2.2 The Power Supply

The primary electrical power for operating the electronic equipment is obtained from solar cells. Individual cells can generate only small amounts of power, and therefore, arrays of cells in seriesparallel connection are required.

Figure shows the solar cell panels for the HS 376 satellite manufactured by Hughes Space and Communications Company.

In geostationary orbit the telescoped panel is fully extended so that both are exposed to sun- light. At the beginning of life, the panels produce 940 W dc power, which may drop to 760 W at the end of 10 years.

During eclipse, power is provided by two nickel -cadmium (Ni - Cd) long- life batteries, which will deliver 830 W. At the end of life, battery recharge time is less than 16 h.

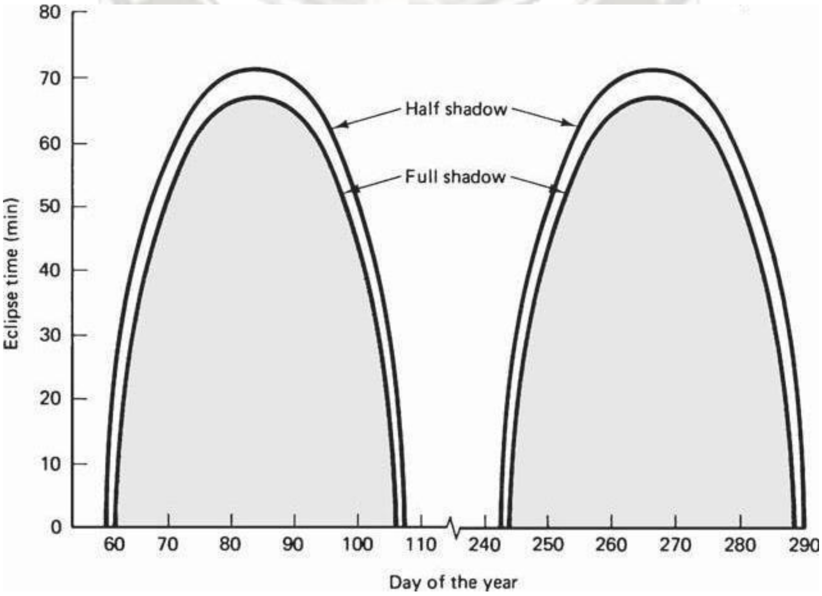


Figure 2.1.(b) Satellite eclipse time as a function of the current day of the year. (*Courtesy of Spilker, 1977. Reprinted by permission of Prentice-*

Hall, Englewood Cliffs, NJ.)

capacity of cylindrical and solar-sail satellites, the cross-over point is esti- mated to be about 2 kW, where the solar-sail type is more economical than the cylindrical type (Hyndman, 1991).

Power Systems

- Options for electrical-power production & storage for space missions, current and under development, are shown in the following figure in terms of power vs. mission duration,

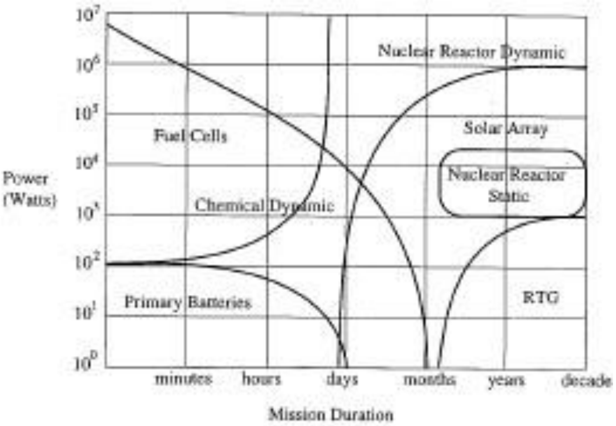


Figure 9.1: Spacecraft power systems (Hyder).

- Primary Batteries:

· Produce direct current by electrochemistry

· Currently used: LiCFx (lithium polycarbon monofluoride) electrolyte · Economical for small spacecraft for missions of relatively short duration.

- Solar PV – Battery:

· Photovoltaic cell, semi-conductor material, directly converts sunlight to electricity.

· Most widely used energy-conversion device for spacecraft

· Provide relatively high power levels over long duration (up to 10 to 15 years). · Batteries required to provide power during eclipse.

