A Study on the Photovoltaic Effect - Solar Cells

A Group Project

by

Thaveesakdi Keowsim, Project Coordinator (Thailand)
Jean Baptiste Bwanakeye (Rwanda)
Htein Lin (Burma)

University of Florida
Training in Alternative Energy Technologies Program

Sponsored by

The U.S. Agency For International Development
(US AID)

5th Session (22 February - 4 June 1982)

Contents

Acknowledgement

We wish to express our sincere thanks to the TAET staff in kindly supporting us with materials, documents, references, advice, laboratory facilities and administrative facilities. Their encouragement and understanding make the result of the completion of this project work possible.

We do appreciate the government of the United States of America through the Agency for International Development (AID) in granting us the sponsorship to participate in this program.

Proposal

A. Objective:

1. Tc study the theoretical basic principles underlying the photovoltaic effect which apply to solar cells in detail.
2. Experiment on solar cells for studying some properties of solar cells:
   - To investigate a matched pair of solar cells.
   - I-V characteristics of solar cells.
   - Variation of the open circuit voltage and short circuit current of solar cell with the time of light-exposure.
   - Shadow effect on the test cell.

B. Design, equipment and components required:

1. Silicon solar cells
2. Solar cell panel
3. Digital multimeter
4. AVO-meter
5. Solar radiometer
6. Load resistor (10 Ω)
7. Rheostat (16 - 220 Ω)
8. Watch
9. Artificial sunlight source (photo-lamp)

C. Experimentation:

1. To investigate a matched pair of solar cells by measuring V_{oc} and I_{sc} of each cell.
2. To observe the I-V characteristics of solar cells by measuring the load current and load voltage at various values of load resistance.

3. To observe the variation of V_{oc} and I_{sc} of solar cells by measuring V_{oc} and I_{sc} vs time.

4. To study the effect of shadow on the test cell by measuring the test cell voltage, load voltage and load current at various shadow conditions on the test cell.

D. Application:

In our countries where there is no electricity available such as in some isolated remote rural areas, electricity from solar cells or solar cell panels might be economically applicable to serve the following needs:

1. Lighting
2. Water pumping
3. Telecommunication
4. Health Centers
5. Schcols

Abstract

Solar cells and solar cell panels are the current devices of the photovoltaic effect, in which the solar energy can be directly converted into electrical energy. In this report, the theoretical basic principles underlying the photovoltaic effect are presented in detail. Experiments concerning the basic characteristics of solar cells were conducted in the laboratory with silicon solar cells. Experimental results are presented. The correlation between the theoretical and experimental values were found.

I. Theoretical Studies

The physical principles and radiation - material interactions of the photovoltaic effect are described.

A. Solar Radiation Principles and Properties:

Electromagnetic radiation emanating from the sun is received by the earth at a rate of 5.1×10^{21} BTU/yr. It is not surprising, therefore, that major interest exists for the capture and conversion to useful work of a significant fraction of this amount of inexhaustible energy. However, radiative energy such as sunlight is a relatively dilute form and hence requires large collection areas to provide the energy equivalent to that obtained from fossil and nuclear fuels. Further, despite the inexhaustibility feature, solar radiation has the characteristic of intermittency due to:

(a) the earth's diurnal cycle,

(b) seasonal angular displacement.

(c) localized weather condition, e.g., clouds, particulate absorption and scattering, etc.

Light is a form of energy and the smallest unit of light energy that can be transferred in a process is called a photon. The energy of the photon is related to the frequency of its associated radiation by the equation $E = h\nu$, where h is equal to Planck's constant, 6.62×10^{-27} erg-sec and ν is the radiation frequency. Since the frequency ν is inversely proportional to the radiation wavelength, viz., $\nu = \frac{c}{\lambda}$, where λ is the wavelength and c is the velocity of light, it is possible to determine the energy associated with photons of a given wavelength, λ. Such energy is often expressed in electron-volts (eV).

B. Semiconductor Basics:

The role played by semiconductor materials is crucial in the energy conversion process. A brief review of semiconductor theory is given here.

1) Band Theory

The conductivities of solid materials vary extensively. Representative values may range from less than 2×10^{-7} mhos/meter for fused quartz, an insulator, to about 6×10^{7} mhos/meter for silver, a conductor. Materials with intermediate conductivity values are called semiconductors. The distinguishing features of conductors, insulators, and semiconductors can be explained in terms of what is called the energy band concept of materials.

Electrons in isolated atoms can exist only at discrete energy levels and are restricted in number at any allowed energy level. When atoms are brought close together, as in a crystal, so that their potential functions overlap, the energy level must split and form clusters of acceptable energy levels. These clusters, or bands, consist of a large number of closely packed discrete energy levels. There are as many levels in the bands as there are atoms in the crystal and as many bands as there are energy levels in an isolated atom of that material. The energy width of these bands depend on the particular material and its atomic spacing.

The electrons are constantly seeking the lower energy levels but can be excited to higher states by interaction with photons. The distribution of electrons in the outermost or highest energy bands determine most of the electrical and thermal properties of the material. If a crystal, for example, of a metal, contains an outermost band which is partially filled, an externally applied electric field can shift the occupation of the energy levels and cause a current to flow. If a band is completely empty, there can be no contribution to an electric current by the band. These materials are then good electrical insulators.

The highest occupied band corresponds to the ground state of the valence electrons in the atom. For this reason the upper occupied band is called the valence band. In an insulator, the valence band is full. In addition, the width of the forbidden energy gap between the top of the valence band and the next allowed band, called the conduction band, is so large that under ordinary circumstances a valence electron can accept no energy at all from an applied field. Semiconductors are similar to insulators, except that in semiconductors the forbidden gap is much narrower. In a semiconductor at room temperature, though the valence band is full, some electrons may receive enough energy from light so that they may jump the narrow forbidden energy gap into the empty conduction band. The greater the intensity of the light source, the larger the number of electrons that will be excited across the gap. The electrons that are raised are then free to accept electrical energy from an applied field and to move through the crystal. In addition, the sites or "holes" left vacant in the valence band become charge carriers themselves. An electron near a hole can jump in and fill it, leaving a new hole in the place it has occupied, and this in turn can be filled by a neighbor, and so on. Current is actually carried by electrons but it can also be pictured as a flow of positively charged holes moving in the opposite direction. Thus conduction is done by both electrons and holes. When the conduction of current is due only to those electrons excited up from the valence band to the conduction band, the material is called an intrinsic semiconductor.

Any disruption of the perfect crystal will disturb the periodicity of the system and result in additional energy levels within and between the allowed bands. Imperfection in crystals usually come from such sources as:

(1) foreign atoms substituted into lattice sites;

(2) vacant lattice sites and interstitial atoms;

(3) dislocations of crystal (or grain boundaries);

(4) the crystal surface.

The technology for producing low-defect crystals has been developed by using ultrahigh purity material and in slowly growing large, single grain crystals. However, with carefully controlled impurity levels it is possible to obtain desirable properties for semiconductors. By adding small amounts of impurities called dopants to semiconductor crystals, it is possible to choose the dominant type of conduction (either electrons or holes) in a material. When the conduction is due to impurities, the material is called an extrinsic semiconductor. Impurities can supply extra electrons, negative charge carriers, in which case they are called n-type materials. If the impurities are deficient in valence electrons, they are called p-type, positive charge carriers.

2) Optical Effects

Electrons can be excited from the valence band to the conduction band by absorption of electromagnetic radiation, e.g. sunlight. To accomplish this, the energy of the photons must be equal to or greater than the energy associated with the forbidden band width in the specific material. A schematic energy diagram for this tranfer is given in Fig. 1.

To obtain useful power from photon interactions in a semiconductor, three processes are required:

(1) The photon must be absorbed and result in electron excitation to a higher potential.

(2) The electron-hole charge carriers must be separated. This is done by use of the p-n junction which provides an internal electric field.

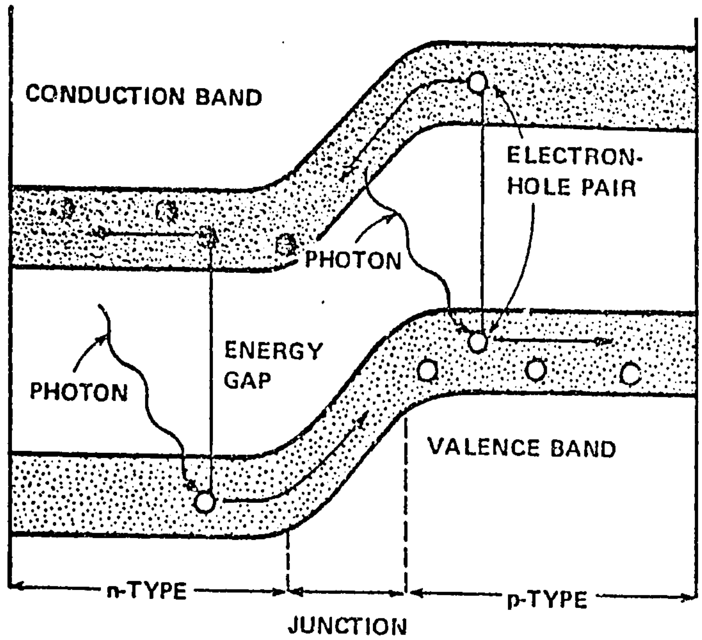


Fig. 1 Electron excitation by photons. A potential barrier is developed resulting in charge separation.

