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Ramond C. Waddel

April, 1967

Goddard Space Flight Center
Greenbelt, Md.

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PURPOSE

The purpose of this report is to make available early results from the Solar Cell Radiation Damage Experiment (SCRDE) carried aboard the spacecraft ATS-1, a synchronous satellite.

EXPERIMENT

The SCRD experiment involved the exposure and observation of thirty one-by-two centimeter solar cells, of various types and covered by various kinds of shields, as they suffered radiation damage after lift-off. The apparatus was such that, following a ground command, each cell was successively connected to one of eight load resistors. The maximum voltage developed across each load resistor (as the spacecraft spun on its axis) was entered in a 2176 bit magnetic memory. Auxiliary information concerning identification, angle of illumination, and time of observation was also entered. After the several minutes required to fill the memory it reverted to a mode in which its contents were presented, as 4 bit words, to a digital PFM telemetry transmitter. The full scale range of the telemetered signals was 765 mv. Pre-launch tests showed results to be accurate to plus or minus 2 mv. A self-contained calibrating source allowed in-flight checking of sensitivity to about 1 part in 200.

The information was recorded by a ground station. The primary data was computer corrected to mean earth-sun distance (140 mw per cm^2) and to illumination at zero degrees angle of incidence. The computer then printed the solar cell current, voltage, and power developed across each load resistor. Temperature corrections were not attempted.

The data allow the construction of voltage-current curves for each cell. The condition of each cell may then be evaluated on a basis of short circuit current, maximum power, power at a given voltage, open circuit voltage, or other criteria of interest.

The spacecraft apparatus used in this experiment is of some technical interest. Relatively complex, it embodied a 2176 bit magnetic core memory with associated address circuitry, an eight-bit analog-to-digital converter, program circuitry for energizing the 80 microminiature relays required for cell and load switching, a precision calibration voltage supply, a sensor for determining the instant the solar cells faced the sun most nearly perpendicularly, and a 7 bit solar aspect sensor for measuring the angle of incidence. The device weighed 5 pounds and required 5 watts of power. Integrated circuits and welded "cordwood" modules were widely used in fabrication of the device.

SOLAR CELLS

The solar cells under examination are listed in Table 1. They are all silicon cells, but have various base resistivities, dopants, shield materials, shield thicknesses, and filters, as shown in the Table.

Cells 1 and 2 have unfiltered sapphire shields which are mechanically supported above the cells without the use of an adhesive, a construction used on a Telstar solar cell experiment. These cells were aluminum doped and are of experimental nature.

The shields made of Corning type 7940 fused silica and Corning type 0211 glass were coated with blue reflecting filters with a 400 millimicron cut-off. They also have an SiO anti-reflective coating. Cells 15 and 16 had integral shields of Corning 7740 glass, with no adhesive or coating. They were applied by sintering at a high temperature. Adhesives, when used, were Dow Corning XR-634-88.

Cells 11 and 12 had a high dopant gradient in their bases. This, theoretically generates an internal electric "drift" field which assists the migration of carriers to minimize trapping by defect centers. The cells are experimental in nature.

It will be noted that there are, generally, two cells of each type. This is not a statistically significant number, but the results will show that the cells of a pair usually acted very similarly.

ORBIT

The early results here presented necessarily reflect the character of the orbit pursued by the spacecraft during the launch procedure. The lift-off was from Cape Kennedy at 1966 year, 341 day, 02 hour, 12 minute, 02 second, GMT. After attaining an altitude of 100 nautical miles the spacecraft was put into an elliptical orbit whose perigee was 100 nm and whose apogee was 19,300 nm (synchronous altitude). After executing one and one-half of these ellipses (and thrice going through the trapped radiation regions) it was put into synchronous orbit about 0.689 days after lift-off. Thereafter, the spacecraft drifted slowly toward its final station at about 150° West longitude, over the equator.

RESULTS

This preliminary report will cover results obtained through two sets of observations, recorded during the first 3.28 days after lift-off. They therefore show solar cell damage which was almost entirely associated with the launch ellipse. For those heavily shielded cells that presumably were undamaged the results show the full normal cell characteristics at air mass zero. Information concerning cell damage occurring after synchronous altitude was attained will be given in later reports.

The times at which observations were made are here expressed as if determined by an observer stationed at the Greenwich Meridian who ascertains the day number from a calendar which terms January one as day zero (not day one). The quantity to the right of the decimal point is the fraction of that day which has transpired. The quantity in parentheses is the last two figures of the year. This kind of time is called GMTM. It can be used numerically without confusion. In this time system the lift-off time given above is 340.0917(66), to an accuracy sufficient for this experiment.

Figures 1 to 30 show the results obtained from two early observations. Unfortunately, it was not possible to obtain a set of data at air mass zero before the possibility of radiation damage. The earliest set (such as Fig. 1) is for 340.1560(66) GMTM, which is 0.0643 days after lift-off. The spacecraft had passed through the radiation belts once. The next data (such as Fig. 2) was taken at 343.3749(66) GMTM, which is 3.2830 days after lift-off. The spacecraft had passed through the radiation belts three times and had been at synchronous altitude for about 2.6 days.

The excellent consistency of the data, as may be judged from the data points on the voltage-current graphs of Figs. 1 to 30, indicates that the data taking, storage, and processing were done with an accuracy close to that theoretically possible with the data system employed. In inspecting the curves (and the tabulated values) it must be kept in mind that these results have not been corrected to a constant temperature.

Physically, the cells were cemented to a 1/8 inch magnesium plate, 4 × 8 inches in size. The single thermistor, calibrated to about 1°C, was centrally attached to the rear of the plate. For angles of incidence of about 24 degrees or less the equilibrium temperature of the plate appears to have been about 25°C. Because of the influence of the mounting structure and adjacent experiments there probably is a temperature variation of several degrees across the damage panel carrying the cells.

DISCUSSION

No detailed analysis of these early results will be here attempted. The fundamental data of Figs. 1 to 30 and the tabulations in Table 2 will be allowed to speak for themselves.

Table 2 show some cell characteristics at the two times of observation, as read from the curves of Figs. 1 to 30. These curves were drawn as a visual average of the data for, generally, a pair of cells of like nature. The two cells of a pair usually gave very similar results. A puzzling exception occurs in the data of Fig. 29 which shows the response of cells 29 and 30 at 340.1560(66) days. While both cells had the same short circuit current and open circuit voltage there is a consistent difference at intermediate points, and a very significant difference in maximum power. Figure 30 shows that these two cells have almost identical characteristics 3.2 days later.

Numerical comparison of the cell responses may be made by consulting Table 2. This table identifies the cells, gives time of observation, the number of days after lift-off, the temperature, the short circuit current (I_{sc}),the open circuit voltage (V_{oc}), the maximum power (MAX. P), the curve factor (F = $I_{sc} \times V_{oc}$ /MAX. P), and the current available at 400 mv.

This table suggests that, within the uncertainty associated with the temperature difference in the two observations (nominally 3.7°C) and that associated with drawing an average curve through 8 pairs of data points, the bare cells (numbers 13, 14, 25, 26) obviously deteriorated because of their triple passage through the radiation belts and their 2.6 days residence at synchronous altitude. It will be noted that the unshielded 1 ohm-cm p-on-n cell 13 was superior to the bare 1 ohm-cm n-on-p cell 14 at 0.0643 days in orbit (1 trip through the belts) but lost this advantage at 3.283 days (3 passages) and later.

The damage to the unshielded cells was accompanied by a drop in curve factor F. This is in contrast with some 1 Mev laboratory electron damage results in which the curve factor is said to have increased with damage.

Cells 15 and 16, with 1 mil integral glass covers appear to have deteriorated slightly but significantly during this time of observation.

Cells with shields of 6 mils thickness, or greater, appear to have suffered no damage. The voltage-current curves for the boron doped 10 ohm-cm cells carrying shields of six mils or greater may be useful in that they show undamaged responses of these widely used cells at one sun, true air mass zero, and at a temperature of about 20°C. Some of these cells show a working efficiency (maximum power/280 mw) in excess of 10 percent.

The presumably undamaged cells show a negative temperature coefficient of open circuit voltage of a few mv per degree Centigrade, and small positive coefficients for short circuit current and maximum power.

CONCLUSIONS

The very early results from the solar cell radiation damage experiment covered by the spacecraft ATS-1 show that significant damage to some cells, presumably from the electrons and protons in the Van Allen belts, occurred during the launch of this synchronous satellite. This procedure involved three near equatorial passages through the belts. Cells with 1 mil covers deteriorated slightly. Cells with thicker shields were apparently undamaged.

Comparison of the results from 1 ohm-cm p-on-n cells, 1 ohm-cm n-on-p cells, and modern 10 ohm-cm n-on-p cells confirms the very great improvement in solar cell radiation damage resistance that has been achieved since the launch of Vanguard I in 1958.

Later reports will show the radiation damage suffered by the 30 test cells at their synchronous altitude of 19,300 miles. Such damage is of great significance in the design of solar cell power supplies for long-lived communications and military spacecraft.

ACKNOWLEDGMENTS

The author wishes to gratefully acknowledge the assistance given him in connection with this experiment. First, he wishes to acknowledge the patient, skilled and long suffering efforts of Clarence B. House in procuring, testing, and adjusting the memory section of the apparatus, as well as help in other matters, always cheerfully extended. To Roland Van Allen goes thanks for his help in scheduling and budgeting, as well as for his efforts in integrating the experiment with the spacecraft. To check the operation of the rather sophisticated circuitry employed in the experiment John Wolfgang devised techniques, designed instruments, and provided hardware that proved essential in the protracted trouble-shooting that was encountered. Luther Slifer and Ralph Sullivan aided in selection, testing and mounting the solar cells. In satisfying the apparently insurmountable restrictions on size and weight the advice and skill of J. Perry is gratefully acknowledged. Thanks are due Andrew B. Malinowski for the design of the 8 bit analog-to-digital converter, which operates near the theoretical limit. Everett J. Pyle, Jr., helped secure the solar aspect sensor and associated circuitry. The data reduction computer program was generated under the capable direction of Joseph B. Bourne.

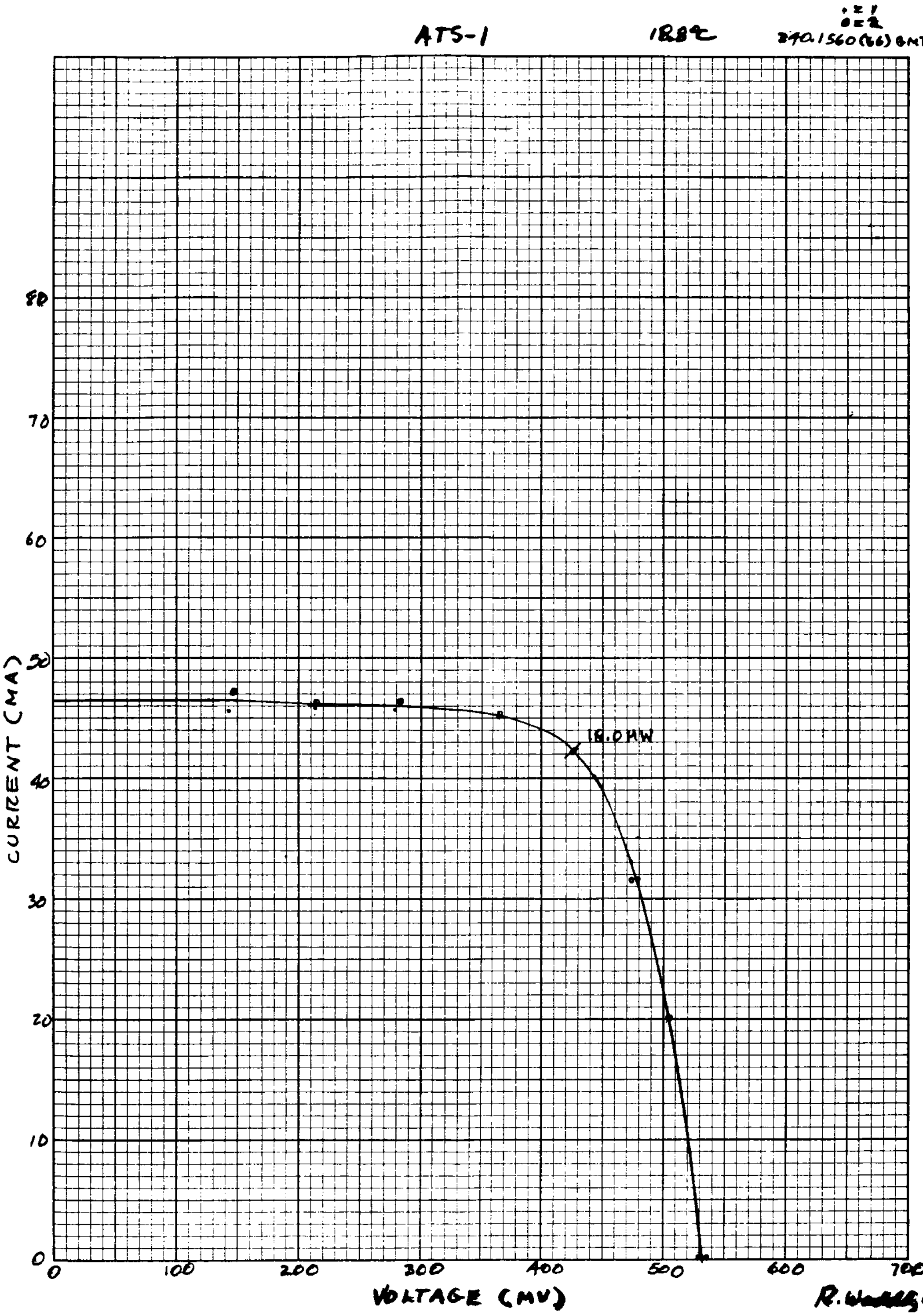
The ATS Project Office, under Robert J. Darcey, cooperated in an understanding manner where difficulties were encountered. To all of these, and others, the author extends his thanks.

Table 1
Solar Cell Description, ATS-1 SCRDE

Solar Cell Number	Type	Base Resistivity ohm-cm	Dopant	Shield Material	Shield Thickness mils
1, 2	n/p	10	Al	Sapphire	30
3, 4	n/p	13	B	7940 Silica	6
5, 6	n/p	10	B	7940 Silica	6
7, 8	n/p	7	B	7940 Silica	6
9, 10	n/p	3	B	7940 Silica	6
11, 12	n/p	Graded	B	7940 Silica	6
13	p/n	1	P	None	0
14	n/p	1	B	None	0
15, 16	n/p	10	B	7740 Glass	1
17, 18	n/p	10	B	0211 Glass	6
19, 20	n/p	10	B	7940 Silica	60
21, 22	n/p	10	B	7940 Silica	30
23, 24	n/p	10	B	7940 Silica	15
25, 26	n/p	10	B	None	0
27, 28	n/p	10	Al	7940 Silica	30
29, 30	n/p	10	Al	7940 Silica	6

