UNIVERSITY OF ARIZONA
STUDENT SATELLITE PROJECT

Technical Note

Doc. no.: PGD-008

Revision no.: 1.0

Status: Draft

Subject: Solar Power Generation Overview **Date:** 7/8/98

Written by: Hanee Barqawi and Appandi Mustafa

Reviewed by:

Revision history:

Revision 1.0: Initial Draft

---

1. Document Overview

This technical note describes a solar array design which will provide power for the operation components on a satellite. The electrical energy is stored in a set of rechargeable batteries for the satellite when in orbit. The goal of this design is to provide the satellite with a reliable source of power, operational under extreme space environment and light in weight. To achieve this goal, research, analysis, testing, simulations, and modifications have been done. The results of the design show that implementing a well studied system will equip the satellite operators with more understanding of the solar array in space.

2. Requirements

2.1 Solar Panels must provide power of more than 35W.

2.2 Panels must operate under extreme temperature changes. The temperature of the satellite is 100º Celsius when it is fully illuminated and -80º Celsius when it is in eclipse.

2.3 Life span of panels must be at least expected duration of UASat orbital lifetime.

2.4 Solar panels must provide power the required power in the specified orbit of UASat (400km, 51.6° inclination).

2.5 Panels must be able to function under radiation expected in UASat orbit.

2.6 All signal and power wires used must be twisted to minimize electromagnetic

interference.

2.7 Solar panels must provide a 28V continuous bus voltage.

2.8 Solar cells should be wired to allow bypassing of defective or shadowed cells.

3. Descriptions/Designs/Discussion

3.1 Characteristics of Solar Cells

Solar cells have many characteristics that would affect the reliability of producing power for satellites. Power in a solar panel is made up of photovoltaic (PV) cells connected in series to build up a desired voltage. PV cells are devices that are capable of converting sunlight into electrical energy. The amount of electrical energy produced by the PV cells depends on a wide number of factors. These factors include the type of PV material, the material covering the cells, and the effects of radiation, temperature and shading on the cells. Before discussing these factors, examination of the process of converting solar energy into electrical energy will be outlined.

3.1.1 PN Junction

The process of converting sunlight into electrical energy is called PV effect. The PV effect is produced when two separate semiconductors are connected together to produce an electrical field. The two types of semiconductors are p-type and n-type. The p-type semiconductors are materials with the number of holes greater than the number of electrons. Therefore, the p-type semiconductors have a positive charge. The n-type semiconductors are materials with the number of electrons greater than the number of holes. Therefore, the n-type semiconductors are negatively charged. If the number of holes is the same as the number of electrons, the semiconductor is said to be electrically neutral as shown in Figure 1a. When the p-type and n-type are connected together, a PN junction is formed at the interface between these two materials. The PN junction is the place where an induced electric field is formed.[3][4]

The motion of the holes from p-type to the n-type or vice versa will produce the induced electric field across the junction. The motion of electrons and holes is excited by sunlight shining on the PV cells. Sunlight is comprised of photons with different wavelengths and different amounts of energy in the solar spectrum. When these photons strike the PV cells, they may get reflected or absorbed by the cells. Generation of electrical energy occurs when photons are absorbed. The electrons in the PV cells gain this absorbed energy. With this energy, the electrons in the valence band will jump through the band gap into the conduction band, forming holes in the valence band as shown in Figure 1b. An electromotive force (EMF) is produced by a built-in electric field causing the holes and electrons to travel in the opposite direction, thus generating current in the solar panels as shown in Figure 1C.[3][4][9]

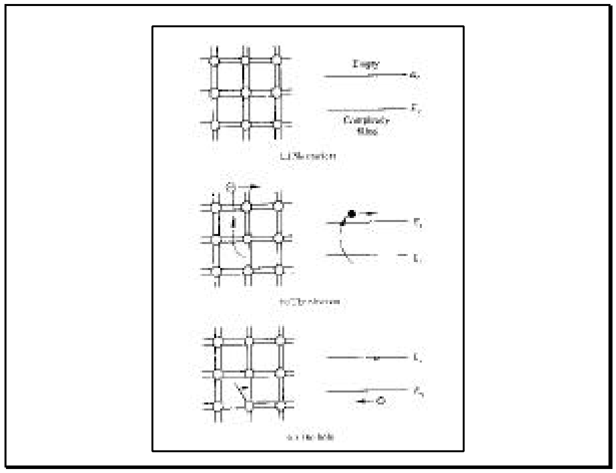

[4]

