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TEST OF CONCENTRATOR SOLAR ARRAY MODEL FOR SEPS

By H. H. Huie
Program Development

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16. ABSTRACT

The use of concentrators to improve the performance of solar arrays in deep space was tested in a simulated deep space environment. The results of these tests are presented and discussed. Areas of discussion include cell temperature and performance in a low temperature, low illumination environment with and without concentration, concentration ratios, and theoretical analysis versus test results. Tests were conducted on a series/parallel configuration and individual cells.

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TEST OF CONCENTRATOR SOLAR ARRAY MODEL FOR SEPS

SUMMARY

Utilization of concentrators to enhance solar cell performance has been studied by Marshall Space Flight Center/National Aeronautics and Space Administration for several space projects. One of the projects that appeared to profit from such a configuration is the SEPS' Halley Comet Rendezvous Mission. Trajectories for this mission placed the vehicle at distances between 0.7 and 5 Astronomical Units (AU) from the Sun. The lack of solar cell test data in the environment of this mission required the analysis to be based on technical extrapolation and predictions. To validate the predicted performance, a series of tests were conducted in a simulated deep space environment.

The test validated the predicted array performance and showed solar cell performance at distant AU to be improved by concentration. Test results showed performance to be within 5 percent of that predicted and temperature to be within 4 percent of calculated values. A 4:1 concentrator model was tested, producing a measured effective concentration ratio of 3.5:1.

A secondary objective of the test was to evaluate the thin film reflector used as concentrators. No degradation in performance was observed from wrinkles in the concentrators. Although no conclusive results were obtained, it was concluded from the test data that tension requirement in the thin film reflectors is determined only by the tension required to support the film. High tensioning to produce wrinkle free, flat planes does not appear to be required.

INTRODUCTION

The use of concentrators to improve the performance of solar arrays per unit area of solar cells has been a desire of designers for several years. In the past, the cost and weight of reflector material and its associated structure have caused interest in these concepts, for space purposes, to be short lived. Recent advancement in thin film technology has overcome a portion of these hindrances and renewed the investigation of concentrator useage.

Utilization of concentrator concepts has been studied recently for the Satellite Power System (SPS) by several companies and National Aeronautics and Space Administration (NASA). Results of these studies show that a potential reduction in cost and weight can be achieved for some space power systems. One project capable of taking advantage of these concepts was the Halley's Comet Rendezvous Mission, studied by Marshall Space Flight Center (MSFC). Trajectories for the mission placed the vehicle at distances from 0.7 AU to 5 AU from the Sun. Analysis showed the mission to profit from the characteristics of the concentrating array. The lack of solar cell test data under the conditions experienced during this mission required the analysis to be based on technical extrapolation and predictions. To validate the predicted performance, a series of tests was conducted by MSFC at the Boeing Aerospace Facility in Seattle, Washington.

TEST GOALS

The primary test objective was to determine the performance of the concentrating array configuration when exposed to deep space environment. The range of space environment for the test ranged from 1 to 5 AU distances from the Sun. Power, temperature, and concentration ratio for the subject configuration were the chief goals of the test.

Although the test article was designed primarily to satisfy only the primary objectives of the test, other goals were observed to the extent possible. These secondary goals include:

a) Concentrator effect on cell view factor and resulting cell temperature.

b) Tension requirements in reflector material (effect of wrinkles on performance).

c) Cell performance with concentration at distance AU's.

d) Information on intensity and temperature variations across the blanket.

Observations were made and data taken when applicable to accommodate the secondary goals. Information from these tests is to be used in the design and analysis of future concentrating array designs.

TEST DESCRIPTION

Data to validate the predicted performance of concentrating arrays when exposed to low illumination levels were unavailable. Tests to simulate the conditions expected during a Halley's Comet Rendezvous Mission were conducted at the Boeing Aerospace Facility in June 1977.

The test article, Figure 1, was constructed by Lockheed to represent a section of the array, Figure 2, Lockheed and MSFC were proposing for the mission. The reflector material used in the test article was aluminized Kapton with a reflectivity of 0.92. Two solar blankets were prepared for tests. The first blanket, Module 1 consisted of 36, 8 mil cells arranged and instrumented with thermocouples as shown in Figure 3. The modules were electrically arranged with 3 cells in parallel and 6 in series in two circuits providing the capability to record the output of either circuit or the two in series.

Module 2 was comprised of 20, 8 mil cells each individually instrumented for current and voltage and with thermocouples as shown in Figure 4.

The reflectors for the modules (Fig. 1) were set at 67.5° and 60°. The larger side reflector was 67.5°. Theoretical effective concentration ratio varies across the blanket from 3.6 to 3.1 (Fig. 5) with an average concentration ratio of 3.55.

The test chamber (Fig. 6) provided a collimated light source with varying intensities from 0.04 to 1.0 Suns. Illumination accuracy was ±3 percent of indicated readings across the total article with ±1 percent repeatability. Chamber pressure was 1.2×10^{-8} Torr with the shroud temperature maintained at approximately -190°C.

The accuracy of the load device was ±0.5 percent with current and voltage reading accurate to ±0.1 percent, linear over the range of operation. A listing of test equipment and its stated accuracies are given Table 1.

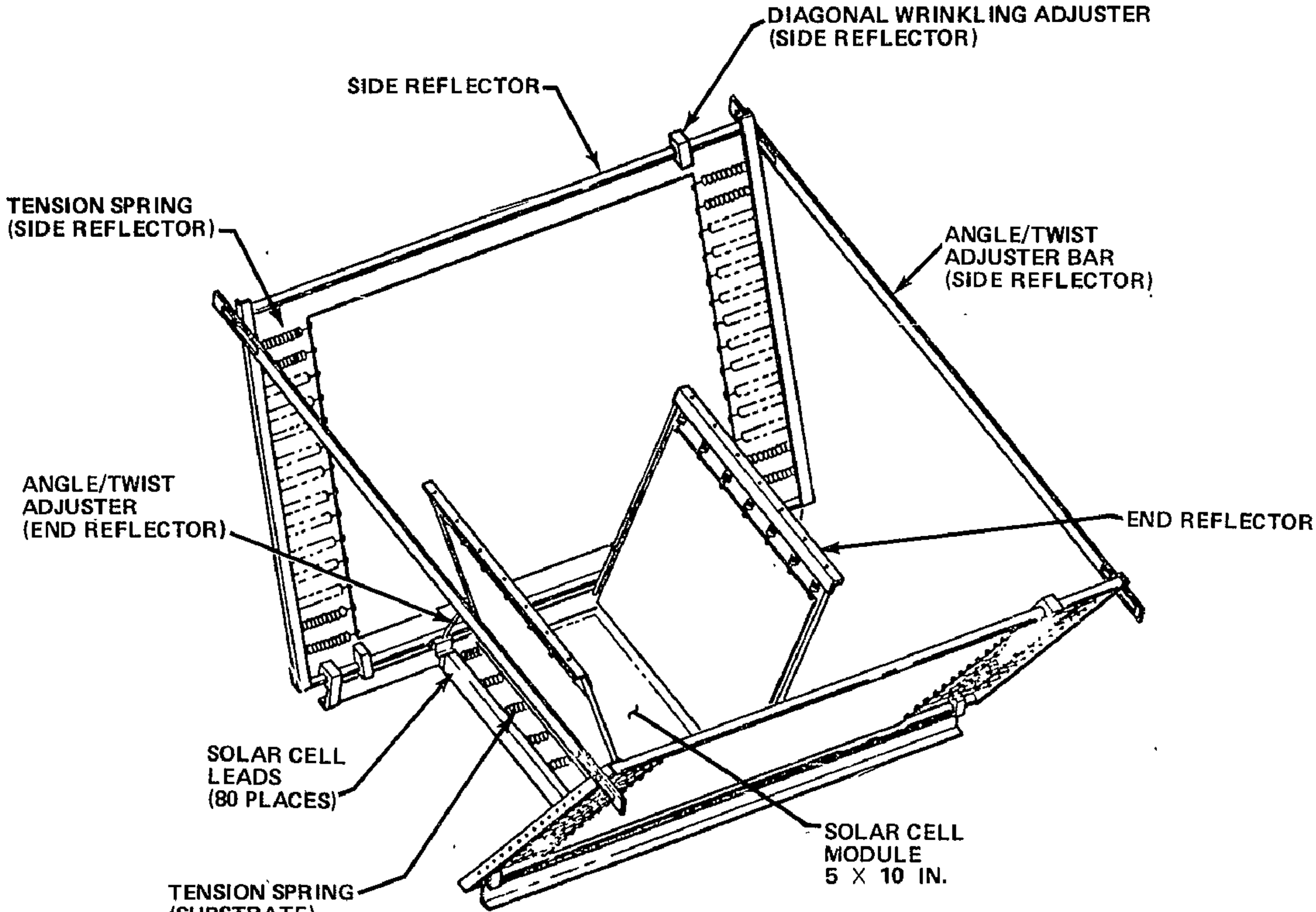


Figure 1. Concentrator model.

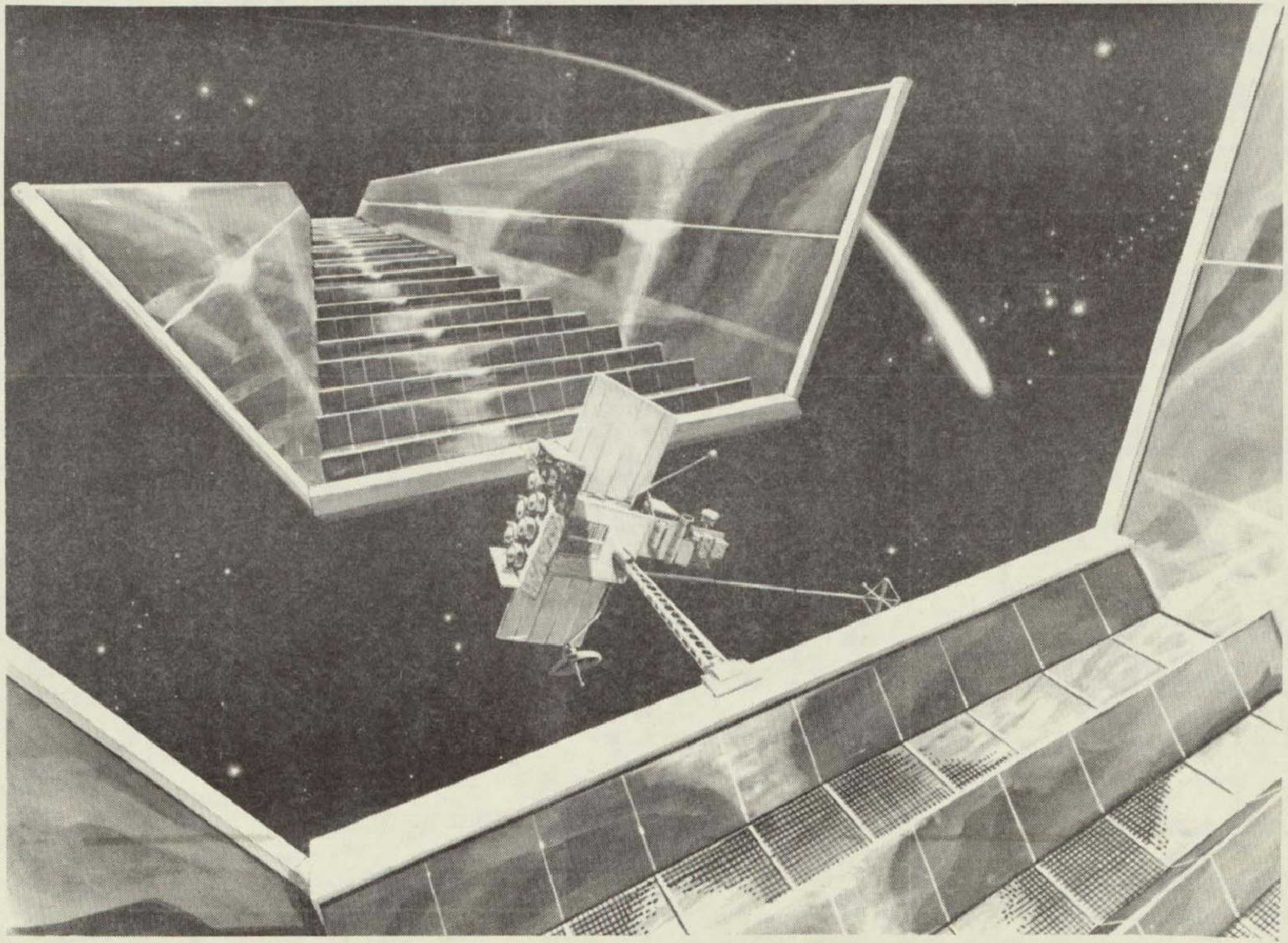


Figure 2. Article concept of solar electric propulsion vehicle for Halley's Comet Rendezous.

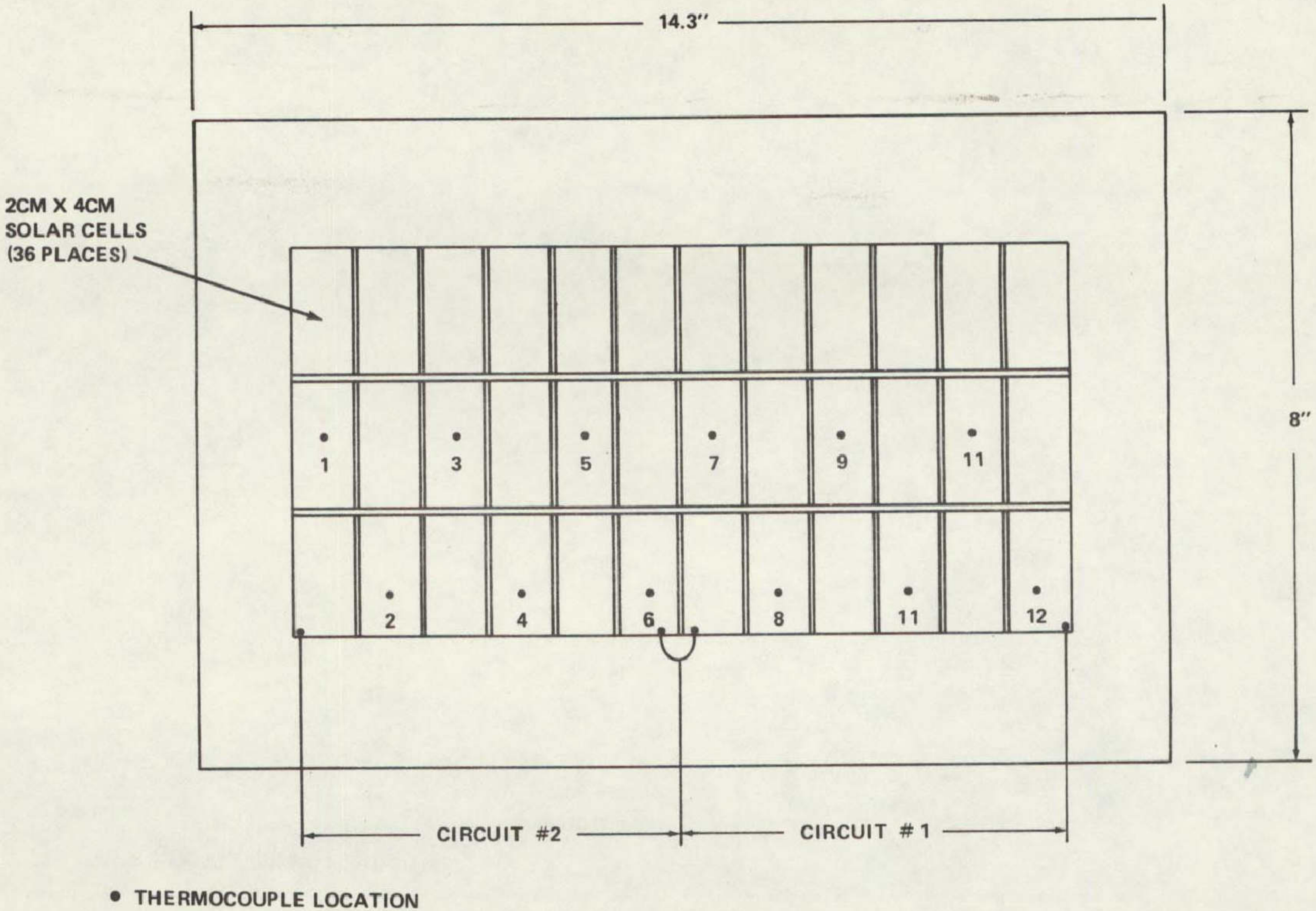


Figure 3. 36-Cell module (module 1)

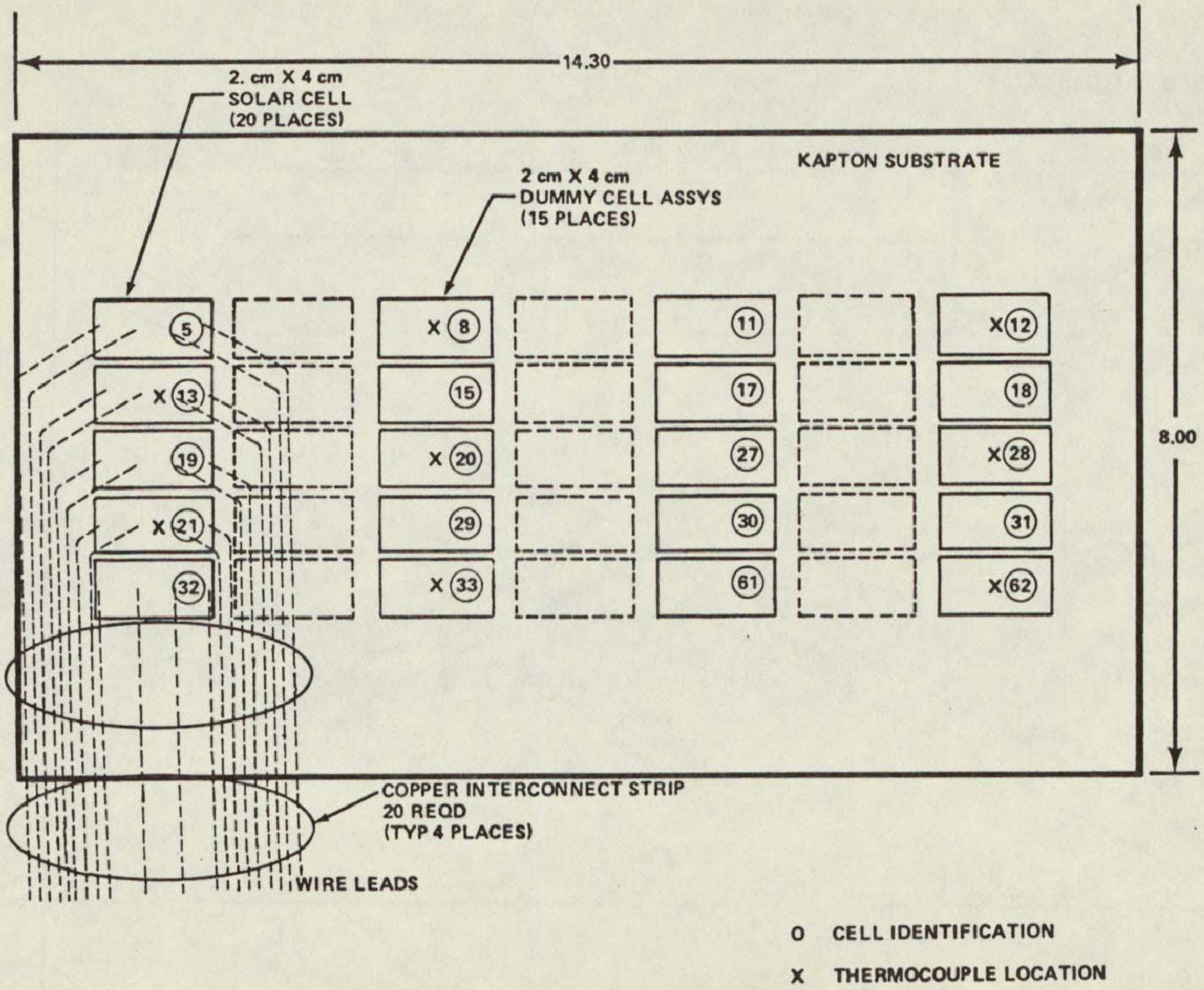


Figure 4. 20-Cell concentrator test module (module 2).

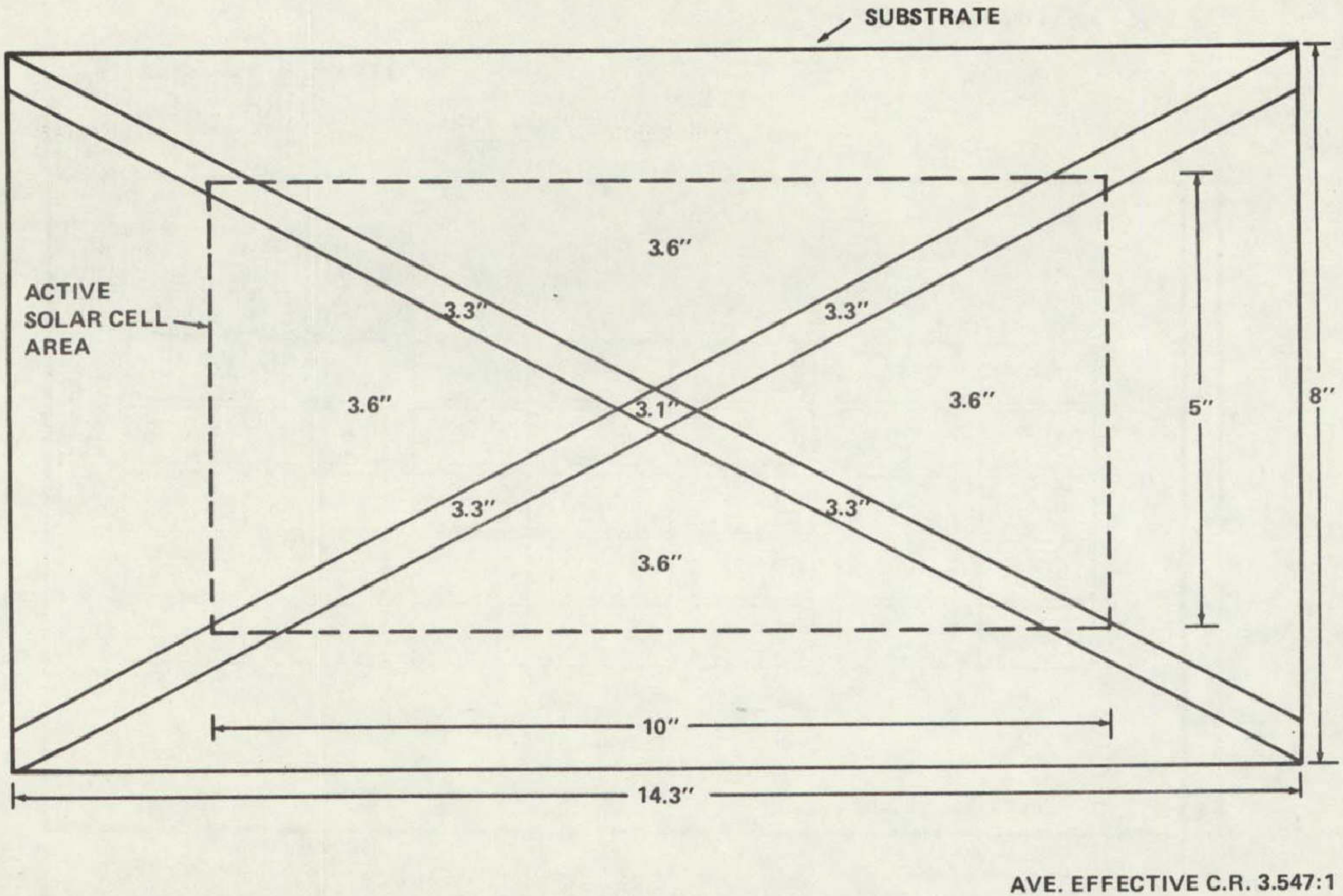


Figure 5. Theoretical effective concentration ratio.

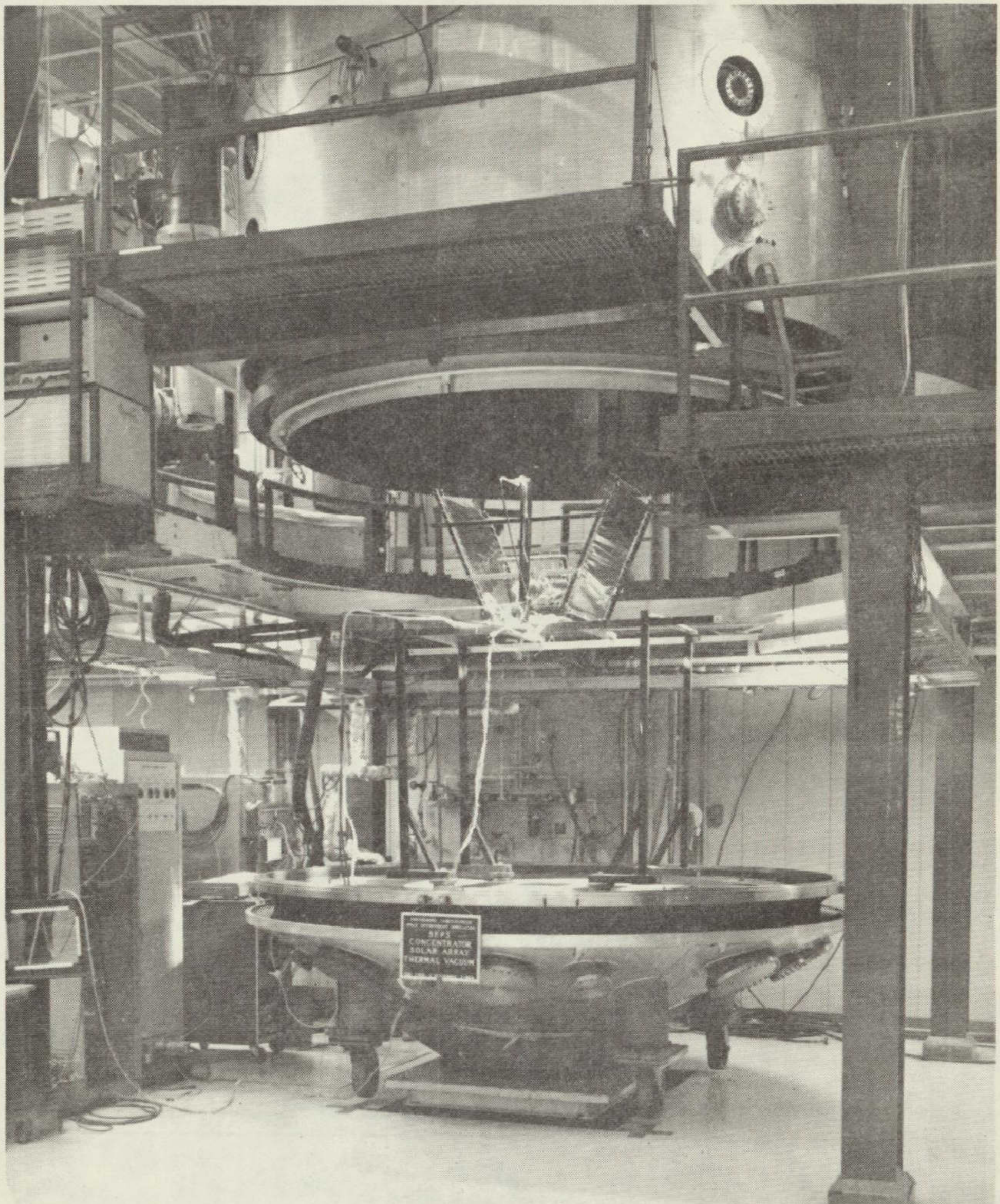


Figure 6. Test chamber.

TABLE 1. TEST EQUIPMENT

Equipment	Serial Number	Manufacturer	Accuracy	Use
Digital Voltmeter	BC 360421	Calico	±0.01 Percent Reading	I_{SC} Current
Digital Voltmeter	BC 555795	Dynascience	±0.1 Percent Reading	V_{OC} Voltage
Electronic Load	BC 554929	Spectrolab	±0.5 Percent Current Reading	Load
X-Y Plotter	BC 554362	Honeywell	-0.6 Percent Full Scale	I-V Plot
Digital Voltmeter	BC 558374	Data Precision	-0.02 Percent Reading	Solar Intensity
Stripchart Recorder	BC 515953	Honeywell	±3.8°F	Temperature

A calibration run on the equipment and Module 1 without concentration (Fig. 7) was conducted prior to the tests. Results of this test are presented in Table 2 and shown in Figures B-4, B-5, and B-6 in Appendix B.

