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SUMMARY

Various types of solar cells were monitored during 416.8 days in synchronous orbit on satellite ATS-I.

Judging by the remaining percentage of initial maximum power qualified conclusions were: (1) degradation was greater than expected; (2) optimum base resistivity was 10 ohm-cm; (3) optimum shield thickness was 6 mils; (4) sapphire and silica shields were comparable; (5) silica shields were superior to glass; (6) boron and aluminum doping were comparable; (7) that it was necessary to presume some radiation damage, some drop in illumination, and a development of series resistance to account for the results.

INTRODUCTION

Solar cells, which directly convert light energy to electric power with an efficiency of about 10 percent, are almost universally used on unmanned spacecraft to energize various electrical devices.

It was early found that the efficiency of such cells degraded rapidly in space. This was ascribed to the action of energetic electrons and protons trapped in the earth's magnetic field (the "Van Allen belts"). Inadequate electrical output can severely restrict the duration of space missions. The government and industry cooperated in developing radiation resistant types of cells and of methods to shield them from the damaging particles.

To assess the value of such efforts many experiments were performed using artificially produced beams of particles, in laboratories. Further, a number of space experiments were undertaken, since it was impossible to simulate the full space environment in a laboratory.

Among these experimenters were Longanecker,[1] Reynard,[2] Slifer and McCarron,[3] Grigor'eva et al.,[4] and Fischel et al.[5] The author[6,7] has reported measurements on Relay I and Relay II, as well as preliminary results[8,9,10] from spacecraft ATS-I (Applications Technology Satellite number one). Most of these measurements were of the short-circuit current available from the cells, a property conveniently handled by the damage theory that was developed. Some experimenters[1,3] approximated the maximum power condition, one of greater practical significance. The solar cell radiation damage experiment reported on here and earlier,[8,9,10] as carried by spacecraft ATS-I, provided information on the full voltage-current characteristics of individual cells, allowing judgments to be made from various standpoints. Further, such information is capable of revealing the character of the damage mechanism(s).

The earlier experiments generally agreed on the superiority of the silicon n-on-p solar cell, and that transparent shields of artificial pure fused silica gave increasing protection as their thickness was increased. The orbits involved were usually highly damaging ones, requiring repeated passages through the radiation belts.

The purpose of this report is to give more complete results from the ATS-I solar cell damage experiment. Since this experiment involved a synchronous orbit where great numbers of spacecraft (experimental, communications, meteorological, military, etc.) are, and will be located, its results are of special interest. The orbit has been considered as having little radiation damage capability, since it is outside the conventional belts.

THE ATS-I RADIATION DAMAGE EXPERIMENT

This radiation damage experiment was carried aboard the first of the Applications Technology Satellite series. It was launched from Cape Kennedy on Dec. 7, 1966 at 2 hours, 12 minutes, GMT. The times in orbit given later were computed from this instant.

After launch the spacecraft spent its first 15 hours executing one and one-half transfer ellipses of apogee 23,240 miles and perigee 100 miles. It then entered its circular, synchronous orbit at 23,240 miles altitude. After drifting westward for a time it was then held on station over the Pacific equator at 157 degrees west longitude. The spacecraft was spin-stabilized at about 100 revolutions a minute.

The ATS-I Apparatus

The thirty solar cells flown in this experiment were selected to exhibit the effects of varying several parameters. Two cells of each type were included. The cells were mounted on a 4 inch by 8 inch magnesium panel, one-eighth inch thick, for temperature uniformity. The temperature was measured at the center. Temperature resolution was about 1 degree C. The panel also carried a solar aspect sensor for measuring the angle of incidence of the illumination. Angle resolution was about 1 degree.

Upon receiving a ground command (which was sent several times a day) a data-taking sequence was initiated in the spacecraft. The voltage developed by each solar cell as successively loaded by resistors of about 3, 4.5, 6, 8, 10, 15, 25 and 2000 ohms was evaluated by an 8 bit analog-to-digital converter (capacity 255 units for 765 mv, or 3 mv per unit) and entered in a 2176 bit magnetic core memory. Also entered were time, temperature, aspect angle, and responses to calibrating voltages of zero and 480.0 mv.

The telemetry signals (digital pulse frequency modulation) were recorded by a ground station.

The apparatus weighed 5 pounds and consumed 5 watts.

Calibration

Before launch certain calibrations were made. The response of each cell, as loaded by each resistor, was measured as a function of illumination angle, using collimated sunlight at about 90 mw per cm^2. Voltage-current curves were recorded. The thermistor network for measuring temperature was calibrated. The analog-to-digital converter was adjusted for zero, linearity, and gain. Stray resistances in the leads to the solar cells were measured.

The Solar Cells

The solar cells were all nominally 1 cm by 2 cm in size and were made of silicon. All were n-on-p except number 13, which was an old style p-on-n. Table I, besides listing some numerical results, identifies the nature of the cells and of their shields. Cell numbers are given in column 1, base resistivities in 2 ("GR" indicates graded base doping), the dopant in 3, the shield in 4 (the first number is the shield thickness in thousandths of an inch (mils), the second is the Corning Glass Company material number, 7940 being artificial fused silica, 7740 and 0211 being types of glass, and "SAP" being clear artificial sapphire). Cell thicknesses were about 14 mils except for cells 1 and 2, which were about 8 mils thick. These two cells were also slightly smaller in area than the others. Further, the sapphire shields were attached, without adhesives, at the edges by a type of solder and there were no anti-reflecting films or filters. The shields were similar in construction to those used on the Telstar satellite. The cells themselves were experimental, with enhanced response to blue light. As indicated, cells 15 and 16 had 1 mil integral shields[11] of 7740 glass. This was applied as a powder and then melted at about 900°C. There was no adhesive or anti-reflecting coating. The 7940 and 0211 type shields were attached with Dow-Corning type XR-6-3488 adhesive. These shields had blue rejection filters with a 400 milli-micron cut-off to minimize adhesive darkening. The outside of the filters was covered with a magnesium fluoride anti-reflection coating.

The electrodes on these cells were of the usual silver-titanium composition. They were not solder-dipped. The front electrode consisted, generally, of a "comb" whose "bar" contact was about 30 mils wide, along the 2 cm cell edge, with 5 narrower "teeth" in the comb. The front connection was made by soldering a ribbon of expanded silver mesh (about 2 mils thick) over the length of the bar contact.

The cell and shield assembly involved in this experiment was probably done with more care than is ordinarily exercised in constructing main solar power panels with thousands of cells. However, post-launch examination of spare experiment panels shows that the cell shields were frequently slightly mis-aligned, leaving small areas of the cell exposed. The effect of this is a matter of some speculation. It undoubtedly occurs to a greater degree on the main solar panels of this and other spacecraft.

Data Corrections

Several corrections were applied to the received data. Pre-launch calibration and aspect sensor information allowed correcting for the fact that illumination was, on occasion, as much as 24 degrees off the perpendicular. The corrections were not greater than 10 percent.

Because of variations in the satellite-sun distance during the year corrections were made to bring the data to that corresponding to 1 astronomical unit (140 mw/cm^2). The maximum correction was 3.3 percent.

Pre-launch measurements on lead resistances were utilized to correct for such strays. Actual load values were as much as 4 percent greater than nominal values.

A final correction was made to bring the results to a common temperature of 24.4°C. The temperature coefficient of the voltage coordinate of a given point on the voltage-current characteristic of a given cell was demined from in-flight observations of the behavior of the cell's open-circuit voltage during a day 10 days after launch. The temperature coefficient of current (0.0758 ma per °C) was provided by Slifer,[12] from measurements on 10 ohm-cm cells. For the data in this report the maximum temperature correction was for an interval of only 5.4°C.

The analog-to-digital conversion, and data storage and transmission occurred essentially without error, as judged by the responses to the calibration signals.

The voltage-current characteristics of each cell were indicated by the eight data points available, and were drawn by eye. In general, the data were extremely regular. In some cases the accuracy of determining short-circuit current was poor because of the minimum load resistor value of 3 ohms. However, the maximum power region was always well delineated, as well as open-circuit voltage. The maximum power point was located with the aid of an overlay of constant power curves.

Data reduction of early results[8,9] was by means of a computer program. However, it became evident that the accuracy in the use of calibration and correction information could be slightly improved by desk calculation and direct reference to the above information, without approximations. The results in this and one earlier report[10] were so obtained.

