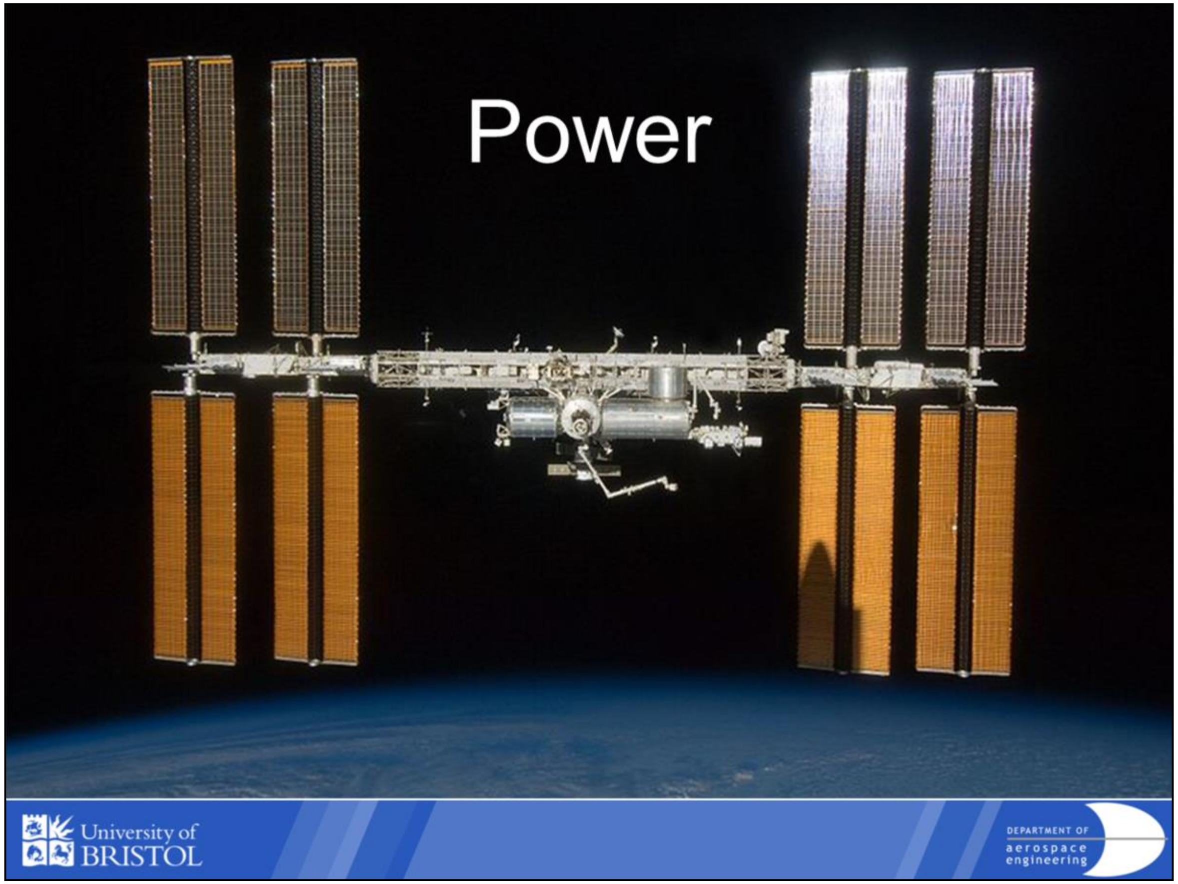
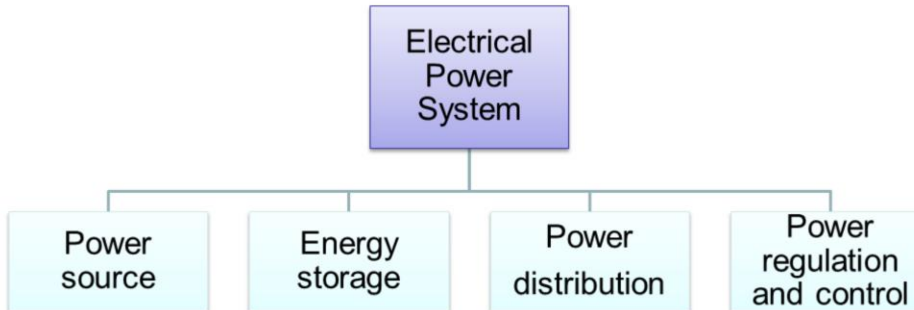


