TG 1103

FEBRUARY 1970

Copy No.

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Operating under Contract NOw 62-0604-c with the Department of the Navy

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
SILVER SPRING MARYLAND

ABSTRACT

This report describes the Solar Panel Test Set developed for testing solar cell panels in artificial sunlight at an equivalent sunlight intensity of 140 mW/cm^2. The test set uses iodine-quartz (tungsten) lamps as the radiant-energy source, and the emerging radiation is uniformly reflected and totally diffused. An air conditioner, which is part of the test set, provides the cooling air necessary to control the temperature of the solar panel under test. The methods of calibrating the test set are described, and the accuracy of the measurement obtained when using artificial light as the radiation source is discussed.

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ILLUSTRATIONS

1. INTRODUCTION

The Solar Panel Test Set is used to functionally test solar panels of current and future APL-built satellites, using controlled illumination to test the solar panel power output in accordance with the design specifications. In addition, the test set is helpful in determining and isolating malfunctions.

The sunlight method for testing solar panels has always presented a problem. There are few cloud-free days with uniform light intensity; therefore, the panels must be tested with existing sunlight conditions, and then the resulting data must be normalized. In the past, many tests on the solar panels and the satellite were delayed or not run because of insufficient sunlight at the scheduled test time. Also, control of the temperature of solar panels being tested in sunlight is difficult, if not impossible, whereas the artificial sunlight of the test set permits the temperature of the solar panel to be measured and controlled.

2. DESCRIPTION

The design of the test set permits solar panels as large as 20 by 55 inches to be tested, with the illumination intensity on the surface of the panel being held within 2% of an equivalent sunlight air mass zero (AM = 0) intensity of 140 mW/cm^2. Larger panels may be tested, but there is a slight degradation of uniformity in the illumination plane. The test set is illustrated in Fig. 1. The major assemblies are the illuminator, solar panel test fixture, air conditioner, power control system, instrumentation rack, and calibration scanner.

The illuminator consists of a rectangular box, approximately 95 inches long, 72 inches wide, and 72 inches high. The sides and roof of the box are made of aluminum panels attached to an aluminum structure that is supported by four legs. A radiant-energy source, located on the ceiling of the illuminator, consists of twenty 1000-watt, 2000-hour iodine-quartz (tungsten) lamps that are capable of maintaining a constant intensity output throughout their rated life. The lamps, mounted in ceramic lamp sockets that are supported on bracket assemblies, are suspended approximately 7 inches from the ceiling of the illuminator. The top portion of the illuminator consists of a cold-air plenum and a hot-air exhaust system. The pressurized air in the cold-air plenum is used to cool the lamp sockets, while the hot-air exhaust system pulls the hot air generated by the lamps out through the top of the illuminator and into the air conditioner.

The solar panel test fixture is a movable carriage that supports the solar panel being tested and allows it to be located in a predetermined position beneath the radiant-energy source. A reversible motor, mounted on the base of the test fixture and coupled to a counter, permits the vertical position of the test fixture to be set accurately.

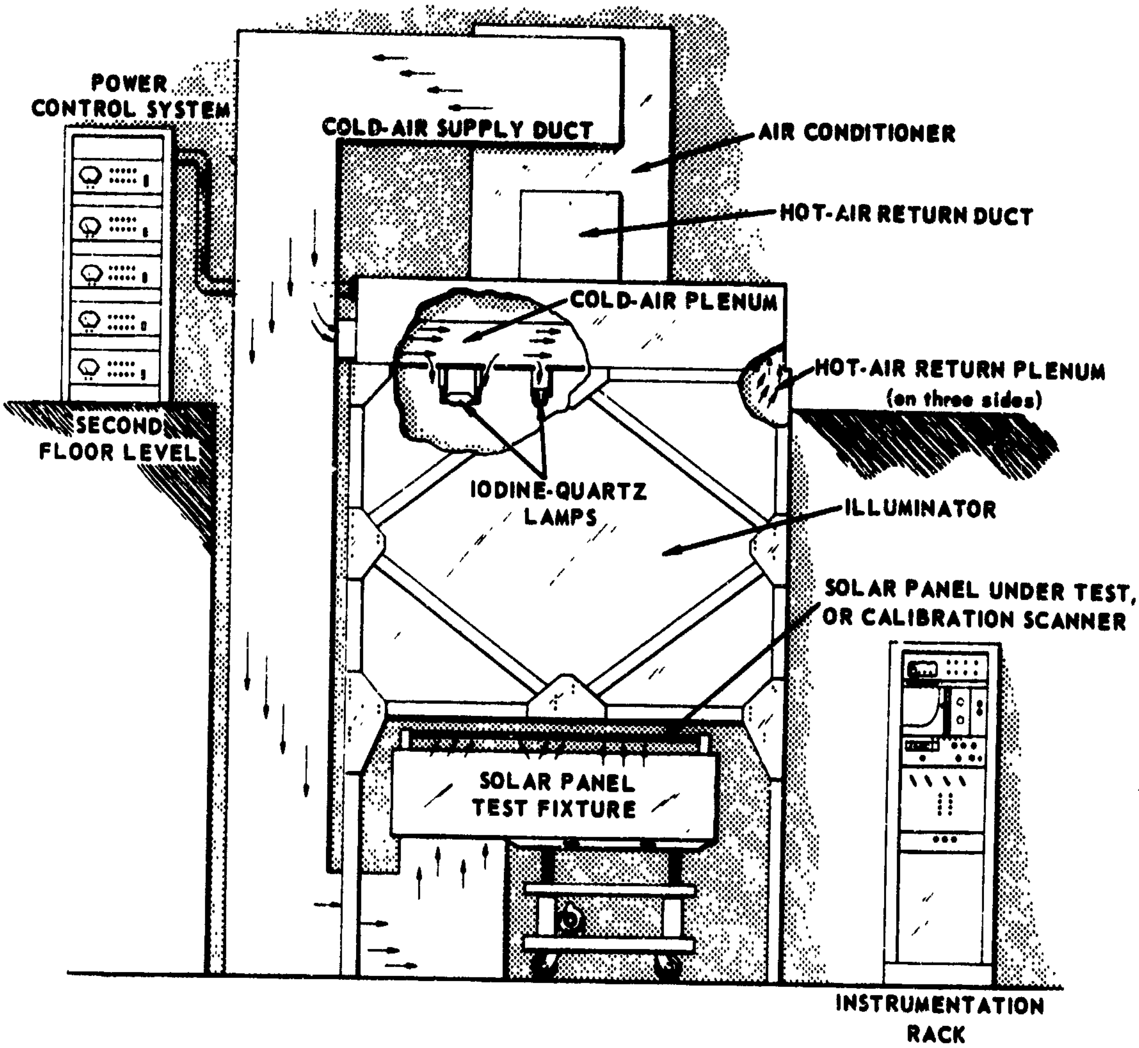

Fig. 1 SOLAR PANEL TEST SET

An airflow and cooling system for the solar panel under test is provided by a 7½-ton air conditioner. Air is fed into the plenum chamber through regulators that direct the air to the underside of the solar panel. The temperature of the solar panel is controlled by adjusting the direction of the air that passes through the regulators.