Results and Discussion

Figure 1 illustrates the type of current-voltage characteristic obtained in this space radiation damage experiment. The cell is 10 ohm-cm, boron doped, with no shield. The eight points corresponding to the eight load resistors are shown. These data, and all others in this report, were corrected to the standard conditions indicated. At the time of writing, data for six times (0.064, 3.28, 20.2, 100.7, 270.4 and 416.8 days after lift-off) have been processed. It is evident from Figure 1 that the data is regular, that power and open-circuit voltage can be accurately determined, and that short-circuit current for severely damaged cells can only be estimated. The maximum power point is indicated on each curve.

The large degradation indicated as having occurred between 0.064 and 3.28 days was undoubtedly caused by the two very damaging passages through the trapped radiation belts that occurred during this time. All unshielded cells showed this effect. The subsequent degradation of the unshielded cells in synchronous orbit occurred almost entirely by steps covering about 5 days each. It was ascertained that these steps correlated well, in time and duration, with the arrival of solar protons, as measured by Paulikas[13] by instruments on the ATS-I spacecraft. The steps are not evident with cells having shields of 1 mil or more. Evidently the radiation damaging the unshielded cells, at synchronous altitude, was protons of energies less than 1.4 Mev, and/or heavier particles.

Table I lists the solar cells involved in this space radiation damage experiment. As mentioned before, columns 1, 2, 3 and 4 describe each cell and its shield. Columns 5, 6, 7, and 8 give certain cell properties as measured 0.064 days after launch. At this time the spacecraft was near its first apogee and the cells, therefore, had passed once through the radiation belts. Examination of the trajectory indicated that the passage was not a highly damaging one. Column 5 gives the short-circuit current (I_{SC}) in milliamperes; column 6 gives the open-circuit voltage (V_{OC}) in millivolts; column 7 gives the maximum power (P_M) in milliwatts; and column 8 gives the value of the "curve factor" or "fill factor" (F). This is the ratio of the maximum power to the product of short-circuit current and open-circuit voltage. It is very sensitive to the presence of series resistance in a cell.

Comparison of cell powers from Table I to powers exhibited in pre-launch tests using collimated sunlight indicates that, probably, none of the shielded cells were appreciably damaged by the first passage through the radiation belts, which preceded the first flight observation. However, it was estimated that unshielded cells 13, 14, 25, and 26 had suffered power degradations of 9, 8, 4, and 3 percent, respectively. Thus, the use of values from Table I as initial reference values characteristic of undamaged cells is not strictly correct for the unshielded cells.

No data is shown for cell 20 which apparently suffered an early switching failure. Also, it will be seen that, for cell 30, the initial power and curve factor were abnormally low. This cell was not considered typical of its kind.

Cell properties for the two members of a pair of similar type tend to be similar. The fact that it was possible to fly so few cells of each kind (2) is a principal defect of the experiment, and should be remedied in future experiments.

Nominal initial efficiencies may be calculated by dividing the powers of column 7 by 280 milliwatts. A number of cells approach 10 percent.

Table II compares the cells, at 416.8 days after lift-off, among themselves, and with their initial properties as given in Table I for 0.064 days after lift-off. Values involving estimation are given in parentheses. The results are grouped to make it easier to see the effect of varying a single parameter. Again columns 1, 2, 3 and 4 identify the cells. Columns 5, 6, 7 and 8 give the values (averaged over, generally, the two cells of a pair) for the indicated cell properties 416.8 days (1.14 years) after launch. Columns 9, 10 and 11 give these properties as percentages of the values obtained at 0.064 days. If one assumes that all of the cells could, by suitable technical development, be brought to the same initial efficiency (a debatable point) then these percentages are valid means for comparison.

Lines 1 to 4 of Table II show the result of, presumably, varying only the resistivity of the material from which the cells were made. It is evident from Table II, columns 9, 10 and 11 that the resistivity had little effect on short-circuit current damage, that it minimized the (small) losses in open-circuit voltage, and that, from a power standpoint, a resistivity of 10 ohm-cm was optimum. Figure 2 shows the somewhat irregular plot of percent initial power versus resistivity.

Lines 5 to 10 of Table II show the effect of varying shield thickness. Figure 2 shows plots of some of these data. Here the bars terminate at the two values of a pair of cells.

It is evident that an unexpected effect had occurred. The short-circuit current and, to a lesser degree, the open circuit voltage of this series of cells is shown to have experienced less damage as the shield thickness was increased, as might be expected. However, the maximum power (and F) show maximum values after 416 days in orbit for an intermediate shield thickness of 6 mils.

Further insight into this peculiar result may be obtained by studying Figure 4. Here some initial and final voltage-current curves are shown for this set of nominally similar cells having shields from zero to 60 mils in thickness.

A comparison of Figure 4A (or Figure 1) with a set of laboratory damage curves obtained by Gdula[14] indicates that low energy protons probably were the damaging agent. These were undoubtedly encountered in the transfer ellipse and from solar flares. Scanning Figures 4B, C, D, E, and F (1, 6, 15, 30, and 60 mil shields) shows the decreasing short-circuit current damage with thicker shields, and the slight effect on open-circuit voltage. The odd behavior with respect to maximum power is correlated with the separation between the curves in their maximum power regions. The knees became "softer" as the shields increased beyond 6 mils in thickness.

A qualitative analysis of this set of curves, using Gdula's data[14] for reference, indicated that, probably, three damage agents were effective. These were: (1) some true radiation damage, presumably by penetrating electrons; (2) a drop in illumination, possibly caused by surface contamination, surface erosion, loss of surface coating, or darkening of shield or adhesive; and (3) an agent particularly effective in the maximum power region, which was aggravated by the use of thicker shields. Among possibilities for the latter effect are: degradation of high energy protons to lower and more damaging values, damage to small, unshielded areas of the cells by lower energy protons (possibly enhanced by thick shields) damage through and under contact areas, damage to contacts by trapped moisture, and a degradation of the outer contact fingers associated with thermal cycling and the presence of thick, rigid shields. Some of these possibilities were discussed in an earlier report.[10] Little can be added at this time. Gdula's data[14] strongly indicates the development of series resistance in the heavily shielded cells. Only a fraction of an ohm would account for the observed effect.

The deleterious effect of using thick shields on solar cells intended for synchronous orbit use, if true, is of considerable significance. Such thick shields could not only add weight and cost, but, apparently, could actually cause the cells to degrade faster than if thinner, lighter shields were used. This experiment indicates (Table II, lines 6 and 10) that 1 mil integral shields were actually superior to 60 mil shields, and that shields between 1 and 15 mils were most effective.

Continuing with Table II, lines 11 and 12 contrast a pair of thin (8 mils), blue sensitive cells (numbers 1 and 2) with 30 mil edge supported sapphire shields and no adhesives or coatings with a conventional cell (number 20) bearing a 60 mil silica shield, with adhesives and coatings. These thicknesses are comparable in shielding effect because of the high density of sapphire. The table indicates that the final power percentages were similar. Figure 5 shows the time variation of these cells. The sapphire shielded cells (as well as a number of other cells in this experiment) showed an improvement in power over the first few days of flight, with subsequent degradation. The sapphire shielded cells were superior (percentage-wise only) to the 60 mil silica, shielded cell (20) over this period of observation, but were degrading rapidly at the end. Their curve factor (F) remained good. The large power drop of these cells (16.5 percent), which had no adhesives or films and negligible unshielded areas, is difficult to account for.

Lines 13 and 14 of Table II, and Figure 6, compare the behavior of cells shielded with type 7940 silica (numbers 5 and 6) and similar cells shielded with type 0211 glass (numbers 17 and 18). There is a slight preference for the 7940 silica, which is known to be more resistant to radiation darkening.

Table II, lines 15 and 16, and Figure 7 contrast conventional, uniformly (base) doped 10 ohm-cm cells (numbers 5 and 6) with "drift field" cells (numbers 11 and 12) whose base doping was highly non-uniform, or "graded." The theoretical effect of the graded doping is to cause an internal electric field in the base which assists the desired migration of minority carriers. These two cells were quite similar and exhibited a high initial open-circuit voltage (about 590 mv). However, the power levels at 416.8 days, both absolute and percentage-wise, are seen to be inferior to the cells of conventional uniform doping.

Lines 17 and 18 of Table II, and Figure 8 compare conventional boron-doped cells (numbers 5 and 6) with a supposedly similar cell, but with aluminum doping (number 29). Cell 30 was abnormal. Judging from these 6 mil shielded cells the boron doping is preferable. However, a similar comparison, using 30 mil shielded cells (21, 22 versus 27, 28) showed a superiority for aluminum. Thus, the comparison is inconclusive. Laboratory damage experiments indicate similarity of boron and aluminum doping.