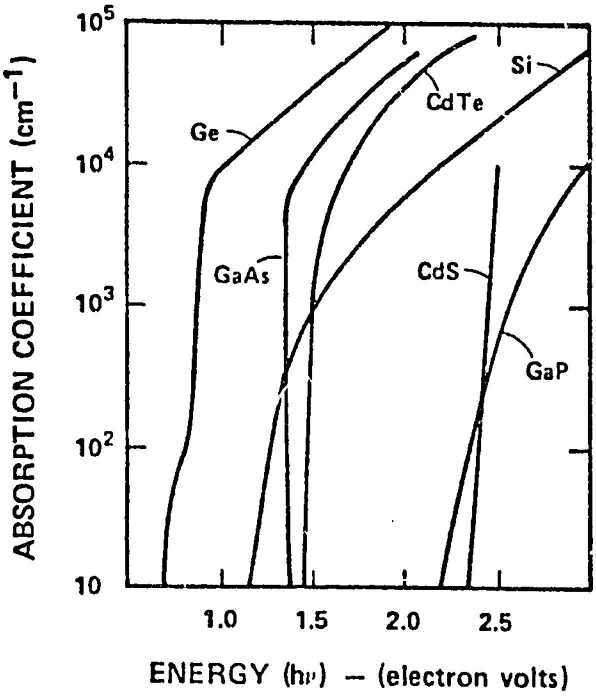


Fig. 2 Optical absorption coefficient of typical semiconductors as a function of photon energy.

(3) The charge carriers must pass through a useful load before they recombine with each other and lose their potential energy.

The absorption of photons in a material is given as a function of distance into the material, x as $I(x) = I_0 e^{-\alpha x}$, where $I(x)$ is the intensity of photons at depth x, I_0 the intensity incident on the material, and α the absorption coefficient. Several materials with absorption coefficients at energy levels of interest are shown in Fig. 2.

3) Photovoltaic Junction Properties

a. P-N Junction. It has been stated previously that certian dopants diffused into a semiconductor will create either p- or n-type materials. The juxtaposition of a p- and an n-type semiconductor will create a p-n junction. A homojunction device has the same base material but different dopants. A heterojunction device is formed from the joining of two dissimilar materials that have different band structures. The simple p-n junction and the more complex heterojunction equivalent permit electrons generated by photonic absorption to be accelerated across a potential gradient (created by the junction) into an external circuit to perform work. A schematic of such a junction is shown in Fig. 3.

b. Voltage-Current Relationship. The voltage-current relationship for a typical p-n junction cell is shown in Fig. 4. The power available for the system is the product of current and voltage with maximum power output generated at point A for a given illumination value.

c. Conversion Efficiency and Materials. The bulk of the solar energy reaching the earth's surface falls in the visible spectrum where photon energies range from ≈1.8 - 3.0 eV. It has been determined that the theoretical efficiency of conversion peaks at ≈1.5 eV but with a broad maximum so that materials with band gap energies between ≈1 and 2.2 eV are

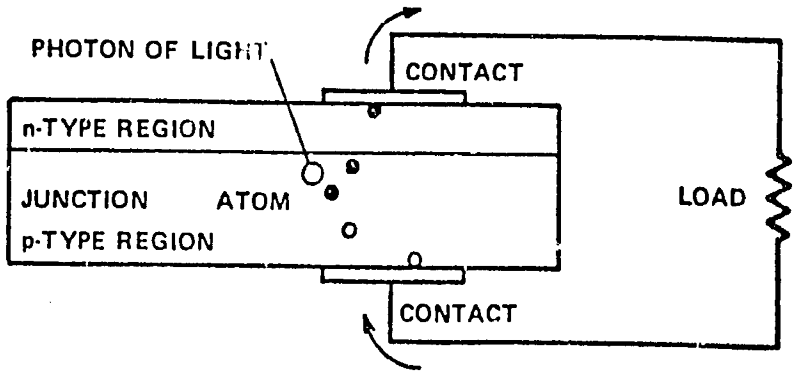


Fig. 3 Schematic of a simple p-n junction.

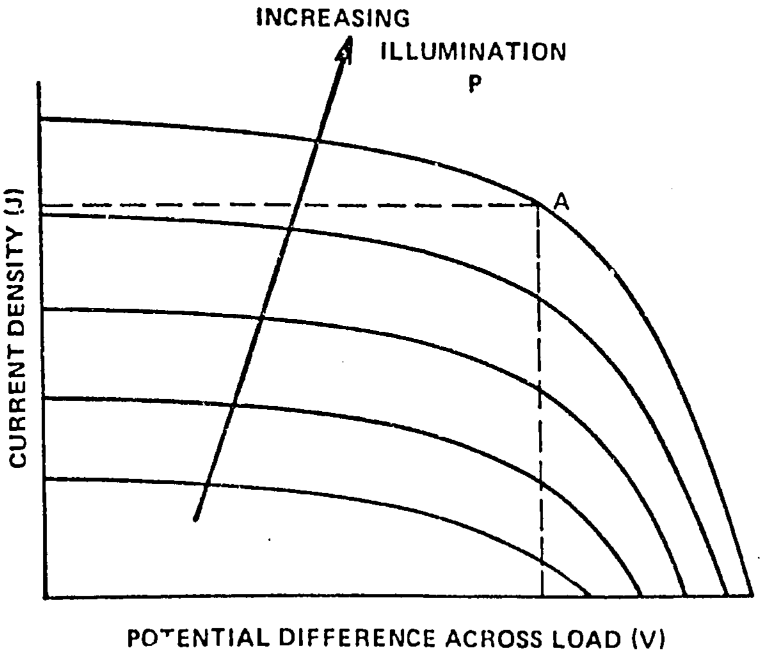


Fig. 4 Characteristic voltage-current curves for a solar cell.

within ≈80% of the maximum. Fig. 5 shows theoretical efficiencies as a function of band gap energies for a variety of suitably - doped semiconductor materials.

d. Limitations. There are a number of factors contibuting to the fact that real photovoltaic cells do not achieve the theoretical efficiencies noted in Fig. 5. These are listed below.

(1) Surface reflection losses

(2) Incomplete absorption of photons

(3) Utilization of a fraction of the available photon energy for the creation of electron - hole pairs

(4) Incomplete collection of electron - hole pairs

(5) Degradation due to excessive internal series resistance

(6) Lack of requisite chemical purity

(7) Crystallographic imperfections

(8) Current collector masking of surface

(9) Fabrication technology problems

e. Temperature Effects. The efficiency of photovoltaic devices varies nearly linearly in the temperature regions of interest to these devices and decreases with increasing temperature, viz.,

$$\eta(T) = \eta(28°C)(1 - \beta[T - 28]),$$

where $\eta(T)$ is the efficiency at temperature T and β is the temperature coefficient. Both the use of the proper material and temperature control will be important in those systems where sunlight concentration is used to enhance total efficiency.

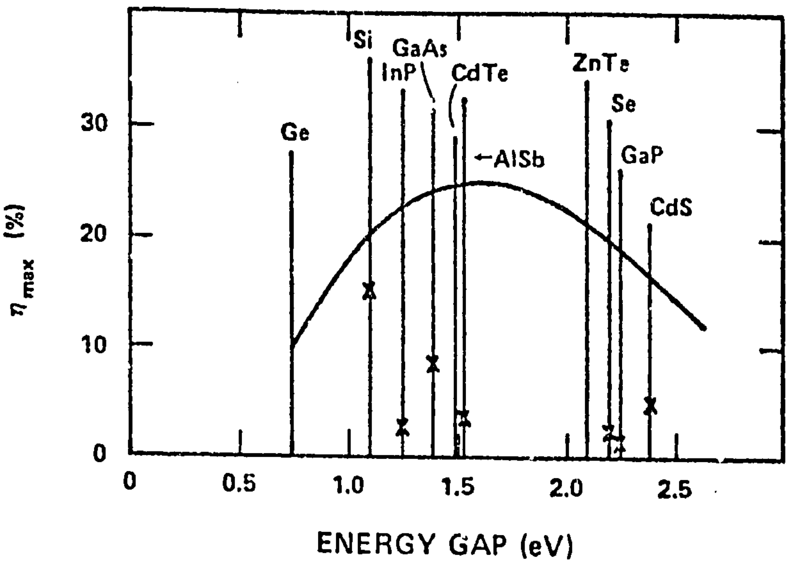


Fig. 5. Efficiency of semiconductors as a function of the energy gap, AMO conditions

C. The Principles Underlying the Photovoltaic Effect:

Three processes are involved in the photovoltaic effect. Firstly, excess positive and negative charges, at least one of which is mobile, must be generated in the semiconductor by the absorption of ionizing radiation. Secondly, the excess charges of opposite sign must be separated at some electrostatic inhomogeneity like a p-n junction, a metal - semiconductor barrier, etc. Thirdly, the mobile generated carriers must retain their mobility for a time long compared with the time they require to travel to the localized charge separating inhomogeneity.

1) Light Absorption in Semiconductors

When a monochromatic beam of light whose photons have an energy in excess of the forbidden energy gap of the semiconductor passes through a semiconductor, the flux of photons remaining in the beam after it traverses a distance x, $[N_{ph}(x)]$ is given by

$$N_{ph}(x) = N_{ph}(0)e^{-\alpha(\lambda)x},$$

where $N_{ph}(0)$ is the photon flux at $x = 0$ and $\alpha(\lambda)$ is the absorption constant for photons of this wavelength (energy). It is found that direct gap semiconductors are better suited for photovoltaic cells because the thickness of the material required to absorb all photons in excess of energy gap E_G for the material is smaller than for indirect gap materials; consequently, less material would be needed for the solar cells.

2) Charge Separation in the Photovoltaic Cell

Charge separation requires that an electrostatic potential barrier be present in the photovoltaic cell. Excess carriers of opposite signs move in opposite directions at such an electrostatic potential barrier, which can be produced by a metal - semiconductor (Shottley) junction or a p-n junction. Two types of p-n junctions can be distinguished and are important in photovoltaic solar cells:

(1) p-n homojunctions in which the junction exists in a single semiconductor;

(2) p-n heterojunctions in which the n- side consists of one semiconductor and the p- side of a different semiconductor.