The power control system includes a power rack and a power distribution panel. Five voltage regulators for the lamp circuits are located in the power rack, along with the necessary cooling fans. The power distribution panel contains the relays and interlocks that operate the lamps and the air conditioner. The interlocking relays are so placed in the system that an air-conditioner failure resulting in either no circulation of air or improper cooling of the returned hot air would cause the power to the lamp voltage regulator to be turned off.

The instrumentation rack contains the equipment required for measuring the output current and voltage of the solar panel under test; these measurements are plotted on an X-Y recorder. The temperature-measuring instruments, the load, and the digital voltmeter are also located in the instrumentation rack.

The calibration scanner is a device that is attached to the solar panel test fixture whenever calibration is to be performed. By means of a standard solar cell and thermistor, it measures the intensity at each point in the solar-panel plane. The standard cell must be of the same dimensions (2 by 2 cm) and spectral characteristics as those of the solar panel. The standard cell and the thermistor are mounted on a platform that can be remotely maneuvered to any location within the illuminator. The standard cell measures the actual intensity, and the thermistor permits the intensity measurements to be correlated with temperature.

3. THEORY OF OPERATION

The radiation emerging from the illuminator (in which the radiation from each lamp is uniformly reflected and totally diffused) is independent of lamp position and differences in lamp intensities. The proper intensity of illumination is achieved by maintaining a minimum number of lamps and by providing diffuse reflectors with high coefficients of diffusion and reflectivity. A white paint (3M Velvet White) is used on the walls as the diffuse-reflector material. Specular reflectors are used on the lower walls of the illuminator, so that a uniform intensity pattern is obtained on the surface of the solar panel. The intensity of emerging illumination is held uniform to within 2% across the surface of the solar panel.

In its operation the Solar Panel Test Set does not simulate the spectral distribution of the sun at air mass zero. The simulation of the sun's spectral distribution is a science in itself, and an attempt at such a simulation in near space would needlessly complicate the test set.

The electrical output of a solar cell, I_{sc} (short-circuit current), is a linear function of the intensity of the incident solar radiation. Figure 2 shows the spectral distribution of the sun and the spectral response of a silicon solar cell. Both are normalized for illustration purposes. The short-circuit current of the solar cell is expressed by the equation:

$$I_{sc} = \int_0^\infty K R_{sc}(\lambda) \cdot R_s(\lambda) d\lambda , \qquad (1)$$

where

I_{sc} = short-circuit current of solar cell,

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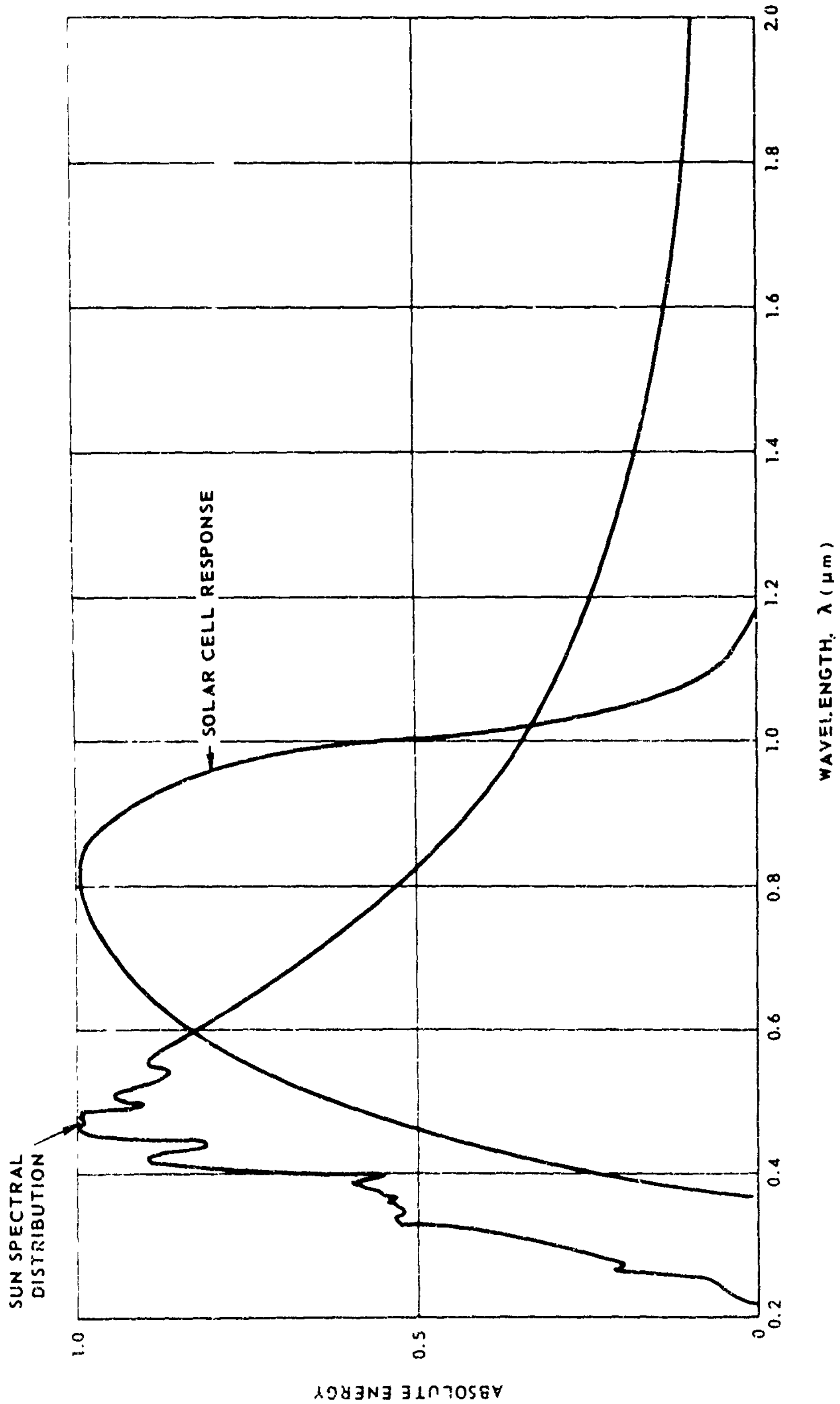

Fig. 2 SUN SPECTRAL DISTRIBUTION, SOLAR CELL RESPONSE VERSUS WAVELENGTH

K = scale factor to correct relative response to absolute response,

R_{sc} = relative spectral response of solar cell,

R_s = relative spectral distribution of the sun.