In Table II, lines 19 and 20 compare aluminum doped cells bearing 6 mil and 30 mil silica shields. There is a 1.6 percent advantage in power to the more thickly shielded cell. This is not in agreement with the results for boron doped cells, in which the 6 mils shielded cells showed a 5.6 percent power superiority over the 30 mil shielded cells.

Lines 21, 22, and 23 of Table II, and Figure 9 show the behavior of unshielded cells. These data indicate the superiority of the 1 ohm-cm, n-on-p cell. However, as mentioned before, the reference values for the unshielded cells, here used in computing percentages, are undoubtedly in error because of damage having occurred before the first observation at 0.064 days. If approximate corrections are attempted the percentage results for the 1 and 10 ohm-cm n-on-p cells become more similar. Further, Table II shows that the final absolute powers (3.2 and 3.1 mw) were almost identical. Thus, for bare cells in this environment, there seems little difference between the two resistivity cells. However, cell 13, an old style 1 ohm-cm p-on-n cell, seems definitely inferior.

Table III compares all cells at 416.8 days by ranking them with regard to various cell properties. While many interesting observations may be made it is apparent that cells 5 and 6 (10 ohm-cm, boron doped, 6 mil 7940 shields) distinguish themselves in absolute and percentage initial power output. Their form factor also remained high. The most heavily shielded cell (number 20, 10 ohm-cm, boron doped, 60 mil silica shield) ranked low in power and form factor.

A general observation, covering all of the above results, and the one of greatest importance, is that the major part of the degradation of solar cells, as customarily assembled in solar arrays, at synchronous altitude may well not be the result of simple radiation damage associated with the passage of penetrating particles and consequent reduction of minority carrier lifetime. It is suspected that, in the low damage rate synchronous orbit environment other technical deficiencies made themselves evident. These could probably have involved surface contamination, trapped moisture, damage to small unshielded areas, and to degradation of contacts. Further research will be required to put the design of solar arrays for synchronous or other low damage rate missions on a sound basis. It may be added that the degradation of the main solar arrays on a number of synchronous spacecraft has exceeded the commonly predicted rate of about 3 percent per year for cells with 10 to 30 mils of shielding.

Conclusions

Certain conclusions may be drawn from this experiment. Such conclusions must be qualified, in view of the limited number of samples. They also apply, strictly, to the ATS-I mission only, with its characteristic launch procedure and subsequent stay in synchronous orbit for 416.8 days.

(1) The solar cell degradation was greater than commonly expected in such a mission.

(2) Many cells showed an initial, temporary improvement in performance during the first week.

(3) A resistivity of 10 ohm-cm was optimum.

(4) A shield thickness of 6 mils was optimum; cells having thicker or thinner shields degraded to a greater degree.

(5) The degradation of heavily shielded cells was particularly prominent in the maximum power region of the characteristic.

(6) Cells shielded with 30 mils of sapphire and having no adhesive degraded the same amount as cells with conventional 60 mil shields.

(7) Type 7940 silica was superior to type 0211 glass, as a shield.

(8) Cells with uniform base doping were superior to those with graded doping (drift field).

(9) There was little difference between aluminum and boron doping of solar cells.

(10) Unshielded 1 and 10 ohm-cm resistivity n-on-p cells degraded greatly and similarly.

(11) Unshielded cells degraded markedly during execution of the transfer orbit.

(12) Unshielded cells degraded, at synchronous altitude, by a series of steps, found correlated with arrival of solar flare particles.

(13) The degradation of shielded cells was attributed to a mixture of three agents: (a) true radiation damage, (b) a drop in illumination, and (c) some agent, such as the development of series resistance, that was particularly effective in the maximum power region and which was aggravated by the use of thick shields.

(14) Continued laboratory and orbital studies of the degradation of solar cells at synchronous altitude will be required to clarify the design of solar power arrays for such missions.

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Table I

Comparison of Solar Cells 0.064 Days After Lift-Off

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cell Number	RHO (ohm-cm)	Dopant	Shield (mils-mat.)	I_{SC} (ma)	V_{OC} (mv)	P_M (mw)	F
1	10	AL	30-SAP	46.3	516	17.7	0.740
2	10	AL	30-SAP	47.1	523	17.6	0.716
3	13	B	6-7940	64.1	542	24.7	0.711
4	13	B	6-7940	64.0	545	23.4	0.670
5	10	B	6-7940	68.4	560	27.7	0.723
6	10	B	6-7940	67.4	558	27.2	0.724
7	7	B	6-7940	63.1	563	25.2	0.709
8	7	B	6-7940	63.2	562	26.5	0.746
9	3	B	6-7940	60.2	577	25.3	0.729
10	3	B	6-7940	63.8	579	25.7	0.696
11	GR	B	6-7940	55.1	588	25.6	0.727
12	GR	B	6-7940	56.2	591	24.0	0.722
13	1	P	NONE	58.1	547	20.8	0.656
14	1	B	NONE	53.6	555	19.3	0.648
15	10	B	1-7740	61.4	539	24.0	0.725
16	10	B	1-7740	63.4	549	25.0	0.718
17	10	B	6-0211	67.2	563	27.5	0.726
18	10	B	6-0211	66.1	560	27.2	0.735
19	10	B	60-7940	NO DATA			
20	10	B	60-7940	69.2	563	28.4	0.729
21	10	B	30-7940	69.1	558	27.6	0.716
22	10	B	30-7940	70.0	560	28.3	0.722
23	10	B	15-7940	67.4	564	27.5	0.723
24	10	B	15-7940	67.9	560	26.8	0.705
25	10	B	NONE	69.0	552	26.2	0.688
26	10	B	NONE	71.5	545	27.3	0.700
27	10	AL	30-7940	67.6	557	27.3	0.723
28	10	AL	30-7940	67.1	557	26.1	0.699
29	10	AL	6-7940	64.1	558	25.4	0.710
30	10	AL	6-7940	64.8	557	21.5	0.595

Table II

Comparison of Solar Cells 416.8 Days After Lift-Off

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Cell Number	RHO (ohm-cm)	Dope	Shield (mils-mat.)	I_{SC} (ma)	V_{OC} (mv)	P_M (mw)	F	I_{SC} (%)	V_{OC} (%)	P_M (%)	Line
9,10	3	B	6-7940	56.7	560	22.3	0.704	91.5	97.0	87.6	1
7,8	7	B	6-7940	58.9	549	21.9	0.679	93.2	97.6	84.9	2
5,6	10	B	6-7940	62.2	552	25.4	0.739	91.7	98.9	92.5	3
3,4	13	B	6-7940	58.7	539	20.1	0.636	91.6	99.3	83.8	4
25,26	10	B	NONE	(29)	302	3.1	(0.349)	(41.3)	55.0	11.4	5
15,16	10	B	1-7740	56.2	529	20.8	0.699	90.1	97.2	84.9	6
5,6	10	B	6-7940	62.2	552	25.4	0.739	91.7	98.9	92.5	7
23,24	10	B	15-7940	62.7	555	24.1	0.692	92.7	98.7	88.2	8
21,22	10	B	30-7940	64.5	551	24.3	0.683	92.6	98.7	86.9	9
20	10	B	60-7940	65.0	554	23.8	0.660	93.9	98.3	83.5	10
1,2	10	AL	30-SAP	40.7	513	14.8	0.707	87.1	98.8	83.5	11
20	10	B	60-7940	65.0	554	23.8	0.660	93.9	98.3	83.5	12
5,6	10	B	6-7940	62.2	552	25.4	0.739	91.7	98.9	92.5	13
17,18	10	B	6-0211	63.9	553	24.4	0.690	95.9	98.5	89.1	14
5,6	10	B	6-7940	62.2	552	25.4	0.739	91.7	98.9	92.5	15
11,12	GR	B	6-7940	51.6	579	20.8	0.696	92.8	98.3	87.4	16
5,6	10	B	6-7940	62.2	552	25.4	0.739	91.7	98.9	92.5	17
29	10	AL	6-7940	60.8	546	23.0	0.694	94.9	97.9	90.7	18
29	10	AL	6-7940	60.8	54.6	23.0	0.694	94.7	97.9	90.7	19
27,28	10	AL	30-7940	62.1	555	24.6	0.715	92.2	99.6	92.3	20
13	1	P	NONE	8.0	183	0.44	0.301	13.8	33.4	2.1	21
14	1	B	NONE	(27.1)	284	3.2	(0.421)	(50.6)	51.2	16.8	22
25,26	10	B	NONE	(29)	302	3.1	(0.349)	(41.4)	55.0	11.4	23

