III. SOLAR ARRAY DESIGN

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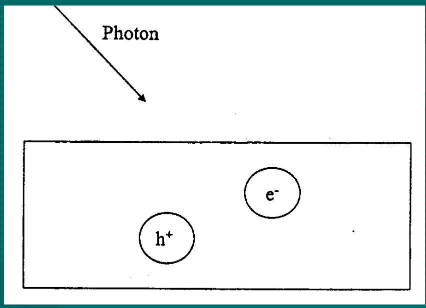
Solar Array Design

- Once the race begins, all of the energy the car uses comes from the sun.
- The power that the solar array produces is one of the most important factors in the performance of the car, and it is important to get as much power as possible.

Solar Cell Fundamentals

- When a material is placed in the sun, some of the photons from the sun will have more energy associated with them than the energy required to remove an outer valence electron out of its orbit in the material.
- The sunlight will create many electron-hole pairs. The density of electron-hole pairs is proportional to the intensity of the sunlight.



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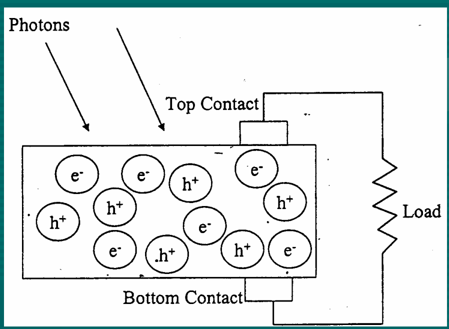
Solar Cell Fundamentals

- Any time there are free electrons and holes, there is the potential for generating electric power, if it can be organized and controlled. Putting two leads on the material and connecting them to a load will generate a small (insignificant) amount of power.



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Solar Cell Fundamentals

- When a surplus of e^- gets near the top contact and a surplus of h^+ gets near the bottom, then some electrons e^- will flow into the top lead, generating a current through the load, which is electric power
- The current through the load for this situation is very small and random in direction.

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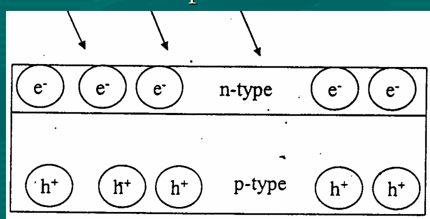
Solar Cell Fundamentals

- Many materials (most commonly silicon) can be doped with impurities to generate n-type and p-type versions of the material.
  - **n-type material –** attracts electrons e^- and repels holes h^+
  - **p-type material –** attracts holes h^+ and repels electrons e^-
- A solar cell is made by putting an n-type layer on top of a p-type layer as illustrated in the figure



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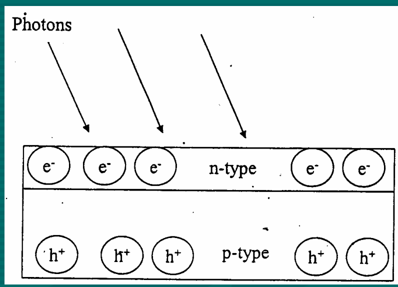
Solar Cell Fundamentals

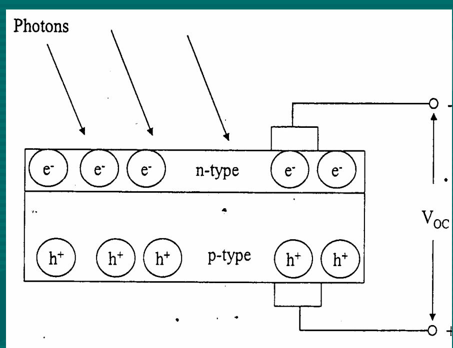
- When a photon liberates an electron e^- it will tend to migrate into the top n-type, while the holes h^+ will tend to migrate into the p-type.



- The junction forms a barrier, which tends to keep the electrons e^- and holes h^+ apart.
- The solar cell will reach some density of free electron-hole pairs.

Open Circuit Voltage

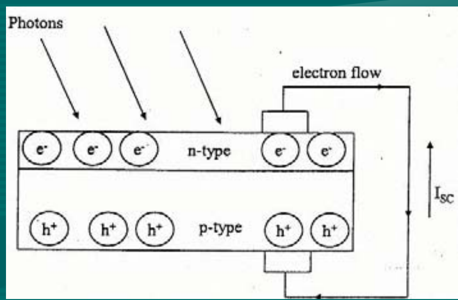
- Connecting a voltmeter to a lead on the top and on the bottom allows for the open circuit voltage of the cell, V_{oc} to be measured.



