DOE/NASA/1022-78/27
NASA TM-78829

(NASA-TM-78829) RESULTS OF MODULE ELECTRICAL MEASUREMENT OF THE DOE 46-KILOWATT PROCUREMENT (NASA) 20 p HC A02/MF A01 CSCL 10B
N78-19658
Unclas
G3/44 09462

RESULTS OF MODULE ELECTRICAL MEASUREMENT OF THE DOE 46-KILOWATT PROCUREMENT

Henry B. Curtis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

February 1978

Prepared for
DEPARTMENT OF ENERGY
Division of Solar Energy
Under Interagency Agreement E(49-26)-1022

NOTICE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-78829		

4. Title and Subtitle
RESULTS OF MODULE ELECTRICAL MEASUREMENT OF THE DOE 46-KILOWATT PROCUREMENT

5. Report Date
February 1978

6. Performing Organization Code

7. Author(s)
Henry B. Curtis

8. Performing Organization Report No.
E-9534

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Department of Energy
Division of Solar Energy
Washington, D.C. 20545

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency ~~Code~~ Report No.
DOE/NASA/1022-78/27

15. Supplementary Notes
Prepared under Interagency Agreement E(49-26)-1022.

16. Abstract
I-V measurements have been made on 661 of the Block I terrestrial solar cell modules of the DOE/JPL Low Cost Silicon Solar Array procurement. Data on I_{sc}, V_{oc}, and P_{max} for the four types of modules are presented in normalized form, showing distribution of the measured values. Standard deviations from the mean values are also given. Tests of the statistical significance of the data are discussed.

17. Key Words (Suggested by Author(s))
Solar cells
Terrestrial photovoltaics
Solar cell modules

18. Distribution Statement
Unclassified - unlimited
STAR Category 44
ERDA Category UC-63b

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

RESULTS OF MODULE ELECTRICAL MEASUREMENT OF THE DOE 46-KILOWATT PROCUREMENT

by H. B. Curtis

Lewis Research Center

E-9534

INTRODUCTION

In the period of April 1976 to January 1977, Lewis Research Center received over 6000 terrestrial solar cell modules as part of the DOE National Photovoltaic Tests and Applications Project. These modules were made by four manufacturers in fulfillment of their contracts with the Jet Propulsion Laboratory (JPL) for the Block I procurement of 46 kW of modules under the DOE/JPL Low Cost Silicon Solar Array Project. These modules are being used in a wide variety of power-producing applications, real time and accelerated endurance tests, and the DOE Systems Test Facility at NASA/Lewis. There is a need for current-voltage (I-V) data for these modules for several reasons. One is to establish electrical output data for efficient design of arrays; a second is to obtain baseline data for environmental and time-dependent performance testing; and a third is to determine if there are any serious potential mismatch losses.

Because over 6000 modules were involved, not every module was measured. I-V data, using a pulsed simulator, were taken on 661 of the modules with samples randomly distributed over the entire delivery schedule. This report presents the results of these I-V measurements in the form of distribution of short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power (P_{max}) for each of the four types of modules in the JPL Block I 46 kW procurement.

DESCRIPTION OF MODULES

Four manufacturers supplied modules (one module type per manufacturer) under the JPL Block I procurement. These module types are identified by the letters W, X, Y, and Z. The modules ranged in size from about 800 cm^2 to 2260 cm^2 and in maximum power from about 5 watts to 14 watts at 1000 W/cm^2 of irradiance. All module types were single series strings between 18 and 25 cells. Cell diameter ranged from 5 cm to 9 cm. All modules were completely encapsulated in silicone, with one type covered with a glass sheet about

3 mm thick. Two of the modules types were aluminum backed while the other two were fiberglass-epoxy composite backed.

MEASUREMENT APPARATUS AND TECHNIQUES

All of the I-V curves for this report were taken indoors at ambient conditions using a commercially purchased pulsed solar simulator. The simulator consists of a long arc, low pressure xenon lamp, a pulse forming network (power supply), and a computer-controlled data acquisition and reduction system. The lamp flashes for about 2 m-sec during which time approximately 50 points on the I-V curve are taken at 20 μ-sec intervals. The main advantage of the pulsed simulator is that there is no heating of the modules by the incident irradiance because of the short duration of the pulse. Hence the cell temperatures within the module are uniform and easily measured.

Cell temperature was measured by taping a small-bead thermocouple to the back of the module. Since the modules had been indoors for several hours at laboratory ambient conditions, it was assumed they were at thermal equilibrium and the module back surface was the same temperature as the cell. When several modules of the same type were being measured, it was assumed that all modules were at the same temperature and temperature measurements were only made occasionally.

For irradiance measurement, a reference cell, matched in spectral response to the cells in the module under test, was used. Four such reference cells were used, one for each manufacturer. The reference cells were calibrated outdoors at the NASA Lewis Research Center using an Eppley Normal Incidence Pyrheliometer as a standard (ref. 1).

The output of the reference cell was measured at each point of the I-V curve by the pulsed simulator data system to adjust small point-to-point variations in incident irradiance. The I-V data were corrected to standard test conditions of 1000 W/m^2 of irradiance and 28° C cell temperature (ref. 2) by the data system of the pulsed simulator. The irradiance of the simulator was set at a value between 960 and 1040 W/m^2 resulting in at most a 4 percent transformation in current due to irradiance corrections. The current and voltage temperature coefficients used to correct the measurements to 28° C were 25 μA/(cm$^2 \cdot$ C$^{\circ}$) and -2.1 mV/C$^{\circ}$. Since the data were all taken indoors in an ambient environment, the cell temperature was always near 28° C. The largest ΔT used in the data transformations was 8° C (28° - 20°).

In an effort to determine repeatability and stability of the data from the pulsed simulator, one module was measured several times during the

8 months data was being taken. These data indicate the system gives results repeatable to about 1 percent.