Table III

Solar Cell Rankings After 416.8 Days

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Rank	I_{SC} (ma)	V_{OC} (mv)	P_M (mw)	F	I_{SC} (%)	V_{OC} (%)	P_M (%)	F (%)
1	20,22	12	5	6	17	3	30	30
2		11	6	9	18	28	28	6
3	17	9	22	5	8,29	27	6	5
4	21	23	27	27		1,6	5	27
5	28,18,5	10,17,28	17	1	30		27	9
6			28	16	4	21	9,29	28
7			24	22	20	24		1
8	24	27,20	23	11	28	17	17	24
9	23		18	28	12,23	23	24	29
10	6	6,24	20	15		5	22	16
11	27		21	24,29	11,21,22	11,22	18	22
12	30	5,21	9,29				11	10
13	29			12		2,20	1,23	11
14	4	22	8	18	24			15
15	8	18	10	17,23	5	18,30	12	12
16	10	7,8	7		9		15	7
17	7		30	2	7,15	4,9,12	7,21	2
18	3	30	16	7				23
19	16	29	12	8	6		4	17
20	15	3	4,11,15	10	10	29	8,10	18
21	9	4		21	27	8		21
22	12	16		20	1	15	16	4
23	11	15	3	3	3	7	20	3
24	1	2	1	30	16	16	3	8
25	2	1	2	4	2	10	2	20
26	25	26	14	14	14	26	14	14
27	26	25	25	26	25	25	25	26
28	14	14	26	25	26	14	26	25
29	13	13	13	13	13	13	13	13

FIGURE CAPTIONS

Fig. 1 - Voltage-Current Curves for Unshielded Solar Cell 25 Over a Period of 416.8 Days in Synchronous Orbit.

Fig. 2 - The Effect of Various Solar Cell Base Resistivities on Cell Characteristics at 416.8 Days.

Fig. 3 - The Effect of Various Shield Thicknesses on Solar Cell Characteristics at 416.8 Days.

Fig. 4 - Initial and Final Voltage-Current Characteristics of 10 Ohm-cm, Boron Doped Solar Cells with Various Shields.

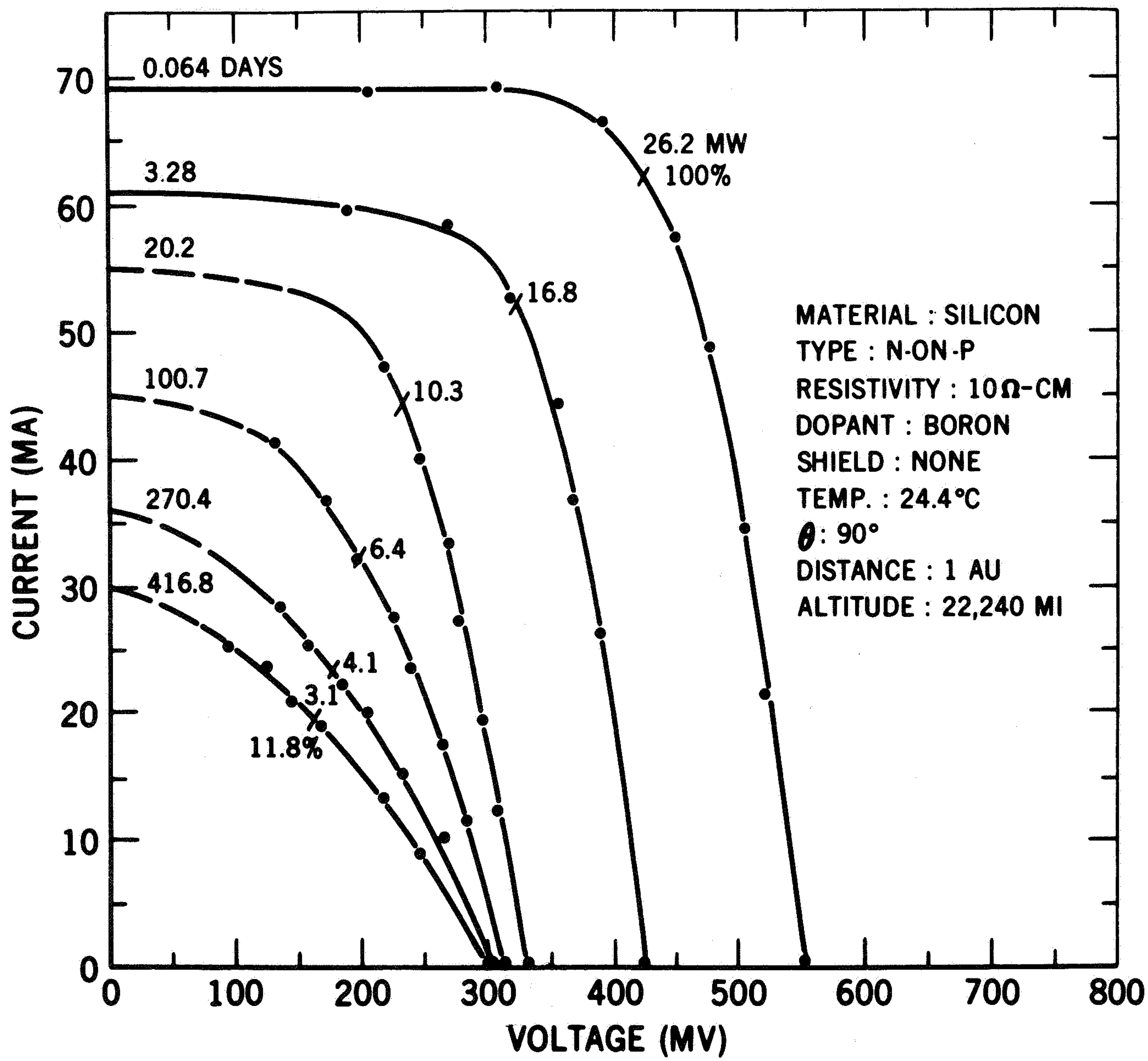
Fig. 5 - Comparison of Solar Cells Shielded with 30 Mils of Sapphire and 60 Mils of Silica.

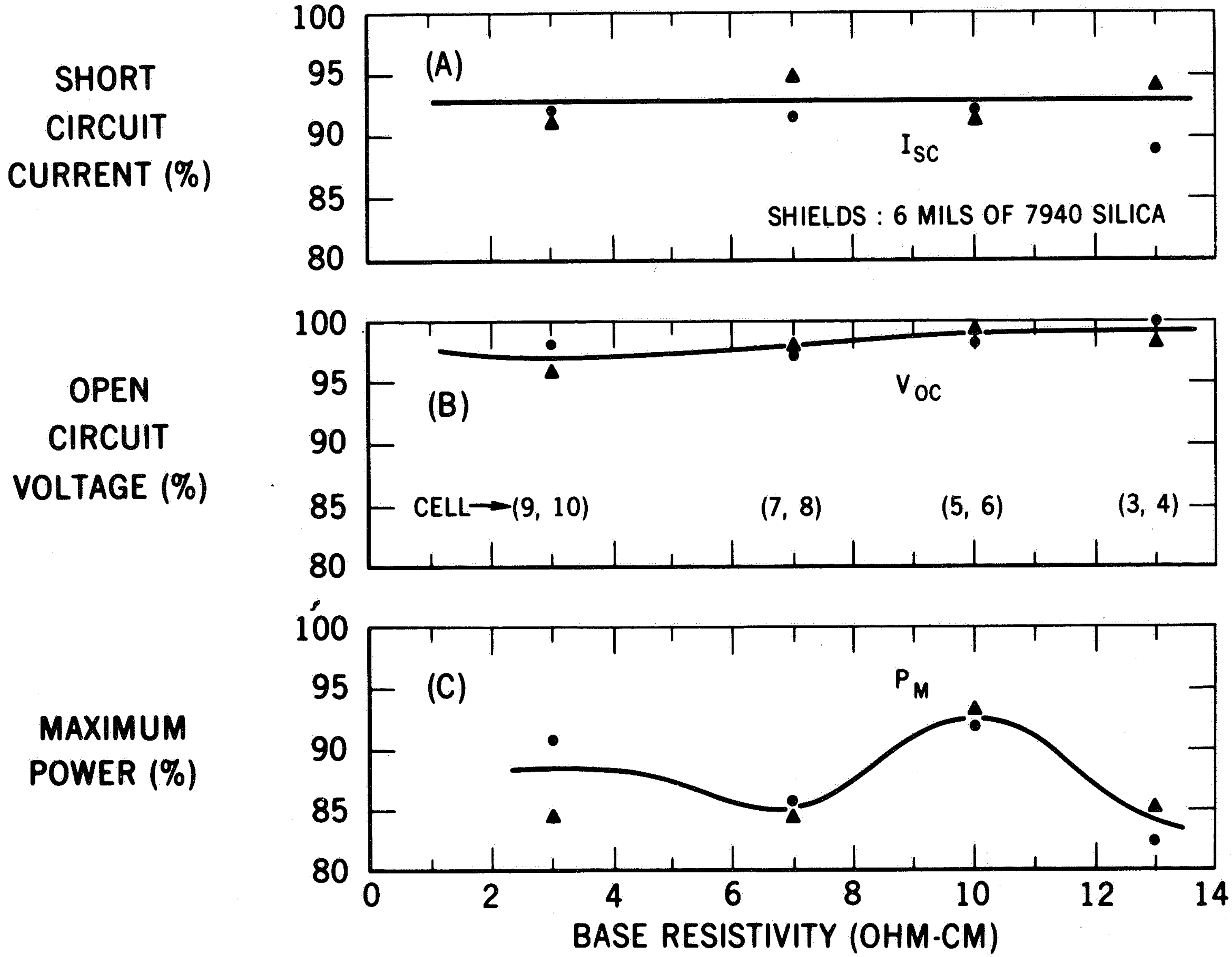
Fig. 6 - Comparison of Solar Cells Shielded with 6 Mils of Type 7940 Silica and 6 Mils of 0211 Glass.