Each test was conducted with the test article and chamber having stabilized at an equivalent of 5 AU from the Sun. Illumination was then increased in increments, and temperature allowed to stabilize at each setting before V, I, and temperature measurement were taken. On Module 1, V and I measurements were recorded for circuit 1, circuit 2, and the two in series. Results are recorded in Table 3 and Figures B-1, B-2 and B-3 of Appendix B. Results of tests on Module 2 are recorded in Table 4 and Figures B-7 through B-26 of Appendix B.

PRIMARY TEST RESULTS

Performance of circuits 1 and 2, Module 1, with concentration is shown in Figure 8. Performance of both circuits without concentration is shown in Figure 9 for comparison. The concentrating array reached its maximum performance near 1.6 AU as expected. Continued performance above that of a flat array could have been maintained had the concentration ratio been variable (no provision for changing the concentration ratio during the test was provided). The decrease in performance at 1.6 AU resulted from the decrease in cell efficiency as a function of temperature having reached a point where it was greater than the improvement in performance obtained by concentration. Figure 10 compares the average temperature of the two configurations under identical test conditions.

Comparison of calculated and test temperatures are shown in Figures 11 and 12. Three factors contributed to the higher test temperatures: (1) different solar absorptance and emittance between theoretical and test models, (2) chamber conditions not exactly duplicating space conditions, and (3) recorded test temperatures were made with the cells operating open circuited. An example of these differences at 2.22 AU for the concentrated model are 1°C from different α and ϵ values, $\approx$ 5°C chamber differences, and 9°C from operating open circuited. The remaining delta between calculated and test temperatures was only slightly greater than 1°C or <4 percent of measured temperature. Since the cells are not attached to the substrate over 100 percent of their area, differences in modeling the heat rejection from the back side of the cell could easily account for any additional differences in temperature. The heat rejection through the substrate varies with blanket flatness and cell contact with substrate.

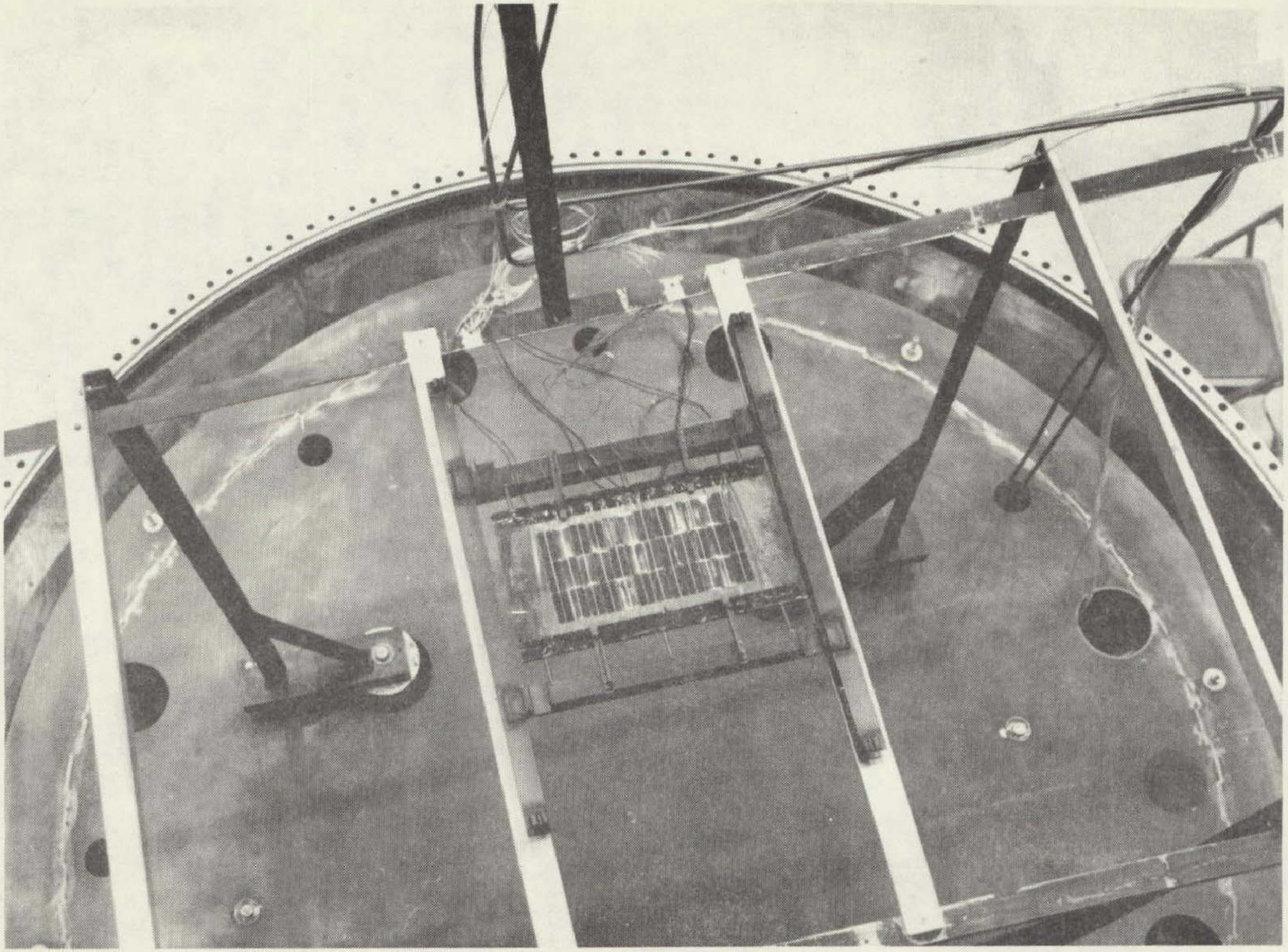


Figure 7. Module 1 (flat array test).

TABLE 2. CALIBRATION RUN FOR MODULE 1 WITHOUT CONCENTRATION (FLAT ARRAY)

AU	Intensity (Suns)	Average Cell Temperature (°C)	Circuit 1			Circuit 2			Circuit 1 + 2		
			I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)	I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)	I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)
4.98	0.040	-112.8	32.7	3.22	0.0405	31.8	3.92	0.044	31.9	7.06	0.090
4.88	0.042	-107.7	34.1	3.31	0.044	33.1	3.92	0.047	33.4	7.10	0.088
4.27	0.055	-102.8	45.5	3.74	0.065	44.4	4.15	0.072	44.5	7.86	0.135
3.61	0.077	-91.9	61.4	4.06	0.098	65.8	4.23	0.120	62.2	8.25	0.214
3.10	0.104	-78.9	86.1	4.25	0.163	91.8	4.22	0.199	86.4	8.45	0.355
2.48	0.163	-57.5	147.9	4.17	0.339	144.0	4.10	0.371	144.4	8.28	0.699
2.22	0.202	-46.1	184.8	4.09	0.448	178.6	4.03	0.476	178.6	8.12	0.924
1.80	0.310	-21.6	280.7	3.85	0.734	275.5	3.85	0.759	275.8	7.68	1.484
1.57	0.408	-5.2	363.5	3.67	0.939	358.0	3.67	0.964	357.8	7.32	1.885
1.41	0.502	11.1	448.0	3.50	1.117	442.8	3.53	1.153	443.1	7.02	2.244
1.29	0.599	23.4	540.0	3.35	1.306	541.0	3.35	1.306	535.0	6.70	2.585
1.19	0.702	36.0	631.3	3.21	1.439	626.6	3.23	1.473	628.0	6.43	2.873
1.00	1.00	66.4	909.5	2.87	1.760	904.9	2.88	1.793	906.0	5.76	3.520

TABLE 3. MODULE 1 CONCENTRATED

AU	Intensity (Suns)	Average Cell Temperature (°C)	Circuit 1			Circuit 2			Circuit 1 + 2		
			I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)	I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)	I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)
4.98	0.040	-62.4	119.9	4.17	0.296	120.6	4.12	0.306			
4.83	0.043	-54.4	142.4	4.18	0.342	144.3	4.14	0.380	142.6	8.36	0.709
4.27	0.055	-46.6	168.7	4.10	0.456	169.7	4.09	0.455			
3.64	0.075	-28.3	239.0	3.88	0.662	237.0	3.87	0.656			
3.08	0.105	-8.1	335.9	3.71	0.936	333.6	3.74	0.926	336.9	7.45	1.875
2.48	0.163	22.5	504.3	3.30	1.279	526.1	3.33	1.324	512.9	6.68	2.651
2.22	0.202	38.4	613.8	3.12	1.446	654.6	3.15	1.512	630.0	6.27	2.913
1.80	0.307	77.1	966.2	2.69	1.832	977.0	2.70	1.822	975.7	5.46	3.676
1.69	0.350	94.4	1229.0	2.50	1.882	1221.0	2.54	1.935			
1.58	0.401	105.3	1314.0	2.35	1.886	1302.0	2.40	1.949	1315.0	4.74	3.800
1.41	0.502	131.2	1760.0	2.06	1.863	1760.0	2.08	1.904	1760.0	4.20	3.780

TABLE 4. MODULE 2 (INDIVIDUAL CELL TEST)

Cell No.	Temperature (°C)	I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)
Intensity - 0.04 Suns (5 AU)				
30	-73.9	48.8	0.76	0.028
29	(-73.9)	40.2	0.76	0.021
27	(-74.4)	48.2	0.74	0.027
20	-74.4	39.9	0.75	0.022
15	(-85)[a]	42.5	0.74	0.024
17	-85[a]	48.6	0.73	0.026
11	(-70)	43.8	0.75	0.024
8	-70	39.5	0.75	0.021
62	-87.8[a]	42.9	0.78	0.025
32	(-87.8)[a]	47.2	0.75	0.028
31	(-75.6)	42.7	0.77	0.026
21	-75.6	48.1	0.76	0.026
28	-71.1	43.9	0.75	0.022
19	(-71.1)	48.3	0.75	0.028
18	(-70)	44.1	0.75	0.023
13	-70	48.2	0.75	0.026
12	-99.4[a]	43.1	0.75	0.025
5	(-99.4)[a]	45.6	0.74	0.026
33	-88.9	39.4	0.77	0.024
61	(-88.9)	46.2	0.78	0.027
Intensity - 0.077 Suns (3.605 AU)				
30	-37.2	91.6	0.70	0.052
29	(-37.2)	79.7	0.71	0.043
27	(-37.8)	91.2	0.69	0.050
20	-37.8	77.4	0.70	0.043
15	(-59.4)[a]	80.4	0.69	0.046
17	-59.4[a]	91.8	0.68	0.048
11	(-33.3)	83.0	0.69	0.045
8	-33.3	78.4	0.69	0.042
62	-53.3[a]	83.6	0.74	0.049
32	(-53.3)[a]	95.0	0.71	0.055
31	(-35.6)	83.6	0.70	0.049
21	-35.6	96.5	0.70	0.053
28	-33.3	85.6	0.69	0.045
19	(-33.3)	98.0	0.68	0.053
18	(-31.6)	84.5	0.69	0.046
13	-31.6	94.9	0.69	0.052
12	-77.2[a]	84.3	0.68	0.046
5	(-77.2)[a]	90.6	0.68	0.048
33	-53.9	79.0	0.73	0.047
61	(-53.9)	89.0	0.72	0.053

NOTE: Temperatures shown in () are temperatures taken at a complementary location and not necessarily actual temperatures of cell.

a. Temperature questionable; thermocouple bond was broken when test was terminated.

TABLE 4. MODULE 2 (INDIVIDUAL CELL TEST) (Concluded)

Cell No.	Temperature (° C)	I_{SC} (mA)	V_{OC} (V)	P_{mp} (W)
Intensity ~ 0.302 Suns (1.82 AU)				
30	78.3	377.2	0.48	0.126
29	(78.3)	378.2	0.47	0.124
27	(82.2)	364.8	0.48	0.123
20	82.2	368.6	0.47	0.120
15	(2.2)[a]	377.8	0.47	0.120
17	2.2	371.0	0.46	0.111
11	(82.8)	362.5	0.47	0.115
8	82.8	368.4	0.47	0.118
62	55[a]	332.1	0.53	0.129
32	(55)[a]	370.6	0.49	0.130
31	(64.4)	337.6	0.48	0.115
21	64.4	375.1	0.48	0.125
28	80.6	362.4	0.47	0.118
19	(80.6)	376.5	0.47	0.120
18	(82.2)	363.7	0.48	0.119
13	82.2	382.8	0.48	0.124
12	-11.0[a]	337.0	0.47	0.108
5	(-11.0)[a]	368.4	0.47	0.115
33	71.1	381.7	0.49	0.133
61	(71.1)	392.8	0.49	0.135
Intensity - 0.164 Suns (2.469 AU)				
30	22.8	202.6	0.59	0.093
29	(22.8)	178.1	0.60	0.081
27	(18.9)	198.7	0.58	0.089
20	18.9	175	0.59	0.081
15	(-26.7)[a]	186.7	0.58	0.085
17	-26.7[a]	205.6	0.56	0.086
11	(22.2)	196.6	0.58	0.085
8	22.2	180.1	0.58	0.080
62	1.7[a]	180.3	0.63	0.091
32	(1.7)[a]	204.2	0.60	0.098
31	(22.2)	180.7	0.59	0.084
21	22.2	211.7	0.59	0.095
28	23.9	189.0	0.58	0.083
19	(23.9)	206.1	0.57	0.090
18	(24.4)	185.0	0.58	0.083
13	24.4	207.4	0.59	0.091
12	-43.9[a]	182.2	0.57	0.080
5	(-43.9)[a]	201.9	0.57	0.088
33	5.6	185.0	0.62	0.093
61	(5.6)	204.9	0.60	0.095

NOTE: Temperatures shown in ( ) are temperatures taken at a complementary location and are not necessarily the actual cell temperature.

a. Temperature questionable; thermocouple bond was broken when test was terminated.

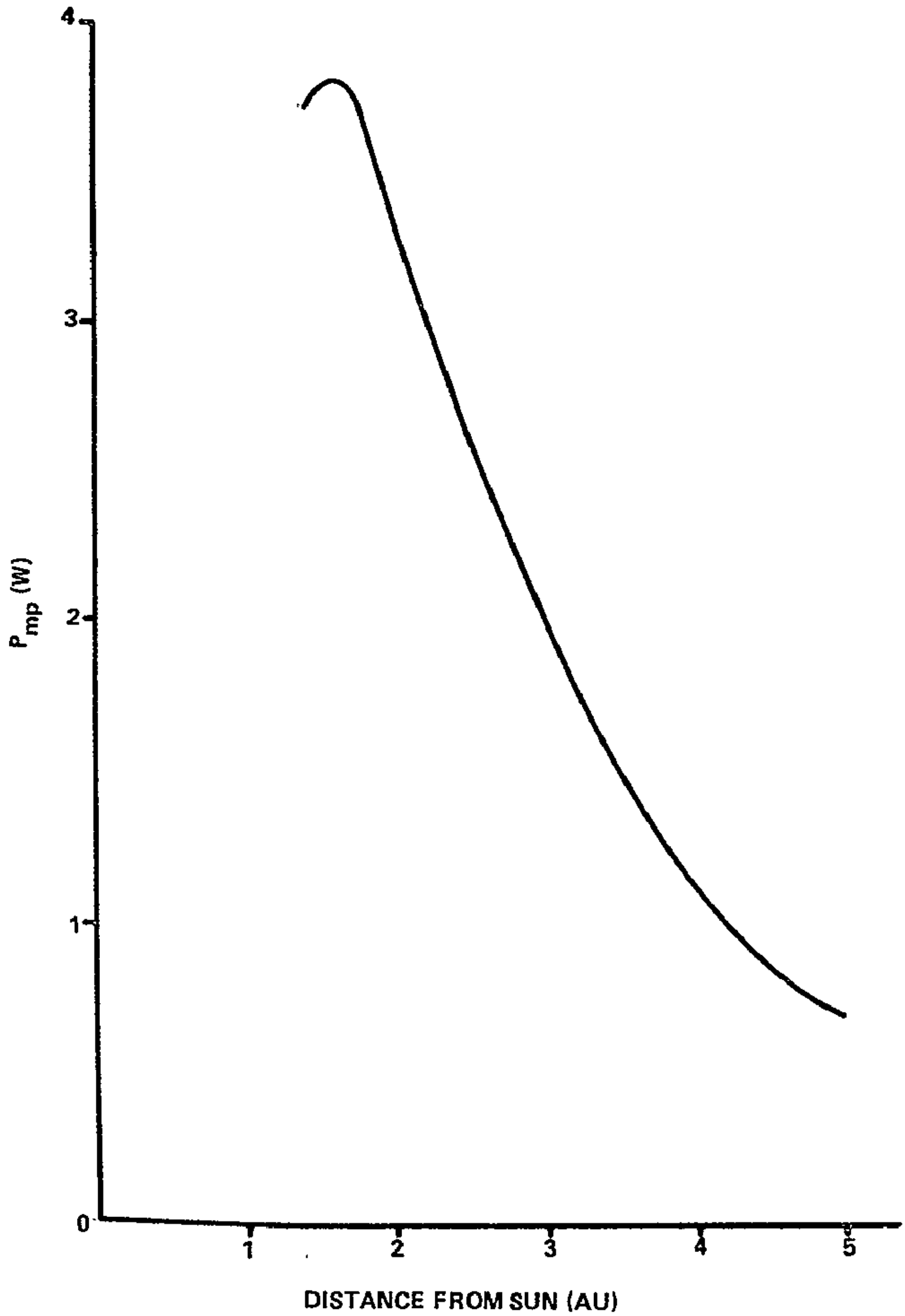


Figure 8. 36-Cell module (module 1) performance with concentration (circuit 1 and 2 in series).

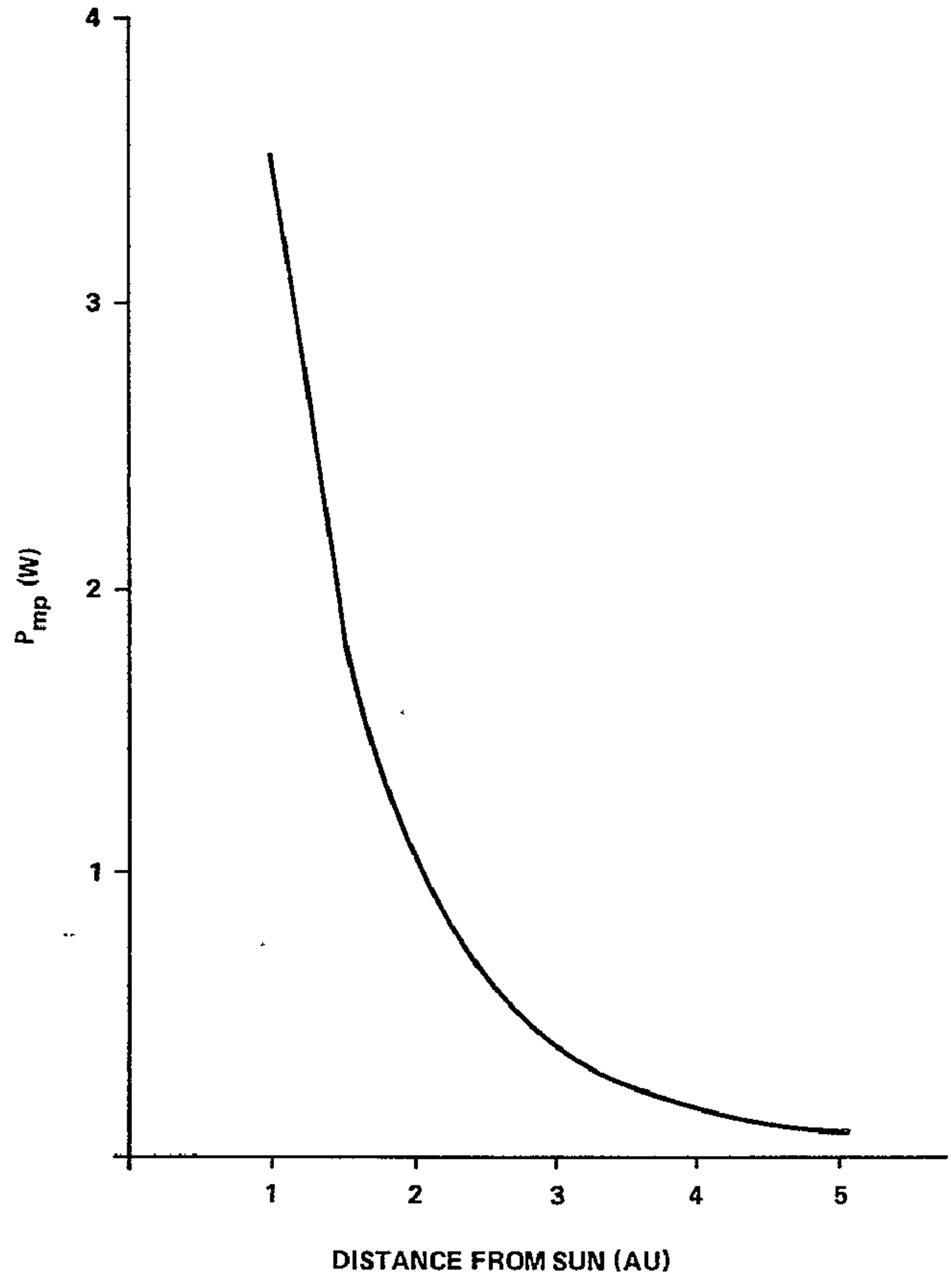


Figure 9. 36-Cell module performance without concentration (circuits 1 and 2 in series).

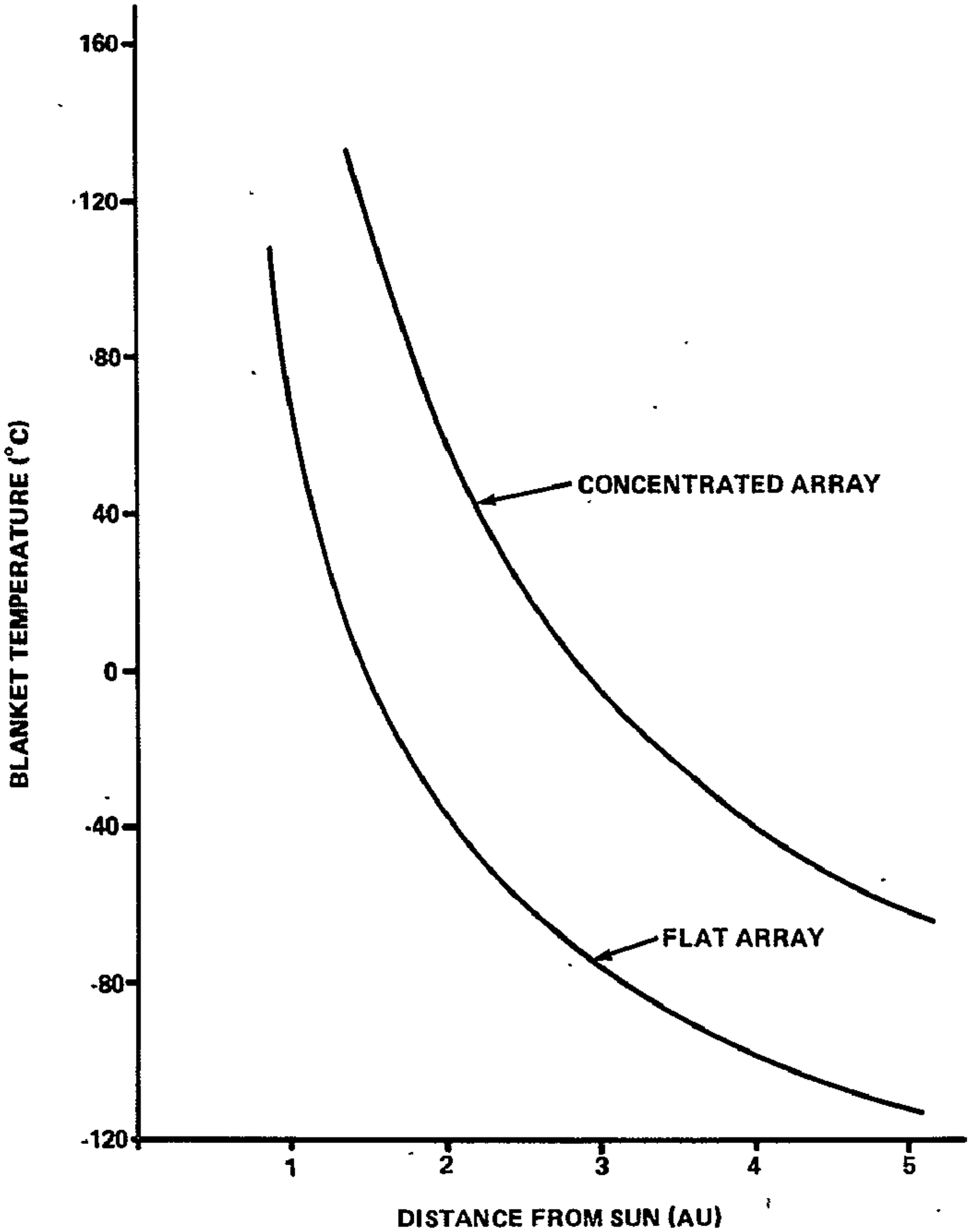


Figure 10. Test temperature module 1.

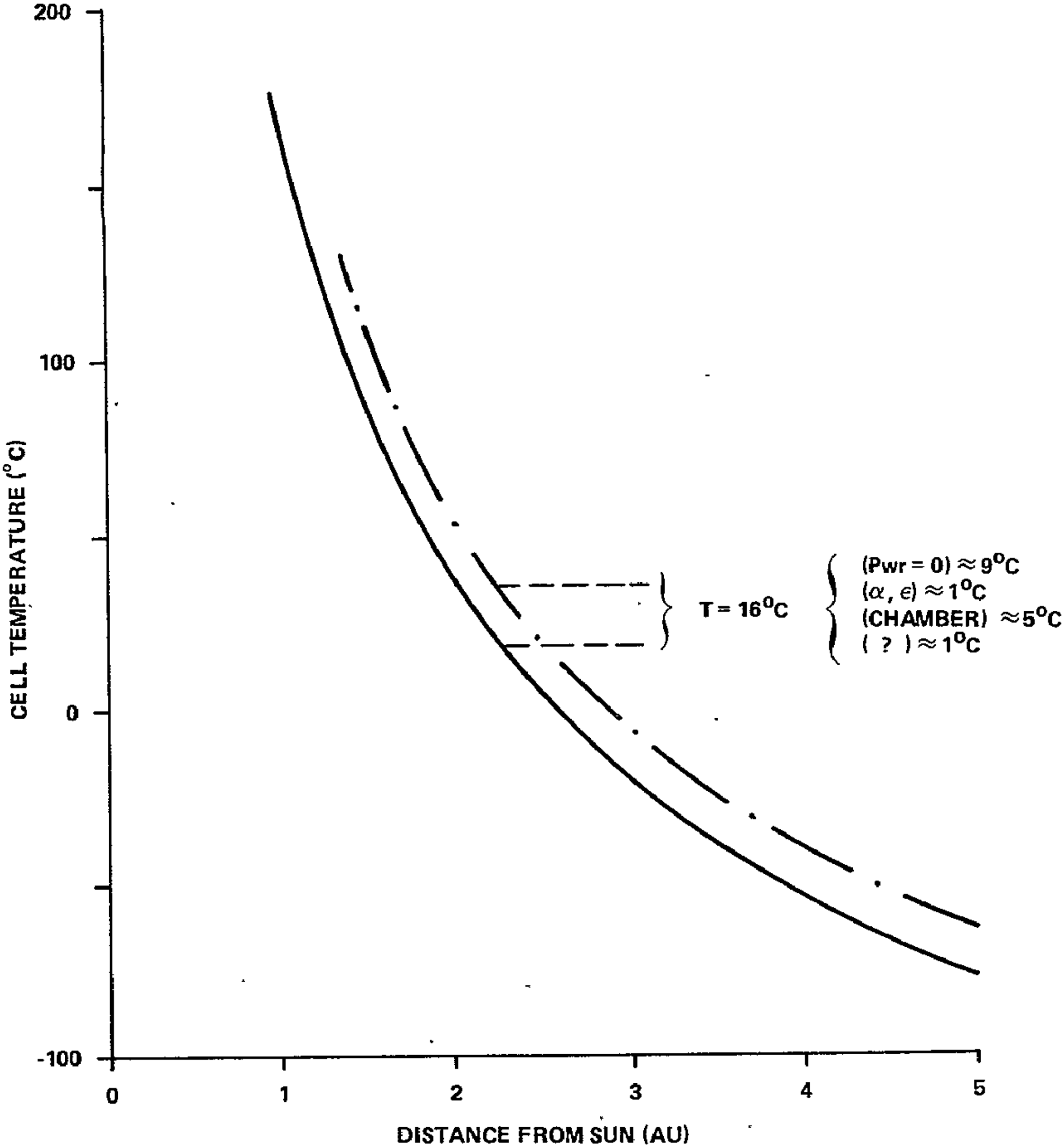


Figure 11. Concentrating array temperature comparison (test versus calculated).