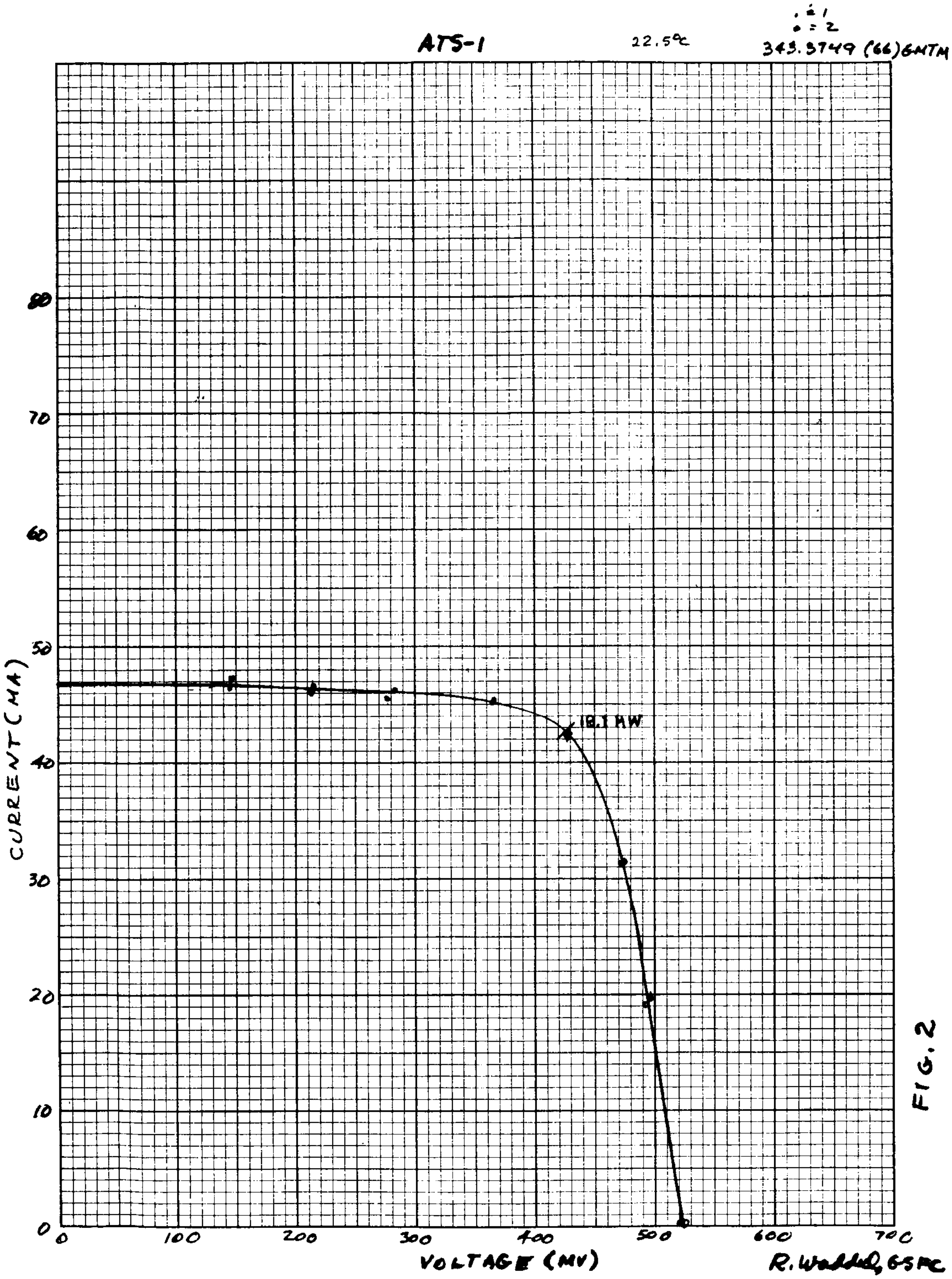
Table 2
Cell Characteristics versus Time – ATS-1 SCRDE

Cell No.	Time, GMTM	Time After Lift-Off Days	Temp, °C	I_{sc}, MA	V_{oc}, MV	Max. P, MW	Curve Factor, F	I AT 400 MV, MA	Fig. No.
1,2	340.1560	0.0643	18.8	46.4	531	18.0	0.730	44.0	1
3,4	340.1560	0.0643	18.8	63.4	554	24.6	0.701	59.7	3
5,6	340.1560	0.0643	18.8	67.5	567	27.7	0.723	65.2	5
7,8	340.1560	0.0643	18.8	62.7	573	26.0	0.723	60.4	7
9,10	340.1560	0.0643	18.8	62.4	586	26.0	0.712	58.8	9
11,12	340.1560	0.0643	18.8	55.5	600	24.1	0.724	54.0	11
13	340.1560	0.0643	18.8	58.7	563	21.6	0.653	52.9	13
14	340.1560	0.0643	18.8	53.7	569	19.8	0.648	49.4	13
15,16	340.1560	0.0643	18.8	62.0	554	25.2	0.734	59.8	15
17,18	340.1560	0.0643	18.8	66.4	575	27.8	0.729	65.1	17
19,20	340.1560	0.0643	18.8	68.0	576	28.6	0.730	66.5	19
21,22	340.1560	0.0643	18.8	68.4	570	28.8	0.738	67.1	21
23,24	340.1560	0.0643	18.8	67.0	572	28.2	0.736	65.3	23
25,26	340.1560	0.0643	18.8	69.5	559	27.8	0.716	67.3	25
27,28	340.1560	0.0643	18.8	66.9	570	27.2	0.700	64.0	27
29	340.1560	0.0643	18.8	64.0	568	26.1	0.719	61.7	29
1,2	343.3749	3.2832	22.5	46.8	522	18.1	0.742	44.2	2
3,4	343.3749	3.2832	22.5	63.8	547	25.0	0.717	60.4	4
5,6	343.3749	3.2832	22.5	67.0	565	28.1	0.742	65.4	6
7,8	343.3749	3.2832	22.5	62.4	566	26.2	0.742	60.6	8
9,10	343.3749	3.2832	22.5	62.4	580	25.8	0.714	59.3	10
11,12	343.3749	3.2832	22.5	55.9	597	24.4	0.732	54.8	12
13	343.3749	3.2832	22.5	21.9	435	5.9	0.618	9.2	14
14	343.3749	3.2832	22.5	40.0	474	12.1	0.638	26.8	14
15,16	343.3749	3.2832	22.5	60.9	545	24.7	0.744	58.9	16
17,18	343.3749	3.2832	22.5	67.2	567	28.5	0.748	65.4	18
19,20	343.3749	3.2832	22.5	68.5	570	28.3	0.725	66.5	20
21,22	343.3749	3.2832	22.5	68.9	565	28.6	0.735	66.6	22
23,24	343,3749	3.2832	22.5	67.6	575	28.3	0.728	65.8	24
25,26	343.3749	3.2832	22.5	60.2	431	17.2	0.664	22.4	26
27,28	343.3749	3.2832	22.5	67.5	561	27.2	0.719	64.2	28
29,30	343.3749	3.2832	22.5	63.0	557	25.8	0.735	61.6	30



ATS-1
18.0MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700

FIG. 1



ATS-1
22.5°C
• = 1
• = 2
343.3749 (66) GMTM
CURRENT (MA)
VOLTAGE (MV)
18.1 MW
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 2

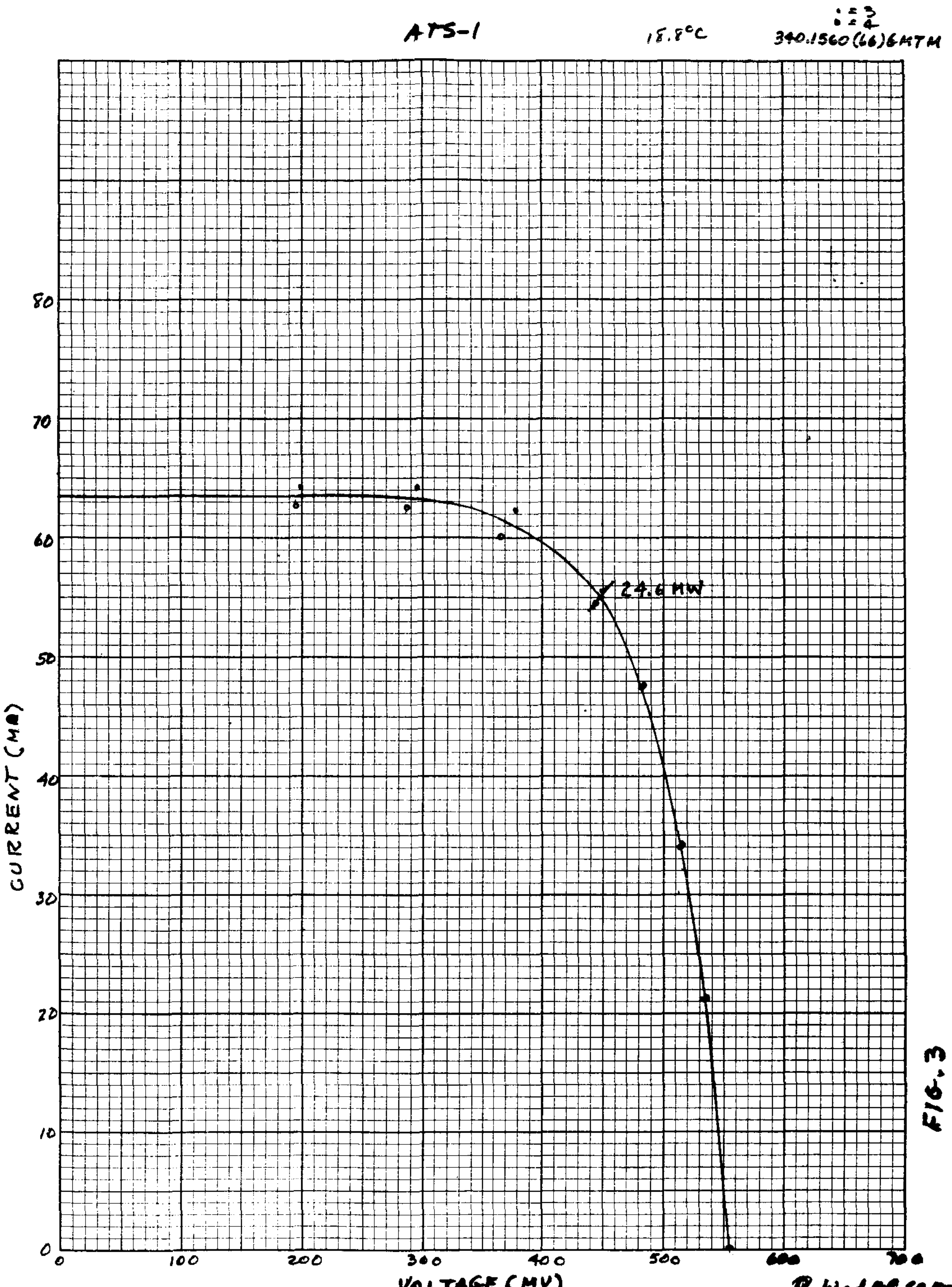
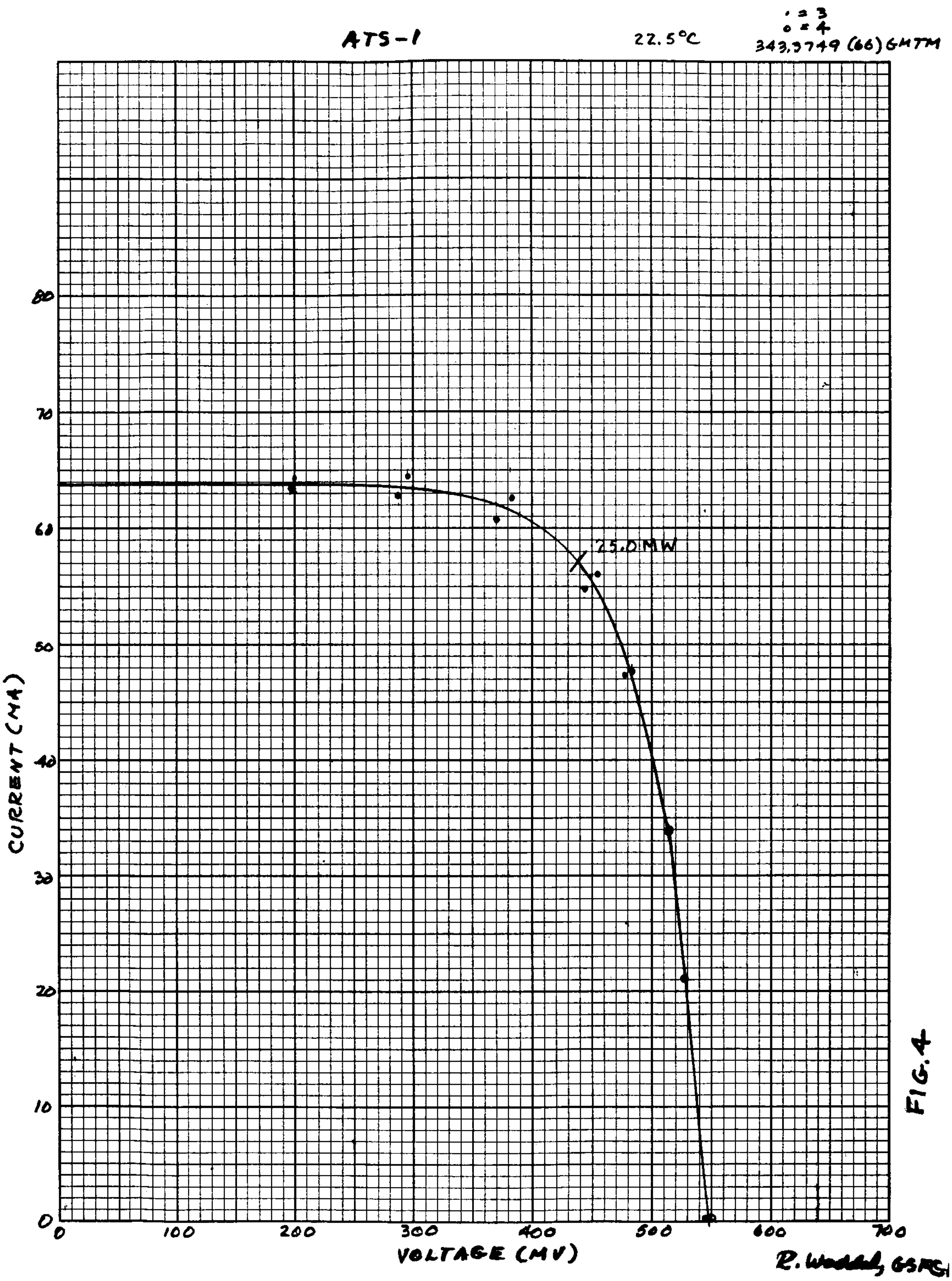


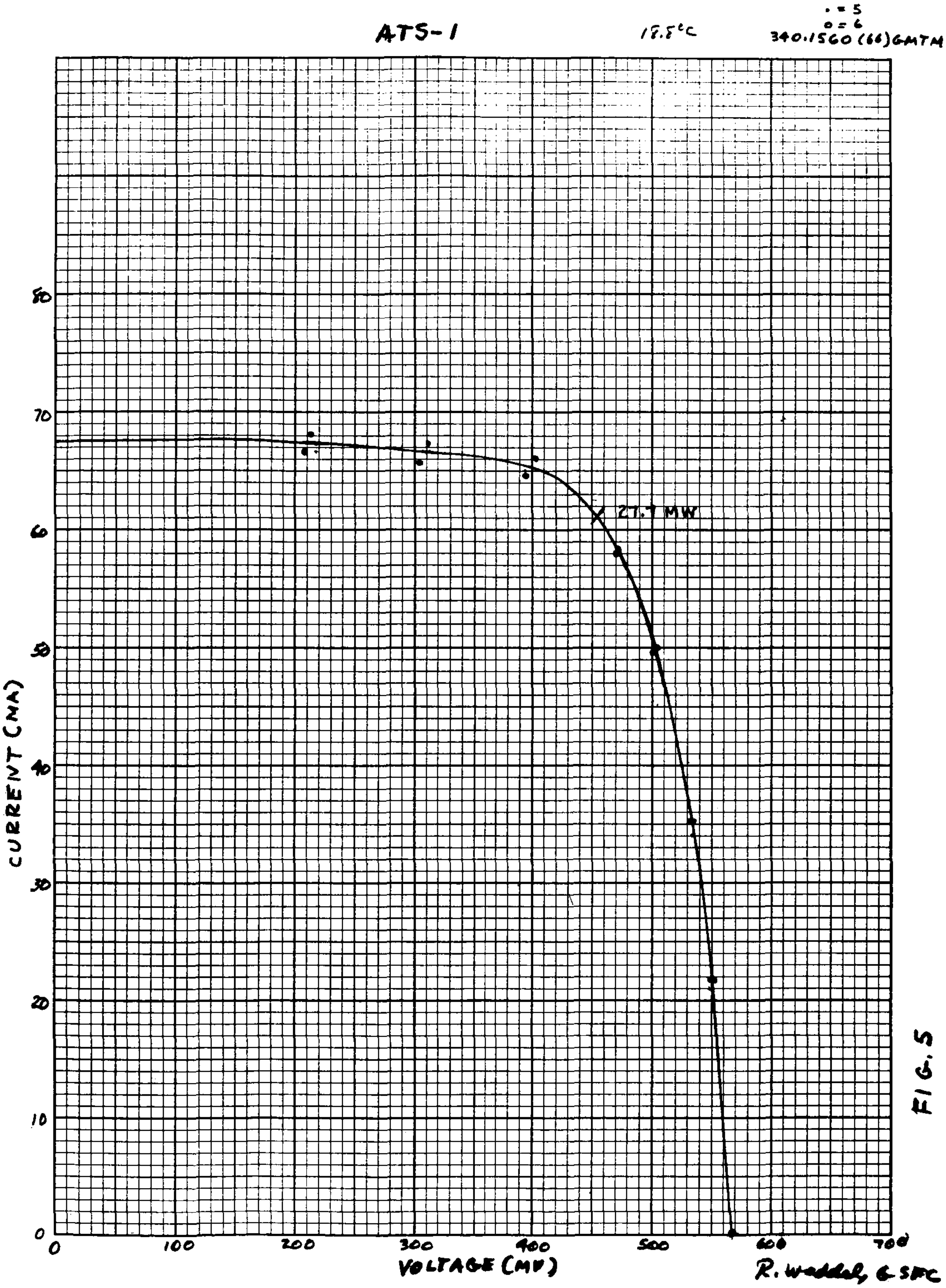
FIG. 3

R. Waddel



ATS-1
22.5°C
· = 3
o = 4
343,3749 (66) GMTM
25.0MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 4



