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SOLAR ENERGY METER

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16. Abstract

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ABSTRACT

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SUMMARY

An instrument was developed to integrate and totalize an instantaneous analog signal that is directly proportional to the power available from light impinging on a sensor surface. This was accomplished by using a voltage to frequency converter plus an engineering unit divider that sets each cycle of frequency equal to a given quantity of energy (i.e., 1 cycle = 2.8×10^{-5} watt-hours/square meter). All cycles are then counted and for each 3.6×10^{5} counts (10 watt-hours/square meter), a mechanical readout is stepped once to provide a visual display. An analog output signal is provided for continuous recording purposes.

INTRODUCTION

In the design of Solar photovoltaic power systems an important quantity that is required is the amount of Sun energy available at the specific location under consideration. Weather Atlas information is typically used for such calculations but may be in error due to mini-climatic variations in specific locations. Therefore, to establish a basis for correctness of calculation data and to effect more accurate energy balance calculations for installed or future systems, an instrument to measure the actual Sun fall energy on a surface at a specific location is required.

This report describes an instrument using a silicon photovoltaic sensor that has an output directly proportional to incident light (ref. 1). The input from the sensor is integrated, totaled, converted to engineering units and displayed. The output display is now specified as energy (watt-hours/square meter) and is used directly for solar power system calculations.

The output is presented two ways by the "Solar Energy Meter", a visual display and an analog output. The difference between individual readings of the visual display is the total amount of energy available within the reading time interval. An analog output signal provides a voltage level directly related to the integrated total and will totalize 1280 watt-hours/square meter before automatically resetting to zero and starting over again.

This instrument was designed for specific use as a "Solar Energy Meter" and is a special case. But the basic design is flexible and with modification may be applied to totalizing of any integrated analog signal. Measurements may be made by totalizing such units as power (solar, wind, electrical), heat (temperature), volume (gallons, cubic feet) or any other unit where a total reading is required. If used in multiples in a system, energy balance information may be read directly and continually.

INSTRUMENT

General Description

The basic operation of this instrument is as shown by the block diagram of figure 1. An analog output from the sensor supplies a signal to the operational amplifier for amplification. That signal at a useable level is presented to the Voltage to Frequency Converter (VFC) where it is converted to a frequency dependent on the signal level. The unit is so calibrated that each cycle out of the VFC is equal to a specific quantity of energy which, in this instrument, is 2.78×10^{-5} watt-hours/square meter/cycle.

Each cycle, the VFC produces an output pulse which is counted and converted into engineering units by dividing the number of counts by 3.6×10^{5} to give an output calibration of 10 watt-hours/square meter. Now, the number of calibrated output pulses are counted and displayed by the following methods. First method is by stepping a six digit mechanical counter providing an output that is visually observable. Delta readings are obtained by finding the difference between two consecutive readings. Also available in this unit is a binary counter with outputs serving as inputs to a digital to analog converter to provide a 128 step analog output voltage that is directely proportional to the accumulated insolation.

Sensor - Amplifier

The sensor for this instrument is a 2x2 centimeter silicon photovoltaic cell. The sensor is calibrated by laboratory methods which provide an I-V curve at an air mass one intensity of 100 milliwatts per square centimeter. The silicon cell when loaded near short circuit current with a 1 ohm precision load provides a millivolt signal across the resistor. That signal is directly proportional to the Sun energy incident on the sensor surface (ref. 1). This sensor output, if calibrated, integrated, and then accumulated, will be a measure of the total energy incident on the surface of the sensor and therefore a surface in the same plane as the sensor.

An amplifier is used to provide sufficient signal gain to allow the voltage to frequency converter to work over a large frequency range for better resolution of the input signal. The amplifier also provides one of the calibration controls, offset adjust, which sets the frequency onset at zero voltage.

If desired, the input to the amplifier may be used with other signals that need to be integrated and totalized. This may be done by using a simple voltage divider that will provide approximately 100 millivolts full scale input to the amplifier. The input divider may be expanded into a multiposition switch that would accept several levels of input voltages covering several decades.