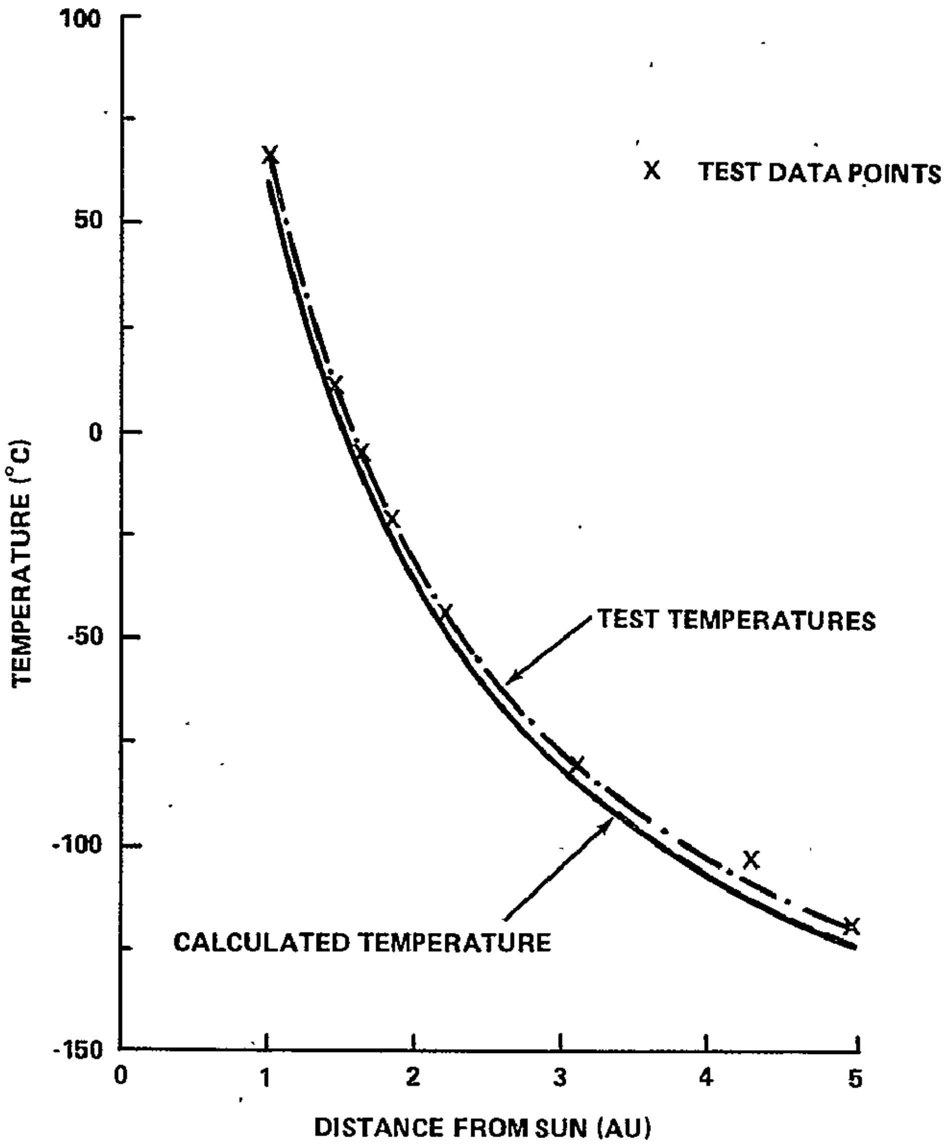


Figure 12. Flat array temperature comparison (test versus calculated).

Test chamber conditions approached those of space; however, two deviations could contribute to higher temperatures than actual space environment: sink temperature, some higher than space temperature, and a reduction in the module's view to space. The large overhead mirror used in conjunction with the solar simulator is responsible for the reduced view angle.

To ascertain the approximate magnitude of this temperature difference, the theoretical temperature and test temperatures of an unconcentrated solar blanket are compared in Figure 12. An average of 5.25°C difference is present over the entire range from 1 to 5 AU. It seems reasonable that this delta in temperature could be expected from the aforementioned differences. Throughout the remainder of this report, it is assumed that a 5° difference existed due to chamber environment.

It should be noted that all calculated temperatures are based on the Stefan-Boltzman equations and at best are an approximation of actual temperature. The theoretical model may not account for all phenomena of heating and radiating, but it is of sufficient accuracy for engineering analysis.

The performance of Module 1 compared to the computerized predictions is shown in Figure 13. Predicted valves were adjusted to reflect test temperature and test cell characteristics. The resultant performance being ≈ 5 mW greater than actual test data.

The cells used on the test module were not matched but selected at random, each cell's performance being matched to the others only within the range of their manufacturer tolerance. As will be covered later in this report some individual cells could also receive lower concentration than the average. Each of these factors contributed to the performance of a series string. The lowest current producing cell limited the output of that string and thereby affected the overall module output.

Some widening of the margin between the curves appears at distant AU's. The predicted performance assumed an ideal cell when predicting the voltage at various AU while actual cell performance did not meet this goal. These differences could account for the wider separation of the curves at greater distances from the Sun. Solar cell experts are quick to point out that by proper selection of the cells the predicted performance could have been achieved. In general, the computer predicted performance was close enough to actual test results to validate the extrapolated performance.

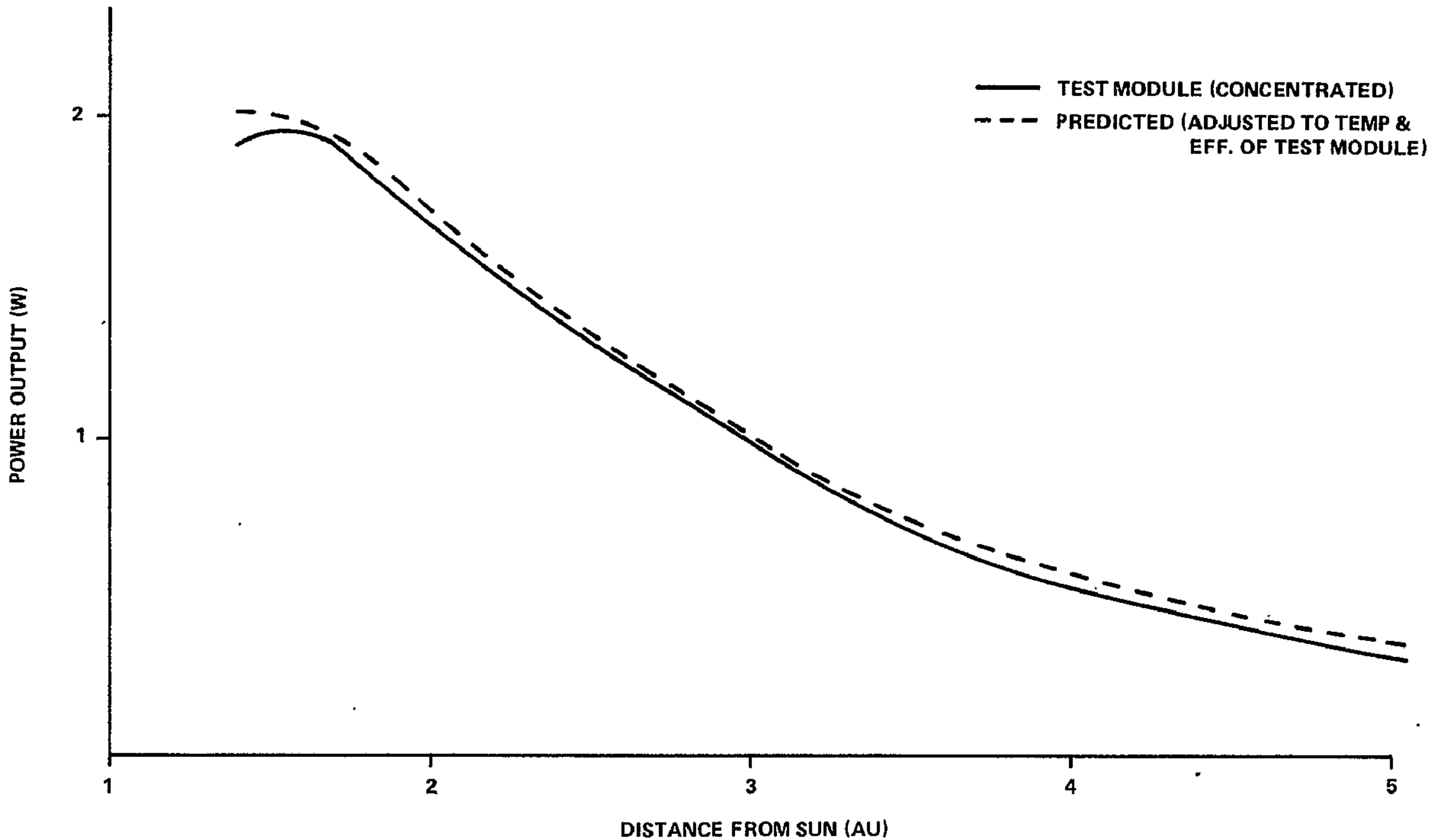


Figure 13. Module 1 performance comparison.

Module 2 test results of a typical cell are shown in Figure 14. Figure 15 compares the performance of the best and worst cells of Module 2 with the Module 1 average performance and the theoretical cell performance. Note that both of the Module 2 cells outperformed the average from Module 1, and the average of the two would have been approximately along the curve of the predicted performance. This tends to support the observations concerning the performance of Module 1.

Comparison of the I_{SC} between the concentrated and nonconcentrated cases should give a representative figure for the effective concentration ratio of the model. This comparison should be a valid comparison since the I_{SC} is nearly linear with intensity. Average module test temperature, different between the two cases, was corrected by a factor of 0.055 percent/°C to correct the current increases from elevated temperatures. Comparison of the results (Fig. 16) shows that the same I_{SC} can be obtained at 0.285 of the Sun intensity with the concentration model than required with the flat array. This is equivalent to a concentration ratio of 3.5. Test results are less than 2 percent lower than calculated values (see Figure 5 for calculated predictions).

It should be noted that the I_{SC} was limited by the poorest performing cell in the circuit, and the temperature used was blanket average. These two conditions do not necessarily coincide and could change from one cell to another with intensity changes. Thermal cycling of the test module produced wrinkles in the reflectors, resulting in some uneveness in cell illumination. Although, these changes were small in magnitude they moved as the temperature varied and wrinkles changed shape. Therefore, concentration and temperature of an individual cell may have varied from the ideal during the test.

SECONDARY TEST RESULTS

Objectives of the secondary goals were pursued to the extent possible. No provisions were made in the test setup to accomplish these tasks. All results are from data and observations made on a noninterference basis with the primary objective.

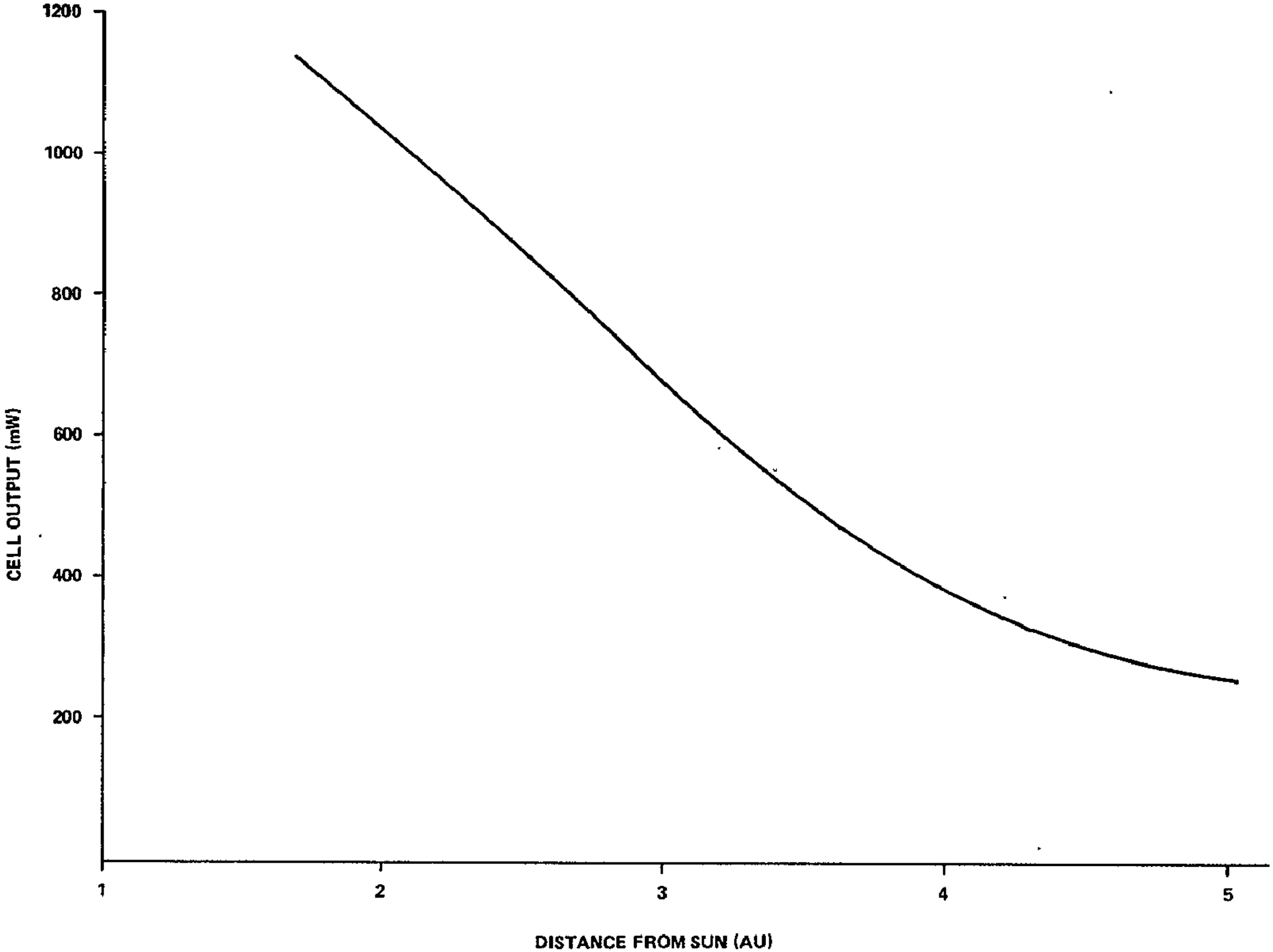


Figure 14. Module 2 typical cell performance.

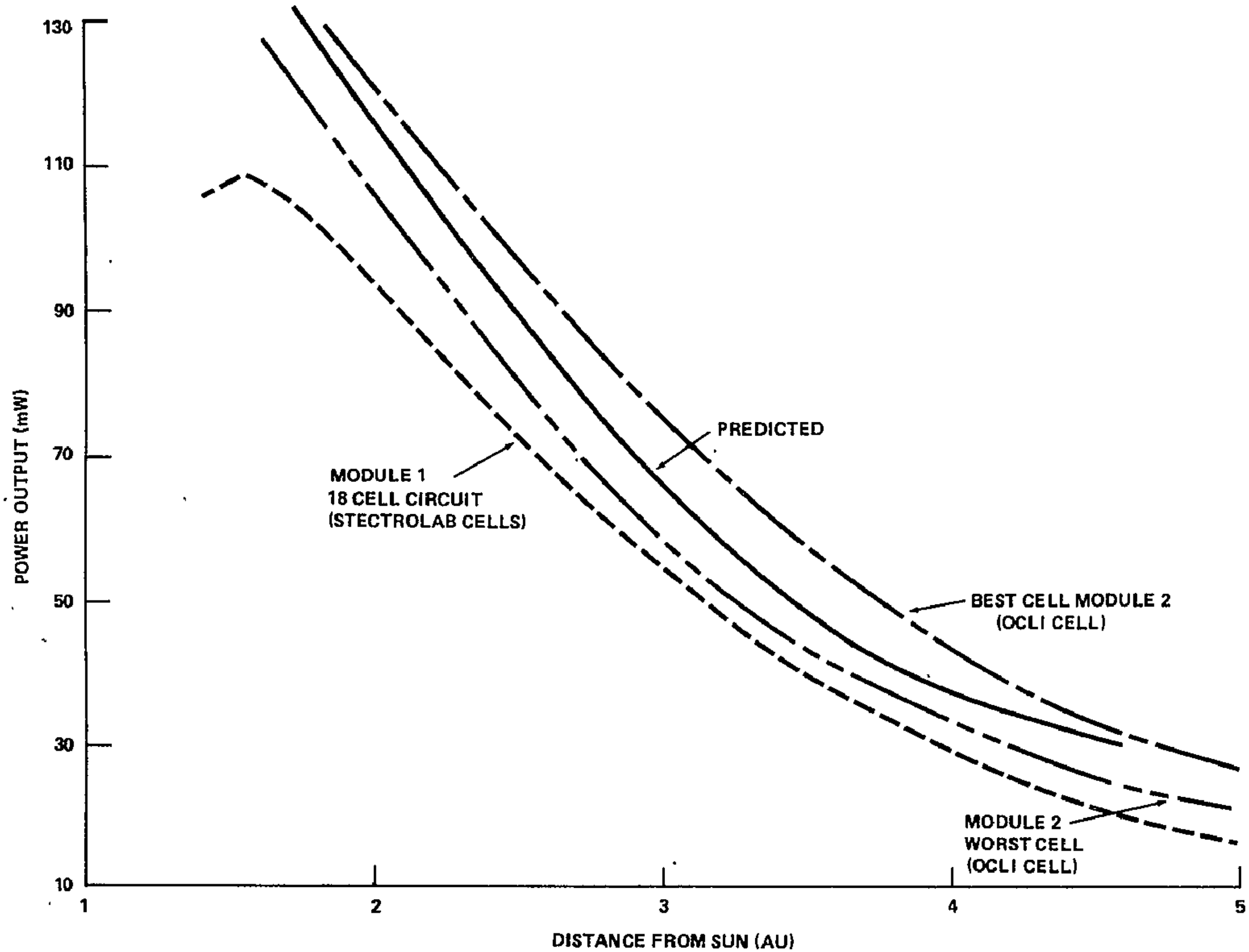


Figure 15. Cell performance comparison.

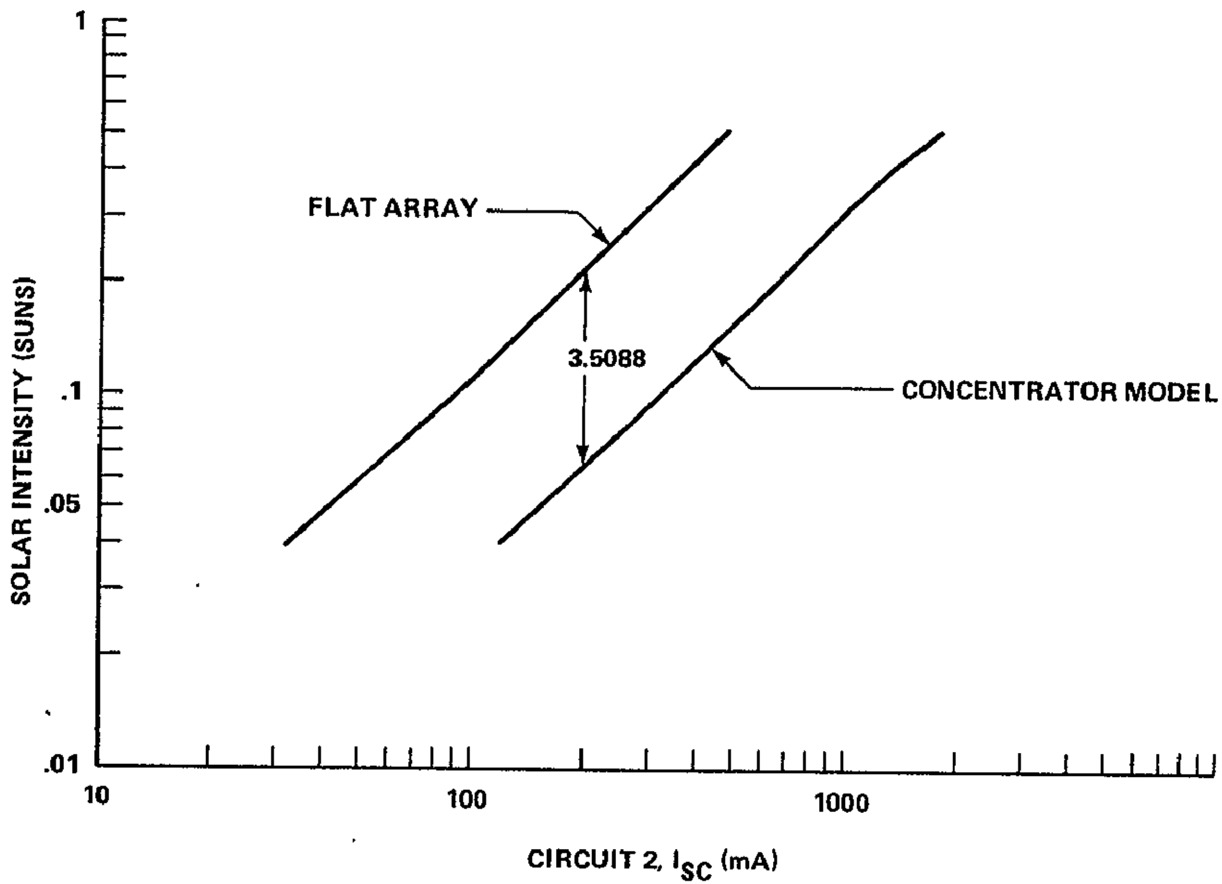


Figure 16. Effective concentration ratio.

View Factor

Two approaches were used to determine the theoretical temperatures of the solar cells for the Halley's Comet Mission Configuration. These calculations produced a delta of 7° to 14°C between the two approaches (Fig. 17). The basic difference between the approaches is the treatment of the view factor for the front side of the solar cell. The first approach, the conventional method, assumed the view factor to be restricted by the concentrators. This approach (diffuse method) has a low view factor resulting in higher temperature and reduced cell efficiency. The second approach (specular method) assumed the view factor was reduced only slightly by the reflective quality of the reflector and the cells were viewing deep space via the reflectors. Lower temperatures result and thus higher cell performance using this approach. Average solar cell blanket temperatures measured during the test more closely followed the predictions of the second approach (Fig. 17). It was therefore concluded that the second approach was a valid and more exacting method for determining temperatures of concentrating array designs. Test data temperatures were adjusted as previously discussed.

Tension Requirements

The effect of wrinkles in the thin film reflector on average array performance was negligible. Tests were begun with the film taut and relatively wrinkle free. As the test continued, wrinkles developed in the large reflectors (Figs. 18 and 19). The depth and severity of these wrinkles (Figs. 18 and 19) are exaggerated by the camera angle. The wrinkles developed as a result of thermal cycling. Provisions for varying the tension in the reflector material while the test article was in the chamber were not available. No significant degradation in average array performance could be noted as a result of the wrinkles. Areas of the array had higher temperatures than predicted or higher than complementary areas of normally equal illumination. The only explantion for these increases was increased illumination from stray reflections generated by the wrinkles. Visual observation during the test was limited to a porthole approximately 10 ft above the test article. Two small areas of higher visible illumination could be noted. These areas moved during the test indicating that they actually were being caused by thermal properties of the blanket and/or reflector. It is not known if the wrinkles in the reflector material or the lack of flatness in the blanket caused this spot of high illumination. The latter is believed to be the cause of the visual abnormalities.

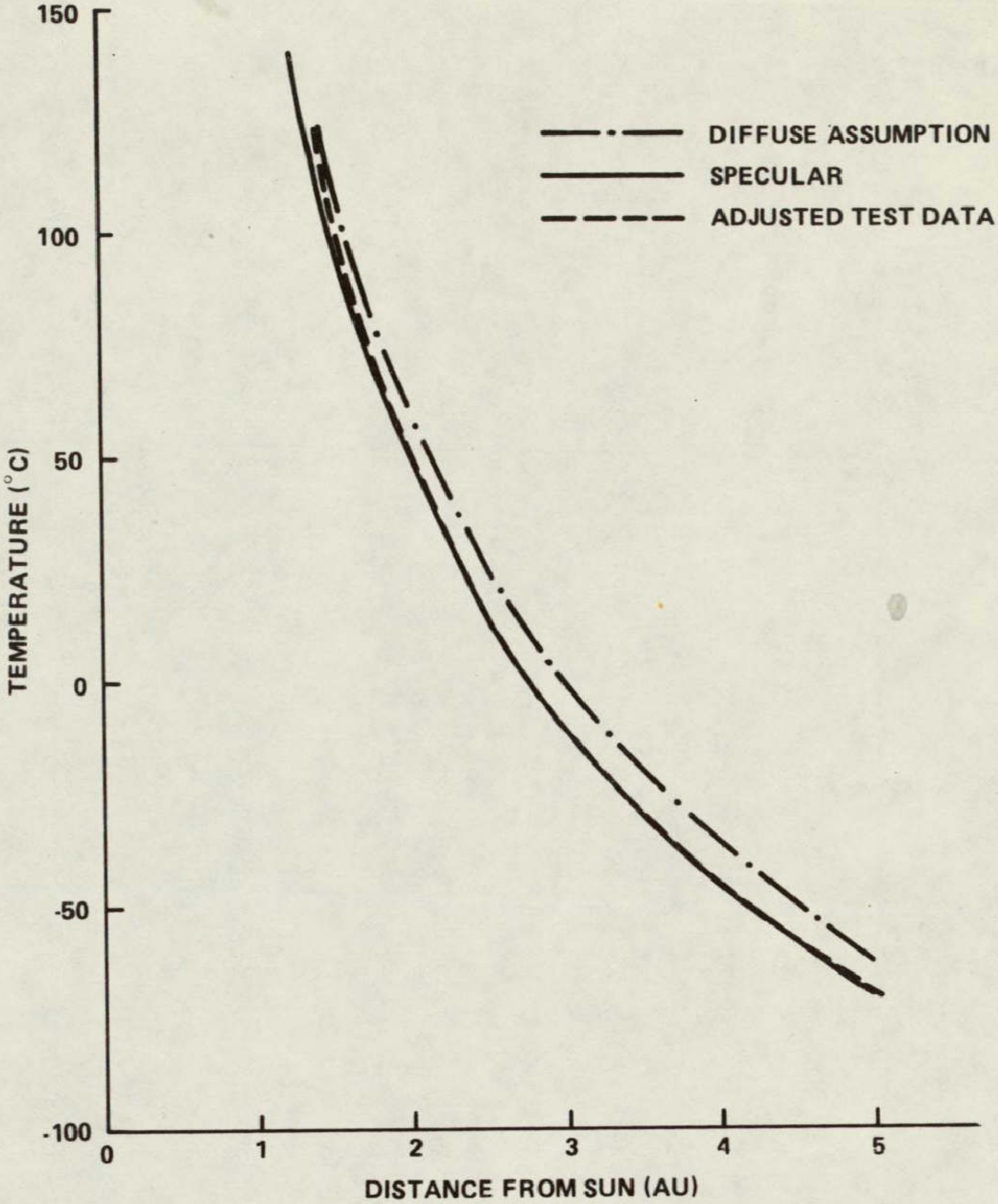


Figure 17. Comparison of diffuse and specular approach to temperature determination.