ATS-1
18.5°C
• = 5
o = 6
340.1560 (66) GMTM
27.7 MW
CURRENT (MA)
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 5

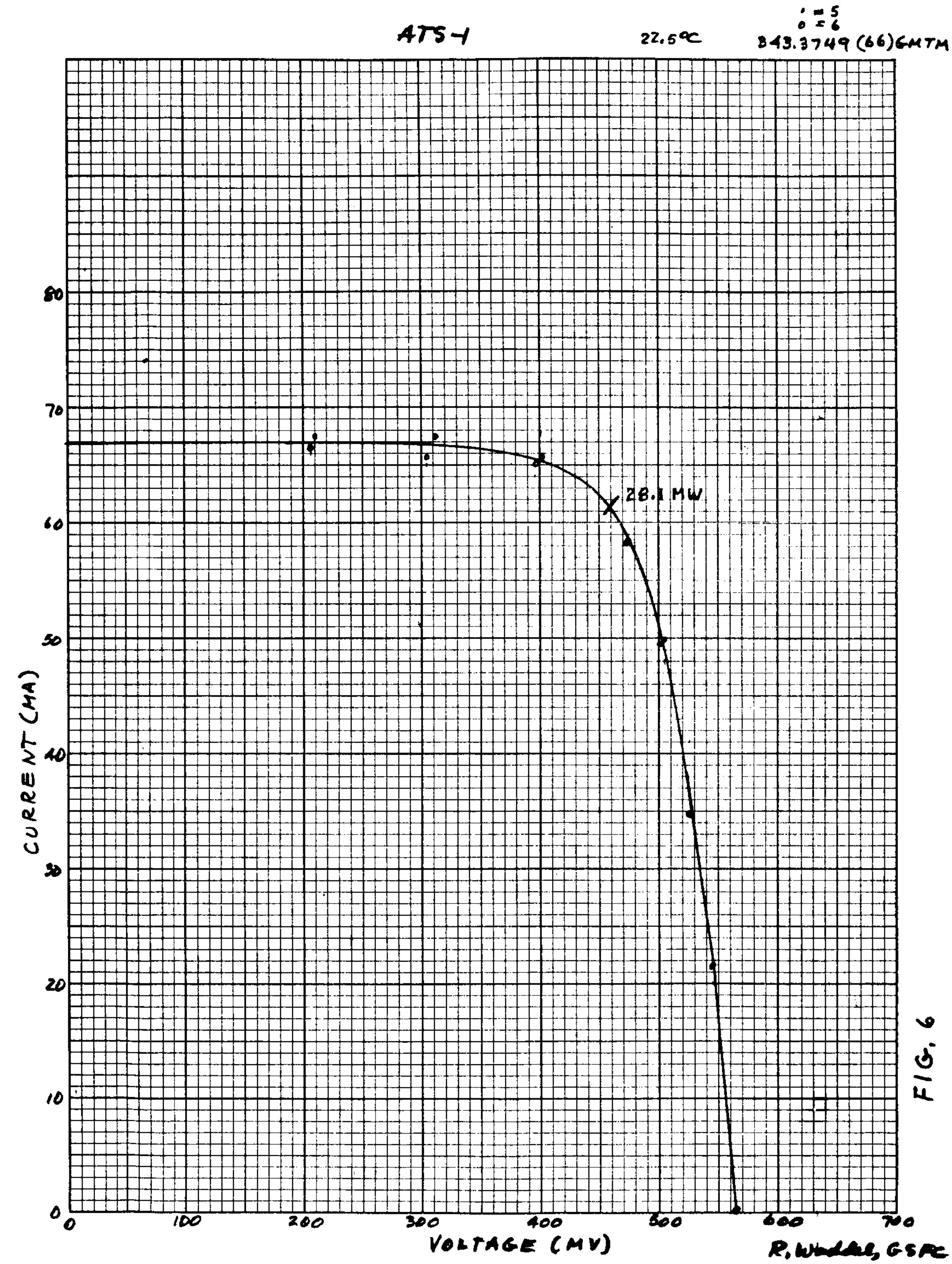
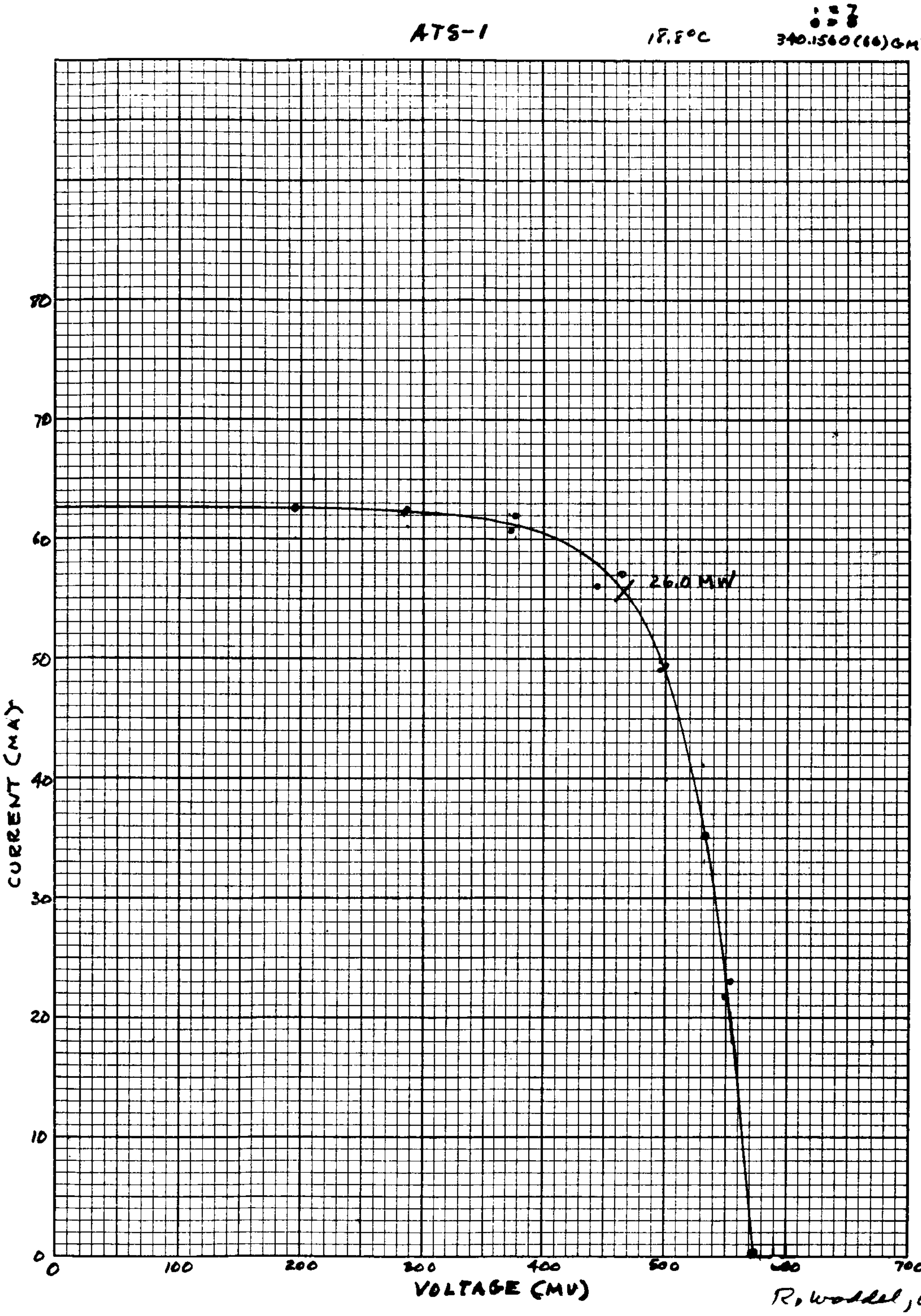
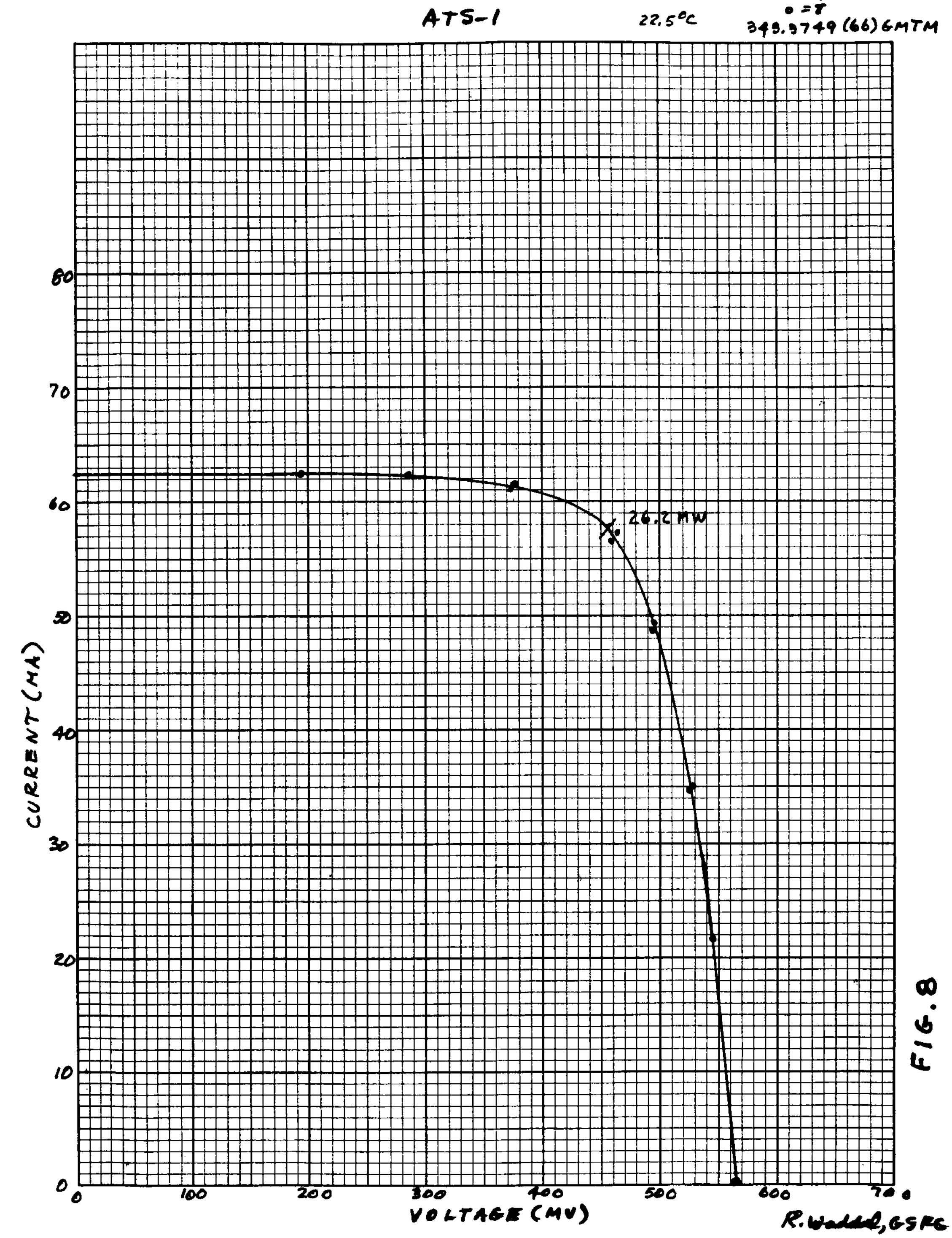

ATS-1
22.5°C
· = 5
o = 6
343.3749 (66) GMTM
28.1 MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 6



ATS-1
18.8°C
340.1560(66)GMTM
26.0 MW
CURRENT (MA)
VOLTAGE (MV)
0
100
200
300
400
500
600
700
10
20
30
40
50
60
70
80

FIG. 7



ATS-1
22.5°C
• = 7
o = 8
349.9749 (66) GMTM
CURRENT (MA)
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
VOLTAGE (MV)
26.2 MW
R. Waddel, GSFC

