	34.7	13	18	117.8	366.0	24.0
	30	122.9	429.2	34.8		34			
6	6				14	0			
	24	124.3	410.3	33.5		3	124.4	365.1	27.9
	31					12			
7	9				15	1	122.8	387.5	29.4
	14					4	120.1	405.9	31.5
8	11	120.3	442.9	35.7		13			
	23	120.1	460.4	38.6	16	2	122.4	395.8	30.5
	27	121.5	457.6	38.7		5	125.0	419.0	33.6

TABLE A-9. ATS-6 DATA FOR DAY 93 OF 1977

CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)	CON	CELL	ISC (MA)	VOC (MV)	PMP (MW)
1	10				9	20			
	15					36			
	22	119.7	544.7	48.7	10	21	118.6	548.1	48.6
2	25	125.9	540.6	49.0		29	121.2	542.9	48.9
	38	118.9	540.6	47.2		39			
3	8				11	7			
	16					17	120.4	531.0	47.3
4	19					32	113.6	535.9	46.3
	35				12	26	138.1	576.1	61.9
	37					33			
5	28	115.8	545.2	47.5	13	18	114.9	482.8	35.9
	30	115.9	548.9	47.0		34			
6	6				14	0			
	24	117.0	531.7	46.2		3	119.9	498.1	42.5
	31					12			
7	9				15	1	115.7	512.8	41.8
	14					4	112.6	519.3	42.7
8	11	113.7	559.7	48.0		13			
	23	113.4	573.0	50.0	16	2	114.2	519.5	42.7
	27	114.7	570.9	50.4		5	117.3	532.1	45.3