RESULTS AND DISCUSSION

I-V curves were taken on 661 modules using the pulsed simulator. They were divided among the module types as shown in Table I. Also shown in Table I are the number of modules received and the time span for receipt of modules. Because the pulsed simulator was not yet operational during a portion of the delivery schedule, some modules were measured outdoors in natural sunlight. For the sake of having the most consistent data, only pulsed simulator measurements are included in this report. It should also be noted that the last shipment of 280 modules from the 1940 modules of type W was shipped directly out without sampling measurements.

Figures 1(a), (b), and (c) show distribution of I_{sc}, V_{oc}, and P_{max}, respecitvely, for type W modules. The standard deviation is shown on each distribution. Also plotted is the normal curve fitted to the number of modules (174) for the given standard deviation. All distributions are normalized so that the average current, voltage on power is unity. Figures 2(a), (b), and (c); 3(a), (b), and (c); and 4(a), (b), and (c) show similar data for module types X, Y, and Z. In general, the distribution of data and the normal distribution will show a reasonably good agreement. This indicates that the data (I_{sc}, V_{oc}, and P_{max}) probably follow a normal distribution curve. The least exact agreements are for the type Y modules, for which there were only 84 measurements, compared to 174 to 203 measurements for the three other types of modules. Table II summarizes the standard deviations for all 12 distribution plots in figures 1 to 4. In all cases, the V_{oc} data have much smaller standard deviations than either the I_{sc} or P_{max} data. This is probably due to the fact that V_{oc} is much less sensitive than I_{sc} or P_{max} to small changes in incident irradiance. Hence V_{oc} is less affected by small differences in optical characteristics of cover glasses, encapsulants, and coatings.

The delivery schedules for the four types of modules occurred over several months (April 1976 to January 1977). I-V data were taken periodically in groups of about 20 similar modules over this entire time span. Figures 5 to 8 show normalized average values of I_{sc}, V_{oc}, and P_{max} plotted against group number for each of the four types of modules. Group number 1 is the first set of modules measured, group number 2 is the second set measured, etc. Group number is roughly proportional to time and delivery schedule. Inspection of figures 5 to 8 indicates no large discernable trends in the data through the entire delivery schedule. There are however some small variations in the average values of the measured data. It is of interest to determine if these small variations have any significant statistical meaning. The Student's t-test (ref. 3) may be used to answer the general question, "Do two samples of data, each having its own average and standard deviation, come from the identical population?" This is easily transformed to determining if a group measured early in the delivery schedule has a high probability of being from the same distribution as a later group. Each group has its own mean and standard deviation. The Student's t-test was applied to all combinations of two groups within a module type for I_{sc}, V_{oc}, and P_{max} data. In about 60 percent of the cases, it was probable that the two groups of modules could come from the same distribution. However this left about 40 percent of the cases where the two groups of modules probably came from different distributions. This indicates that there are some statistically significant changes in module output during delivery schedule. However, figures 5 to 8 indicate that changes are small and they are scattered throughout the delivery.

In any sampling set of measurements, there is a minimum number of data points required to obtain a certain probability that the measured sample mean is within a given percentage of the true mean. If it is assumed that the distribution is normal, the number of required data points is proportional to the square of the standard deviation and inversely proportional to the square of the percentage difference between measured and true mean (ref. 4). Using the largest measured standard deviation for I_{sc}, V_{oc}, and P_{max} (4.66 percent), it was calculated that 84 measurements are necessary to have a 95 percent probability that the measured mean is within 1 percent of the true mean. 145 measurements are required to obtain a 99 percent probability. Hence for all modules except the Y type, there is over a 99 percent probability that the measured mean is within 1 percent of the true mean of all the modules in the procurement. Since only 84 measurements were taken on the Y modules, there is only a 95 percent probability that the two means are identical within 1 percent.

CONCLUSIONS

Current-voltage measurements using the pulsed simulator have been made on 661 modules from the DOE/JPL 46 kW procurement. These measured modules were randomly selected from over 6000 modules from four manufacturers delivered to Lewis as part of the DOE National Photovoltaic program. The data indicated two major items.

1. The modules of each manufacturer were fairly closely grouped in terms of short-circuit current, open-circuit voltage and maximum power. Standard deviations ranged between 3.3 and 4.7 percent for I_{sc} and P_{max} between 0.8 and 1.7 percent for V_{oc}.

2. There were no large observable trends in data throughout the module delivery schedule.

REFERENCES

1. Weizer, V. G.: Consideration of Design and Calibration of Terrestrial Reference Solar Cells. Terrestrial Photovoltaic Measurements, II. ERDA/NASA 1022/76/4, NASA CP-2010, 1976, pp. 203-222.

2. Brandhorst, Henry; et. al.: Interim Solar Cell Testing Procedures for Terrestrial Applications. NASA TM X-71771, 1975.