FIG. 8

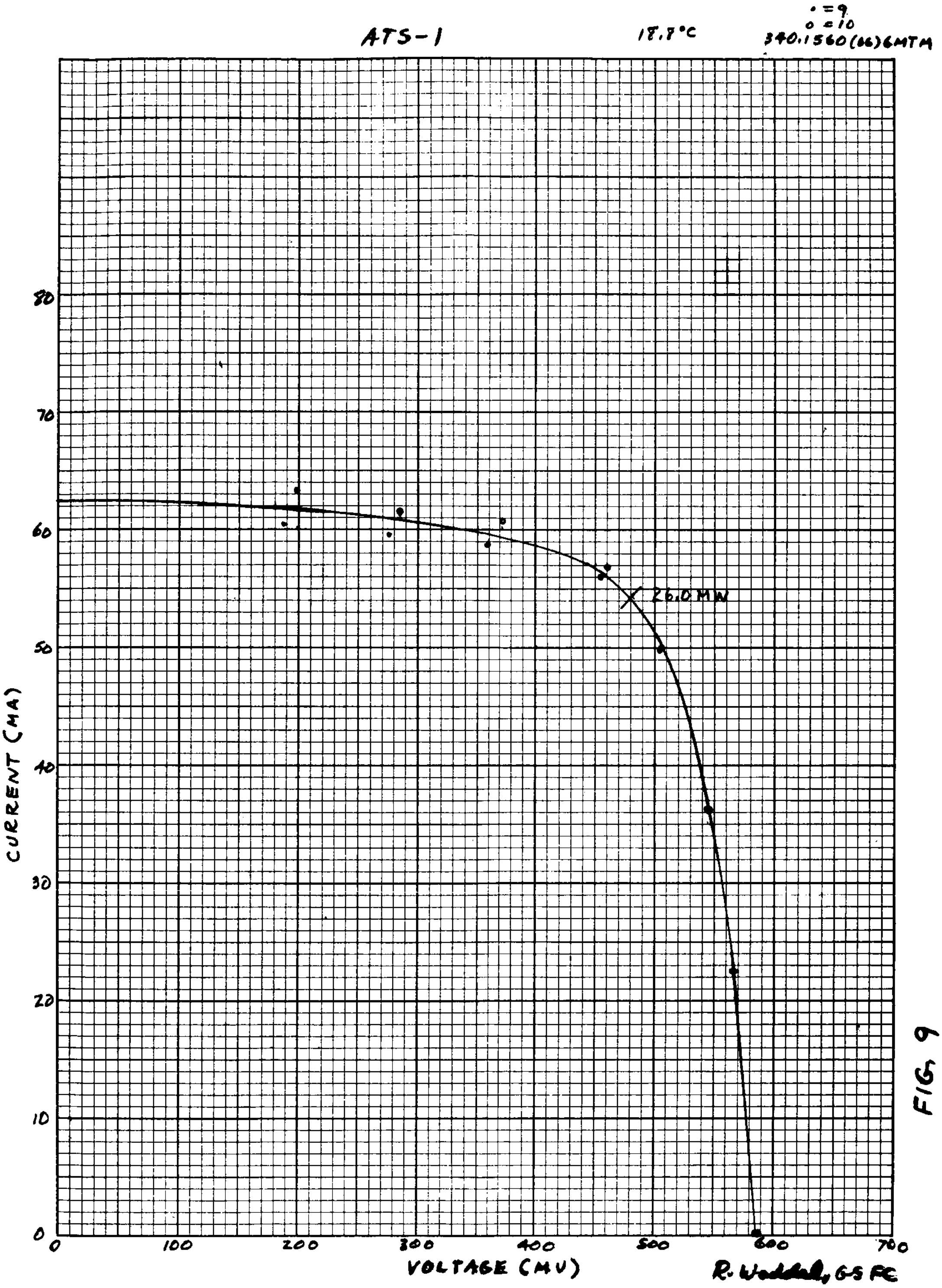
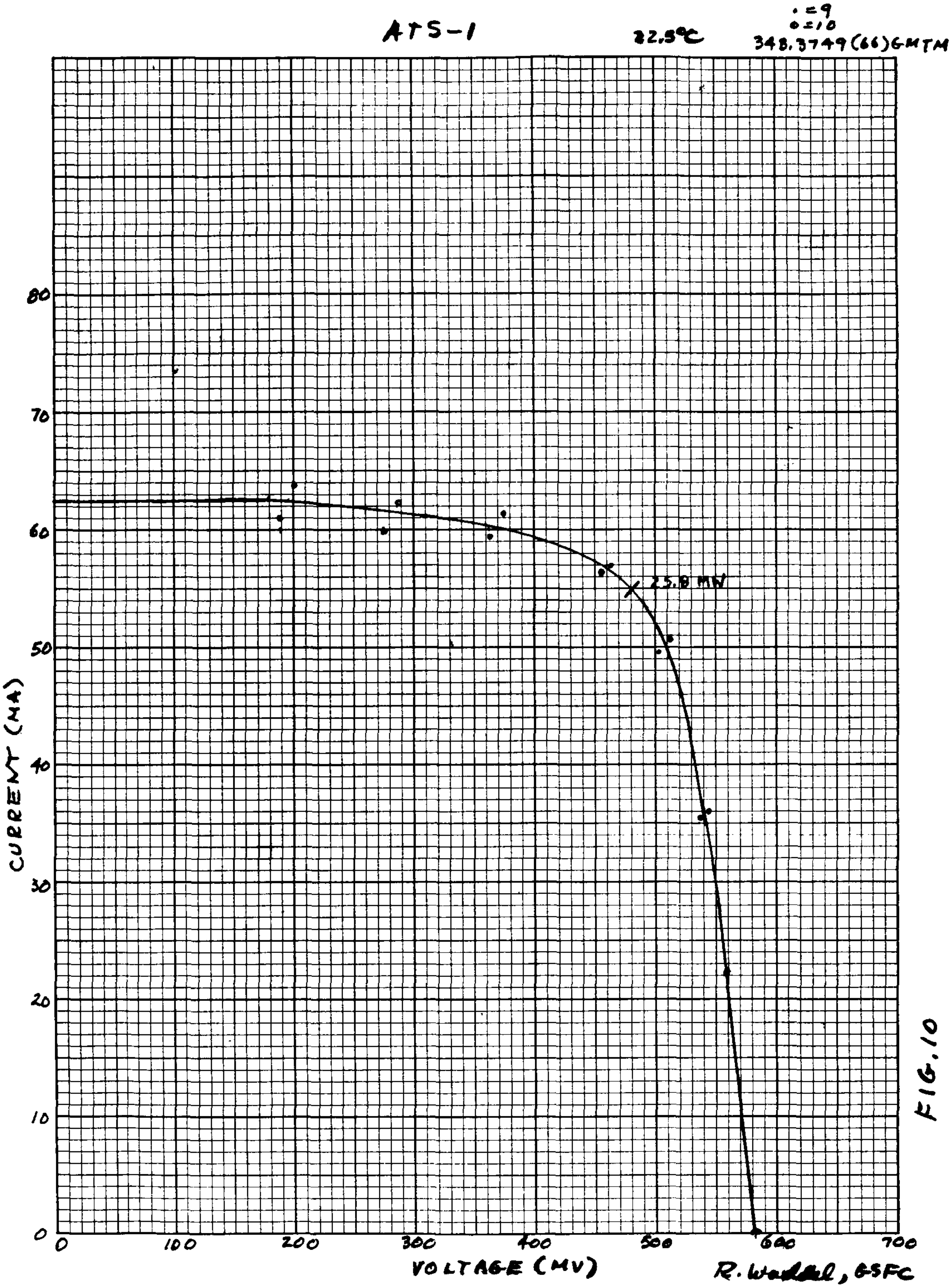
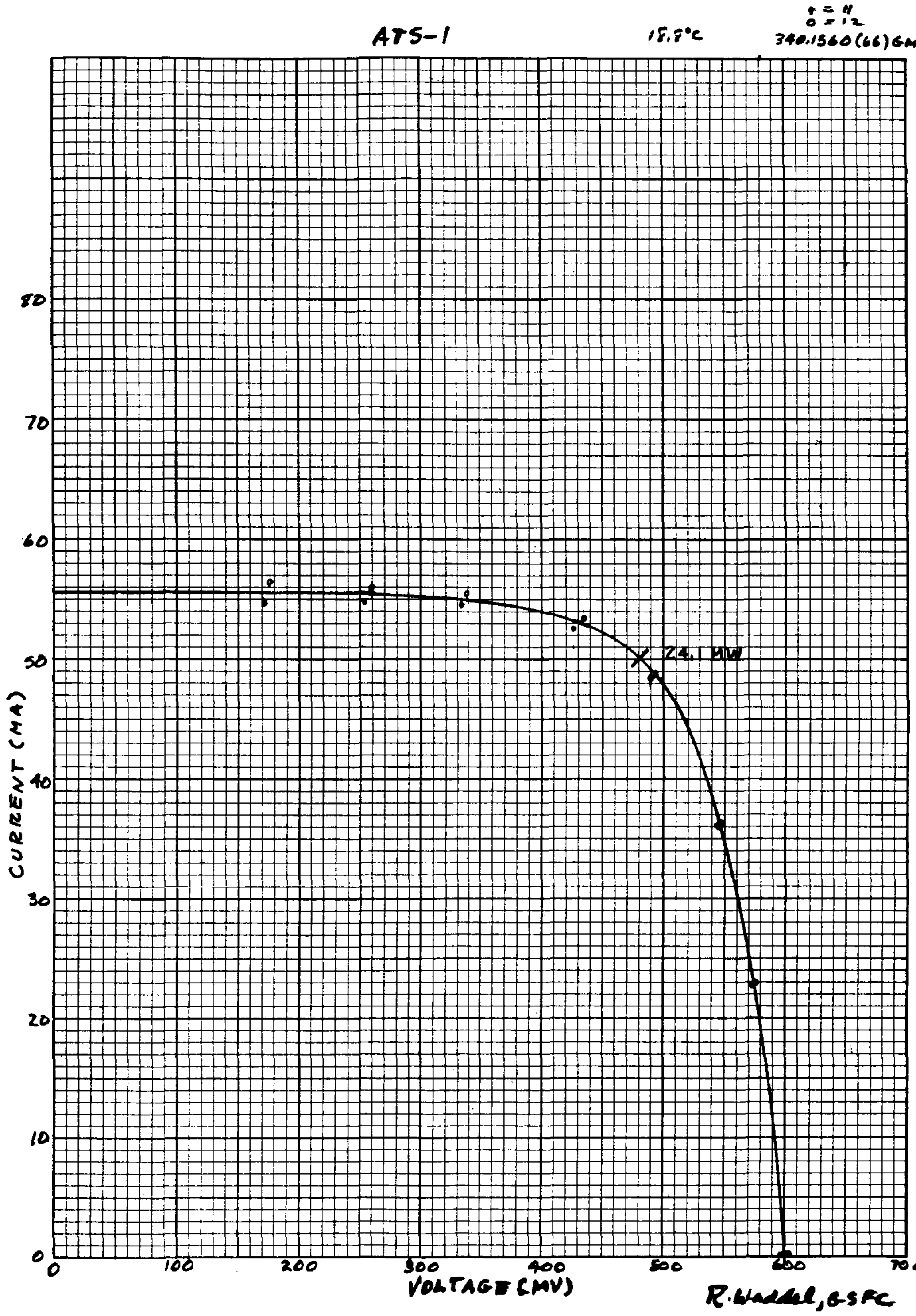

ATS-1
18.7°C
• = 9
o = 10
340.1560(66)6MTM
26.0 MW
CURRENT (MA)
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 9



ATS-1
22.5°C
• = 9
○ = 10
348.3749 (66) GMTM
25.8 MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 10



ATS-1
18.8°C
+ = 11
o = 12
340.1560(66)GMTM
24.1 MW
CURRENT (MA)
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 11

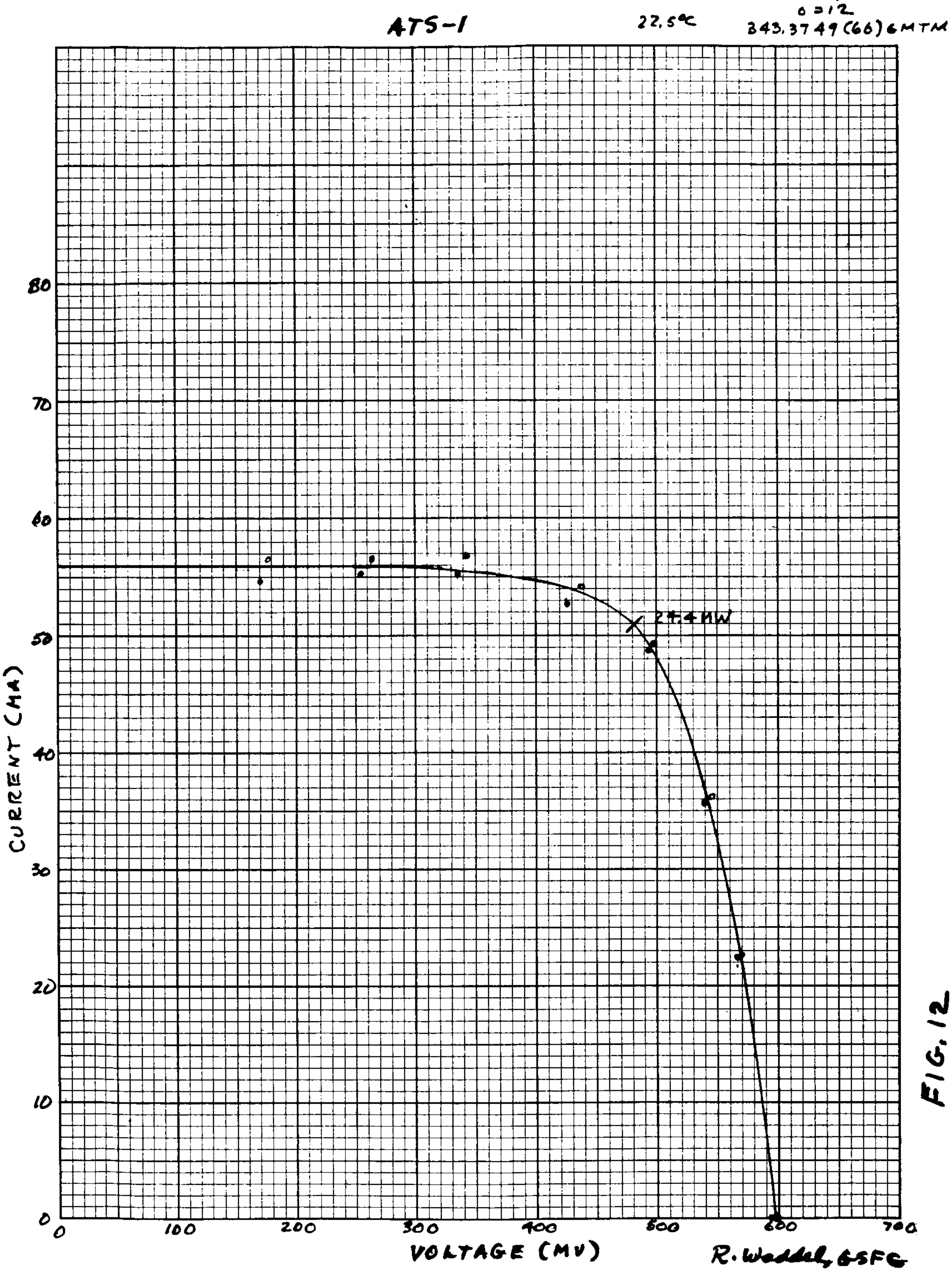

ATS-1
22.5°C
• = 11
○ = 12
343.3749 (66) 6MTM
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
CURRENT (MA)
VOLTAGE (MV)
27.4 MW
R. Waddel, GSFC