Voltage to Frequency Conversion

Voltage is converted to frequency by continually integrating the input analog signal which is directly proportional to instantaneous power into the sensor. When the input analog signal is greater than zero volts it is amplified and then applied to an active integrator that continuously accumulates the integration products. The integrator output provides an output signal that is inversely proportional to the amount of accumulated integrationbetween each integrator reset condition. Output voltage from the integrator is applied to one input of a comparator located in the Voltage to Frequency Converter (VFC) where it is compared to an accurate stable reference voltage applied to the second input. When the integrator voltage is higher than the reference voltage the comparator is in an "off" condition. Conversely, when the integrator voltage is equal to or lower than the reference, the comparator is "on" and triggers a precision one shot circuit in the VFC. The one shot provides a specific quantity of energy into the integrator which charges the feedback capacitor to reset the integrator and initiate the next precision integration cycle.

Because the analog input voltage determines the rate of integrator feedback capacitor discharge the following conditions prevail. When the analog input voltage is zero the integrator is inoperative since the integrator feedback capacitor is not being discharged except by capacitor self discharge. If the capacitor is of high quality this self discharge is low and errors attributable to it are very small. As the analog input voltage is raised the integrator discharges at a rate directly proportional to the analog voltage level. Under this condition the integrator output voltage will drop until the reference voltage is reached turning on the comparitor and providing a precise amount of reset energy to the feedback capacitor to start the next cycle.

Each cycle of integrated energy for this "Solar Energy Meter" is equivilent to 2.7778×10^{-5} watt-hours/square meter and the following is the method used to calibrate the unit. Using the zero set control on the amplifier set the VFC frequency output to zero. The full scale calibration control is next set to 10,000 hertz with a full scale input corresponding to an input equal to the milliampere output for an Air Mass one sensor calibration of

100 milliwatts per square centimeter with the 2x2 centimeter sensor loaded with a precise 1 ohm load. With the values of components as shown in Fig. 2, the energy represented by each cycle is shown below.

$$(1)\ \text{Cell Calibration} = \frac{.1\ \text{watt}}{\text{square centimeter}}$$

When the voltage to frequency conversion is set to 10K hertz at the cell calibration (1) the following calibration for one cycle is as shown in (2).

$$\frac{.1\ \text{watt}}{\text{square centimeter}} = \frac{10{,}000\ \text{cycles}}{\text{second}}$$

$$\text{or 1 cycle} = \frac{.1\ \text{watt - second}}{1 \times 10^4\ \text{square centimeters}}$$

Convert to watt-hours/square meter

$$1\ \text{cycle} = \frac{.1\ \text{watt - second}}{1 \times 10^4\ \text{square centimeters}} \times \frac{1 \times 10^4\ \text{square centimeters}}{\text{square meter}} \times \frac{1\ \text{hour}}{3600\ \text{seconds}}$$

$$(2)\ 1\ \text{cycle} = 2.7778 \times 10^{-5}\ \frac{\text{watt - hour}}{\text{square meter}}$$

ENGINEERING UNIT DIVIDER

Having determined the amount of incident energy represented by each cycle, it is necessary to put the output in terms that are useable. This is accomplished by accumulating a sufficient number of cycles to be equal to a specific engineering unit. The readout is desired to be in units equal to 10 watt-hours/square meter; therefore, using the quantity in (2), the following is determined:

$$(3)\ \frac{10\ \text{watt-hours}}{\text{square meter}} \times \frac{\text{square meter-cycle}}{2.7778 \times 10^{-5}\ \text{watt-hour}} = 3.6 \times 10^5\ \text{cycles}$$

In this instrument the accumulation is accomplished in two steps because the amount required is large. The steps are 32 and 11250 giving the needed amount of 3.6×10^5. A programmable divide by N counter is used to provide the more variable number needed while the 32 figure is obtained by taking the output from stage 5 of a 12 stage ripple-carry binary counter/divider.

At this point the positive going signal is specified to represent 10 watt-hours/square meter.

