A PHOTOVOLTAIC POWER SYSTEM FOR A VILLAGE IN LIBYA

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CHAPTER I

INTRODUCTION

Over the years, photovoltaic power systems have proven to be a reliable, cost effective source of power in many rural areas where conventional methods of supplying electricity are not available. These systems use photovoltaic (or solar) cells, which absorb sunlight and convert it directly into electricity. They require no moving parts and no intermediate conversion of solar energy to heat.

Solar cell developments have gone from a laboratory curiosity to an expensive but essential component of the space program to relatively large scale terrestrial applications in the past three decades. Applications of solar cells are rapidly spreading to a wide variety of sites and applications throughout the world, offering great potential benefits to people in developing, as well as developed countries.

The objectives of this thesis fall in the following categories: a) to survey worldwide solar cell research and development activities; b) to provide a technical assessment of the photovoltaic systems for several applications in many countries; c) to present the results of a series of experiments conducted on solar cell panel acquired as a part of this study; and d) to show how a photovoltaic system might benefit a remote village in Libya.

Chapter II reviews the history of solar cells. Since 1839 when the photovoltaic effect was first discovered, the photovoltaic technology has grown from a laboratory curiosity into a mature science. Silicon is the number one semiconductor material of choice for producing photovoltaic converters.

Chapter III summarizes solar cell principles. Equations describing the current, voltage and power relationships for solar cells are presented and discussed. Typical current-voltage curves are displayed as a function of illumination level. The chapter also indicates the relationship between the efficiency of several semiconductor materials as a function of the energy gap (Eg) associated with these materials for various temperatures.

Chapter IV describes a series of experiments on four solar cell modules. The experiments examine the effect of changes in solar insolation on the output characteristics of the solar cell power.

Chapter V describes some of the constraints associated with a solar cell power system for a typical rural village in Libya. The chapter describes the general conditions of such a village and the benefits that could be a result from such a system.

Chapter VI summarizes the conclusions reached by this study and outlines some suggestions for future work in photovoltaics in Arab countries.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the history of photovoltaic cells. It includes a survey of recent solar research and development activities.

2.2 History of Photovoltaic Cells

Photovoltaic energy converters appear to be one of the more desirable approaches to harness solar energy. Direct conversion of solar radiation into electricity can be achieved with a simple device that has no moving parts, needs no additional sources of energy and requires minimum maintenance. The photovoltaic devices or solar cells, are based on the properties of certain materials that can produce electricity when exposed to sunlight.

The photovoltaic effect was first observed by Edmond Becquerel in 1839 (22), when he discovered that a voltage was produced between silver chloride (AgCl) and platinum (Pt) electrodes immersed in an electrolyte solution, when light was directed to one of the electrodes. Forty years later the phenomena was observed in a solid (selenium) by W. G. Adams and R. E. Day (24). Between the First and Second

World Wars a significant effort in photovoltaic research was undertaken in many countries including the USA, UK, Germany and France. Important contributions also came from research in the USSR. The materials used were primarily selenium (Se) and cuprous-oxide(CU_2O). This work led to the use of the photovoltaic effect as a source of power for electric exposure meters (16). At that time the metallurgy of semiconductor materials had not advanced to a point where such materials could be used. In 1954, Pearson, Fuller and Chapin (21) demonstrated the first practical solar cell made from silicon (Si) at the Bell Telephone Laboratories. Their cells were of circular shape with 3 cm. diameter. They achieved conversion efficiences as high as six percent (25) by means of junctions of p-type and n-type semiconductors. Later workers in the area have achieved efficiency above fifteen percent (21) by improving the silicon p-n junctions.

During the 1970's the development of silicon solar cells for terrestrial applications was pursued with a primary goal of lowering cell fabrication costs rather than with improving cell efficiency. Major progress in cost reduction was made by making larger, and purer silicon crystals.

One potential technique to reducing the cost of solar cells is to use the concentrated sunlight systems by increasing the cell output power density (25). These concentrators could be lenses or mirrors to focus sunlight on solar cells which should have a very high conversion efficiency. But the sunlight concentration can lead to large increases in cell temperatures that decreases the cell efficiency.

Other types of solar cells are under study including cells made from cadmium sulphide (CdS) and gallium arsenide (GaAs).

A basic goal of solar cell research and development is to make them economically competitive with other techniques of electric power generation. Because of their simplicity, reliability, low weight and lack of moving parts, solar cells have become indispensable as a source of power supply for satellites and other space apparatus.

The advantages of photovoltaic solar cells as power systems for terrestrial applications include the following:

1. They have an extremely long life time.

2. Modular construction, with efficiences that are very nearly independent of size.

3. No fuel costs, and the energy resource is universally available.

4. They are quiet and clean, and compatible with most environments.

5. They produce a nearly constant voltage output under widely varying sunlight conditions.

These major advantages are not matched by any other technique of harnessing solar energy.

2.3 Industrial Production and Applications

Commercialization started with silicon solar cells between the years 1955-1960, for terrestrial and space applications with small amounts of power from 5 milliwatts to power a radio transmitter to 15 watts of power for satellite (18). By 1973, production levels went up for use in space when the National Aeronautics and Space Administration (NASA, USA) launched a sky lab in space with its 20 KW solar generator (21). The 1975 world production rate of silicon cells for use in space was about 100 KW a year (18). Solar cell production for terrestrial application grew rapidly in the 1970's. The energy crisis of October 1973 gave a clear signal to the world that the time of cheap and easily available hydrocarbon fuel is coming to end, and that alternative energy sources should be harnessed as a substitute for conventional fuels. During 1979 the volume of sales of solar cells in the United States was about 4 MW. It increased to 7.5 MW in 1980 and jumped to 18 MW in 1983 (6), (11). As the production level of PV cells increased, the cost of the solar system decreased and the number of potential applications increased. Many applications have developed, including low power, remote applications where utility power is not available and where the alternative fuel is expensive. The various applications projected for photovoltaics (PV) power systems in the US includes microwave repeaters, cathodic protection of pipe lines, irrigation water pumping, railway control signals, remote village applications, weather stations, navigational lights (23), and in central power stations (16 MW in California) (18).

Based on the power required for the application of the PV power system, applications can be classified as listed below (23):

1. Very small systems (smaller than 10 w) such as watches, calculators, radios, and music systems.

2. Small systems (10 w - 1 KW) such as remote communication, cathodic protection pipe lines, and highway warning signals.

3. Kilowatt-size systems (1 - 10 KW) such as rural power systems for remote villages, irrigation pumps, or single family residences.

4. Intermediate Systems (10 - 100's KW) operating with utility backup. Typically used in commercial and industrial systems for public services, such as, hospitals, schools, airports, desalination of sea water, village power systems and shopping centers.

5. Large systems (1 MW - 100's MW) operated with utility backup. Central utility applications systems for supplying power to special industrial consumers that required DC power generation such as an aluminum plant.

In recent years, PV conversion plants have become important to many countries. Table I lists the effort of

TABLE I

WORLD WIDE PHOTOVOLTAIC PROJECTS (9), (11)

Location	Size (Kw)	Application
Carissa, CA, USA	16,500	Power Station
Japan	200	School Power
Rural Area, Mexico	30	Power Rural Applications
Pellworm Island, W. Germany	300	Power Recreation Center
Southern Part, UK	100	Grid Interconnection
Kythons Island, Greece	100	Island Grid
Vester Bøgebjerg, Denmark	100	Village Power
Vulcano Islan, Italy	80	Village Power
Chevetgne, Belgium	63	Swimming Water Pumps & Lights
Nice Airport, France	50	Tower Control Power
Fota Island, Ireland	50	Dairy Farm Power
Terschelling Island, Holland	50	Marine School Power
Al-Jubaylah, Sauid Arabia	350	Village Power
Remote Area, Oman	15	Seawater Desalination
Sadat City, Egypt	10	Water Pump & Lighting
Garak, Mauretania	5.0	Water Pump
N. West Somalia	3.0	Water Pump
Syria	0.8	Experimental Purpos
Island of La Reunion	60	Island Power
Djiola, Mali	16	Hospital
Niger	1.8	Water Pump
Tangaye, Upper Volta	1.8	Water Pump & Grain Mill
Senegal	1.8	Water Pump
Ivory Coast	1.0	Water Pump
Java, Indonesia	5.5	Village Power
Mamnialia, Pakistan	5.0	Village Power

various countries to use photovoltaic power system in a wide range of applications. The figures correspond to the maximum power output of the PV system in one project in each location. Table II lists the major photovoltaic energy projects in the US (8), (18).

Japan has also a long term large scale project for photovoltaic production, called the sunshine project (14). It started in 1974, and resulted in several PV systems. Japan expects solar cell production to be increased from 500 KW to 5000 KW and to 50,000 KW in several stages. The medium scale of 200 KW projects for school and factory have been completed. Large scale as central-station photovoltaic power plants are not considered feasible in Japan because of the limited land availability (11).

European work in photovoltaic systems is directed toward working with developing countries in their rural electrification and production of PV systems for use in Europe. Research, development and production have been overseen by the Commission of the European Communities (CEC) since 1975. Under the CEC, 13 of 15 pilot plants were completed by December 1983 (11). The total production capacity in the CEC reached about 6 MW in 1982, and it is expected to reach 10 GW by the year 2000.

Photovoltaic power systems have been established in several locations in Arab countries. The largest photovoltaic project is the 350 KW system recently completed in

TABLE II

MAJOR PHOTOVOLTAIC PROJECTS IN US (8), (18)

Location	Size (Kw)	Application
Kauai, HI	80	Hospital
Phoenix, AZ	225	Airport
Albuquerque, NM	50	Office Building
Dallas-Ft. Worth, TX	27	Airport
Orlando, FL	110	Seaworld Park
Lovington, NM	100	Shopping Center
El Paso, TX	20	Computer UPS
Oklahoma City, OK	150	Museum
Bevely, MA	100	High School
Blytheville, AR	250	Community College
Bryan, OH	25	Radio Station
Mead, NB	25	Irrigation System
Mt. Laguna, CA	60	Air Force Base
Senatobia, MS	200	Junior College
Georgetown, Washington DC	300	International Center
National Monument, Utah	100	National Park
Hesperia, CA	1000	Power Station
Carissa, CA	16500	Power Station

Saudi Arabia with assistance from the US Department of Energy.

CHAPTER III

PHOTOVOLTAIC CELLS: PRINCIPLES AND CHARACTERISTICS

3.1 Introduction

This chapter studies the basic principles and characteristics of photovoltaic solar cells. The photovoltaic operation is based on the photovoltaic effect, which describes the generation of charge carriers inside a material by the absorption of energy from incident radiation. When light photons are absorbed, an electron-hole pair is created if the photon energy is greater than the band-gap energy. The most suitable and common material used for solar cells is silicon.

3.2 Solar Radiation

The sun is a thermonuclear reactor that emits energy continuously from its surface, where the temperature is approximately 5900° K. The radiant energy is mainly in a form of electromagnetic waves of wavelengths ranging from 0.22 microns to 3.3 microns (3).

Solar radiation is composed of tiny bundles of energy called photons. The energy of each photon varies with the frequency of radiation. The relationship between photon energy and frequency was developed by Max Planck in 1901 and is given as:

$$E = hf \tag{3.1}$$

where E is the photon energy, h is Planck's constant (6.63 x 10^{-34} Joule/sec), and f is the frequency in Hz. Since the frequency varies inversely as the wavelength λ, Equation 3.1 can be written as:

$$E = hc/\lambda \tag{3.2}$$

where c is the speed of light.

It is convenient to describe photon energy in electron volts (eV). An electron volt is defined as the energy gained by an electron when it is accelerated by a voltage difference of 1.0 volt. The photon energy equation has another form related to the wavelength in terms of eV (3)

$$eV = \frac{12398\ \mathring{A}}{\lambda} \tag{3.3}$$

where Å is the angstrom unit (10^{-10}m). The energy of sunlight photons varies between 0.5 eV and 4.15 eV as it reaches the earth's atmosphere (20). The earth's atmosphere, which contains water vapor, dust, carbon dioxide, smoke and clouds, has a considerable effect on the spectral distribution of sunlight reaching the earth's surface as shown in Figure 3.1 (3). The area between the dotted line and the solid line represents the portion of sunlight absorbed by the earth's atmosphere. The ultraviolet radiation

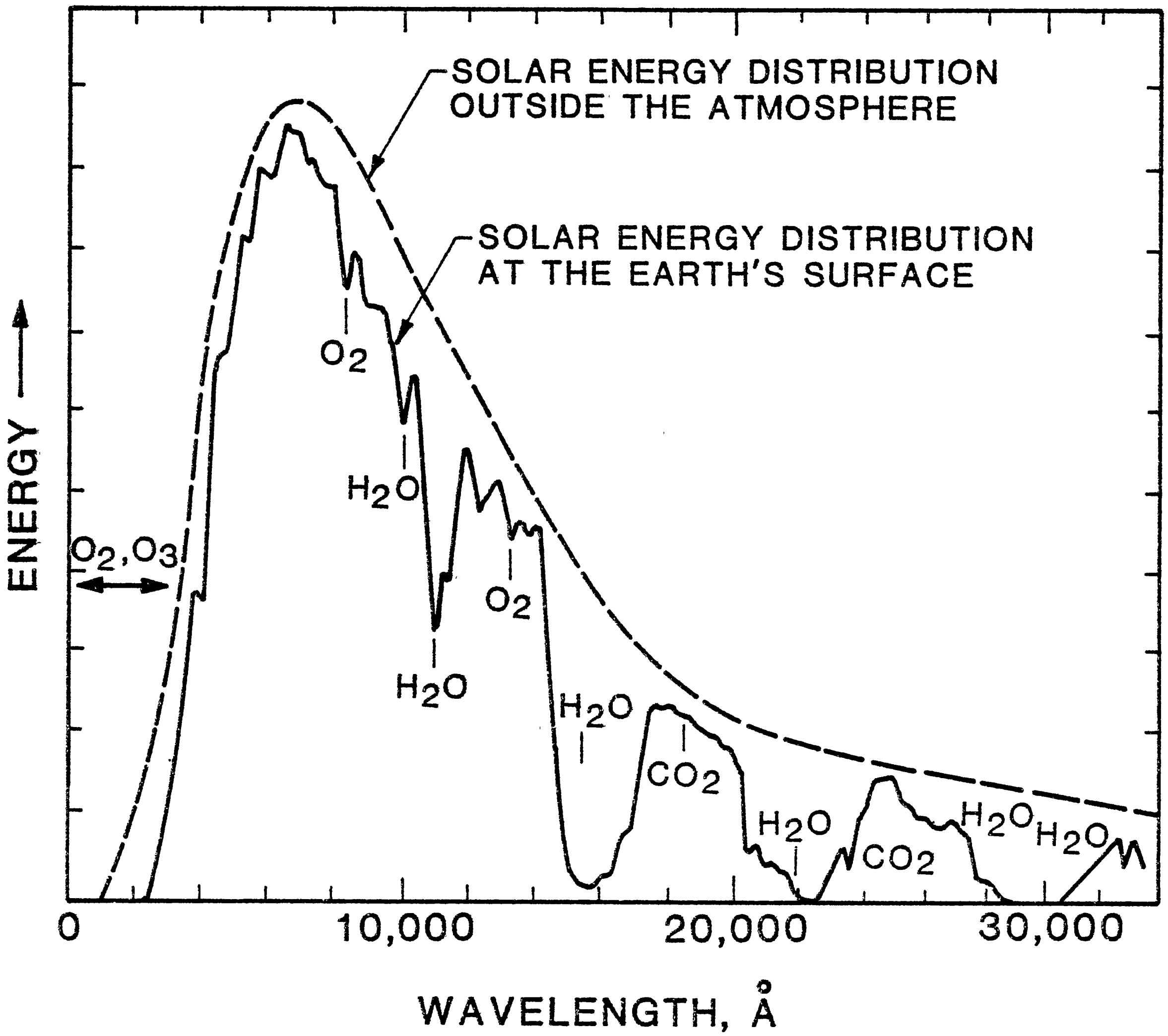

Figure 3.1. Spectral Distribution of Sunlight Arriving at Earth's Surface.

at wavelengths less than 0.38 micron, and the infra-red radiation at wavelengths greater than 0.8 micron is shown to be significantly affected.

3.3 Basic Principles of Solar Cells

Energy-level diagram for a semiconductor material is shown in Figure 3.2. Valence electrons can leave the valence band and cross the band gap to the conduction band, if they gain enough energy above the band gap energy. The energy in light can be transferred to electrons when a photon strikes an atom in a semiconductor material. The collision can cause electrons from a fixed position in the valence band to jump to the conduction band if they have energies above the threshold value. An empty position (or hole) is left behind at the site of the collision. Holes have positive charges. The process of forming an electron-hole pair from a photon-electron collision is depicted in Figure 3.3.