▪ Radioisotope-Thermoelectric Generators (RTGs):

· Compact and continuous source of power

· Used in deep-space missions over several decades

· Considered nuclear fuel but relatively easy to handle safely:

Curium-244 & Plutonium-238

[strontium-90 less expensive but not safe to handle]

· High energy particles heat a thermoelectric material that, in turn, produces an electric potential:

Lead telluride SiGe (silicon germanium) doped w. phosphorous

▪ Fuel cells:

· Produce direct current by chemical reaction of an oxidant and a fuel.

· Currently used: O_2 & H_2.

· Work as long as supply of oxidant & fuel available.

▪ Solar Concentrator – Dynamic:

· Mirrors used to concentrate sunlight to heat a working fluid that powers a turbine:

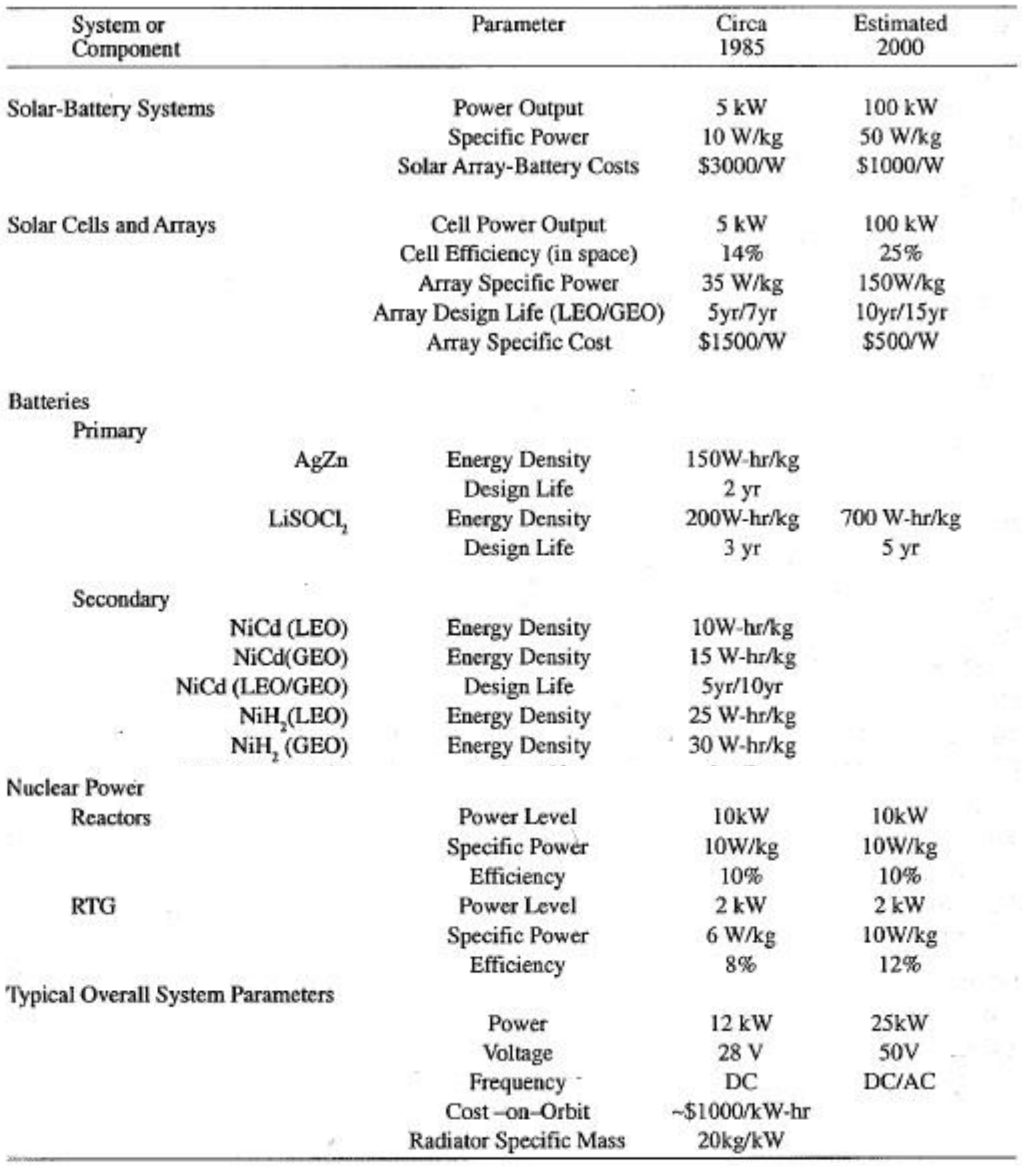
Steam Liquid metal, e.g. potassium chloride Gas, e.g. helium, xenon

▪ Chemical Dynamic:

· Burn fuel & oxidant, e.g. H_2 & O_2, CH_4 & O_2, to power a turbine.