DATA ACCUMULATION AND DISPLAY

From the counter step specified to be 10 watt-hours/square meter a signal is fed to a one shot circuit which provides a pulse of energy sufficient to step a mechanical counter providing a visual output.

The seven steps on the binary counter, from the 6th to 12th, are fed into a digital to analog network. This network provides an analog signal directly proportional to seven binary inputs which provide 128 discrete voltage levels equal to a total of 1,280 watt-hours per square meter before resetting to zero to begin again.

The display method used to display the accumulated information is dependent upon the requirements of the user. It may range from the mechanical display included, strip recorders, and up to sophisticated computer readouts if desired by the user.

CONCLUDING REMARKS

The basic instrument (figure 3) as described performs the design requirement of obtaining the total amount of solar energy impinging on a surface. The instrument in conjunction with other measuring equipment (figure 4 & 5) has been placed into operation in several areas such as Puerto Rico, Arizona, New Mexico, Ohio, California, and New York with more areas to be specified. At NASA LeRC a unit has been placed in close proximity to laboratory type solar radiation detection devices and results are being compared over long term operation.

Nominal supply voltage range of the Solar Energy Meter is 11 to 20 volts with a power requirement at the 12 volt level of 0.1 watts. Input-output signals and operating power are supplied through a connector to a weather resistant case that houses the electronics. Initial calibration of the solar energy meter is made at 20°C and provides an input voltage to output frequency curve that is a straight line of zero slope which is linear within 0.1% over the full input range. The meter is capable of operation over a range of -20° to +60° centigrade with a calibration curve change that is less than ±1% of full scale reading. At all temperatures the linearity stays within 0.1% range. Errors may be reduced by use of internal compensation if required.

This instrument may be configured as a completely self contained unit with its own power supply as viewed in figure 3. An internal 12 volt nominal Nickel-Cadmium battery is charged by a solar array panel located just below the sensor cell. This method provides continuous power for remote operation of the "Solar Power Meter".

Applications requiring integration and totalization are the uses to which modifications of this instrument may be used. Specific uses such as electrical energy, temperature, volume flow and others are dependent upon the sensors and inputs available. Several units may be combined to provide total energy balances of operating systems.

Reference

1. **Selcuk, Kudret; and Yellot, John I.: Measurement of Direct, Diffuse, and Total Solar Radiation with Silicon Photovoltaic Cells. Solar Energy, vol. 6, no. 4, 1962, pp. 155-163.**

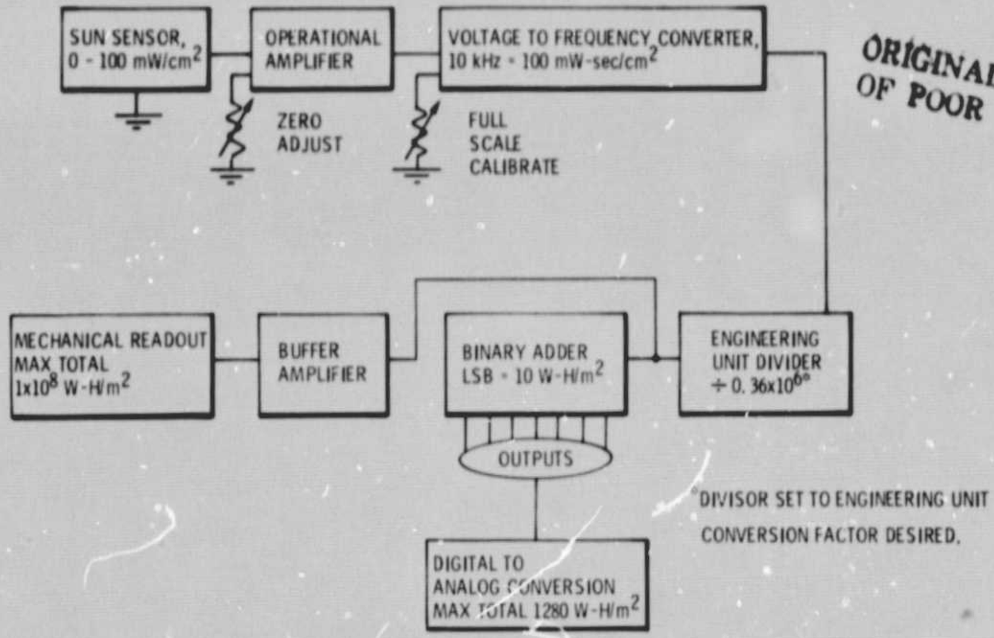

Figure 1. - Block diagram of "Solar Energy Meter."

