AIRPLANE TESTING OF SOLAR CELLS

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At the present time there are two primary facilities that utilize sunlight to obtain the outer space short-circuit current of solar cells. The first, which has been studied extensively by the Boeing Company and the Jet Propulsion Laboratory, uses balloons to reach altitudes in excess of 75,000 feet. While the balloon is at its maximum altitude, short-circuit currents of the cells on board are measured and telemetered to the ground station. At the conclusion of the experiment, the cells are parachuted to earth and later recovered.

The second facility is at Table Mountain which provides a good location for testing large arrays as well as individual cells. Various techniques exist for obtaining outer space short-circuit currents from the data taken at this facility.

One of these methods, originated by J. A. Zoutendyk of JPL, makes use of a Langley-type Plot. In this technique, short-circuit currents are measured throughout the day and then plotted logarithmically as a function of air mass. Air mass is simply a quantity which relates the geometric position of the sun to the amount of atmosphere through which the light is passing. Air mass 1 is defined as being that quantity of air between a sea level observer and the sun under standard conditions when the sun is directly overhead. Air mass 2 occurs when the sun is at an elevation of 30° above the horizon, again under standard conditions. This geometric factor must also be multiplied by the ratio of the ambient pressure to standard sea level pressure to adjust for pressure differences. Thus, as one goes to higher altitudes, the pressure ratio in space eventually drops to zero, hence the air mass becomes zero also.

As can be seen from figure 1, a plot of log I_{sc} versus air mass is a reasonably straight line out to air mass 3. Balloons reach air masses of 0.03 and below, hence they are practically in outer space. On Table Mountain, an air mass as low as 0.8 can be obtained. However, extrapolation of a Langley Plot from Table Mountain to air mass 0 can be suspect for several reasons: First, small errors made at large air masses can drastically change the value of the outer space short-circuit current $I_{sc,o}$. It is also quite difficult to find days on which the atmosphere does not change for many hours thus complicating the measurement. Finally, the extrapolation is a fairly long one because the last point is still some 20 percent below the desired value. By using high altitude

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aircraft to fill in this gap below air mass 1, it was felt that the accuracy of this technique could be greatly increased.

The use of an airplane to obtain outer space short-circuit currents by use of a Langley Plot has several advantages. First, it is most certainly above ground haze and low-lying atmospheric disturbances. Secondly, instrument errors on any one point do not appreciably affect the extrapolated value of the outer space short-circuit current. Thirdly, the airplane is a convenient, versatile, and stable system whose flying time is practically unlimited.

The airplane, which was chosen because of its performance as well as its availability, is the B-57B as shown in figures 2 and 3. It is a twin-jet aircraft with a crew of two, a pilot and a research observer. Experimental equipment can be installed in several locations in this plane. Installation of the present system is in two locations. Electronic recording equipment is placed in the cockpit where it is convenient as well as being in a controlled environment. The pyrheliometer and collimating tube assembly containing the solar cells are mounted in the tail section as shown in figure 4. There need be no window over these units because this area is unpressurized. Both items are mounted in a frame that can be pivoted from 20° to 75° in elevation. The elevation is selected so as to correspond to the position of the sun during the flight.

Because there is no window over these units, the cells are exposed to a rather harsh environment with ambient temperatures as low as -50° C. Therefore, the cells are mounted on a heated plate whose temperature is thermostatically controlled. The entire assembly is pictured in figure 5. A 3" × 3" CdS cell is mounted on the heater. The average temperature attained by the cells depends on the type of mounting used. For various holders, temperatures between 15° and 30° C have been obtained. It should be stressed that for any given mounting, a variation of less than 4° C from the average temperature is observed during the run. These sample temperatures are measured two ways: First, a thermistor is attached directly to the sample holder. Secondly, and most importantly, the open-circuit voltage of one cell is recorded. Both measurements confirm that sample temperatures change by less than 4° C during any one run.

Figure 6 shows the sample holder used for flying silicon solar cells. It is three inches square and can accommodate six cells with dimensions to 2 centimeters by 2 centimeters. The contacts are spring loaded, and the unit is gold plated to minimize contact resistance. Consistency of the results is assured by using one cell as a monitor and flying it every time. The open-circuit voltage of this cell is also used for temperature indication.

The short-circuit currents are converted into voltages with a precision 1-ohm resistor, which is accurate to 0.1 percent and has a temperature coefficient of 20 ppm/$^{\circ}$C.

The collimating tube was designed so that a 2° variation is pitch, roll, and yaw would still maintain complete illumination over a $4\frac{1}{4}$-inch-diameter circle. This insures that a 3-inch square area will be under constant illumination. Once again, the angle of the tube is chosen to correspond to the altitude of the sun at the time of the flight. Once airborne, proper orientation of the tube to the sun is assured by having an optical sight for the pilot that is exactly parallel to the tube in the rear section (fig. 7). A limit circle of 2° radius is inscribed on the face of the sight, and the sun image is centered and maintained within this circle. Periodic ground calibrations confirm this parallelism.

The pyrheliometer is a normal incidence type that has been temperature compensated. The temperature of this unit is also recorded during the flight.

A block diagram of the data acquisition system can be seen in figure 8. For a typical run on six solar cells, there will be six short-circuit currents, one open-circuit voltage, the temperatures of the mounting and the pyrheliometer, and the output from the pyrheliometer. The ten voltages are sequentially indexed through the stepping switch. All readings are voltages hence a recording digital voltmeter system was chosen to collect the data.