3. Schenck, Hilbert, Jr.: Theories of Engineering Experimentation. Second ed. McGraw Hill Book Co., Inc., 1968.

4. Meyer, Stuart L.: Data Analysis for Scientests and Engineers. John Wiley & Sons, 1975.

TABLE I. - NUMBER OF MODULES RECEIVED AND MEASURED

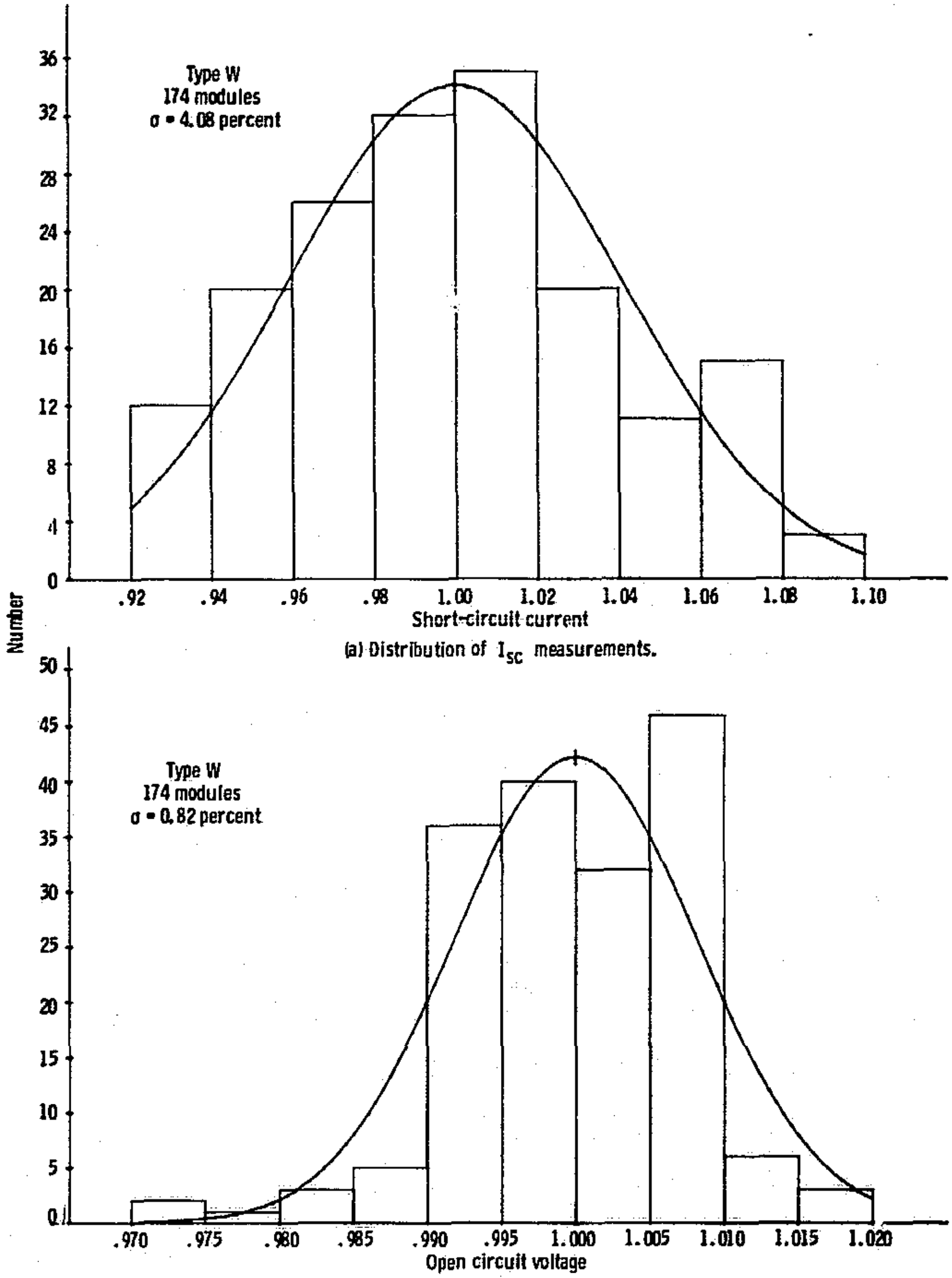
AND TIME SPAN FOR RECEIPT OF MODULES

Module type	Number received	Number measured in pulsed simulator	Span of receiving time
W	1940	174	June - Nov. 1976
X	1522	203	May - Sept. 1976
Y	1026	84	April - Oct. 1976
Z	1847	200	May 1976 - Jan. 1977
Totals	6335	661	

TABLE II. - STANDARD DEVIATION FOR MODULES

FROM 46-KILOWATT PROCUREMENT

Module type	Number of measurements	I_{sc}, percent	V_{oc}, percent	P_{max}, percent
W	174	4.08	0.82	4.21
X	203	3.56	1.18	3.37
Y	84	4.66	1.65	4.63
Z	200	3.61	1.23	3.84

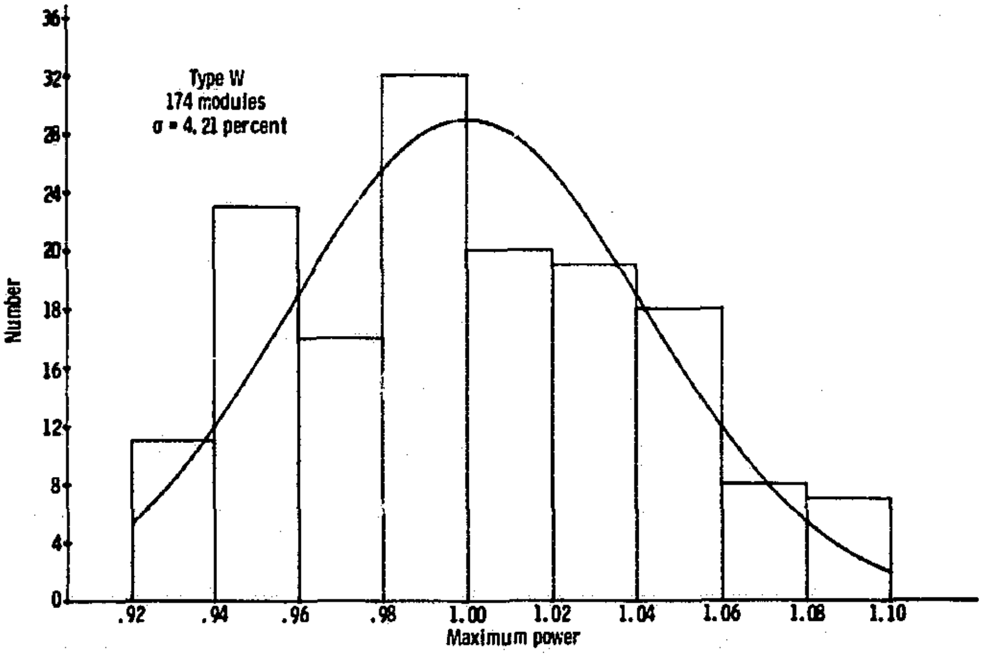


(a) Distribution of I_{sc} measurements.

(b) Distribution of V_{oc} measurements.