FIG. 12

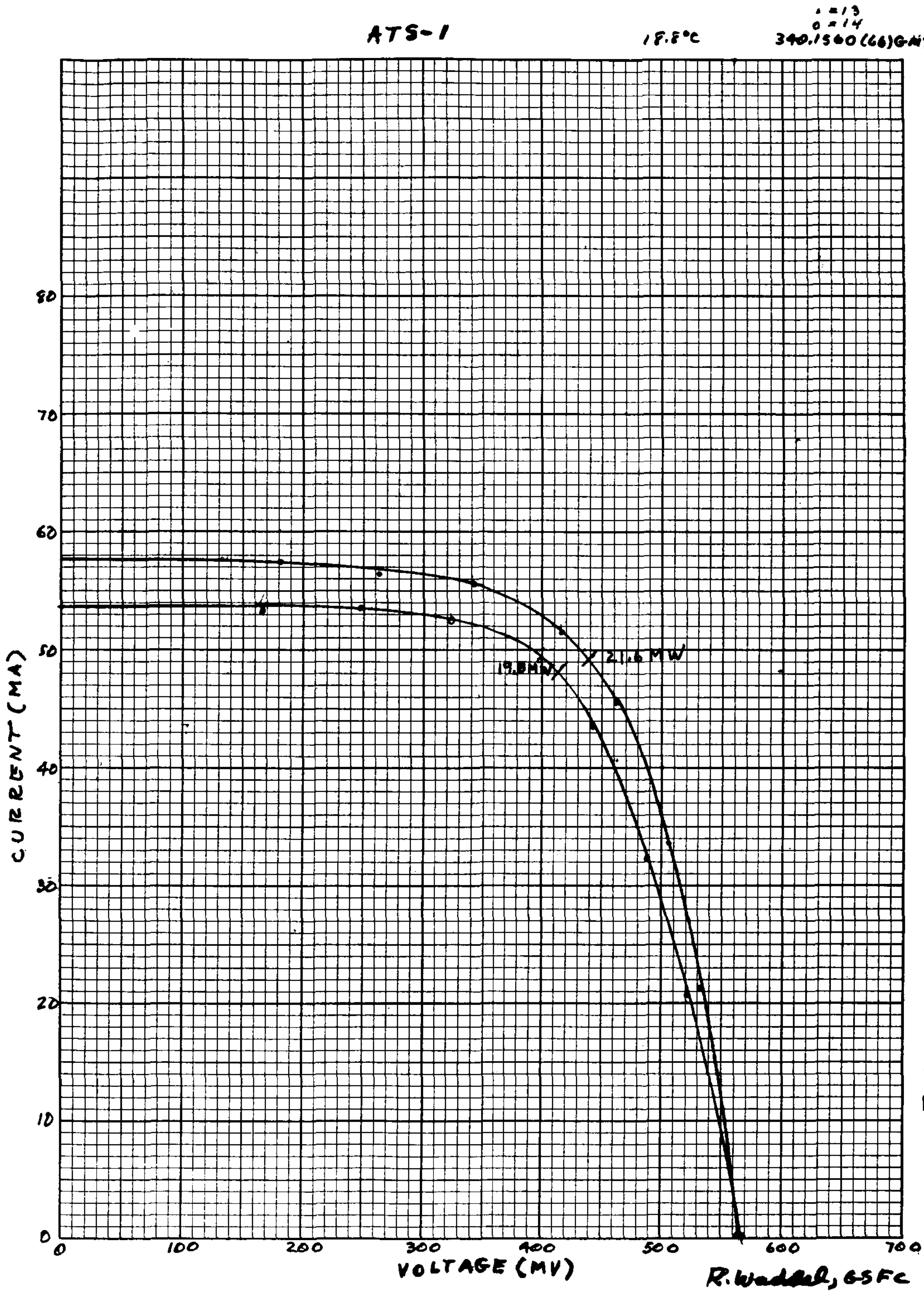
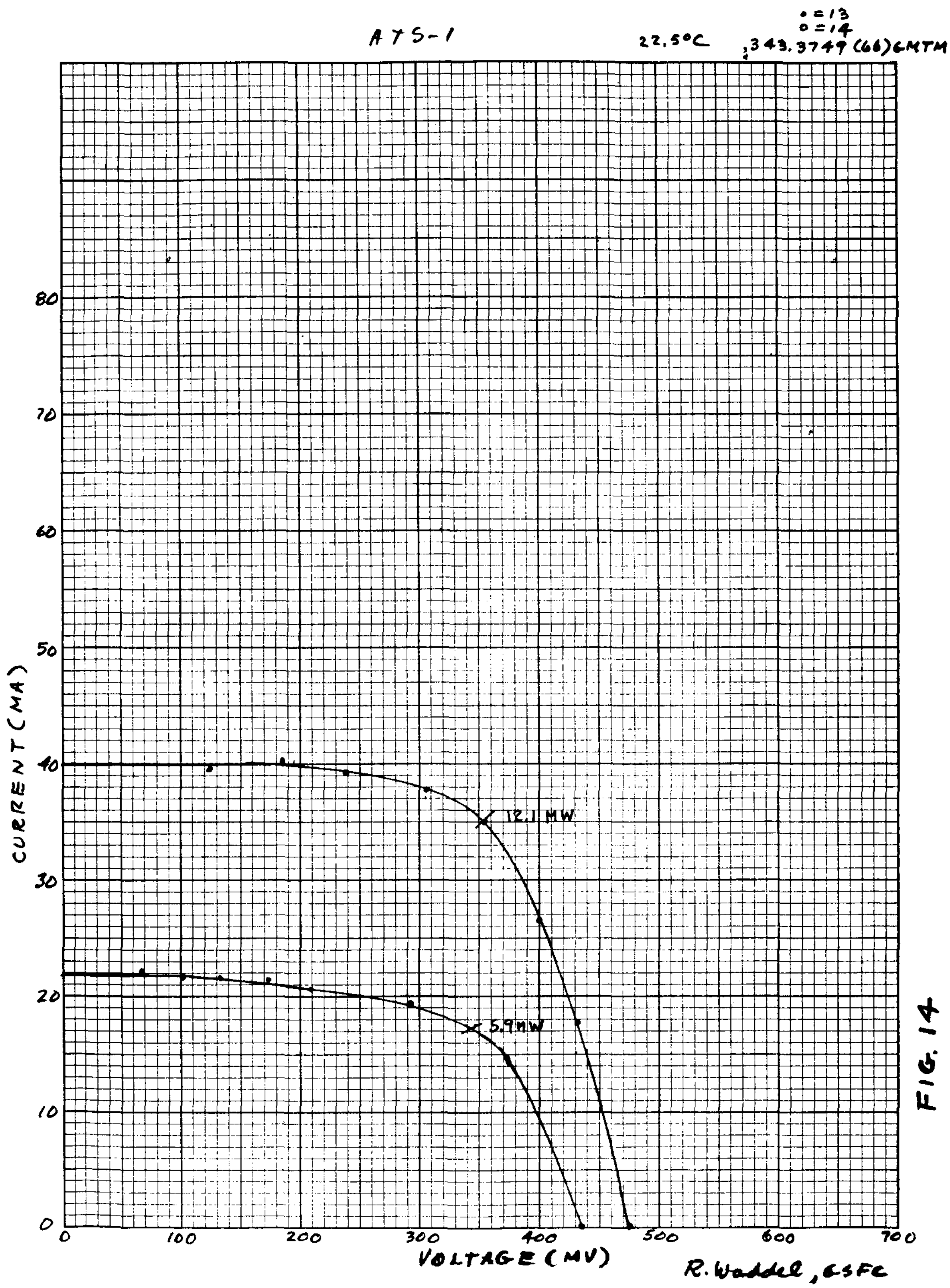
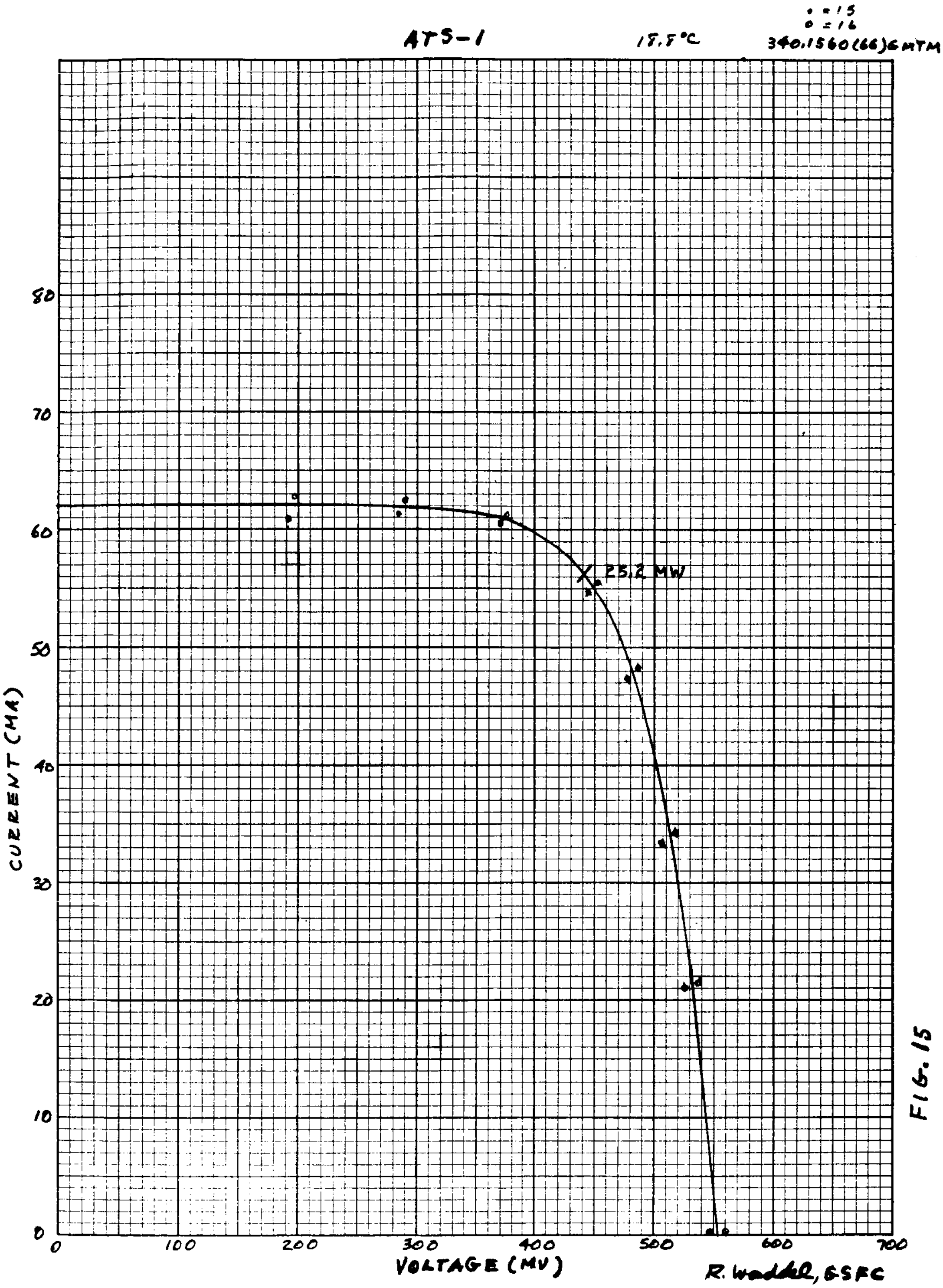

ATS-1
18.8°C
• = 13
o = 14
340.1560 (66) GMTM
CURRENT (MA)
0
10
20
30
40
50
60
70
80
VOLTAGE (MV)
0
100
200
300
400
500
600
700
19.8 MW
21.6 MW
R. Waddel, GSFC

FIG. 13



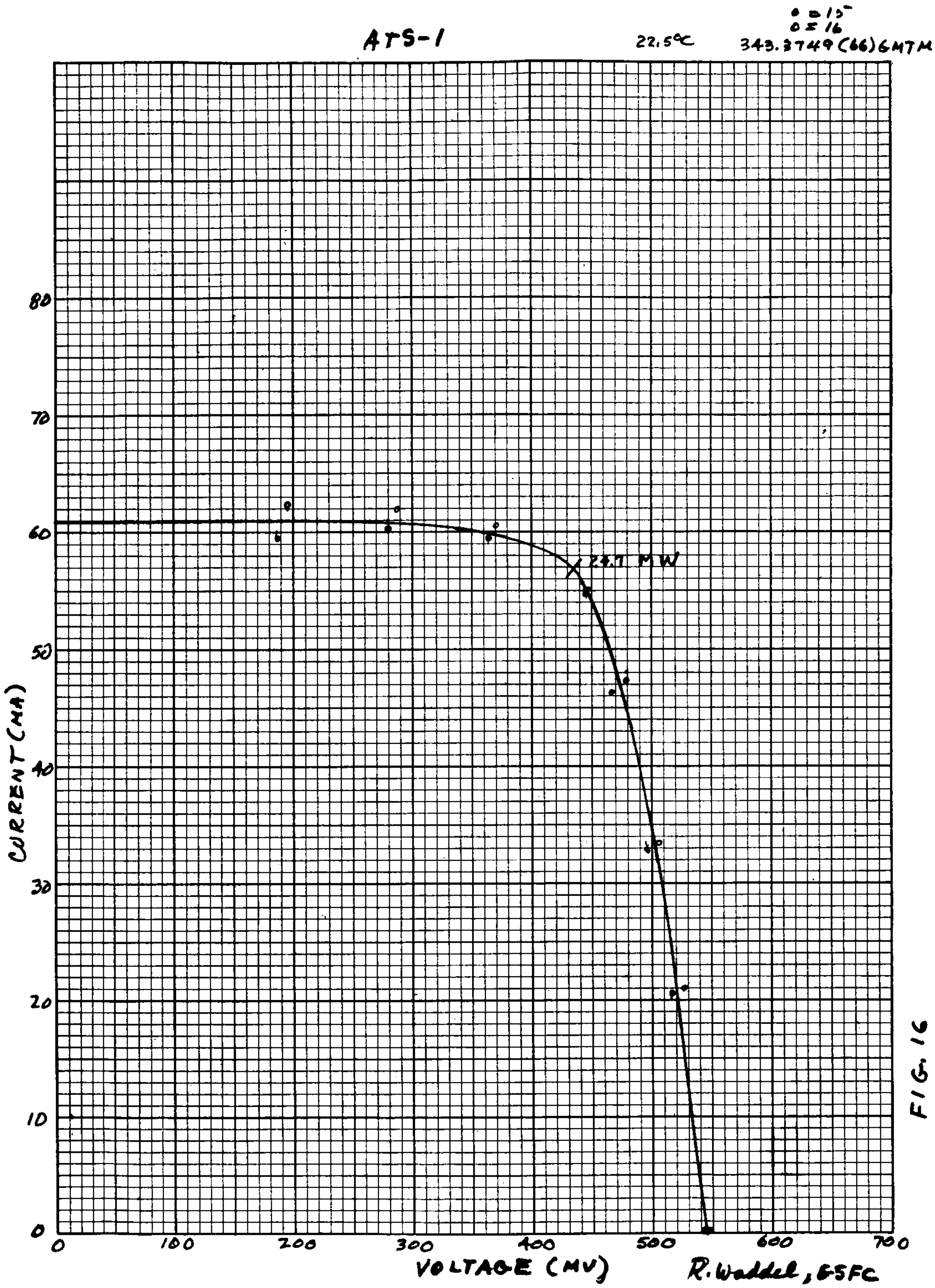
ATS-1
22.5°C
• = 13
o = 14
343.3749 (66) GMTM
CURRENT (MA)
VOLTAGE (MV)
12.1 MW
5.9 MW
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 14



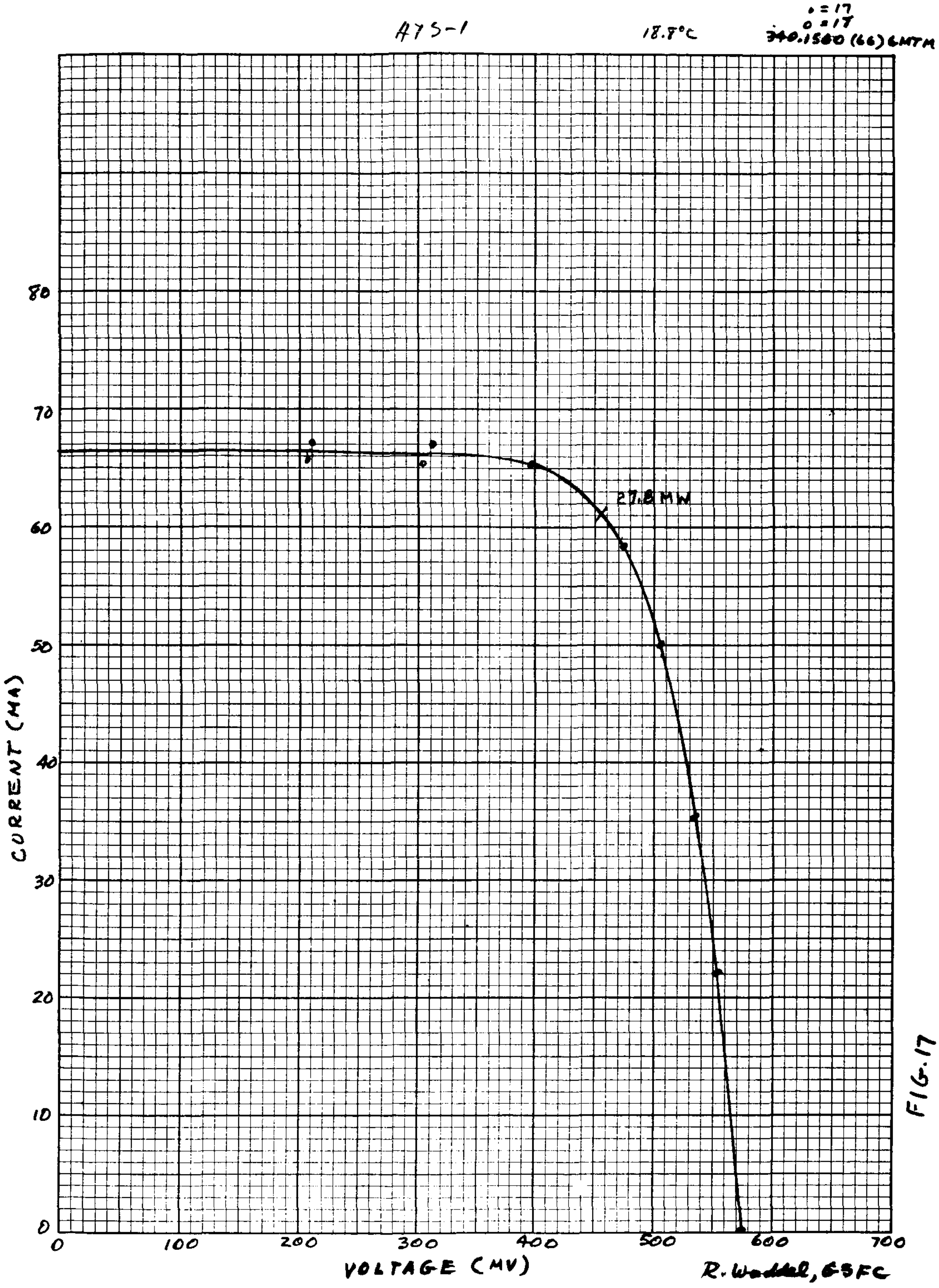
ATS-1
18.5°C
• = 15
o = 16
340.1560(66)GMTM
80
70
60
50
40
30
20
10
0
CURRENT (MA)
25.2 MW
0
100
200
300
400
500
600
700
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 15



ATS-1
22.5°C
• = 15
○ = 16
343.3749 (66) GMTM
24.7 MW
CURRENT (MA)
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 16



A7S-1
18.8°C
• = 17
o = 17
340.1580 (66) GMTM
80
70
60
50
40
30
20
10
0
CURRENT (MA)
0
100
200
300
400
500
600
700
VOLTAGE (MV)
27.8 MW
R. Waddel, GSFC
FIG. 17