Figure 9 shows the pattern used in these flights. The area chosen is at 40° north latitude and 82° 30' west longitude, which is just east of Columbus, Ohio. The airplane enters the flight pattern at 42,000 feet. An appropriate heading is chosen so that the plane is nearly perpendicular to the sun. The pilot then centers the sun image in the sight and stabilizes the craft. This is by no means an easy task and requires considerable skill on the part of the pilot. Let me therefore express my appreciation to the pilots Earle Boyer and Larry Herron for their invaluable services in this study. Once the plane is on course and stable, the observer initiates the print sequence, and at least four repetitions of the data are recorded. Time and altitude are also noted. The time of the flights is chosen close to solar noon to insure both minimum air mass and minimum elevation change of the sun. All altitudes are based on a pressure altimeter which is reading relative to sea level pressure. After the 42,000 foot point, the airplane descends to 37,000 feet and the sequence is repeated. The descent continues in 5,000 foot intervals until 27,000 feet is completed. If a point is to be obtained at 47,000 feet, the flight plan follows the alternate route. Data points then pick up at 22,000 feet and continue to 12,000 feet, weather permitting.

After the flight, the various altitudes are converted into air mass as mentioned previously. The geometric factor is obtained from the elevation of the sun as determined from the date and time. The pressure ratio p/p_0 is obtained from the pressure altitude and the standard atmosphere table.

With the sun at its maximum elevation and flying at an altitude of 47,000 feet, an air mass of 0.14 is obtained. Conversely, flying at 12,000 feet with the sun at its lowest point over the test area, the air mass is about 1.4. Of course, both these conditions cannot be met in one flight, so the practical range lies from 0.14 to 0.67 in June and from 0.3 to 1.4 in January.

Once air masses have been obtained, a Langley Plot is made by plotting log I_{sc} versus air mass (fig. 10). Several additional corrections have been applied to the recorded data to obtain these plots. All readings must first be corrected to one astronomical unit. This correction ranges from 0 to ±3.3 percent depending on time of year. Secondly, a 0.1 percent correction must be applied to correct for the resistance change of the standard resistors due to their low ambient temperature.

A third correction is caused by the nonuniform distribution of ozone in the atmosphere. About 80 percent of the ozone is still above 47,000 feet. While the major ozone absorption occurs in the ultraviolet region below the response of most solar cells, there is a weak absorption in the visible region between 0.4 and 0.7 μ known as the Chappuis band. Very briefly, this correction was calculated by multiplying the fraction of solar cell response in the appropriate wavelength intervals by the percentage decrease of the solar spectrum caused by zone absorption in the same intervals. This value was then multiplied by the amount of ozone still above the test area. Typical corrections are 0.9 percent for silicon cells and 1.1 percent for GaAs cells at these altitudes. All these corrections have been applied to these data, and all three different materials show the typical straight line plot. Data on the silicon cell are from two different runs.

An example of the reproducibility of this system is demonstrated in figure 11. This cell was flown over a period of three months from January to March. All values of the outer space short-circuit current agree to within 1 percent even though the slopes are sometimes different. The low slope is apparently caused by the nonconstancy of the atmosphere and its constituents and has been observed on about 25 percent of the flights.

For calibration purposes, a number of silicon solar cells that had been calibrated by earth-bound techniques were flown. These cells were obtained from the Bell Telephone Laboratory and had been calibrated on their simulator. As a check on the calibration, these cells were measured on the modified Bell simulator here at Lewis at the time of the flights. Both calibrations were essentially the same. The results of these flights are shown in table I. For the sake of uniformity, the same cell was flown on every flight to serve as a monitor. These cells had also been measured on two carbon-arc simulators and at Table Mountain. A factor of 1.17 was used to convert the Table Mountain readings to outer space values. This factor was obtained at the time the cells were measured at Table Mountain. Excellent agreement with the airplane data is obtained. Also, agreement between the airplane and the Bell simulator is generally within 1 percent, while the carbon-arcs seem to be about 3 percent higher than the airplane. As can be seen from the data on cell 460 the reproducibility of the system is again within 1 percent.

In conclusion, it appears from these data and series of measurements that high altitude aircraft can be used to calibrate solar cells, and that the accuracy of such a measurement is ±1 percent.

TABLE I. - COMPARISON OF AIRPLANE CALIBRATION OF SILICON SOLAR CELLS WITH OTHER TECHNIQUES

Cell number	Airplane				Modified Bell simulator	Carbon arc number 1	Carbon arc number 2	Table Mountain (100 mw/cm^2) × 1.17
460	57.7	58.1	58.2	58.6	58.7	61.0	60.9	59.2
469	58.5	58.5	----	----	57.0	60.5	60.3	59.0
454	55.1	55.1	----	----	54.8	56.9	56.0	55.0
471	57.7	----	----	----	57.2	59.4	59.7	57.8
443	56.7	----	----	----	57.0	58.5	56.9	56.9