3) Migration of Charge Carriers to the Charge Separation Site

The excess carriers generated as a result of the absorption of ionizing radiation must remain free until they reach the charge separation site, i.e., their recombination prior to separation must be minimized. Recombination can be intrinxic or extrinsic in origin; it can occur at the surface or in the bulk.

The magnitude of the intrinsic bulk recombination rate is determined mainly by the dependence of electron energy E on wave number k in the conduction and valence bands of the semiconductor, i.e., on whether the semiconductor is of the direct or indirect type.

When voltages of opposite polarities are applied across the p-n structures, the current flowing through them is high in one direction -- the so-called forward direction -- and low in the other -- the so-called reverse direction. If the voltage is varied continuously, rectifier current-voltage characteristics having the form of curve (a) in Fig. 6. are obtained. When light is absorbed in the junction space charge region and/or in the adjacent material on either side of the junction, minority carriers flow toward the junction and increase the reverse current. The current voltage characteristics of the illuminated cell has the form of curve (b) in Fig. 6. For curve (b), part of the I-V curve is now located in the fourth quadrant, where the current is negative and the voltage is positive; the I-V product -- the electrical power -- is negative, i.e., the device is generating power which can be delivered to a load connected across the junction.

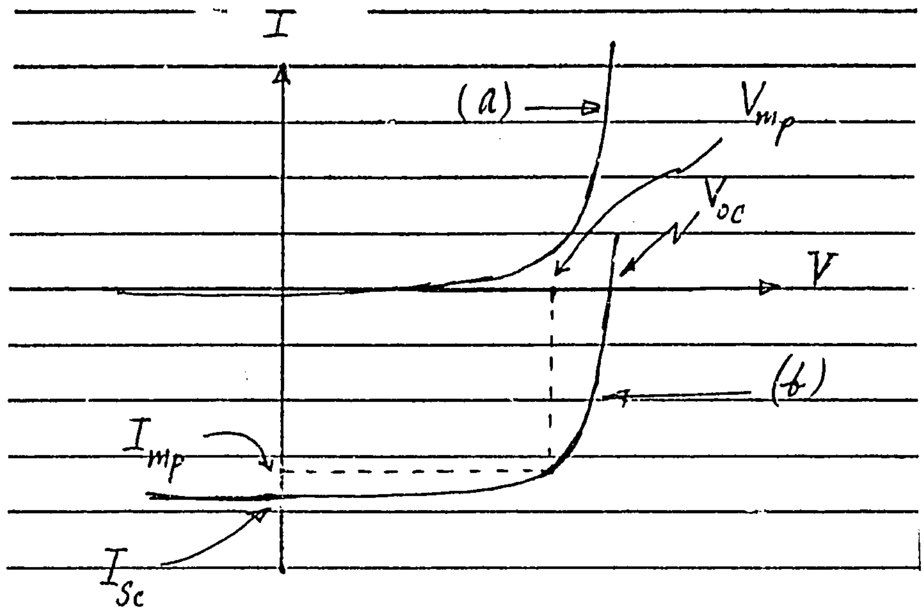


Fig. 6. Current voltage characteristic of a solar cell
(a) in the dark, and
(b) subjected to illumination

4) Short Circuit Current

The magnitude of the light generated short circuit current I_{sc} can be determined from the following integral:

$$I_{sc} = q\int_{E_G=h\nu_G}^{\infty} Q(h\nu)N_{ph}(h\nu)d(h\nu) \tag{1}$$

Here q is the charge on the electron; $Q(h\nu)$, the minority carrier collection efficiency of the absolute spectral response of the cell, is defined as the fraction of carriers generated by absorption of photons of energy $h\nu$ which contribute to I_{sc}; and $N_{ph}(h\nu)$ is the number of photons/cm^2sec with energy $h\nu$ incident on the solar cell. The collection efficiency $Q(h\nu)$ is a function of the absorption constant α, the bulk lifetime τ, the surface of the cell, and of the cell geometry. $Q(h\nu)$ can be and has been calculated for various models of a cell.

It is an objective of solar cell technology to produce cells in which the absolute spectral response is close to unity for all solar photons having energies in excess of the forbidden energy gap. In the limit the response curve would have the form of a step function, i.e.,

$$Q(h\nu) = \begin{cases} 0 \text{ for } h\nu < E_G \\ 1 \text{ for } h\nu \geq E_G \end{cases}$$

It is found that for $1.0 \leq h\nu \leq 2.5$ ev, I_{sc} is an exponential function of energy gap; in this range of $h\nu$ values

$$I_{sc} \simeq I_{sco} \exp[-k_1 E_G] \quad (2)$$

For the AMO spectrum, k_1 ranges between 1.2 and 2 and $I_{sco} \leq 200$ mA/cm^2.

5) Current Voltage Characteristic and Maximum Efficiency

The current through an "ideal" unilluminated p-n junction can be described by the expression

$$I_j = I_0[\exp(qv_j/AkT) - 1] \quad (3)$$

if internal series and shunt resistant are neglected. Here I_0 is the reverse saturation current of the junction, q the charge on the electron, v_j the voltage across the junction, k Boltzmann's constant, T the absolute temperature, and A a constant whose minimum value is A = 1 for an "ideal" p-n junction but whose actual value is higher; its value depends on imperfections in the space charge region, etc.

For moderate illumination level, the load current-voltage characteristic of an illuminated photovoltaic cell (Fig. 6b) has the form

$$I_L = I_j - I_{sc} = I_0[\exp(qv_j/Akt) - 1] - I_{sc} \quad (4)$$

The cell may also contain internal series and shunt resistances so that a lumped parameter model of a cell including these resistances would have the form snown in Fig. 7. For this circuit model the load current-voltage characteristic is described by the equation

$$I_L = I_0 \exp[q(v_L + I_L R_L)/AkT] - 1 - [(v_L + I_L R_L)/R_{sh}] - I_{sc} \tag{5}$$

A more general model of the cell would treat the series and shunt resistances as distributed resistances and would decompose the series resistance into components contributed by the contacts to the two side of the p-n junction, by the base region and by the diffused skin region; this last contribution is usually the largest.

In a well-designed solar cell, R_{sh} must be large compared to the dynamic impedance of the junction at the operating point. The operating point is usually chosen so that maximum power is transferred from the cell to the load. The resistance of the matched load for which this occurs is calculated from the relation

$$R_{Lmp} = \left(\frac{\partial v_j}{\partial I_j}\right)_{v=v_{mp}} = \frac{v_{jmp}}{I_{Lmp}} \tag{6}$$

(The subscripts "mp" refer to the values of the indicated parameters under maximum power transfer conditions.)

Now from Eq. (3)

$$R_j = \frac{\partial v_j}{\partial I_j} = \frac{AkT}{I_0 q} \exp\left[\frac{-qv_j}{AkT}\right] \tag{7}$$

In the case of single crystal cells, the main contribution to R_{sh} arises from the periphery of the junction; in practice, it is found that no special treatments of the periphery is needed to satisfy the requirement $R_{sh} \gg R_{jmp}$.

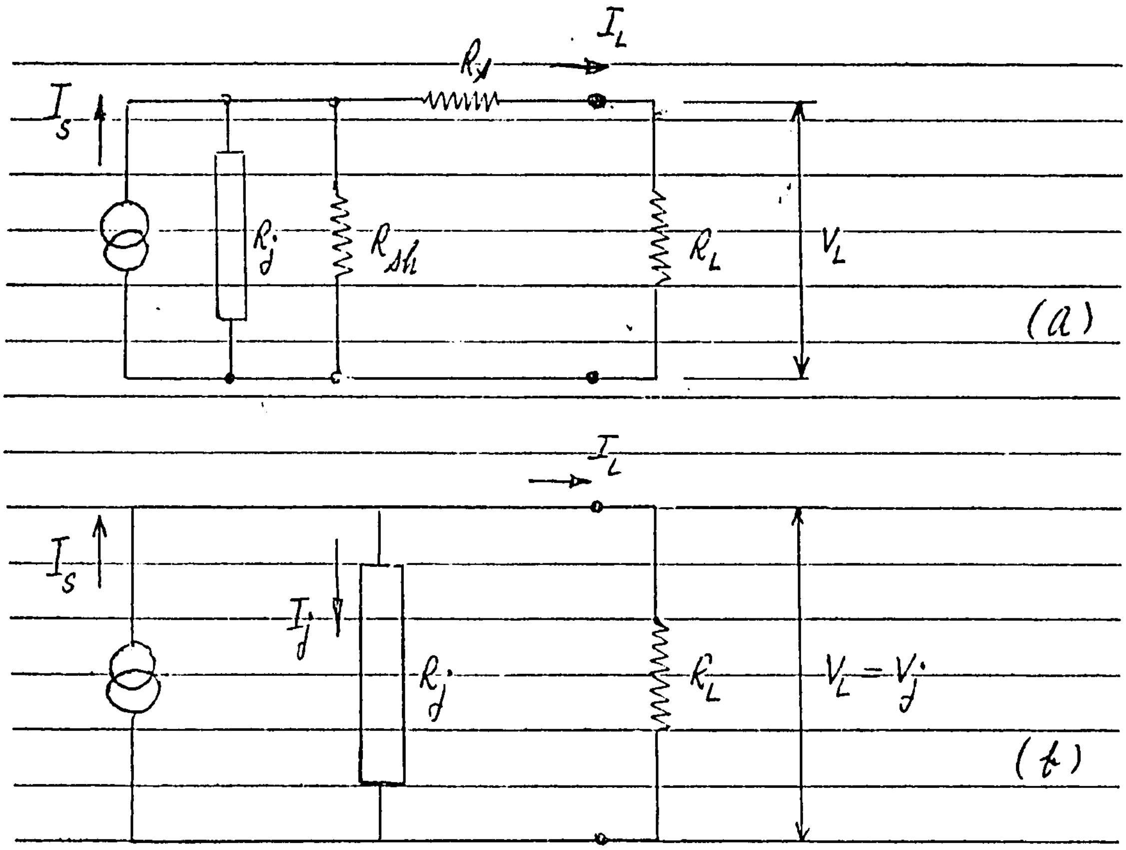


Fig. 7. Circuit model of an illuminated solar cell
(a) including internal series and shunt resistances (R_s and R_{sh}, respectively), and
(b) without these resistances

The contribution to the series resistance R_s from the sheet resistance of the diffused skin can be reduced by forming a contact grid over the light receiving surface. In conventional diffused silicon solar cells, this sheet resistance is a few tenths of an ohm for cells with an optimized grid geometry.