- V_{oc} depends on the material the cell is made of and the intensity of the sunlight.

Short Circuit Current

- The voltage across the cell drops to zero and the current flowing through the wire is the short circuit current.
- Short Circuit current I_{sc} depends on the material, the intensity of the sunlight, and on how the leads are designed.



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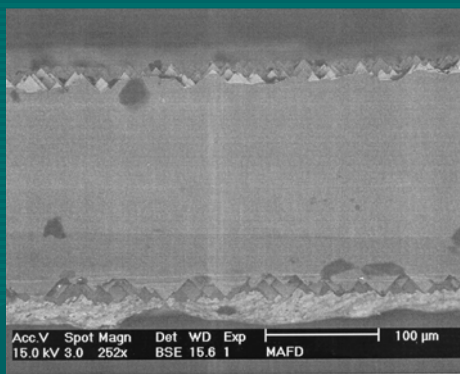
Short Circuit Current

- Most cells are made with the n-type on top.
  - The electrons e^- have more “mobility” than the holes h^+.
- The leads on the top of the solar cell block the sunlight, so it is desirable to use as small and as few leads as possible on top.



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Solar Cell Efficiency – Solar Spectrum

- One of four things can happen when a photon strikes a solar cell
  - The photon is reflected away and no electric power is generated.
  - The photon does not have enough energy to knock the electron out of orbit. Photon energy is converted to heat and no electric power is generated.
  - The photon has exactly the right amount of energy to knock the electron out of orbit. Essentially all of the photon energy is converted to electric power.
  - The photon has more than enough energy to knock the electron out of orbit. The energy required to knock the electron out of orbit will be converted to electric power, and the excess will be converted to heat.

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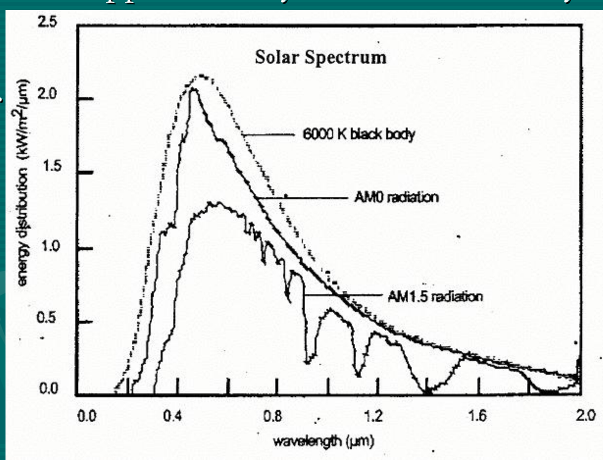
Solar Cell Efficiency – Solar Spectrum

- The AM0 radiation is approximately what is received by satellites above the atmosphere.



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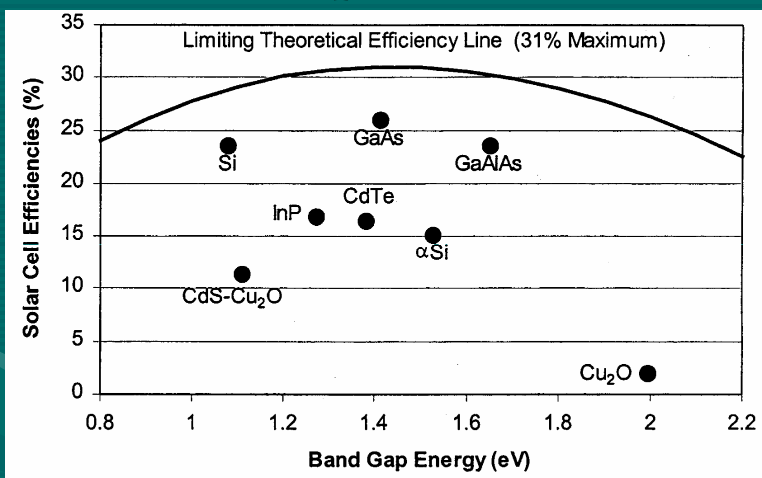
Solar Cell Efficiency – Solar Spectrum

- For any mater chosen, some photons will not have enough energy and will be wasted. Others will have more than enough energy, and their excess will be wasted. The material should be selected to match the solar spectrum.
  - A silicon cell can be theoretically 29% efficient in converting sunlight to electricity. The common grades of silicon cells are 12% to 15% efficient.
  - Gallium Arsenide (GaAs) has a higher theoretical efficiency than silicon.
- Examining the solar spectrum, it can be shown that the ideal material would have a theoretical efficiency of approximately 31%, and GaAs is very near the ideal.