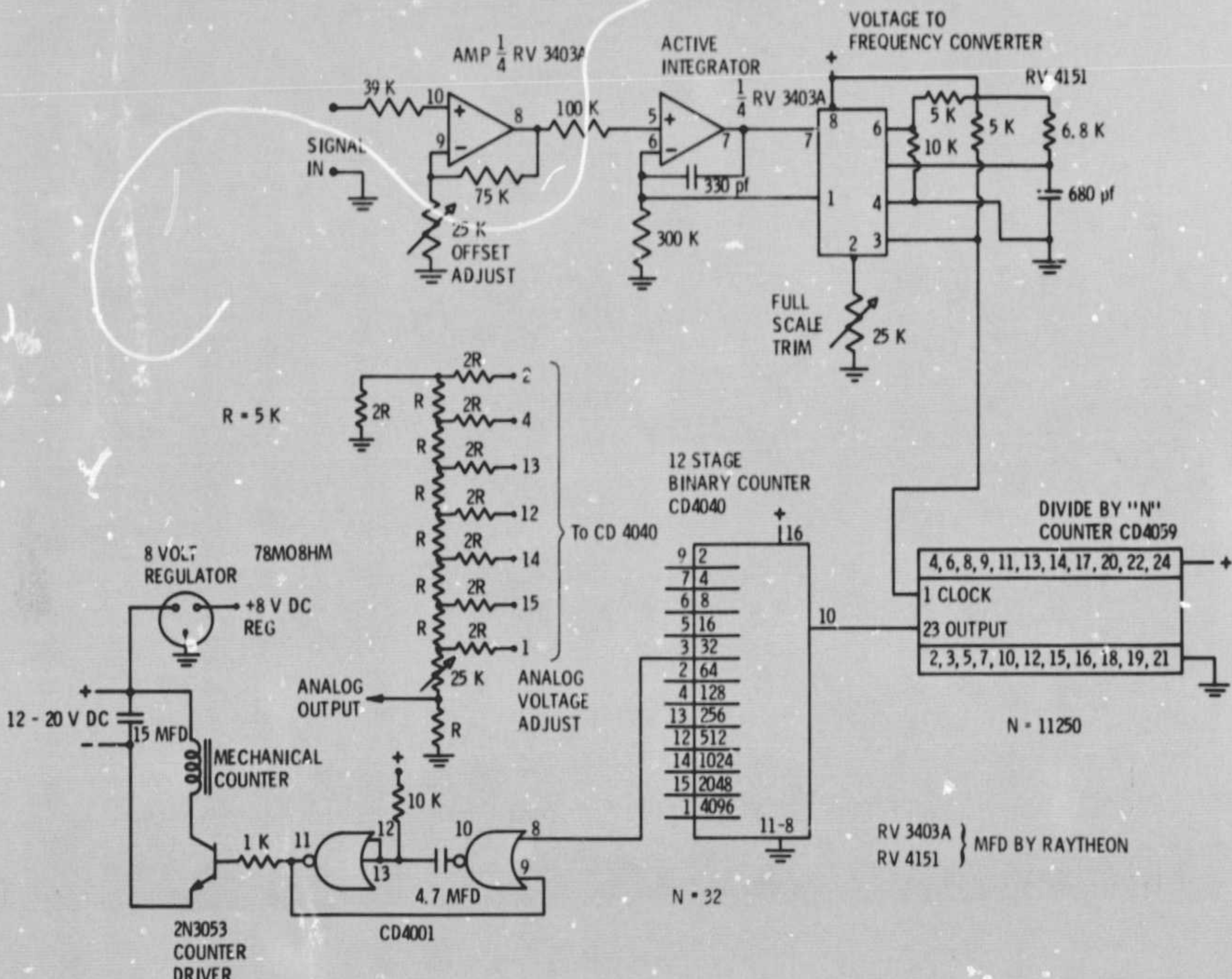

Figure 2. - Schematic for "Solar Energy Meter."