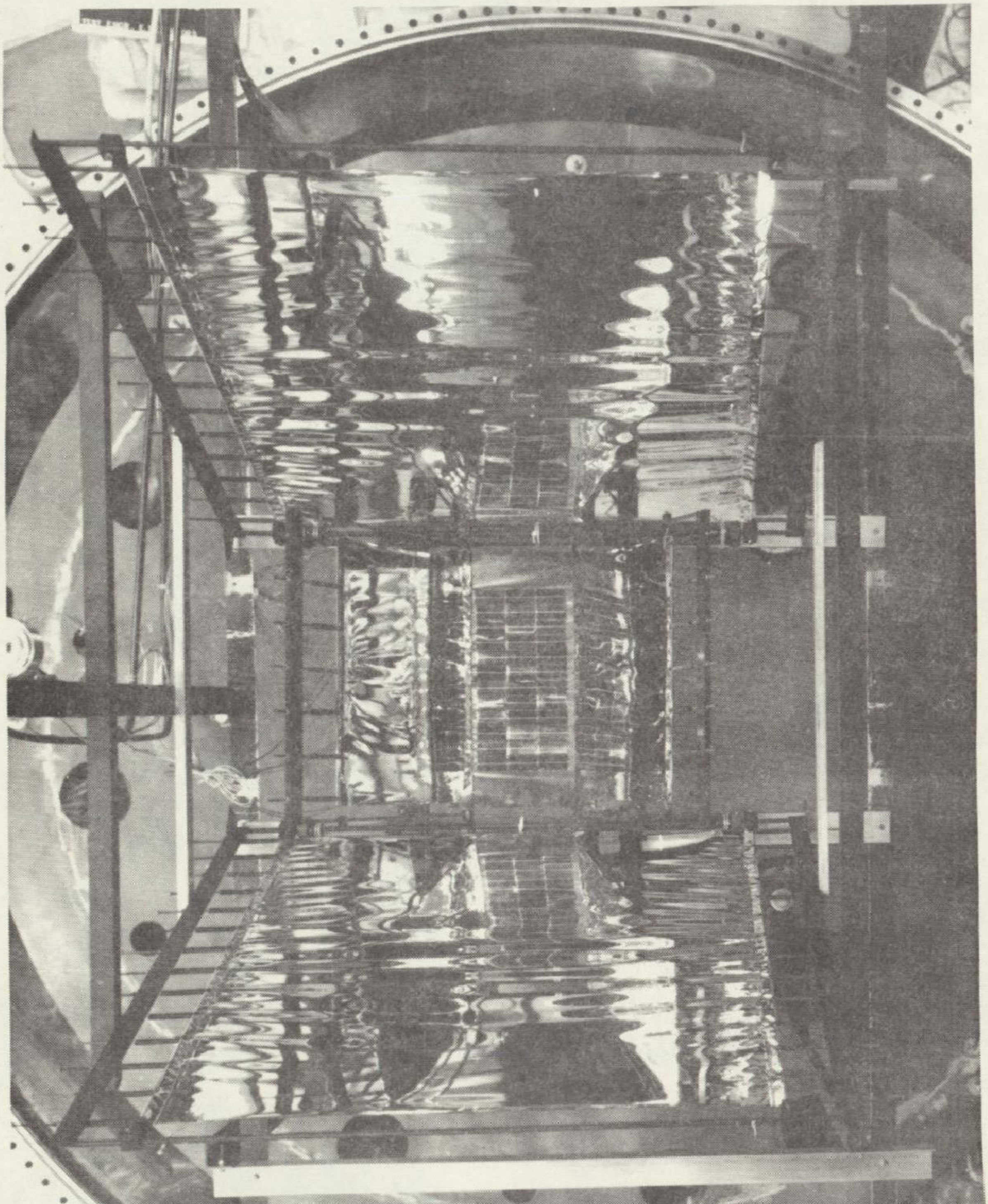


Figure 18. Test module after test (top view).

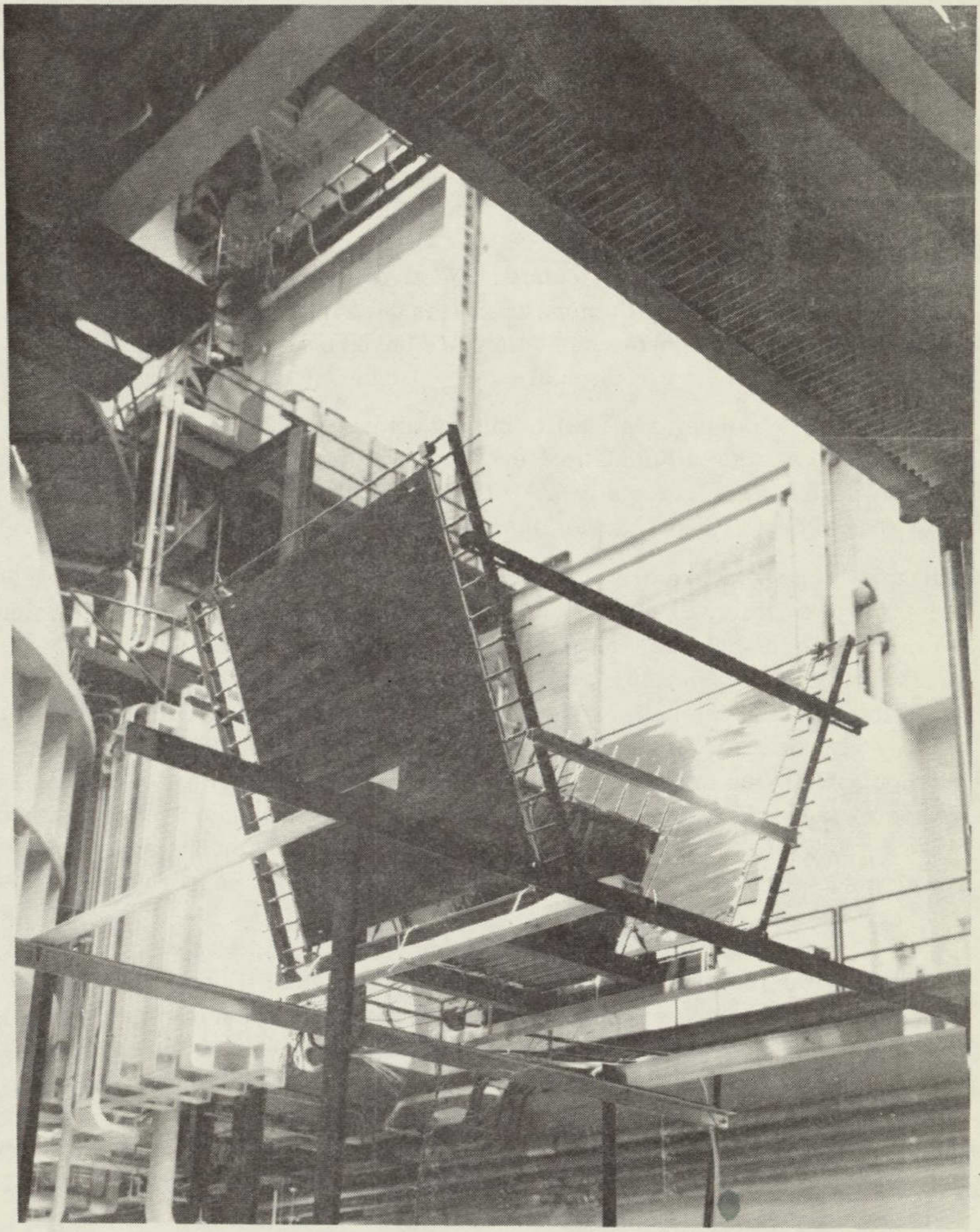


Figure 19. Test module after test (bottom view).

Illumination Distribution

Module 2 was designed such that intensity and temperature mapping could be performed over the panel area. Each cell was individually wired and thermocouples selectively located over the area. Figure 20 shows the cell arrangement and thermocouple locations. The theoretical illumination pattern resulting from the secondary reflections is superimposed on Figure 20.

Correlation between calculated effective concentration ratios ECR's (Table 5) and theoretical illumination ratios does not appear to exist. Calculated ECR's are questionable since they are based on several assumptions. Temperature and short circuit current (I_{SC}) data for the flat array were taken at 1 AU only. Chamber availability did not allow continued testing to record performance at other illumination levels. As a result, data for the concentrated configuration were corrected to 1 AU for comparison. Two basic assumptions were required: (1) that I_{SC} was linear with illumination level and (2) current increase due to temperature change was correctable by 0.055 percent/°C. Some degree of uncertainty exists in both of these assumptions; therefore, any close correlation in the data was not expected. Only one-half of the cells were instrumented for temperature, and four of these were lost during the test due to poor attachment to the cells. The remaining uninstrumented cells were assumed to have the same temperature as another instrumented cell in a complementary location. Wrinkles in the reflectors and solar cell blanket, in most cases, probably made this assumption invalid. Only the instrumented cells (marked by an a) in Table 5 were assumed to be valid points for serious analysis; they are also subject to the previously mentioned assumptions concerning I_{SC}.

The data in Table 5 show a minimum ECR of 3.5, a value near the theoretical illumination value. Note that the theoretical illumination pattern (Fig. 20) is constant over most of the test article. The narrow band crossing the module having a slightly lower illumination level lowering the average concentration ratio very little. Since the concentrators are not perfect mirrors, the narrow bands are most likely blended into the larger area and do not exist. The resulting theoretical pattern would therefore have to be assumed equal over the entire area at ECR = 3.55. With the uncertainty of the actual number of strikes on any one spot, it might be interesting to note that if the theoretical illumination is bounded by 0 to 4 strikes of secondary reflections, the concentration ratio would vary from 3.1 to 4.12 on any one point. Considering this

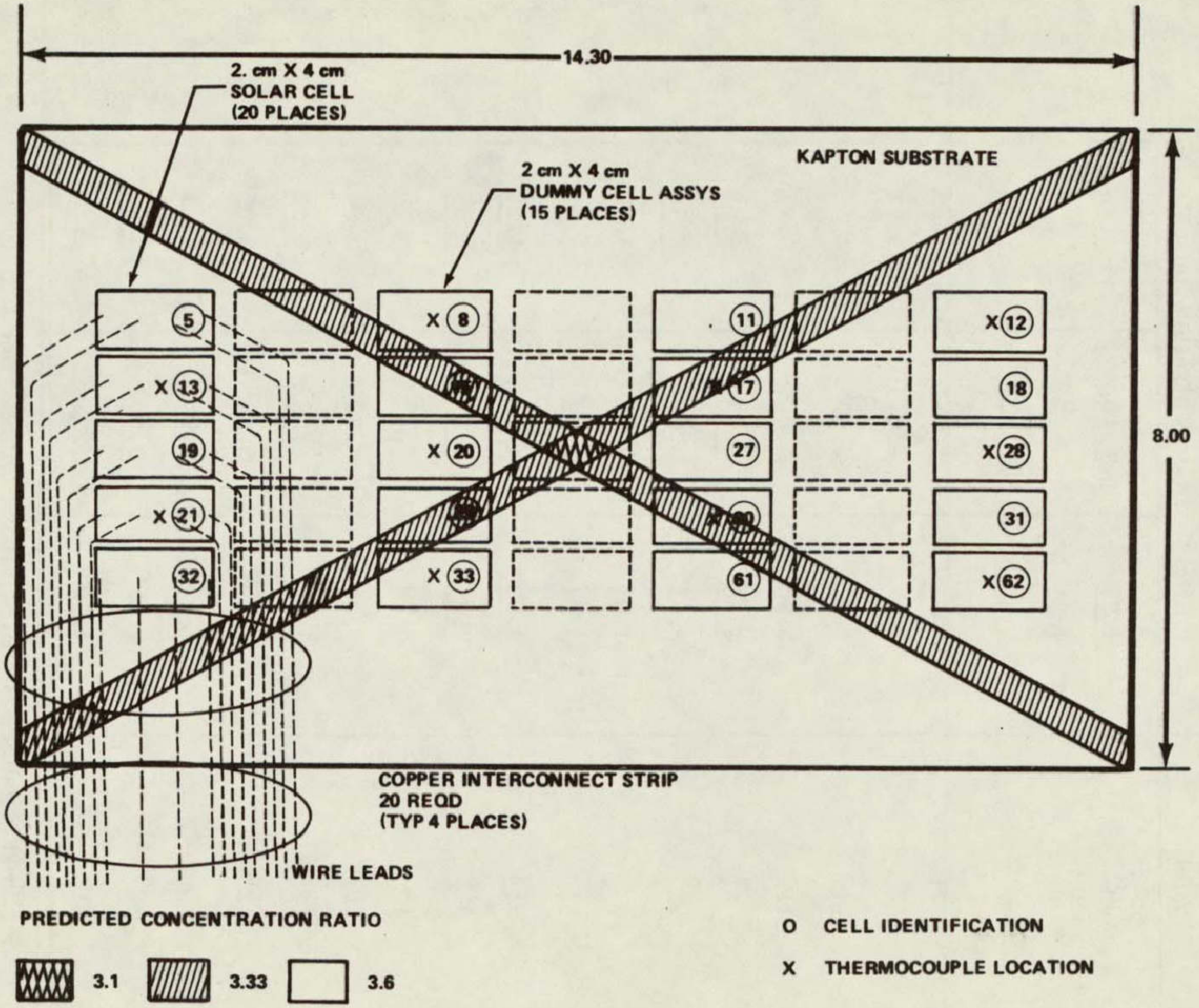


Figure 20. Thermocouple location for module 2.

TABLE 5. MODULE 2 CONCENTRATION RATIO COMPARISON

Cell Number	Distance from Sun (AU)		
	1.82	2.5	5.04
	Effective Concentration Ratio		
30[a]	4.08	4.16	4.39
29	4.21	3.76	3.72
27	3.90	4.04	4.29
20[a]	4.09	3.70	3.69
15		4.01	3.92
17[a]	b	4.29[c]	4.36[c]
11	3.93	4.06	3.96
8[a]	4.06	3.78	3.63
62[a]	3.51[c]	3.61[c]	3.75
32	4.01	4.19	4.23
31	3.64	3.68	3.81
21[a]	3.99	4.24	4.23
28[a]	3.84	3.8	3.87
19	3.99	4.15	4.26
18	3.99	3.77	3.94
13[a]	4.02	4.19	4.28
12[a]	b	3.90[c]	3.95[c]
5		4.25	4.11
33[a]	4.22[c]	3.90	3.64
61	4.19	4.17	4.12

NOTE: Underlined Numbers Believed Most Reliable (see text).

a. Thermocouple Location.

b. Thermocouple Lost During Test.

c. Temperature Questionable.

possibility and the wrinkles in the reflectors, the ECR's calculated in Table 5 are within realistic limits. It should be noted that the average concentration ratio for a series string would be set by the lowest ECR of any cell in the series string.

CELL PERFORMANCE AT DISTANCE (AU)

Typical solar cell performance under low illumination level in space is characterized by Figure 21. Tests on silicon cells by Boeing "Solar Cell Selection and Characterization for Solar Electric Propulsion" (Contract NAS8-31670) and TRW "Solar Cell Array Design Handbook" (JPL SP 43-38) show similar results. Tests conducted with Module 2 verified that performance could be improved over a flat array by concentration. The performance more nearly tracked that of an ideal cell (Fig. 21).

The performance of several cells is shown in Figure 22, which also shows theoretical boundaries at four points over the mission range. The results from Module 2 under concentration are overlaid to show that the test results were within the theoretical limits. Higher temperature and illumination resulting from concentration overcame the phenomena normally occurring at approximately 2 to 2.5 AU from low temperature and low illumination.

Similar V_{mp} performance can be seen in the results from tests on Module 1 (Fig. 23). Results from the flat array and concentrated array are contrasted here versus that predicted by analysis. The predicted results were based on a higher efficiency cell and lower temperatures. Predicted performance adjusted to module average temperature is also shown for comparison. Module 1 cells did not perform as well at the greater distances in AU's as Module 2. Judicious selection of solar cells would help overcome the falloff at these distant AU's.

The purpose of this test was not to evaluate cells, but to determine the change in their performance resulting from concentration. However, examination of the IV curves in the appendix shows that the cells used were not of the desired quality. The presence of series and shunt resistance and shockey barrier effect are noticeable in these curves. Had better cells been used overall performance would have been improved, especially at distant AU's.

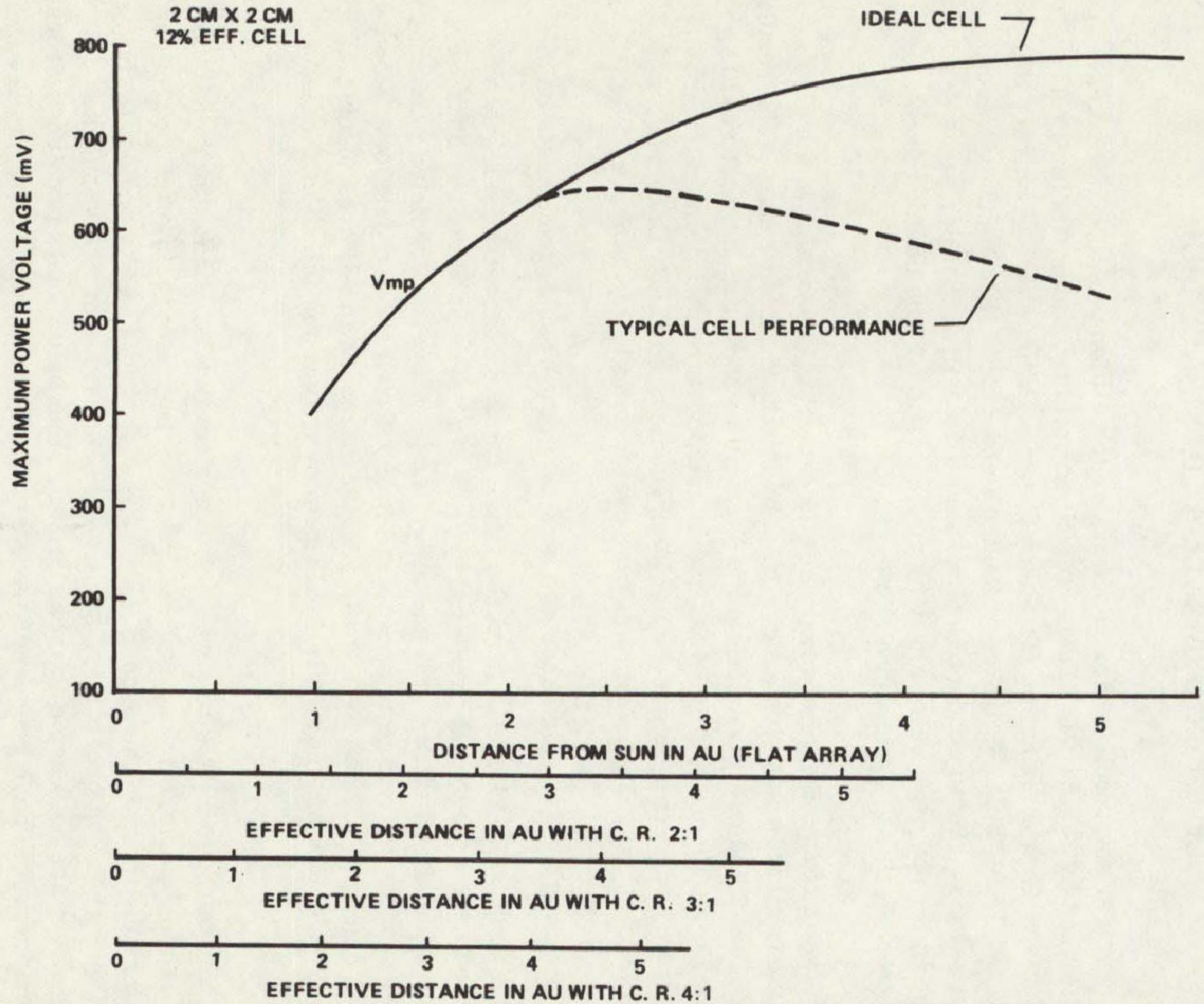


Figure 21. Low illumination cell performance.

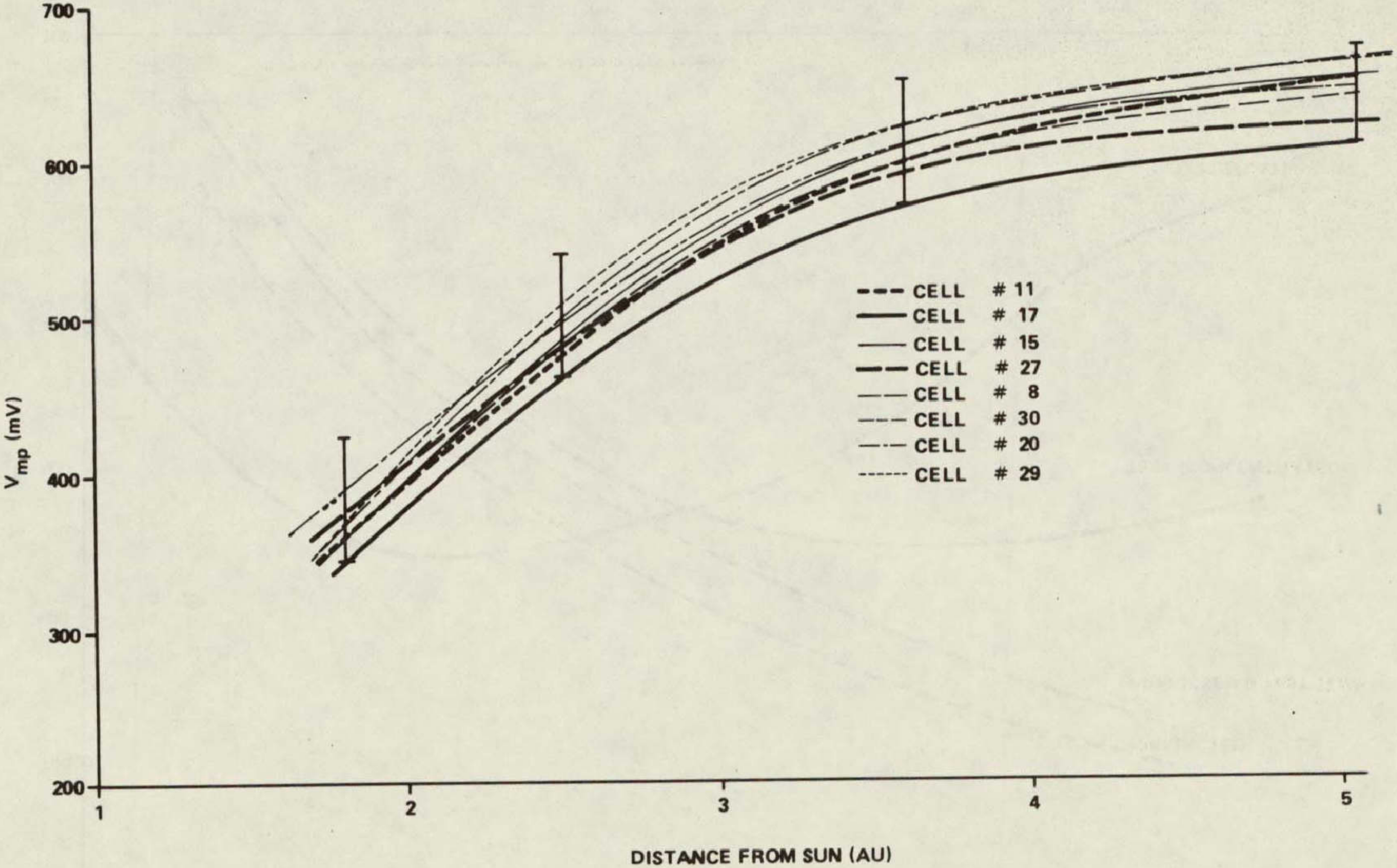


Figure 22. Individual cell performance, module 2.

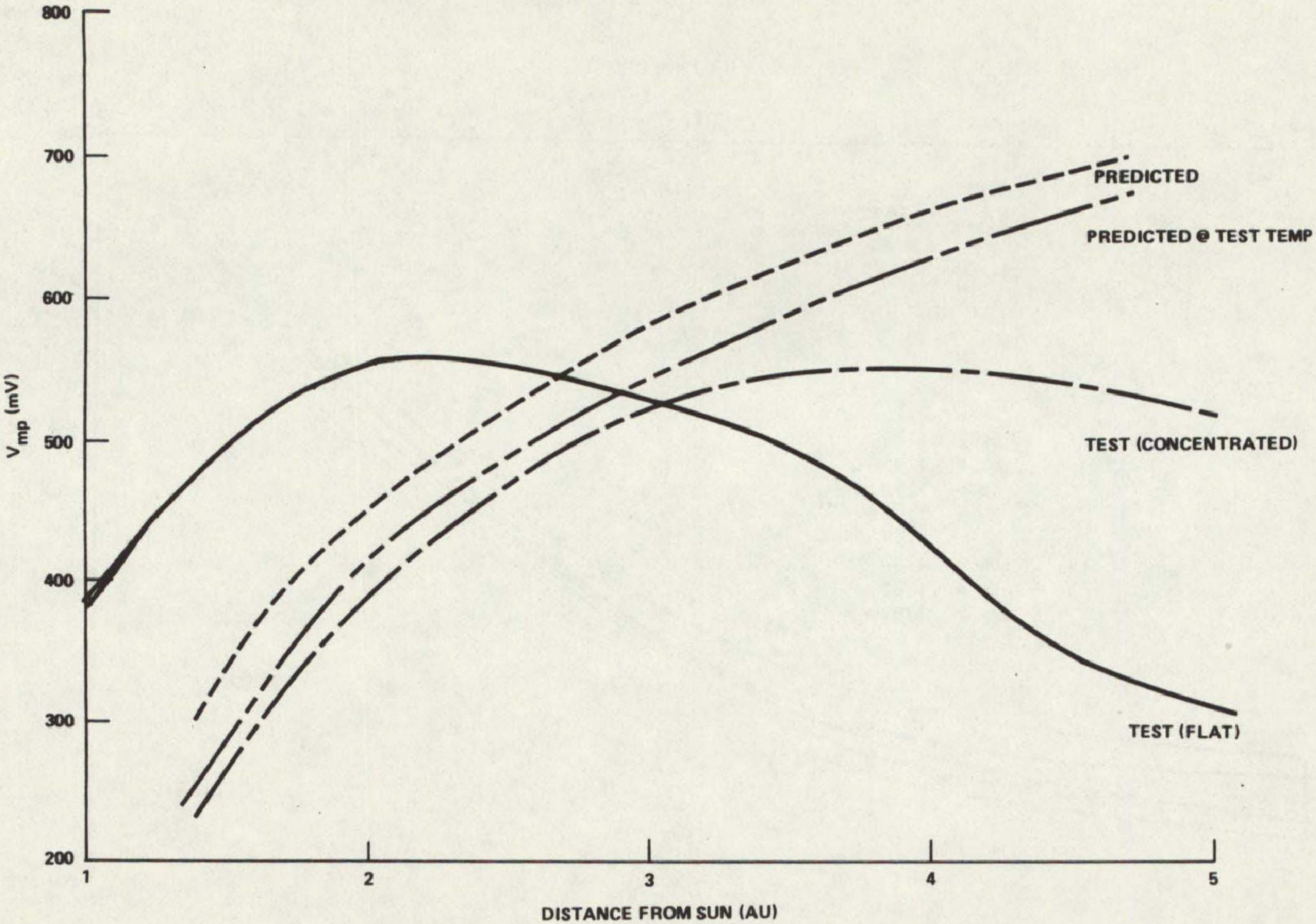


Figure 23. Module 1 V_{mp} versus AU.

CONCLUSIONS

The test validated the predicted array performance and provided useful information for future concentrating array designs. The test showed that the configuration under test could produce an effective concentration ratio of 3.6:1.

Performance within 5 percent of predicted array output was shown to be achievable. An average concentration ratio of 3.5 was measured. A slight increase in this number would actually be obtained due to reflector pattern differencies (see Appendix A). Temperatures were within 4 percent of predicted values, validating the temperature model used for predicting cell temperature. Peak performance occurred at 1.6 AU requiring a decrease in concentration ratio at distances nearer to the Sun to maintain an acceptable temperature and power output level. Improvement in cell performance with concentrators at distant AU's was also verified.

No degradation in performance resulting from wrinkles in the concentrators was observed. Although no conclusive results were obtained, it was concluded from the test data and observations that tension requirements in the thin film reflectors are determined only by the tension required to support the film. High tensioning to produce wrinkle free, flat planes does not appear to be required.

APPENDIX A

SOLAR CELL BLANKET ILLUMINATION

The illumination pattern on the cell blanket area is determined by array pointing and construction. Four factors in the construction influence the illumination pattern: (1) the angle the concentrator makes with the blanket, (2) the length to width ratio of the blanket, (3) reflector and blanket flatness, and (4) alignment errors between the concentrator and the blanket. The latter two are unpredictable and a function of construction technique. They, as well as pointing, will be assumed ideal for this analysis.

Assuming the array is properly constructed and aligned, the entire blanket will be illuminated by five sources of illumination: one direct and four reflections from the side and end reflectors. In addition to the five main sources of illumination, secondary reflections from the corners of the concentrator (see Figure A-1, shaded area) add to the primary illumination and thus to the total energy available. Areas of the array may receive from zero to four strikes of illumination from secondary reflections depending on the length/width ratio and reflector angle. This analysis deals with this illumination distribution.