As Eq. (1) shows, the solar cell does not convert all radiant energy of the sun into electrical energy but only converts that energy falling within the spectral response of the solar cell.

Now, consider the spectral distribution of the iodine-quartz lamps and the spectral response of the solar cell, as shown in Fig. 3. The short-circuit current in this case is expressed by the equation:

$$I_{sc} = \int_0^\infty KR_{sc}(\lambda) \cdot R_T(\lambda)d\lambda \,, \tag{2}$$

where

R_T = relative spectral distribution of tungsten.

Similarly, the solar cell will convert that portion of the radiant energy of the iodine-quartz lamps that falls within the spectral response of the solar cell.

Although the spectral distributions of the iodine-quartz lamps and the sun are different, the solar cell is responsive to a certain portion of the spectral distribution of each. By adjusting the number of lamps used and the lamp color temperature, the electrical output of the solar cell exposed to the radiant energy of the test set can be made to produce the same electrical output that it would produce in space. The test set intensity is controlled by a standard solar cell, which has been carefully calibrated in sunlight and also in a solar simulator. It is important that the solar cells or solar arrays being tested have the same spectral response as the standard solar cell; therefore, they are all selected from the same production lot.

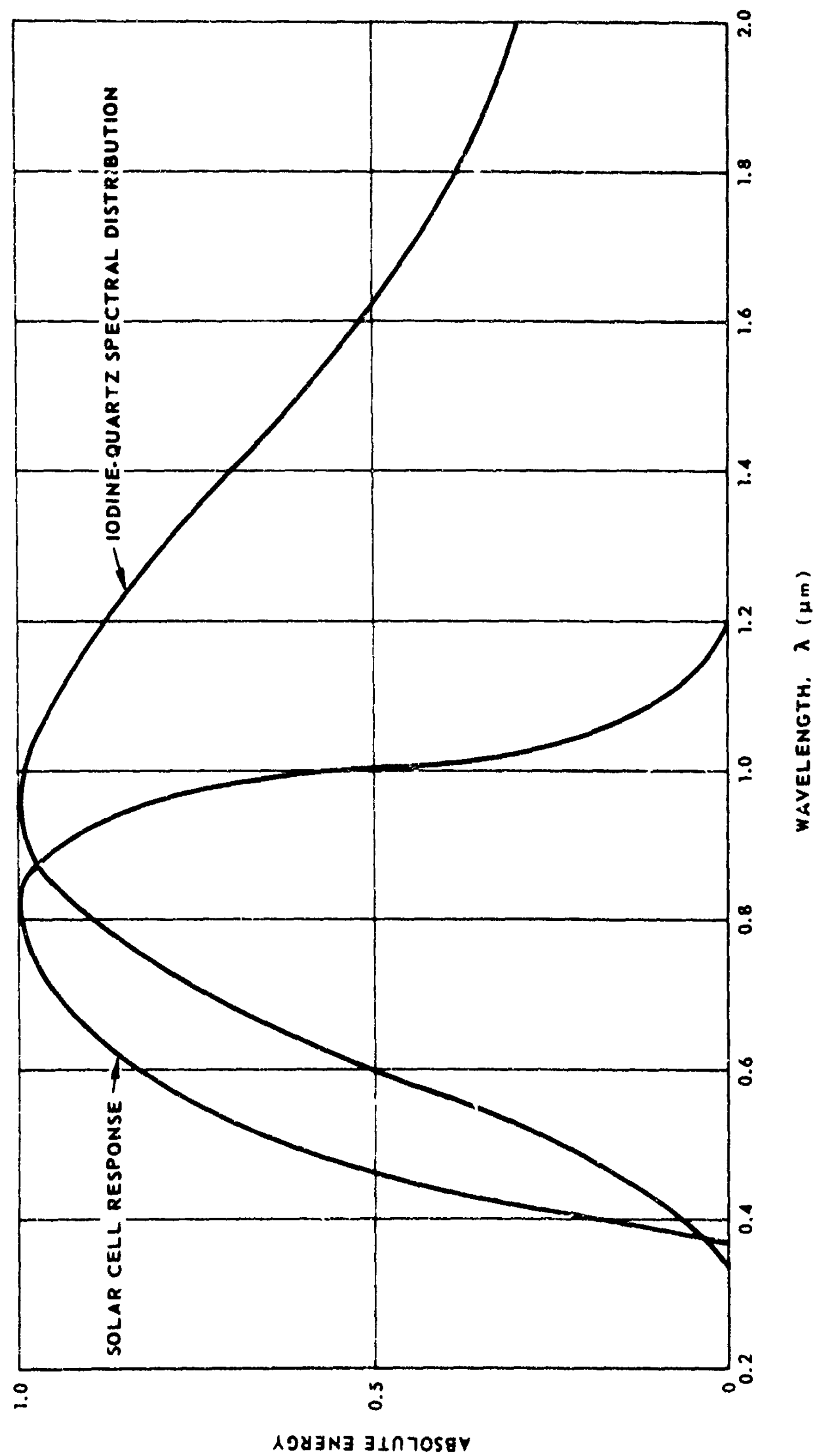

Fig. 3 IODINE-QUARTZ SPECTRAL DISTRIBUTION, SOLAR CELL RESPONSE VERSUS WAVELENGTH

As can be seen in Fig. 3, the electrical output of the solar cell will change if there is a change in the spectral response.

The illuminator is so designed and built that the radiation energy reaching the array under test is totally diffused from a multiunit radiant-energy source rather than collimated from a single-point radiant-energy source. The total diffusion of the light is accomplished by distributing the iodine-quar . lamps on the ceiling of the illuminator and by painting t. e ceiling and wall of the illuminator with a white paint that has a high coefficient of diffusion and reflectivity. Specular reflectors are placed on the lower walls of the illuminator so that the intensity at the bottom of the test plane will not vary more than 2% across the area where the array will be located. Figure 4 shows the irradiation at the test plane with and without the reflectors at the bottom of the illuminator. Figure 5 shows the directional reflectance of the 3M Velvet White paint, used on the walls of the illuminator, at various viewing angles when illuminated from an angle of -70°. The paint does not burnish to a higher gloss, and thus the walls of the illuminator can be kept clear by periodic cleaning with a mild detergent.