The internal electric field in a photovoltaic device can be established in the depletion layer at the p-n junction. The electron-hole pairs of charge carriers can be separated by the electric field, and collected by electrodes, and made to flow as a useful current in an external circuit, thereby directly achieving light to electricity conversion. Figure 3.4 illustrates the principle of photovoltaic operation. As shown in the figure, a photon penetrates through the n-type before reaching the p-n junction

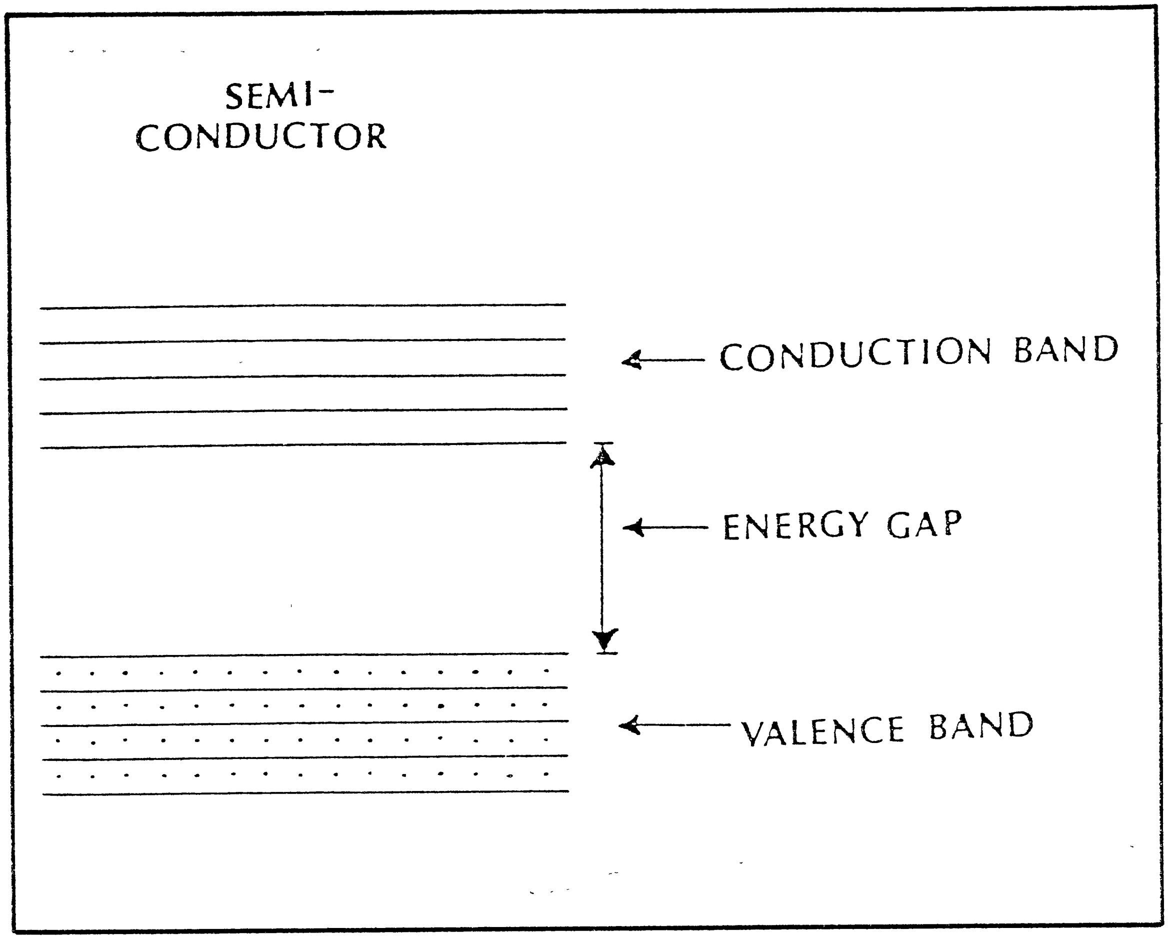

Figure 3.2. Energy-Levels Diagram for a Semiconductor.

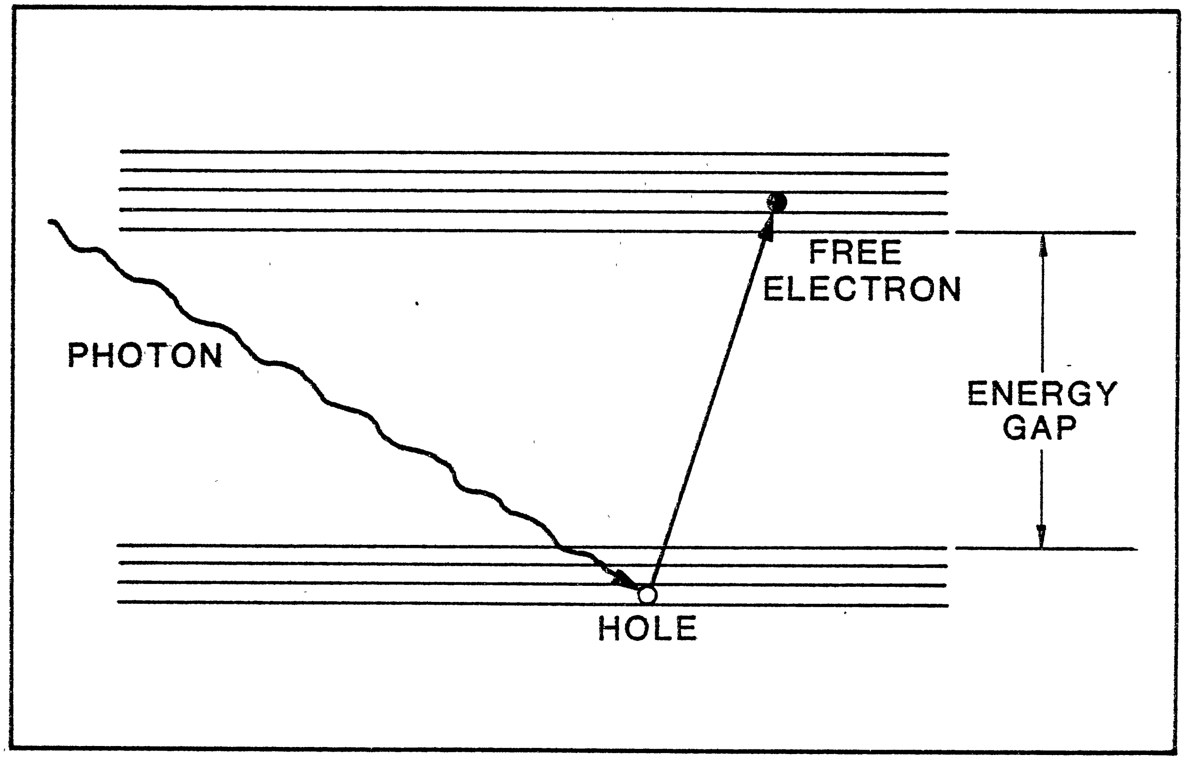

Figure 3.3. A Photon-Electron Collision can Activate an Electron across the Energy Gap and form an Electron-Hole Pair.

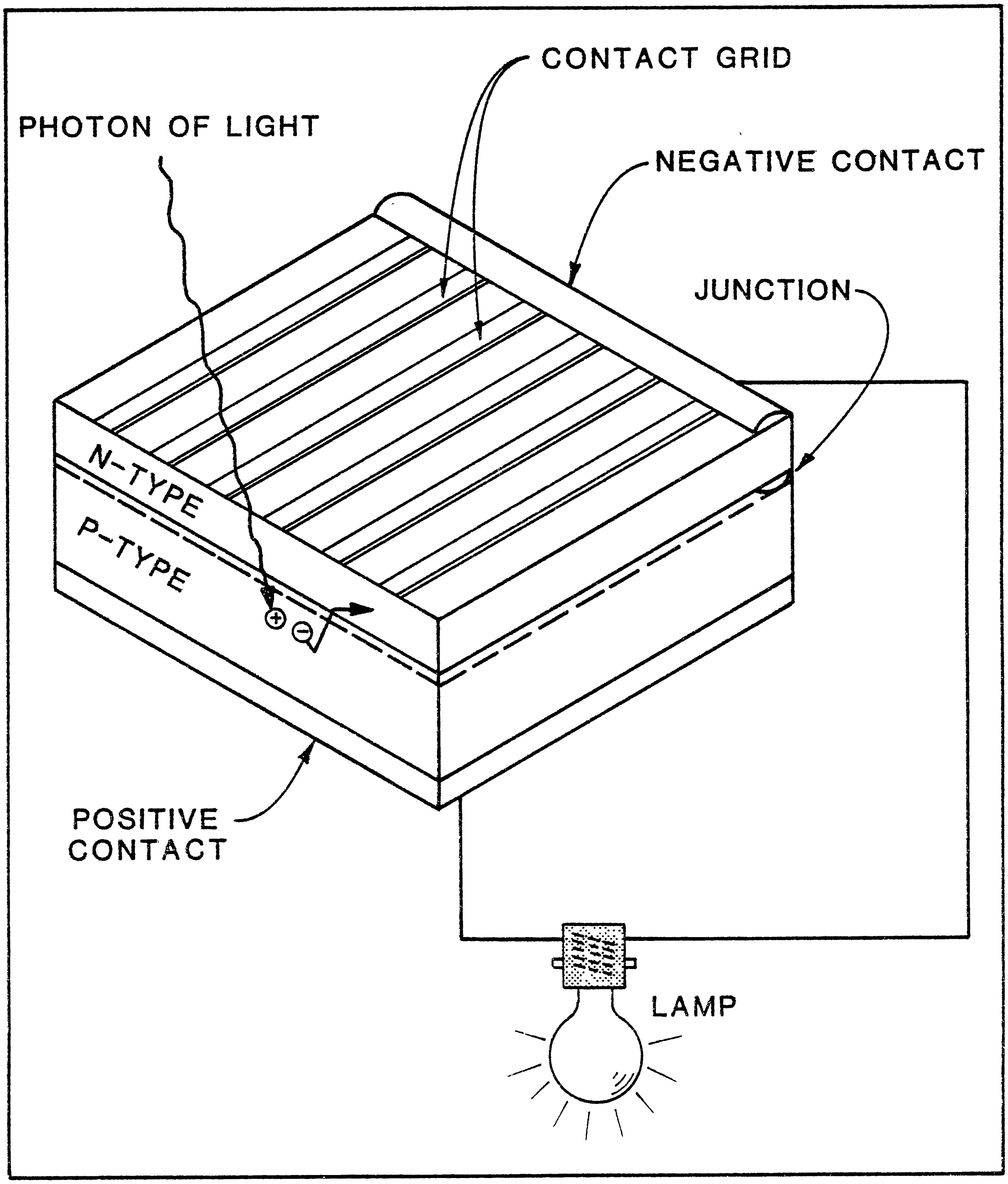

Figure 3.4. Principle of Photovoltaic Operation

where a photon-electron collision can activate an electron across the energy gap, and produce charges that can be separated by the internal electric field. The freed electron then moves across the junction, into the p-type material, then to the contact electrode, through the external circuit, constituting an electric current, back through the other electrode into n-type material to recombine with a hole and complete the circuit.

The internal electric field in a photovoltaic device can also be established by joining two different semiconductor materials to create a "hetrojunction" cell or by joining semiconductor material to a metal, creating a "Schottky" barrier junction (1). In each case, however, the internal electric field acts on the charge carriers that produce a current to flow in the external circuit.

3.4 Photovoltaic Cells Characteristic Equations

The basic character of a solar cell is determined by the familiar diode equation

$$I = I_o[\exp(eV/KT) - 1] \quad (3.4)$$

where I_o is the maximum reverse biased diode current or the dark current, e is the charge on an electron, and K is Boltzmann's constant.

The form of the current-voltage characteristic described in Equation 3.4 is shown in Figure 3.5. The I-V

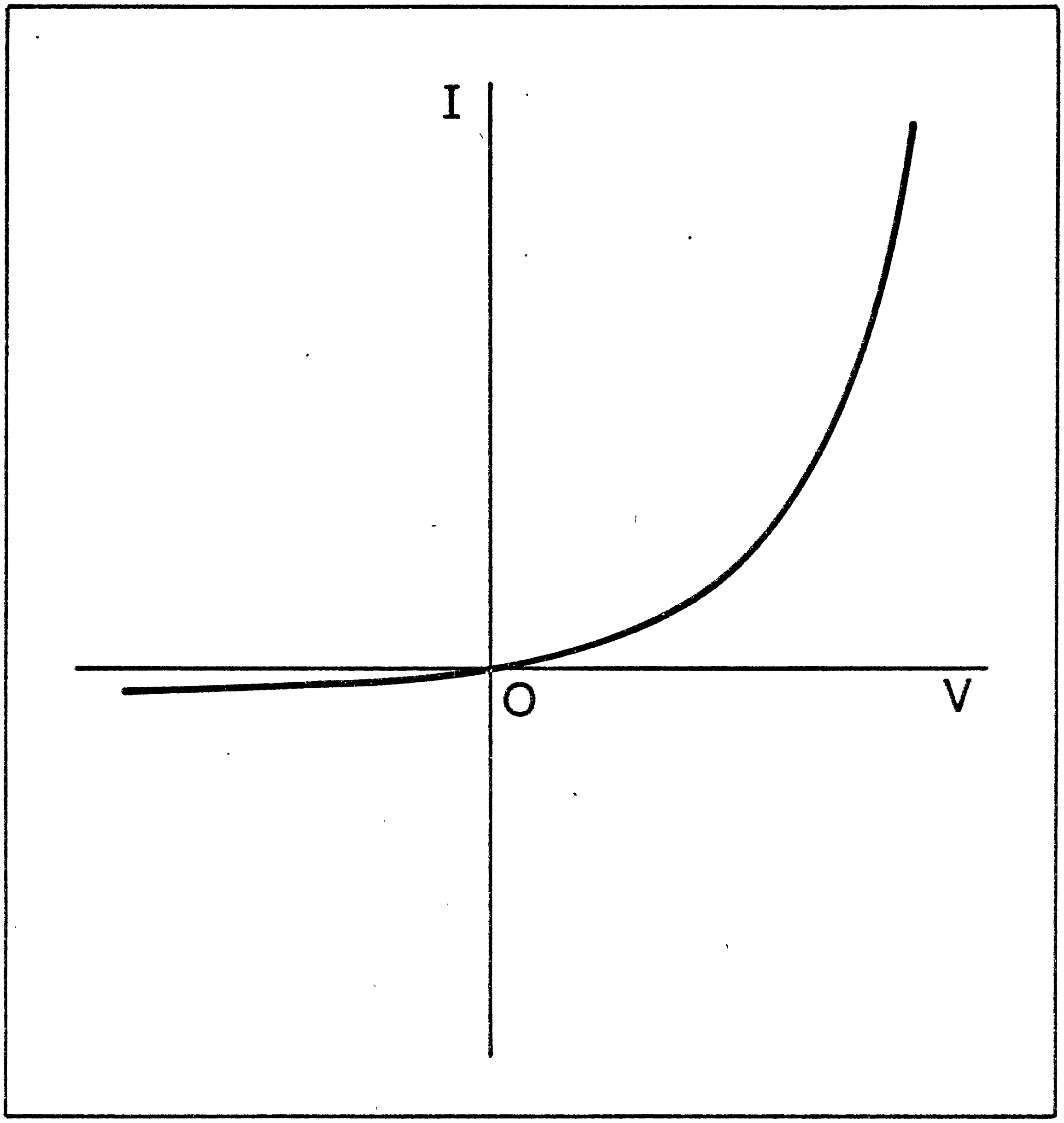

Figure 3.5. Typical I-V Characteristic for a Semiconductor Diode.

characteristics of a solar cell are identical to the characteristics shown in Figure 3.5, when no photons are present. When the p-n junction is illuminated by light energy, a current I_s is added to the diode equation and part of the I-V curve shifts from the first quadrant to the fourth quadrant as shown in Figure 3.6. A new equation can be written as:

$$I = I_o[\exp(eV/KT) - 1] - I_s \quad (3.5)$$

I_s represents as a source current, so it will have an opposite sign from I_o. The value of I_s is directly proportional to the light intensity. Note that in Figure 3.6 that the voltage is in the forward direction but the current flows in the opposite direction of the biased mode. Since the cell is a power deliverer, so it is standard to flip over the shown curve to the first quadrant as shown in Figure 3.7, this changes the sign of the diode equation to emphasize that the solar cell produces power and Equation 3.5 can be written in the new form as:

$$I = I_s - I_o[\exp(eV/KT) - 1] \quad (3.6)$$

By setting I = 0 in Equation 3.6, the open circuit voltage (V_{OC}) of the solar cell is given by:

$$V_{OC} = (KT/e) \ln(I_s/I_o + 1) \quad (3.7)$$

and by setting V = 0 in Equation 3.6, the short circuit current of the cell is given as:

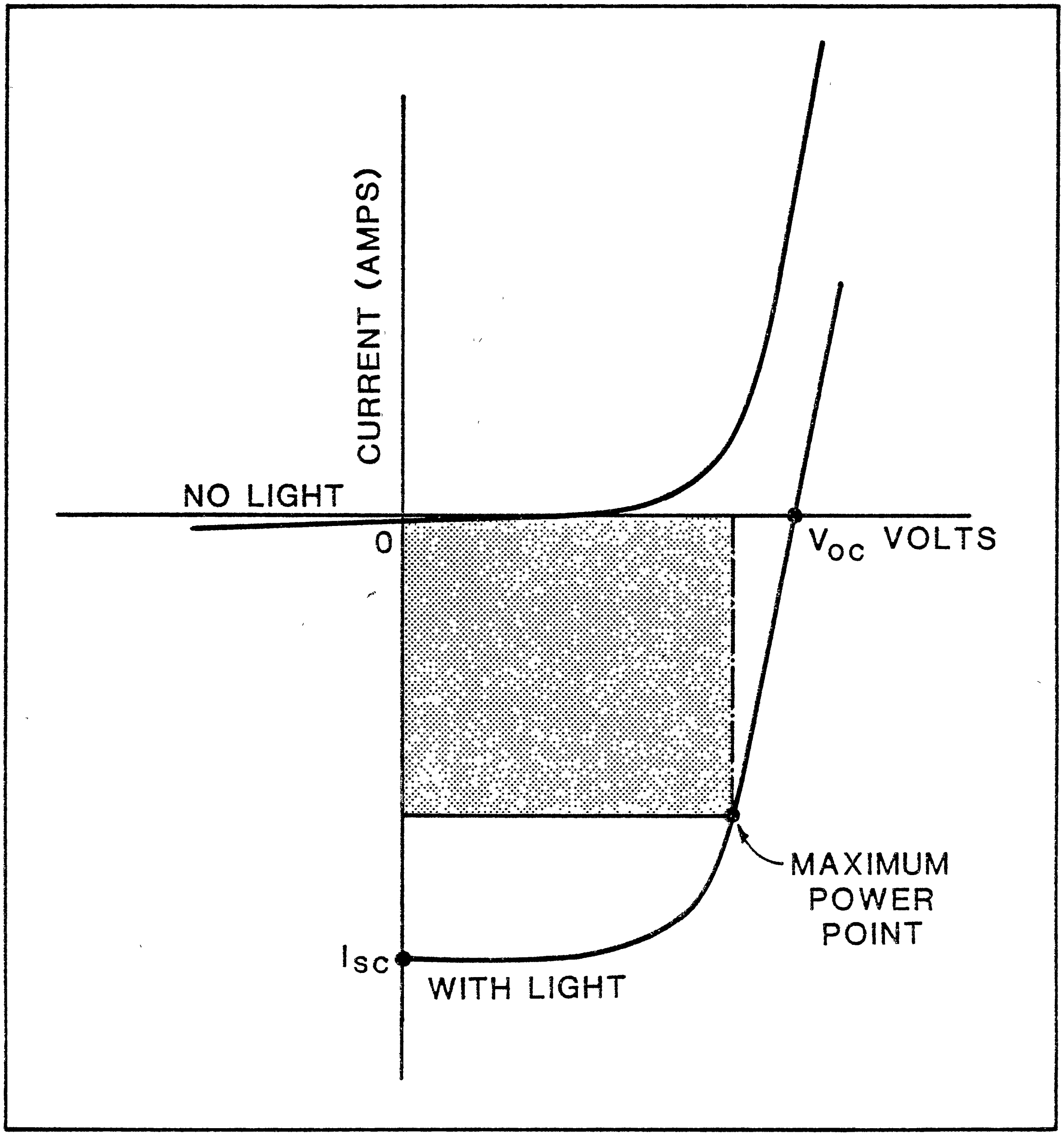

Figure 3.6. Effect of Light on I-V Curve

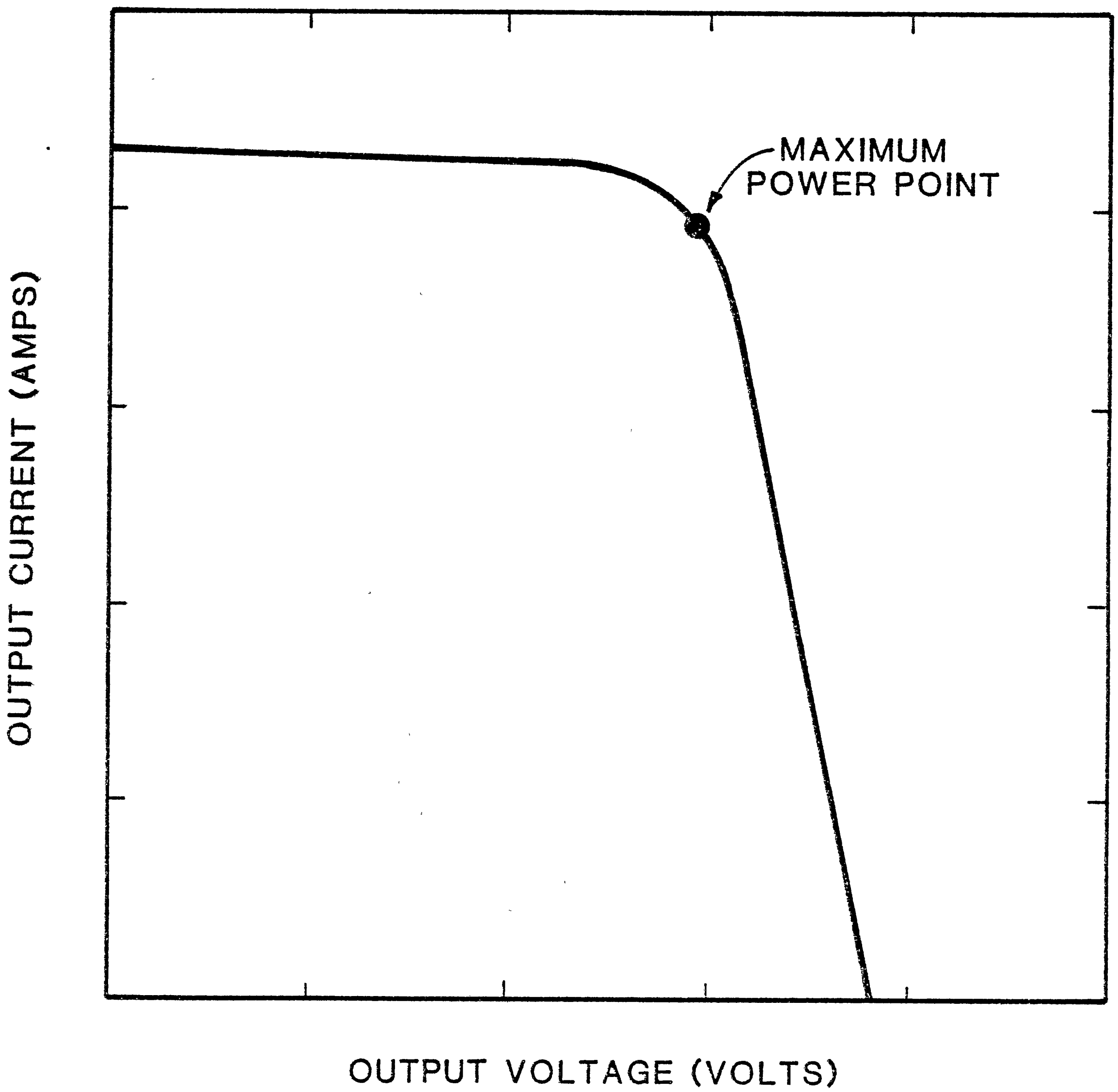

Figure 3.7. Typical I-V curve for a solar cell.

$$I_{SC} = I_s \tag{3.8}$$

The voltage corresponding to maximum output power can be obtained by differentiating power with respect to voltage and setting the result equal to zero. The voltage that maximizes the power is given by:

$$\mathrm{Exp}[eV_{mp}/KT][1 + eV_{mp}/KT] = [1 + I_s/I_o] = E_{xp}[eV_{oc}/KT] \tag{3.9}$$

Thus the current corresponding to the maximum power can be written as:

$$Imp = \frac{[e\ Vmp/KT]\ Is}{1 + e\ Vmp/KT} \left[1 + \frac{I_o}{I_s} \right] \tag{3.10}$$

where I_{mp} and V_{mp} are the current and voltage that maximize the output power. Then the maximum power output is simply given by:

$$P_{max} = I_{mp} \cdot V_{mp} \tag{3.11}$$

This maximum power generated can be represented by the rectangle shown in Figure 3.8.

Figure 3.9 shows a typical current-voltage curve for a silicon solar cell for three different illumination levels. It shows that the open circuit voltage is dependent logarithmically on the illumination level and the short circuit current varies linearly with illumination. This can be confirmed in Equations 3.7 and 3.8, respectively. It also shows that the actual voltage that can be delivered is

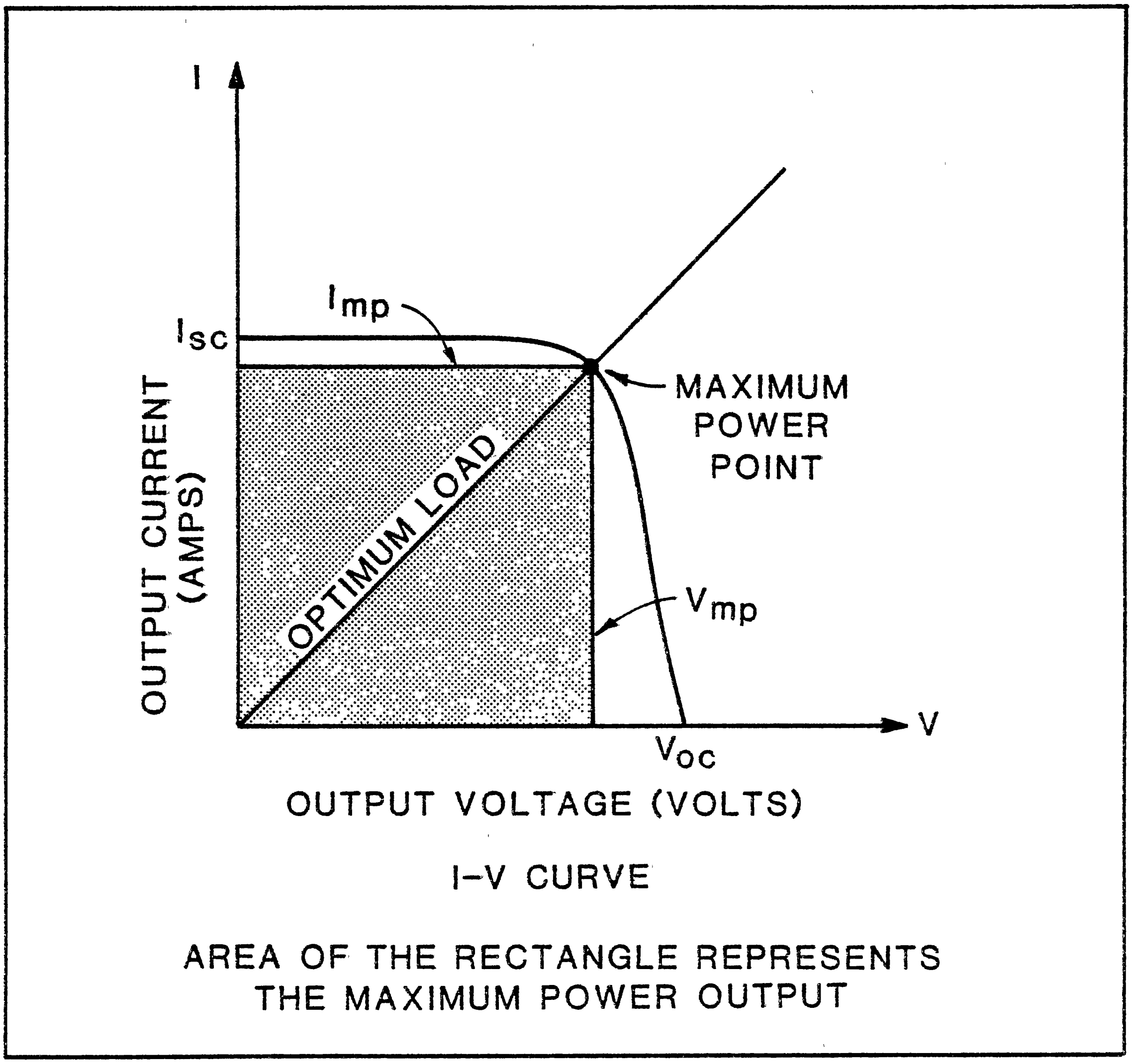

Figure 3.8. I-V curve represents the Maximum power output.

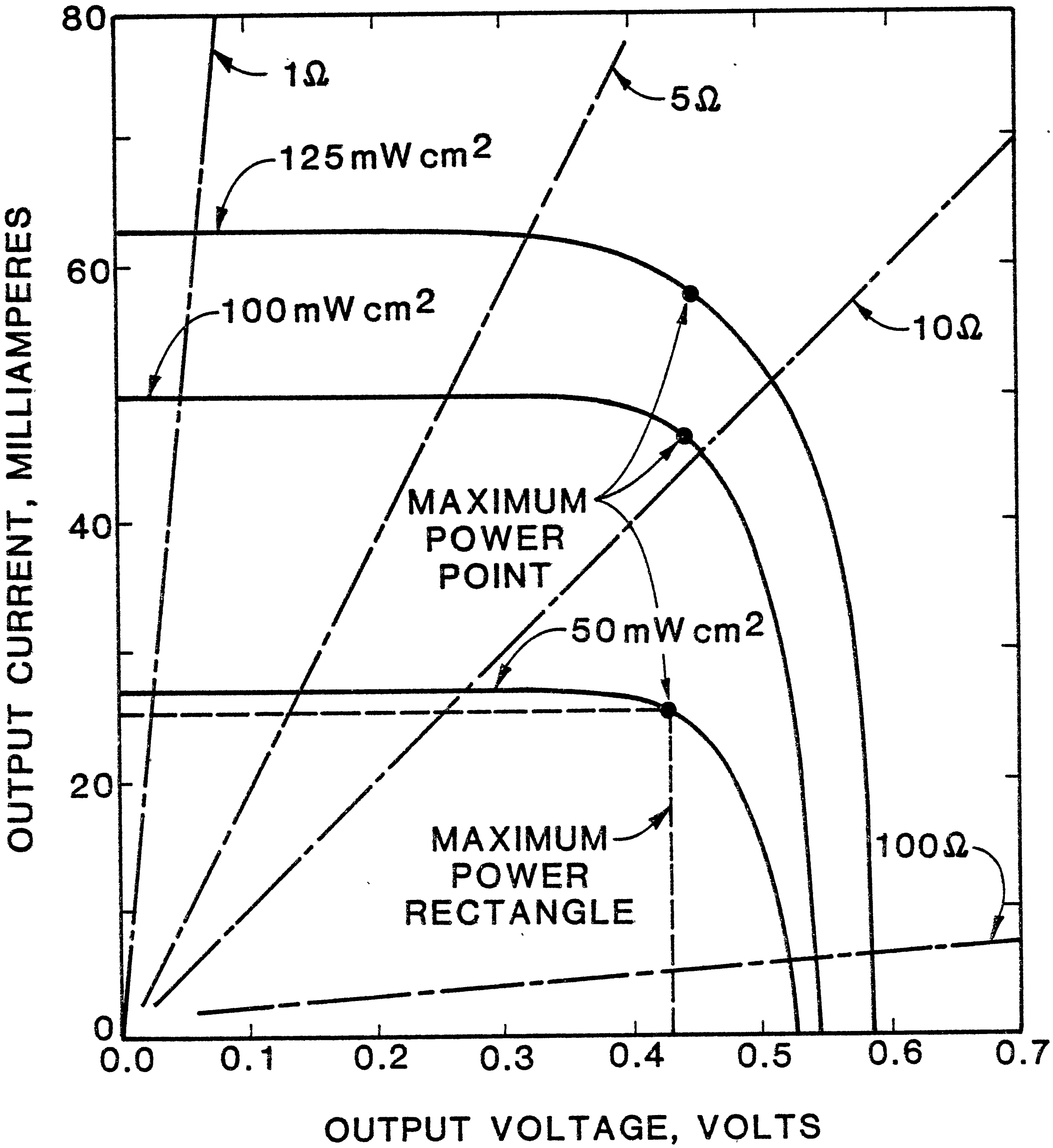

Figure 3.9. Typical I-V curves for a silicon solar cell, for Three Different Illumination Levels.

a function of load resistance and illumination level. Output current depends on the illumination level, load resistance and cell area. It is clear that the power extracted from the solar cell varies significantly as a function of the load resistance and the illumination level. It is therefore, of great important that the load resistance should be selected to correspond as closely as possible to the maximum power operating point for each cell. This requirement is difficult to meet when different cells are connected in series (or in parallel) to produce high voltage (or current) in a particular application.

The power density input to the cell is simply defined as the total number of photons in the solar spectrum, N_{ph}, times the average energy of each photon E_{av}, times the area of the cell (A). The energy conversion efficiency is defined as the relationship between the power output from solar cell to the power input to the cell.

$$\eta = \frac{\text{Power output from the cell}}{\text{Power input to the cell}} \tag{3.12}$$

Then from Equations 3.10 and 3.11, the maximum energy conversion efficiency can be given as:

$$\eta_{max} = \frac{[e\ Vmp/(KT)]Vmp\ I_s}{[1 + e\ Vmp/(KT)]\ Nph.\ Eav \cdot A} \tag{3.13}$$

There are fundamental factors limiting the efficiency of the solar cell: (1) photons with energies below the band gap energy are not absorbed and hence cannot be used to create a photovoltaic current; (2) the energy given to electrons which exceed the band gap energy cannot be recovered as useful current, and it is dissipated as heat; (3) reflection losses due to the presence of foreign matter that covers part or all the surface of any single cell in a series string in a solar panel. These losses can effectively eliminate the power producing capability of the entire panel (3).

Figure 3.10 indicates the relationship between the maximum efficiency of several semiconductor materials as a function of the energy gap (Eg) associated with those materials and temperature. The figure assumes that the incident solar radiation has spectral characteristics as shown in Figure 3.1 (3). The output power of a solar cell panel directly depends on the solar radiation that strikes it. The total daily solar radiation incident on a solar cell can be maximized when the cell is tilted so that the cell will always be directed towards the sun. The angle of tilt is approximately equal to the site latitude, referenced to a horizontal plane.

The daily variations in the output of a solar cell for a clear day in summar and in winter will be as shown in Figure 3.11 (23). These profiles give an indication of the amount of power that can be expected by using the solar cell in various types of environments.

Photovoltaic devices can be classifed according to the selected semiconductor material used.