Power conversion & storage options and status:

Table 9.1: Power system current and estimated performance (Hyder et al.).



System or Component		Parameter	Circa 1985	Estimated 2000
Solar-Battery Systems		Power Output	5 kW	100 kW
		Specific Power	10 W/kg	50 W/kg
		Solar Array-Battery Costs	\$3000/W	\$1000/W
Solar Cells and Arrays		Cell Power Output	5 kW	100 kW
		Cell Efficiency (in space)	14%	25%
		Array Specific Power	35 W/kg	150W/kg
		Array Design Life (LEO/GEO)	5yr/7yr	10yr/15yr
		Array Specific Cost	\$1500/W	\$500/W
Batteries				
Primary				
	AgZn	Energy Density	150W-hr/kg	
		Design Life	2 yr	
	LiSOCl$_2$	Energy Density	200W-hr/kg	700 W-hr/kg
		Design Life	3 yr	5 yr
Secondary				
	NiCd (LEO)	Energy Density	10W-hr/kg	
	NiCd(GEO)	Energy Density	15 W-hr/kg	
	NiCd (LEO/GEO)	Design Life	5yr/10yr	
	NiH$_2$(LEO)	Energy Density	25 W-hr/kg	
	NiH$_2$ (GEO)	Energy Density	30 W-hr/kg	
Nuclear Power				
Reactors		Power Level	10kW	10kW
		Specific Power	10W/kg	10W/kg
		Efficiency	10%	10%
RTG		Power Level	2 kW	2 kW
		Specific Power	6 W/kg	10W/kg
		Efficiency	8%	12%
Typical Overall System Parameters				
		Power	12 kW	25kW
		Voltage	28 V	50V
		Frequency	DC	DC/AC
		Cost–on–Orbit	~\$1000/kW-hr	
		Radiator Specific Mass	20kg/kW	

Table 9.2: Power Limits & Performance.

System	Limit, kW	Eff, %	SP, W/kg	Source
Solar-PV	20	15-30	5-10	experience
RTG	1	7-15	7-15	same
Nuclear-TEC	100	7-15	?	projected

SP is specific power

R&D always seeking improvements:

Example) NASA funding development of solar array design for SP
100 W kg .

- Copper-indium-diselenide thin-film PV cell

- Low-mass structure

▪ Basic Power System

· A general system is shown in the following block diagram,

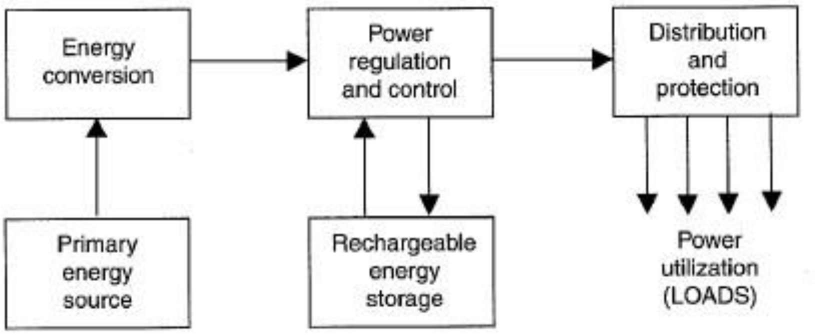


Figure 9.2: Power system block diagram (Patel).

▪ System Voltage

· Initial spacecraft designed for 28 VDC (automotive typically 12 VDC).

· Higher the power requirement → higher the operating voltage to reduce losses, i.e.

$P = IV$ $V = IR$ $I =$ current, amperes $R =$ resistance,ohms

$P_{loss} = I R^2$ in conductors

For fixed power: Higher the voltage, lower the current, lower the loss.