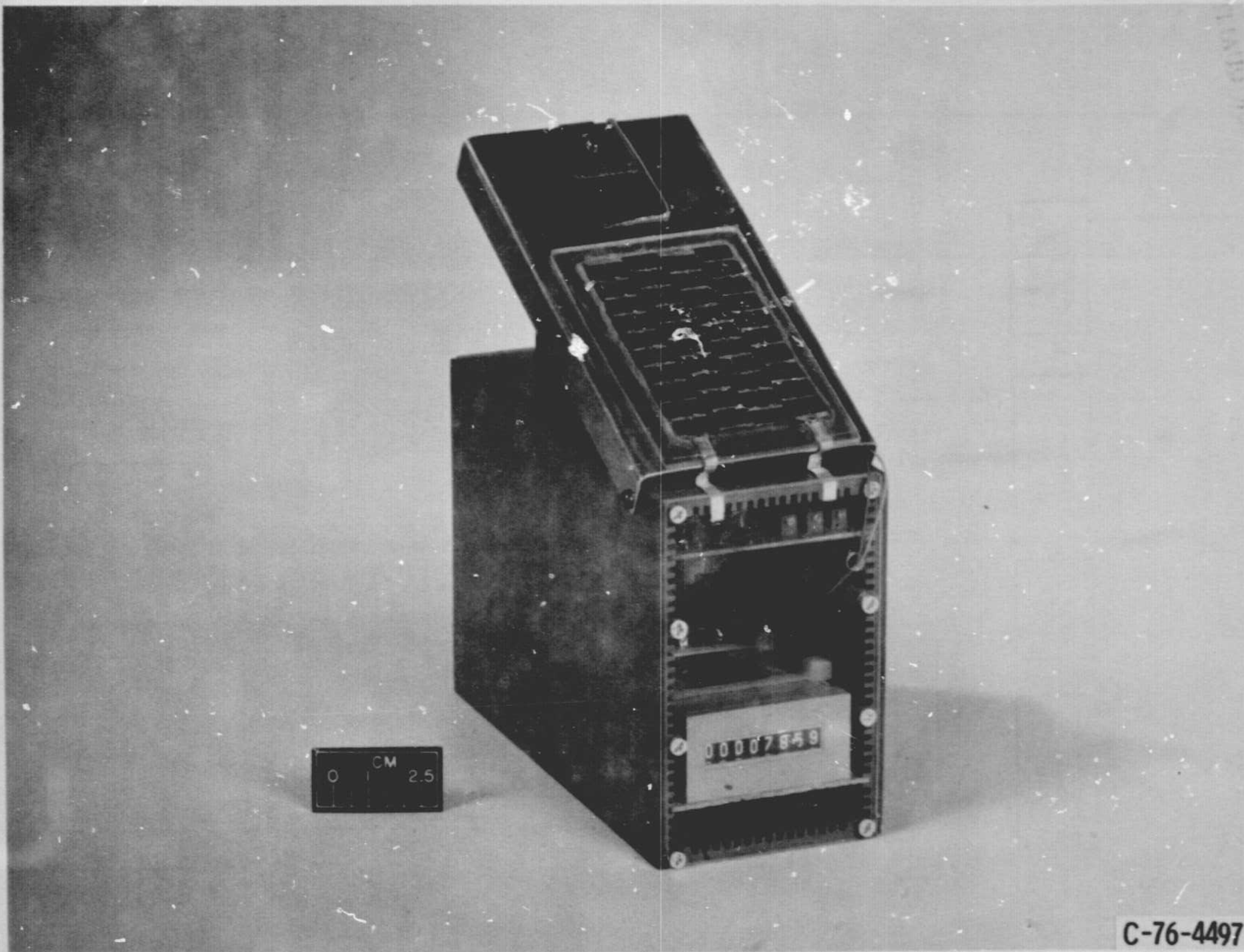

Figure 3. - Solar energy meter.