Solar Cell Efficiency – Solar Spectrum



Solar Cell Efficiency – Solar Spectrum

- Multi-junction cells have been developed to further improve efficiency.
  - For two band gaps the maximum theoretical efficiency increases to 50%, for three it is 56% and for 36 it is 72%.
- Multi-junction cells are the best solution in bright sunny conditions because they produce the most power. They may not be the best solution in cloudy conditions; single crystalline or even polycrystalline silicon cells may produce more power in cloudy conditions.
- It may be that the clouds attenuate some wavelengths more than others, causing one junction of the cell to be starved for free electrons.

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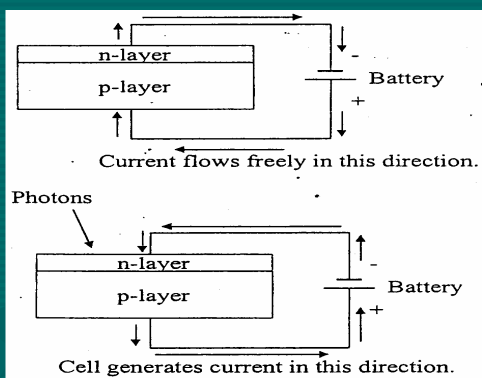
Solar Cell Model

- A solar cell is a special kind of diode. If no sunlight is striking the cell, then it will behave exactly like a diode, allowing current to flow freely in one direction, and preventing flow in the other direction.



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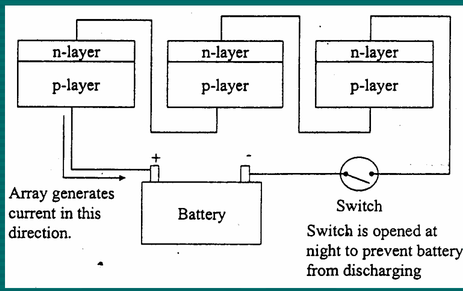
Solar Cell Model

- If a solar array is charging batteries, then a switch or some other means must be included for when there is no sunlight on the array, to prevent the batteries from discharging through the array.



- One shaded cell will stop current flow from the entire string, even if the other cells are receiving good sunlight.

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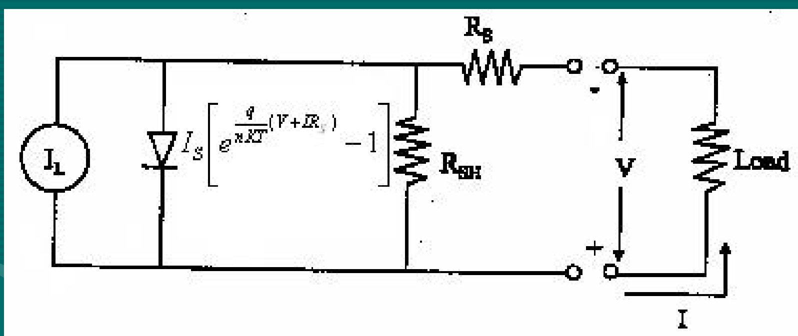
Solar Cell Model

- Electrical model of solar cell



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Solar Cell Model

where

I_L is current source which is analogous to the current potential the sunlight creates.

I_S is the diode saturation current, assuming the cell is completely shaded.

R_{SH} is the shunt resistance. Some electron-hole pairs will recombine across the junction. Ideally a solar cell would have infinite shunt resistance, i.e. $R_{SH} = \infty$ ideally, but for real cells that is not possible.

R_S is the series resistance of the cell. Cells have an internal resistance which absorbs some of the energy they create. Ideally $R_S = 0$, but for real cells that is not possible.

I is the output current of the cell.

V is the output voltage of the cell.

q is the charge of an electron(1.6×10^{19} Coulomb), K is Boltzman's constant (1.38×10^{-23} J/°K), and n is 1.5 for silicon cells.