Figure 1. Electron and hole movement in the PN junction

3.1.2 Materials of the solar cells

The amount of current generated by the holes and the electrons differs with different types of material used in the PV cells. The two most common types of semiconductor materials used for space application PV cells are Silicon (Si) and Gallium Arsenide (GaAs). The efficiency and degradation rate of both Si and GaAs are shown in Table 1. This table shows the theoretical efficiency, achieved efficiency, degradation rate, power delivered and maximum current produced by Si and GaAs.[2]

The reason for GaAs to have a higher conversion efficiency than Si is due to the larger bandgap of GaAs. With a larger bandgap, GaAs is able to absorb and convert more energy than Si. However, with a larger bandgap, GaAs absorbs a wider spectrum of solar radiation. This spectrum includes some harmful solar radiation that causes defects to be produced in the semiconductor. Defects in PV cells cause the degradation rate to increase and the efficiency to decrease.[2] In general, there are many ways to increase the efficiency of the semiconductor. One of the more prominent concepts is to decrease the recombination process, thereby increasing the output power of the semiconductor.[4]

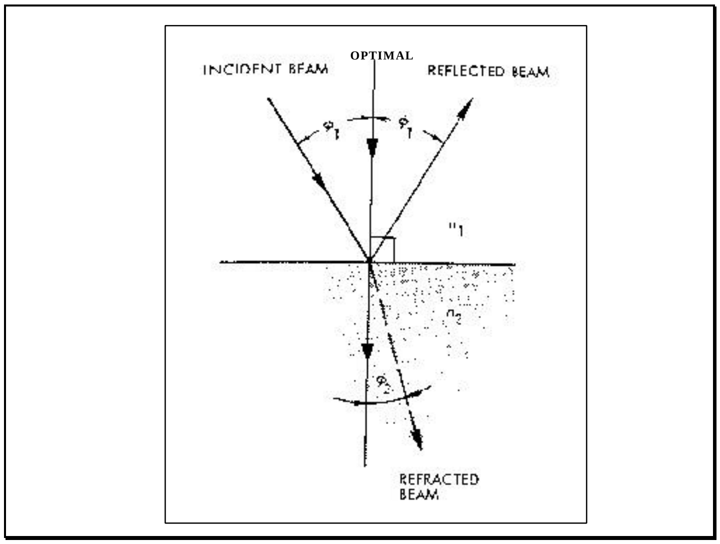
Table 1. Types of material use in space grade PV cells

Cell Type	Silicon	Gallium Arsenide
Planar cell theoretical efficiency	18%	23%
Achieved efficiency	14%	18%
Equivalent time in geosynchronous orbit for 15% degradation • 1 MeV electrons • 10MeV protons	10 yrs 2yrs	33yrs 6yrs
Total power delivered	59.27W	76.2W
Max current	2.12A	2.72A

[8]

3.1.3 Angle of the Sunbeam and Texturing

To maximize the power output of the semiconductor, there is an optimal amount of sunlight entering the PV cells. This amount is also known as the ideal generating temperature. The optimal amount of sunlight entering the cells is obtained at an angle of zero degree incident.