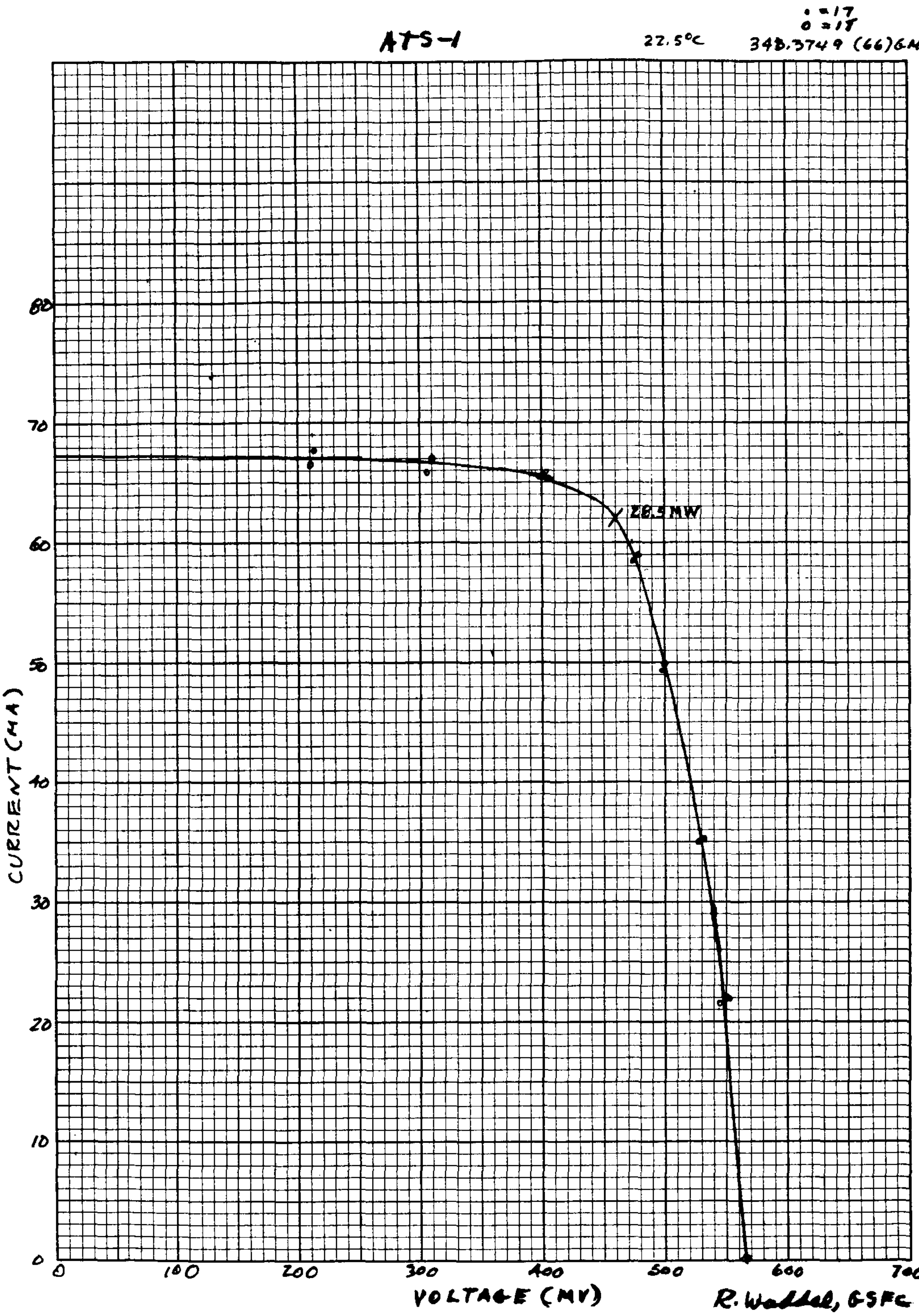

ATS-1
22.5°C
348.3749 (66)6MTM
28.5 MW
CURRENT (MA)
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 18

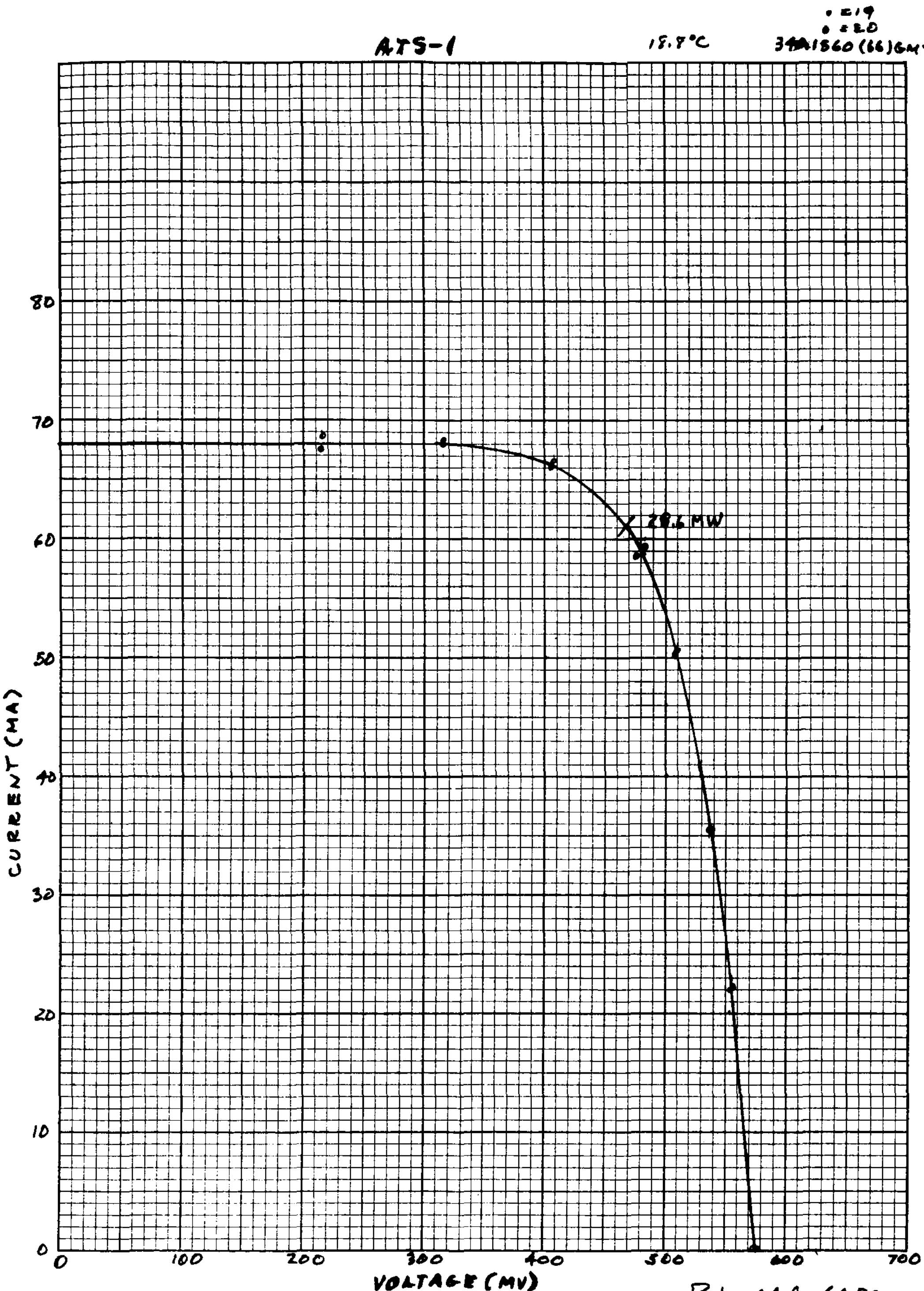
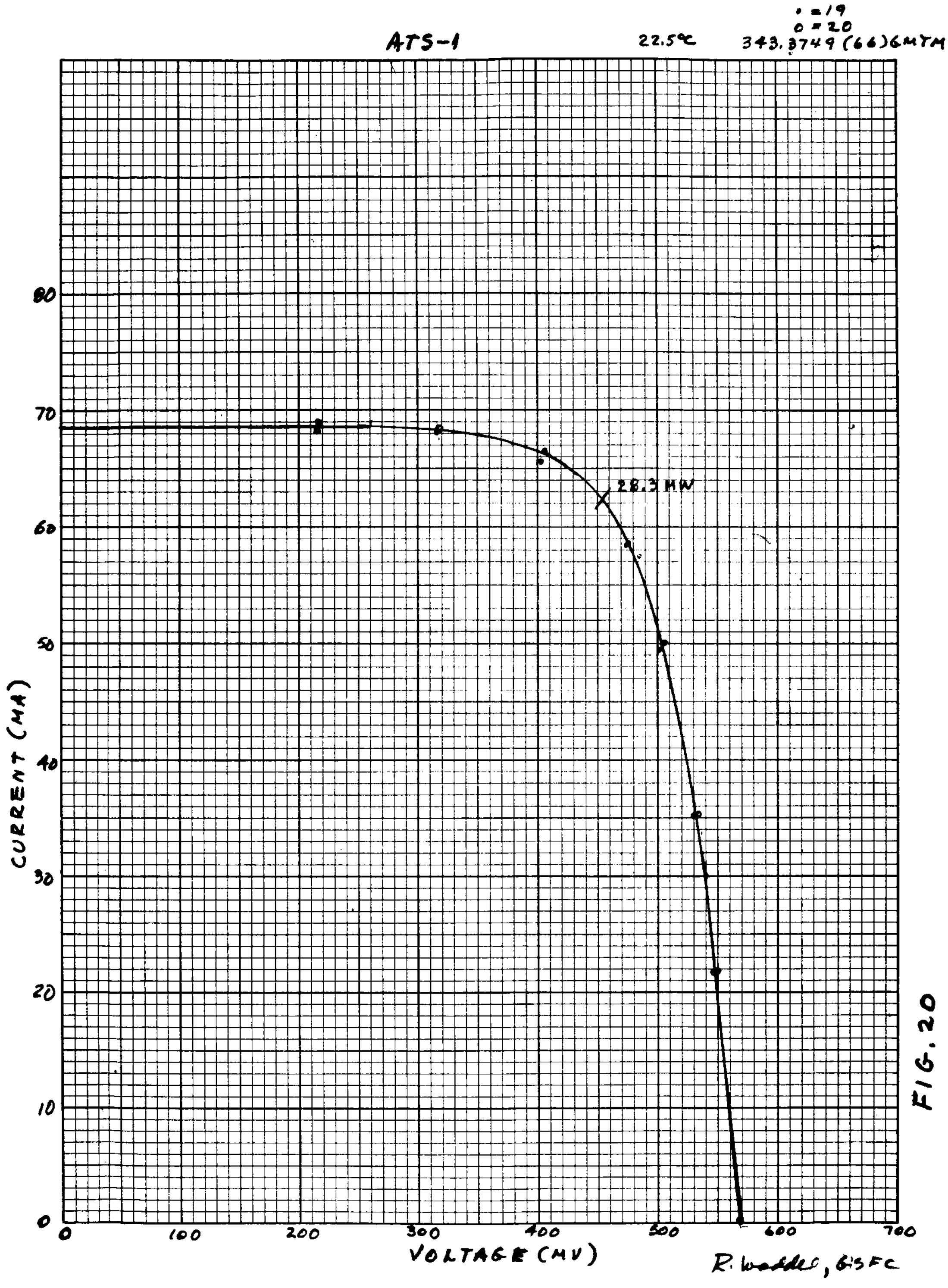


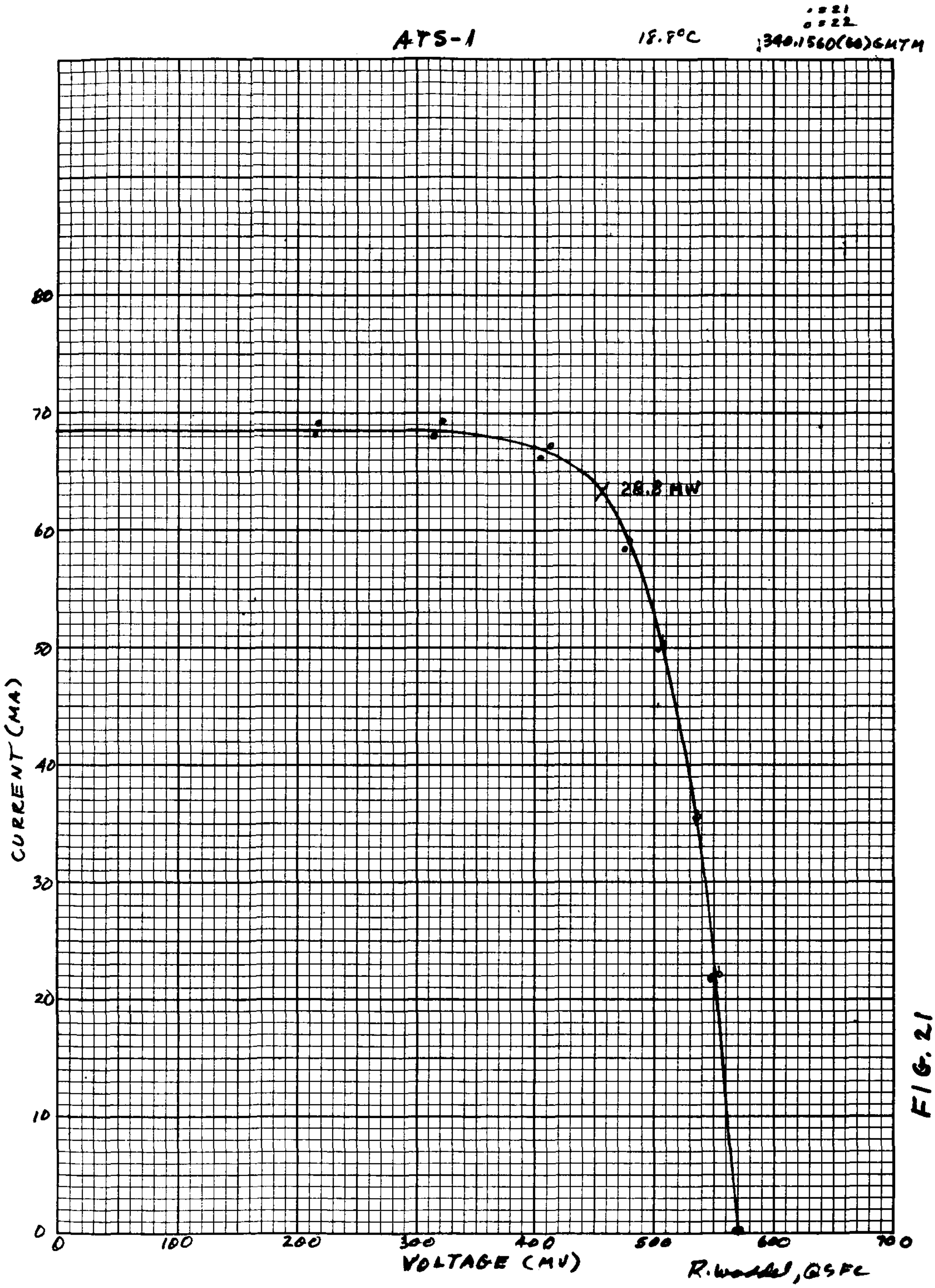
FIG. 19

R. Waddel, GSFC



ATS-1
22.5°C
• = 19
o = 20
343.3749 (66) 6MTM
28.3 MW
CURRENT (MA)
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 20



ATS-1
18.8°C
• = 21
○ = 22
340.1560(60)GMTM
28.3 MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R.Waddel, GSFC