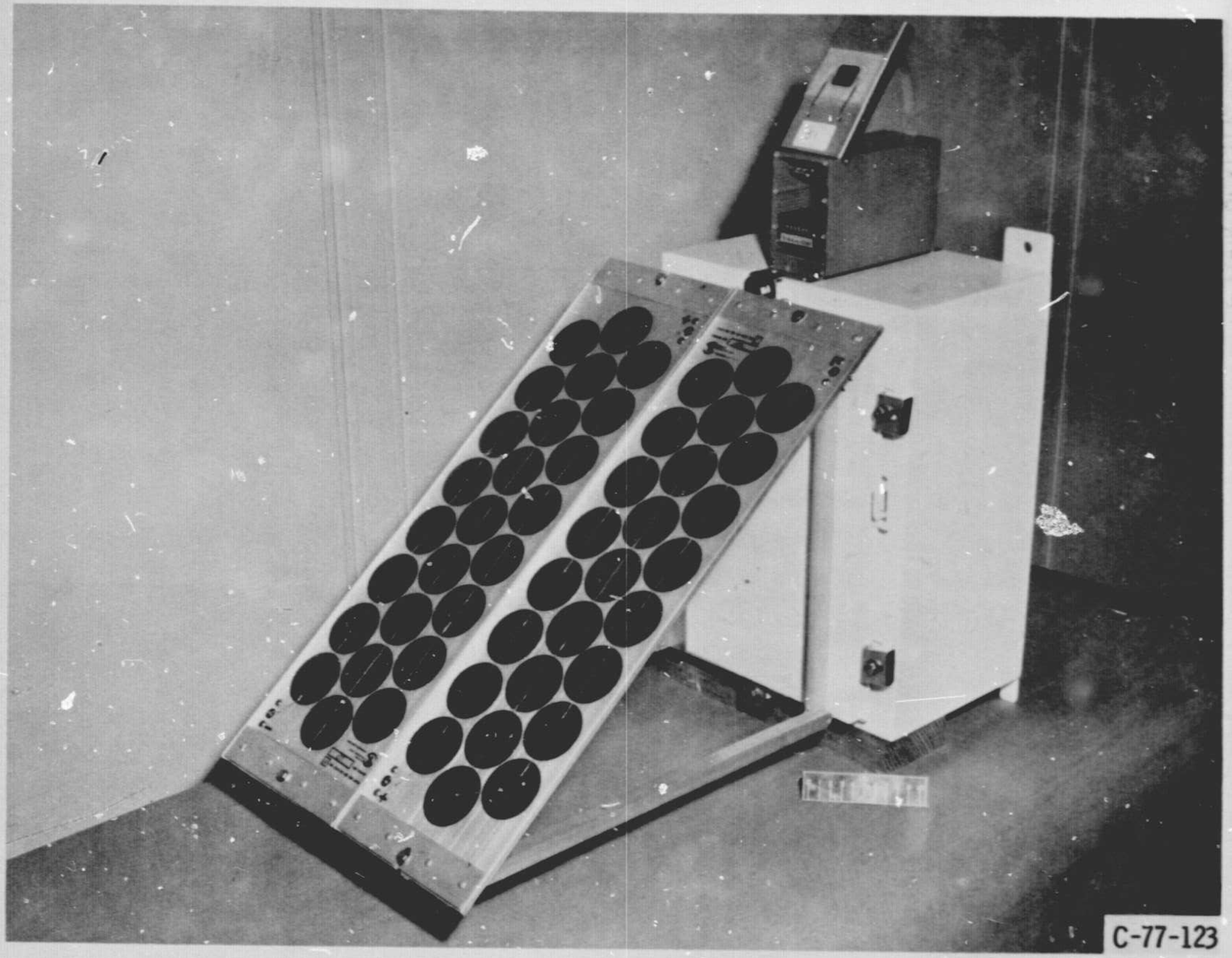

Figure 4. - Remote energy measuring data system.