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Solar Cell Model

$$I = I_L - I_S\left[e^{\frac{q}{nKT}(V+IR_S)} - 1\right] - \frac{V+IR_S}{R_{SH}}$$

- The above model can be fit
  - $V = V_{OC}$ when $I = 0$
  - $I = I_{SC}$ when $V = 0$
- There is a characteristic resistance R_{CH} for the cell defined as:

$$R_{CH} = \frac{V_{OC}}{I_{SC}}$$

- The resistances R_S and R_{SH} are related to the characteristic resistance. For a typical silicon solar cell, approximate relations are:
  - $R_{SH} = (1000)\ R_{CH}$
  - $R_S = (0.1)\ R_{CH}$
- Knowing the open circuit voltage V_{OC} and short circuit current I_{SC} a model can be developed for the cell using the above assumptions.

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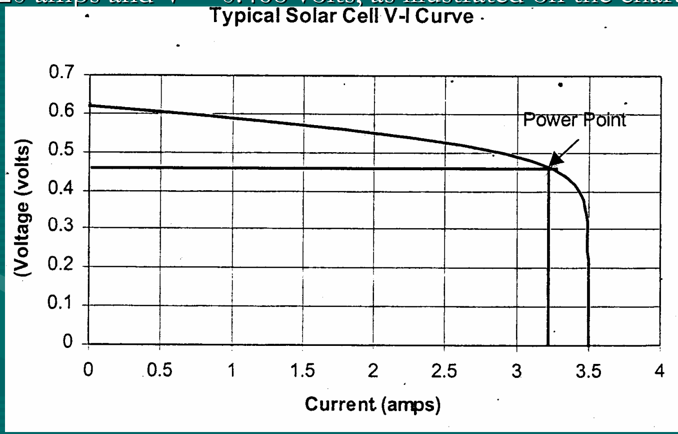
Solar Cell Model

- Assume I_{SC} = 3.5 amps and V_{OC} = 0.62 volts at 300K.
- The maximum power output for this cell is 1.5 watts when I = 3.20 amps and V = 0.468 volts, as illustrated on the chart.



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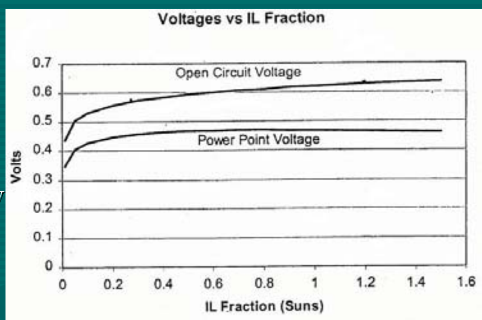
Illumination Level (I_L)

- Open circuit voltage varies only slightly with the illumination level over a broad range of illumination levels.
- The increase in power from the cell with increased illumination comes primarily from its increased ability to provide current.
- For one-sun illumination, I_L was set to 3.5035 and the following charts were developed.



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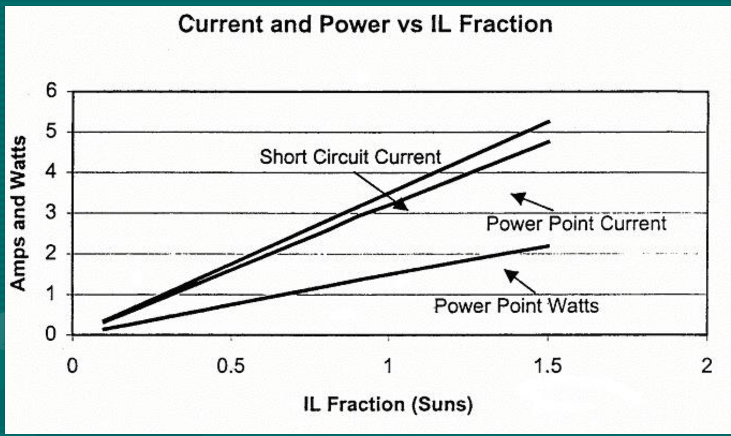
Illumination Level (I_L)

- Effect of illumination level on solar cell currents and power



Temperature

- The diode saturation current I_S for the solar cell is a function of temperature such that:
  - $I_{S\infty}$ is the saturation current for T = ∞ (a fictitious value).
  - E_g is the bandgap energy for the material. E_g = 1.12 eV for silicon.