A typical illumination pattern for a solar panel on the Halley's Comet Mission is shown in Figure A-2. The number of secondary reflections vary from two to four, areas 1 through 3 respectively. Shape and area covered by each is a function of reflector angle and length/width ratio. As the length/width ratio becomes small, as in the test module, the illumination pattern changes. Area 3 becomes smaller until it disappears and a new pattern such as Figure A-3 is formed. Note that area 3 now receives no secondary reflections and areas 1 and 2 are equal with two reflections each and a new area (area 4) receives one secondary reflection. A computer program was written to analyze the illumination pattern on this configuration with reflector angle and length/width as variables.

Figure A-4 is a scale drawing of the illumination pattern for the test module with effective concentration ratio indicated in each area. Note that the illumination level is constant over the major part of the cell area. The narrow bands of lower illumination decrease the average illumination very slightly. Any alignment imperfections or wrinkles in the reflector material would most likely blend these narrow bands into the surrounding areas. Theoretical effective concentration ratios for each area and the average are given in Figure A-4.

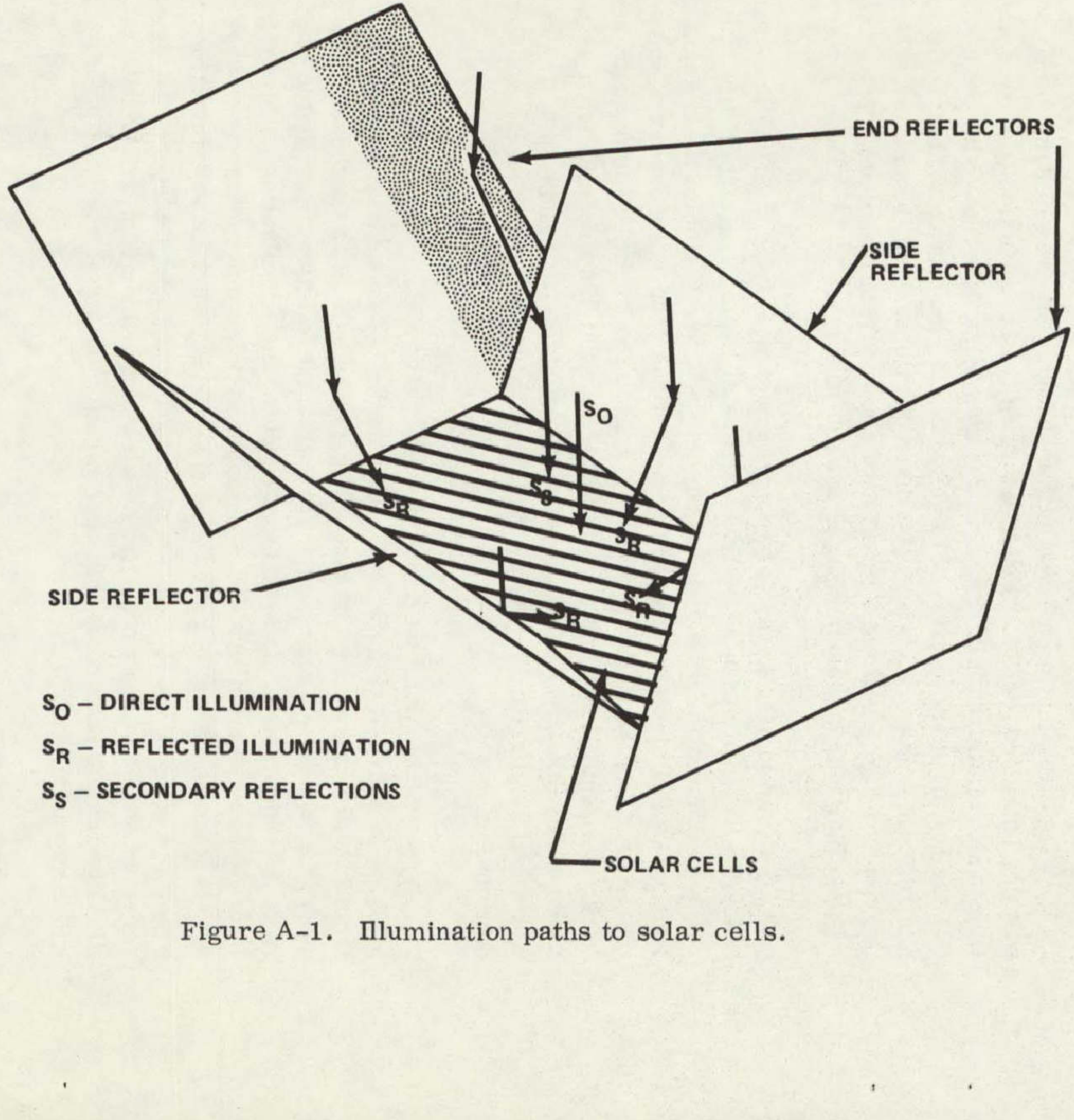
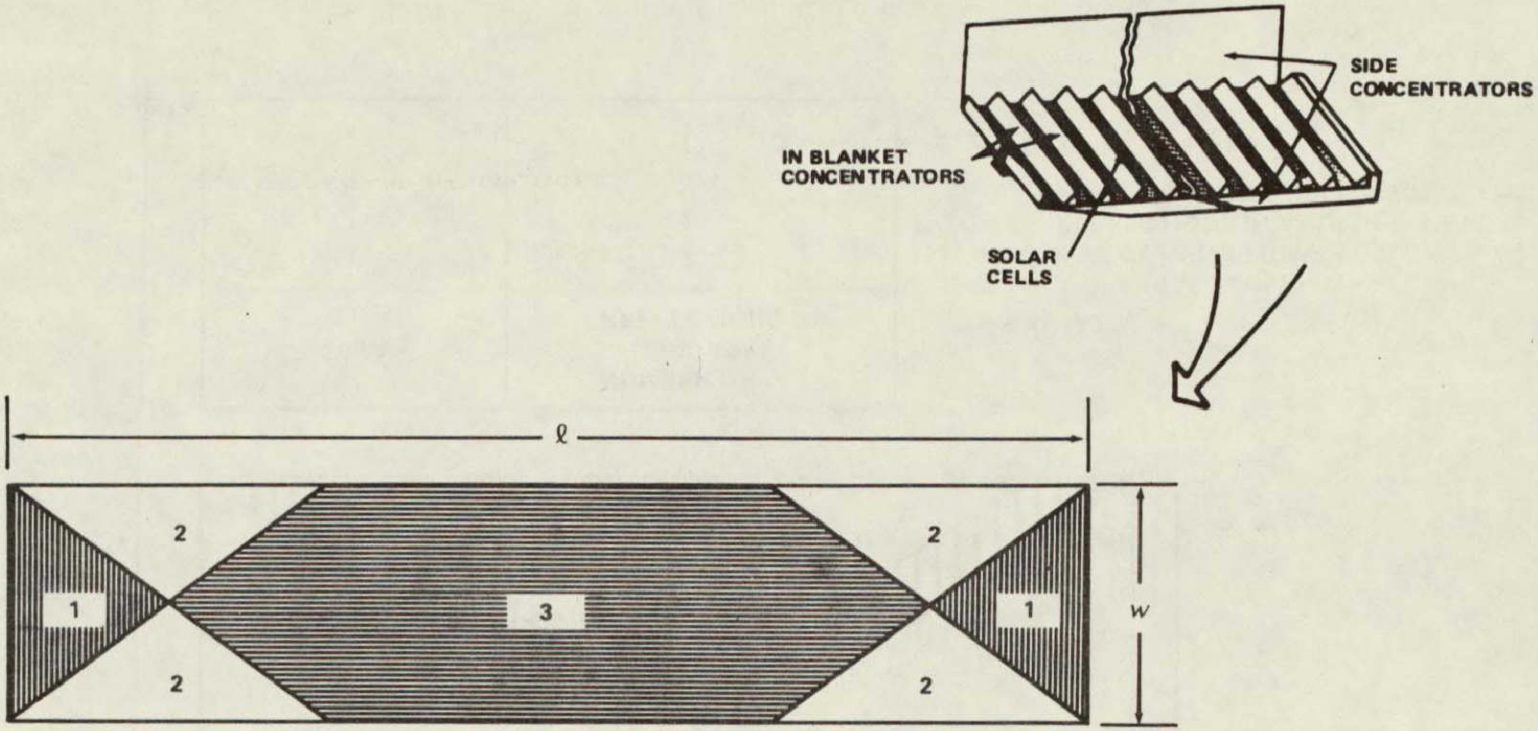


Figure A-1. Illumination paths to solar cells.

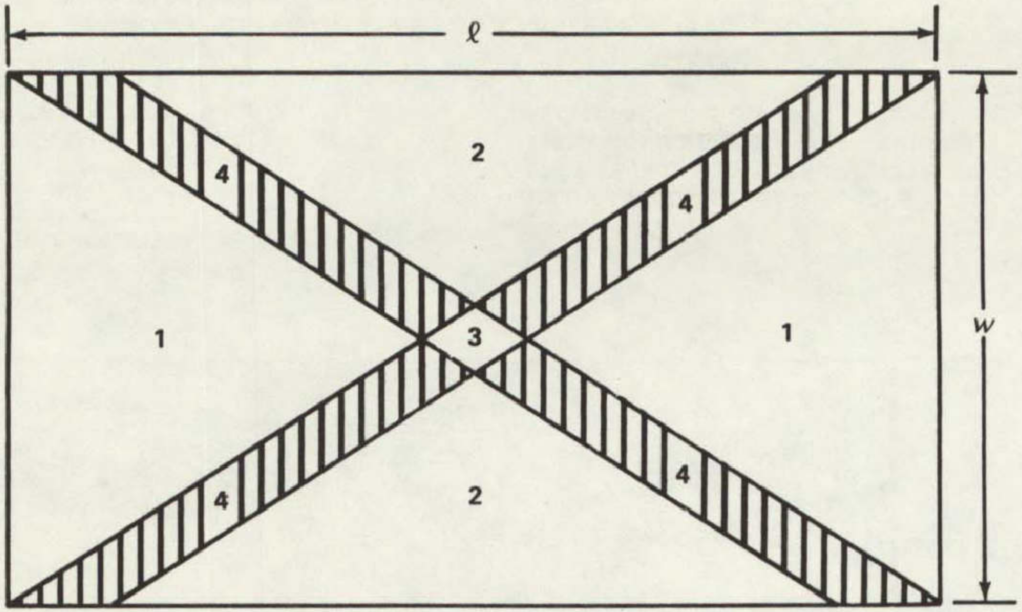


AREA	C.R. (EFFECTIVE)
1	3.1:1
2	3.35:1
3	4.1:1

ILLUMINATION LEVEL INCLUDES ENERGY FROM DIRECT SUN, REFLECTION FROM SIDE AND END REFLECTOR AND SECONDARY REFLECTION

AREAS AND C.R. VARY WITH ℓ/w RATIO & ANGLE OF REFLECTOR
NUMBER GIVEN IS FOR BASELINE CONFIGURATION

Figure A-2. Typical illumination pattern.

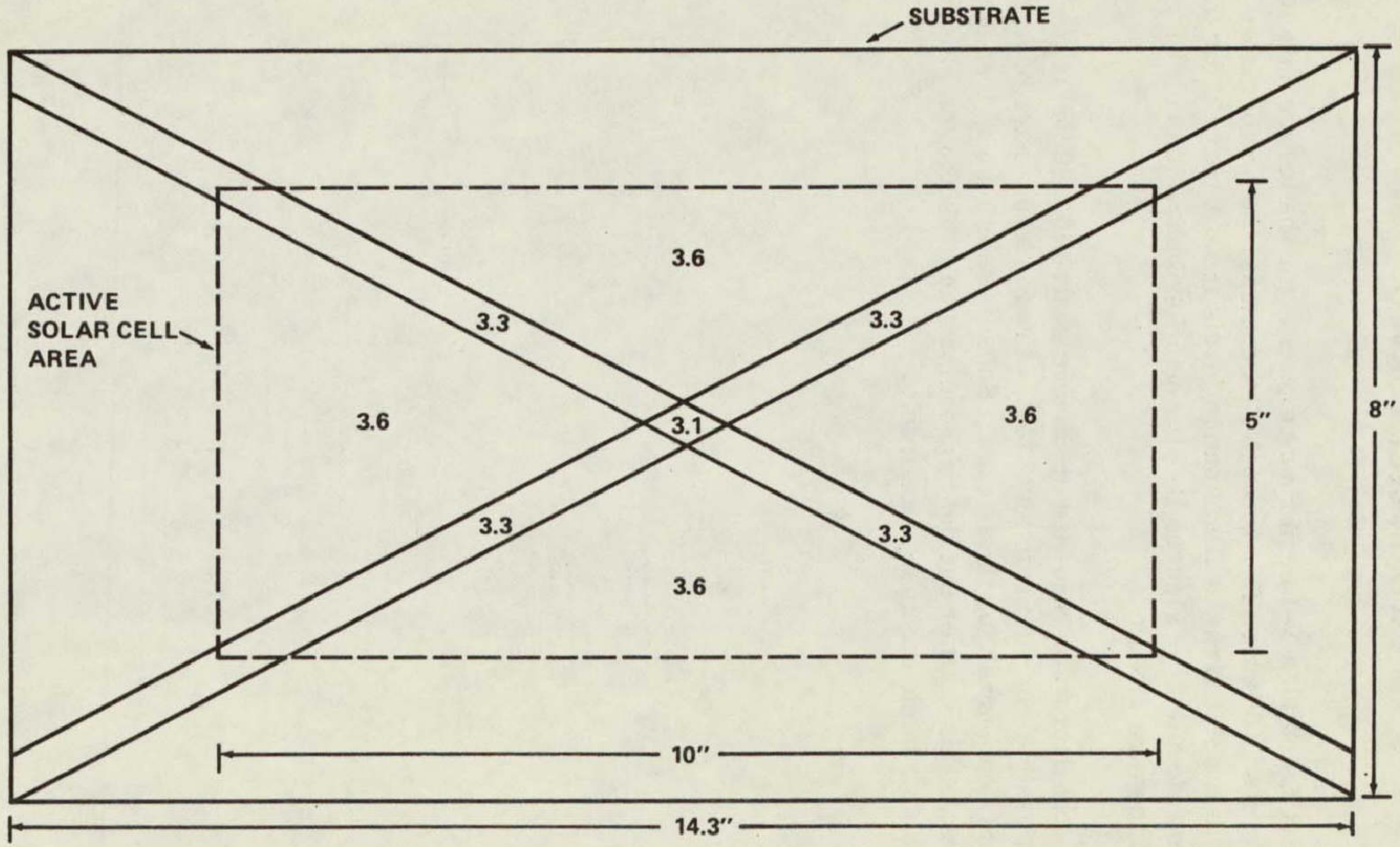


AREA	NUMBER OF SECONDARY REFLECTIONS
1	2
2	2
3	0
4	1

NOTE:

ALL AREAS RECEIVE 1 DIRECT AND 4 PRIMARY REFLECTIONS IN ADDITION TO THE SECONDARY REFLECTIONS

Figure A-3. Illumination pattern as ℓ/w approaches 1.



AVERAGE EFFECTIVE C.R. 3.547:1

Figure A-4. Test module illumination pattern.

APPENDIX B

PERFORMANCE CURVES

Appendix B contains V-I performance curves for the tests conducted during this exercise. Figures B-1 through B-6 contrast the performance of concentrator versus flat array at illumination levels from 1 to 5 AU for the 36-cell module (Module 1). Figures B-7 through B-26 show the results of the individual cell tests on Module 2.

Actual test data were recorded at various scales to achieve as much resolution as possible for each individual test. These results have been reconstructed into composites for this report. Some resolution was lost in presenting the data in this manner but the improvement in presentation plus the reduction in volume made the change desirable.

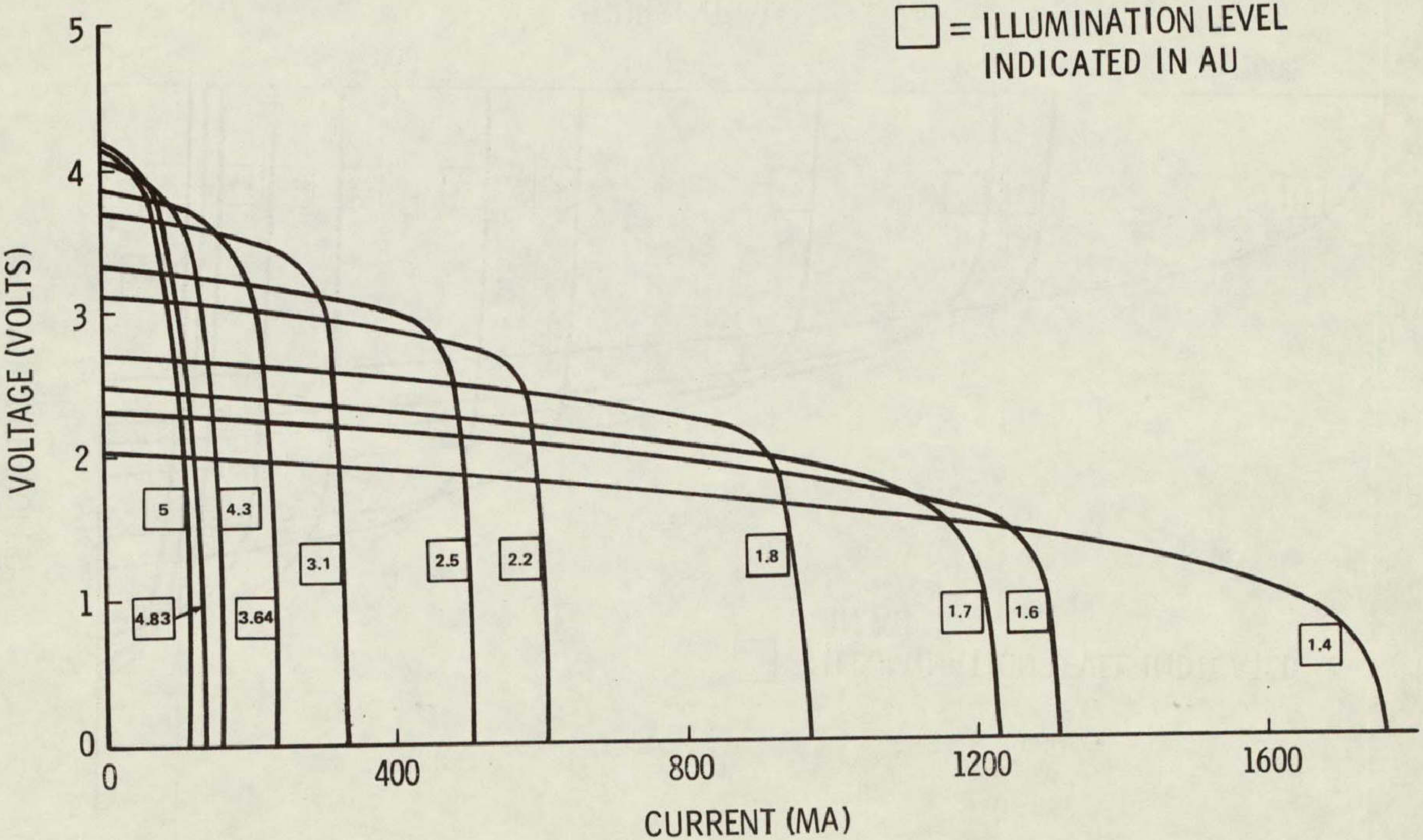


Figure B-1. Concentrated array performance (module 1, circuit 1).

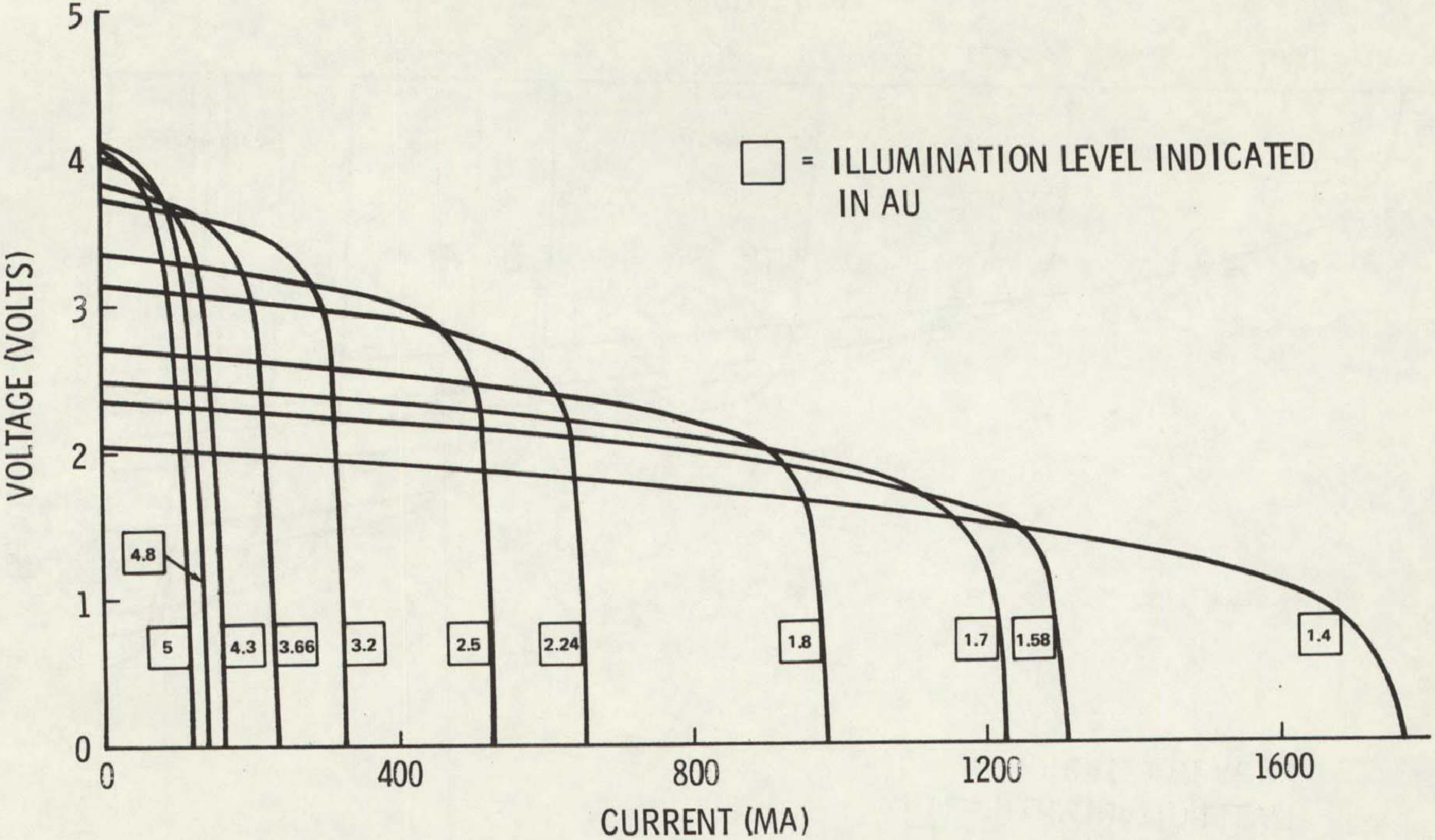


Figure B-2. Concentrated array performance (module 1, circuit 2).

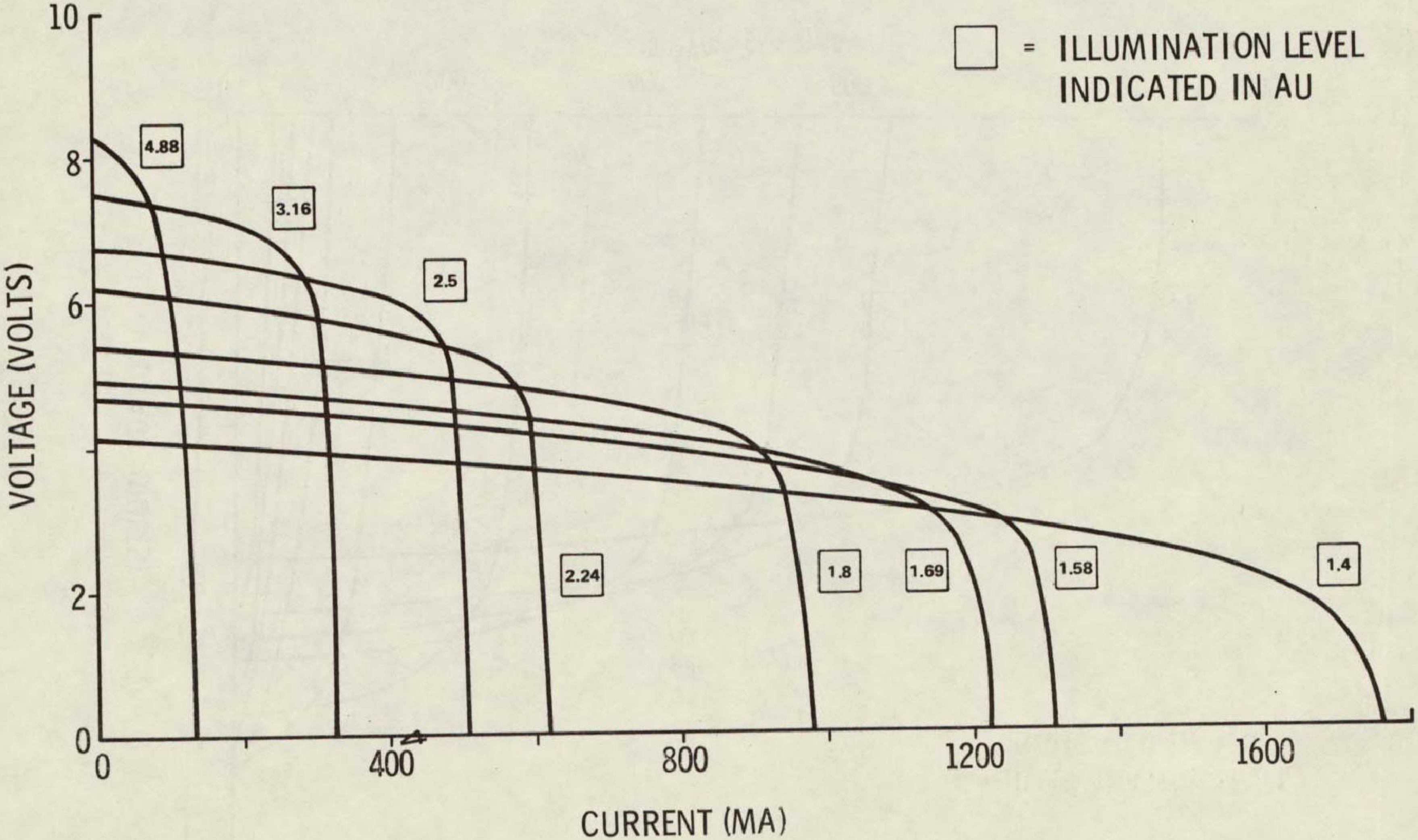


Figure B-3. Concentrated array performance (module 1, circuits 1 and 2 in series).