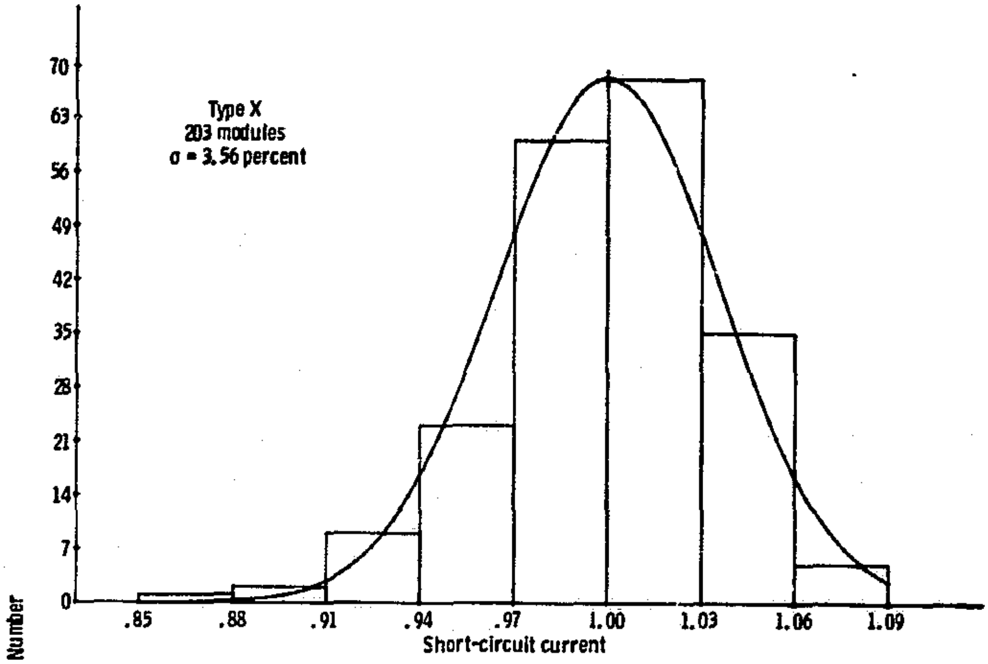
Figure 1. - Distribution of I_{sc}, V_{oc}, and P_{max} for Type W modules.

ORIGINAL PAGE IS
OF POOR QUALITY

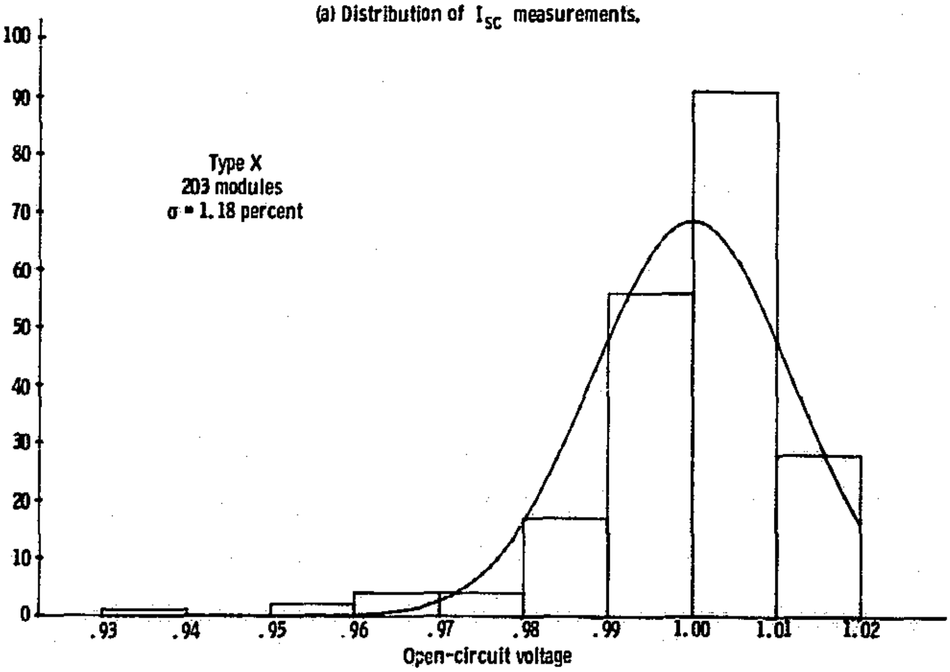


(c) Distribution of P_{max} measurements.

Figure 1. - Concluded.

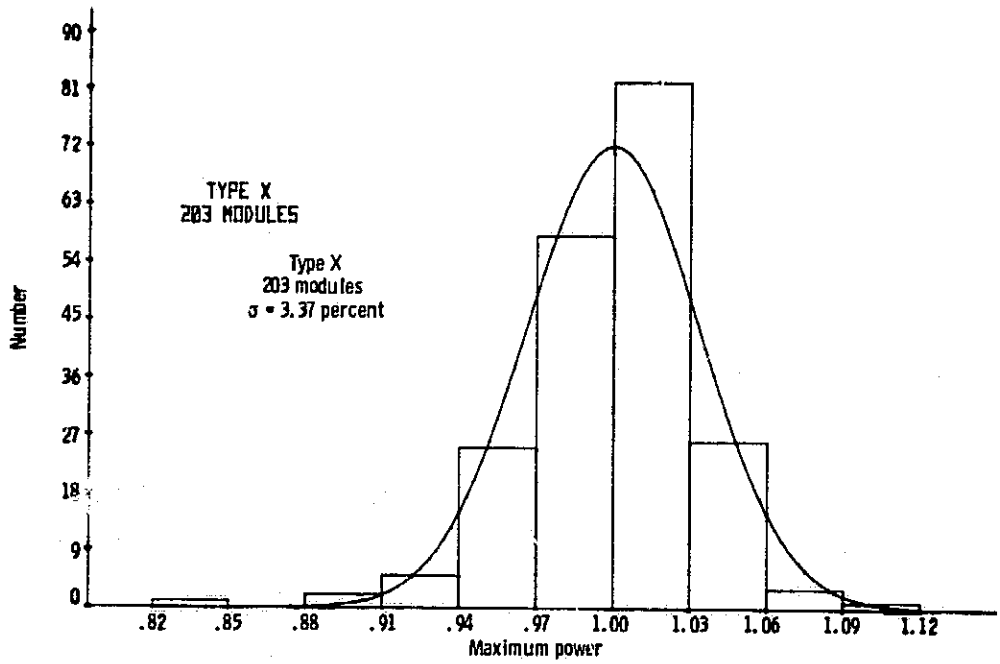


(a) Distribution of I_{sc} measurements.