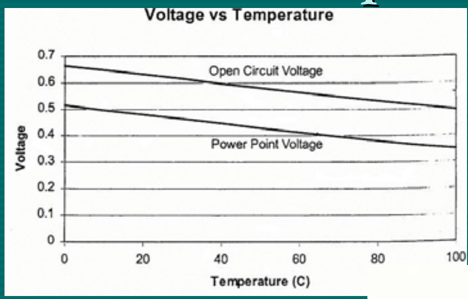
$$I_S = I_{S\infty} e^{-\frac{E_g}{nRT}}$$

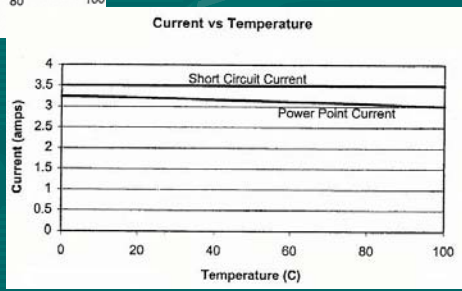
- For the model cell it was determined that $I_S = 3.9819\times10^{-7}$ amps when T = 300°K. It can be shown that:

$$I_S = (1{,}391{,}435)e^{-\frac{8664.7}{T}}$$

- Substituting this for I_S in the model, it is possible to draw curves of how voltage, current and power vary with temperature.
- Both open circuit voltage and power point voltage decrease linearly with temperature. The model shows short circuit current I_{SC} to be constant with temperature.

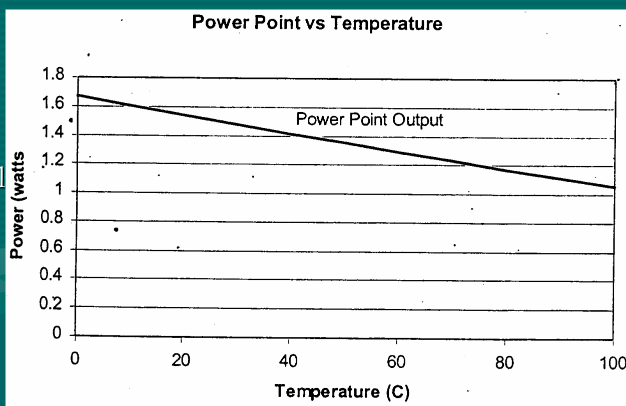
Temperature





Temperature

- Rule of thumb.
  - The array output decreases by 0.5% for each 1℃ rise in temperature for silicon cells.
  - This rule of thumb is a good estimate for terrestrial grade silicon cells.



Temperature

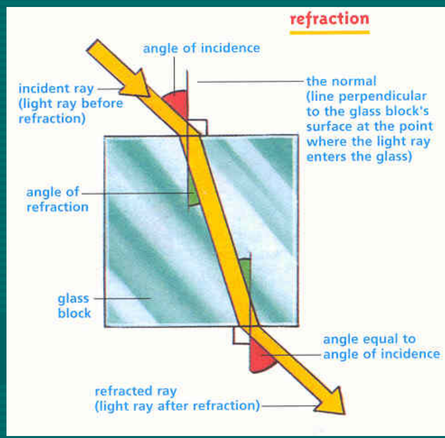
- Many teams cut holes in the body behind the solar cells to keep them cooler while driving.
- The cells can reach temperatures of 70-80℃ when to array in on the charging stand.
- Cooling the silicon cells increases power output by increasing the voltage output of the solar array.

Coatings

- The solar array must be coated to keep it from shorting out when it gets wet. A major disadvantage of a coating is that it insulates the cells and makes them hotter and less efficient.
- Stationary arrays such as those used on the roof of buildings commonly use a glass coating. Glass is too heavy for solar cars.
- Polymer coatings are used exclusively on solar cars, and it is important to be careful when cleaning the car so that the coating is not scratched. Tedlar, Tefzel, Lexan and Epoxy have all been used successfully.

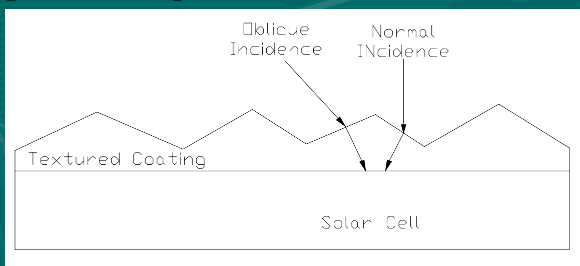
Coatings

- Anti-Reflection Coatings
  - Bare solar cells reflect a significant portion of the light that hits them, especially light coming from oblique angles.
  - Ideally the coating would have an index of refraction of 1.0, so finding suitable polymers with 1.0<n<1.5 will slightly increase array power as compared to bare cells.
  - Approximately 4% increase in array power is the maximum possible benefit of using a coating instead of bare cells.