The characteristics of the iodine-quartz lamp are shown in Figs. 6 and 7. Figure 6 shows the color temperature as a function of the supply voltage. As can be seen from the graph, a 3% change in voltage from the power supply will cause a change of color temperature of less than 1%. Figure 7 shows the lamp output in lumens as a function of the supply voltage.

The AC voltage across the lamps is regulated by five voltage regulators (four lamps for each regulator). The regulators are capable of maintaining the load voltage to within ±1%, with input voltage variations of ±10%.

The lamps and the illuminator are protected against excessive temperatures by means of interlocks with the plenum airflow and temperature sensors. Loss

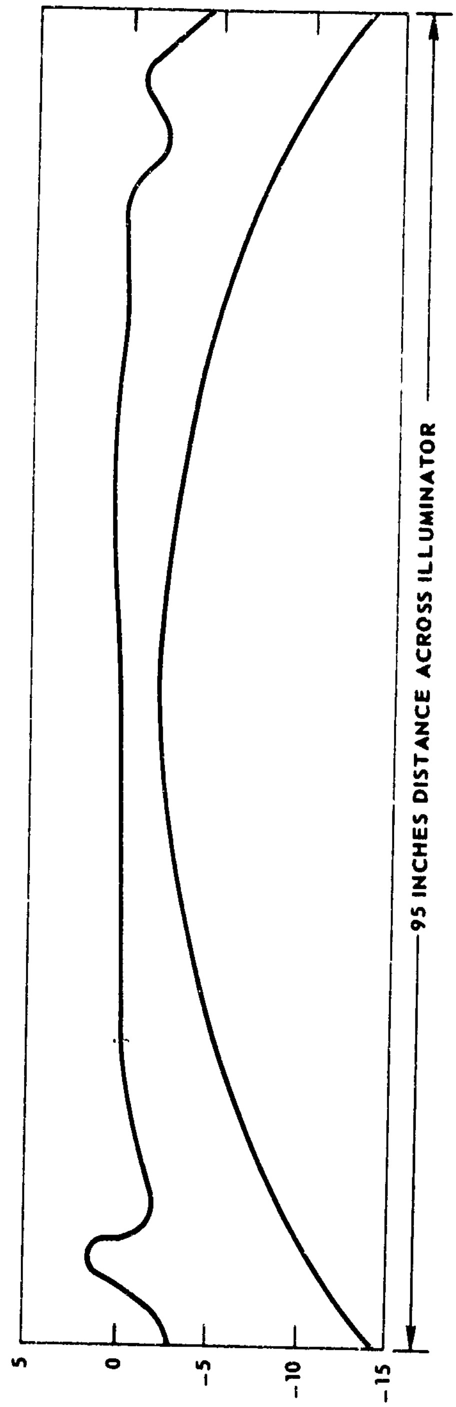

Fig. 4 ILLUMINATOR EMERGING-INTENSITY PATTERN

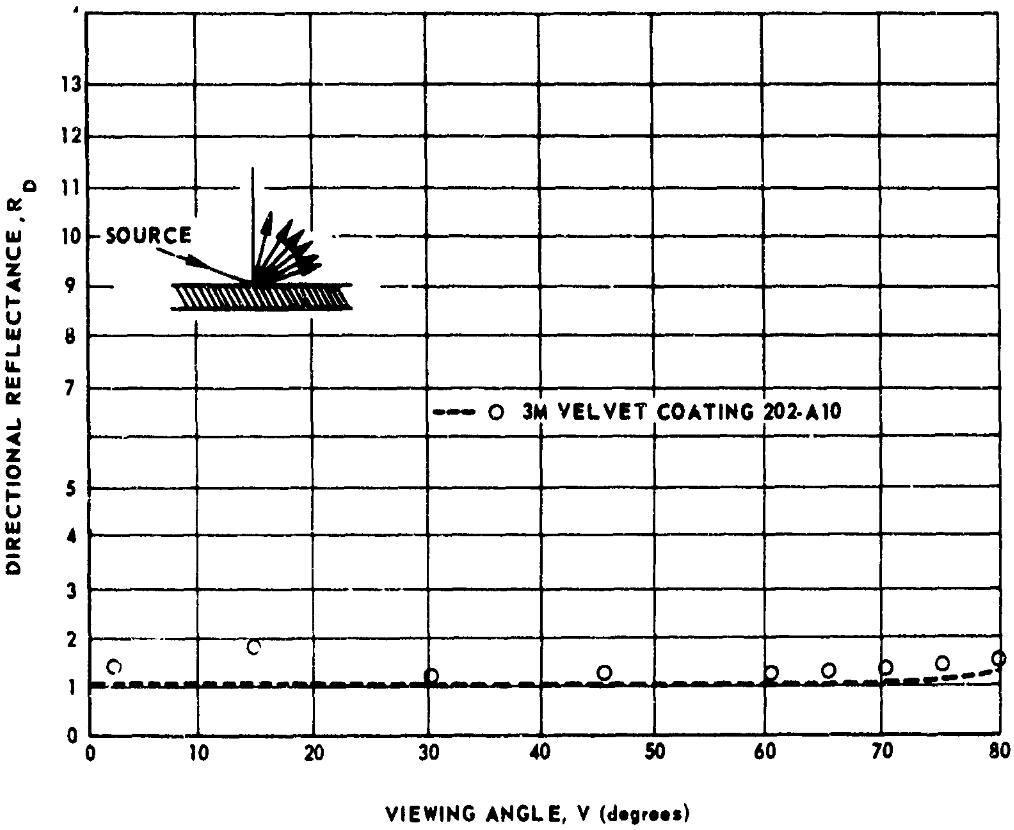

Fig. 5 DIRECTIONAL REFLECTANCE VERSUS VIEWING ANGLE, SOURCE AT −70°

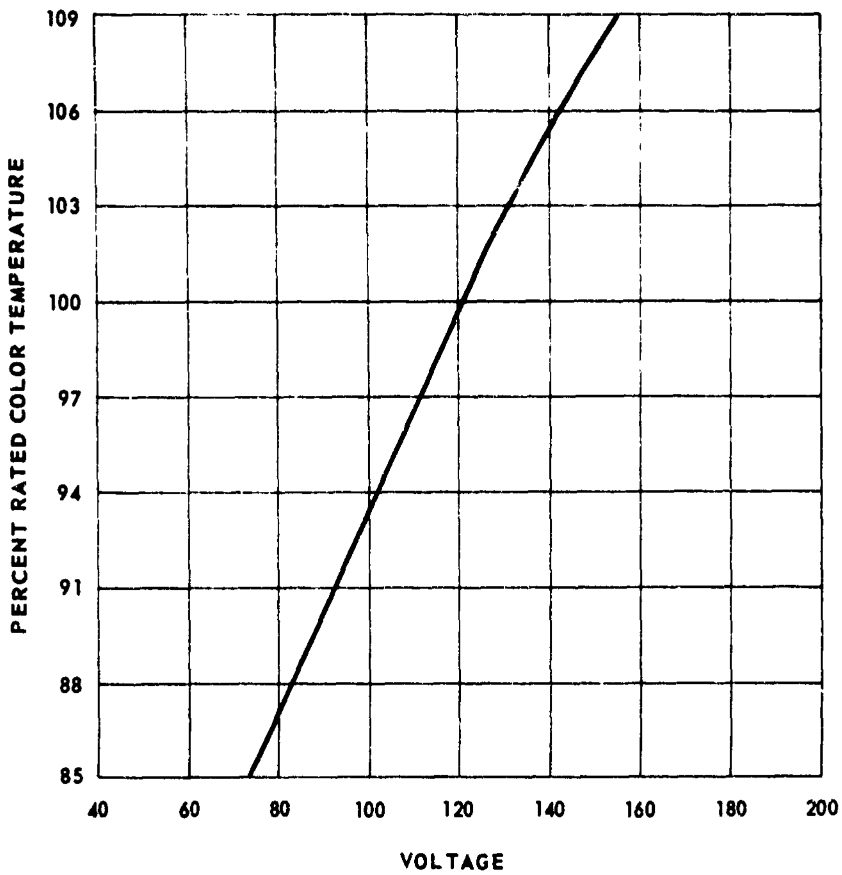

Fig. 6 IODINE-QUARTZ LAMP COLOR TEMPERATURE AS A FUNCTION OF SUPPLY VOLTAGE

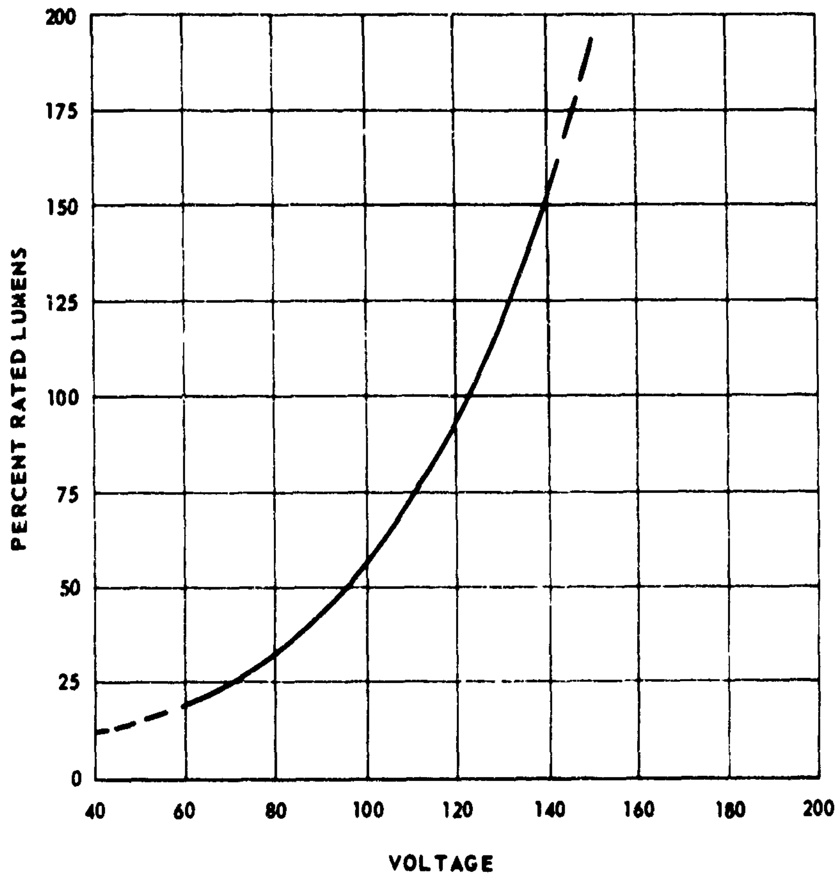

Fig. 7 IODINE-QUARTZ LAMP OUTPUT IN LUMENS AS A FUNCTION OF SUPPLY VOLTAGE

of the cold airflows will open an air-vane switch located in the outlet duct, and too high temperature of the air returned to the air conditioner will open the temperature-sensor switch. The actuation of either switch will deenergize the lamps.

The solar panel test fixture (Fig. 8) provides a means for positioning the solar panel vertically under the illuminator, with a high degree of repeatability, by means of a factional-horsepower gear motor that is mechanically coupled to the four legs of the fixture. A mechanical counter attached to the test fixture and geared to the drive motor indicates the height of the test fixture to the nearest 10 mils (0.010 inch). The total possible vertical travel of the solar panel mounted in the test fixture is approximately 18 inches.

The test fixture also provides the controlled cooling needed for accurate measurement of the solar panel output. The temperature across the panel is maintained constant by means of the airflow to the panel through the air duct system, which is an integral part of the solar panel test fixture. The top of the air plenum is fitted with four air registers, and the airflow through these registers is controlled by two sets of deflection vanes set in the register at 90° angles to each other. In addition, each air register has an airflow damper that controls the air passing through it.

The solar panel bracket, which holds the solar panel being tested on the test fixture, is designed to accommodate the Navy Navigation Satellite, OSCAR, solar panels. The bracket prevents any movement of the blade that could be caused by the cooling air from the air register putting pressure on the underside of the solar panel. A blade-mounting adapter can be attached to accommodate solar arrays of different shapes, such as those used on the GEOS-type satellites. The bracket is also designed to accommodate the calibration scanner.