Though the internal shunt and series resistances must be included in detailed analyses of the photovoltaic cell, for most purposes the simplified circuit model of Fig. 7(b) can be used to describe the solar cell because it is possible to design cells so that effects of R_{sh} and R_s can be neglected. neglected. The I-V characteristic of this circuit is described by Eq. (4), from which parameters like open circuit voltage V_{oc}, current and voltage at the maximum power point, and the maximum efficiency can be calculated. For convenience the symbol $\Lambda \equiv q/AkT$ is introduced into Eq. (4) which then has the form

$$I_L = I_o[\exp(\Lambda v) - 1] - I_{sc} \tag{8}$$

The open circuit voltage V_{oc} is found by setting the load current $I_L = 0$,and

$$V_{oc} = (1/\Lambda) \ln(I_{sc}/I_o + 1) \tag{9}$$

The values of current and voltage at the maximum power point can be found by setting the load impedance equal to the dynamic impedance at the maximum power point:

$$R_{Lmp} = \left(\frac{\partial v}{\partial I}\right)_{v_{mp}} = \exp(-\Lambda v_{mp})/I_o\Lambda = v_{mp}/I_{mp} \tag{10}$$

After substitution the following equations are derived for v_{mp} and I_{mp}

$$[\exp(\Lambda v_{mp})][1 + \Lambda v_{mp}] = I_{sc}/I_o + 1 = \exp(\Lambda v_{oc}) \tag{11}$$

$$I_{mp} = [\Lambda v_{mp}/(1 + \Lambda v_{mp})] (I_{sc}/I_o + 1)I_o \tag{12}$$

From a plot of Λv_{oc} and Λv_{mp} as functions of $\ln(\frac{I_{sc}}{I_o})$, it can be seen that for $(I_{sc}/I_o) > 10^4$, $\Lambda v_{mp} \geq 10$. And from Eqs. (11) and (12), $I_{mp} \geq 0.9\, I_{sc}$ and $v_{mp} \geq 0.8\, v_{oc}$.

The maximum efficiency, i.e., the efficiency for matched load conditions, is given by

$$\eta_{max} = (\text{Power Out})/(\text{Power In}) = \frac{I_{mp}\, v_{mp}}{P_{in}}$$

$$= \frac{\Lambda v_{mp}}{1 + \Lambda v_{mp}} \cdot \frac{\Lambda v_{mp}}{\Lambda v_{mp} + \ln(1 + \Lambda v_{mp})} \cdot \frac{I_{sc}\, v_{oc}}{P_{in}} \tag{13}$$

$$\equiv \frac{CF\, I_{sc}\, v_{oc}}{P_{in}} \tag{13a}$$

where CF is the curve factor, i.e., a measure of how closely the I-V curve approaches rectangular shape. As $v_{mp} \longrightarrow v_{oc}$ and $I_{mp} \longrightarrow I_{sc}$, $CF \longrightarrow 1.0$. From the discussion presented above, for $I_{sc}/I_o > 10^4$, $CF \gtrsim 0.72$, i.e.,

$$\eta_{max} \gtrsim 0.72\, I_{sc} v_{oc}/P_{in} \tag{14}$$

6) <u>Open Circuit Voltage and Its Dependence on I_o</u>

Let us now turn our attention to the parameter v_{oc} and explore its dependence on the properties of the semiconductor. According to Eq. (9), v_{oc} is determined by I_{sc}, I_o and Λ. We have already discussed I_{sc} and its dependence on α, L, s, etc. The other two parameters appear in the expression for the I-V characteristic of a diode, i.e.

$$I_j = I_o[\exp(\Lambda v) - 1] \tag{15}$$

Such an equation assumes that the I-V characteristic is a simple exponential curve. In fact this is not so; for example, the I-V characteristic curve of the silicon p-n junctions has two distinctly different slopes -- one in the low voltage region and the other at intermediate voltages. Furthermore, at high voltages the internal series resistance begins to affect the shape of the curve and it departs from exponential behavior. Such an I-V curve can be fitted by an equation of the form

$$I_j = I_{o1}[\exp(\Lambda_1 v) - 1] + I_{o2}[\exp(\Lambda_2 v) - 1] + v/R_s \tag{16}$$

where the values of I_{o1}, I_{o2}, Λ_1, Λ_2, and R_s are determined by fitting the experimental I-V curve; R_s is the series resistance of the diode, whose magnitude could be a function of illumination level, i.e., it could be a photoresistor. In general, therefore, the I-V characteristic for voltages and currents having values low enough so that internal series resistance can be neglected should be represented by an equation of the form

$$I_j = \Sigma\, I_{oi}[\exp(\Lambda_i v) - 1] \tag{17}$$

Two basic mechanisms which can control the I-V curves of a p-n homojunction have been identified and analyzed theoretically. The first is based on the assumption that minority carriers move only under the influence of concentration gradients and that they cross the space charge region without any change in their concentrations. This is the classical p-n junction diode and the I-V expression has the form

$$I_j = I_{o1}[\exp(qv/kT) - 1] \tag{18}$$

and

$$I_{o1} \simeq n_i^2\left[\frac{1}{\sigma_n L_n} + \frac{1}{\sigma_p L_p}\right] \tag{19}$$

where n_i^2 is the concentration of carriers in intrinsic material; σ_n and σ_p are the dark conductivities of the two sides of the junction; L_n and L_p

are minority carrier diffusion lengths in the two regions. Now

$$L \simeq (D\tau)^{1/2} \tag{20}$$

where D and τ are the minority carrier diffusion constant and lifetime, respectively. Also

$$n_i^2 = N_C N_V \exp(-E_G/kT) \tag{21}$$

Consequently,

$$I_{o1} \simeq \exp(-E_G/kT) \tag{22}$$

A second mechanism is based on the assumption that generation and recombination occur in the space charge region. Under certain assumptions about the nature of the process, the I-V relation assumes the form

$$I_j \simeq (\frac{n_i}{\tau})[\exp(qv/2kT) - 1] \tag{23}$$

or

$$I_{o2} \simeq \exp(-E_G/2kT) \tag{24}$$

For these two cases one can therefore write,

$$I_{ji} = k_i \exp(-E_G/B_i kT)[\exp(qv/A_i kT) - 1] \tag{25}$$

with $A_1 = B_1 = 1$, $A_2 = B_2 = 2$, and $k_1 << k_2$.

Recombination and generation in the space charge region can at least, in principle, be controlled by controlling the recombination center concentration. If this concentration is low enough, the I_j-V curve will be governed by the ideal diode equation. Now high efficiency requires high values of v_{oc}. The question arises: which of these two mechanisms would produce a higher v_{oc} for a given value of I_{sc}? The difference between v_{oc} values produced in the two cases is

$$v_{oc}^{(2)} - v_{oc}^{(1)} = (A_2 - A_1)(kT/q) \ln(\frac{I_{o1}}{I_{o2}}) \tag{26}$$

From Eq. (26), $v_{oc}^{(1)} > v_{oc}^{(2)}$ provided only that $I_{o2} > I_{o1}$, which is always true. Because v_{oc} -- and therefore η_{max} -- is higher in cells in which space charge recombination and generation do not occur, it is a goal of of solar cell technology to fabricate cells in such a way that their I-V characteristics conform to the ideal diode form, i.e., so that A = B = 1.

7) Dependence of η_{max} on E_G

The dependence of η_{max} on E_G can now be calculated starting with Eq. (14). The dependence of v_{oc} on E_G can be deduced by substituting the band gap dependence of I_{sc} on E_G [Eq. (2)] and of I_o on E_G [Eq. (24) into Eq. (9)]:

$$v_{oc} \approx \frac{1}{\Lambda i} \ln\left(\frac{I_{sco} \exp(-k_1 E_G)}{k_i \exp(-E_G/B_i kT)}\right) \tag{30}$$

$$\approx \frac{1}{\Lambda i} \left[E_G\left(\frac{1}{B_i kT} - k_1\right) + \ln\left(\frac{I_{sco}}{k_i}\right)\right] \tag{31}$$

For the case of A = B = 1 (the ideal diode case) and T = 300 K, this becomes

$$v_{oc} = \left(\frac{kT}{q}\right)\left[38.8\ E_G + \ln\left(\frac{I_{sco}}{k1}\right)\right] \tag{32}$$

For the case A = B = 2 (recombination - generation in the space charge region) and T = 300 K, this becomes

$$v_{oc} = \left(\frac{2kT}{q}\right)\left[18.8\ E_G + \ln\left(\frac{I_{sco}}{k_2}\right)\right] \tag{33}$$

In both cases, at a fixed temperature, v_{oc} increases as E_G increases. On the other hand, I_{sc} decreases with E_G; consequently, η_{max} passes through a maximum.