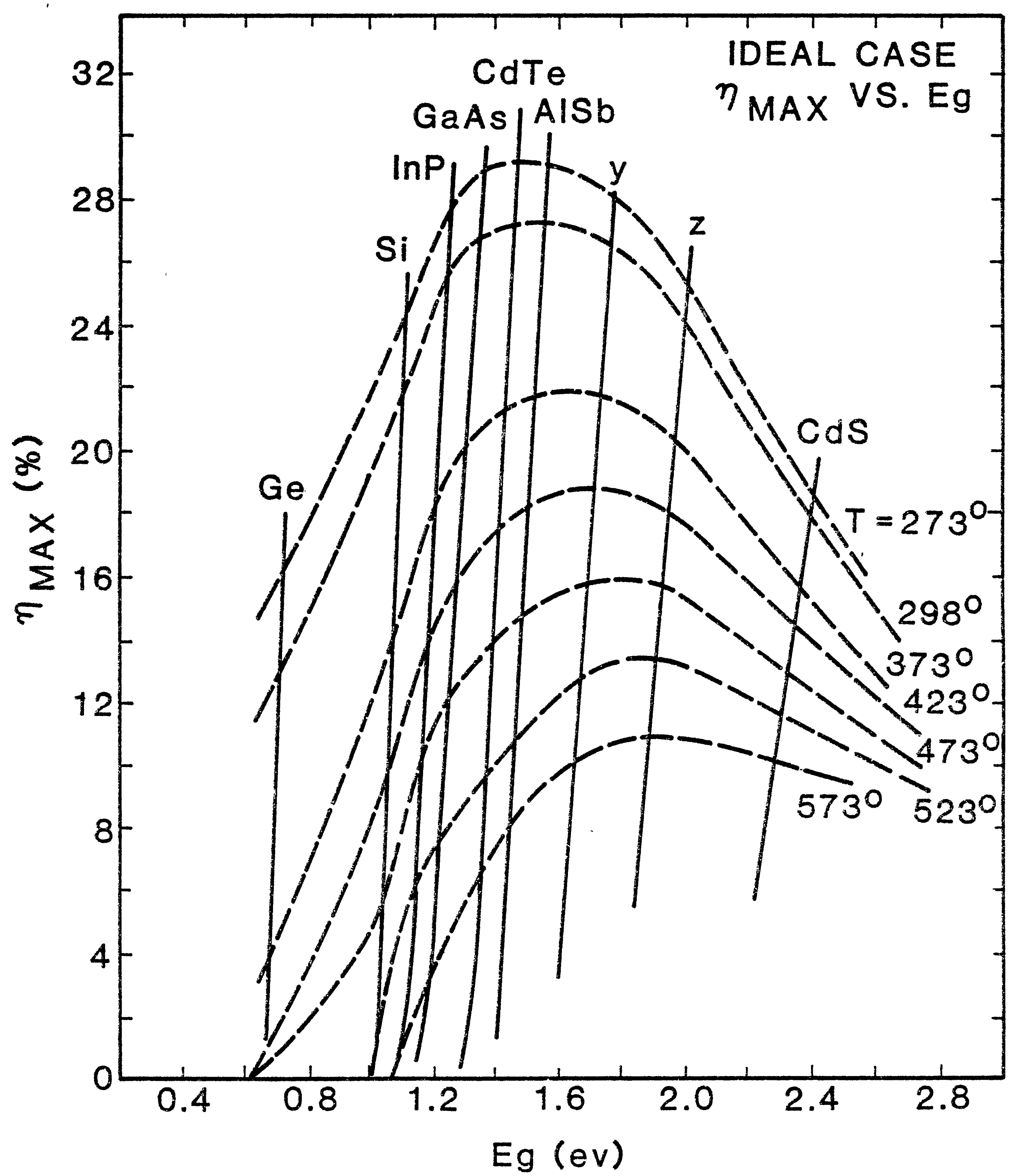

Figure 3.10. Efficiency Versus Energy Gap for Different Temperatures.

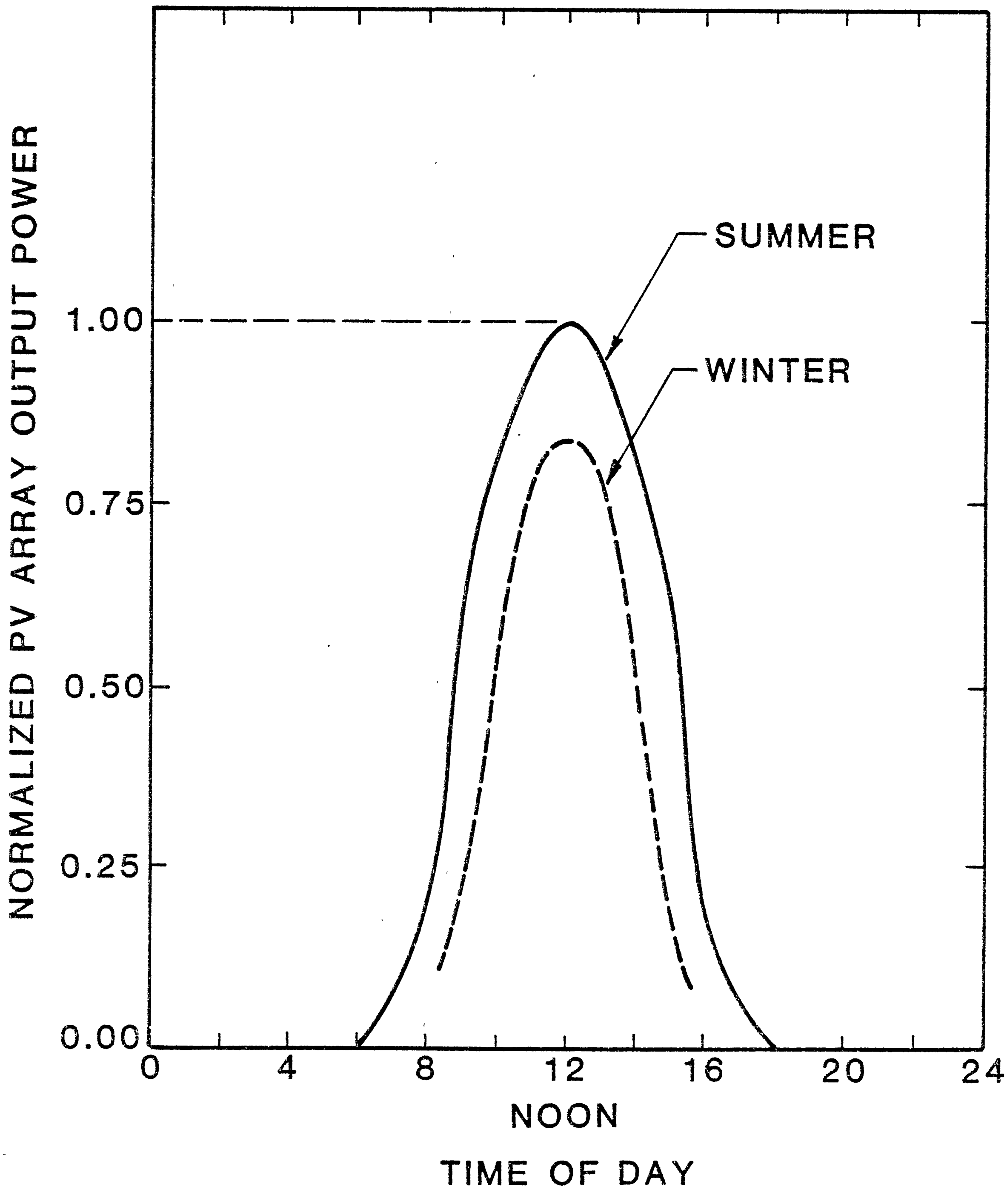

Figure 3.11. Typical Daily Solar Cell Power Output.

Silicon is the most well known semiconductor material of interest to most diodes, transistors and integrated circuits. Thus for producing photovoltaic solar cells, silicon technology is more advanced than other materials. Silicon is the second most abundant element in the earth's crust, and it seems logical to expect that if Libya becomes involved in the photovoltaic production, silicon will be the material of choice where the raw of silicon is available to satisfy the demand.

Silicon has dominated the photovoltaic field. In 1982 about 96% of the available solar cells were silicon based.

CHAPTER IV

EXPERIMENTAL METHODS AND RESULTS

4.1 Introduction

This chapter describes a series of experiments that were performed on four solar cell modules. The experiments examined the effects of the changes in solar insolation on the performance of the modules.

The purpose of these experiments fall in the following categories: a) verify the module characteristics as specified by the manufacturer; b) to gain experience in using solar cell modules to generate electric power; c) to estimate the performance of such modules in a Libyan climatic environment.

4.2 Experimental Apparatus and Procedures

The system illustrated in Figure 4.2.1, is composed of a photovoltaic solar panel, a pyranometer to measure the solar insolation, a D-C ammeter and digital voltmeter.

4.2.1 Solar Panel

The solar panel consists of four type M51 modules manufactured by ARCO Solar Inc. Each module contains of thrity-five cells approximately 4 inches diameter. The 35 cells

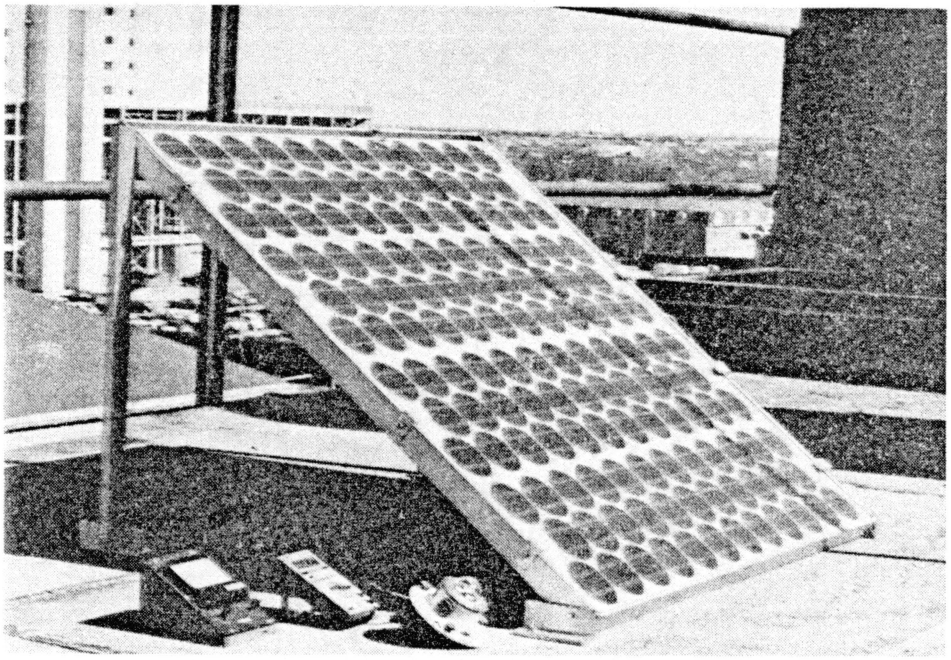

Figure 4.2.1. OSU PV Test Facility

are connected in series. They can produce a nominal 40 watts at 17.3 volts of peak power at 25^{o} C temperature and 100 mW/cm^2 of insolation. A data sheet for the ARCO M51 solar cell is reproduced and shown in Figure 4.2.2. An individual solar cell in the M51 module is illustrated in Figure 4.2.3. Figure 4.2.4 shows the M51 module. Note that the 35 solar cells are arranged and mounted on a white surface which reflects light that strikes between the cells. About five percent of this light is then refracted by the front glass and captured for use (5). The four-module solar panel was installed in an aluminum frame which was oriented to face the equator (south) and tilted by an angle of about 45^{o} S.

4.2.2 The Radiometer

A pyranometer (radiometer) is a light measuring instrument which detects and measures radiant energy. The pyranometer used in these experiments is shown in Figure 4.2.5. It was manufactured by Eppley Laboratories Inc. Its sensing element, a thermopile consists of electroplated copper thermocouple junctions. The hot junction is coated with black lacquer and the cold junction is coated with white barium sulphate. The thermopile is covered by hemisphere precision ground optical glass envelope. There are three levelling screws and a level indicator. The impedance of the thermopile is 300 ohms and it has a response time of one second (12), (20).

Cell Characteristics (typical)

- Area of 81.29 square cm
- Voltage coefficient of −0.00225 volts $°C^{-1}$
- Current coefficient of +0.0002977 amps $°C^{-1}$
- Shunt conductance of 0.035 MHO
- Series resistance of 0.014 OHM
- J_{01} of 2.36×10^{-12}
- J_{02} of 7.60×10^{-7}
- N of 2.47

Physical Characteristics

- Interchangeable standard dimensions: Length 48" (121.9cm) Width 12" (30.5cm) Depth 1.5" (3.8cm).
- Weight of 12.5 pounds (5.7Kg).
- Forty-four total contacts on each cell for enhanced reliability
- Metal foil back plane for hermeticity.
- Standard cell operating temperature (SOCT) of 36°C.
- Operating conditions of −40°C to +90°C, 0 to 100 percent humidity.
- Self-cleaning tempered water-white glass front
- Desiccated polymeric encapsulation.
- High emissivity back side.
- Specular reflection by inside of front glass
- Efficient conversion of both direct and diffuse light
- Five layer coating behind cells
- Fault tolerant cells and interconnects.
- Single crystal silicon cells

Module Characteristics (typical)

- 100 percent electrically matched solar cells mean the module is not effected by sustained operation at the I_{sc} or V_{oc} points
- All modules have leakage current of less than 50μA at 3000 V, even above 60°C.
- Ground continuity of less than 1 Ohm for all metallic surfaces (including metal back plane which has quadruple redundant connections to the integral frame).
- Module capacitance of 0 0022 micro farads.

Power Specifications

	100mW/cm^2, AM 1.5 spectrum and 25° (± 0 5° C) cell temperature
Open Circuit Voltage	21.0 volts
Short Circuit Current	2.6 amps
Voltage, Test	17.3 volts
Current, Test (±10%)	2.31 amps
Module Efficiency	10 76%
Power (Watts @ Test)	40 0 watts

Testing

The ARCO Solar M51 meets the demanding requirements of the U.S. Department of Energy as proven by the Jet Propulsion Laboratory Block IV Test Requirements. Additionally, the modules must pass numerous tougher tests including a 5 day exposure to 95 percent humidity at 95°C. The ARCO Solar test sequence is shown below

- Thermal Soak
- Thermal Cycling
- Thermal/Freezing and High Humidity-Cycling
- Mechanical, Wind, and Twist Loading
- Hail Impact
- Salt Fog
- Hot Spot
- Thermal/Humidity Soak
- Field Exposure

Figure 4.2.2. Data Sheet, M51 Module, ARCO Solar, Inc.

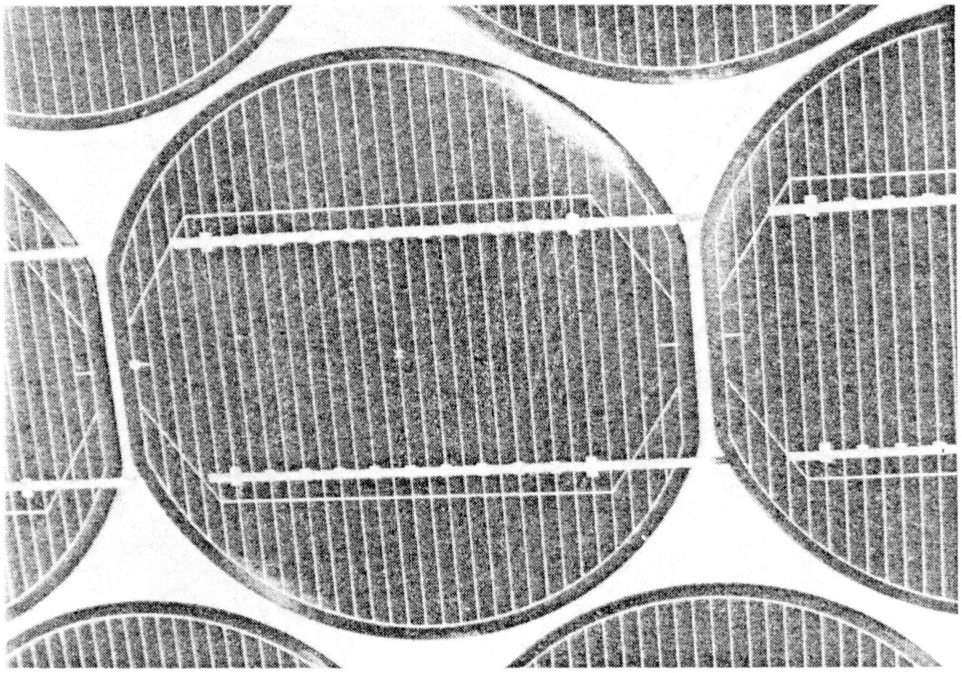

Figure 4.2.3. View of Single Cell in M51 Module

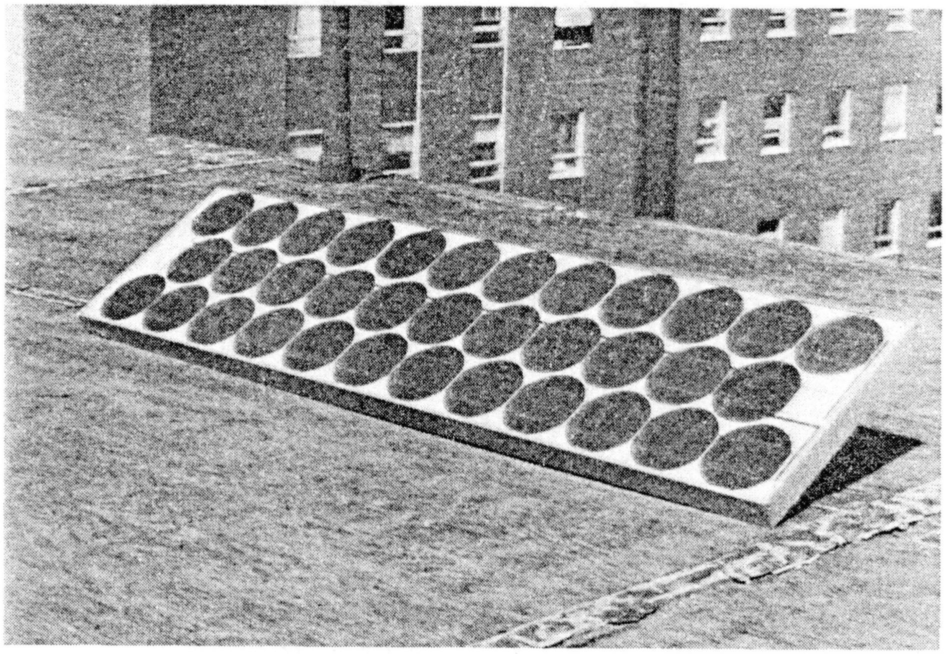

Figure 4.2.4. M51 40 Watt Solar Module.