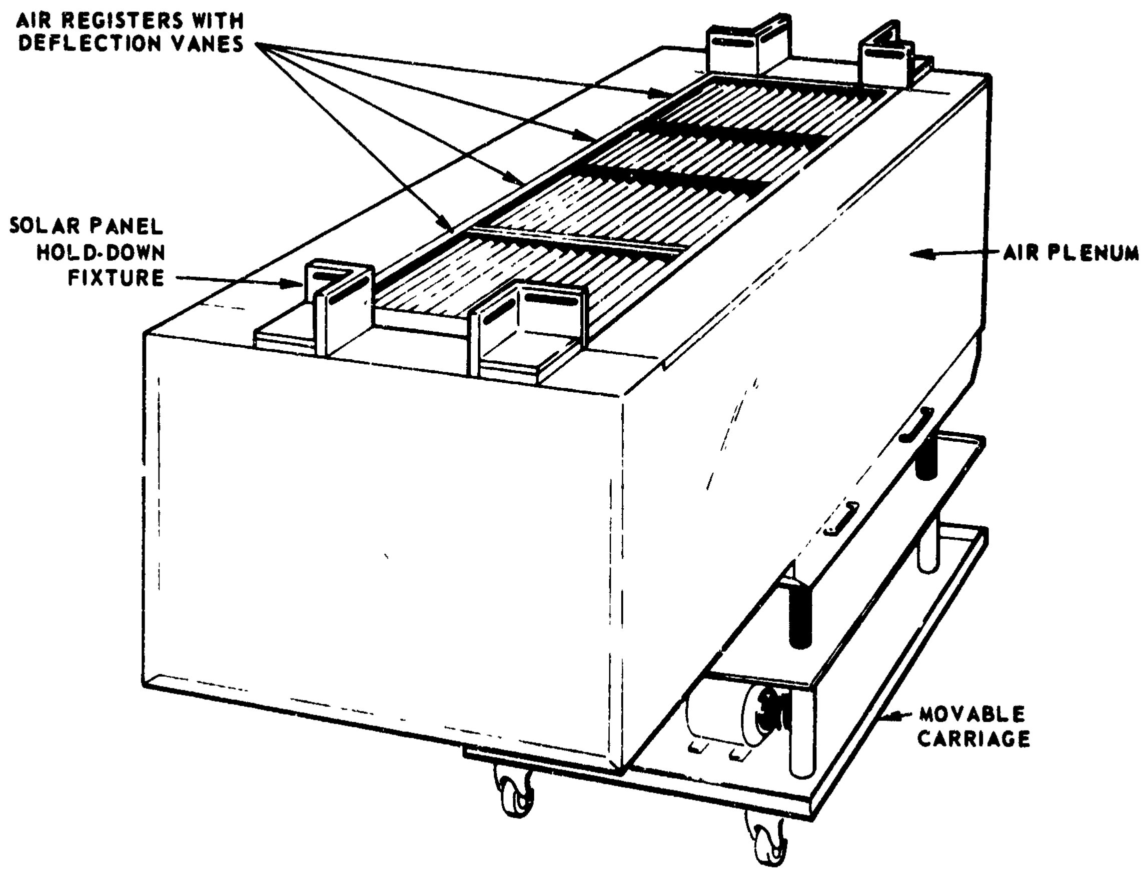

Fig. 8 SOLAR PANEL TEST FIXTURE

The equipment located in the instrumentation rack measures the electrical output characteristics of the solar array under test and, in most cases, presents the information in the form of a permanent current-voltage (I-V) curve plotted on the X-Y recorder. The voltage potential across a circuit of an array under test is plotted on the X-axis of the recorder. The current is recorded on the Y-axis by means of the voltage drop across a precision resistor. The temperature of the solar panel is monitored by thermistor probes that are attached to the solar panel during test. The digital thermometer indicates the temperature in degrees centigrade from any one of four selectable channels. The digital voltmeter and the precision ammeter are used to calibrate the system.

The air-conditioning system is a closed-loop system; that is, the hot air generated by the iodine-quartz lamps and the solar panel is returned to the air conditioner to be cooled and recirculated. The unit has a two-stage compressor. The cool air is fed into the inner air plenum at the top of the illuminator for cooling the lamps and lamp sockets and is also fed to the solar panel test fixture. The cool-air duct is connected to the solar panel test fixture by means of a flexible coupling, which permits the test fixture to be raised and lowered while the air conditioner is operating.

The electrical distribution system and the safety interlock system are shown in Fig. 9.