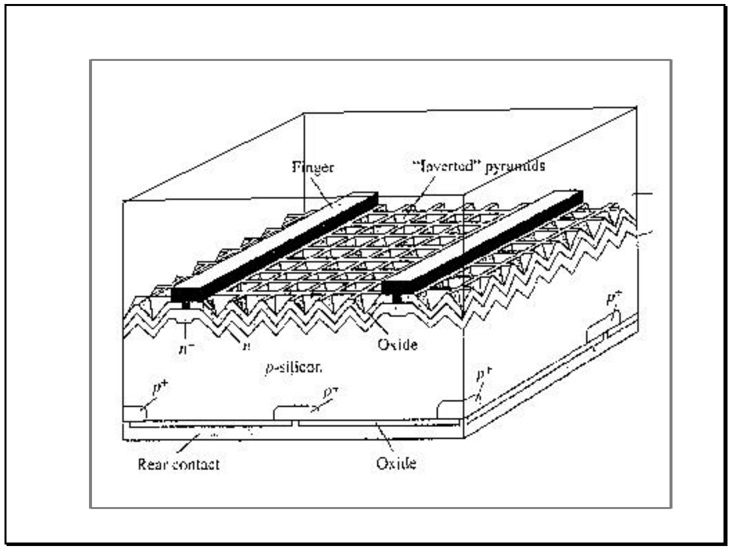


[3]

Figure 2. Angle for optimal amount of sunlight entering the cell

The angle between the sunrays and the normal to the surface of the PV cells must be zero so that maximum power will be collected. Minimum power occurs at an angle of 90 degrees with the normal to the surface. When the angle of sunrays incident on the surface is between 0 to 90 degrees, some of the rays will get reflected while some will be absorbed as shown in Figure 2. [2][3]

Another method to maximize power output is to reduce the amount of the sunlight being reflected away, the surface of the solar cells is textured and coated with an anti-reflective coating. The textured surface will force the light photons to strike the surface of the solar cells more than once to prevent these photons from leaving the surface of the cells as shown in Figure 3. The most commonly used anti-reflective coating is Tantalum Pentonide (Ta2O2) or Multi-layer Coating (ML).[2][4]



[4]

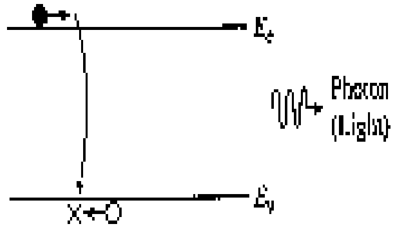
Figure 3. Texturing of the PV cell to increase power output

3.1.4 Cover Material

Photons have to pass through a cover material before entering the anti-reflection coating. This cover is made of fused Silica, which is a material that is capable of tolerating thermal shocks. In addition, it has high radiation and temperature resistivity. Furthermore, the cover material functions as a protection against physical damage up to a certain extent. Not only can the cover serve as a protection, but it can also be used as a filter. This filter is for reflecting and blocking the harmful radiation from entering the cells. The effects of using such a filter are to minimize the degradation and increase the efficiency of the PV cells.[2]

3.1.5 Effects of Radiation

When sunlight strikes the cover material of the PV panel, there are numerous types of radiation particles hitting the panel. As a result, they tend to collide with an electron or a hole, causing them to recombine. Sometimes, the radiation particle will knock one of the electrons from the conduction band that and generate a photon (light). This is shown in Figure 4. In effect, this significantly reduces the output power and severely degrades the performance of the PV panels.[4]

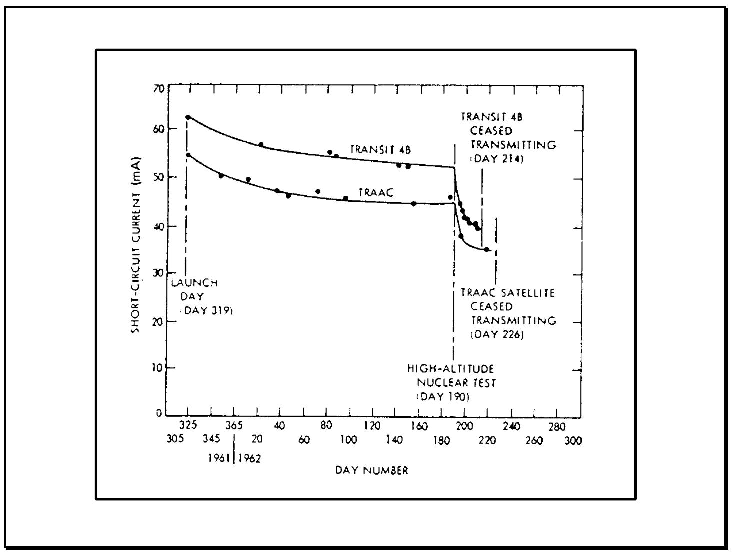


[4]