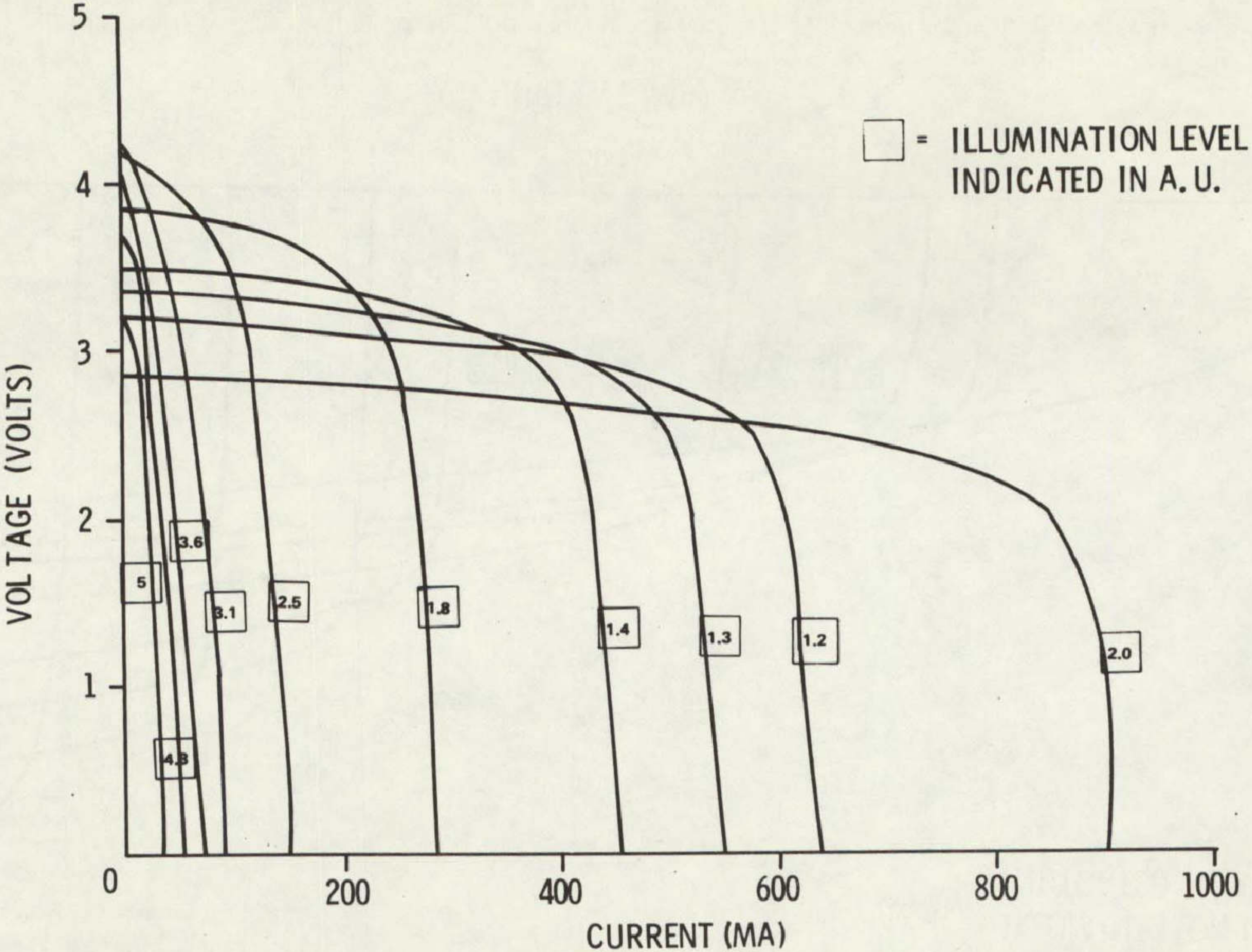


Figure B-4. Flat array performance (module 1, circuit 1).

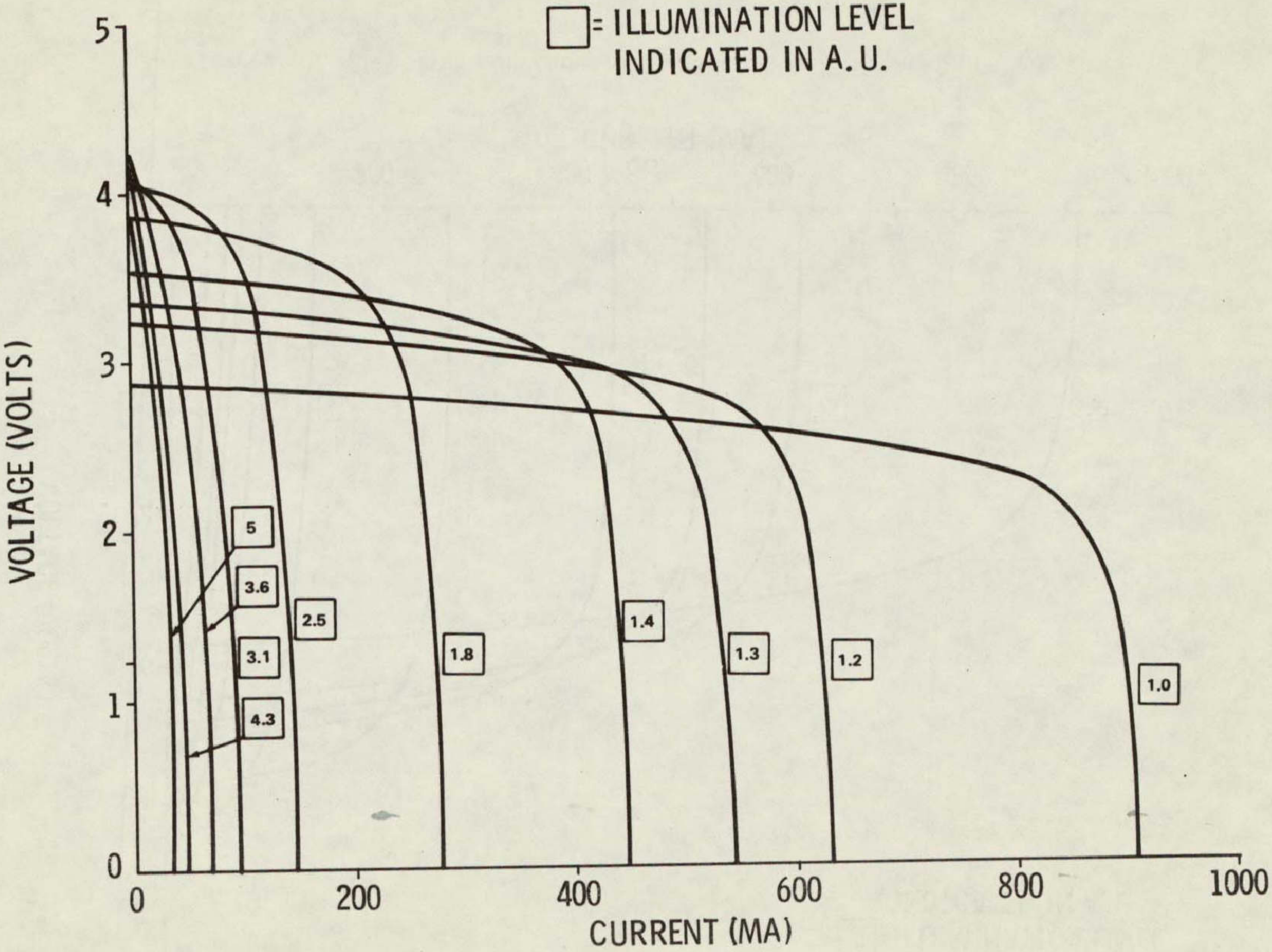


Figure B-5. Flat array performance (module 1, circuit 2).

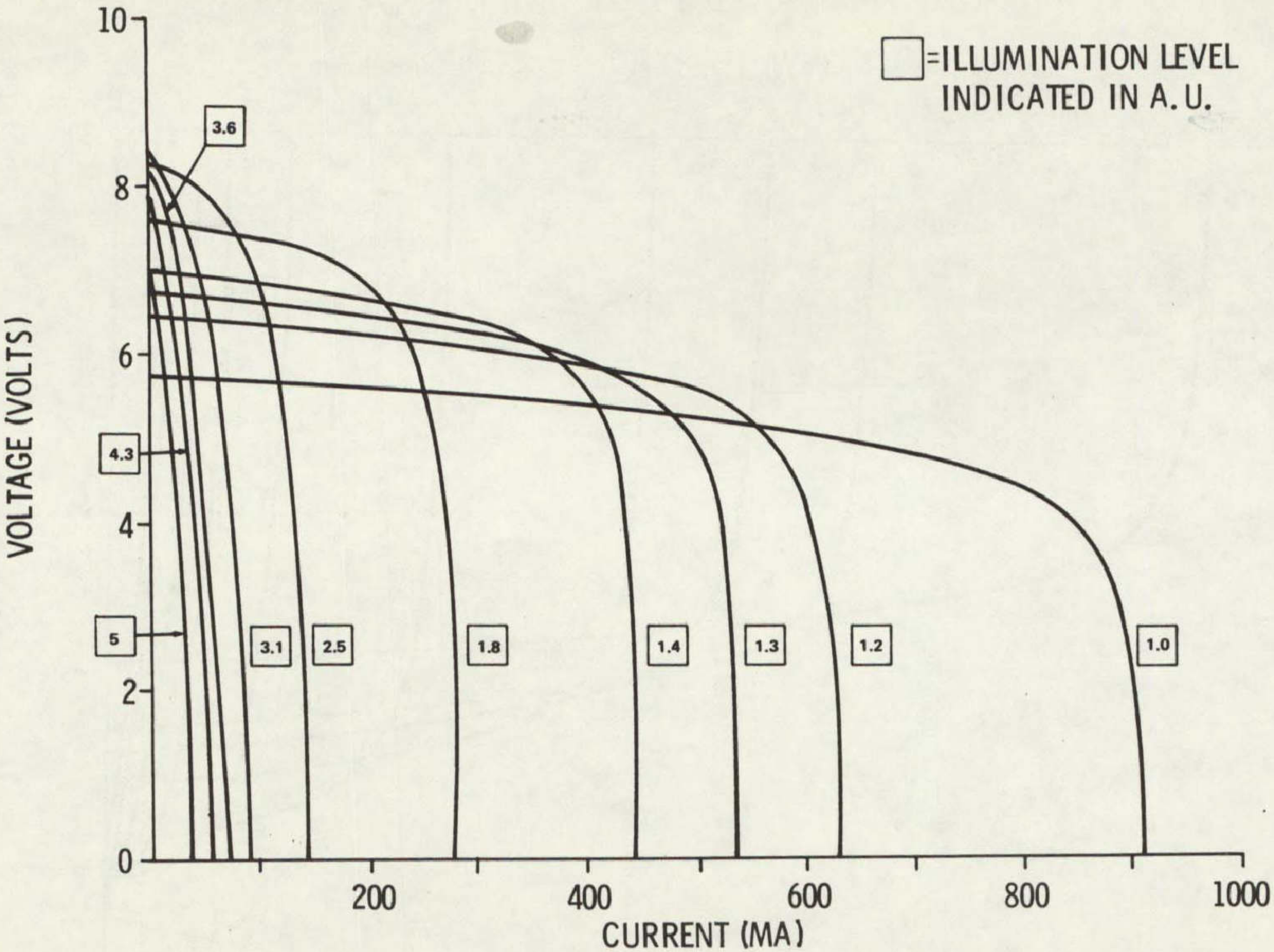


Figure B-6. Flat array performance (module 1, circuits 1 and 2 in series).

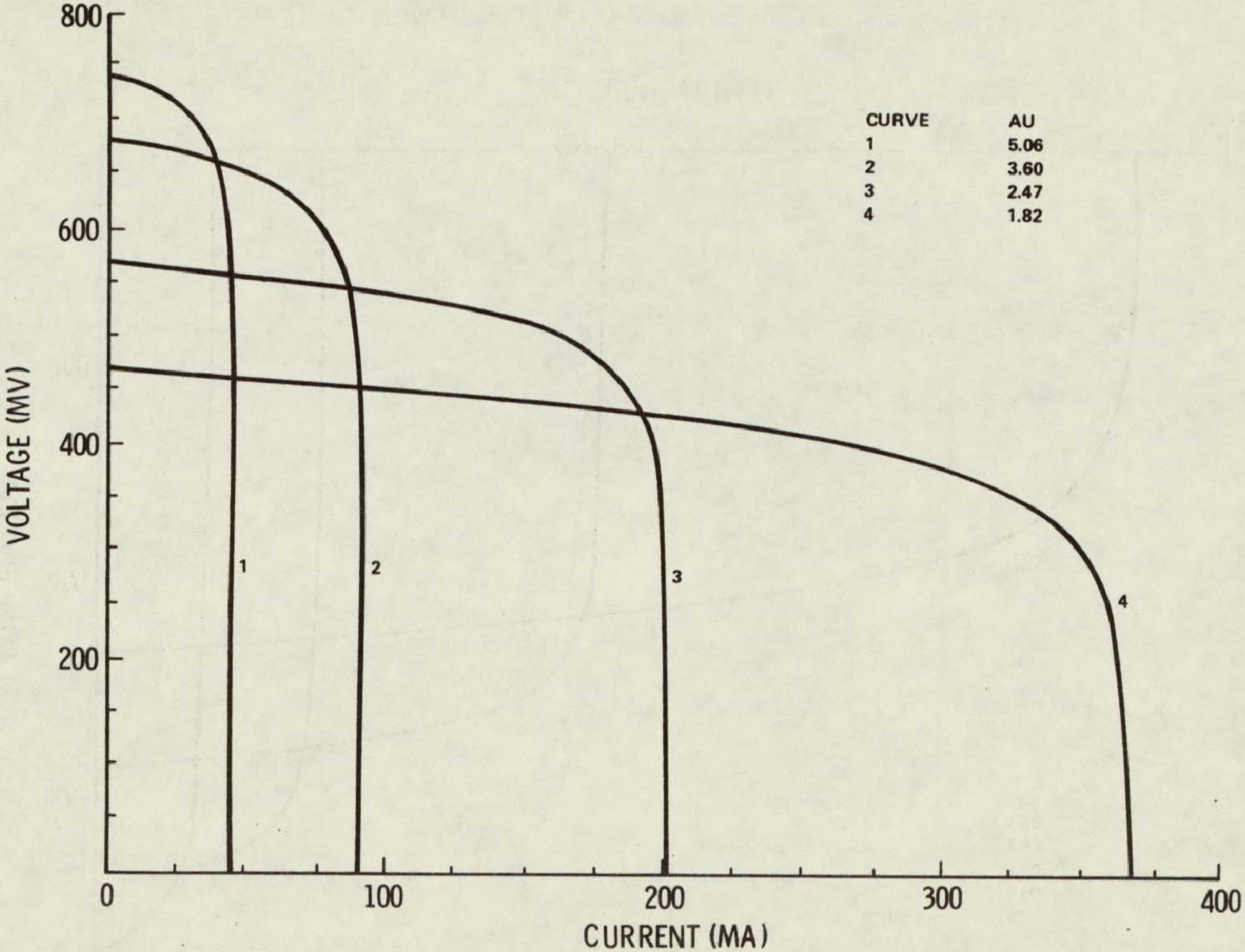


Figure B-7. Concentrated array performance (module 2, cell No. 5).

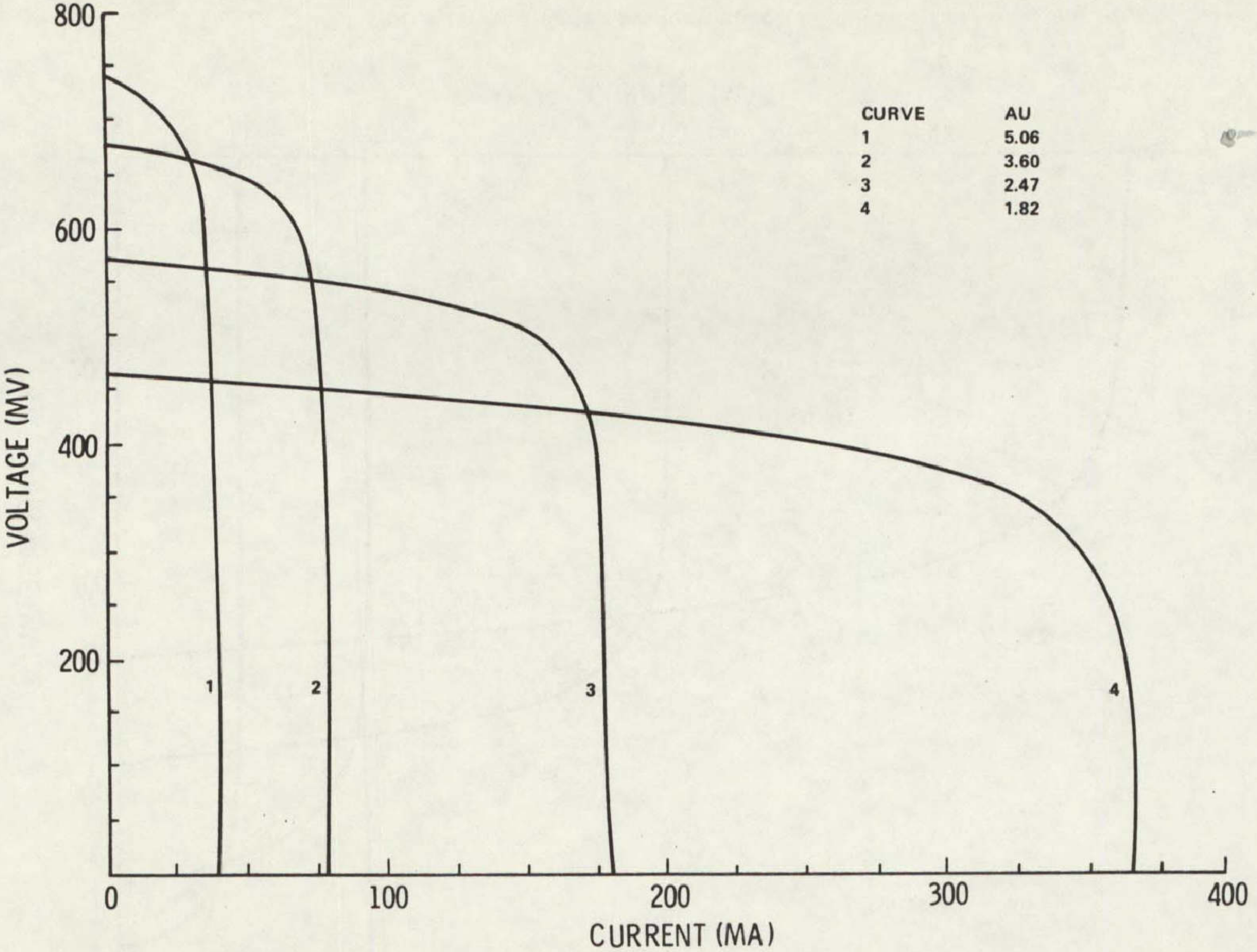


Figure B-8. Concentrated array performance (module 2, cell No. 8).

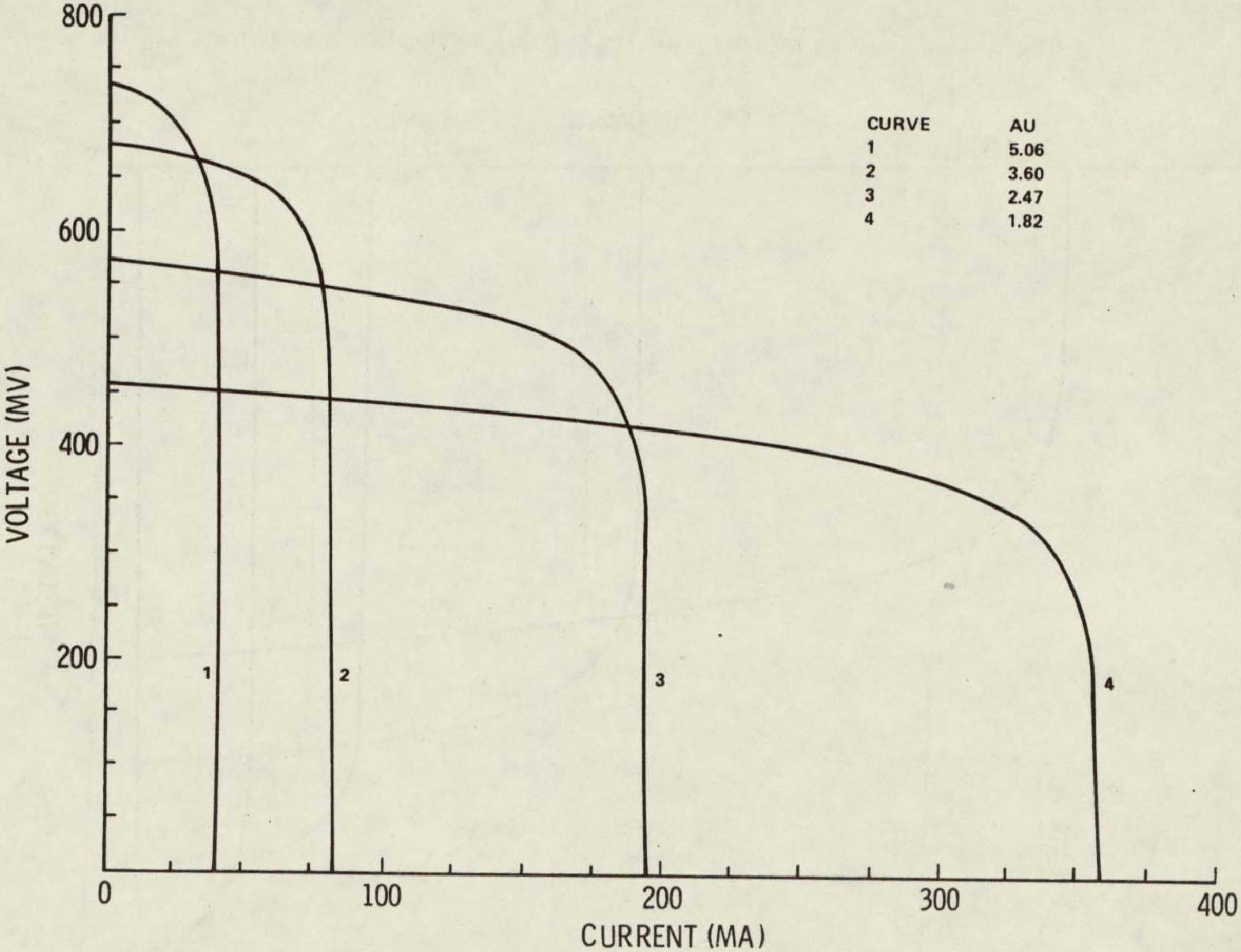


Figure B-9. Concentrated array performance (module 2, cell No. 11).

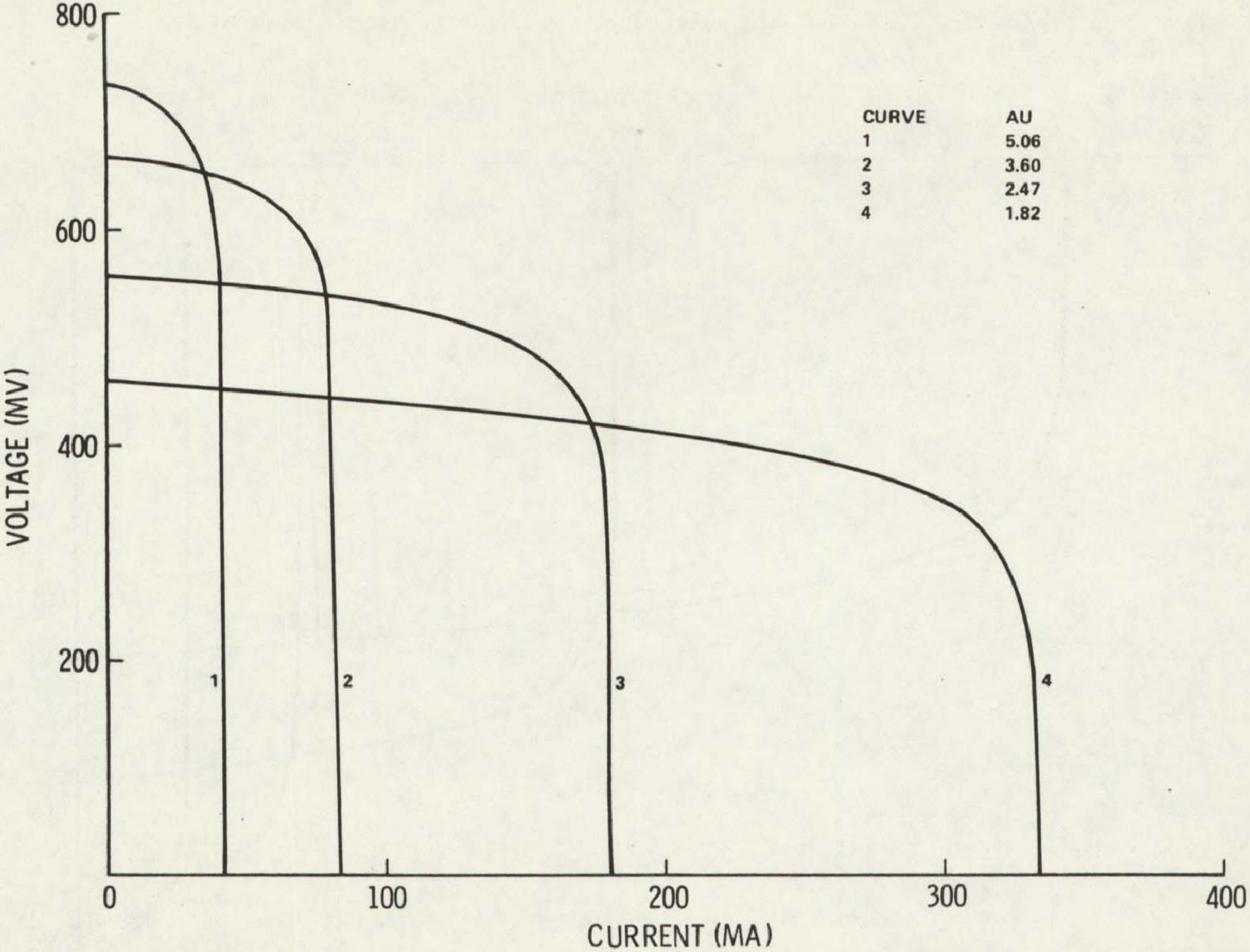


Figure B-10. Concentrated array performance (module 2, cell No. 12).

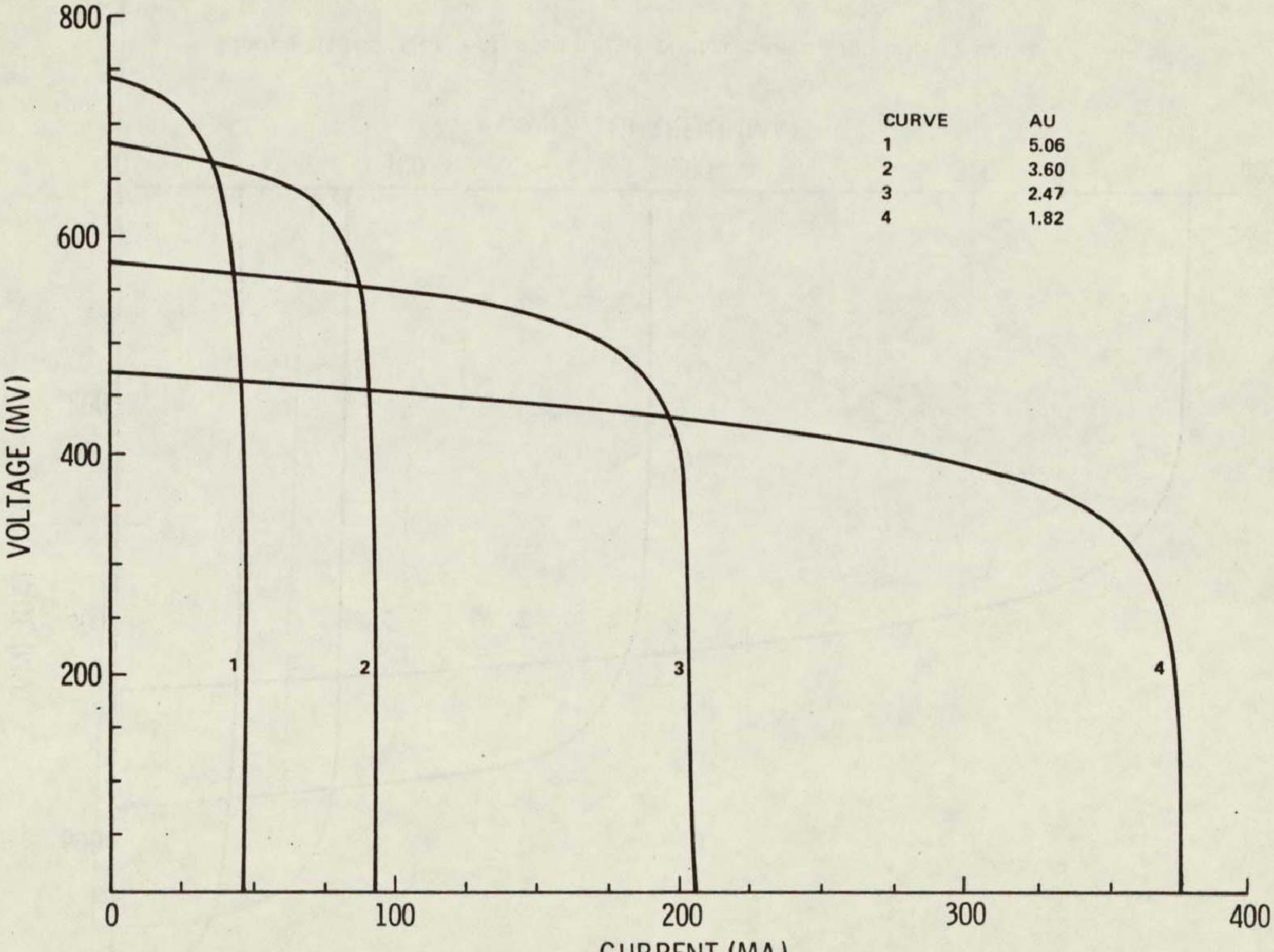


Figure B-11. Concentrated array performance (module 2, cell No. 13).