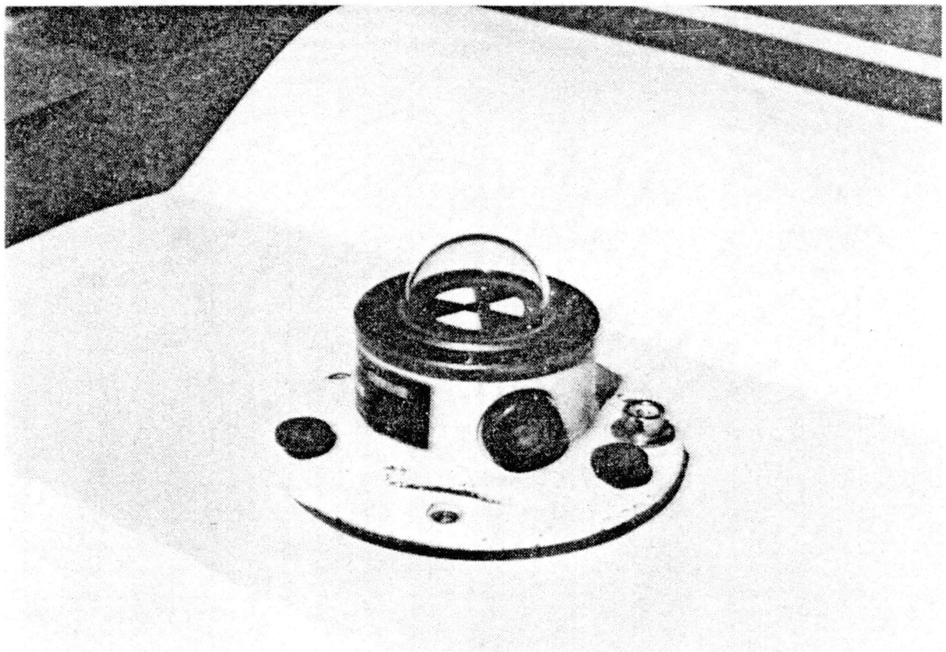

Figure 4.2.5. An Eppley Black and White Pyranometer.

The pyranometer output was displayed on a digital voltmeter in millivolts with 10 mv = 1000 watts/m^2 scale factor. A DC multiscale ammeter, a digital voltmeter and a variable load resistor (capable of handling 10 amps) were used in the tests to measure the output power of the modules.

The solar panel was mounted on the aluminum rack and installed on the roof of the Engineering South building at OSU. The panel was tilted to the south with angle of about 45^{o}.

Each module was tested individually for open-circuit voltage and short-circuit current. Readings were recorded and tabulated. Modules were tested individually under load by connecting a load resistance (R_L) across each module as shown in Figure 4.2.6. Readings of voltage and current were recorded, tabulated and plotted. This test was repeated for different insolation levels. The input power density was measured in each test by the pyranometer. Power output was calculated, and module efficiency was determined from the output power, input power density and module area.

4.2.3 Series Connection

The four modules were connected in series, and tested for open-circuit voltage and short-circuit current. Then a load resistance (R_L) was connected across the panel in series with the ammeter. Readings of current and voltage

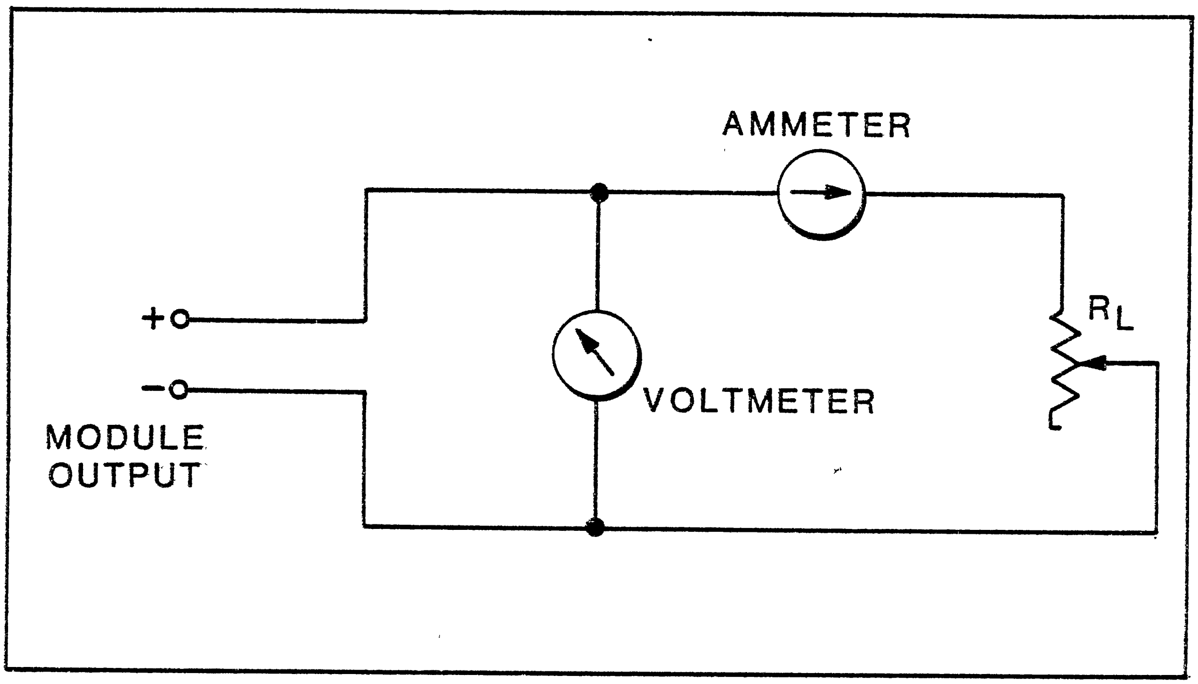

Figure 4.2.6. Testing Solar Module Under Load Resistance R_L.

were recorded, tabulated and plotted. The panel was tested for several insolation levels and different temperatures.

4.2.4 Parallel-Series Connections

The modules were connected in the parallel-series configuration as shown in Figure 4.2.7. Readings of current, voltage and power were recorded, and I-V characteristics were plotted for this arrangement.

4.3 Photovoltaic Solar-Panel Experimental Results

This section consists of a discussion of the results obtained from the experiments performed over several months on the solar panel under different climatic conditions and insolation levels.

a. Case One: Results obtained from experiments on each module separately. As discussed in Chapter III, the effect of change in solar insolation on the output characteristics of the solar cell power was investigated.

The solar modules were tested individually and data were recorded in the Tables III, IV, V, and VI to examine the power specifications and compare them from the I-V characteristics and conversion efficiency. For purposes of clarity, individual points are not shown on the curves presented. This provides more emphasis for critical points on the curves, such as open circuit voltage, short circuit current, and maximum power.

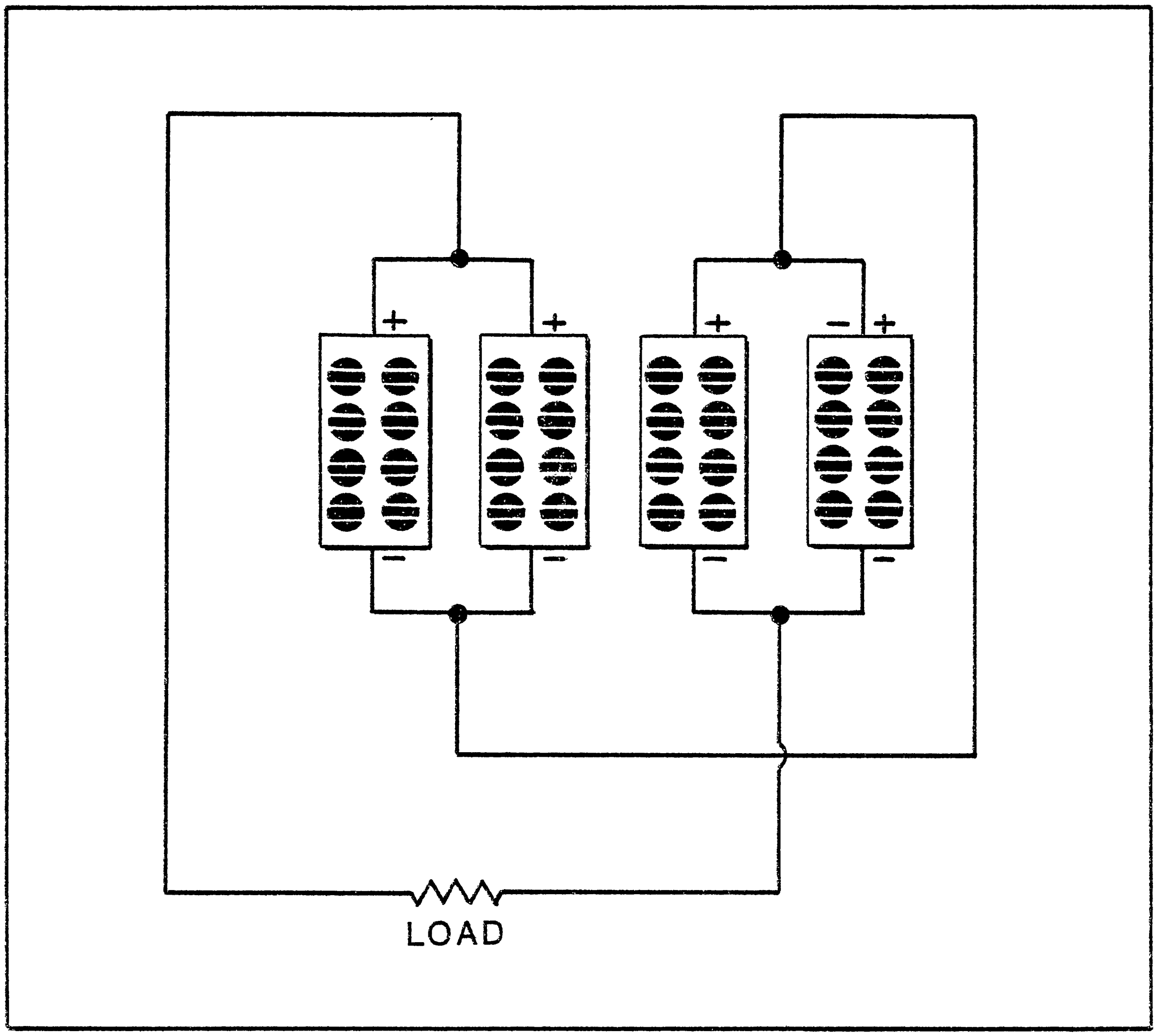

Figure 4.2.7. Parallel-Series Connections.

Module No. 1:

Time: 2:00 noon

Date: November 16, 1983 (sunny day)

Input power density P_{in} = 9.3 mv or 930 W/m^2

The open circuit voltage, V_{oc} = 19.04 Volts

The short circuit current, I_{sc} = 2.15 amps

The total area of each module (A) is 0.3717 m^2. It was determined that a load resistance of 7.6 Ω resulted in maximum power output. The module efficiency was calculated at maximum output power using data from Table III as:

$$\eta_{m1} = \frac{\text{output power}}{P_{in} \times \text{area of the module}} \quad (4.1)$$

$$\eta_{m1} = \frac{1.95 \times 14.8 \times 100}{930 \times 0.3717} = 8.35\% \quad (4.2)$$

The I-V characteristic was plotted as shown in Figure 4.3.1.

Module No. 2: At the same date and time as No. 1.

P_{in} = 9.3 mv or 930 w/m^2

V_{oc} = 19.04 Volts

I_{sc} = 2.15 amps

At maximum output power, module efficiency was calculated using data from Table IV as:

$$\eta_{m2} = \frac{1.95 \times 14.77}{930 \times 0.3717} \times 100 = 8.33\% \quad (4.3)$$

TABLE III

CURRENT-VOLTAGE VARIATIONS FOR MODULE NO. 1 AT INSOLATION OF 930 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
0.4	18.4	7.36
0.8	17.6	14.08
1.2	16.8	20.16
1.8	15.6	28.08
1.95	14.8	28.86
2.0	14.38	28.76
2.05	14.00	28.7
2.1	13.2	27.7
2.14	0.409	0.88

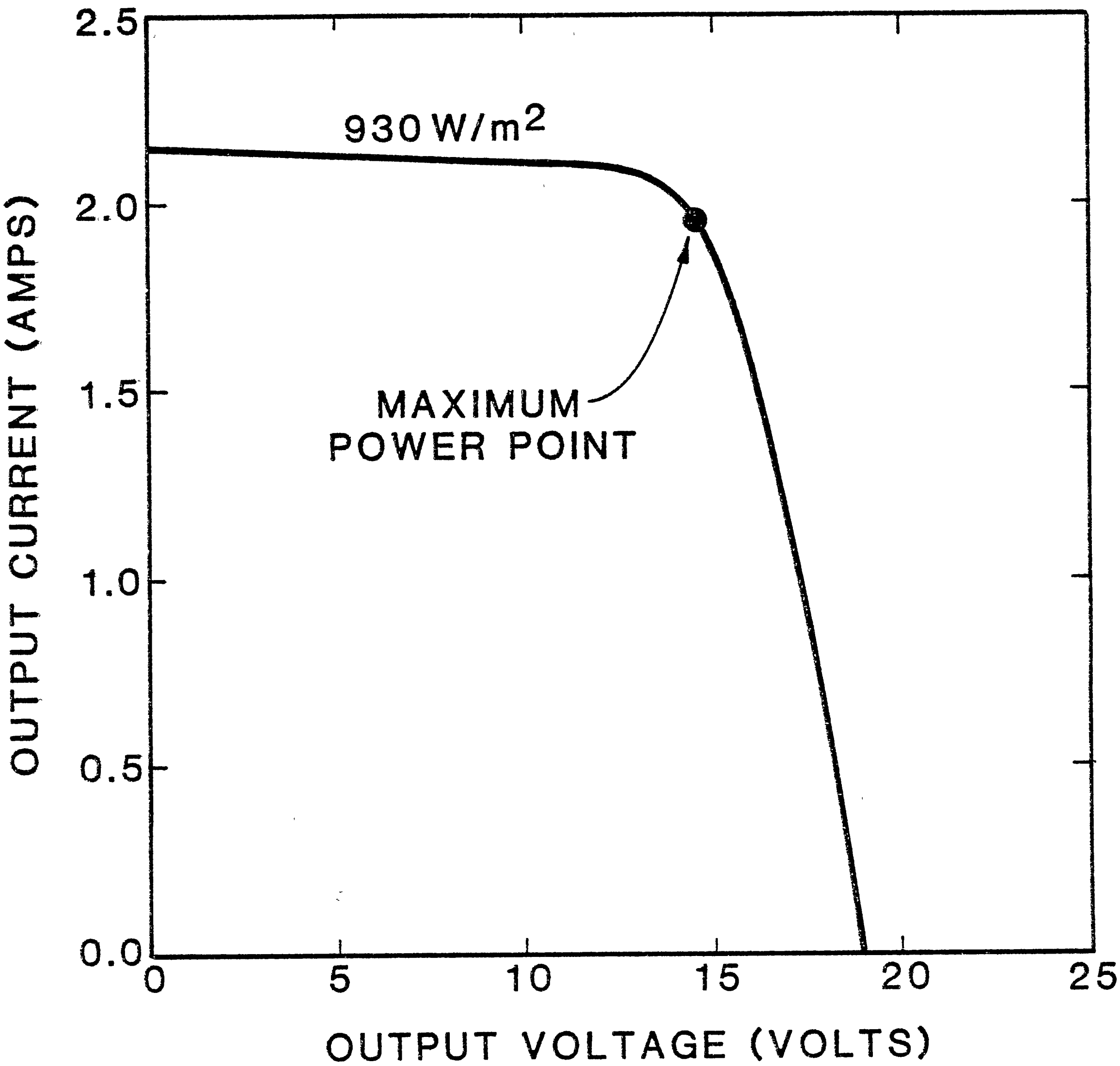

Figure 4.3.1. I-V Characteristic for Module No. 1.

TABLE IV

CURRENT-VOLTAGE VARIATION FOR MODULE NO. 2 AT INSOLATION OF 930 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
0.6	17.8	10.68
1.0	17.2	17.2
1.6	15.75	25.2
1.95	14.77	28.8
2.0	14.32	28.64
1.05	13.87	28.43
2.1	12.74	26.75
2.14	0.40	0.86

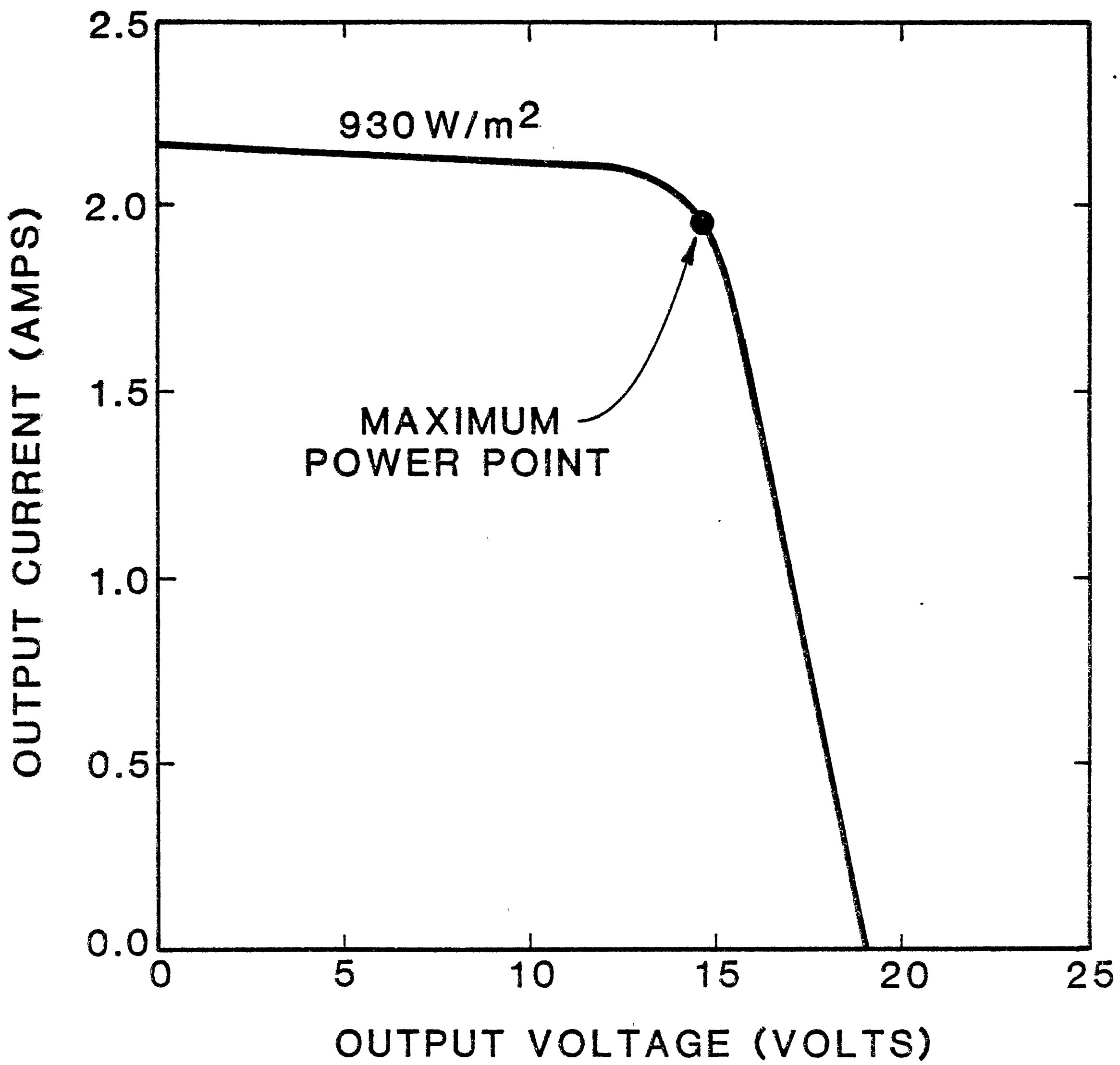

Figure 4.3.2. I-V Characteristic for Module No. 2.