8) Dependence of η_{max} on Temperature

The dependence of η_{max} on E_G is a strong function of temperature T because of the strong temperature dependence of I_0. This leads to a linear relation between v_{oc} and T. From Eq. (30)

$$v_{oc} \simeq \left(\frac{AkT}{q}\right)\left[\left(\frac{E_G}{BkT}\right) - E_G k_1 + \ln\left(\frac{I_{sco}}{k_i}\right)\right] \tag{34}$$

$$\simeq \frac{AE_G}{Bq} - \left(\frac{AkT}{q}\right)\left[k_1 E_G + \ln\left(\frac{I_{sco}}{k_i}\right)\right] \tag{35}$$

Thus, the value of v_{oc} decreases as T increases. If A = B, the intercept of Eq. (35) is equal to the energy gap E_G/q. Now according to Eq. (13)

$$\eta_{max} = CF\ I_{sc}\ v_{oc}/P_{in} \tag{36}$$

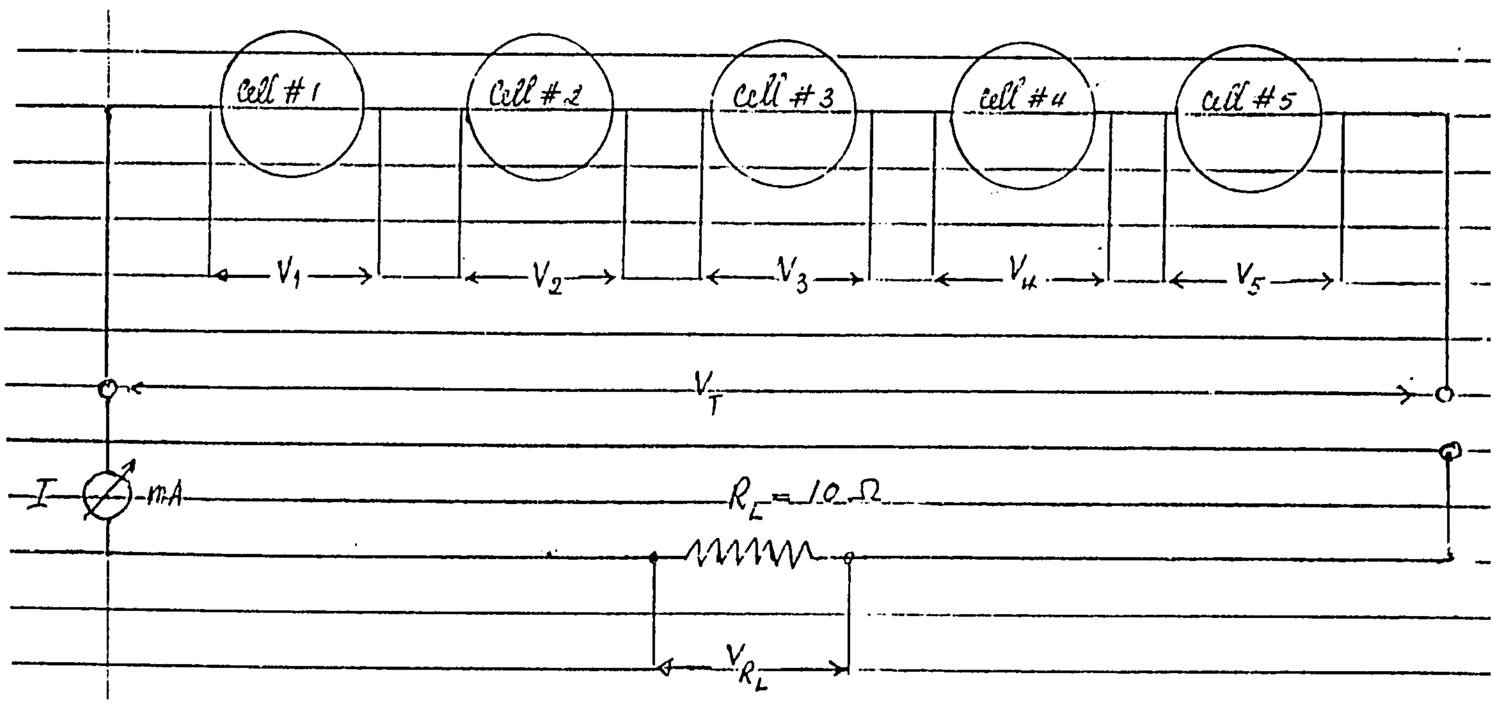
The curve factor CF has a very weak temperature dependence because its numerator and denominator are both approximately linear functions of T. Therefore, the temperatures dependence of η_{max} is essentially the same as that of v_{oc}, i.e., η_{max} is a linear function of T.

II. Experimental Results

Experiment #1: To investigate a matched pair of silicon solar cells

Equipment & Components:

- 4 Silicon Solar Cells (ARCHER - Silicon Solar Cell. Cat. #276-127, 4" Diameter ± 1/8")
- 1 Silicon Solar Cell (Edmund Scientific - Sicon Solar Cell, 4" Diameter)
- 1 Digital Multimeter (HP 3465 A)
- 1 AVO-Meter (Simpson 260)
- Solar Radiometer (Matrix, Mark VI - Sol-A-Meter)
- 10Ω Load Resistor
- Artificial Sunlight Source



Cell #1-#4: ARCHER Silicon Solar Cell

Cell #5 : Edmund Scientific Silicon Solar Cell

Procedure:

Four Archer silicon solar cells and one Edmund Scientific silicon solar cell are used in this experiment. The cells are temporarily fixed to a transparent plastic plate. They are arranged such that they can be simultaneously and uniformly exposed under any light source. Wires from each cell are orderly connected to the barrier strip for ease of measurement and flexibility. All cells are connected in series. The open-circuit voltage and the short-circuit current of each cell are measured. With the load resistance of 10 Ω in the series circuit, the load current and the voltage drop across the load are measured. The experiments are performed under the insolation of 100 Btu/hr-ft^2. The data are presented.

Data

Insolation, $I_o = 100 \frac{Btu}{hr\text{-}ft^2}$

Load condition	cell #1	cell #2	cell #3	cell #4	cell #5	
Open circuit condition, $R_L = \infty$	v_{oc}=0.449 volt	v_{oc}=0.494 volt	v_{oc}=0.492 volt	v_{oc}=0.473 volt	v_{oc}=0.486 volt	v_{oc}=2.353 volt
Short circuit condition	I_{sc}=289.5 mA	I_{sc}=490.0 mA	I_{sc}=485.0 mA	I_{sc}=461.7 mA	I_{sc}=490.2 mA	I_{sc}=336.0 mA
With load resistance of 10 Ω (R_L=10 Ω)						I=188.9 mA v_{R_L}=1.95 volt

ARCHER silicon solar cell (cat. #276-127)

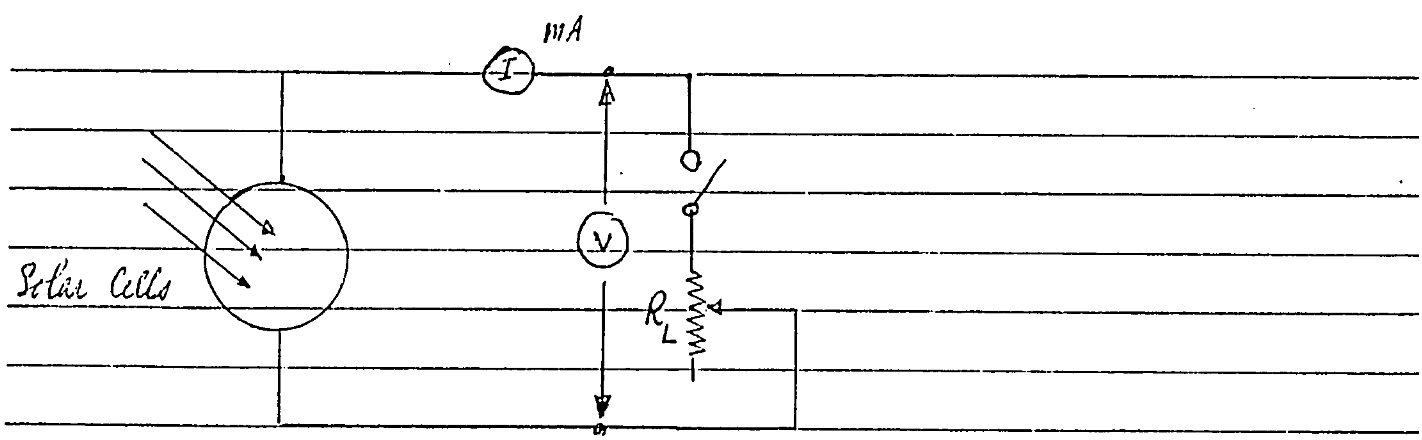
Specification: 4" diameter ±1/8" (10.1 cm ±3 mm)
Positive lead (back)
Negative lead (front)
v_{sc} = 0.55 v
I_{sc} = 2.0 A } Absolute maximum rating at full Sunlight at noon, at 25°C

From the experimental data, the cells #2 and #3 or the cells #2 and #5 can be considered as a matched pair of solar cells.

Experiment #2: I-V characteristics of 5 silicon solar cells in series and solar cell panel

Equipment & Components:

- 1 SOLAR ELECTRIC INTERNATIONAL - Solar Cell Panel
- 4 ARCHER - Silicon Solar Cells
- 1 Edmund Scientific Silicon Solar Cell
- 1 HP - Digital Multimeter
- 1 Simpson AVO-Meter
- 1 Matrix Solar Radiometer
- 16-220Ω Rheostat
- Artificial Sunlight Source



Procedure:

(1) Five Solar Cells in Series:

Five solar cells are connected in series and then are exposed under the photolamp with the insolation of 70 Btu/hr-ft^2, 100 Btu/hr-ft^2 and 120 Btu/hr-ft^2 respectively. The circuit diagram for the I-V characteristic measurement is shown. The load current and the load voltage of the circuit are measured and recorded. The experimental data of I and V are then plotted for the I-V characteristic curves. The I-V characteristics of the solar cells in series are presented.