· Standard distribution (“bus”) voltages:

$\boxed{28}$ $\boxed{50}$ $\boxed{70}$ $\boxed{100}$ $\boxed{120}$ $\boxed{160}$ V

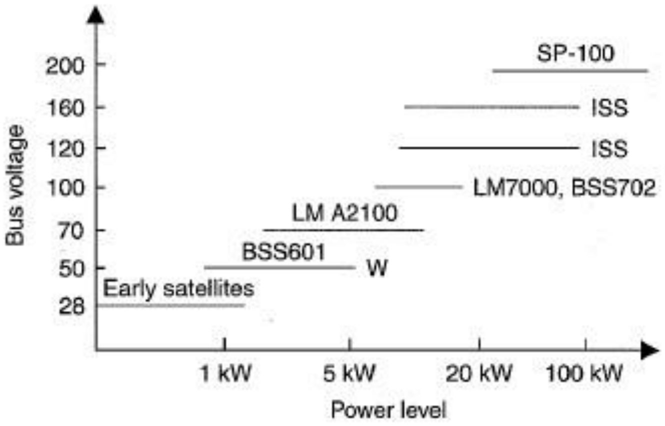


Figure 9.3: Bus voltage versus power level for several spacecraft (Patel).

LM A2100: Communications satellite

LM7000: Communications, Intelsat, 1998

BSS702: Communications, VSAT, 2001
ISS: International Space Station
SP-100: Space Power 100 kW (program canceled)

▪ Rules-of-thumb for bus voltage in LEO orbits:

1. Above ~160 V, solar-array current-leakage to space plasma (negatively charged electron field) starts to increase exponentially, with electric arcing above ~180 to 200 V.
2. At 100 V, for every square meter of exposed conductor area, $\boxed{\text{leakage current} \approx 1 \text{ mA}}$.

Leakage current increases with voltage.

3. Above 160 V, conductors require insulation (additional mass).

Voltage Scaling Law:

· Design experience has shown empirically,

$$V_{opt} = 0.025\, P \qquad (9.1.1)$$

where V_{opt} = optimum system voltage
P = required system power

▪ Mass Scaling Law:

· An empirical scaling law to estimate mass of a new system, from design experience, is,

$$m_{new} = m_{exist} \times \left(\frac{P_{new}}{P_{exist}} \right)^{0.7} \qquad (9.1.2)$$

where m_{new} = mass of a new system
m_{exist} = mass of an existing, similar system
P_{new} = power requirement of the new system
P_{exist} = power of existing system

▪ A more detailed system diagram showing various power subsystems is given below,

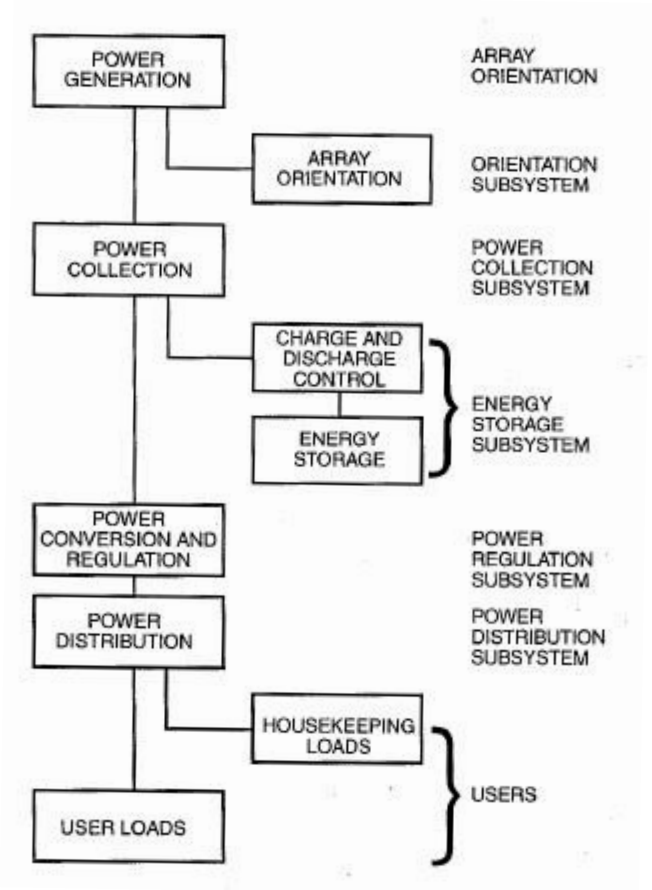


Figure 9.4: Spacecraft power system block diagram (Hyder et al.)