The I-V characteristic was plotted from the data obtained and shown in Figure 4.3.2.

Module No. 3: At the same time and date

P_{in} = 9.3 mv or 930 w/m^2

V_{oc} = 19.04 Volts

I_{sc} = 2.15 amps

From Table V, module efficiency at maximum output power is given by:

$$\eta_{m3} = \frac{1.95 \times 14.66}{930 \times 0.3717} \times 100 = 8.3\% \qquad (4.4)$$

The I-V characteristic was plotted from the data obtained and shown in Figure 4.3.3.

Module No. 4: At the same time and date

P_{in} = 9.3 mv or 930 w/m^2

V_{oc} = 19.04 Volts

I_{sc} = 2.15 amps

At the same value of the load resistance (7.6 Ω) and from the data obtained in Table VI, the module efficiency was calculated as:

$$\eta_{m4} = \frac{1.95 \times 14.68 \times 100}{930 \times 0.3717} = 8.3\% \qquad (4.5)$$

The I-V characteristic was plotted from the data listed and shown in Figure 4.3.4.

From the experiments and the results obtained in Case 1, it was clear that the modules are very similar to

TABLE V

CURRENT-VOLTAGE VARIATION FOR MODULE NO. 3 AT INSOLATION OF 930 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
0.4	18.4	7.36
0.68	18.0	12.25
1.0	17.55	17.55
1.6	16.0	25.6
1.8	15.35	27.63
1.95	14.66	28.6
2.0	14.10	28.2
2.05	13.48	27.63
2.10	12.23	25.7
2.14	0.5	1.07

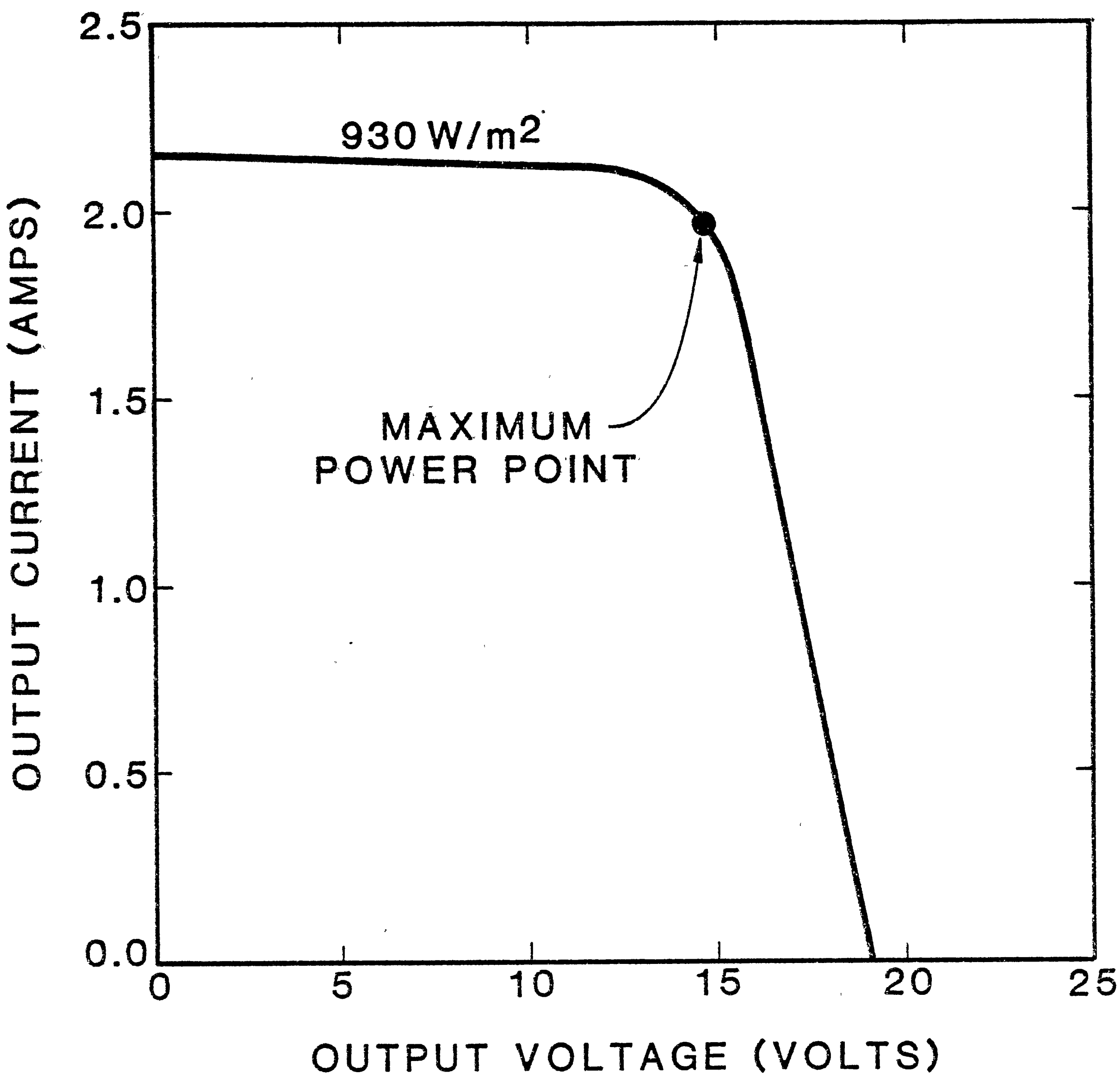

Figure 4.3.3. I-V Characteristic for Module No. 3.

TABLE VI

I-V VARIATION FOR MODULE NO. 4
AT INSOLATION OF 930 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
0.5	18.17	9.1
0.8	17.5	14.0
1.2	16.8	20.16
1.5	16.0	24.0
1.8	15.5	27.9
1.95	14.68	28.62
2.0	14.27	28.54
1.05	13.84	28.37
2.10	13.03	27.36
2.14	0.45	0.96

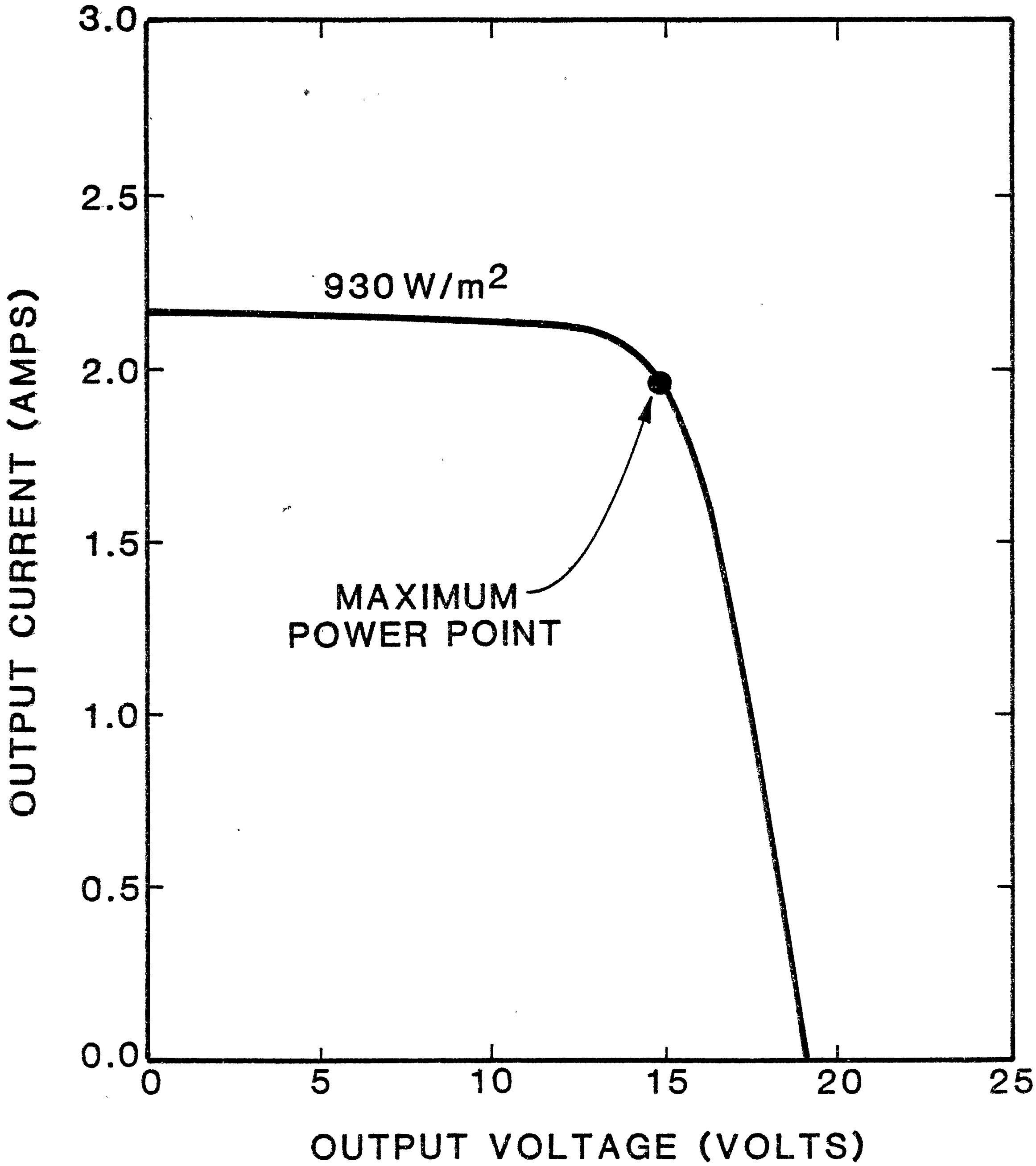

Figure 4.3.4. I-V Characteristic for Module No. 4.

TABLE VII

I-V VARIATION FOR M51 ON CLOUDY DAY AT INSOLATION OF 780 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
2.02	0.8	1.616
2.0	4.2	8.4
1.95	14.93	29.12
1.85	15.23	28.18
1.8	15.63	28.13
1.65	15.92	26.27
1.6	16.21	25.94
1.5	16.5	24.75
1.0	17.4	17.4
0.5	18.36	9.18

each other. They have almost identical I-V characteristics and efficiency values. Another test was applied to one module to examine its efficiency on a partially cloudy day and the data taken from this test is listed in Table VII.

Time 12:00 noon on November 21, 1983, partially cloudy, at temperature of 76° F (ambient).

P_{in} = 7.8 mv or 780 w/m^2

V_{oc} = 19.2 Volts

I_{sc} = 2.05 amps

Maximum power was fixed by load resistance of 7.6 Ω, where the output power was at the maximum point, and from the data taken in Table VII , the module efficiency was calculated as:

$$\eta_m = \frac{1.95 \times 14.93}{780 \times 0.3717} \times 100 = 10.04\% \qquad (4.6)$$

The I-V characteristic was plotted from the data listed and shown in Figure 4.3.5.

Also, as a part of this case, a module was tested under different insolation levels. This test was conducted in an effort to investigate the effect of changes in solar insolation on the output power characteristics of the solar cells. Data obtained of this part is listed in Tables VIII and IX.

The experiments were conducted on two different days as described below:

Time: 12:00 noon, on January 31, 1984, temp. 62.5° F

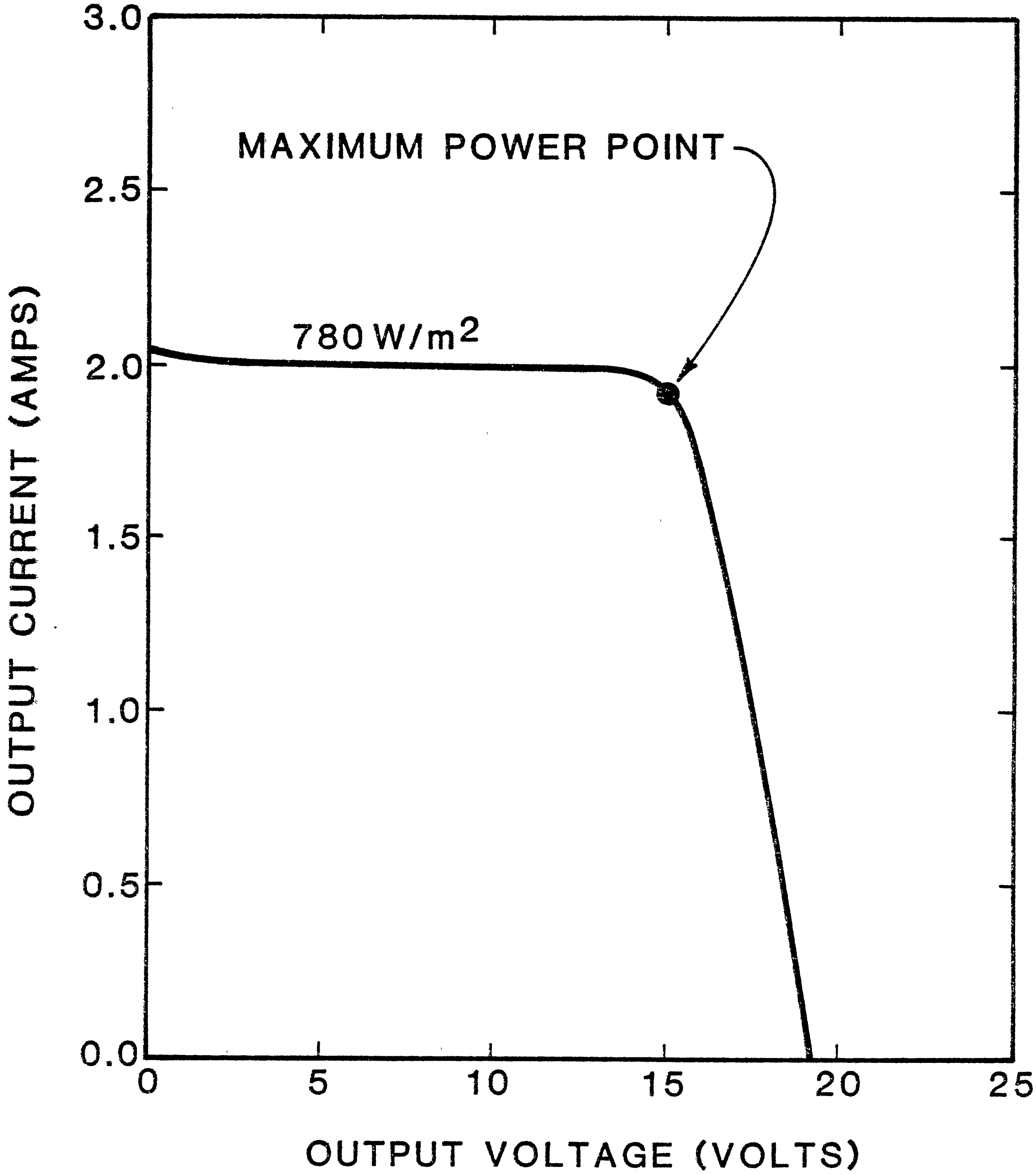

Figure 4.3.5. I-V Characteristic on Cloudy Day at Temperature 76°F.

TABLE VIII

I-V VARIATION FOR SOLAR MODULE AT INSOLATION OF 860 W/M^2

I_L (amps)	V_L (V)	P_o (W)
0.4	18.97	7.59
0.5	18.92	9.46
0.6	18.78	11.27
0.7	18.62	13.034
0.8	18.50	14.8
0.9	18.34	16.5
1.0	18.18	18.18
1.1	18.00	19.8
1.2	17.81	21.37
1.3	17.6	22.88
1.4	17.35	24.29
1.5	17.02	25.53
1.7	16.18	27.51
1.8	15.58	28.04
1.85	14.75	27.29
1.9	13.44	25.54
1.91	12.00	22.92
1.93	4.5	8.69
1.95	0.5	0.98

P_{in} = 8.6 mv or 860 w/m^2

V_{oc} = 19.45 Volts and I_{sc} = 1.98 amps

The module efficiency at the maximum power point was calculated from Table VIII as:

$$\eta_m = \frac{1.8 \times 15.58}{860 \times 0.3717} \times 100 = 8.77\% \qquad (4.7)$$

On February 3, 1984, a second test was conducted, resulting the data listed in Table IX.

Time: 12:00 noon, February 3, 1984, temp. 62.0° F

P_{in} = 9.1 mv or 910 w/m^2

V_{oc} = 19.56 Volts and I_{sc} = 2.15 amps

The module efficiency at the maximum power point was calculated as:

$$\eta_m = \frac{15.58 \times 1.9}{910 \times 0.3717} \times 100 = 8.75\% \qquad (4.8)$$

The I-V characteristics of these two different tests are shown together on Figure 4.3.6.

b. Case Two: In this case the four modules were connected in series to determine the maximum value of voltage that could be produced. The solar panel was tested to show also the effect of insolation variations on the output power of the panel. Data taken from the experiments are listed in Tables X and XI.