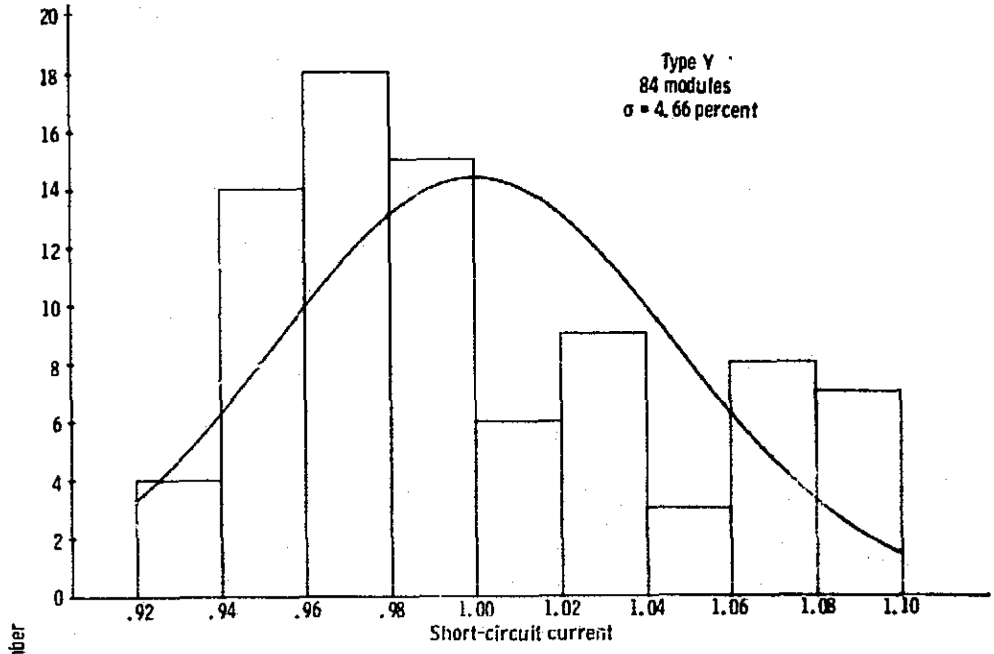
(b) Distribution of V_{oc} measurements.

Figure 2. - Distribution of I_{sc}, V_{oc}, and P_{max} for Type W modules.

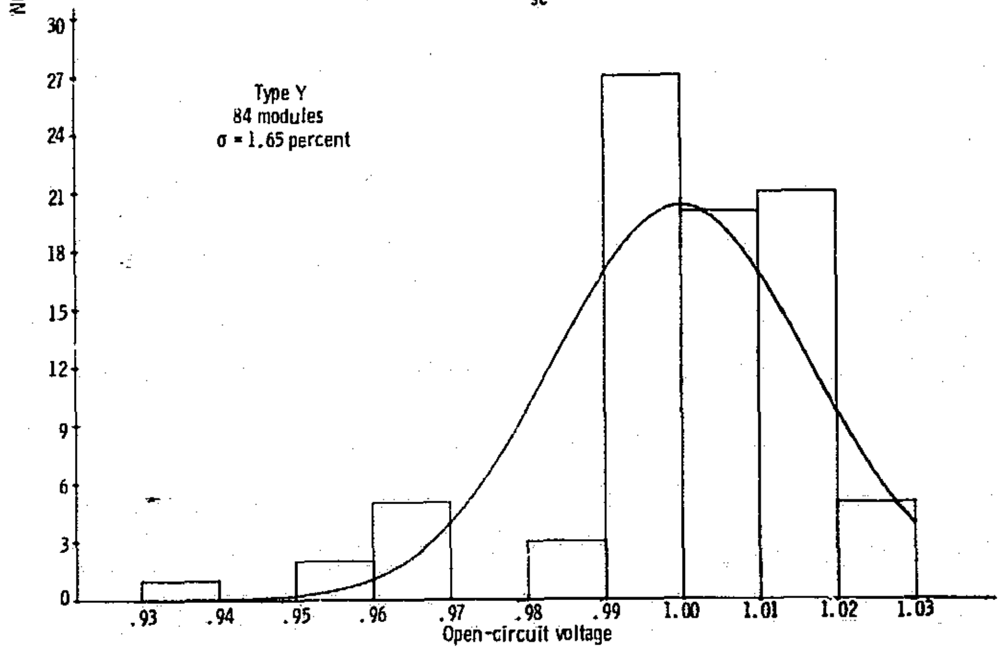


(c) Distribution of P_{max} measurements.

Figure 2. - Concluded.