THEORETICAL LANGLEY PLOT OF A TYPICAL SILICON SOLAR CELL

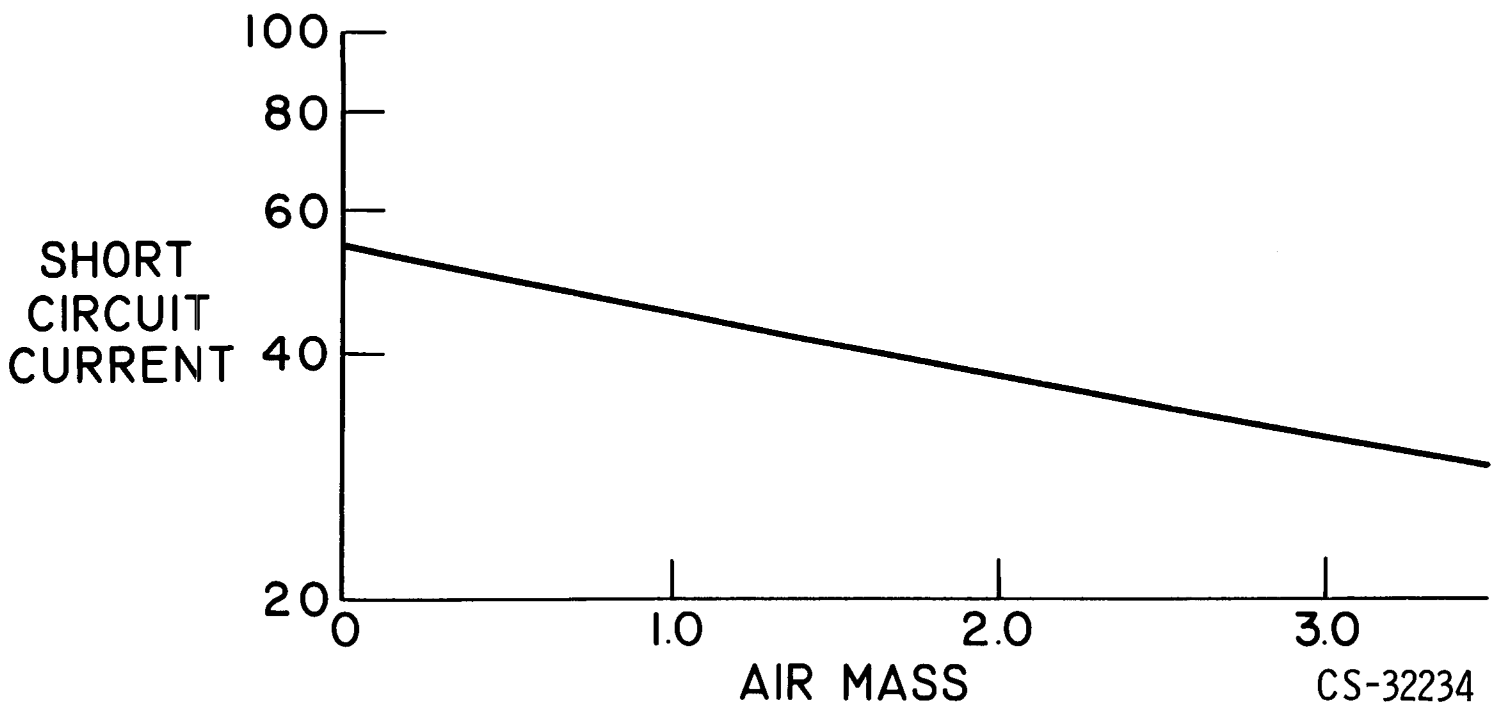

Figure 1.

B–57B USED IN SOLAR CELL TESTING PROGRAM

Figure 2.

B–57B USED IN SOLAR CELL TESTING PROGRAM

Figure 3.