Figure 4. Recombination of electrons and holes

The radiation particles found in the spectrum of sunlight are electrons, protons, gamma ray, and x-ray radiation. In particular, a proton can cause more damage than an electron due to its larger mass. As an illustration of radiation effects on PV panels, Figure 5 shows how two operational satellites were incapacitated by radiation.[2][5]

In 1961, two satellites were observed to be in good operating condition. However, after a high altitude nuclear device had been set off in the vicinity of the two satellites, the short circuit current of both satellites dropped to the extent that both of these satellites ceased to transmit. The two satellites were decommissioned shortly thereafter. The cross section of this example illustrates the relationship between radiation and degradation rate of a PV panel.[2]

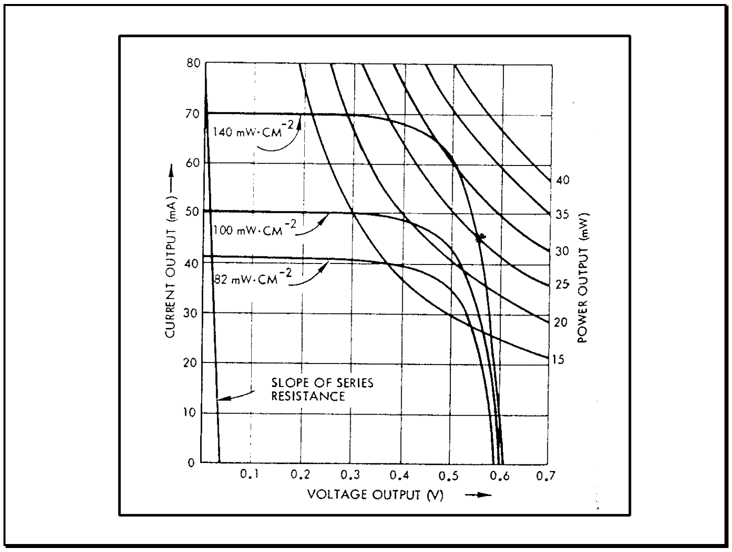


[2]

Figure 5. Time taken for radiation to damage two satellites

3.1.6 Effects of Solar Intensity

The intensity of sunlight incident on the PV cells will affect the operating temperature of the cells. The technical term used to describe solar intensity is radiant solar energy flux density, measured in watts per square meter (W/m^2). As sunlight is incident on the cells, many factors can affect this unit. The first factor is the angle of the cells facing the sunlight with respect to the normal of the cells. The second factor is the solar distance, which is the distance between the sun and the position of the cells. Third, the concentration ratio of the sunlight is the ratio of the amount of sunlight shining on the cells to the amount that is being collected. The last factor is loss in energy when light passes through the device medium before reaching the cells. The above are some of the common factors that will affect solar intensity hitting the cells. In addition to the above, solar intensity can be affected by solar eclipse or shadowing of the cells by other parts of the satellite.[2] The effects of changing solar intensity are shown in Figure 6.



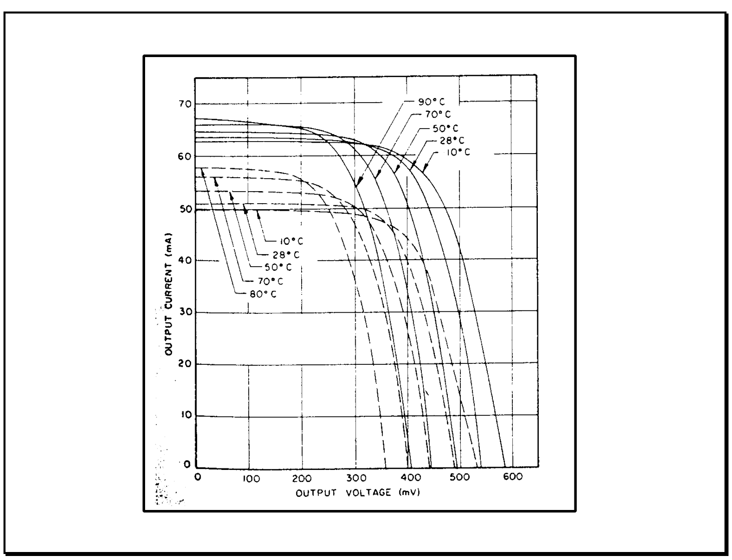
[2]