Solar PV – Battery System

- The most common electrical-power-generation system for spacecraft is the combination of solarphotovoltaic arrays and batteries as shown schematically in the following figure,

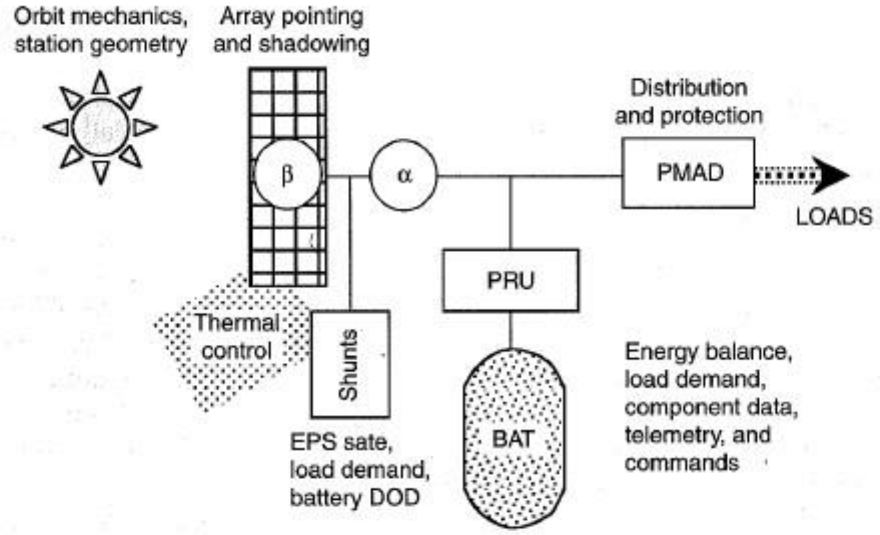


Figure 9.5: Photovoltaic- battery system (Patel).

PMAD = power management and distribution

PRU = power regulation unit

BAT = batteries

EPS = electrical power system

α = α- drive,rotates 360° once per orbit

β = β- gimbals, rotate $\pm\beta°$ to compensate for the solar β angle

The PV Cell

- The building block of the solar array is the PV cell:
  - Diode-type junction of two crystalline semiconductors
  - Generates electricity directly under sunlight
  - Photons transferred to electron system of the material, create charge carriers
  - Charge carriers produce a potential gradient (voltage), circulate as current in an external circuit
  - Concept illustrated in the following simple schematic,

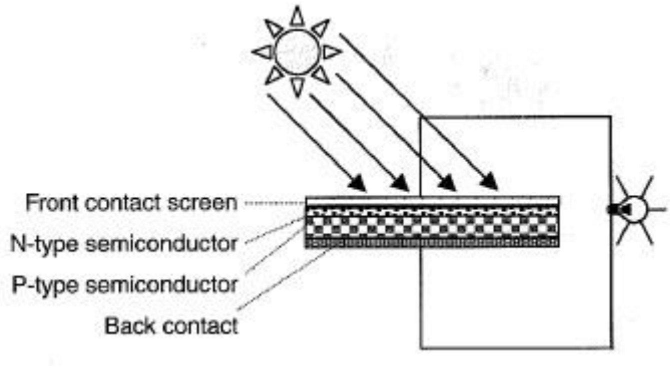


Figure 9.6: Photovoltaic cell cross-section (Patel).

The conversion efficiency of a PV cell is given by,

$$\eta = \frac{\text{electrical power output}}{\text{solar power incident on the cell}} = \frac{IV}{P_{SF}} \qquad (9.2.1)$$

- Conversion efficiency for three common PV cell materials:

Silicon (Si) 12-14%

Gallium arsenide/Germanium

(GaAs/Ge)	18-19%
GaInP2/GaAs/Ge	24-26%

▪ The useful energy absorption of the sunlight spectrum for silicon is illustrated in the following figure,