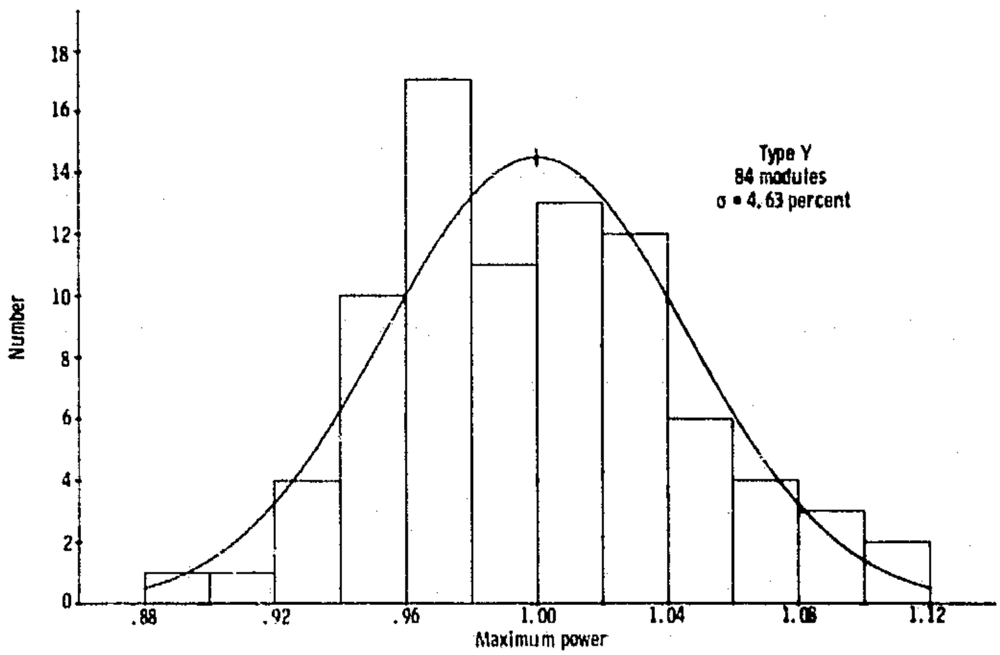
(a) Distribution of I_{sc} measurements



(b) Distribution of V_{oc} measurements.

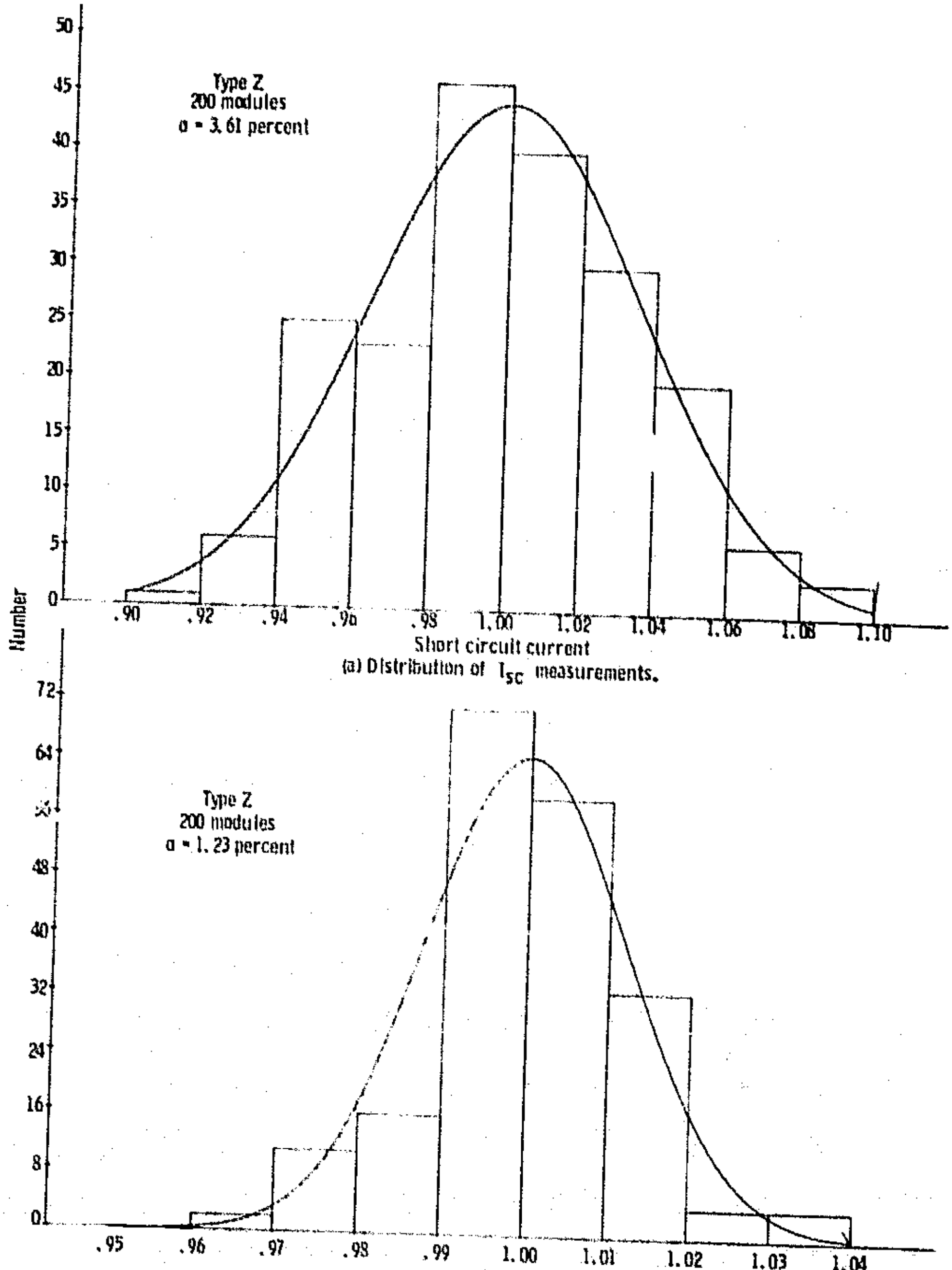
Figure 3. - Distribution of I_{sc}, V_{oc}, and P_{max} for Type Y modules.

ORIGINAL PAGE IS
OF POOR QUALITY



(c) Distribution of P_{max} measurements.