Time: 12:30 on February 12, 1984, Temp. 76° F

TABLE IX

I-V VARIATION FOR SOLAR MODULE AT INSOLATION OF 910 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
0.4	19.12	7.65
0.5	19.05	9.53
0.6	18.91	11.35
0.7	18.77	13.14
0.8	18.53	14.9
0.9	18.48	16.63
1.0	18.33	18.33
1.1	18.18	20.0
1.2	17.97	21.56
1.3	17.73	23.05
1.4	17.5	24.5
1.5	17.28	25.92
1.6	16.98	27.17
1.7	16.65	28.305
1.8	16.16	29.09
1.9	15.58	29.602
2.0	14.443	28.86
2.1	6.3	13.23
2.13	1.5	3.2

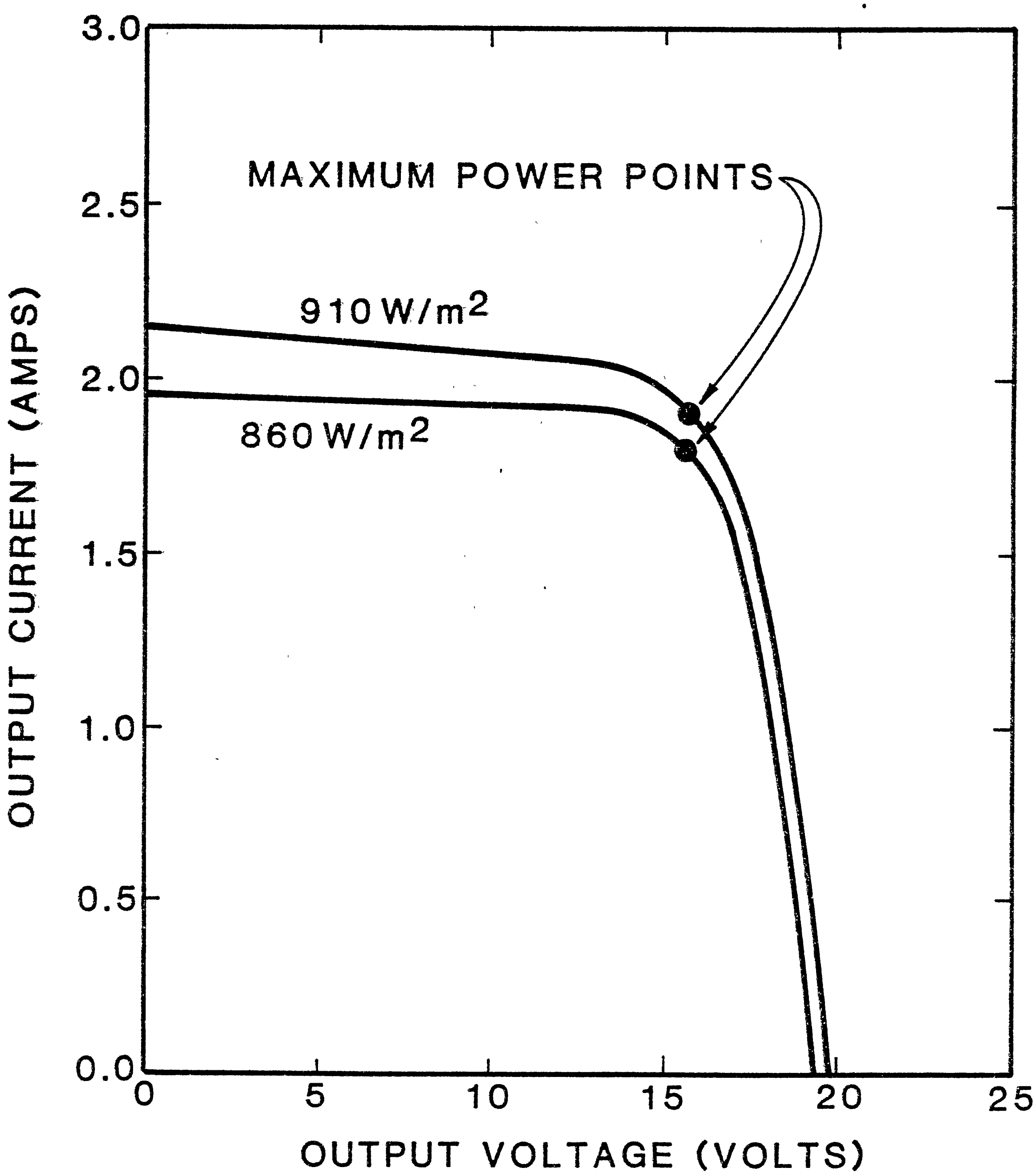

Figure 4.3.6. I-V Characteristics for Module M51 at Various Light Levels.

TABLE X

I-V VARIATIONS FOR SOLAR PANEL (SERIES CONNECTION) AT INSOLATION OF 990 W/M^2

I_L (amps)	V_L (V)	Pout (W)
1.4	70.7	99.0
1.45	70.2	101.8
1.5	69,4	104.1
1.55	68.9	106.8
1.6	68.1	109.0
1.65	67.7	111.7
1.7	67.0	113.9
1.75	66.4	116.2
1.8	65.4	117.72
1.85	65.5	119.33
1.9	63.4	120.46
1.95	62.5	121.9
2.0	60.7	121.4
2.05	58.3	119.52
2.1	54.3	114.03
2.15	31.9	68.6
2.2	0.88	1.34

TABLE XI

I-V VARIATION FOR A SOLAR PANEL WITH SERIES CONNECTION AT INSOLATION OF 910 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
0.95	72.0	68.4
1.0	71.6	71.6
1.05	71.2	74.76
1.2	70.0	84.0
1.4	68.0	95.2
1.6	65.6	105.0
1.8	62.4	112.32
1.85	61.0	112.85
1.9	58.6	111.34
1.95	48.2	94.00
2.0	18.8	37.6
2.03	0.55	1.12

P_{in} = 9.9 mv or 990 w/m^2

V_{oc} = 76.2 Volts and I_{sc} = 2.25 amps

At a certain load resistance (31.0 Ω). Solar panel efficiency was calculated at the maximum power point

$$\eta_p = \frac{1.95 \times 62.5}{990 \times 4(0.3717)} \times 100 = 8.3\% \tag{4.9}$$

A second test was run at a different insolation level.

Time: 12:00 noon, February 14, 1984, Temp. 76° F

Pin = 9.1 mv or 910 w/m^2

Voc = 75.2 Volts and Isc = 2.05 amps

At the same value of load resistance (31.0 Ω) the solar panel efficiency was calculated

$$\eta_p = \frac{1.85 \times 61.0}{910 \times 4(0.3717)} \times 100 = 8.3\% \tag{4.10}$$

The I-V characteristics of the two tests are shown together in Figure 4.3.7

c) Case Three: In this case the modules were connected in a parallel-series combination. The solar panel was tested for two different values of insolation to show the effect of this configuration on the output power of the solar panel, and to calculate the efficiency of the solar panel. Data obtained from the experiments are listed in Tables XII and XIII.

Time: 12:15 on February 21, 1984, temp. 70° F

P_{in} = 9.3 mv or 930 w/w^2

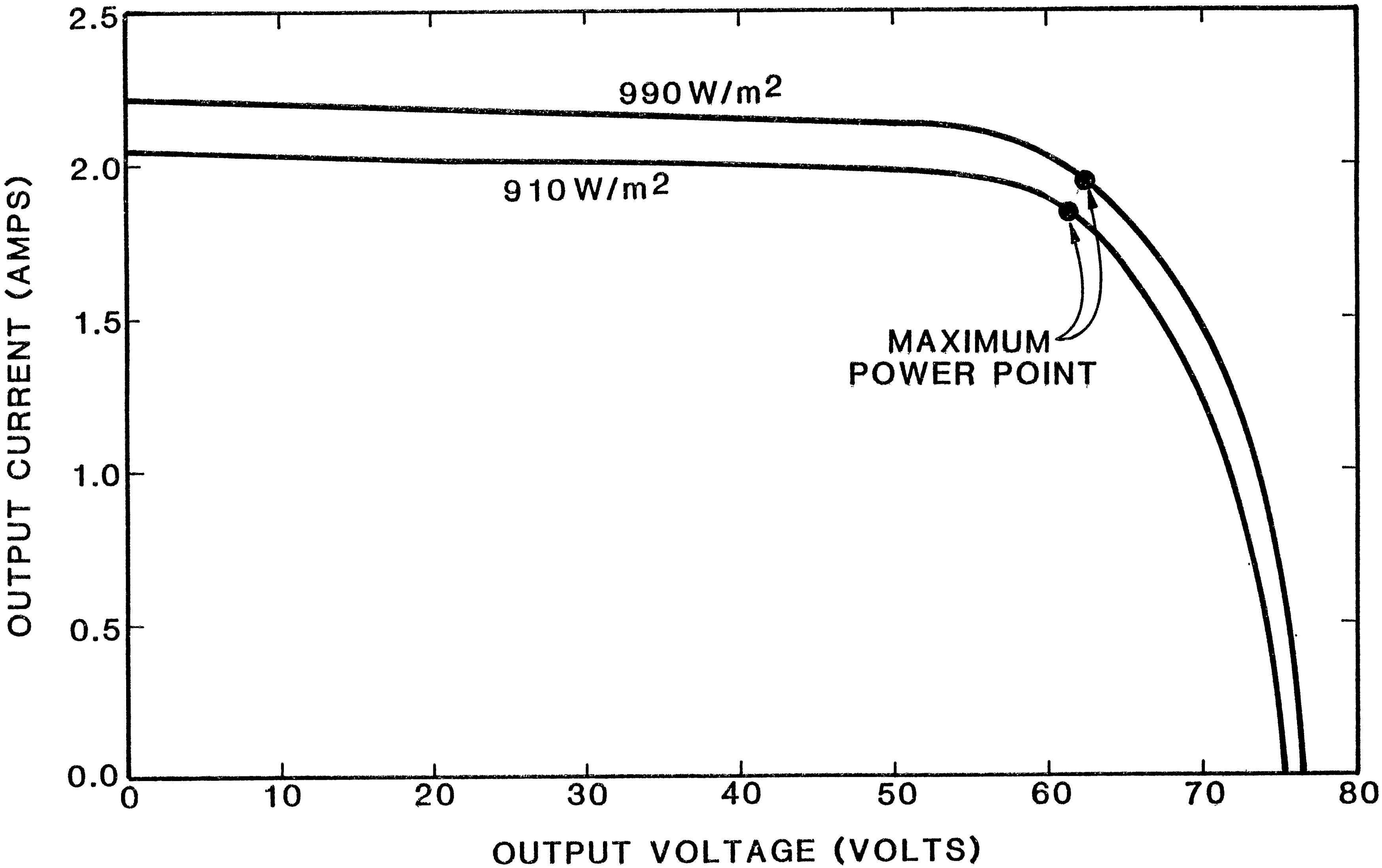

Figure 4.3.7 I-V Characteristics for the Solar Panel (Series-Connection) with Various Light Levels.

TABLE XII

I-V VARIATION WITH PARALLEL SERIES CONNECTION AT INSOLATION OF 930 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
4.0	0.91	3.64
3.9	21.9	85.4
3.8	27.7	105.26
3.7	29.1	107.7
3.5	30.9	108.2
3.3	31.9	105.3
3.1	32.8	101.7
3.0	33.1	99.3
2.8	33.7	94.4
2.5	33.9	84.75
2.45	34.5	84.53
2.3	34.9	80.3
2.0	35.5	71.0
1.8	35.8	64.4
1.6	36.1	57.76
1.4	36.3	50.82
1.2	36.7	44.04
1.0	36.9	36.9
0.9	37.1	33.39
0.8	37.3	29.84

V_{oc} = 37.6 Volts and I_{sc} = 4.05 amps

From the data obtained in Table XII and at the maximum power point where the load resistance was (7.8 Ω), the panel efficiency was calculated as:

$$\eta_p = \frac{3.5 \times 30.9}{930 \times 4(0.3717)} \times 100 = 7.82\% \qquad (4.11)$$

On another day the test was run under the following conditions:

Time: 12:00 on February 22, 1984

P_{in} = 10.3 mv or 1030 W/m^2

V_{oc} = 37.9 Volts and I_{sc} = 4.3 amps,

The solar panel efficiency was calculated at the maximum power using data from Table XIII as:

$$\eta_p = \frac{3.7 \times 32.5}{1030 \times 4(0.3717)} \times 100 = 7.85\% \qquad (4.12)$$

The I-V characteristics for the experiments at this case are plotted in Figure 4.3.8.

The curves shown in Figure 4.3.6 through 4.3.8 are significant in that they demonstrate the effect of changes in solar insolation on the output characteristics of the solar panel. They indicate that the insolation changes have a significant effect on the output current, while the output voltage is relatively insensitive to insolation changes.

TABLE XIII

I-V VARIATION FOR THE PANEL WITH PARALLEL-SERIES CONNECTION AT INSOLATION OF 1030 W/M^2

I_L (amps)	V_L (V)	P_{output} (W)
4.24	0.9	3.82
4.2	6.0	25.2
4.15	15.0	62.25
3.9	30.5	118.95
3.8	31.5	119.7
3.7	32.5	120.25
3.0	33.4	100.2
2.8	34.2	95.76
2.5	34.7	86.75
2.0	35.4	70.8
1.8	35.8	64.44
1.6	35.9	57.44
1.5	36.0	54.00
1.3	36.2	47.06
1.0	36.6	36.6
0.7	36.8	25.76

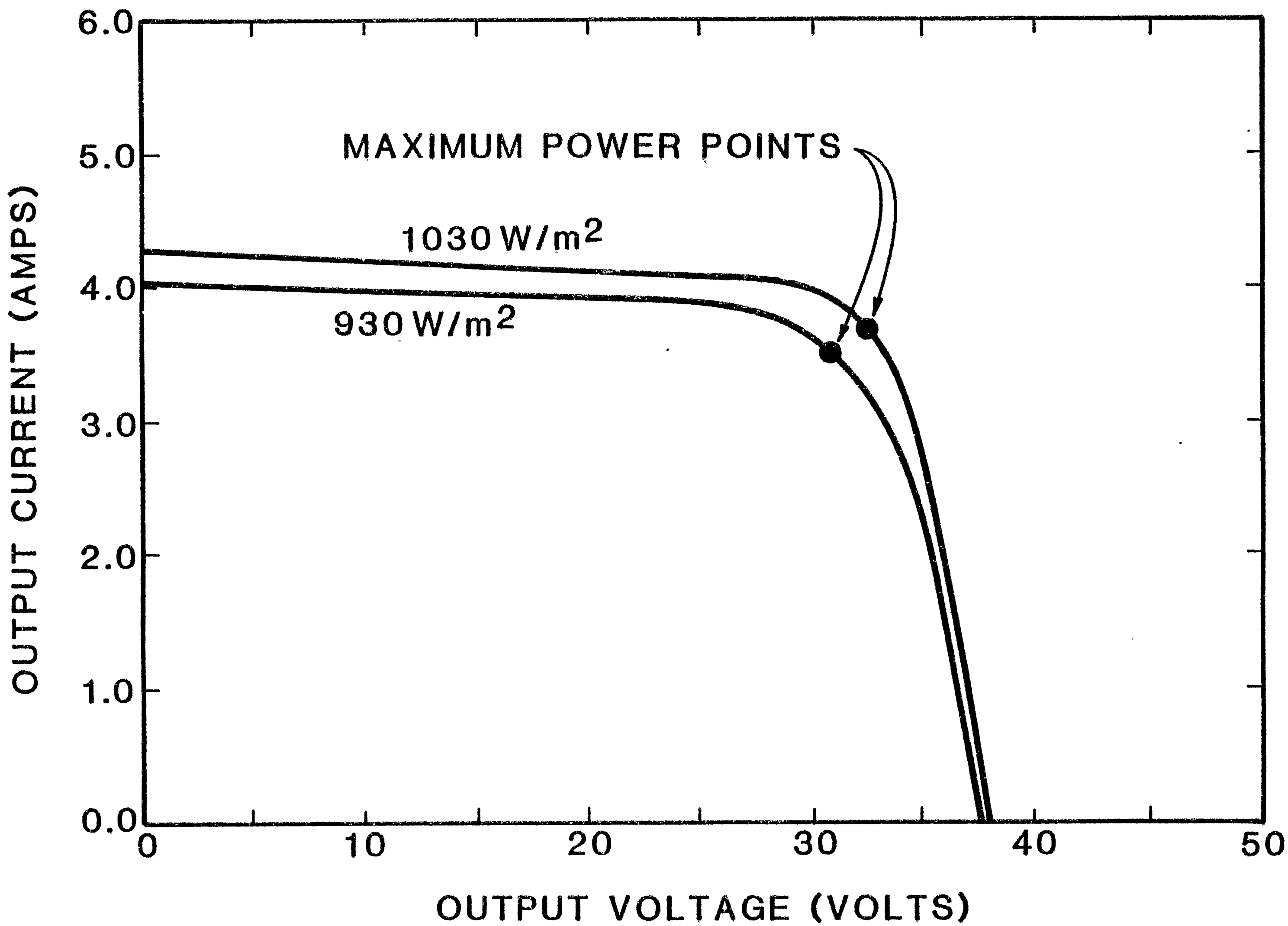

Figure 4.3.8. I-V Curves for the Solar Panel with Parallel-Series Connections at Various Light Levels.

Chapter V

A PHOTOVOLTAIC WATER PUMPING SYSTEM FOR A VILLAGE IN LIBYA

5.1 Introduction

Photovoltaic systems have considerable potential for applications to power remote villages in many countries. Such applications include a water pumping system for drinking and small scale irrigation. A photovoltaic system to power a water pump for a remote village in Libya is described in this chapter.