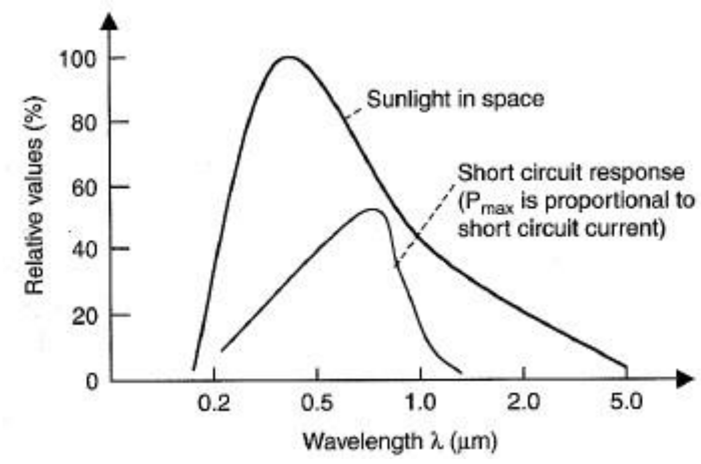


Figure 9.7: Sunlight spectrum and useable photovoltaic spectrum.

· About two-thirds of solar-radiation energy lies between wavelengths, $\lambda = 0.4 - 1.1\ \mu$m.

· Silicon has a cut-off wavelength of about, $\lambda =$ 1.1 μm.

· Radiation absorbed and not converted to electrical power is converted to heat in the cell material

Example:A photon of blue light, energy of 3 eV, generates about 0.5 eV of electricity and 2.5 eV of heat.

▪ Photon energy is given by,

$$e_p = h\nu \qquad (9.2.2)$$

h Planck's constant $= 6.626\times10^{-34}$ J-s

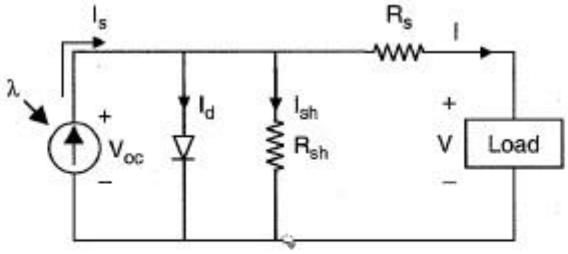
$\nu =$ frequency, cps

$$= c/\lambda \qquad (9.2.3)$$

c speed of light 2.9979×10^{8} m/s

$\lambda =$ wave length

- The complex physics of a PV cell can be represented by the electrical circuit in the following diagram,



where

and,

where

Figure 9.8: Photovoltaic-cell equivalent circuit (Patel).

- The cell acts as a constant current source shunted by a perfect diode:

Here, I_s = source or photo current

I_d = the diode current

I_{sh} = the ground shunt current

R_s = internal resistance of the material

R_{sh} = resistance to internal current leakage to ground

In an ideal PV cell, $R_s = 0$ (no series loss)

$R_{sh} = \infty$ (no leakage to ground)

In a typical silicon cell, $R_s = 0.05$ to $0.10\ \Omega$

$R_{sh} = 200$ to $300\ \Omega$

- The current delivered to the external load is,

$$I = I_s - I_d + I_{sh} \qquad (9.2.4)$$

- An important parameter for PV cells is the open-circuit voltage, V_{oc}, and is the case for zero load current, i.e. an open circuit, given by,

V_{oc} V IR_s (9.2.5)