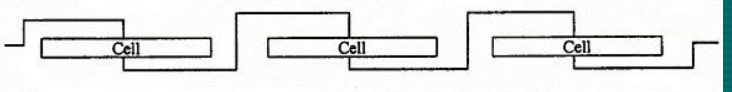
Coatings

- Texturing
  - Texturing the surface of the coating will have very little effect on normal incident light rays, but will assist in absorbing the oblique angle rays.
  - The disadvantage to texturing is that it makes it difficult to clean the array.



Wiring the Array

- The array voltage must be matched with the battery system voltage and the power point trackers.
  - Ideally the array voltage should be slightly higher than the battery system voltage.
  - This allows for the use of a step down transformer, which is more efficient than a step up transformer.



Series Wiring of the Cells

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Wiring the Array

- In a series wiring circuit, it is important that all cells in the string have approximately the same power point current .
- Example
  - Cell #1 has a power point of 1.497 watts at 0.468 V and 3.199 amps.
  - Cell #2 has a power point of 1.0546 watts at 0.470 V and 2.244 amps.
  - If both cells could operate at their power point, the two cells could generate 1.497 + 1.0546 = 2.5516 watts between them.

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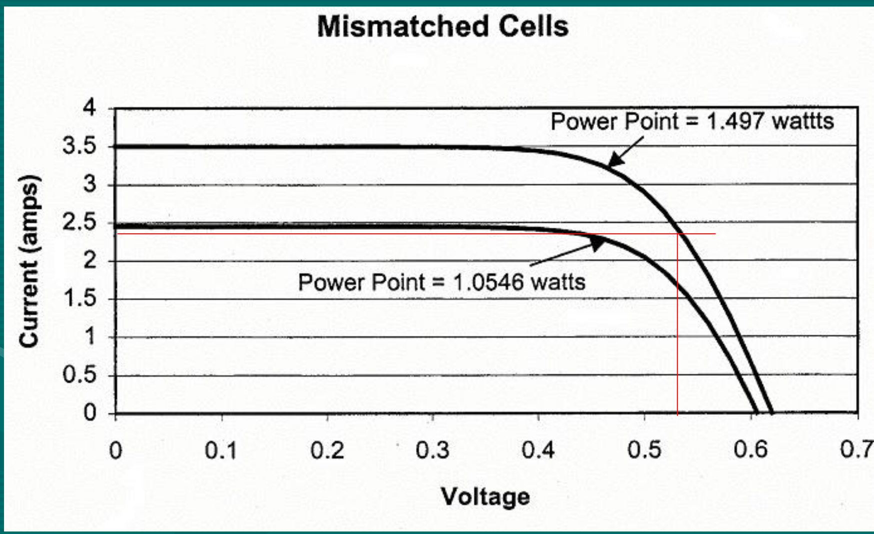
Example



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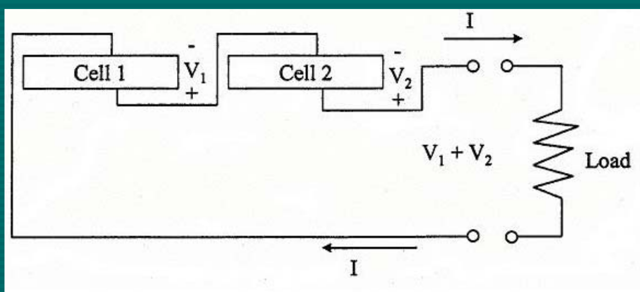
Example

– If these two cells are wired in series,



– To maximize the power, it is necessary to maximize the quantity $I(V_1 + V_2)$.

– The power point current for the two cells in series will be near the power point current for the weaker cell (cell #2).

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Example –
A spreadsheet can be developed (1/2)

Series Current	Cell #2 Voltage	Cell #1 Voltage	Cell #2 Power	Cell #2 Power	Total Power
2.21	0.4766	0.5241	1.053286	1.198041	2.251327
2.22	0.4747	0.5416	1.053834	1.202352	2.256186
2.23	0.4728	0.5412	1.054344	1.206876	2.261220
2.24	0.4708	0.5407	1.054592	1.211168	2.265760
2.25	0.4687	0.5402	1.054575	1.215450	2.270025
2.26	0.4665	0.5397	1.054290	1.219722	2.274012
2.27	0.4642	0.5392	1.053734	1.223984	2.277718
2.28	0.4618	0.5387	1.052904	1.228236	2.281140
2.29	0.4592	0.5382	1.051568	1.232478	2.284046
2.30	0.4545	0.5377	1.049950	1.236710	2.286660

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Example –
A spreadsheet can be developed (2/2)