Note the shadow of the shuttle on the arrays
Notice that the arrays are tilting to follow the sun, how are they doing this?

Learning Objectives

1. Describe process for designing a space power system
2. Compare and contrast different power sources
3. Size solar arrays and battery systems
4. Vocabulary for energy storage

Electrical power systems



<u>Background reading</u>

1. *Spacecraft Systems Engineering*, 3rd Edition 2003, Fortescue and Stark. Pub. Wiley.
2. *Space Mission Analysis and Design (or SMAD)*, 3rd Edition, J.R. Wertz and W.J. Larson, 1999. Pub. Kluwer

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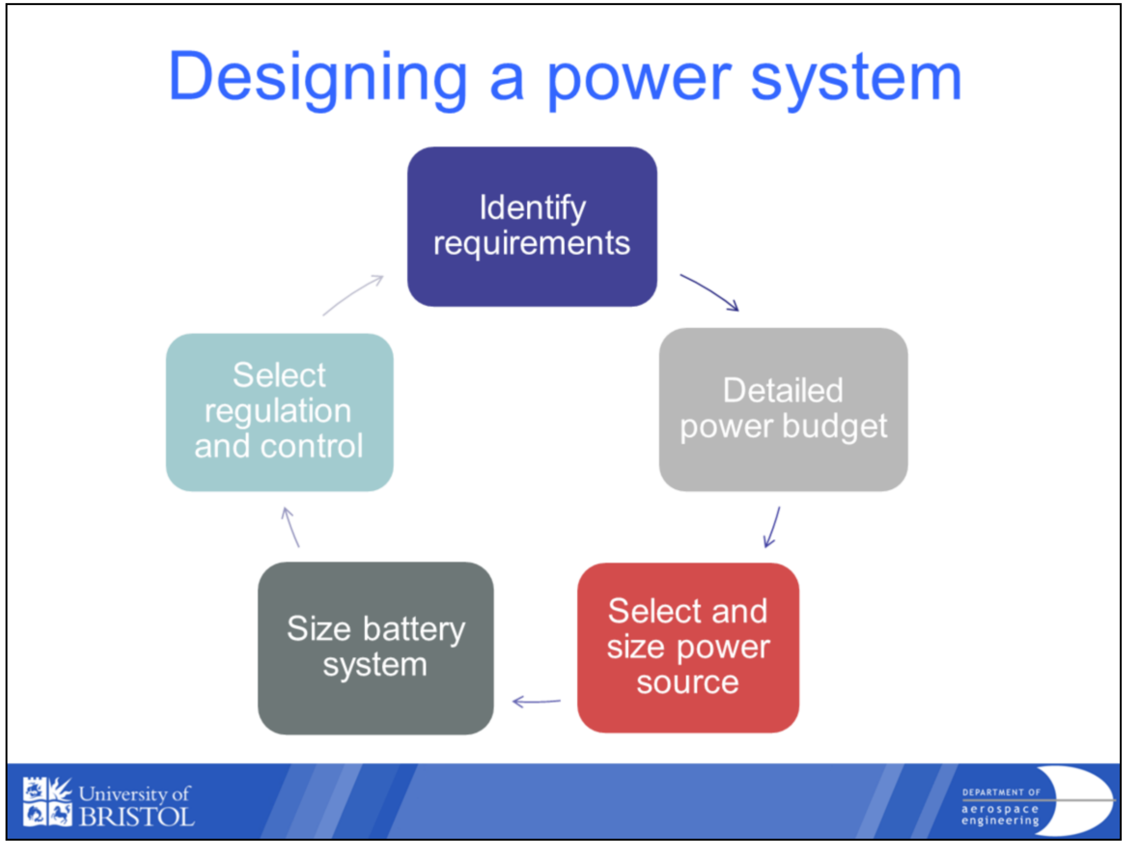
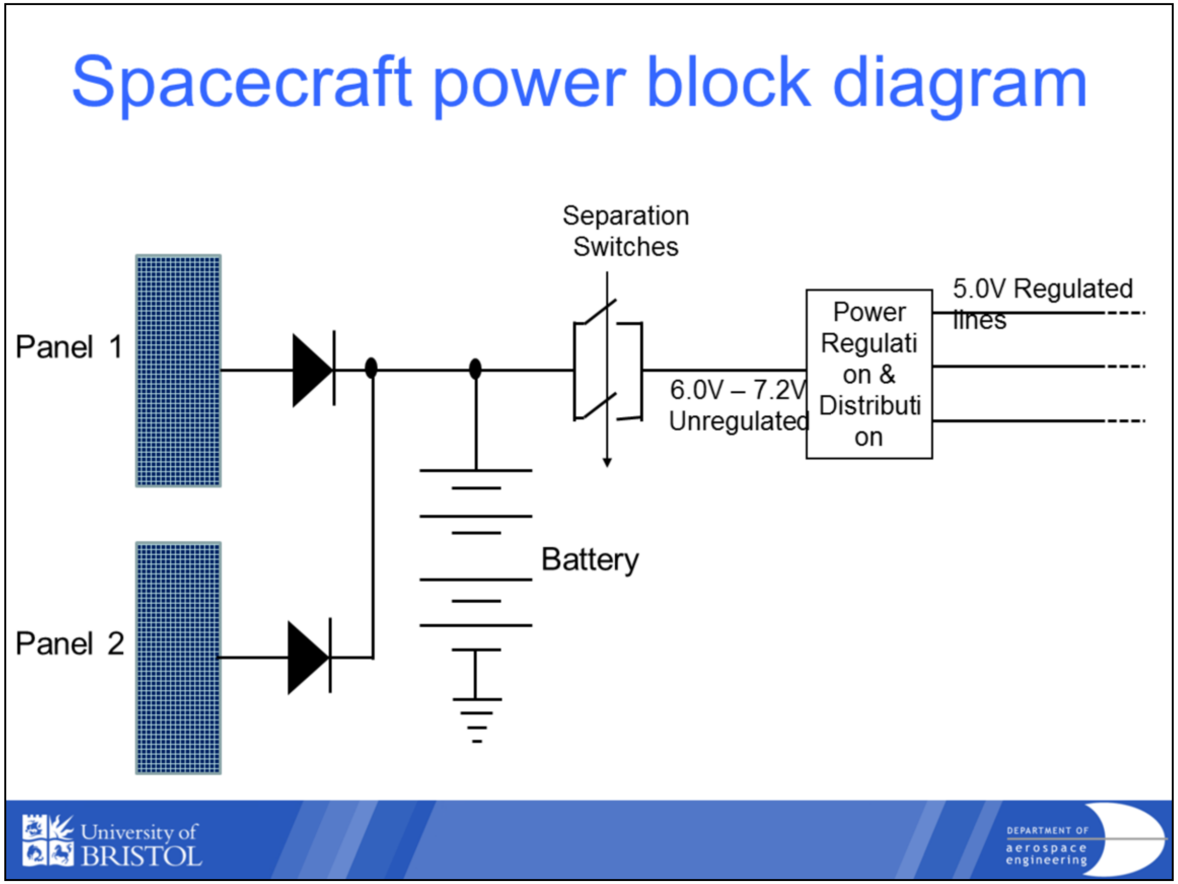


- Identify requirements
- mission profile, load profile, lifetime, environment, averagepower, etc.
- Determine power source such as the Sun, so often we will have solar arrays. Work out size of array
- Select battery type, calculate battery size
- Determine power regulation and control, select bus voltage and conversion



What is this symbol? A diode. It allows current through in one direction only.
Separation switches are a safety system used during launch to cut off the power system from the spacecraft.