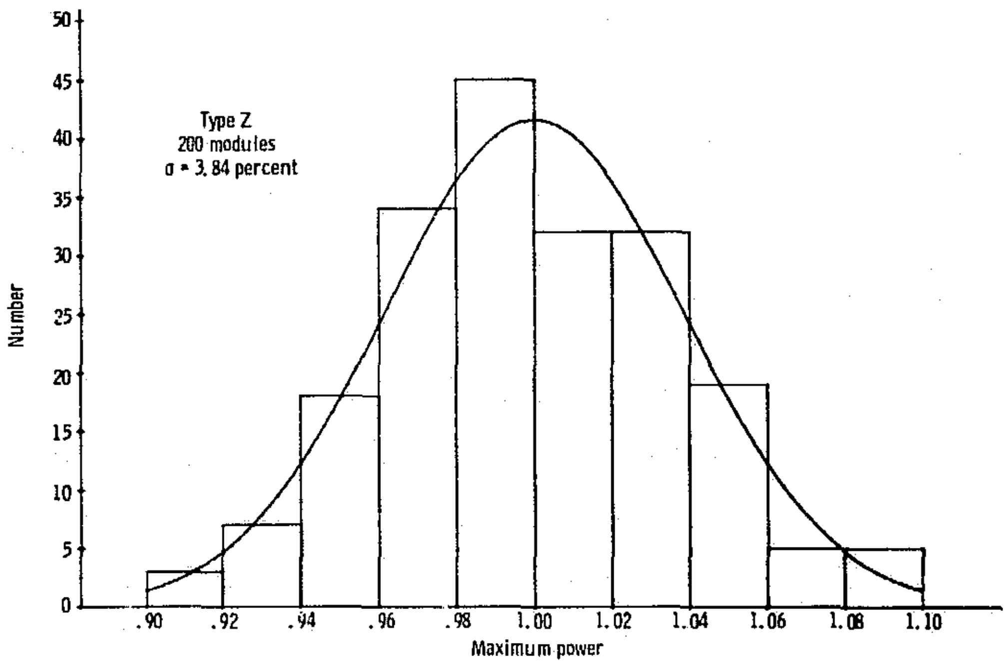
Figure 3. - Concluded.



(a) Distribution of I_{sc} measurements.

(b) Distribution of V_{oc} measurements.

Figure 4. - Distribution of I_{sc}, V_{oc}, and P_{max} for Type Z modules.



(c) Distribution of P_{max} measurements.

Figure 4. - Concluded.

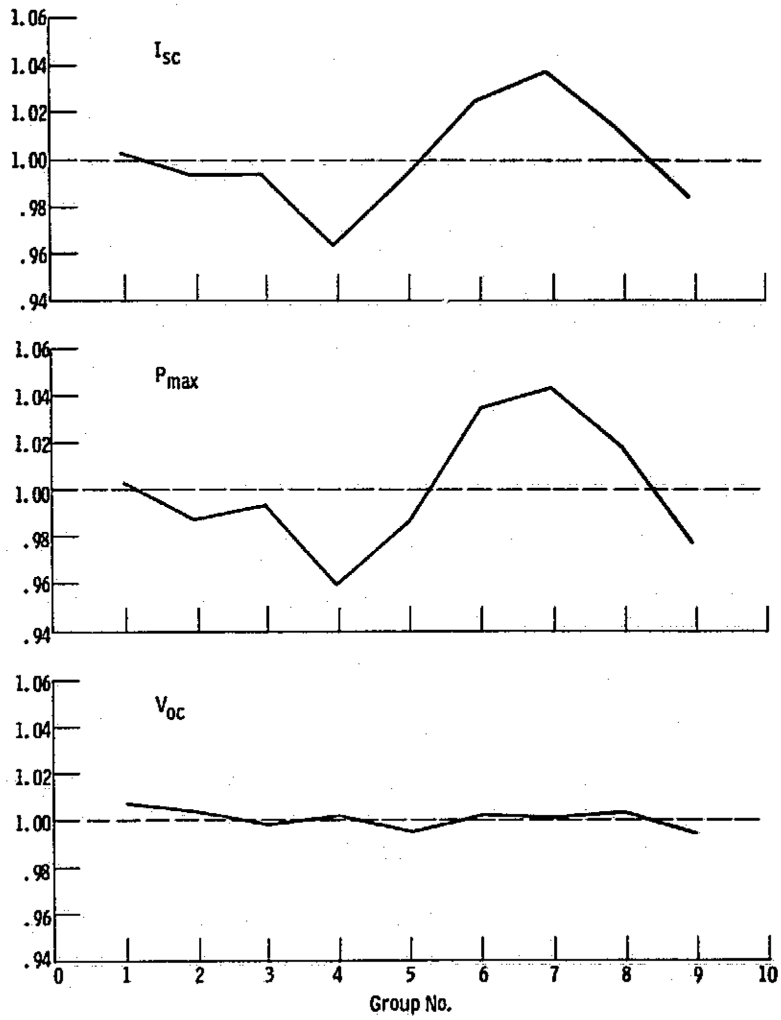


Figure 5. - Type W measured module parameters versus group number.