EXTERNAL VIEW OF PYRHELIOMETER
AND COLLIMATING TUBE

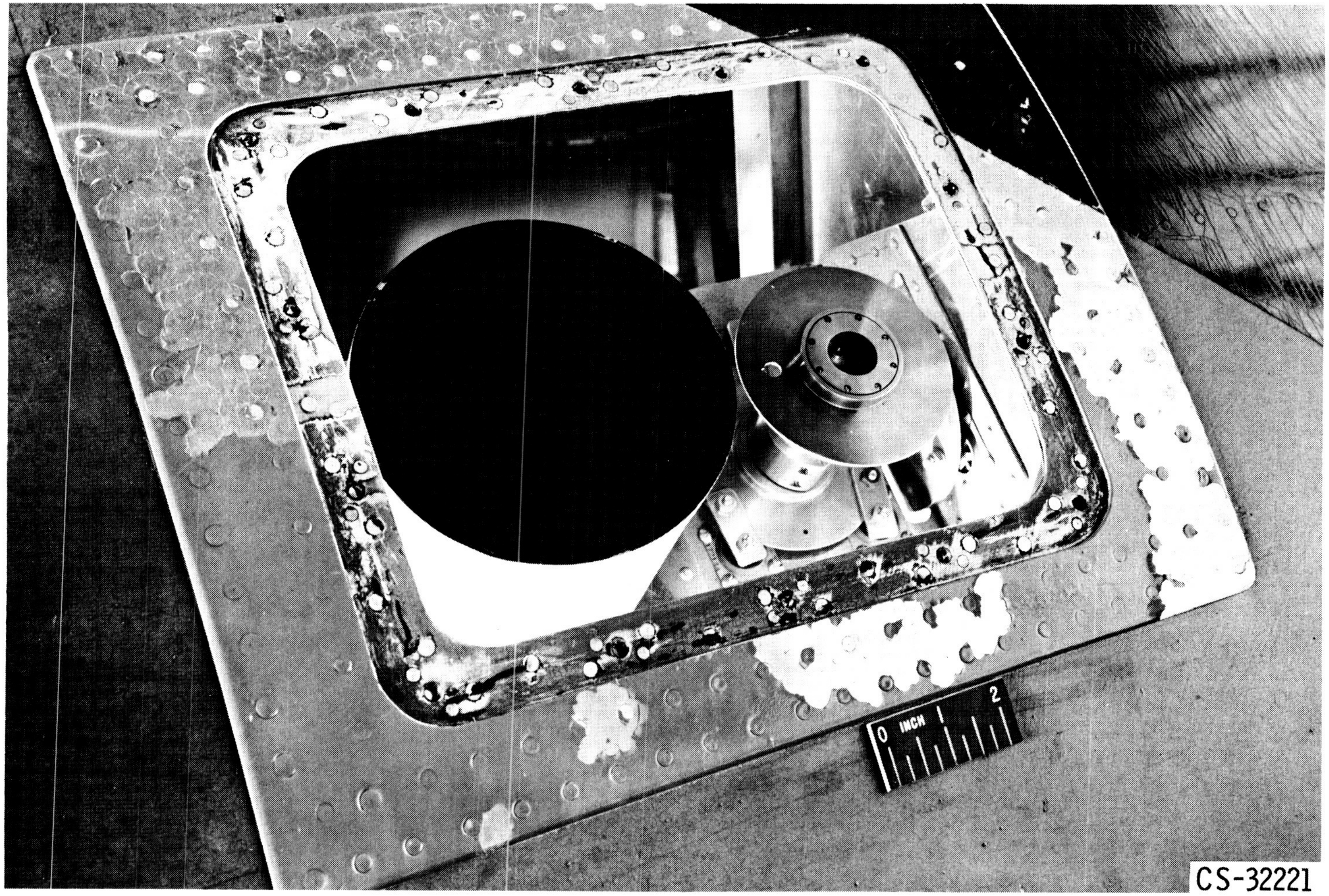

Figure 4.

DETAIL OF COLLIMATING TUBE ASSEMBLY

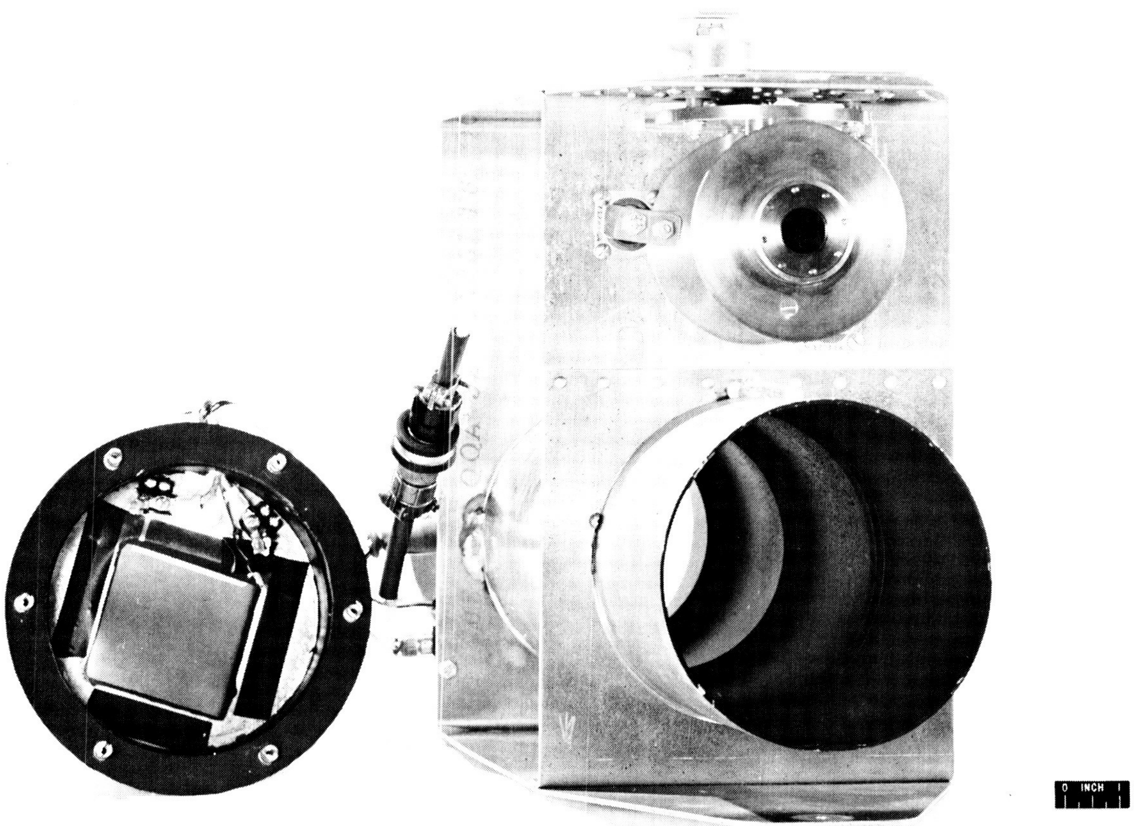

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Figure 5.