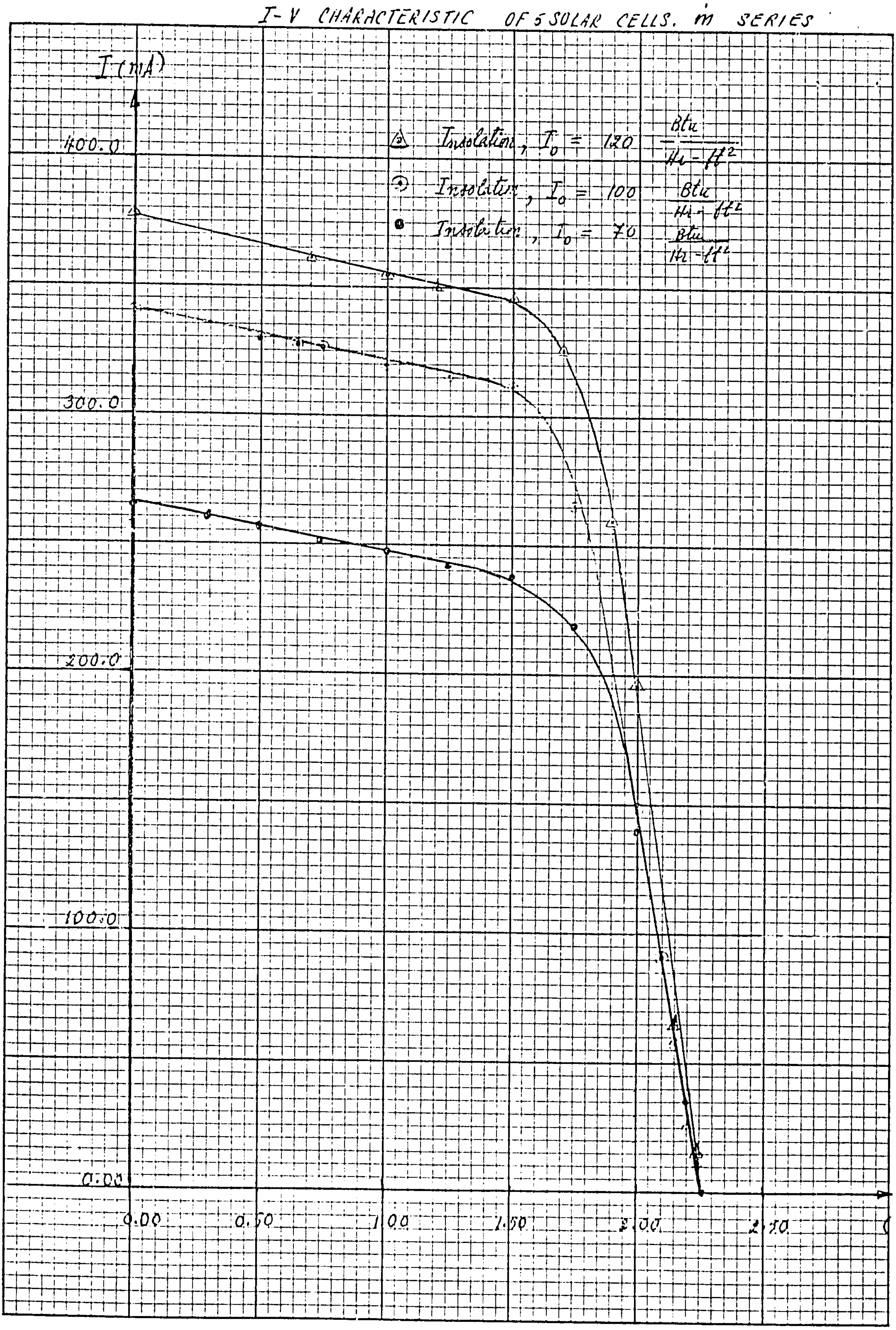
(2) Solar Cell Panel:

The solar cell panel is exposed under the photolamp at the insolation of 100 Btu/hr-ft^2 and 120 Btu/hr-ft^2. The load current and voltage of the solar cell panel are measured and recorded. The I-V characteristic curves are obtained.

Data:

No. 1 $I_0 = 70 \frac{Btu}{hr\text{-}ft^2}$		No. 2 $I_0 = 100 \frac{Btu}{hr/ft^2}$	
I (mA)	v (volt)	I (mA)	v (volt)
I_{sc} = 265.0	0	I_{sc} = 340.0	0
262.0	0.25	330.0	0.50
257.0	0.50	328.0	0.65
252.0	0.75	327.0	0.75
247.0	1.00	320.0	1.00
243.0	1.25	316.0	1.25
238.0	1.50	311.0	1.50
219.0	1.75	265.0	1.75
139.0	2.00	147.0	2.00
91.0	2.10	90.8	2.10
64.8	2.15	57.5	2.15
36.5	2.20	24.2	2.20
12.3	2.25	12.0	2.22
0	v_{oc} = 2.26	0	v_{oc} = 2.26

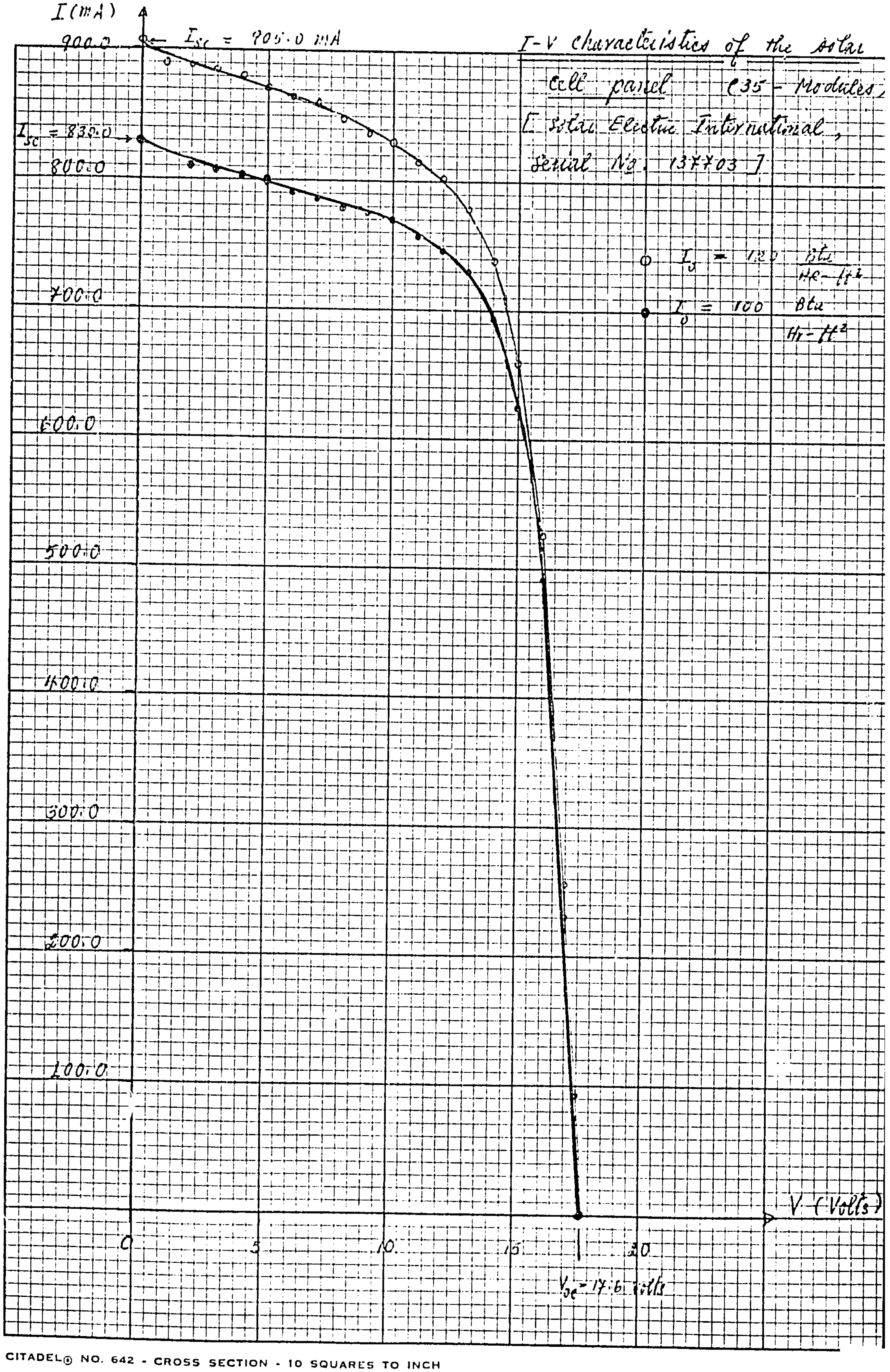
No. 3 $I_0 = 120 \frac{Btu}{hr\text{-}ft^2}$		No. 4 $I_0 = 110 \frac{Btu}{hr/ft^2}$	
I (mA)	v (volt)	I (mA)	v (volt)
I_{sc} = 378.0	0	I_{sc} = 366.0	0
362.0	0.70	356.0	0.25
354.0	1.00	346.0	0.60
350.0	1.20	342.0	0.90
347.0	1.50	339.0	1.00
326.0	1.70	334.0	1.30
259.0	1.90	328.0	1.50
196.0	2.00	292.0	1.75
138.0	2.10	248.0	1.85
95.2	2.15	199.0	1.95
61.8	2.20	172.0	2.00
31.0	2.24	113.0	2.10
12.3	2.25	76.3	2.15
		37.0	2.20
		12.2	2.25
	v_{oc} = 2.26		v_{oc} = 2.26