FIG. 21

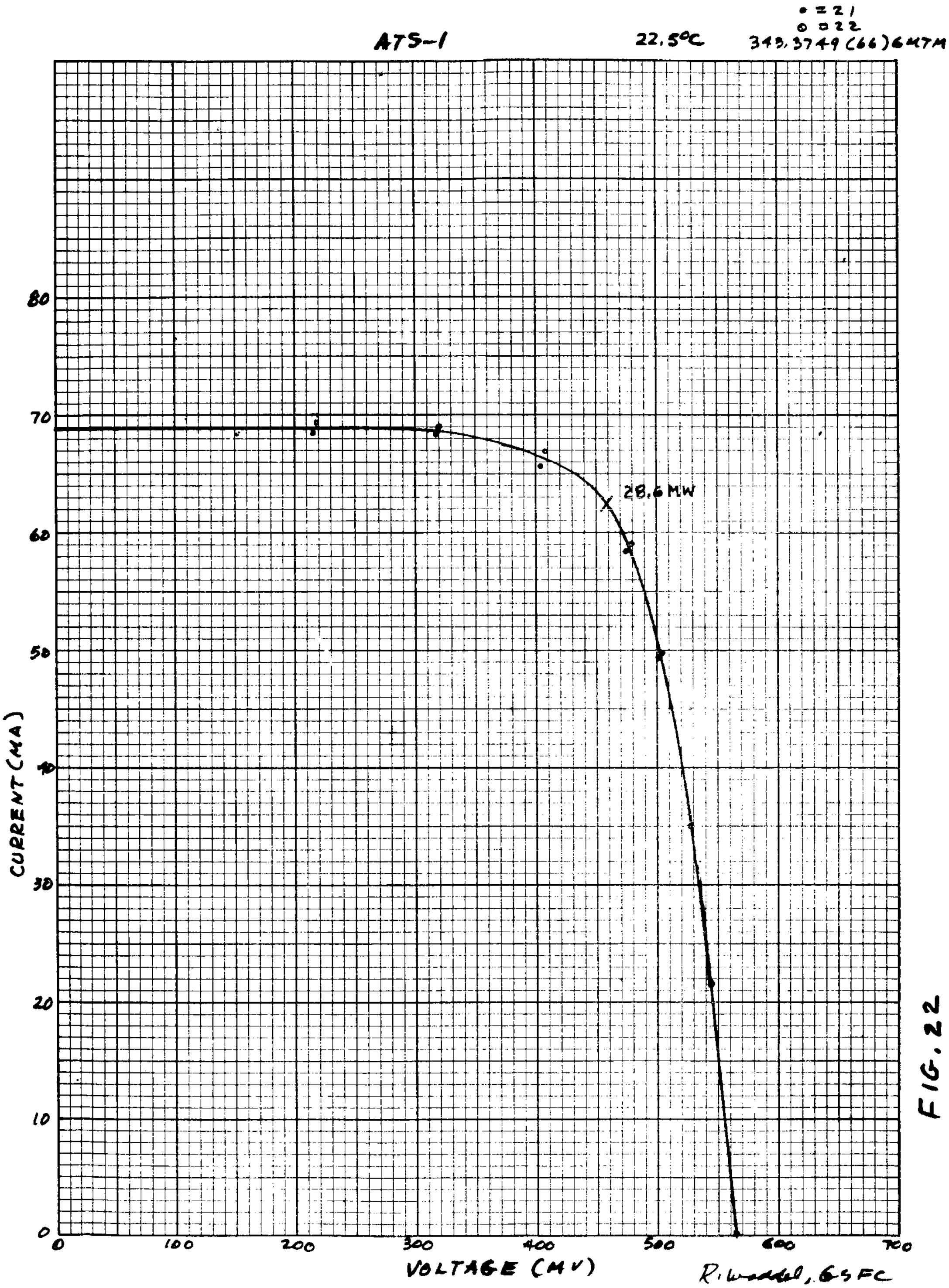
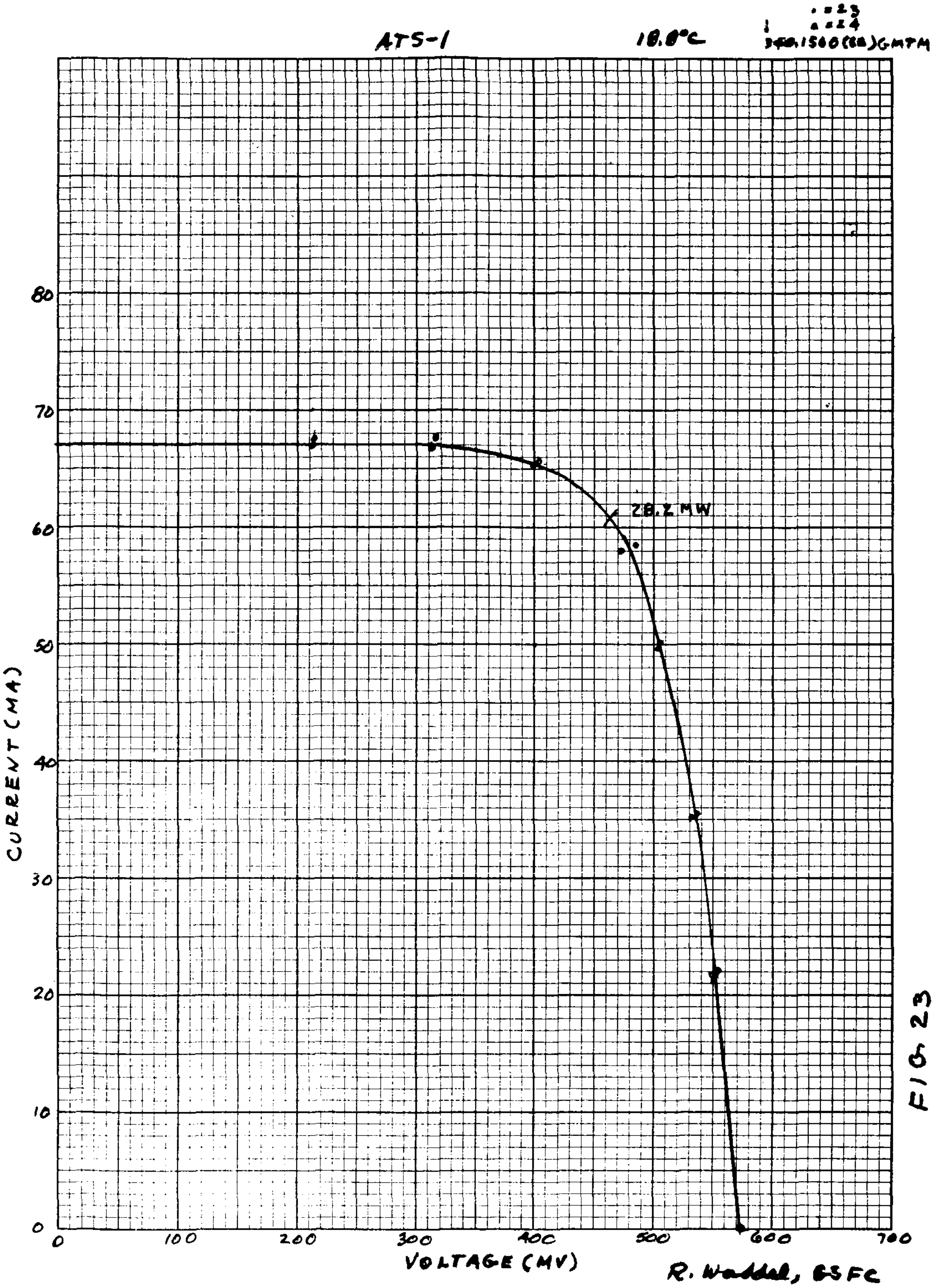

ATS-1
22.5°C
• = 21
○ = 22
343,3749 (66) 6 MTM
28.6 MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 22



ATS-1
18.8°C
1500(88)GMTM
CURRENT (MA)
VOLTAGE (MV)
28.2 MW
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG 23

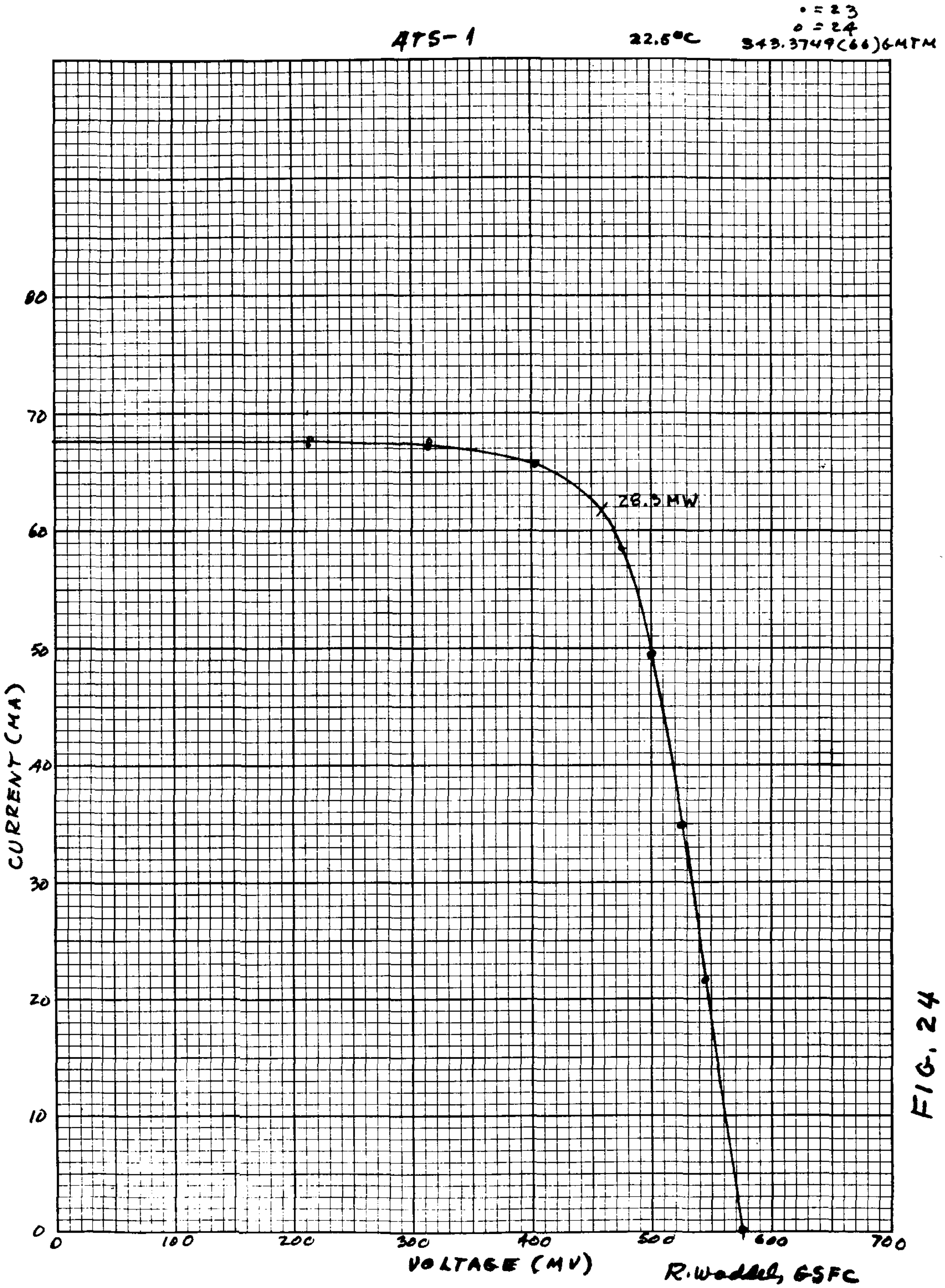
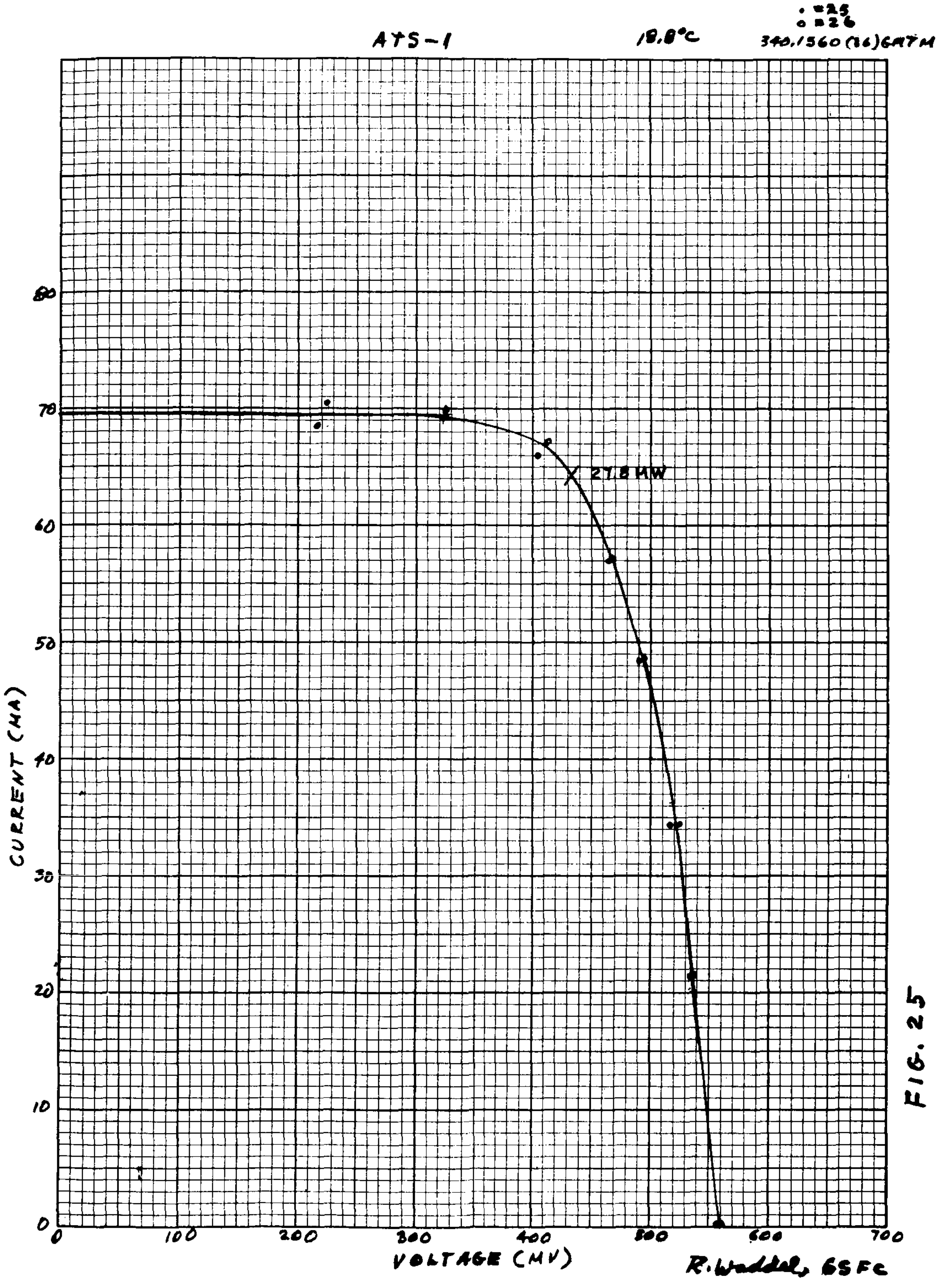
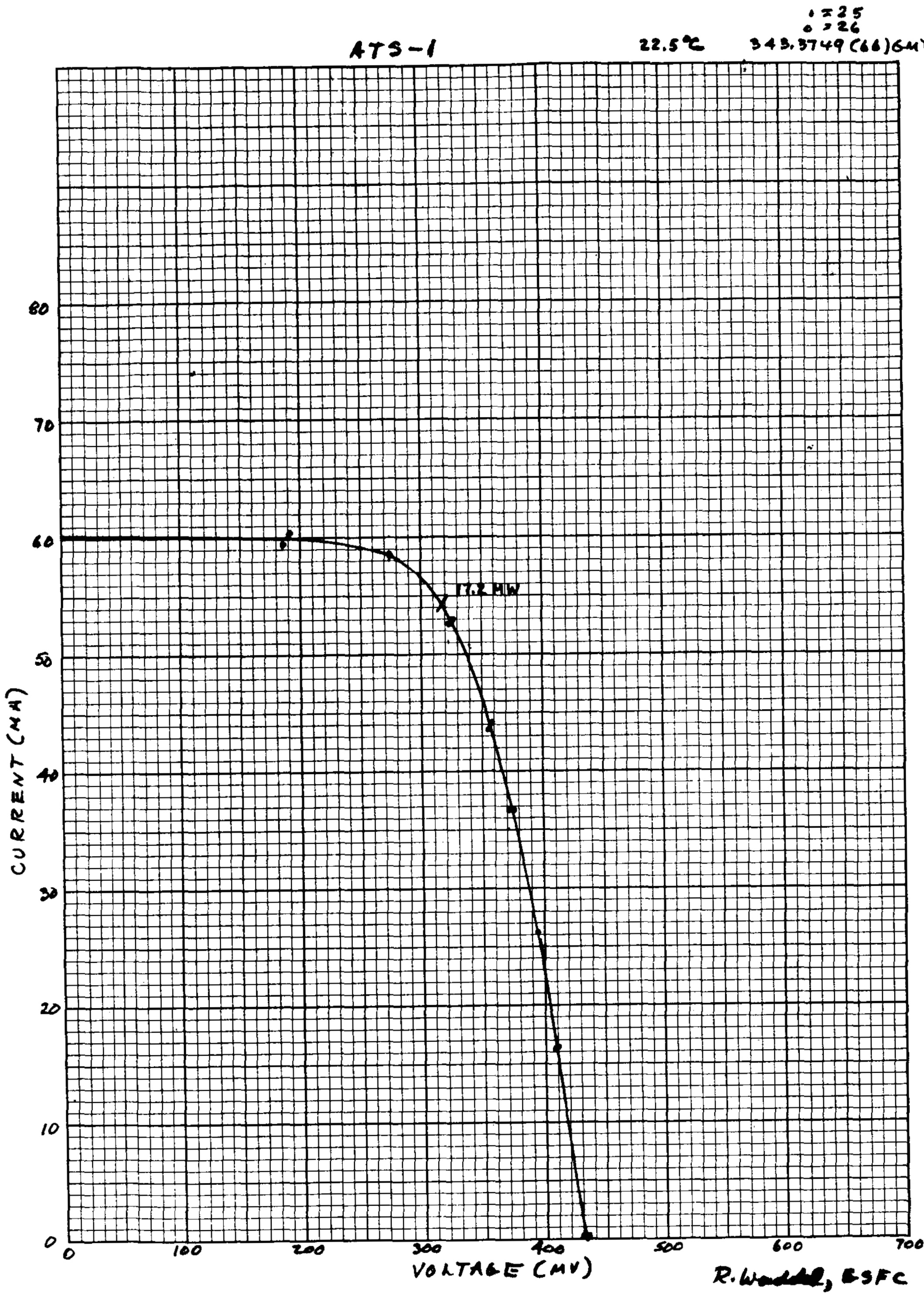