SAMPLE HOLDER FOR SILICON SOLAR CELLS

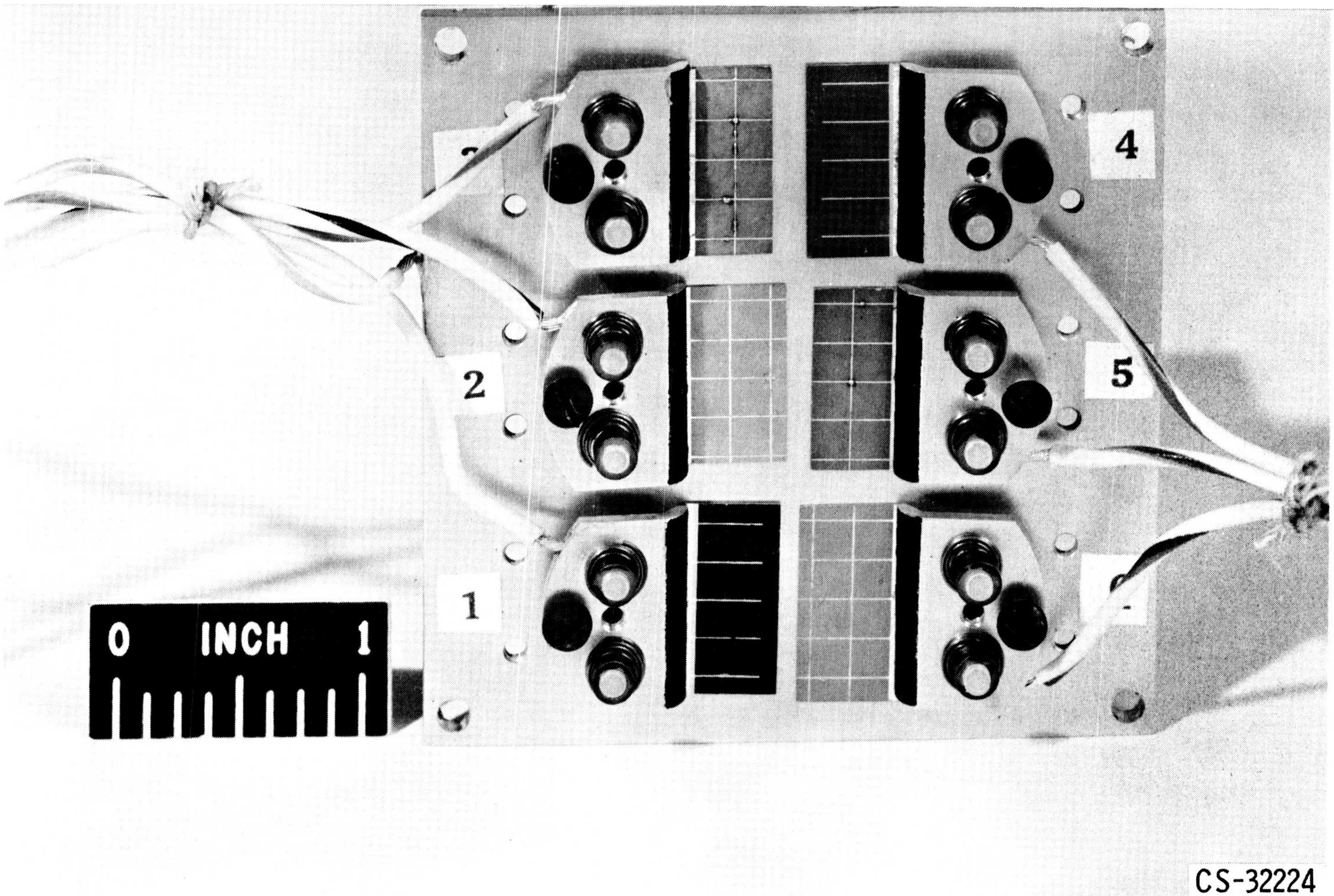

Figure 6.