CITADEL NO. 642 - CROSS SECTION - 10 SQUARES TO IN

No. (1) $I_o = 100 \frac{Btu}{hr-ft^2}$		No. (2) $I_o = 120 \frac{Btu}{hr/ft^2}$	
I (mA)	v (volt)	I (mA)	v (volt)
I_{sc} = 830	0	I_{sc} = 905.0	0
		890.0	0.50
		888.0	1.00
		885.2	1.50
812.0	2.00	884.0	2.00
809.0	3.00	884.0	3.00
806.0	4.00	880.0	4.00
800.0	5.00	872.0	5.00
793.0	6.00	867.0	6.00
788.0	7.00	858.0	7.00
778.0	8.00	844.0	8.00
774.0	9.00	835.0	9.00
770.0	10.00	830.0	10.00
757.0	11.00	817.0	11.00
745.9	12.00	802.0	12.00
728.9	13.00	779.0	13.00
694.5	14.00	738.0	14.00
626.8	15.00	660.0	15.00
493.8	16.00	526.0	16.00
234.0	17.00	255.0	17.00
91.8	17.50	95.0	17.50
	v_{oc} = 17.6		v_{oc} = 17.60

From the experimental results (the I-V characteristic curves), one can select the proper operating point in order to get the maximum power output of the systems.

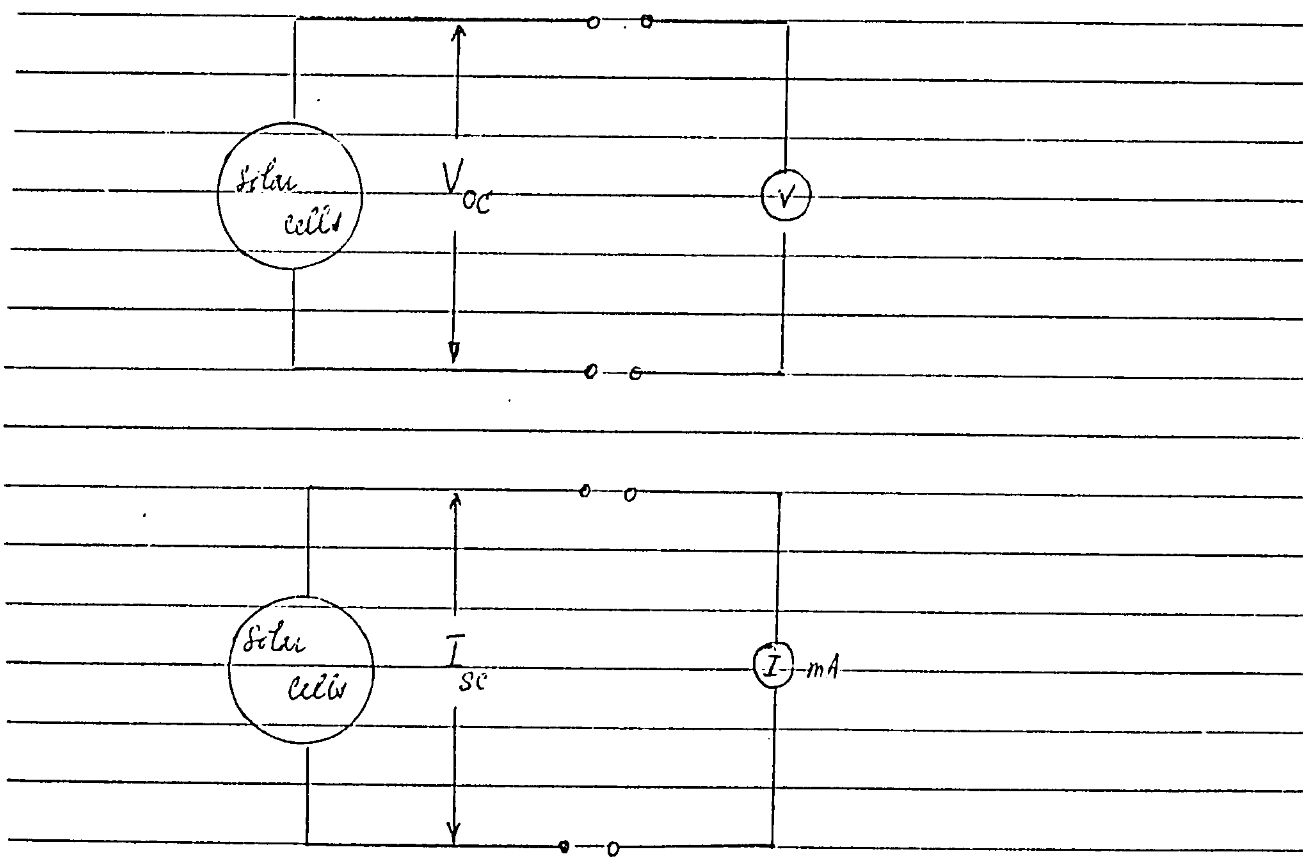


CITADEL® NO. 642 - CROSS SECTION - 10 SQUARES TO INCH

Experiment #3: Variation of v_{oc} and I_{sc} vs Time, t, of the five solar cells in series

Equipment & Components:

- 4 ARCHER - Silicon Solar Cells
- 1 Edmund Scientific Silicon Solar Cell
- 1 HP - Digital Multimeter
- 1 Matrix Solar Radiometer
- 1 Watch
- Artificial Sunlight Source

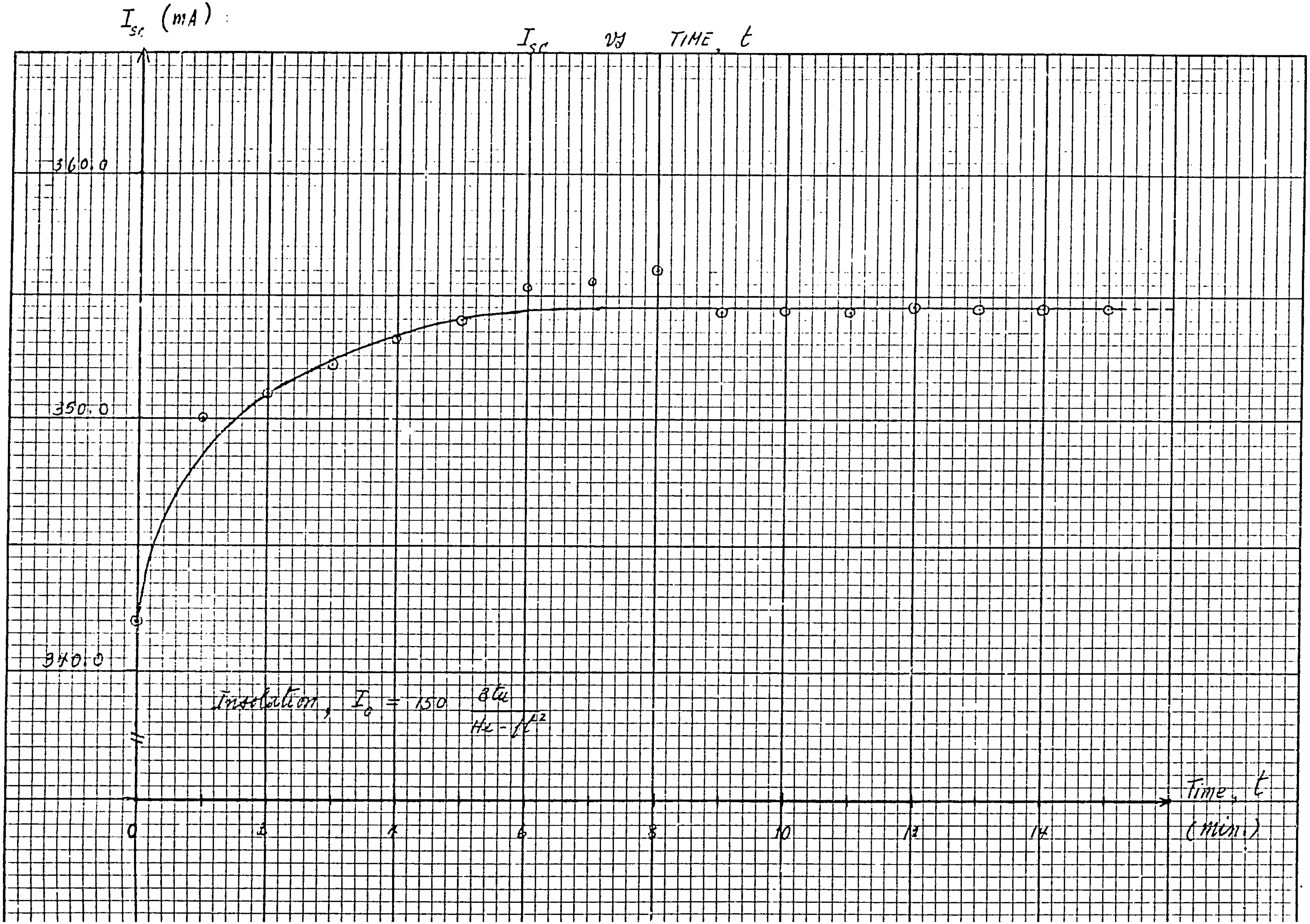


Procedure:

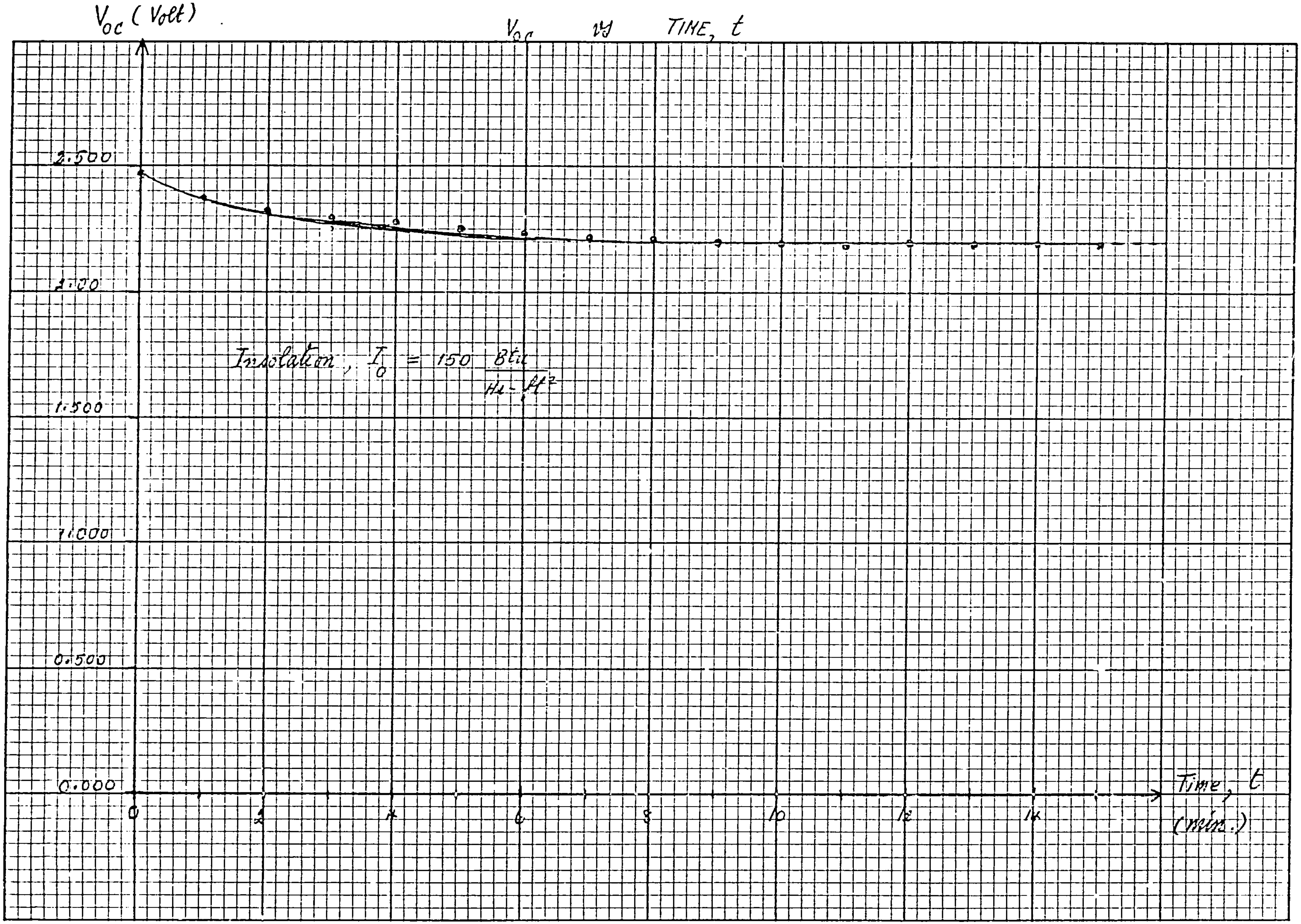
The open-circuit voltage, v_{oc}, and the short-circuit current, I_{sc}, of of the five solar cells in series are observed as time goes on. The results are recorded. The $(\frac{\Delta v}{\Delta t})$ and $(\frac{\Delta I}{\Delta t})$ can be observed and measured in this experiment. From this experiment, the cells should be allowed to expose to the insolation for not less than 7 minutes before any measurement to perform, in order that the cell temperature is constant.

Data

$I_o = 150 \frac{Btu}{hr\text{-}ft^2}$		$I_o = 150 \frac{Btu}{hr/ft^2}$	
Time, t (min)	v_{oc} (volt)	Time, t (min)	I_{sc} (mA)
0	2.465	0	342.0
1	2.376	1	350.0
2	2.337	2	351.0
3	2.306	3	352.1
4	2.283	4	353.2
5	2.262	5	354.0
6	2.246	6	355.4
7	2.236	7	355.6
8	2.223	8	356.1
9	2.215	9	354.2
10	2.202	10	354.3
11	2.194	11	354.4
12	2.200	12	354.6
13	2.198	13	354.6
14	2.196	14	354.7
15	2.193	15	354.4



I_sc (mA)
I_sc vs TIME, t
360.0
350.0
340.0
Insolation, I_o = 150 Btu/Hr-ft^2
0
2
4
6
8
10
12
14
Time, t
(min.)

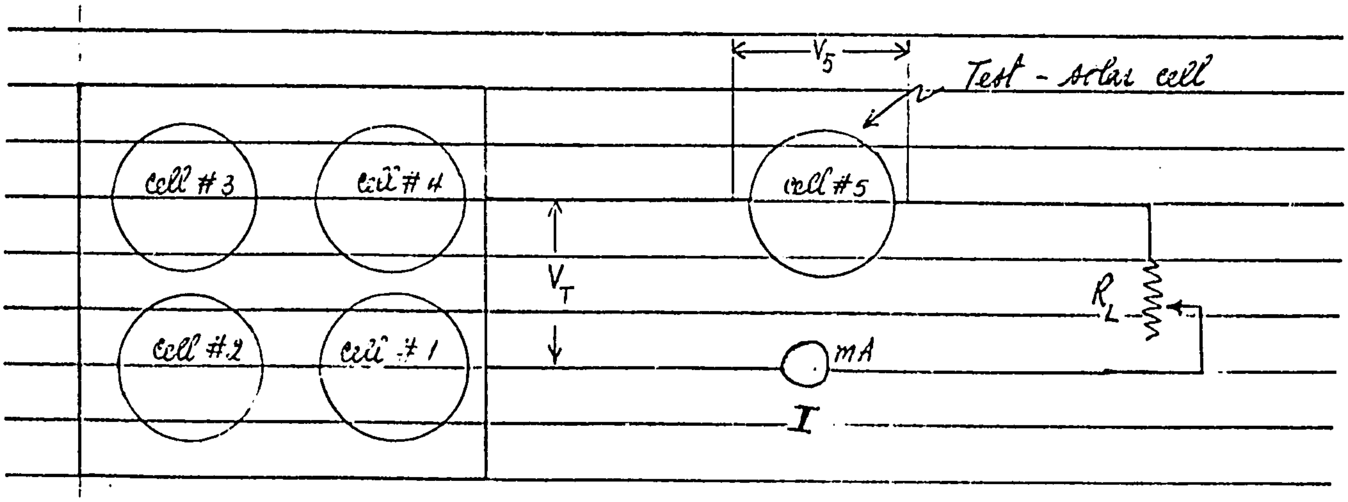


V_{oc} (Volt)
V_{oc} vs TIME, t
2.500
2.000
1.500
1.000
0.500
0.000
Insolation, I_o = 150 Btu / Hr-ft²
0
2
4
6
8
10
12
14
Time, t
(min.)

Experiment #4: Shadow effect on the test solar cell

Equipment & Components:

- 4 ARCHER - Silicon Solar Cells
- 1 Edmund Scientific Silicon Solar Cell
- 1 HP - Digital Multimeter
- 1 Simpson AVO-Meter
- 1 Matrix Solar Radiometer
- 16-220 Ω Rheostat
- Artificial Sunlight Source



The experimental circuit was arranged as shown in the circuit diagram. The cell #5 was used as the test cell for shadow effect study. The voltage drop across the test solar cell was measured at various shadow conditions. The load voltage and load current were also measured. The experimental results are presented.

Data: Shadow effect on the test solar cell (cell #5)

Conditions	v_T (volt)	v_5 (volt)	v_{R_L} (volt)	I (mA)
- No shadow	1.9	0.45	2.3	90
- Partially shadow (Half-cell)	1.78	0.43	2.17	86.03
- Total shadow	1.75	-0.68	1.1	43.20

Insolation, $I_0 = 120 \frac{Btu}{hr\text{-}ft^2}$

Experimental results seem to confirm with the theoretical predictions about the shadow effect.

III. The Cost of the System

1) ARCHER Silicon Solar Cell (cat. #276-127, 4" diameter ±1/8") ≃ @ \$20.00

2) Edmund Scientific Silicon Solar Cell (≃ 4" diameter) ≃ @ \$20.00

3) Solar Electric International - Solar Cell Panel (35 modules, serial #137703) ≃ @ \$600.00

At the present time, the cost of a solar cell (or a solar cell panel) which is made of single crystal silicon is still very high. The technology for solar cells is being developed. It is expected that the cost of the system will be lower in the future.

IV. Conclusion

It is our conclusion that the experimental results agree with the theoretical predictions. From a technical point of view, the generation of electricity from the solar cell is applicable, but from an economic point of view, the cost of the system is very high at the present time. It is felt that there will be a trend toward lower prices as technological breakthroughs occur.

References

1. William C. Dickinson and Paul N. Cheremisinoff (eds.), Solar Energy Technology Handbook - Part A: Engineering Fundamentals - Chapter 18: Photovoltaic Materials (by Joseph J. Loferski), Mercel Dekker, Inc. 1980.

2. Materials Science in Energy Technology, Chapter 4: Materials for Solar Energy Conversion (by Joseph J. Loferski), Academic Press, Inc. 1979.

3. David L. Pulfrey, Photovoltaic Power Generation, Van Nostrand Reinhold Co., 1978.