ATS-1
22.5°C
• = 23
o = 24
343.3749(66)GMTM
28.3 MW
CURRENT (MA)
VOLTAGE (MV)
R. Waddel, GSFC
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700

FIG. 24



ATS-1
18.8°C
• = 25
o = 26
340.1560 (16) GMT M
80
70
60
50
40
30
20
10
0
CURRENT (MA)
0
100
200
300
400
500
600
700
VOLTAGE (MV)
27.8 MW
R. Waddel, GSFC

FIG. 25



ATS-1
22.5°C
343.3749 (66) GMT
17.2 MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700

FIG. 26

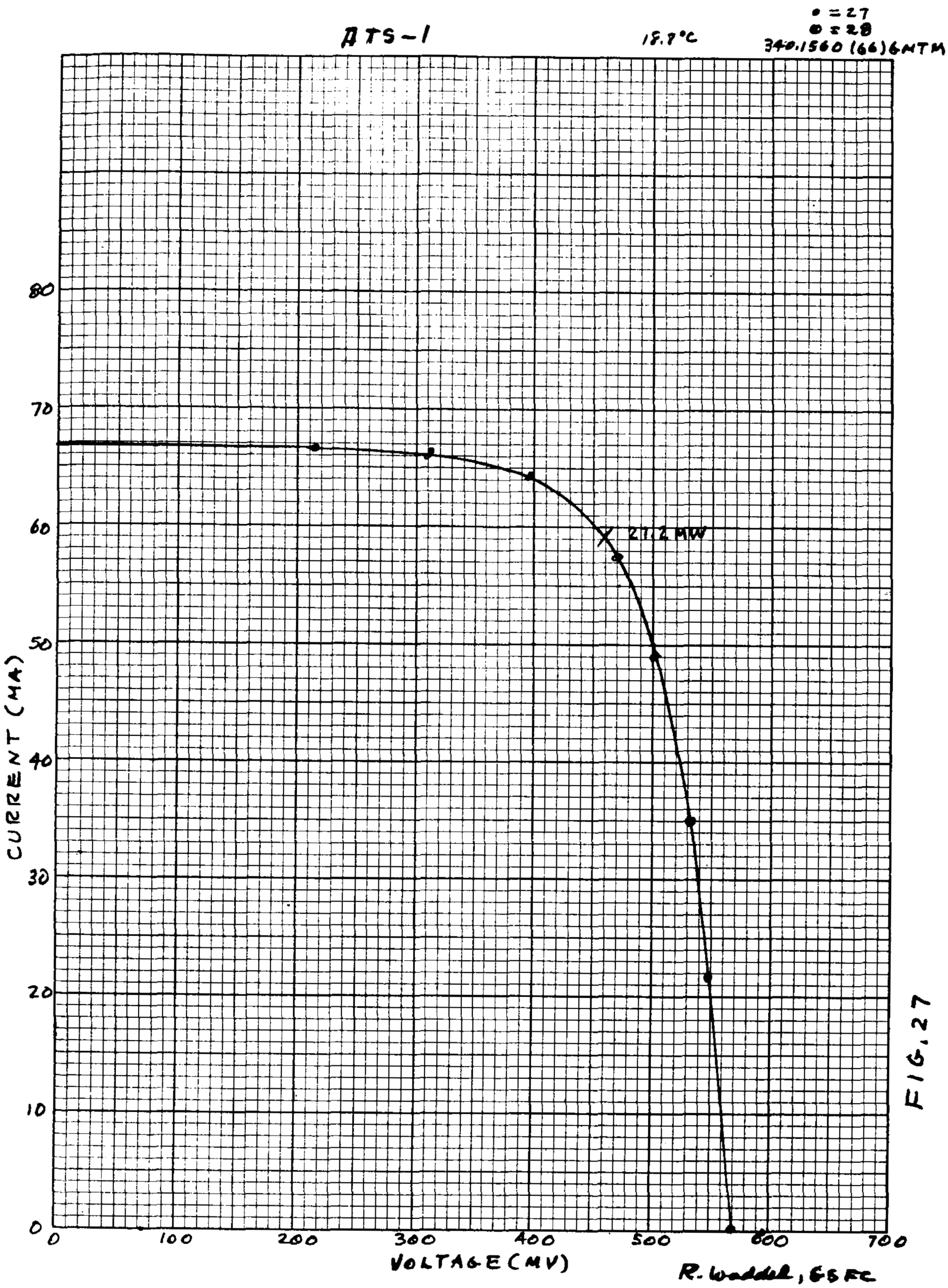
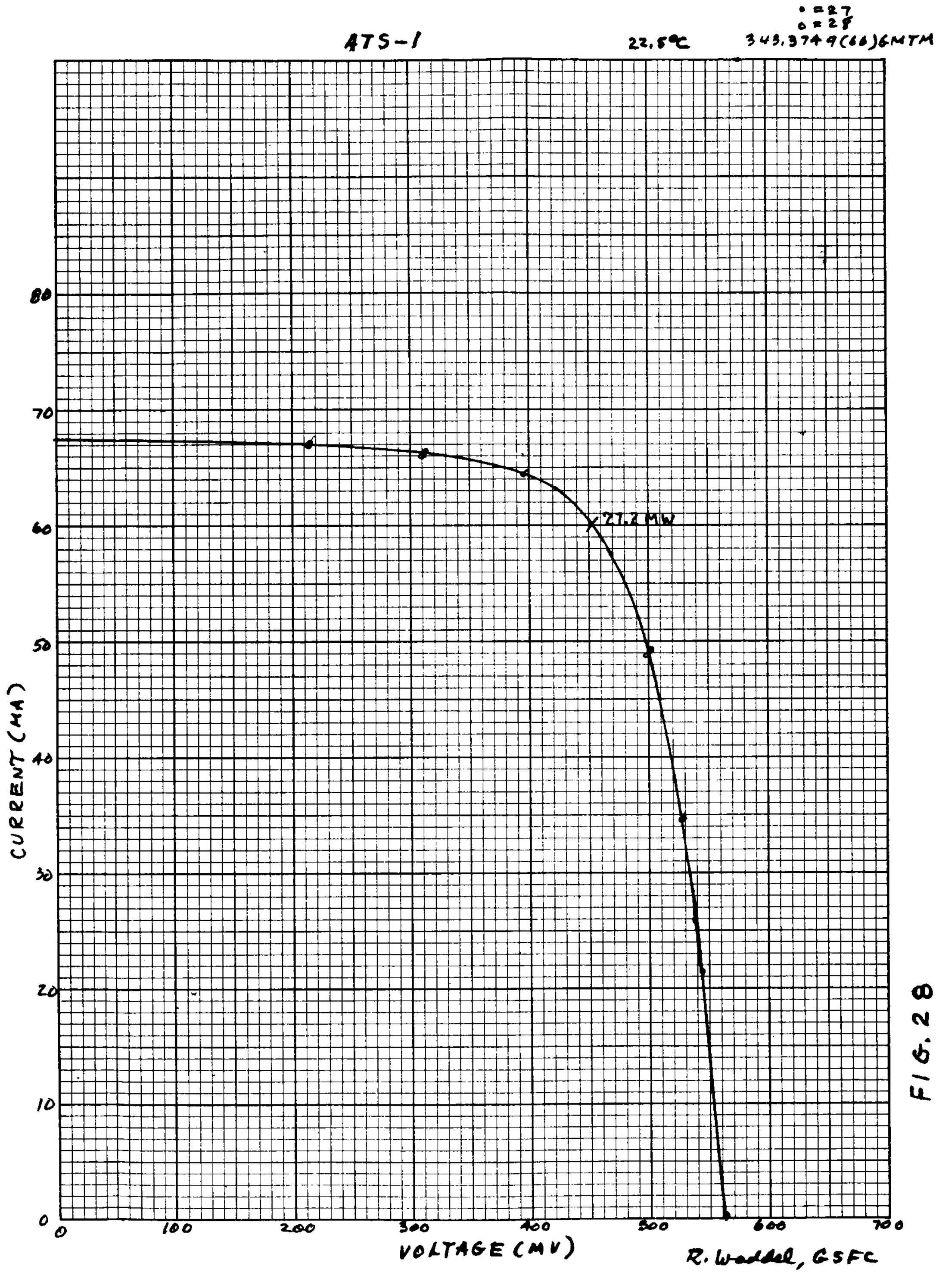
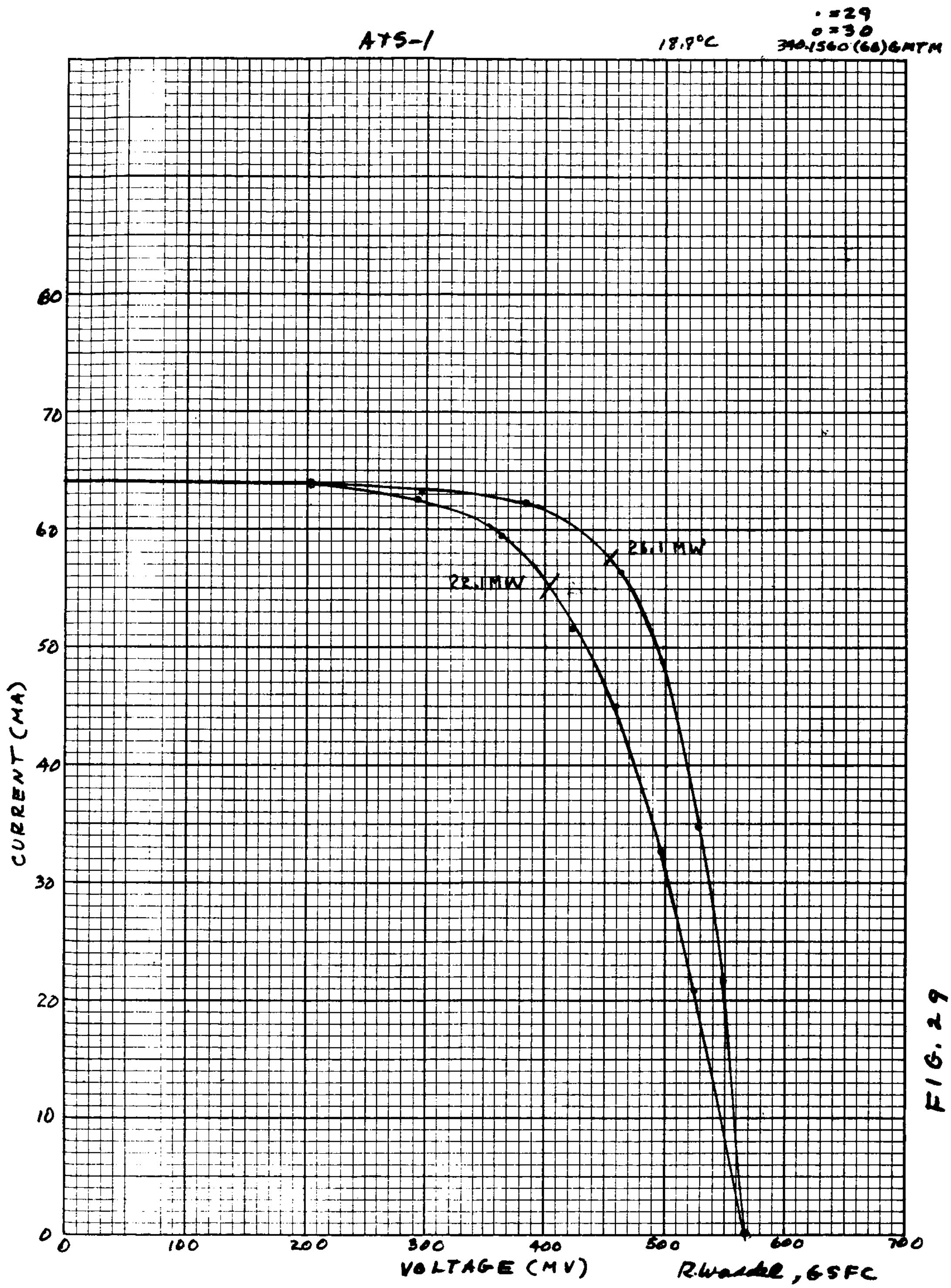

ATS-1
18.7°C
• = 27
⊕ = 28
340.1560 (66) GMTM
27.2 MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R. Waddel, GSFC

FIG. 27



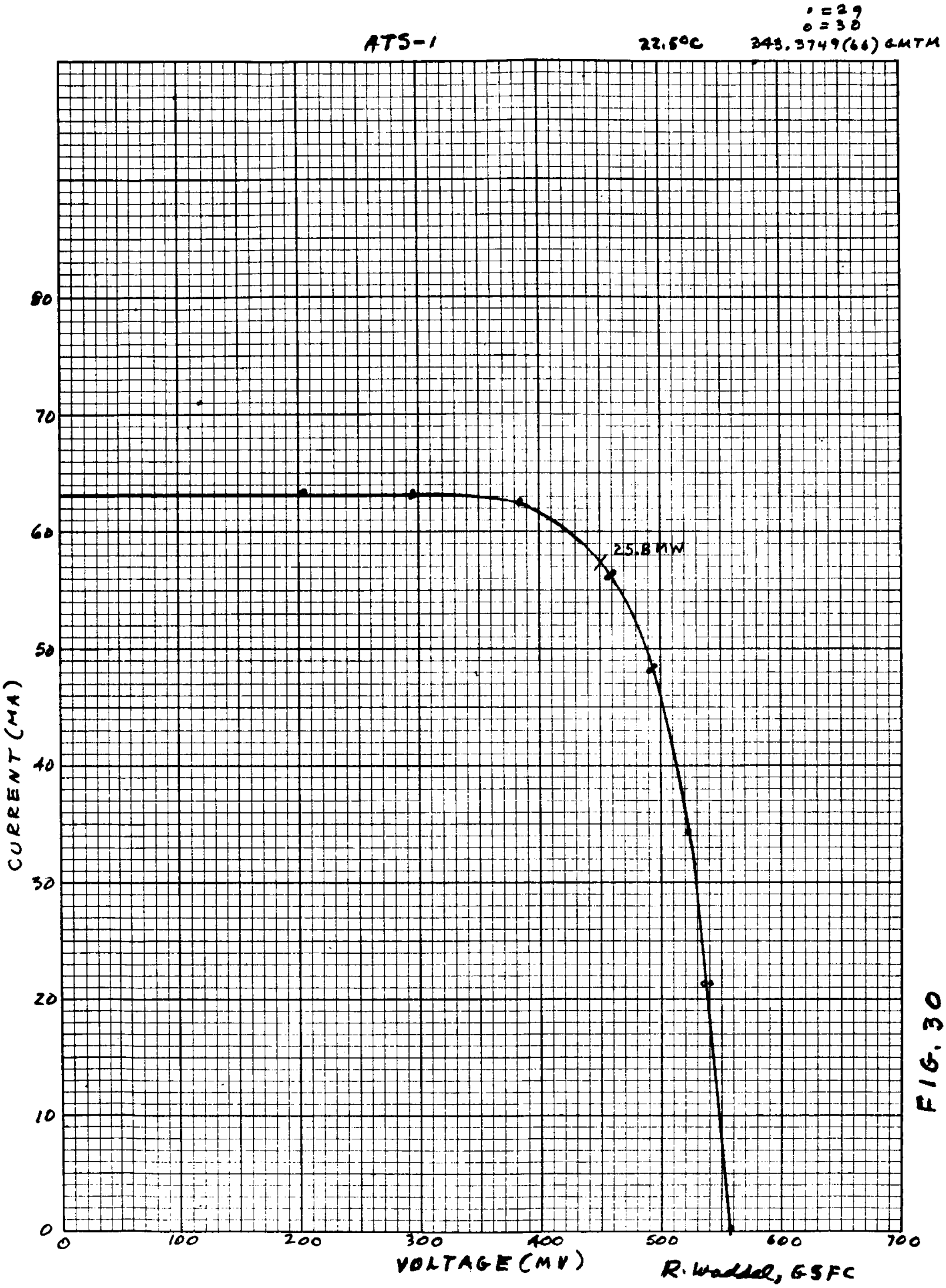
ATS-1
22.5°C
• = 27
o = 28
343,3749(66)GMTM
CURRENT (MA)
VOLTAGE (MV)
27.2 MW
R. Waddel, GSFC

FIG. 28



ATS-1
18.8°C
• = 29
o = 30
340-1560 (66) GMTM
22.1MW
25.1MW
CURRENT (MA)
VOLTAGE (MV)
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
700
R.Waddel, 65FC

FIG. 29



• = 29
o = 30
ATS-1
22.5°C
343.3749(66) GMTM
25.8 MW
CURRENT (MA)
VOLTAGE (MV)
R. Waddel, GSFC

FIG. 30