5.2 Libya

Libya is located in central North Africa, bounded on the north by the Mediterranean Sea, on the east by Egypt and Sudan, on the south by Chad and Niger, and on the west by Algeria and Tunisia as shown in the map (Figure, 5.2.1). It is situated between latitutdes 18^{o} 45' N - and 33^{o} 10' N and between longitudes 9^{o} 58' E and 25^{o} E. Libya occupies an area of about 685,000 square miles. More than 85% of Libya is desert, 2% of the total area is cultivated, and 5% is pasture or forest. There are no rivers, except a few natural springs which are scattered in some valleys and oases. Water is available in some areas either as surface

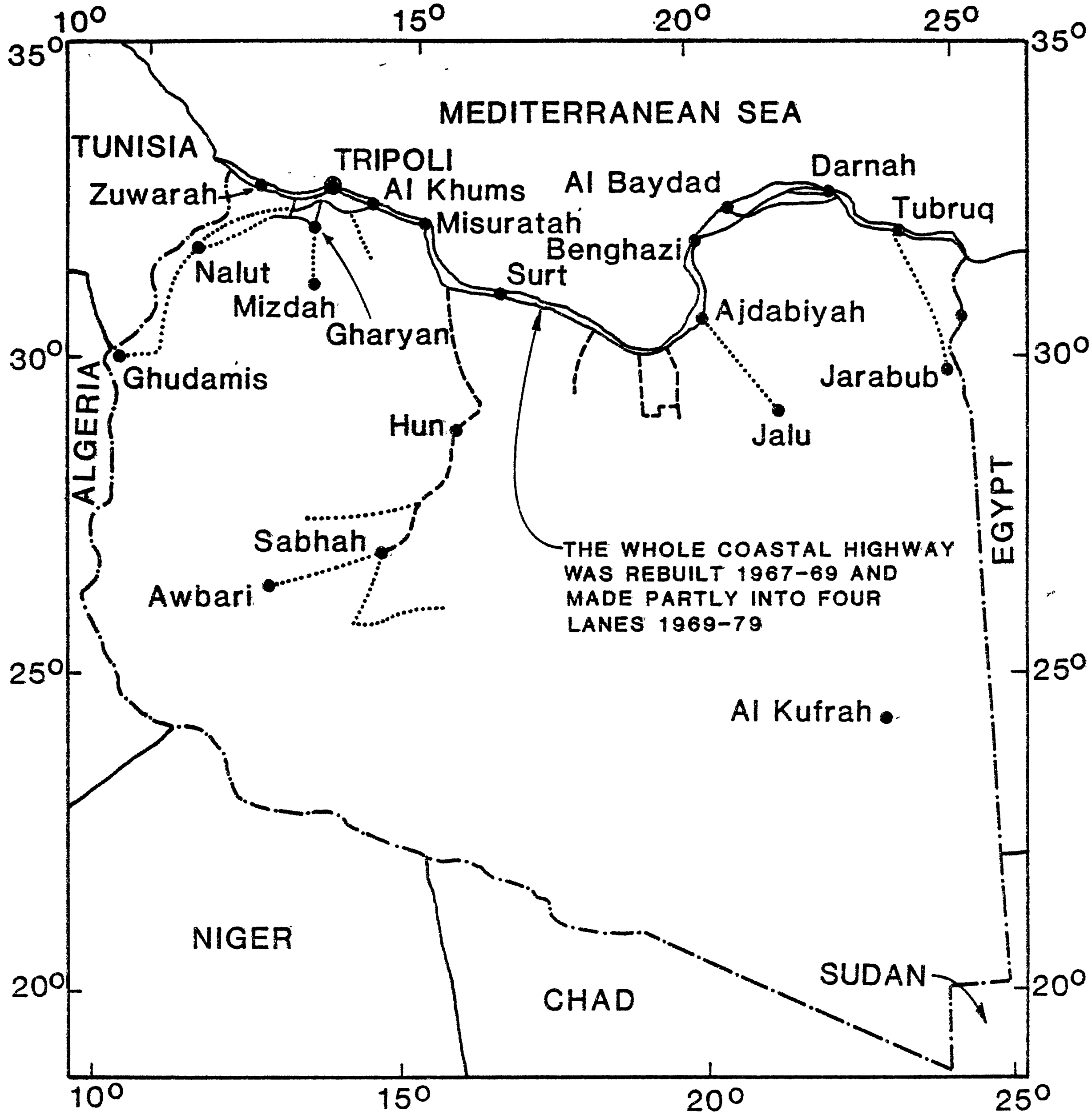

Figure 5.2.1. Map of Libya.

runoff in a number of wadis, or as groundwater. Less than 5% of the cultivated land is irrigated. Rainfall is irregular even in the coast region. Drought is a major problem and it is worse in the south where the rainfall is low. Heavy rain storms, however, occasionally occur in the desert. Figure 5.2.2 shows a map of ground water distribution and the approximate depth below the surface (2).

High temperatures are common, but there are wide variations in many parts of the country. In coastal areas, temperatures often rise up to 40° C in the summer and drop to 10° - 20° C in winter. In interior areas, maximum daily temperatures rise up to 50° C in the summer and to below zero sometimes in the deep south in winter (4).

Libya is a developing country with an estimated 1978 population of about 3.0 million. Most of the people in the rural areas are engaged in settled agriculture. Some work in agriculture and livestock, and the others (Beduin tribes) are engaged in pastoral livestock breeding in the grazing lands. In the past, the economy of the country was based on agriculture production, livestock, fishing and trading. For the past twenty years, it has become heavily dependent upon the oil revenue. The economic boom in the major cities, and the harsher climatic conditions worsened by persistent droughts since 1973 have encouraged people from the rural agricultural villages to migrate to the big cities. This migration has created serious problems, including a shortage

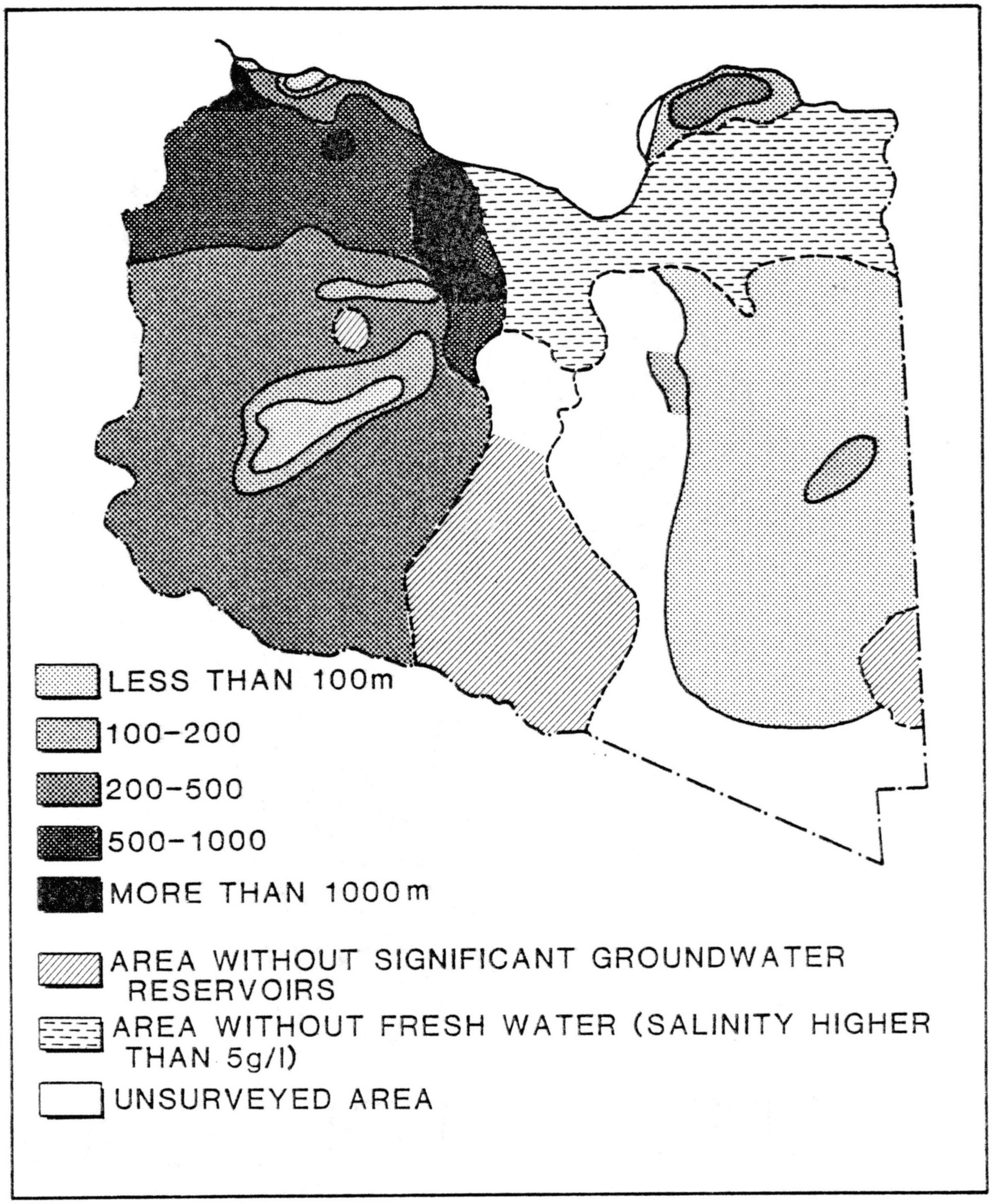

Figure 5.2.2. Libya Ground-Water Distribution Map.

in food production. Because of this migration much of the productive land is turning into desert.

The government has attempted to revive rural-agricultural villages by giving financial support to the farmers, reclaiming new land and giving it to the people. The Council of Land Reclamation and Development has set the following goals (13): 1) increase agricultural production, seeking self-sufficiency in cereals and meat; 2) preserve and develop natural resources, including soil, water and forests; 3) encourage people to return to rural areas, and create residential communities in agricultural areas by providing means to guarantee an adequate standard of living. There are however, some difficulties associated with reaching these goals, including: 1) the large area of the country and the isolation of many desert villages, 2) to the lack of paved road networks, 3) and skilled labor shortages. Thus establishing essential services in these areas is difficult and very expensive. Sometimes spending money is not enough. It must be allocated effectively, economically and used in a socially beneficial manner.

5.3 The Potential Sites For A Photovoltaic System

As previously noted, the southern part of Libya is a desert. As shown in figure 5.2.2, underground water is the major water resource in these areas. Most of desert villages are isolated from the electric power grid and from the water pumping stations that serve the cities in the north.

The selected zones for a PV system in Libya are situated either between latitudes 22^{o} - 29^{o} N and longitude between 20 - 25^{o} E, such as the Elkufrah and El-Sarir area or between longitudes 12^{o} - 16^{o} E in Sebhah and Shati. The zones were identified for the following reasons:

1. They have the highest solar insolation in Libya. The mean intensity insolation is about 3000 Kwh/m^2 annually, and the total duration of sunshine is about 3600 hours per year.
2. The ground water map in Figure 5.2.2 indicates that water is available in these areas and can be found less than 300 feet below the surface (2).
3. In the selected areas, it is common to find a group of villages clustered together, far away from other villages or towns. Most of the villages are not electrified because they are far away from the utility grid.
4. There are some agricultural projects in Elkufrah and El-Sarir, and a PV pumping system may encourage more agricultural projects in these areas.

5.4 Photovoltaic Water Pumping System

A photovoltaic power system could be utilized to generate electricity in such a village to improve its basic living environment and agricultural productivity. Such systems have been proven in many remote areas to be reliable, simple, clean, quiet and easy to install and maintain, relative to other alternative sources of electrical power.

Although solar cells are basically simple, their fabrication requires sophisticated technological capabilities. Libya can avail itself of this technology by acquiring it through international trade until it can develop the necessary industrial fabrication processes inside the country.

In rural villages people obtain potable water from wells by human power and draft animals, or by diesel pumps which are rarely used because of fuel and maintenance problems. There is no water supply system or water tap in most houses. Women and children ususally carry water to their homes in containers or barrels.

The price of fuel has increased in domestic markets by as much as 300% since 1979. This has affected the cost of electricity and transportation in Libya. In remote areas fuel transport costs increase the cost of the fuel to a price that is three times higher than the fuel price in the major cities. The government usually subsidizes the fuel costs in remote areas in an effort to have uniform fuel cost for the country. Photovoltaic system could significantly reduce the need for such subsidies.

5.4.1 The Proposed System:

The proposed photovoltaic power system that might be set up in such a village in the selected area that was mentioned in the previous section could therefore be used to provide significant power for a water pumping system to deliver the necessary water for that village.

An analysis assumes that there are 35 families in a typical village, with 7 people in each family, and a total of 400 animals. The estimated daily water consumption for such a village was calculated and is shown in Table XIV, (7) (10).

TABLE XIV

Daily Water Consumption for Such a Village

Consumer	each (G/day)	total (G/day)
245 people	50	12,250
25 camels	30	750
10 cows	15	150
15 horses & donkies	10	150
350 sheep	2	700
4 watering points	800	3,200

The total daily consumption is about 17,200 gallons per day.

The water supply system can be divided into two main groups:

a. Pumping System: A pump that is driven by a PV system must be capable of supplying the maximum daily consumption of water. The power required to drive the pump is a function of pump capacity, total head and pump efficiency. Input power requirements can be determined from Eq. 5.1 (15).

$$P = fhs/3960 \qquad (5.1)$$

where P = power input in Hp.

f = pump capacity in gallon/min

h = total head in feet

s = water specific gravity = 1

= pump efficiency.

b. Storage Tank: The storage tank should be capable of storing a 10 days supply of water. Water should be pumped from the well into a closed tank to keep it clean, and to minimize evaporation in the summer and freezing in winter. The tank should have several sensors to control the water levels in the tank by turning the pump on and off. The storage tank should have a capacity of 172,000 gallons.

The total water required per year can be calculated as following: 172,000 + 17,200 x 365 = 6,450,000 Gallons/year and the total water that should be pumped per day is about 18,000 Gallons per day.

It is assumed that the well is 300 feet deep, and that the tank is elevated 20 feet above the ground. If the water pump will be operated for about five hours a day, then a pumping unit with a capacity of 60 gallons per minute would provide the required water. From equation 5.1, the power required to power the motor pump is about 6.0 HP or about 5 Kw.

The total energy required per day is about 25 Kwh and the total energy needed for the water pumping system during the year will be 9,125 Kwh/year.

5.4.2 Photovoltaic System Description:

The proposed 5.0 Kw photovoltaic power system is composed of the photovoltaic arrays. The experimental work that was discussed in Chapter IV indicated that the output power of the system is affected by insolation and temperature changes, and that system efficiency decreases when temperature increases. The experiments have shown that the maximum efficiency at a temperature of 24° C was about 8.3% when the insolation level was 990 watts/m^2. In desert areas of Libya the temperature is higher than the temperature in Stillwater, Oklahoma, so the expected module efficiency will be less than those values that given in the experiments conducted in Stillwater. The efficiency will be in the range of 6.0 - 10%, according to the weather conditions.

According to the climate of the desert the photovoltaic system is designed to be utilized of 200 modules which can produce a power output of 25 watts each. These modules will be arranged in photovoltaic panels. The arrays should be tilted to face the sun by an angle that is typically equal to the local latitude plus $10^{\circ} - 15^{\circ}$ (16) to optimize the power output. In the site locations that tilt angle will be in the range of $35^{\circ} - 45^{\circ}$ South. The modules are connected in series - parallel configuration to obtain a desired voltage and current.

The photovoltaic system will be connected directly to the D-C water pump through switches (sensors) which control the operation of the pump and the water level in the tank.

For proper selection of a pump and motor/pump units, it is important that the units should have a high speed of 3000 rmp to 4000 rpm, and high efficiency to minimize the size of the photovoltaic power system (17). Several types of pumps are considered for this application such as displacement rotary and reciprocating pumps and centrifugal pumps.

The system described could satisfy the basic need for water for a typical village in the deserts of Libya. Its cost would be a function of a variety of constraints, including solar cell panel costs, interest rates, maintenance costs, and the cost of the water pump and storage system. The cost of photovoltaic systems has decreased significantly in the past few years, and most experts agree that further cost reductions can be expected. An increased market for solar cell systems of the type described in this Thesis could contribute to future cost reductions.

If Libya should choose to install several water pumping systems of the type described in this Thesis, it is easy to predict that villagers would soon perceive a need to expand the capacity of the system to accommodate other essential services, such as lighting, refrigeration, and communications. The system described here could represent a first step toward the utilization of photovoltaic system in developing countries in the Arab World.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The conversion of solar energy directly into electric energy by photovoltaic cells has many attractive features. Photovoltaic systems have proven to be reliable, suitable, and clean. Solar insolation is abundant at sufficient densities to provide electricity for a wide variety of terrestrial applications throughout the world. These can be categorized by small and predictable loads, and often by their remote location operation where conventional fuels and utility grid supply are not available.

In spite of these attractive features, photovoltaic systems must overcome many hurdles in order to make significant contributions as an energy source. The basic problems of photovoltaics system are its low efficiency and its relatively high initial cost. Continued market penetration of photovoltaic systems will result in price reductions and additional research efforts may lead to improving the efficiency of photovoltaic devices.

PV systems can provide electric energy to satisfy basic human needs and build up rural socio-agricultural structure. Photovoltaic systems can offer great potential benefits to people in developing, as well as developed countries.

The socio-economic effects at a remote village in Libya could be changed by providing electricity for pumping water. There will be change in life style specially with villagers who are usually moving from one place to another seeking water to grow their crops and graze their animals. The system will encourage those people to settle in the village and help them to increase agricultural production and therefore create residential communities in this area.

The system may be extended to provide electricity in the whole village to improve basic living conditions such as household electricity, potable water, health service, education and communication systems ... etc.

6.2 Recommendations

It is time for Libya to face the reality that the reserve of Libyan oil is finite. Libya should take steps now to build an economy that is independent of the oil production.

If Libya is to be involved in solar energy applications, it will have to encourage local researach, development and manufacture of photovoltaic systems. Such cooperation should be formed between the Arab countries.

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