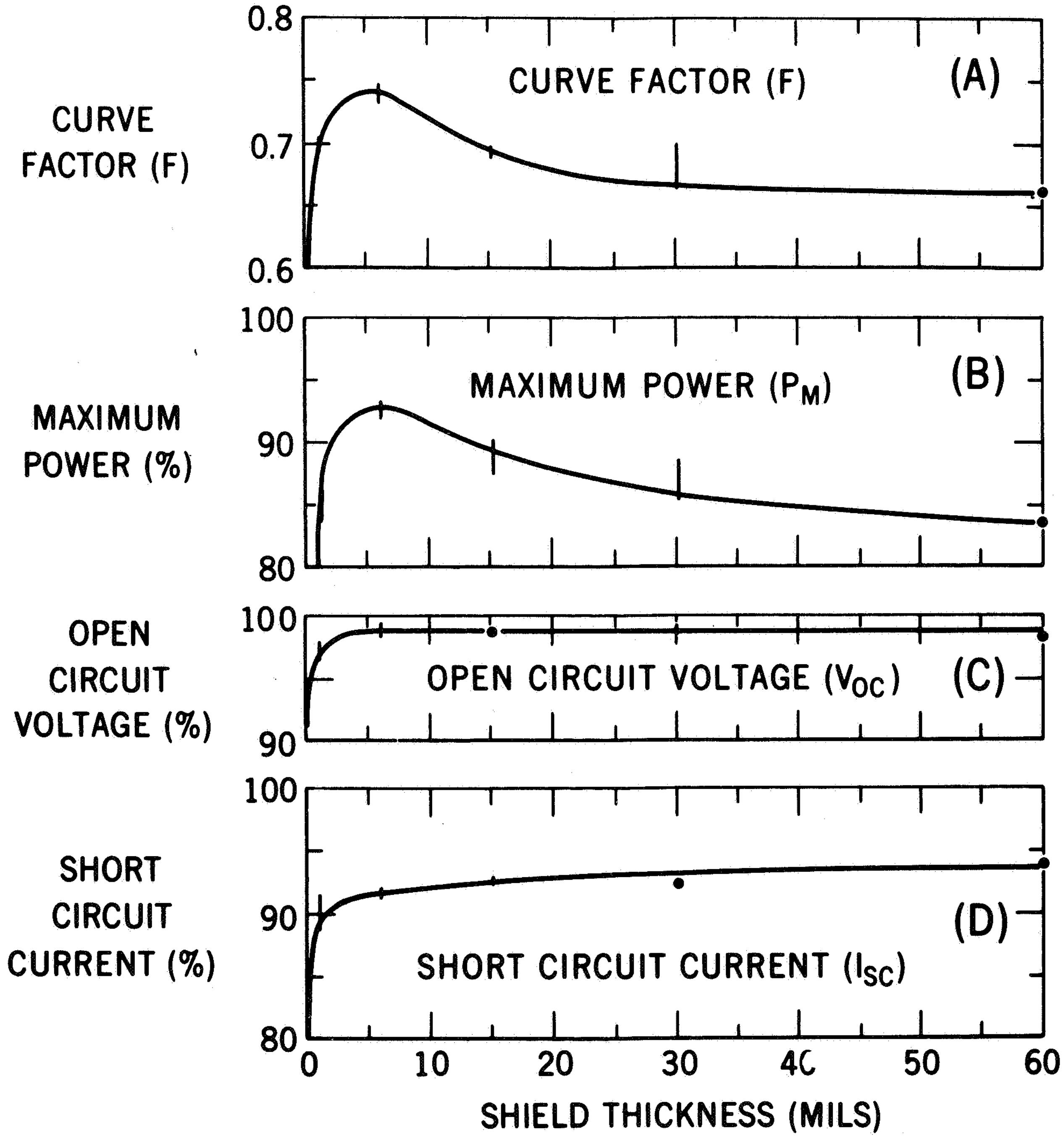
Fig. 7 - Comparison of Graded Base (Drift-Field) Solar Cells and Conventional 10 Ohm-cm Cells.

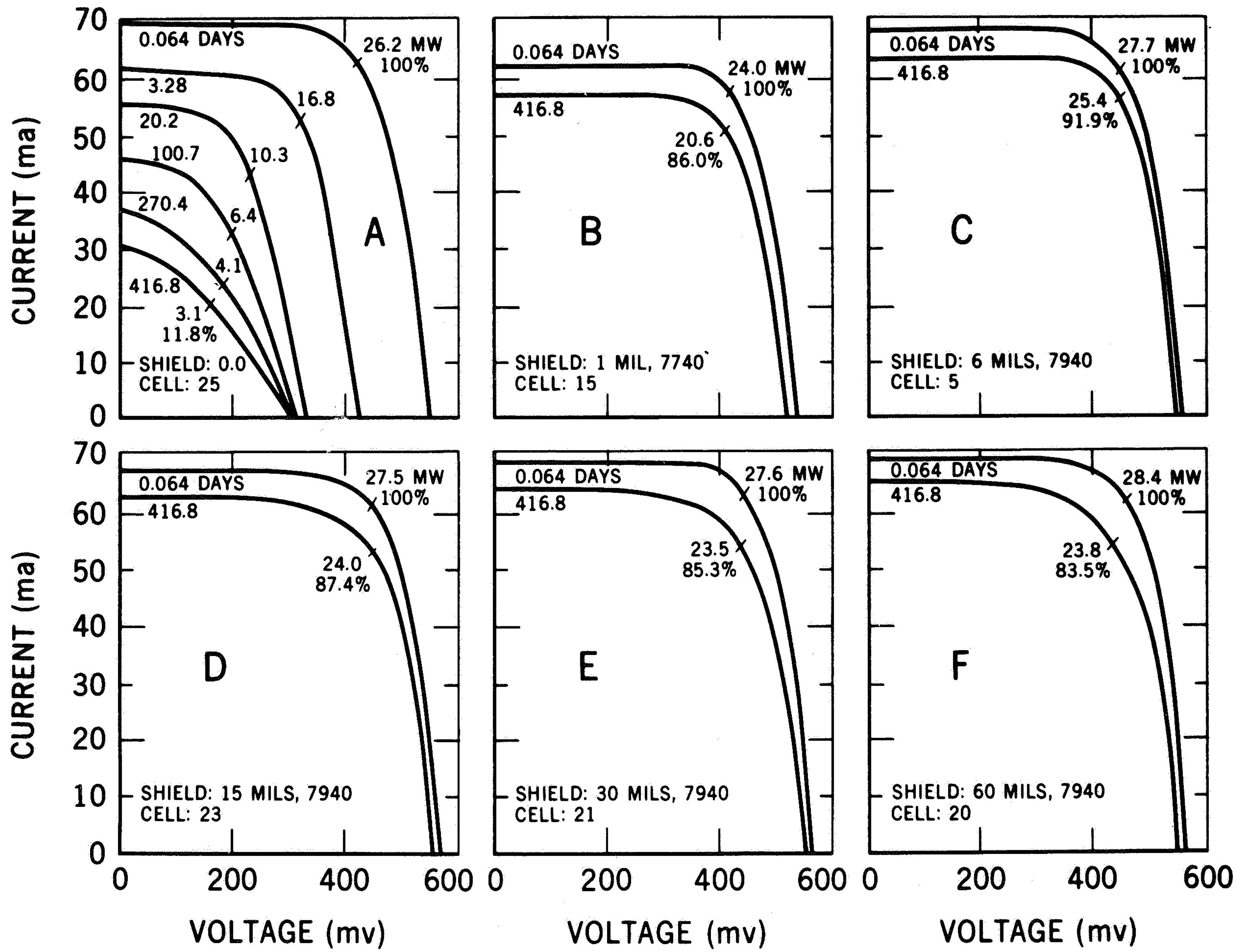
Fig. 8 - Comparison of Aluminum and Boron Doping of 10 Ohm-cm Cells with 6 Mil Silica Shields.