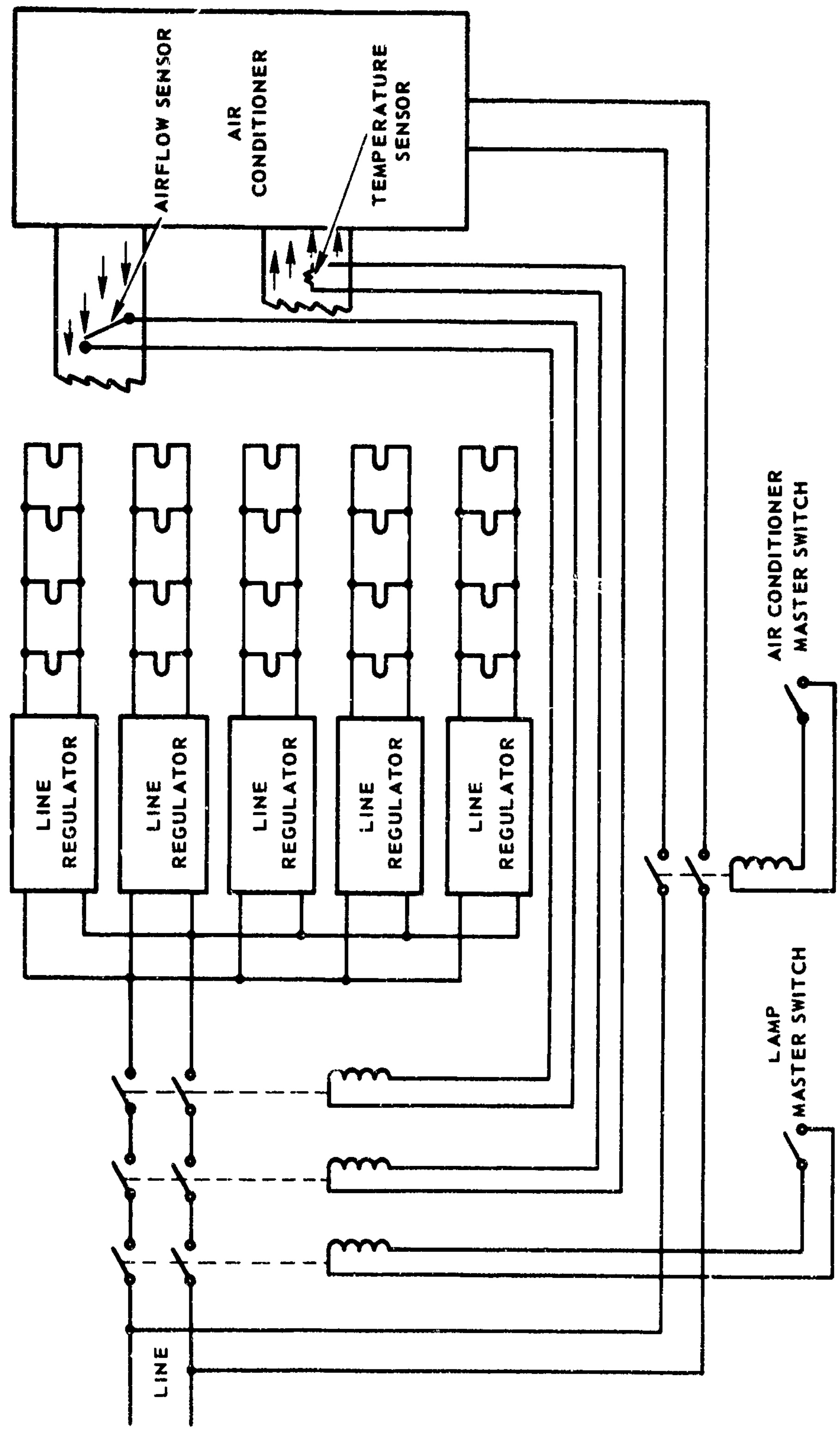

Fig. 9 POWER CONTROL SYSTEM

4. CALIBRATION

The illuminator is calibrated to determine the uniformity of the intensity level in a plane at the test level. The calibration scanner consists of a two-axis traversing mechanism to which a platform is attached in such a way that the platform can travel to any location within the illuminator at a predetermined height. Mounted on the platform are a standard solar cell and a thermistor with leads going from the platform to the instrumentation rack. The standard solar cell short-circuit current is plotted on the Y-axis of the X-Y recorder, and the location of the platform along the long axis of the illuminator is plotted on the X-axis. By moving the platform in 2-inch increments along the short axis and traversing the platform along the long axis, the short-circuit current of the standard solar cell can be plotted for the entire test-plane area. Since both the current and voltage characteristics of a solar cell temperature-dependent, the temperature of the standard cell is concurrently displayed on the digital thermometer.

Figure 10 shows the percent variance of the irradiation intensity in the test plane as measured by a 2 by 2 cm, 10 ohm-cm solar cell.

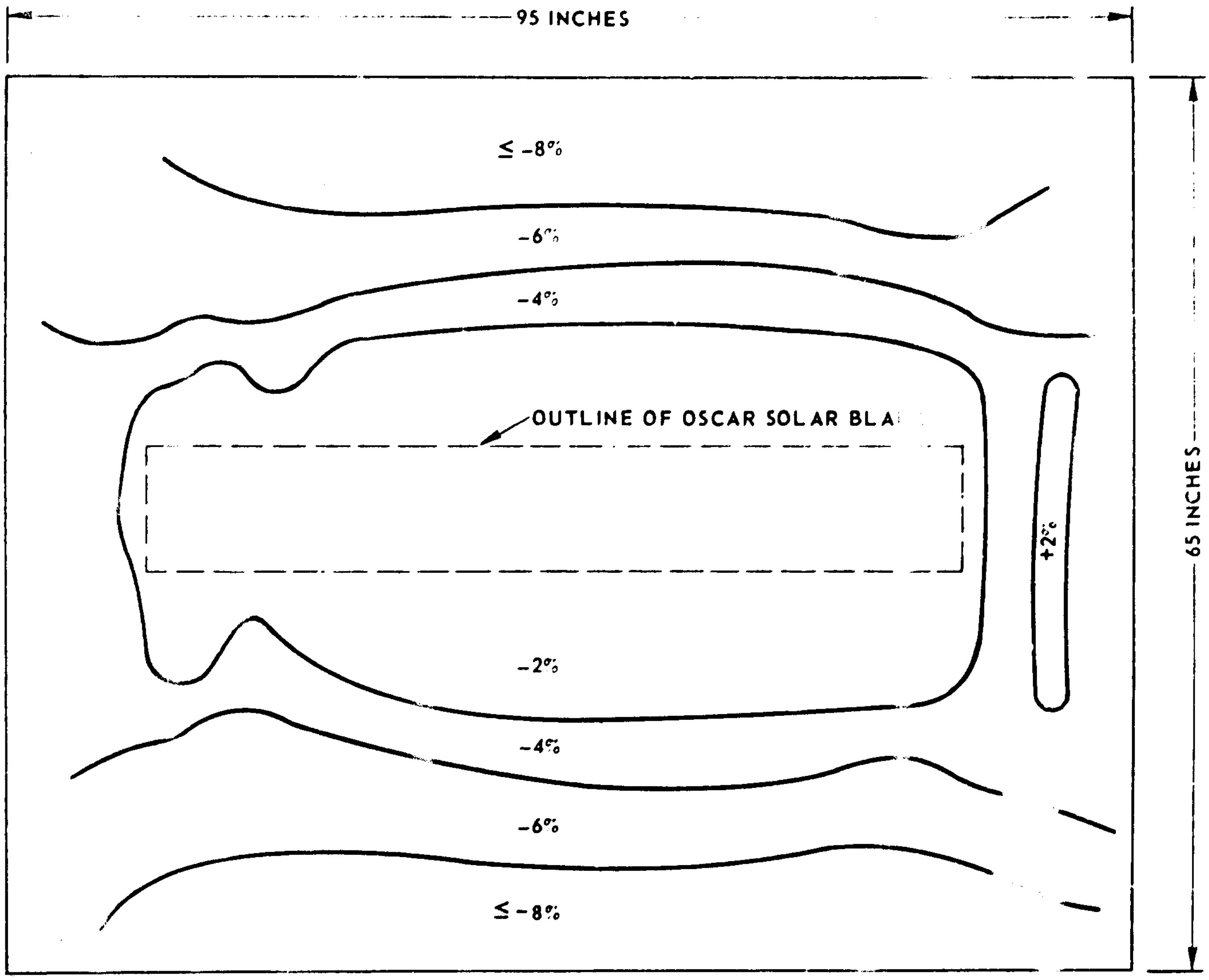

Fig. 10 PERCENT VARIANCE OF IRRADIATION INTENSITY IN TEST PLANE MEASURED BY 2x2 cm, 10 ohm-cm SOLAR CELL; I_{sc} 140 mA

5. PERFORMANCE

Usually, the solar array manufacturer supplies an I-V curve for each circuit on each array delivered to APL. These curves are produced from data obtained by means of the manufacturer's solar simulator tests or from the Jet Propulsion Laboratory's Table Mountain, California, facility tests. These test data are corrected to reflect the output of the circuits in outer space (AM = 0) and at an operating temperature of 28°C.