ORIGINAL PAGE IS
OF POOR QUALITY

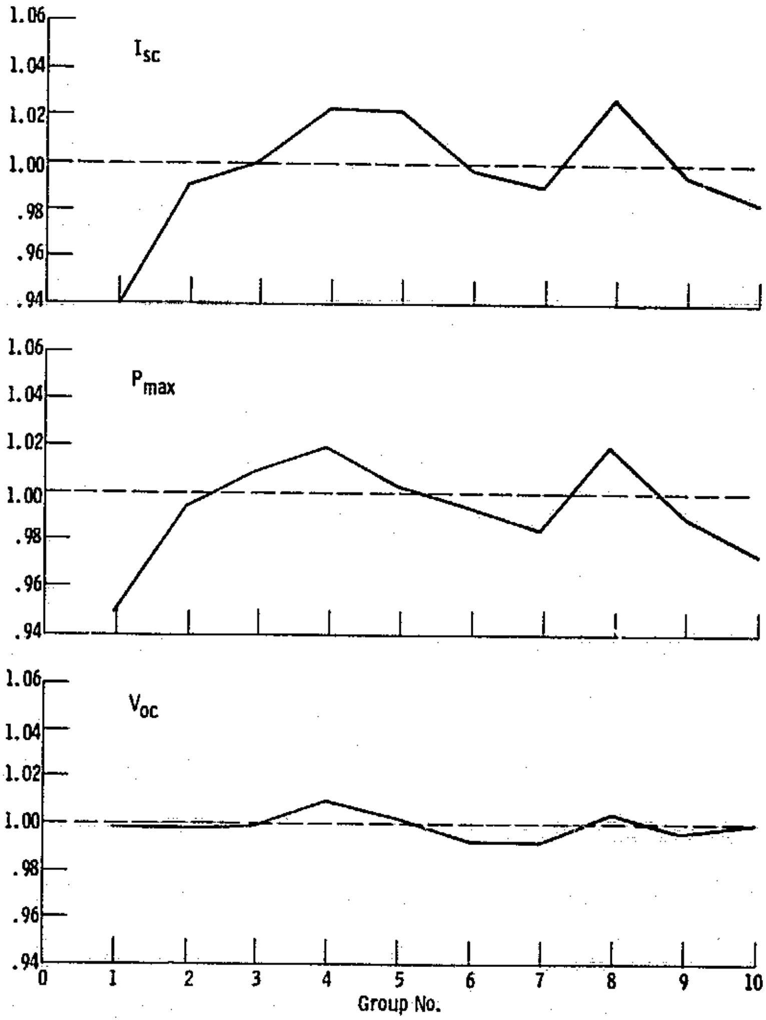


Figure 6. - Type X measured module parameters versus group number.

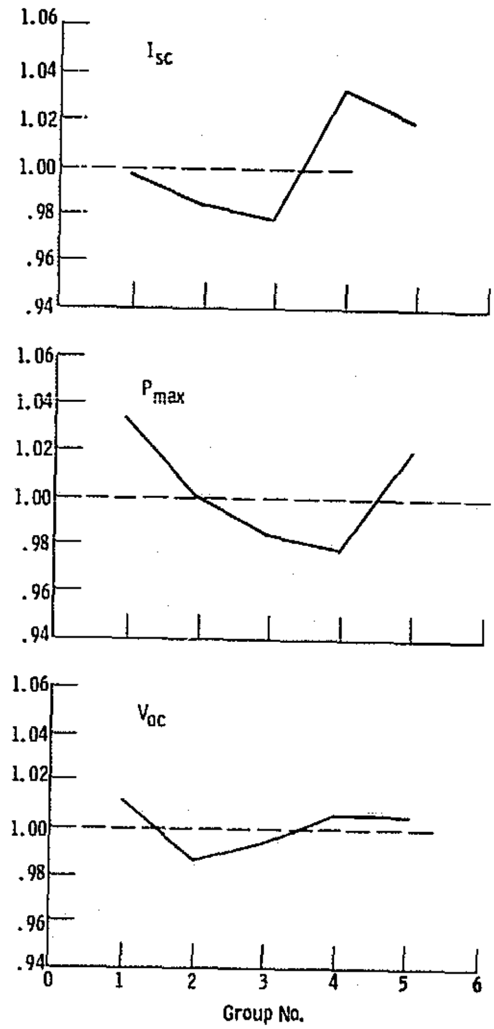


Figure 7. - Type Y measured module parameter versus group number.

ORIGINAL PAGE IS OF POOR QUALITY

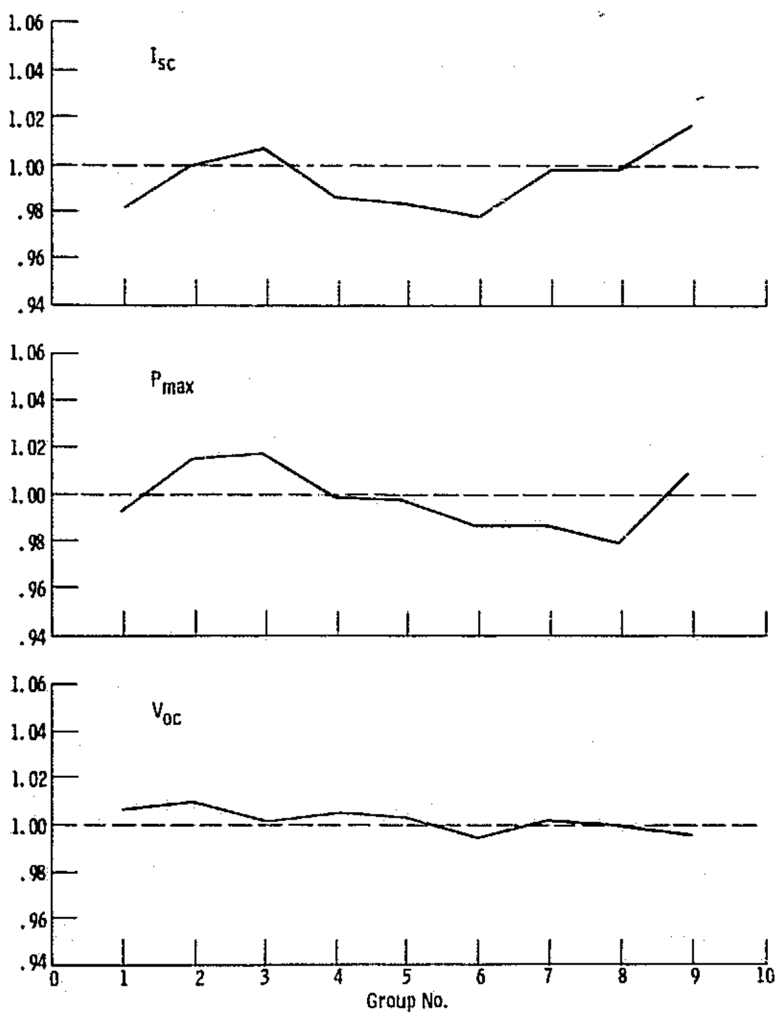


Figure 8. - Type Z measured module parameters versus group number.