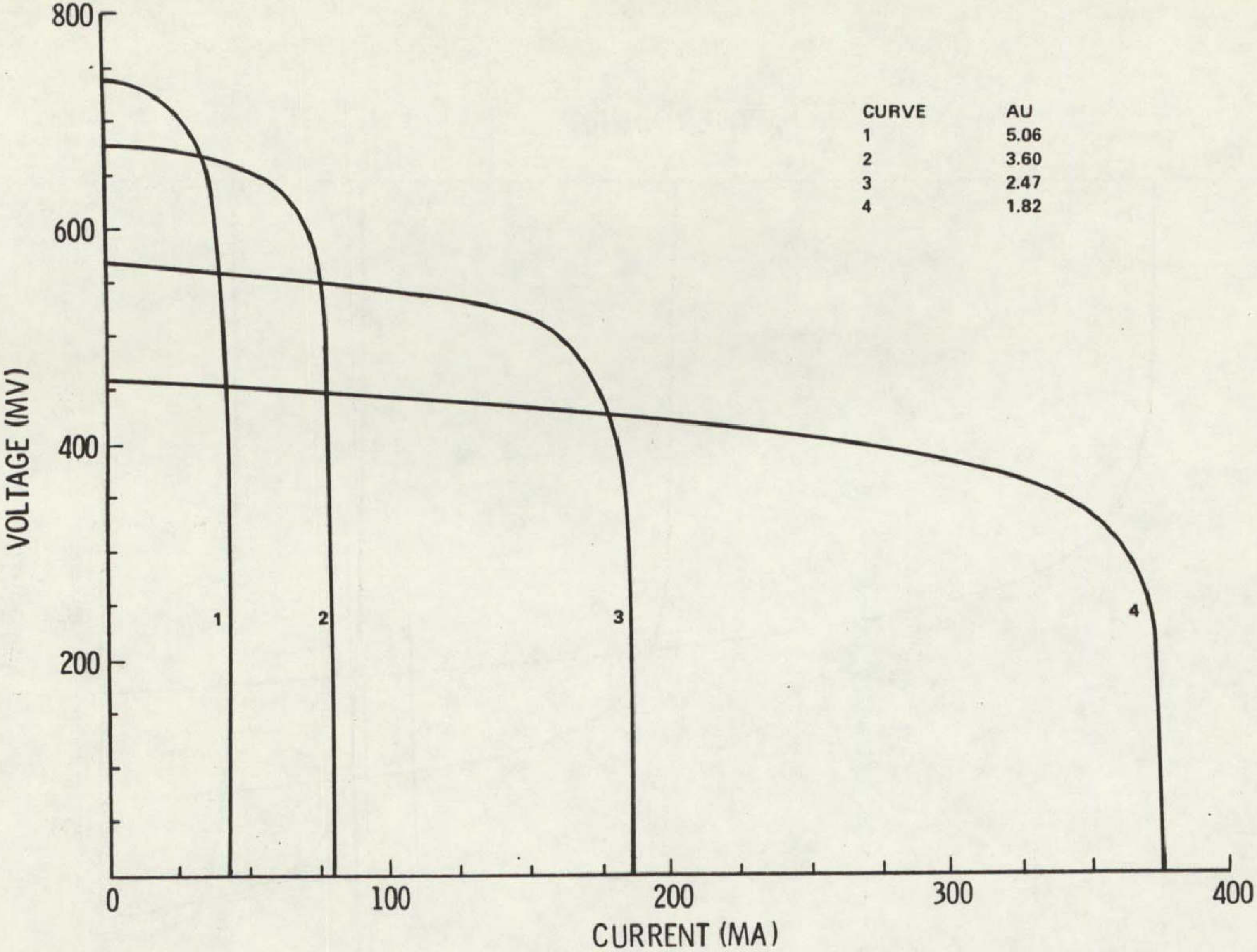


Figure B-12. Concentrated array performance (module 2, cell No. 15).

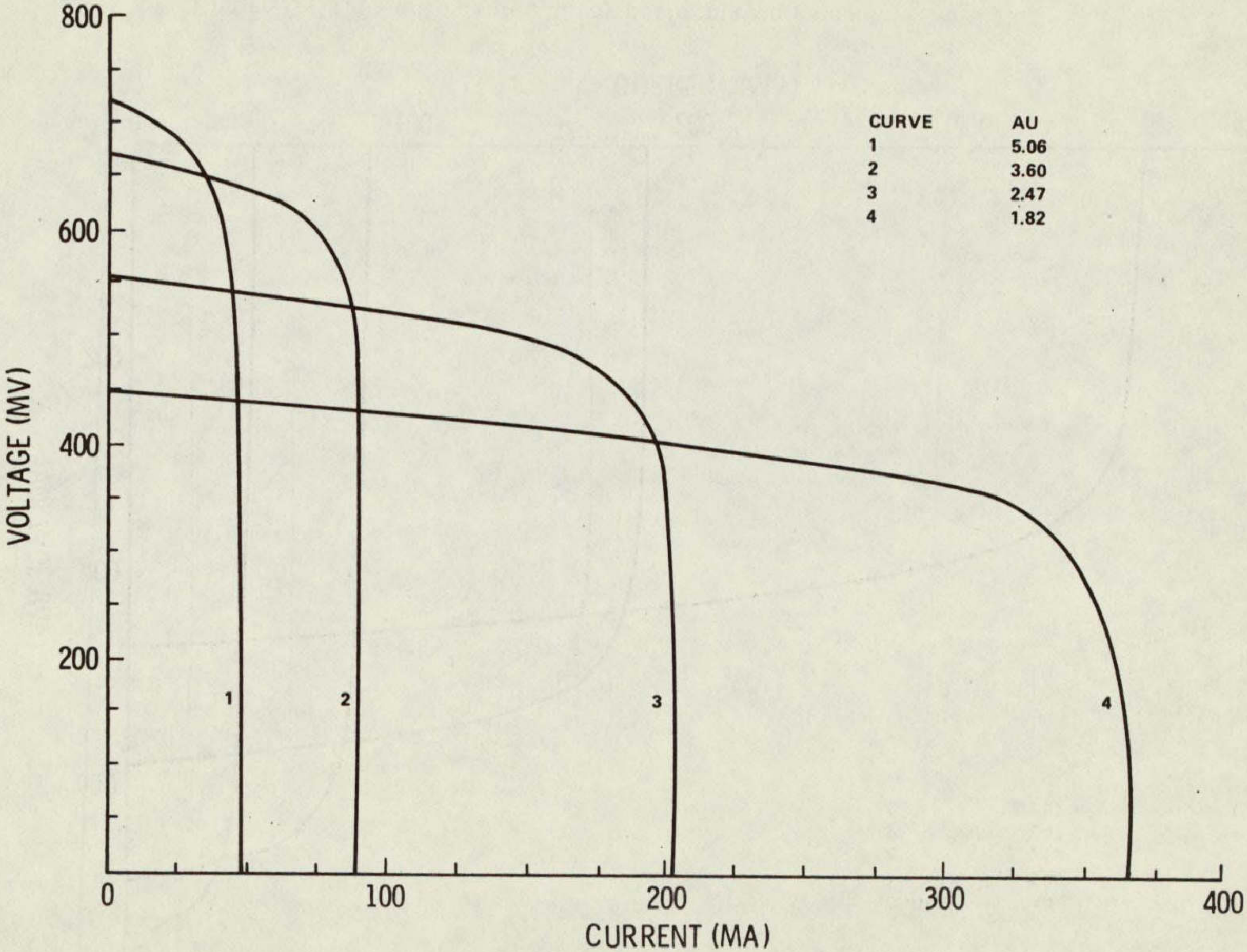


Figure B-13. Concentrated array performance (module 2, cell No. 17).

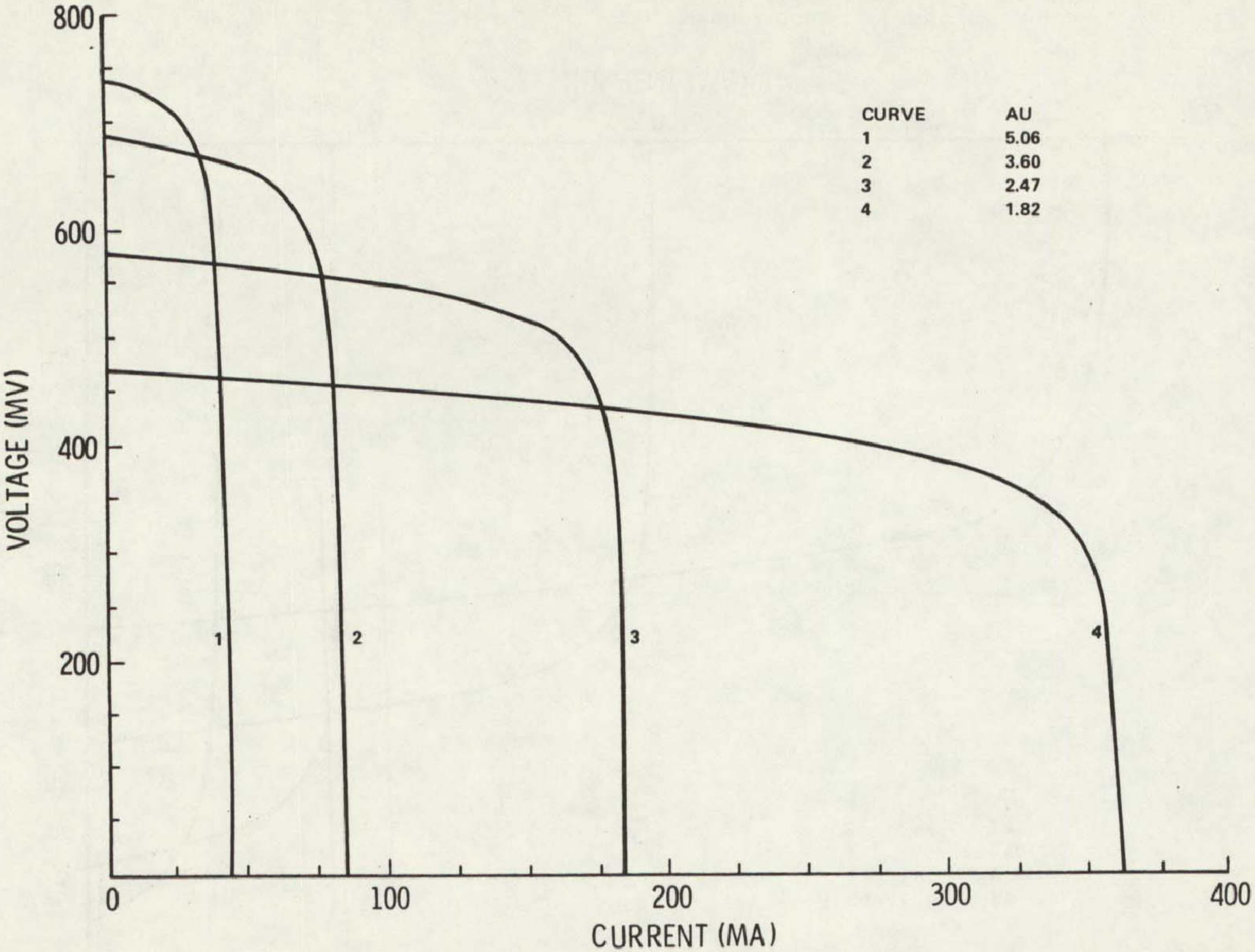


Figure B-14. Concentrated array performance (module 2, cell No. 18).

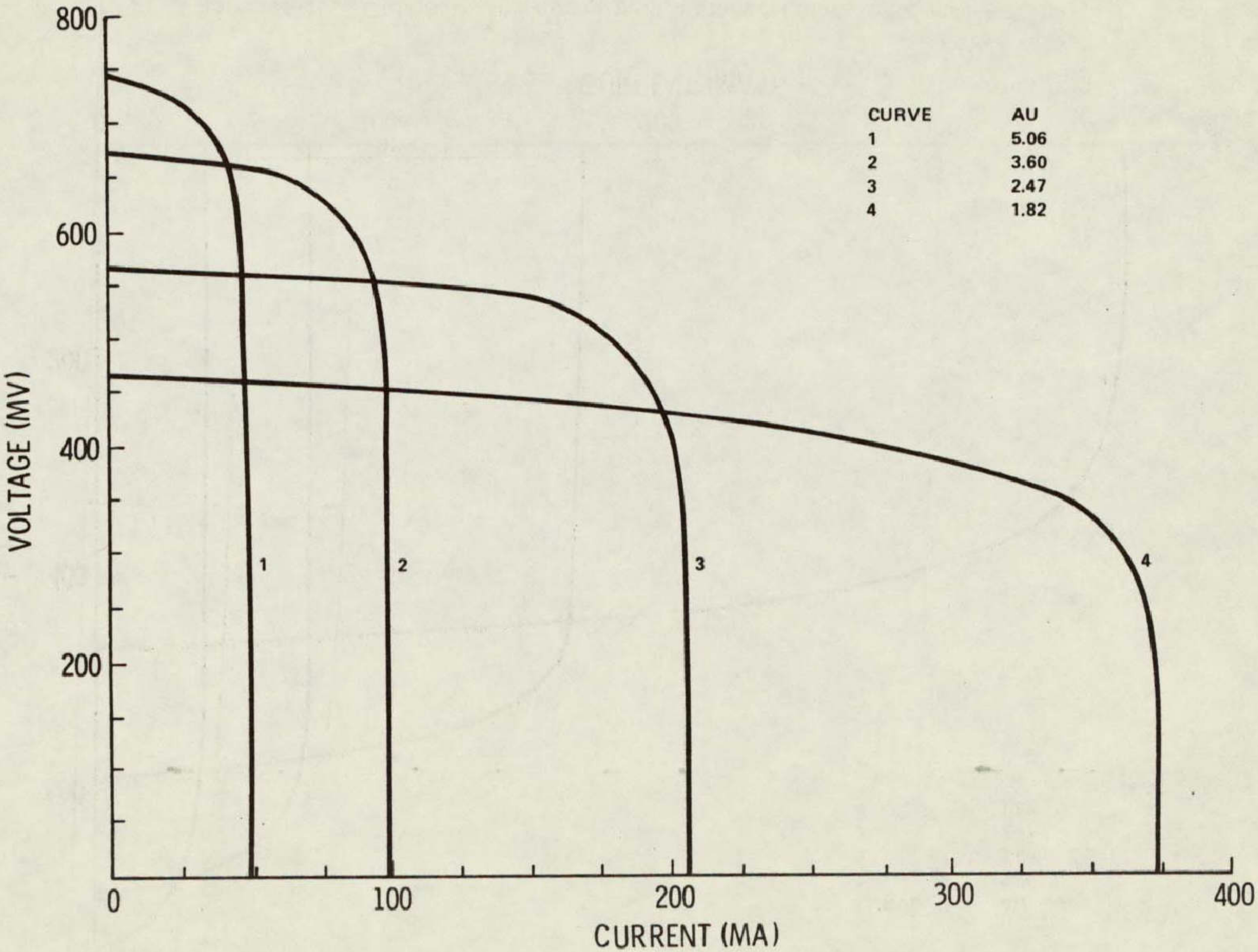


Figure B-15. Concentrated array performance (module 2, cell No. 19).

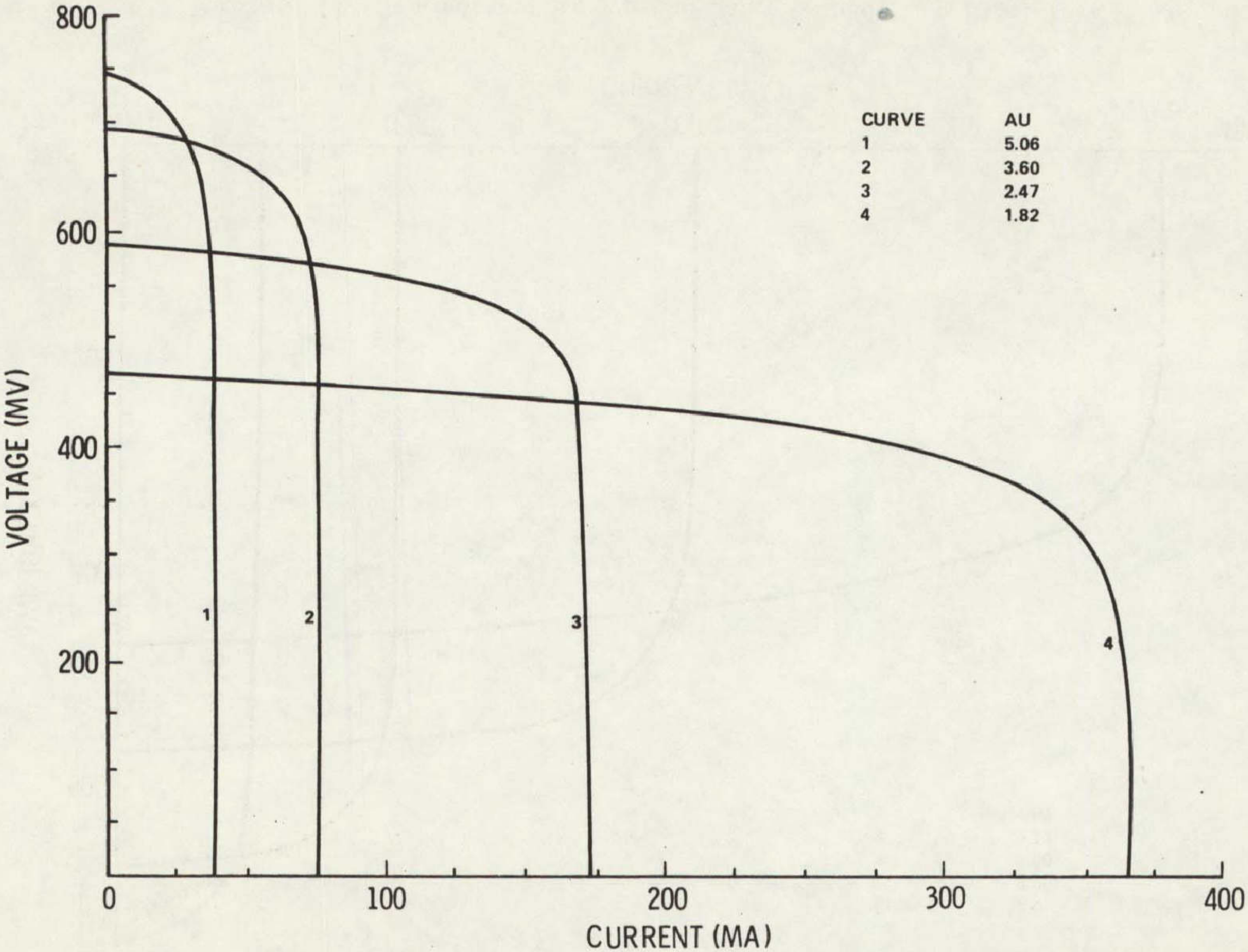


Figure B-16. Concentrated array performance (module 2, cell No. 20).

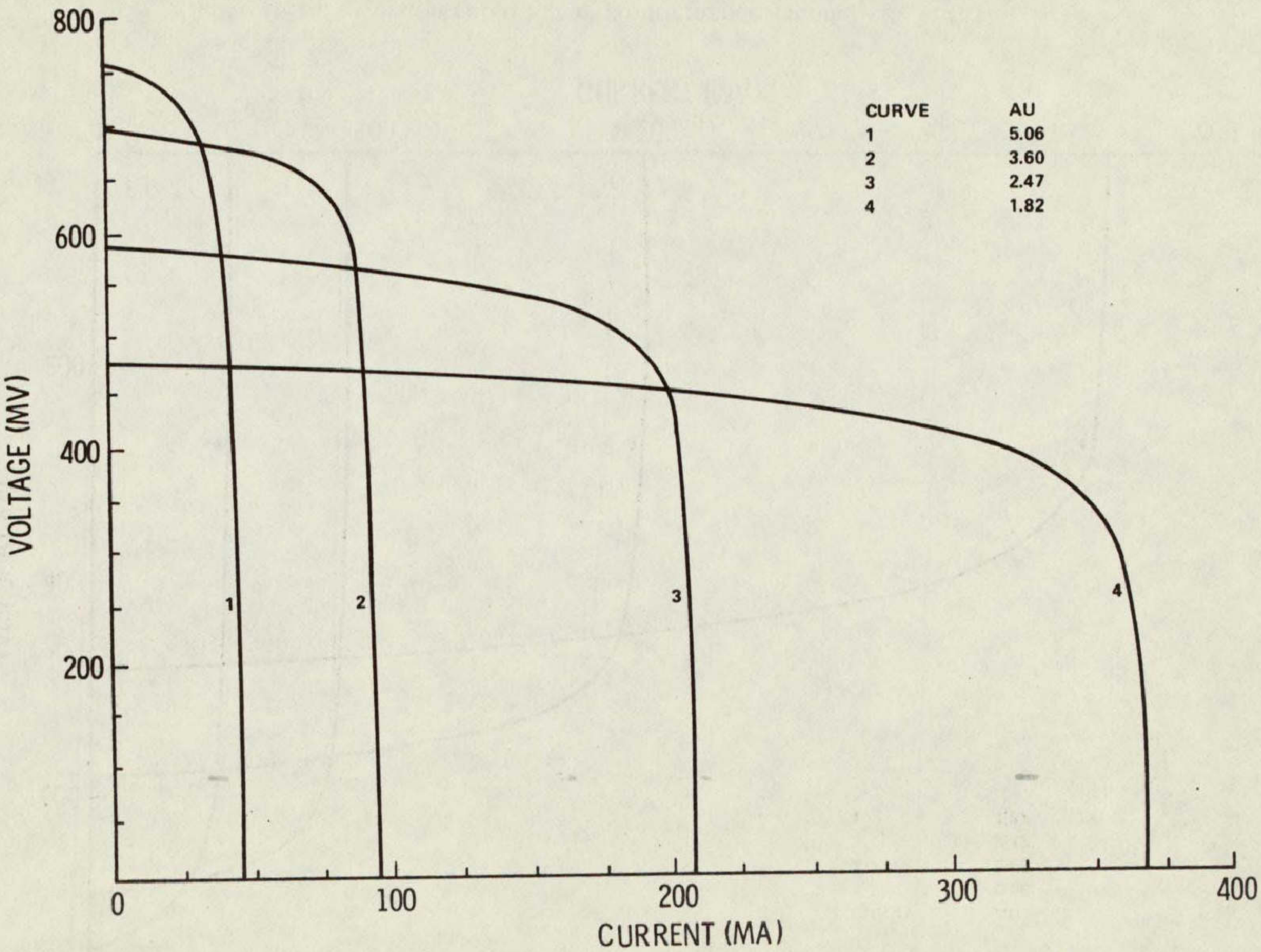


Figure B-17. Concentrated array performance (module 2, cell No. 21).

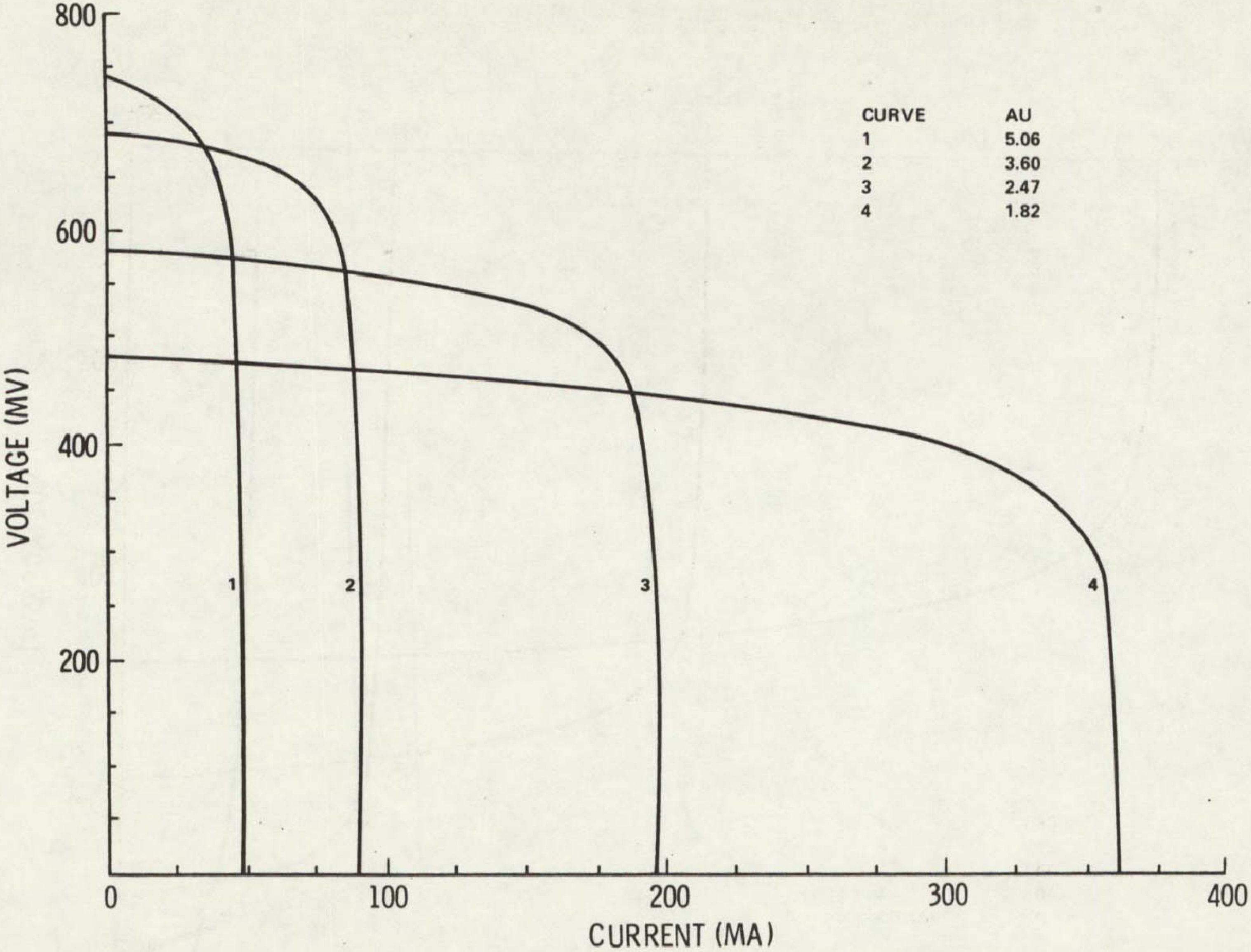


Figure B-18. Concentrated array performance (module 2, cell No. 27).

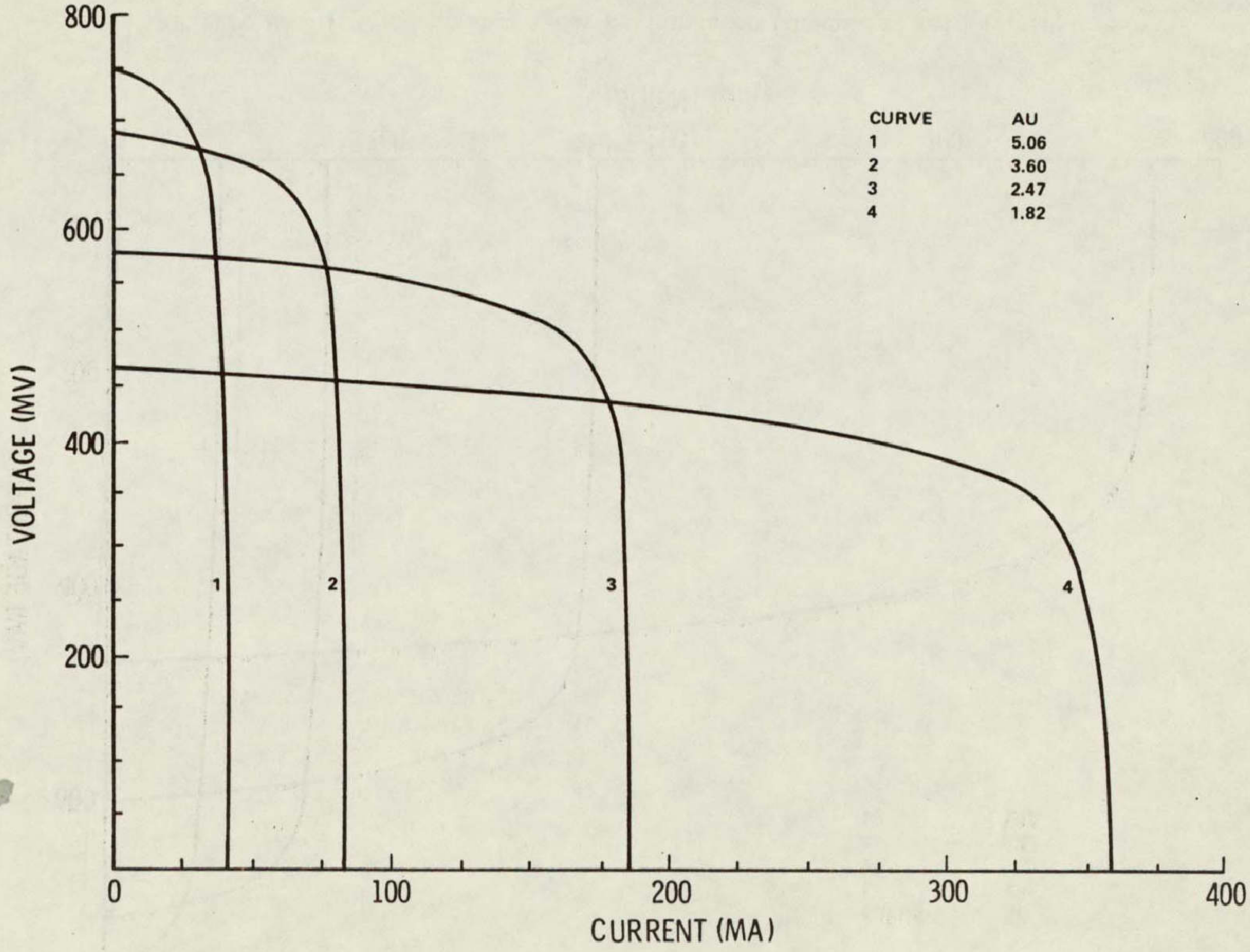


Figure B-19. Concentrated array performance (module 2, cell No. 28).