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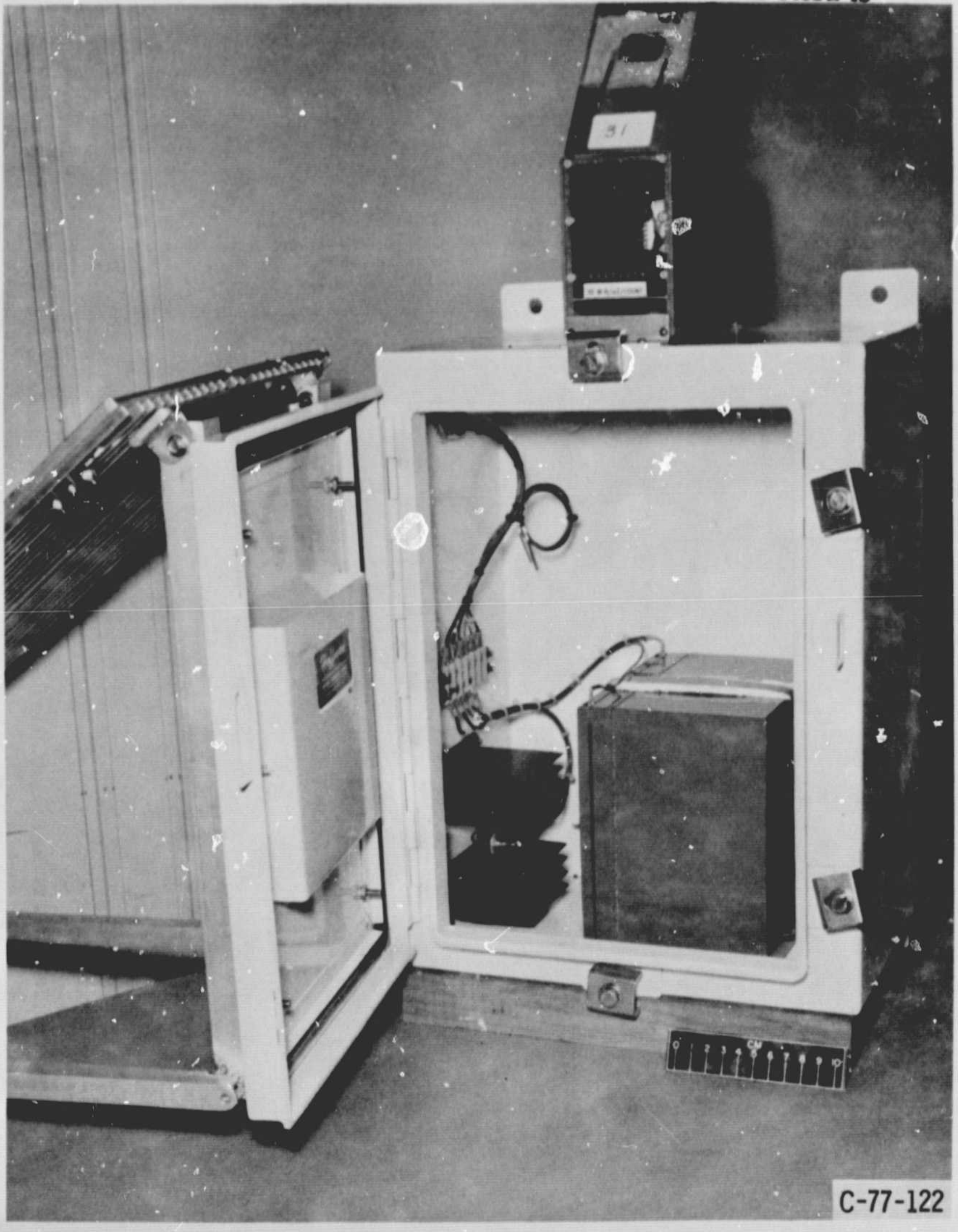

Figure 5. - Inner view energy measuring data system.