Figure 6. The relationship between solar intensity and IV curves

As shown in Figure 6, when the unit of solar intensity drops, the IV curve of the panel will shift inward. The shift in output current is more predominant than the shift in output voltage. This reduction in the output current will decrease the output power.[2]

3.1.7 Effects of temperature

The effects of temperature can be classified into reversible effects and irreversible effects. Reversible effects come in the form of changing output of the IV curve. Figure 7 illustrates the effects of changing operating temperature on the IV curve of a cell.



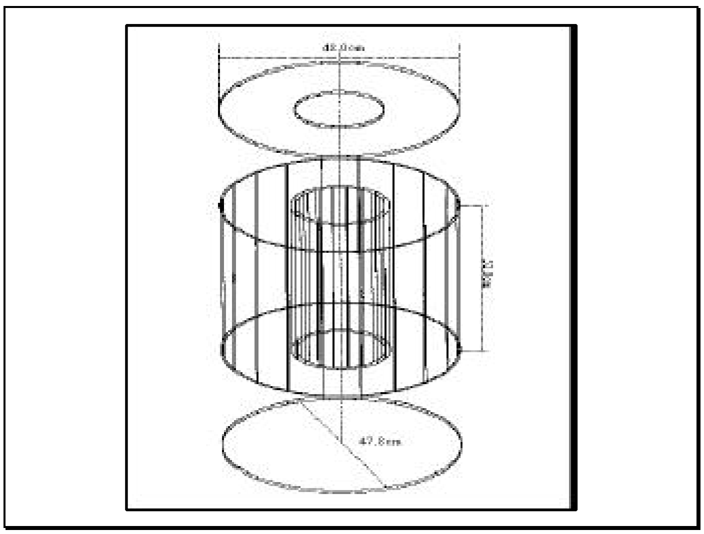
[2]

Figure 7. Changes in IV curve with respect to changes in operating temperature

The illustration shows that as temperature in a PV cell increases, the output voltage will decrease while the output current increases at a higher rate. The overall effect of this change will lead to a drop in the output power. Other than the above mentioned, the operating temperature can have irreversible effects on the solar cells. Under extremely high temperatures, the solder that connects the wiring and terminals of the cells will melt. Under extremely low temperatures the material of the PV cells will cease to operate. Under constant changing temperature, expansion and contraction of the panels will lead to a mechanical stress and a formation of cracks. As a result of changing temperature, the epoxy used to bond the panels to the satellite will lose its bonding properties, causing the panel to peel from the satellite.[2][6]

3.2 Analysis of the overall satellite design

3.2.1 Fixed Variables of the Design



[7]

Figure 8. Physical dimensions of the satellite

The outer diameter of the satellite, Outer Dia.	=	48.0 cm.
The inner diameter of the satellite, Inner Dia.	=	47.8 cm.
Height of the satellite, H	=	52.0 cm.
Life span of satellite	=	6 months to 15 months.
Thus, life span of the panels must	>	15 months.
Apogee/perigee	=	400km.
Time per orbit	=	90 min.
Time per orbit in the sun	≈	45 min.
Angle of inclination	=	51.6 degrees. [1]

The figures above are fixed variables of the satellite that are very unlikely to change. The definitions of the first three variables are shown in Figure 8. The life span of the satellite is the duration of the operation in space. Knowing the life span of the satellite, the life span of the solar arrays must be greater than the life span of the satellite. The apogee and perigee are the longest and shortest radius of the satellite's path, respectively. Time per orbit is the time taken for the satellite to orbit Earth once. This value is divided by two to give the approximate time taken for the satellite to be on the bright side of Earth. The angle of inclination is the angle between the satellite's flight path with respect to the equatorial line. These are the fixed data regarding the UASat that will be taken into consideration when the design for the solar array is formulated.[2][8]

3.2.2 Design Analysis

Total curve surface area	=	Outer Dia * H * Π
	=	48.0 cm * 52.0 cm * Π
	=	7841.42 cm^2