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PILOT SIGHT TUBE

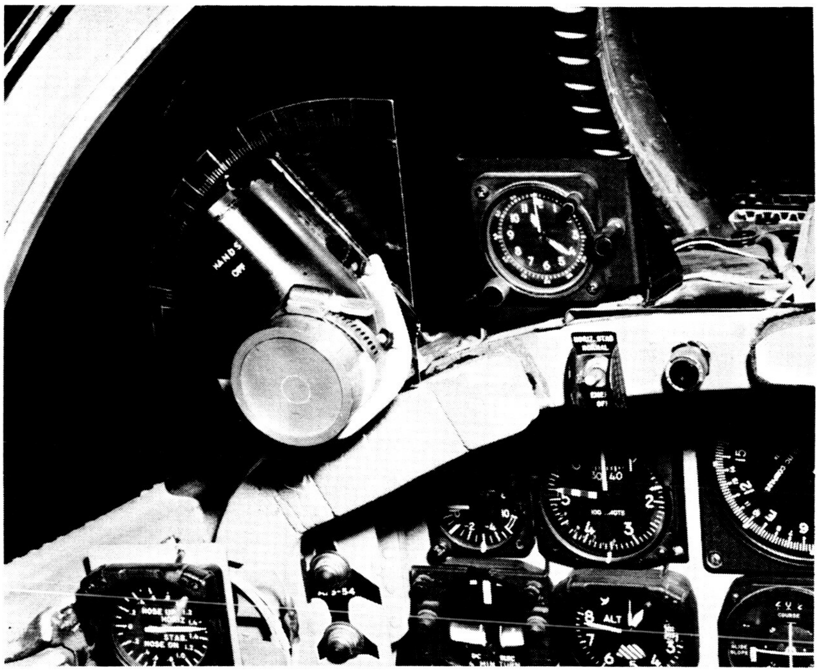

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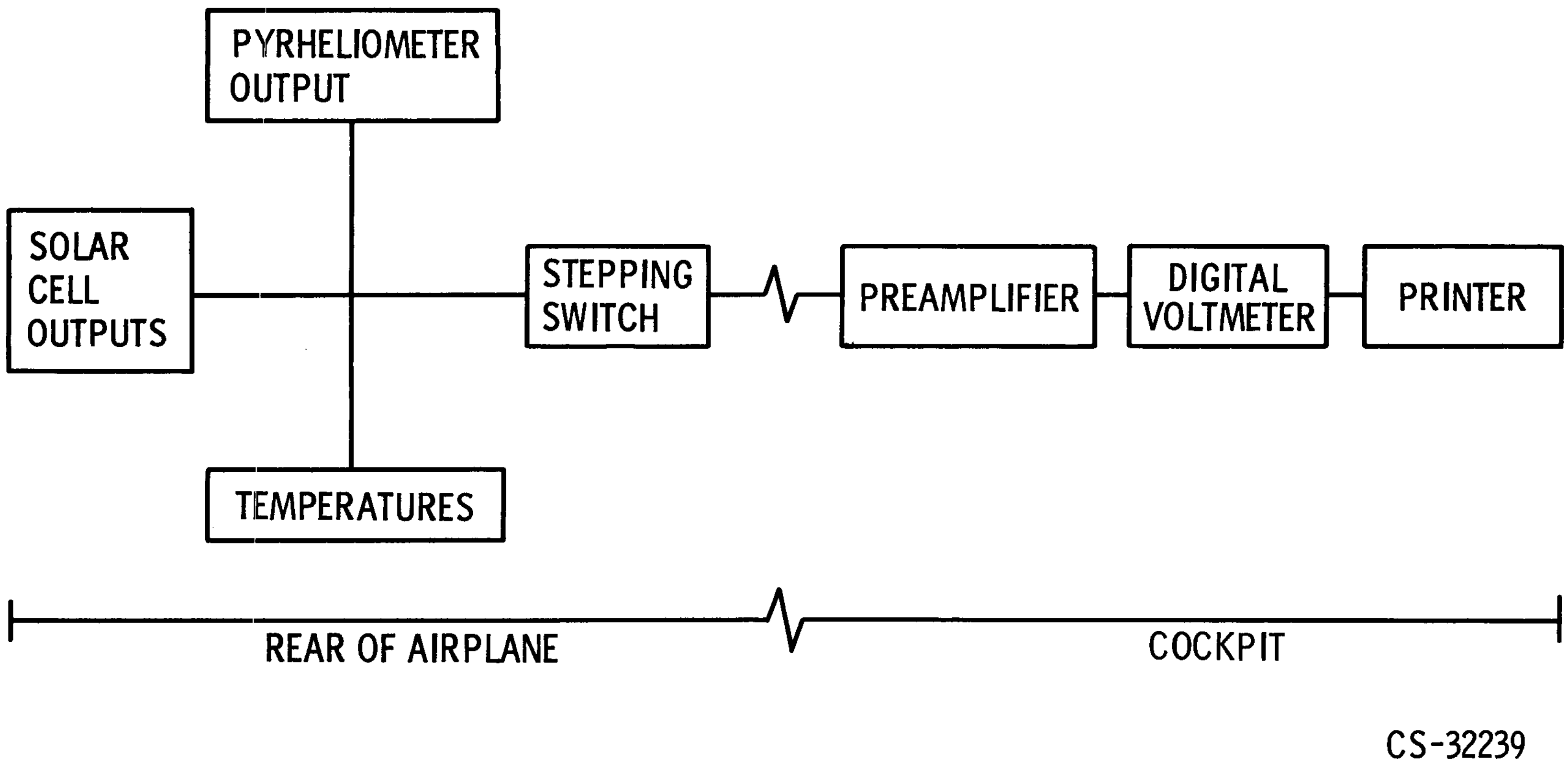
Figure 7.



BLOCK DIAGRAM OF DATA ACQUISITION SYSTEM.

Figure 8.