The I-V curves obtained from the APL Solar Panel Test Set are compared with the I-V curves supplied by the manufacturer to determine if the purchase specification is met. In addition, I-V curves are obtained from the APL Solar Panel Test Set after the arrays have completed such qualification and evaluation tests as vibration and thermal vacuum tests. These I-V curves are then compared with the I-V curves initially obtained to determine if the tests caused any degradation in the output of any circuit on the arrays.

Figure 11 shows a typical I-V curve obtained from the APL Solar Panel Test Set compared with the I-V curve supplied by the manufacturer for the same circuit. Both curves have been corrected for an AM = 0 output at 28°C. In general, the curves from APL and from the manufacturer are in good agreement, with the greatest deviation occurring at open-circuit voltage (V_{OC}). Typically, the short-circuit current measurements agree to within 2% and the open-circuit voltage to within 4%. The greater deviation in the open-circuit voltage measurement is due to its being more sensitive to temperature than is the short-circuit current. The packing density of the solar cells on the substrate does not permit a thermocouple or a sensistor to be placed so that a reliable temperature measurement can be obtained. Nevertheless, the APL Solar Panel Test Set has been proven to be a reliable instrument for the evaluation of solar cell arrays.

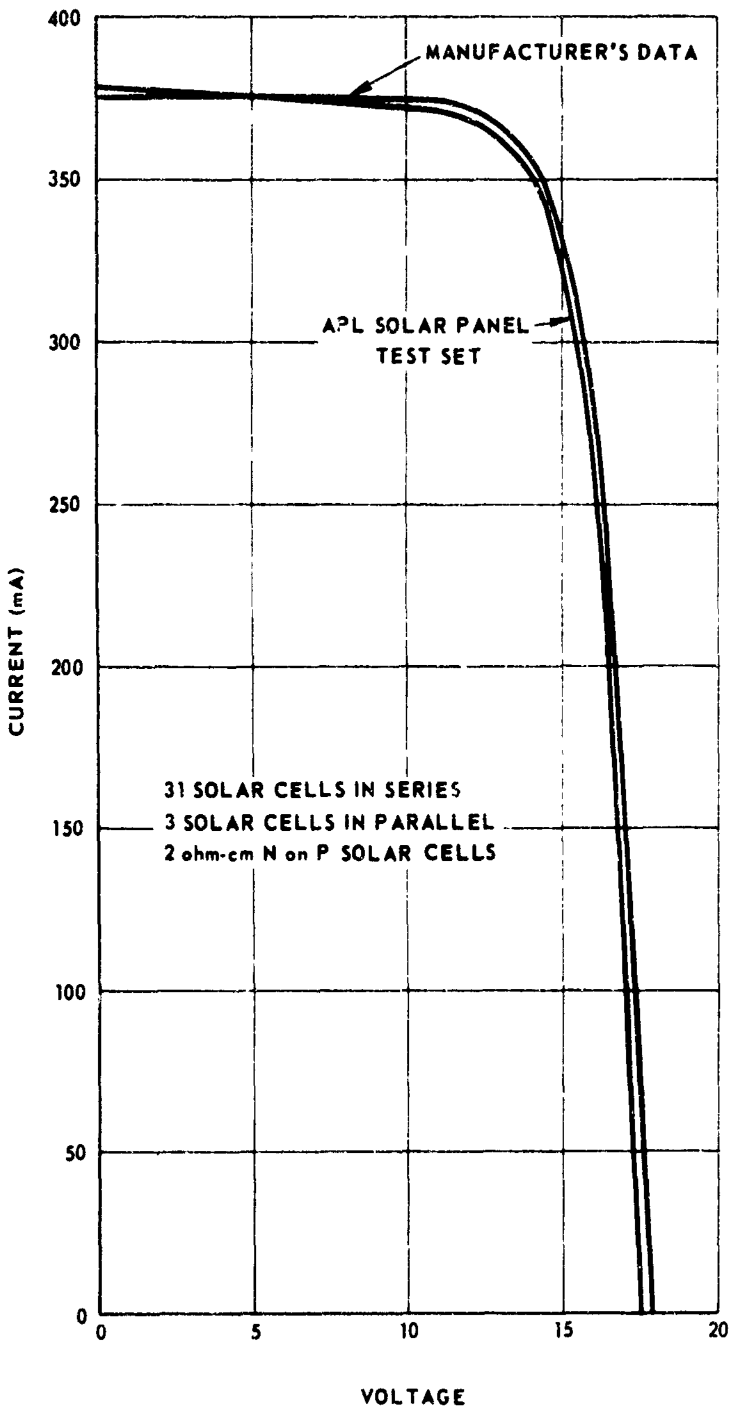

Fig. 11 TYPICAL CURRENT-VOLTAGE CURVE

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The Johns Hopkins University Applied Physics Lab. 8621 Georgia Ave. Silver Spring, Md. 20910	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP NA

3. REPORT TITLE

Solar Panel Test Set

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Memorandum

5. AUTHOR(S) (First name, middle initial, last name)

William E. Ray

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1970	27	0

8a. CONTRACT OR GRANT NO. NOw 62 0604-c b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TG 1103 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

This report has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Strategic Systems Project Office

13. ABSTRACT

~~This~~ report describes the Solar Panel Test Set developed for testing solar cell panels in artificial sunlight at an equivalent sunlight intensity of 140 mW/cm^2. The test set uses iodine-quartz (tungsten) lamps as the radiant-energy source, and the emerging radiation is uniformly reflected and totally diffused. An air conditioner, which is part of the test set, provides the cooling air necessary to control the temperature of the solar panel under test. The methods of calibrating the test set are described, and the accuracy of the measurements obtained when using artificial light as the radiation source is discussed.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
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14. KEY WORDS

Illuminator
Illumination plane
Diffused multiunit radiant-energy source
Current-voltage curves
Solar cell
Solar panel
Solar array
Standard solar cell