3.2.3 Percentage of area in the sun = Λ%

Total effective curve surface area	=	7841.42 cm^2 * Λ%
	=	0.7841Λ% m^2
Power delivered by the sun	=	1350 W/m^2
Total power delivered	=	1350 W/ m^2 * 0.7841Λ% m^2
	=	1058.5Λ% W
Efficiency of the panels	=	Σ%
Power generated by the panel	=	1058.5Λ% W * Σ%
	=	1058.5(Λ%)(Σ%) W [9]

This section consists of two uncertain yet crucial variables, which may be subjected to changes over time. The two uncertain variables are symbolized by Λ and Σ. Both of them are percentage values. Λ is the percentage of the satellite area facing the sun. This figure primarily depends on the shape of the satellite. The shape of the satellite is the number of facets that the satellite has. With more facets, the percentage area will be higher with the maximum percentage belonging to that of a cylindrical satellite. Σ is the efficiency percentage of the material used to make the solar cells. The total curved surface area is the area of the satellite excluding its flat top and bottom. Total effective area is the area of the satellite that is illuminated by the sun. Power delivered is the amount of power radiated from the sun. This number is about 1350 W/m^2 for the altitude the UASat is located when in operation. Total power delivered is the total power produced by the solar arrays when the efficiency of the cells is 100%. Power generated by the panel is the power produced by the array after taking into consideration the efficiency of the cells. This figure will be the output power produced by the array.

This section is meant to make calculations of power produced by the array more efficiently and more effectively. Below is an example of a power calculation. [2][8]

Percentage of area in the sun	=	40% (assumption)
Total effective curve surface area	=	7841.42 cm^2 * 40%
	=	3136.57 cm^2
	=	0.3137 m^2
Power delivered by the sun	=	1350 W/m^2
Total power delivered	=	1350 W/m^2 * 0.3137 m^2
	=	423.44 W
Efficiency of the panels	=	20% (assumption)
Power generated by the panel	=	423.44 * 20%
	=	84.69W [8]

Table 2. Efficiency and corresponding output power.

3.3 Efficiency of Cells (%)	**3.4 Output Power (W)**
5	21.17
10	42.34
20	84.69

According to Table 2, with 40% of the area of the satellite illuminated, the output power of different efficiencies can be calculated. With the power output, the exact efficiency needed for the satellite could be estimated accurately. With the design analysis, the value for Λ and Σ, which are uncertain, could be changed whenever needed. Changes would only affect the final equation {Power generated by the panel = 1058.5(Λ%)(Σ%) W} as seen in the example given above. In addition, the design analysis would also aid the project in choosing among the available options in the following section.[1]

4. Lists

5. Interface Requirements and Specifications

6. Current Status

7. Test Plan

8. Concerns and Open Issues

9. References

1. http://www.physics.arizona.edu/ssp/
2. H. S. Rauschenbach, *Solar Cell Array Design Handbook*. New York, NY: Van Rostrand Reinhold Company, 1980.
3. R. J. Komp, *Practical Photovoltaics*. Ann Arbor, Michigan: Aatec Publication, 1984.
4. R. F. Pierret, *Semiconductor Device Fundamentals*. Natick, MA: Addison-Wesley Publcation Company, Inc, 1996.
5. J. C. Bourgoin, R. Kiliulis, C. Gonzales,m G. Strobl, C. Fores, K. Bogus, C. Signorini, "Deep Space Degradation of Si and GaAs Solar Cells," *IEEE Photovoltaic Specialist Conference*, Vol. 25, pp. 211-214, May 1996.
6. J. J. Wysocki, P. Rappaport, "Effect of Temerparture on Photovoltaic Solar Energy Conversion," *J. Appl. Phys*., Vol. 31, pp. 571-578, Mar. 1960.
7. http://www.u.arizona.edu/ic/msa/
8. Wiley J Larson, James R. Wertz, *Space Mission Analysis And Design.* Torrance, California: Microcosm, Inc, 1992.
9. John F, Peck, "*Aerospace Senior Laboratory and PV cells lecture*". The Department Of Aeronautical And Mechanical Engineering, The University Of Arizona.