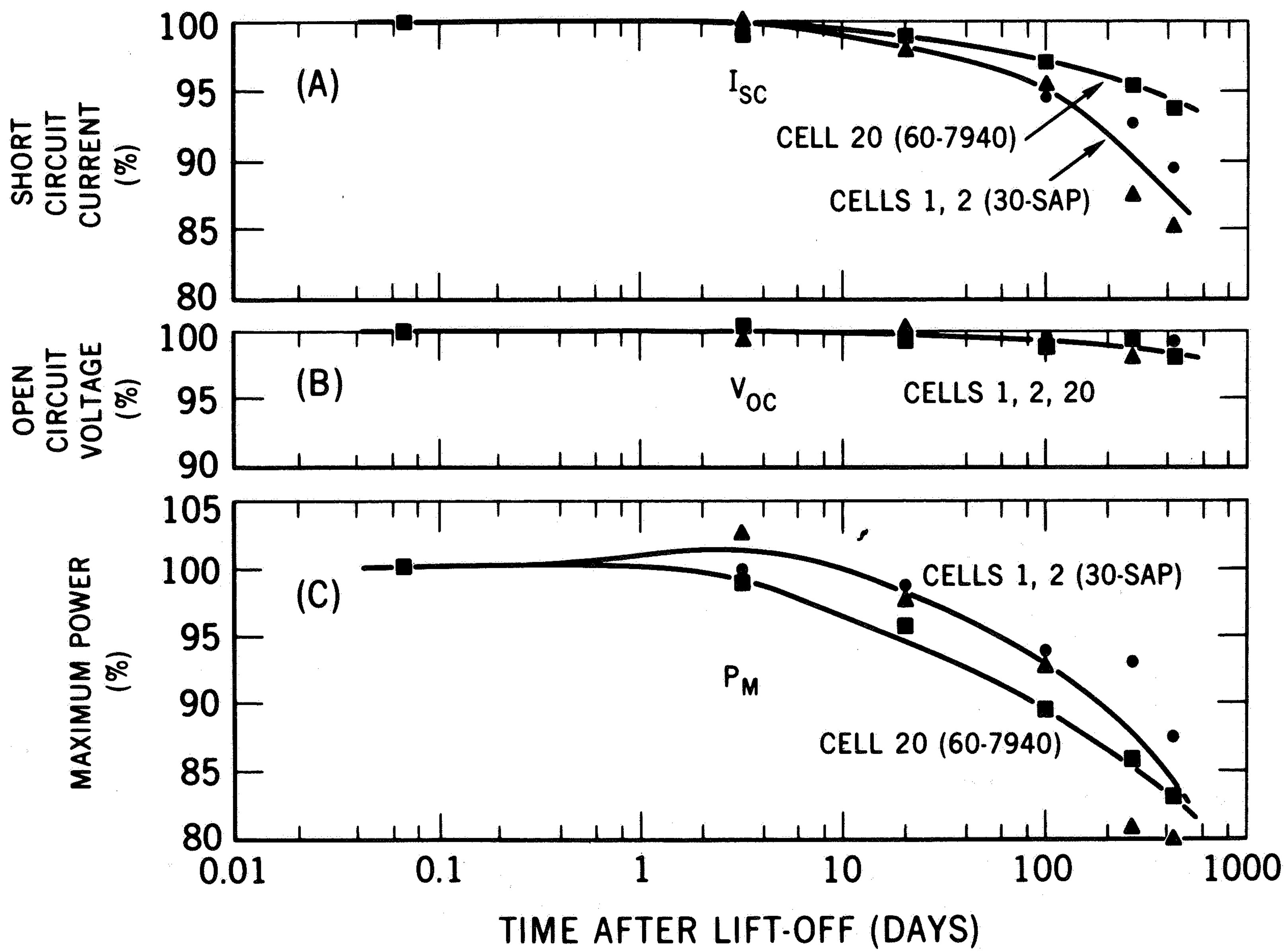
Fig. 9 - Comparison of an Unshielded 1 Ohm-Cm p-on-n Cell with 1 and 10 Ohm-cm n-on-p Unshielded Cells.

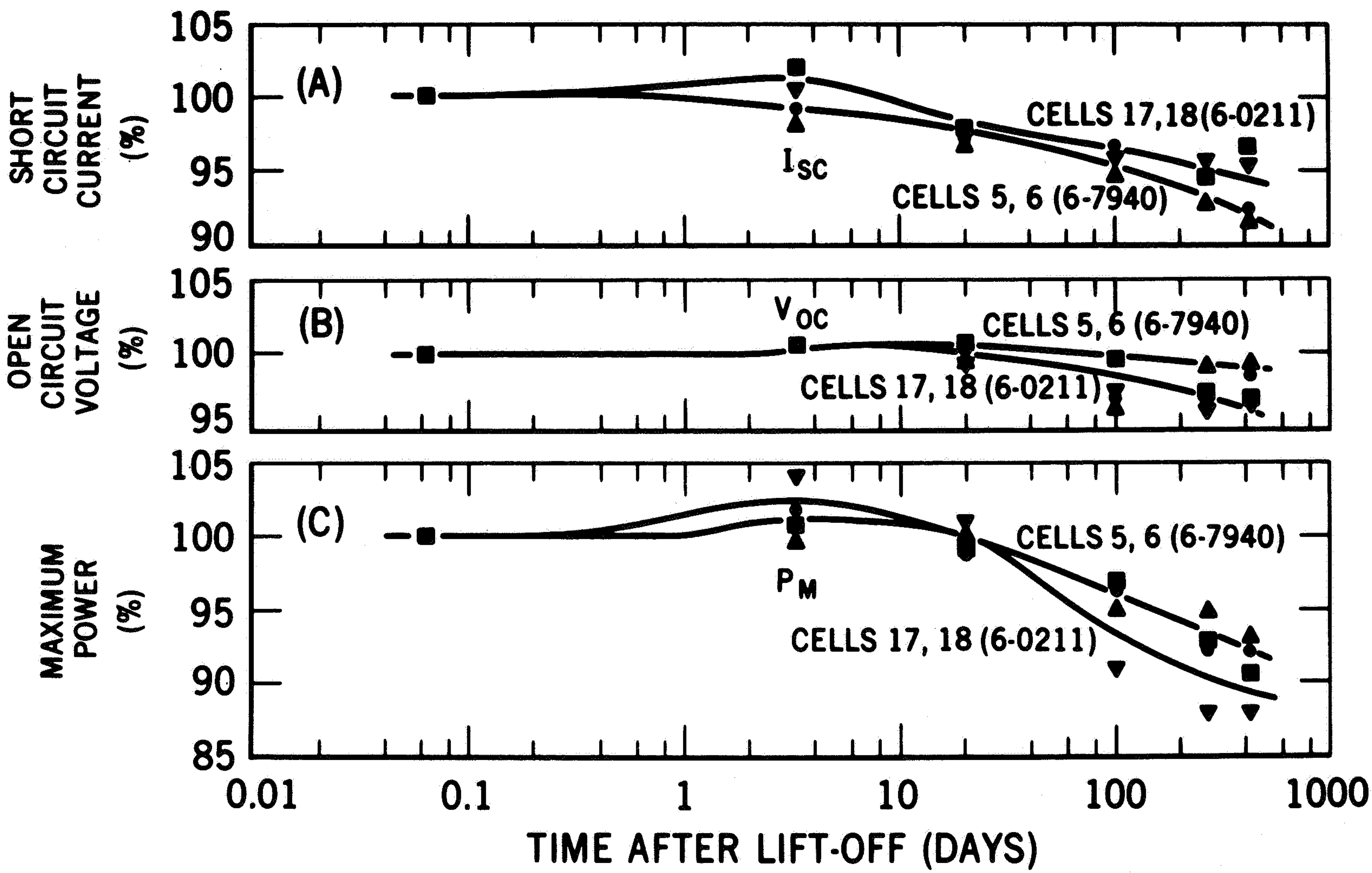

0.064 DAYS
3.28
20.2
100.7
270.4
416.8
26.2 MW
100%
16.8
10.3
6.4
4.1
3.1
11.8%
MATERIAL : SILICON
TYPE : N-ON-P
RESISTIVITY : 10Ω-CM
DOPANT : BORON
SHIELD : NONE
TEMP. : 24.4°C
θ: 90°
DISTANCE : 1 AU
ALTITUDE : 22,240 MI
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
800