FLIGHT PATTERN FOR B–57B SOLAR CELL TESTING FLIGHTS

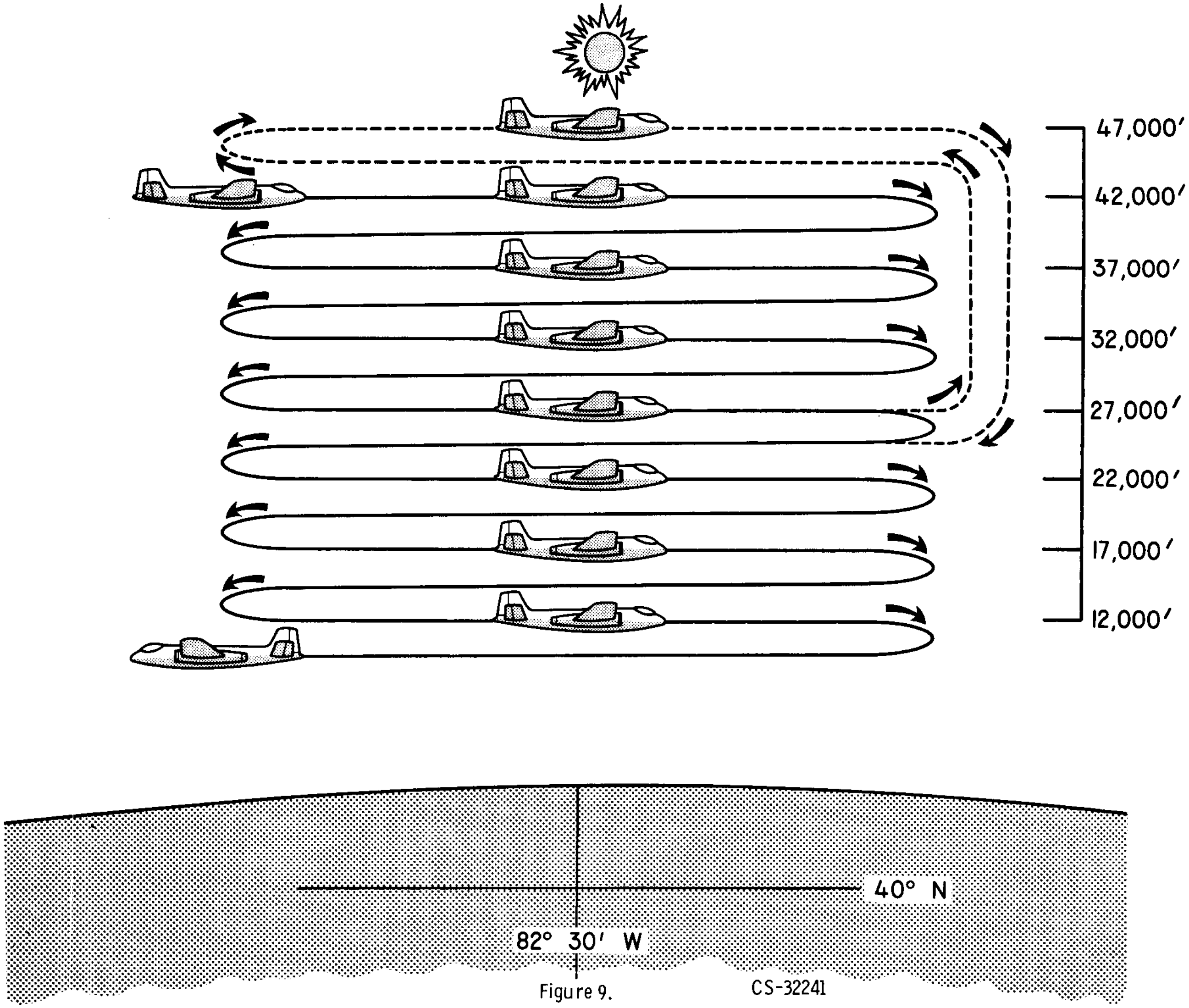


Figure 9.