Series Current	Cell #2 Voltage	Cell #1 Voltage	Cell #2 Power	Cell #2 Power	Total Power
2.31	0.4536	0.5372	1.047816	1.240932	2.288748
2.32	0.4505	0.5367	1.045160	1.245144	2.290304
2.33	0.4470	0.5362	1.041510	1.249346	2.290856
2.34	0.4436	0.5357	1.038024	1.253538	**2.291562**
2.35	0.4396	0.5352	1.033060	1.257720	2.290780
2.36	0.4352	0.5347	1.027072	1.261892	2.288964
2.37	0.4304	0.5341	1.020048	1.265817	2.285865
2.38	0.4248	0.5337	1.001024	1.270206	2.281230
2.39	0.4185	0.5331	1.000215	1.274109	2.274324
2.40	0.4110	0.5326	0.986400	1.278240	2.264640

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Wiring the Array

- The true power point for the two cells in series is only slightly greater than what would be calculated by assuming that the power point current for the two cells is the same as the power point current of the weakest cell.
- Two bounds can be set for the power point current for a string of cells.
  - The true power point current will be greater than the lowest power point current of any cell in the string.
  - The true power point current will be less than the short circuit current for any cell in the string.
- $I_{P\ weakest} < I_{P\ string} < I_{SC\ weakest}$

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Wiring the Array

- A good first approximation is to assume that

$$I_{P\ string} \approx \left[\frac{I_P + I_{SC}}{2}\right]_{for\ weakest\ cell}$$

- Example
  - Assume there are ten cells in a string. Nine are good ones like cell#1 and one is a weak one like cell#2. What is the estimated power of the string?

$$Assume \quad I_P = \frac{2.244 + 2.45}{2} = 2.347 \quad amps$$

$V_{1\text{-}9}$=0.5354 Volts V_{10}=0.4408 Volts

Power=9(2.347)(0.5345)+(2.347)(0.4408)=12.344 watts

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Wiring the Array

- An important thing to notice is that if the one weak cell were removed, then each of the nine good cells would produce 3.199 amps at 0.468 volts for a total of 13.474 watts, which is more than the ten cells produce. So the tenth cell is actually reducing the power of the string.
- Sometimes the cells are cut into smaller pieces, the power point current is linearly proportional to the size of the cell, so it would never be proper to put cells of different sizes in the same string.

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Shading of the Array

- If one cell in a string is shaded, then its illumination level current (I_L) will be drastically reduced.
- If the cell is completely shaded and receives no solar energy, then the cell will act as a diode blocking the current and the string of cells will pass essentially zero current.
  - The power output of the entire string will be zero.

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Cell Matching

- One approach to matching is to measure the I-V curve for every cell and group them so that they are as perfectly matched as possible.

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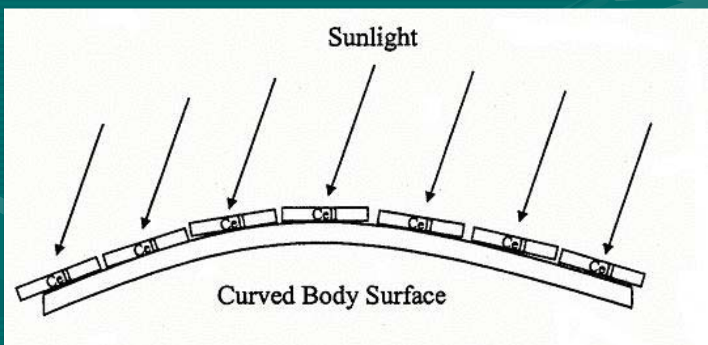
Angling of Cells in a String

- The body of the car will be curved to optimize aerodynamics, and the cells will be placed on a curved surface.



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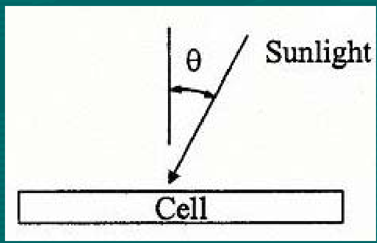
Angling of Cells in a String

- The I_L current varies approximately with $\cos\theta$ of the angle between the sun and the cell.
- If the angle between two perfectly matched cell is $\theta_2 - \theta_1$, then the power loss for misalignment of solar cells can be approximates as:

Misalignment Power Loss

$= (\cos\theta_1 - \cos\theta_2)\times 100\%$



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Misalignment Power Loss Table