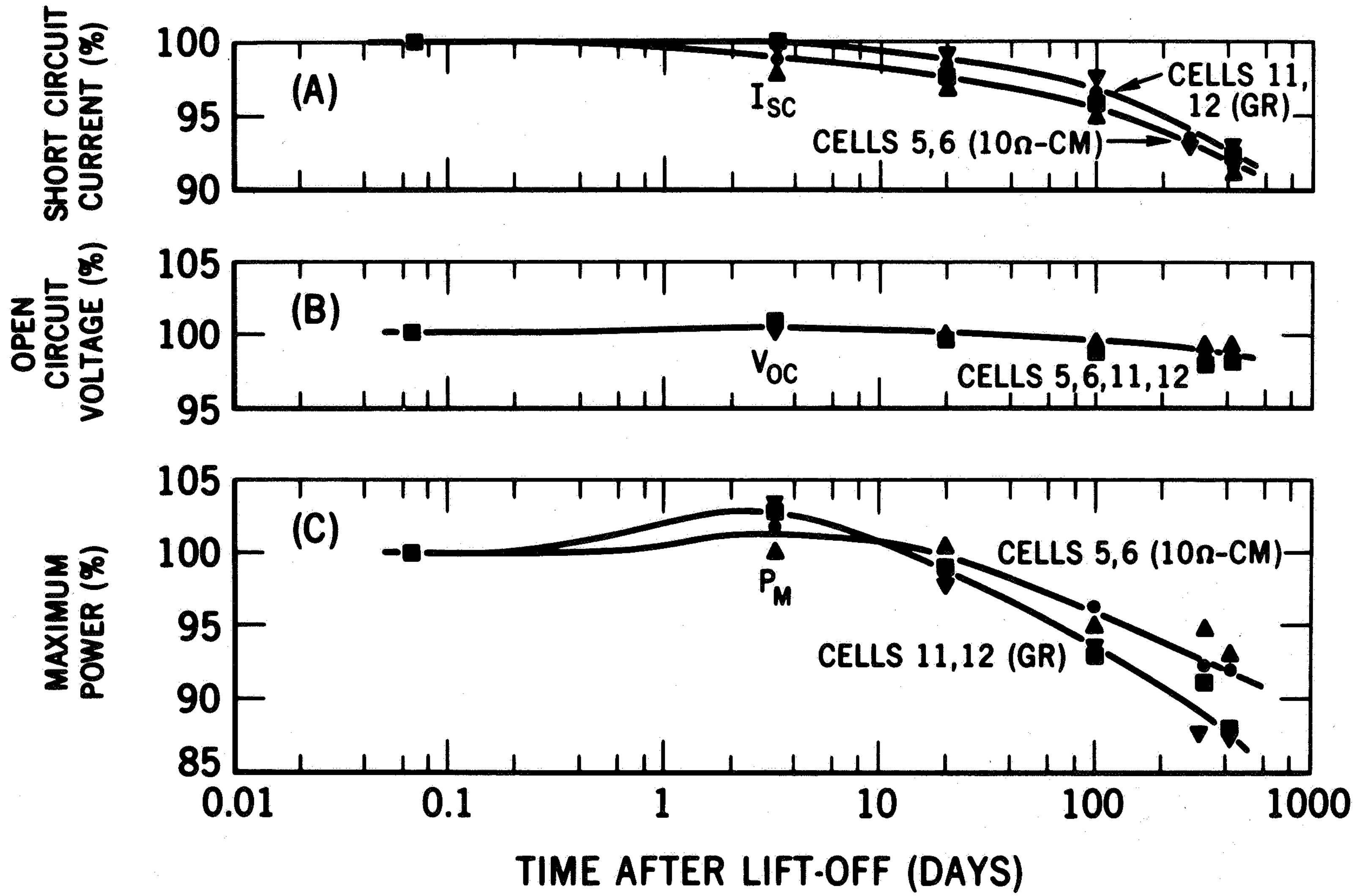

SHORT CIRCUIT CURRENT (%)
OPEN CIRCUIT VOLTAGE (%)
MAXIMUM POWER (%)
(A)
(B)
(C)
I_{SC}
V_{OC}
P_M
SHIELDS : 6 MILS OF 7940 SILICA
CELL→(9, 10)
(7, 8)
(5, 6)
(3, 4)
100
95
90
85
80
0
2
4
6
8
10
12
14
BASE RESISTIVITY (OHM-CM)


CURVE FACTOR (F)
0.8
0.7
0.6
CURVE FACTOR (F)
(A)
MAXIMUM POWER (%)
100
90
80
MAXIMUM POWER (P_M)
(B)
OPEN CIRCUIT VOLTAGE (%)
100
90
OPEN CIRCUIT VOLTAGE (V_{OC})
(C)
SHORT CIRCUIT CURRENT (%)
100
90
80
(D)
SHORT CIRCUIT CURRENT (I_{SC})
0
10
20
30
40
50
60
SHIELD THICKNESS (MILS)