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TYPICAL LANGLEY PLOTS FOR VARIOUS TYPES OF CELLS

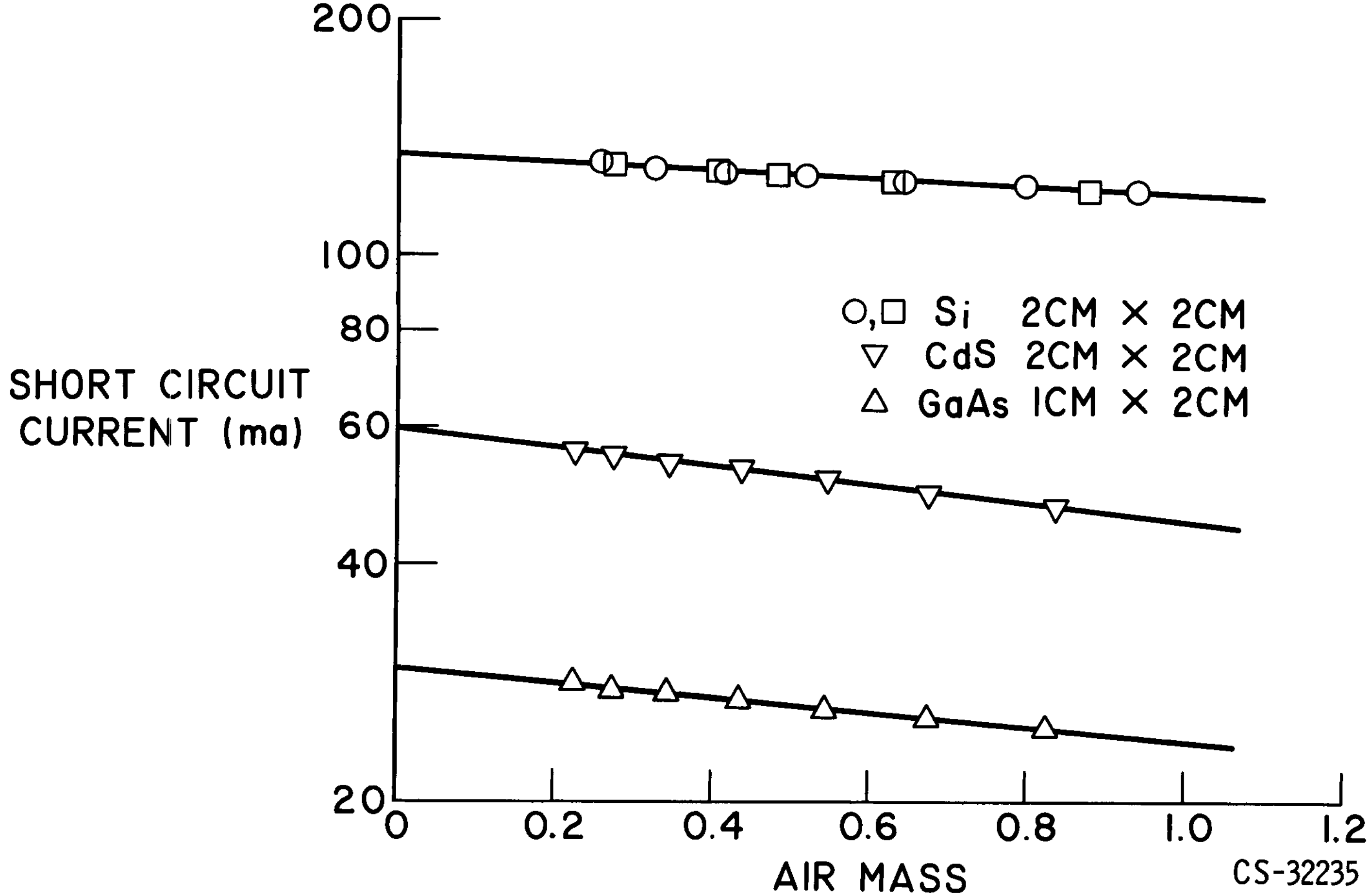

Figure 10.

REPRODUCIBILITY OF AIRCRAFT SYSTEM

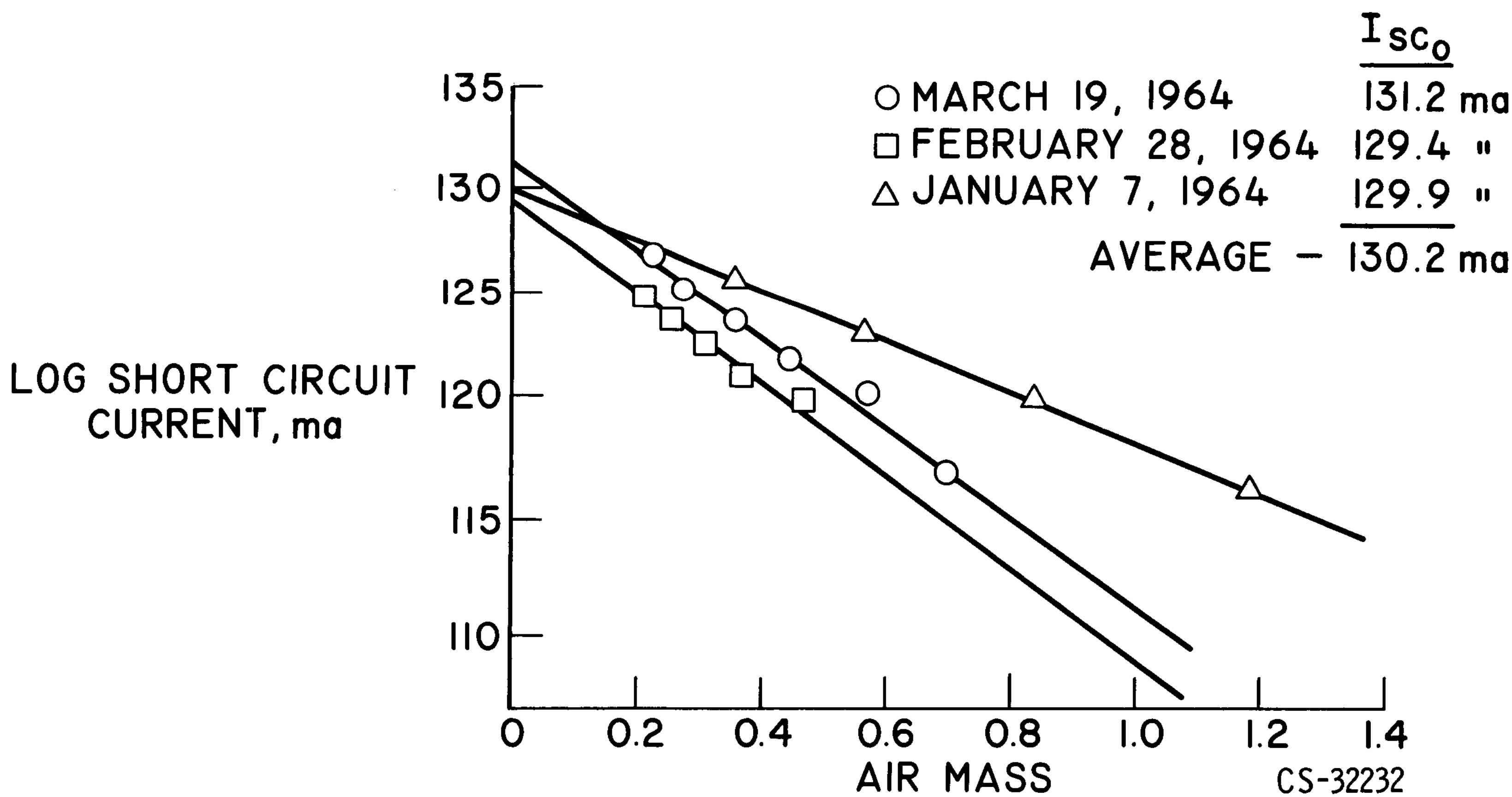

Figure 11.