= +

- The diode current is given by the classical diode-current expression,

I_d I_o e qV_{oc} AkT 1 (9.2.6) where I_o diode-saturation (dark) current q

=

electron charge 0.1592 10 ^{18} coulombs × k Boltzmann's constant 1.381 10

^{23} J/K = = × −

=

=

T absolute temperature, K

A curve-fit constant

= − / −

- From (3.4) & (3.6), the load current is,

I $I_s I_o$ e qV_{oc} AkT 1 $\frac{V_{oc}}{R_{sh}}$

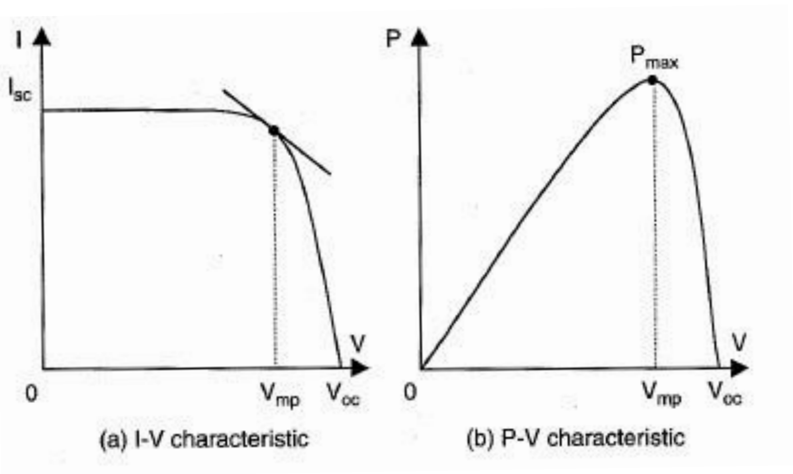
(9.2.7)

where V_{oc}/R_{sh} = ground leakage and can be ignored compared to I_s & I_d .

- The diode-saturation current is measured by applying an open-circuit voltage, V_{oc}, to the cell in the dark and measuring the current going to the cell.

- Under sunlight, the diode current, I_d , is small compared to I_s.

The *I-V* and *P-V* curves for a cell in sunlight are shown in the following figures,



(a) I-V characteristic

(b) P-V characteristic

Figure 9.9: Photovoltaic-cell current-voltage and power-voltage characteristics (Patel).

- In figure (a), I_{sc} is the <u>short-circuit current</u> that is determined by shorting the output terminals and measuring the resultant current under <u>full sunlight</u>.

- Ignoring the small diode and ground leakage current in (2.7), the <u>short-circuit current</u> is ~ equal to the load current, where the load current is a <u>maximum</u>.

- This is the maximum current a cell can provide.

- At the bottom right of the curve, at zero current, is the <u>open-circuit voltage</u>, V_{oc}.

Ignoring ground-leakage current, the open-circuit voltage can be obtained from (3.7) for I 0, where,

$$I_S = I_o\left[e^{qV_{oc}/AkT} \quad 1\right]$$

or

$$V_{oc} \quad \frac{AkT}{q}\ln\left(\frac{I_S}{I_o}+1\right) \quad (9.2.8)$$

- In practical photocells, the photo current I_S □ I_o.

- Under constant illumination, I_S/I_o is a function of cell temperature.

▪ Cell output power is the product of load current and voltage. The functional relationship is shown in (b) in the figure at the top.

· The maximum power of a photo cell occurs at the knee in the *I-V* curve.

- Solar panels are designed to operate at this point.
- Solar panels are modeled in the electrical system as a constant-current source, per (a) above.

· Typical photo-cell characteristics:

Material	Vmp, V	Imp, mA/cm^2	Pmp, mW/cm^2
Silicon	0.50	40	20
GaAs	1.0	30	30

▪ An important effect for solar-array design is PV-cell degradation from radiation of charged particles in space: Protons, electrons, alpha particles.

· Different particles have different damaging effect on I_{sc} &V_{oc}.

· Radiation levels measured in MeV (10^6 electron-volts) for a given period of time.

· Degradation of p/n GaAs solar cells is shown in the next figure for proton fluence,

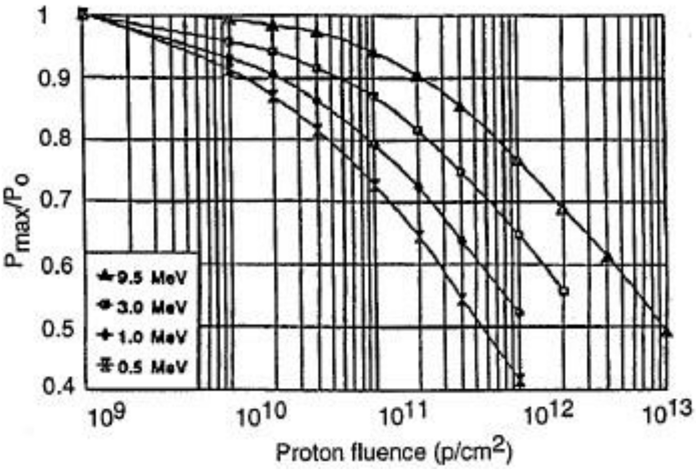


Figure 9.10: Photovoltaic-cell power output as a function of proton fluence (Hyder et al.).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