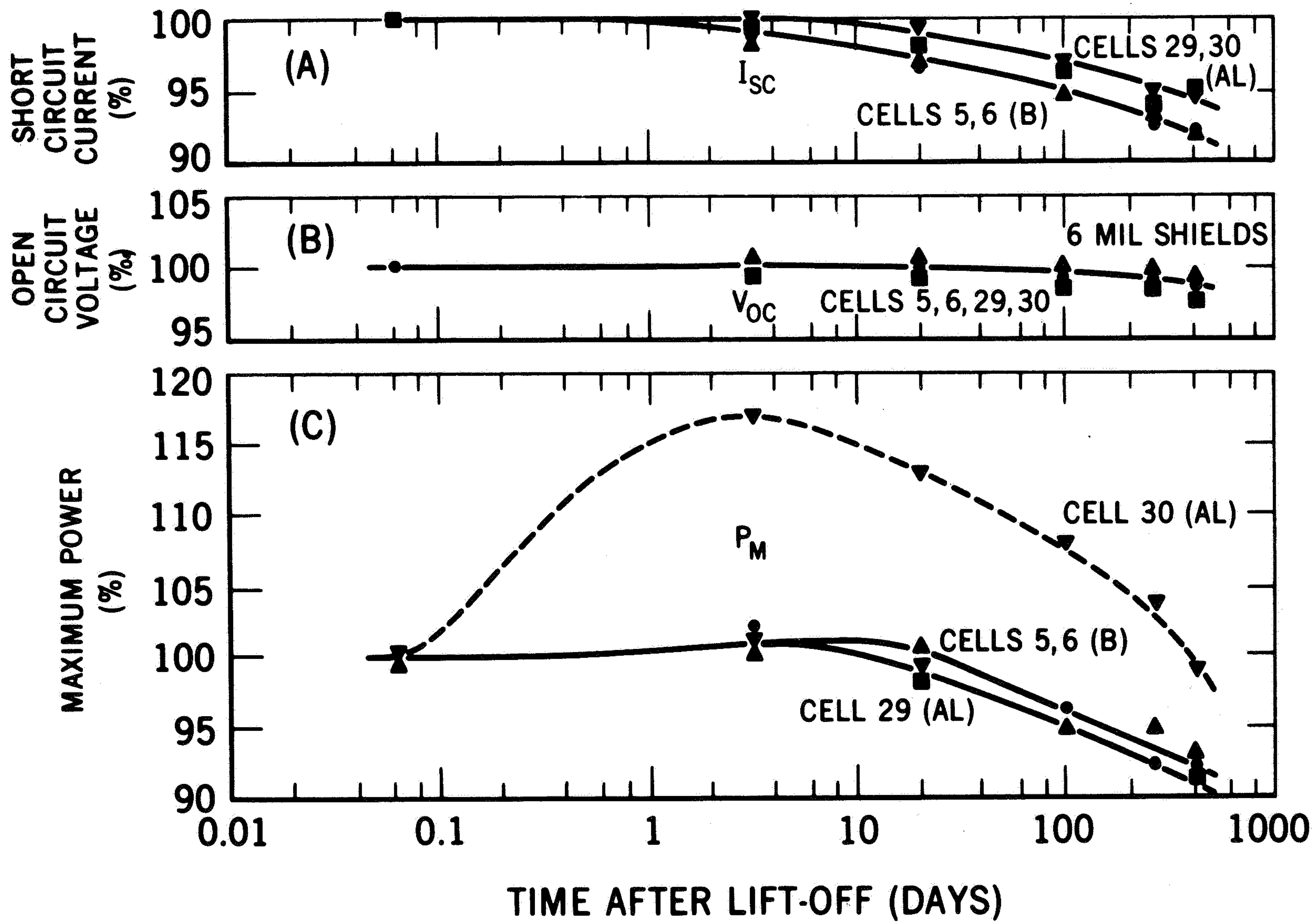

A
0.064 DAYS
3.28
20.2
100.7
270.4
416.8
26.2 MW
100%
16.8
10.3
6.4
4.1
3.1
11.8%
SHIELD: 0.0
CELL: 25
B
0.064 DAYS
416.8
24.0 MW
100%
20.6
86.0%
SHIELD: 1 MIL, 7740
CELL: 15
C
0.064 DAYS
416.8
27.7 MW
100%
25.4
91.9%
SHIELD: 6 MILS, 7940
CELL: 5
D
0.064 DAYS
416.8
27.5 MW
100%
24.0
87.4%
SHIELD: 15 MILS, 7940
CELL: 23
E
0.064 DAYS
416.8
27.6 MW
100%
23.5
85.3%
SHIELD: 30 MILS, 7940
CELL: 21
F
0.064 DAYS
416.8
28.4 MW
100%
23.8
83.5%
SHIELD: 60 MILS, 7940
CELL: 20
CURRENT (ma)
0
10
20
30
40
50
60
70
VOLTAGE (mv)
0
200
400
600

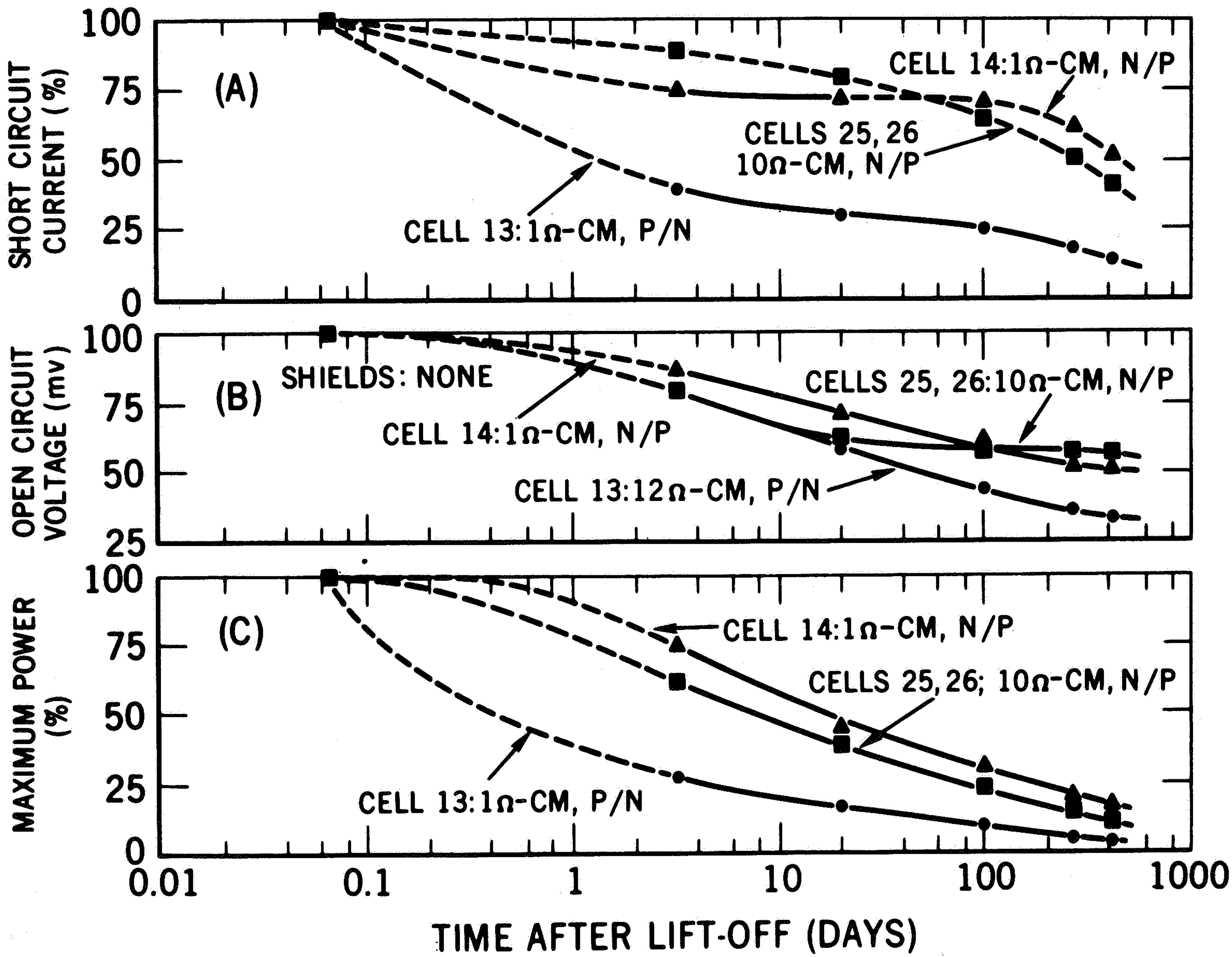

SHORT CIRCUIT CURRENT (%)
100
95
90
85
80
(A)
I_SC
CELL 20 (60-7940)
CELLS 1, 2 (30-SAP)
OPEN CIRCUIT VOLTAGE (%)
100
95
90
(B)
V_OC
CELLS 1, 2, 20
MAXIMUM POWER (%)
105
100
95
90
85
80
(C)
P_M
CELLS 1, 2 (30-SAP)
CELL 20 (60-7940)
0.01
0.1
1
10
100
1000
TIME AFTER LIFT-OFF (DAYS)


SHORT CIRCUIT CURRENT (%)
OPEN CIRCUIT VOLTAGE (%)
MAXIMUM POWER (%)
105
100
95
90
85
(A)
(B)
(C)
I_{SC}
V_{OC}
P_M
CELLS 17,18(6-0211)
CELLS 5, 6 (6-7940)
CELLS 5, 6 (6-7940)
CELLS 17, 18 (6-0211)
CELLS 5, 6 (6-7940)
CELLS 17, 18 (6-0211)
0.01
0.1
1
10
100
1000
TIME AFTER LIFT-OFF (DAYS)



SHORT CIRCUIT CURRENT (%)
100
95
90
(A)
I_{SC}
CELLS 11, 12 (GR)
CELLS 5,6 (10Ω-CM)
OPEN CIRCUIT VOLTAGE (%)
105
100
95
(B)
V_{OC}
CELLS 5,6,11,12
MAXIMUM POWER (%)
105
100
95
90
85
(C)
P_M
CELLS 5,6 (10Ω-CM)
CELLS 11,12 (GR)
0.01
0.1
1
10
100
1000
TIME AFTER LIFT-OFF (DAYS)


SHORT CIRCUIT CURRENT (%)
100
95
90
(A)
I_{SC}
CELLS 29, 30 (AL)
CELLS 5, 6 (B)
OPEN CIRCUIT VOLTAGE (%)
105
100
95
(B)
6 MIL SHIELDS
V_{OC}
CELLS 5, 6, 29, 30
MAXIMUM POWER (%)
120
115
110
105
100
95
90
(C)
P_M
CELL 30 (AL)
CELLS 5, 6 (B)
CELL 29 (AL)
0.01
0.1
1
10
100
1000
TIME AFTER LIFT-OFF (DAYS)


SHORT CIRCUIT CURRENT (%)
OPEN CIRCUIT VOLTAGE (mv)
MAXIMUM POWER (%)
(A)
(B)
(C)
CELL 14:1Ω-CM, N/P
CELLS 25, 26 10Ω-CM, N/P
CELL 13:1Ω-CM, P/N
SHIELDS: NONE
CELLS 25, 26:10Ω-CM, N/P
CELL 14:1Ω-CM, N/P
CELL 13:12Ω-CM, P/N
CELL 14:1Ω-CM, N/P
CELLS 25, 26; 10Ω-CM, N/P
CELL 13:1Ω-CM, P/N
0.01
0.1
1
10
100
1000
TIME AFTER LIFT-OFF (DAYS)