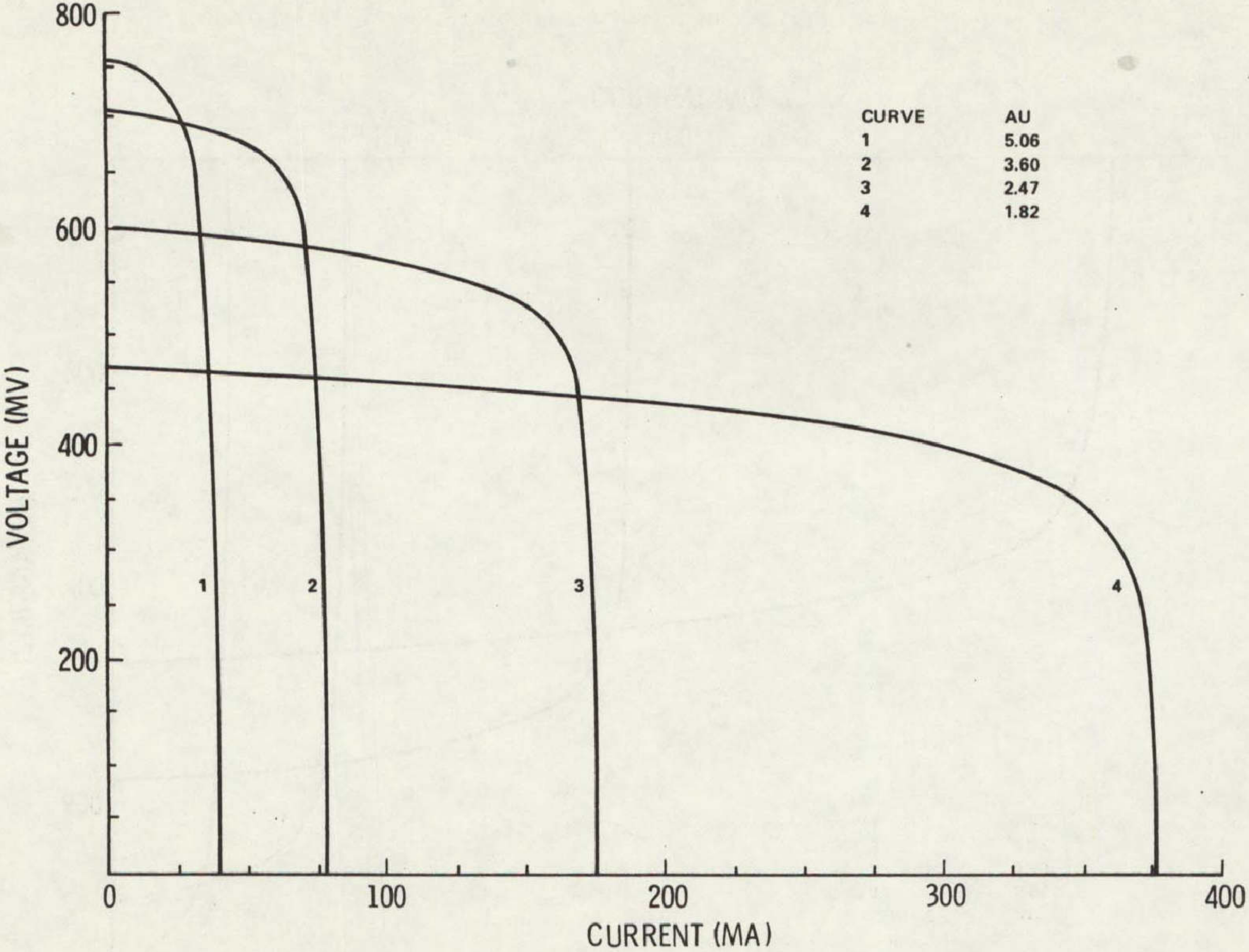


Figure B-20. Concentrated array performance (module 2, cell No. 29).

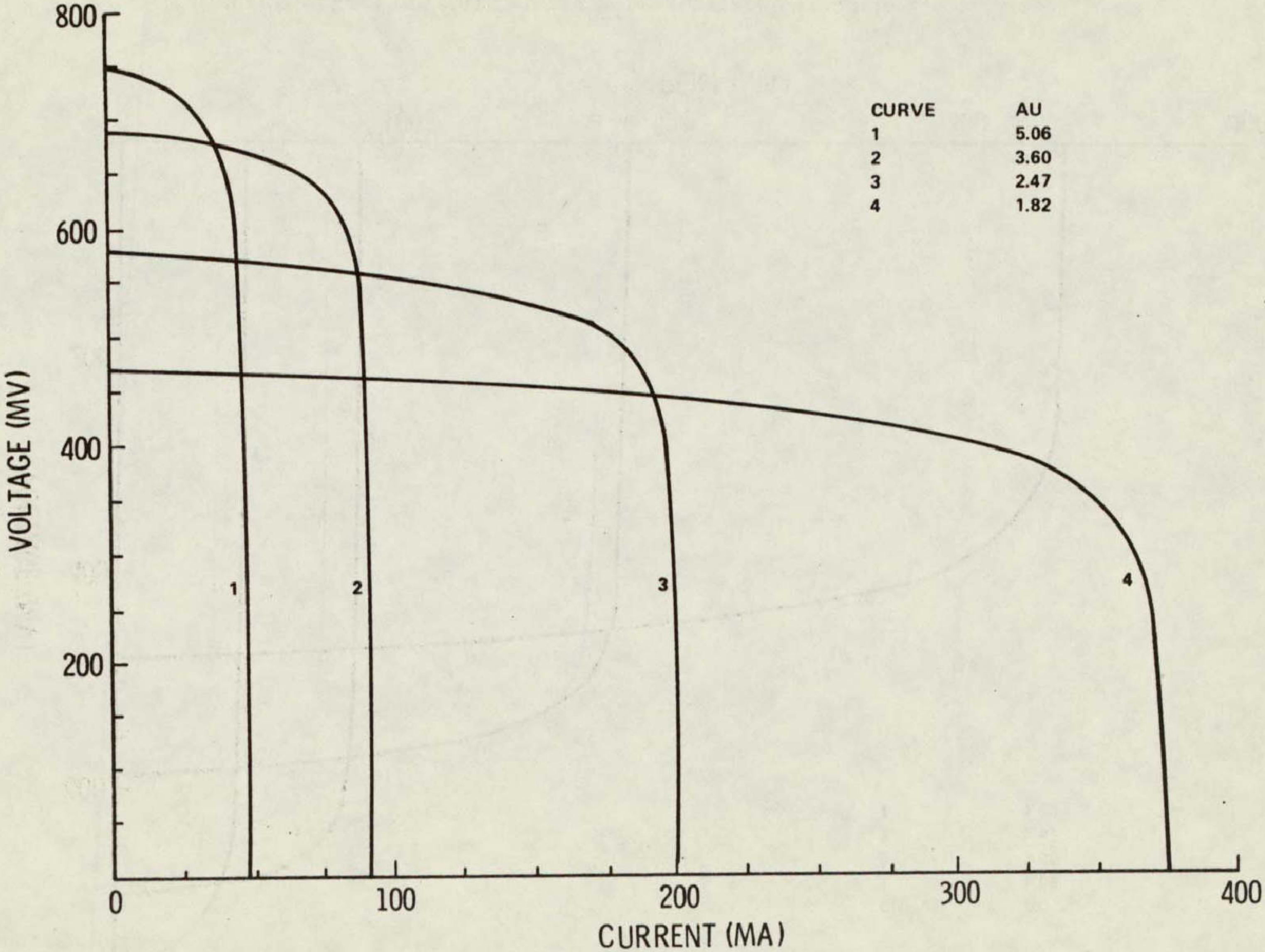


Figure B-21. Concentrated array performance (module 2, cell No. 30).

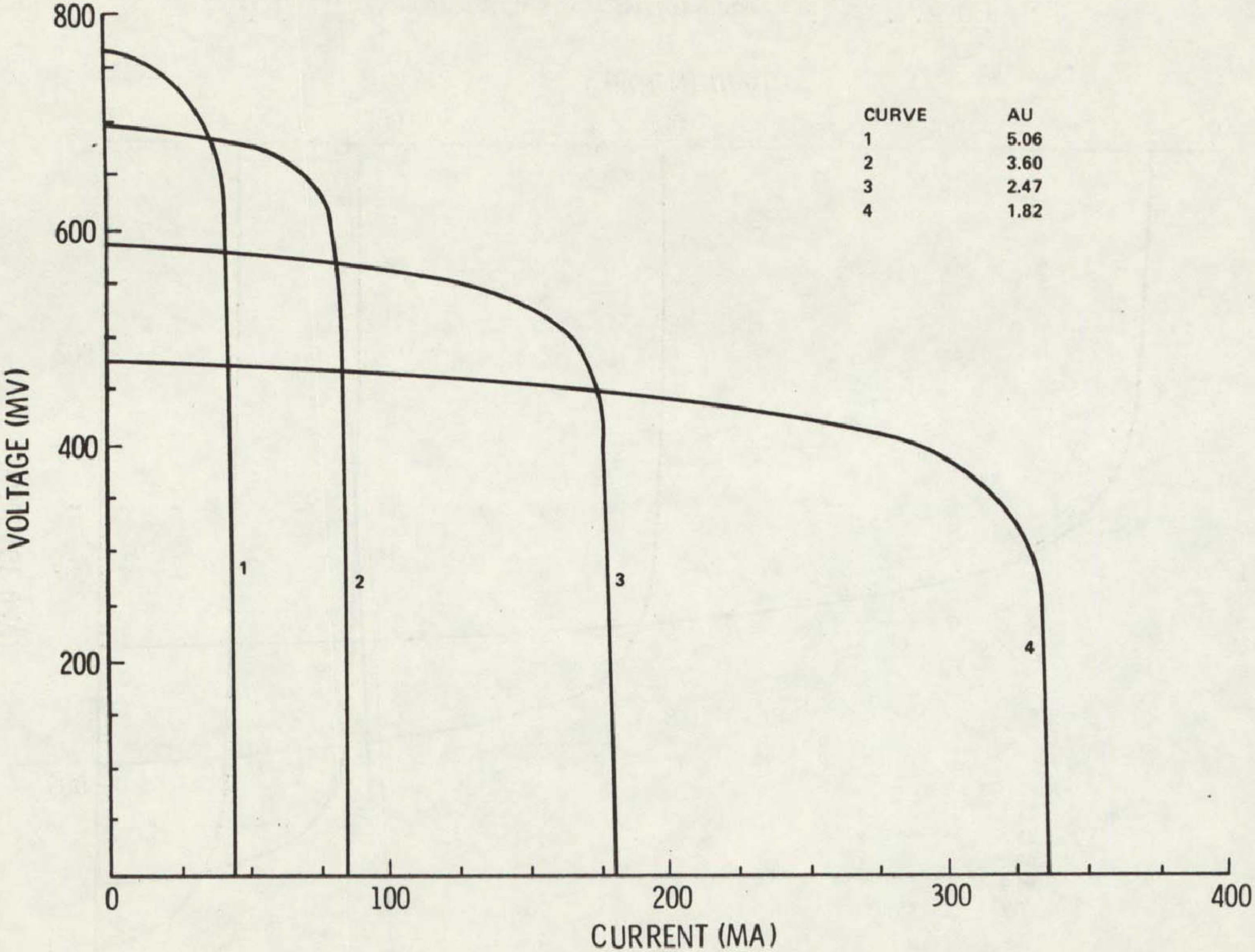


Figure B-22. Concentrated array performance (module 2, cell No. 31).

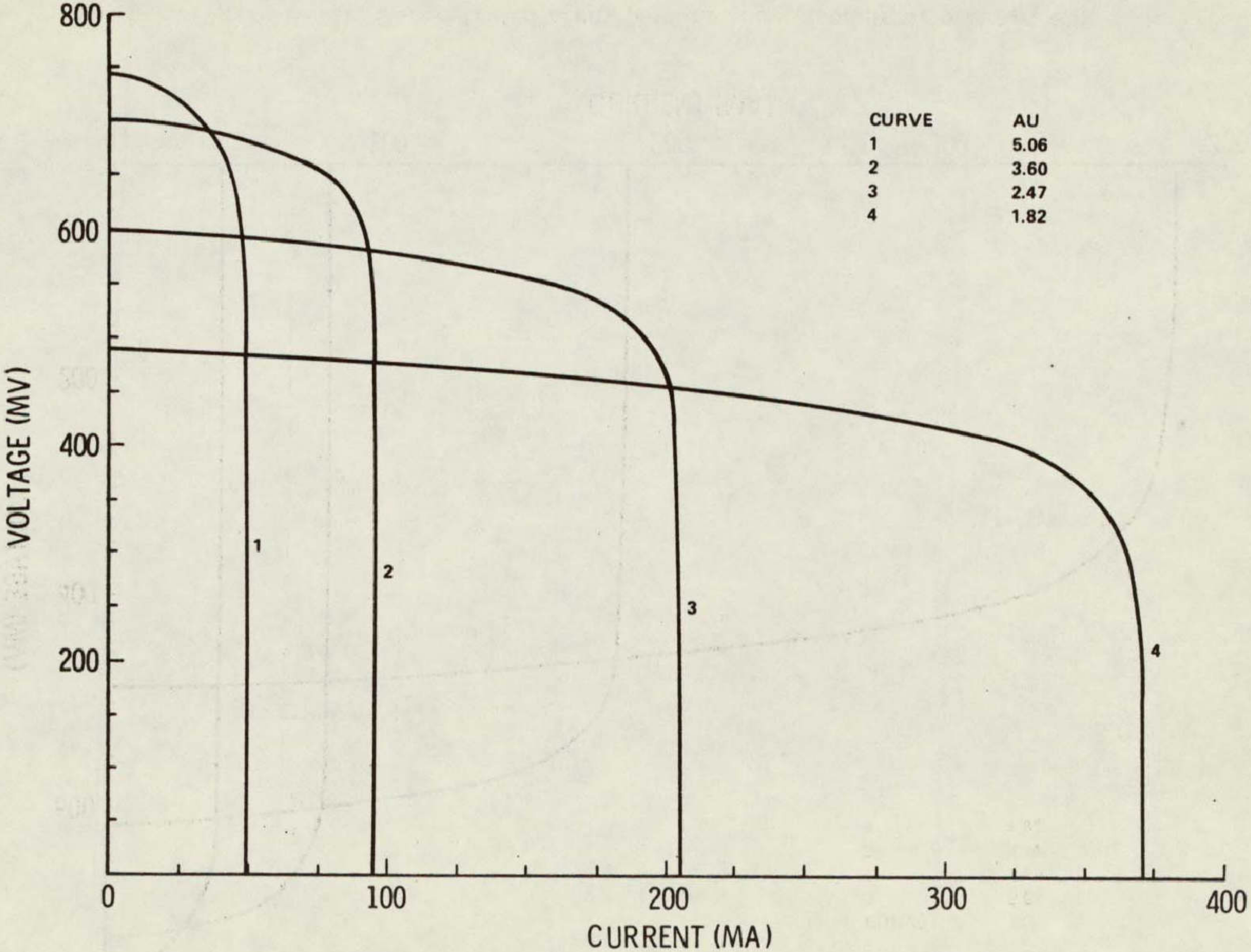


Figure B-23. Concentrated array performance (module 2, cell No. 32).

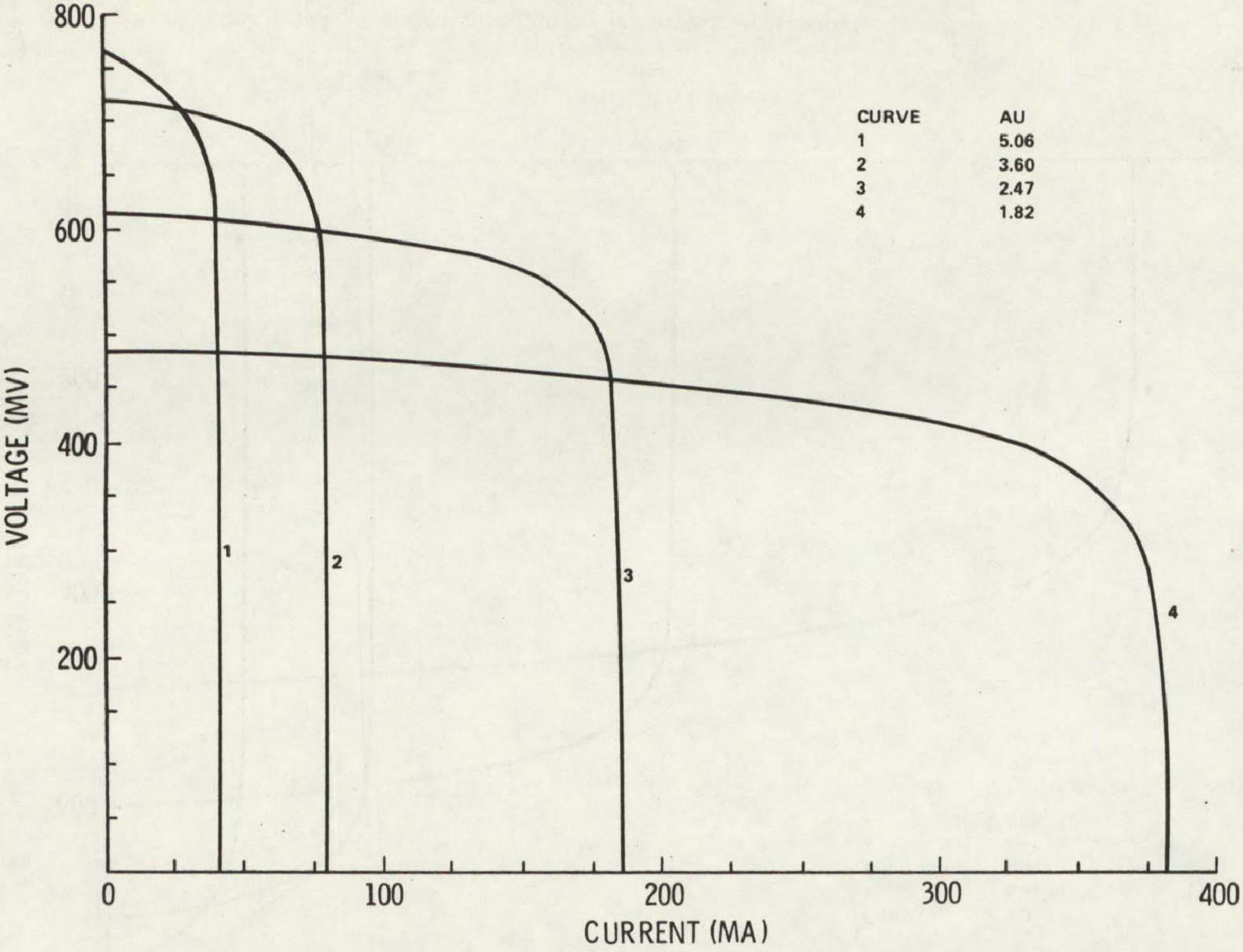


Figure B-24. Concentrated array performance (module 2, cell No. 33).

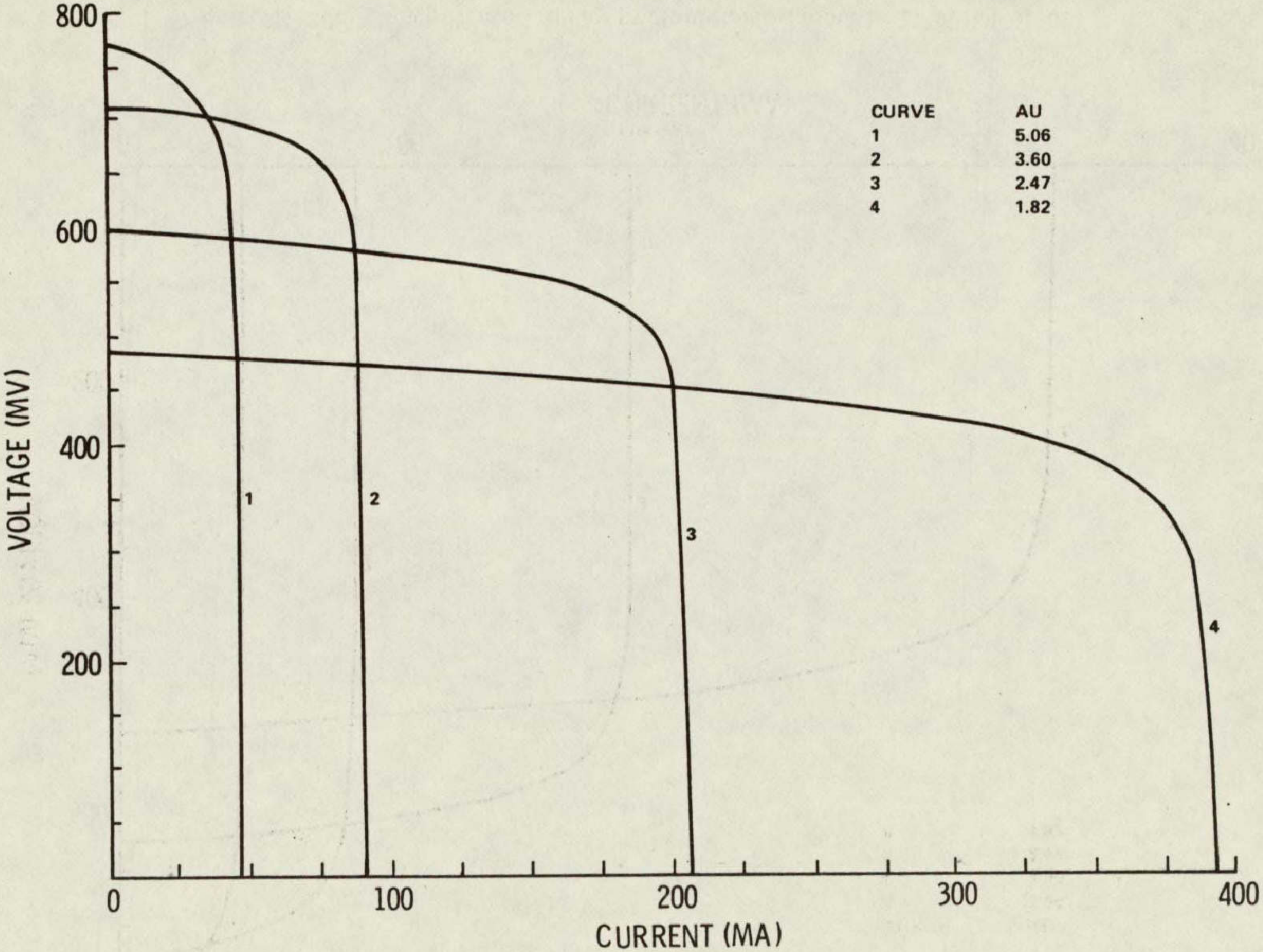


Figure B-25. Concentrated array performance (module 2, cell No. 61).

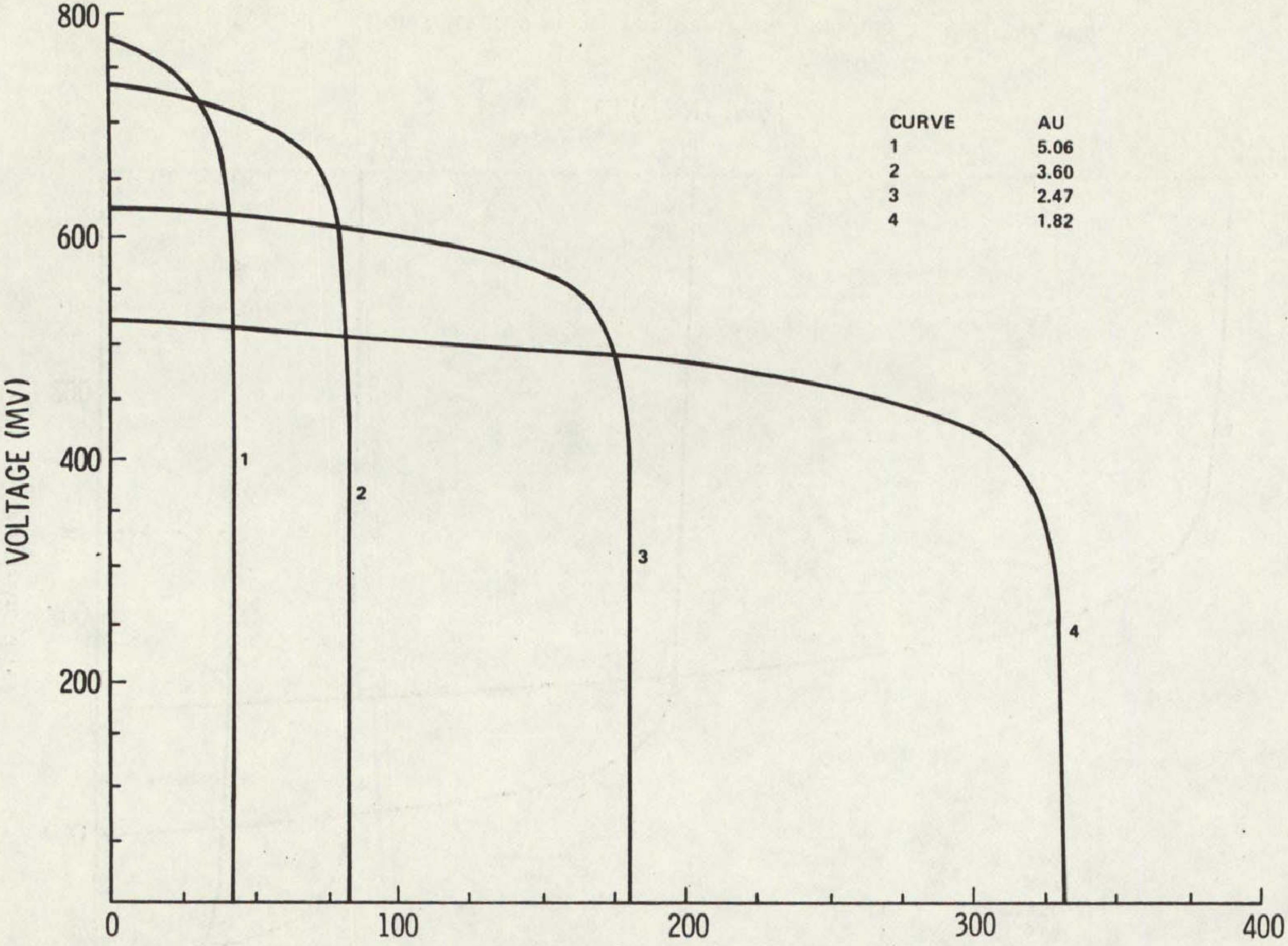


Figure B-26. Concentrated array performance (module 2, cell No. 62).

APPROVAL

TEST OF CONCENTRATOR SOLAR ARRAY MODEL FOR SEPS

By H. H. Huie

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

Charles R. Darwin

Charles R. Darwin
Director, Preliminary Design Office

James T. Murphy

James T. Murphy
Director, Program Development