θ_1	θ_2	Mismatch	θ_1	θ_2	Mismatch
0	2°	0.06%	10°	12°	0.67%
0	4°	0.24%	10°	14°	1.45%
0	6°	0.55%	10°	16°	2.35%
0	8°	0.97%	10°	18°	3.38%
0	10°	1.52%	10°	20°	4.51%
30°	32°	1.80%	50°	52°	2.71%
30°	34°	3.70%	50°	54°	5.50%
30°	36°	5.70%	50°	56°	8.36%
30°	38°	7.80%	50°	58°	11.29%
30°	40°	10.00%	50°	60°	14.28%

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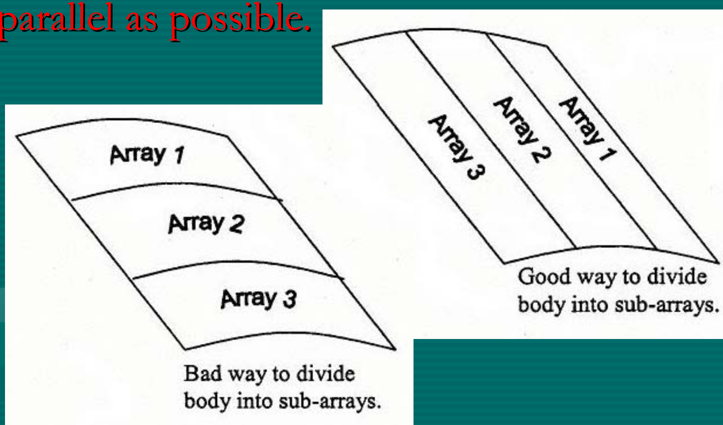
Misalignment Power Loss Table

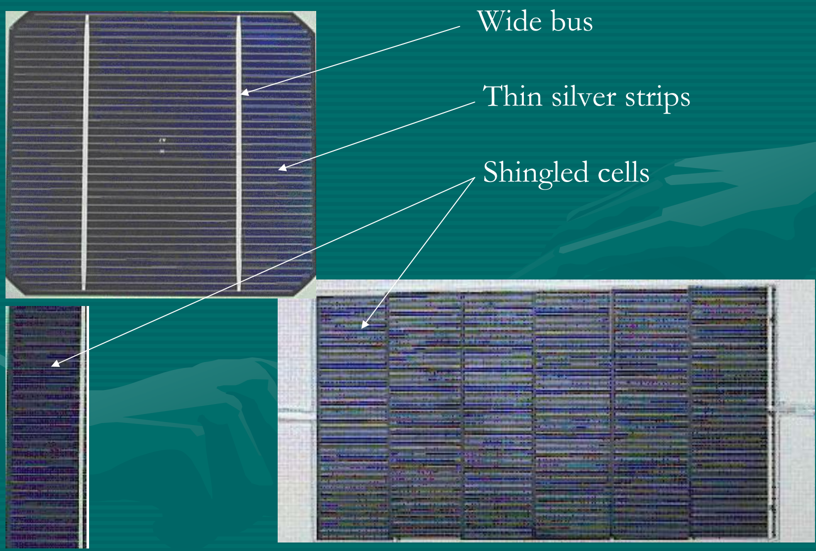
- Misalignment of cells in the solar array is less critical when the array is pointed at the sun, as it would be on the charging stand.
- When driving the car, the solar array will not be aligned with the sun, and misalignment of the cells in the sub-arrays becomes more critical.

Angling of Cells in a String

- Ideally all cells in the sub-array should be parallel, or as parallel as possible.



Shingling of Cells



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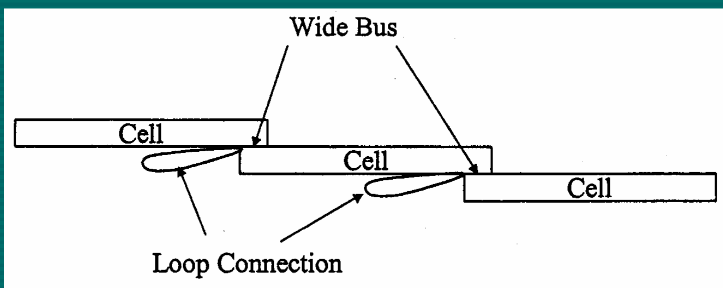
Shingling of Cells



- Cells are then overlapped as shown so that the wide buses are no longer blocking the sunlight.
- It is a lot of work and complexity for a small benefit, but shingling will increase array power by a few percent.

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