Power budget for different modes (then add a margin!)

	Launch	LEO Ops	Cruise To Mars	Mars Insertion	Mars Observation	Comms
Payload instruments	0 W	0 W	0 W	0 W	105 W	40 W
Landers	0 W	0 W	0 W	0 W	20 W	0 W
Comms	15 W	15 W	85 W	85 W	10 W	115 W
Data Handling	30 W	30 W	30 W	30 W	50 W	50 W
AOCS	0 W	105 W	105 W	105 W	105 W	105 W
Propulsion	0 W	5 W	5 W	80 W	0 W	0 W
Power	10 W	15 W	20 W	25 W	20 W	25 W
Thermal	20 W	50 W	50 W	50 W	20 W	35 W
Total	75 W	220 W	295 W	375 W	330 W	370 W

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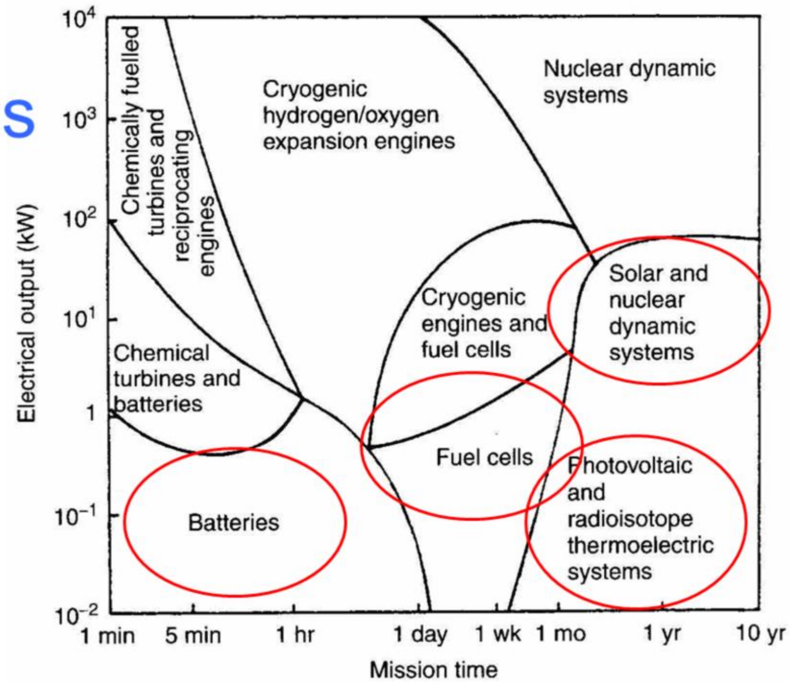
The first thing you do when you are trying to design your electrical and power system is ask all the subsystems designers for an estimate of their power needs so that you can size the system. This is then iterated.

Across the top are the different phases of an example Mars mission

We use the worst case (Mars insertion) 375W as the design case. This is the power needed.

Power sources



Power outputs: mission duration relationship between energy source and appropriate operational scenario [2] (From Angrist, S. W. (1982) *Direct Energy Conversion*, 4th edn, Copyright Allyn and Bacon, New York)

For short missions or covering eclipses batteries are excellent.
For week-long missions, such as shuttle, then fuel cells are particularly suitable.
For longer term Photovoltaics are suitable for LEO, interplanetary or geostationary satellites
For ISS in the longer term, higher demands will be made on the power, so then new technologies such as nuclear dynamic systems may be needed.

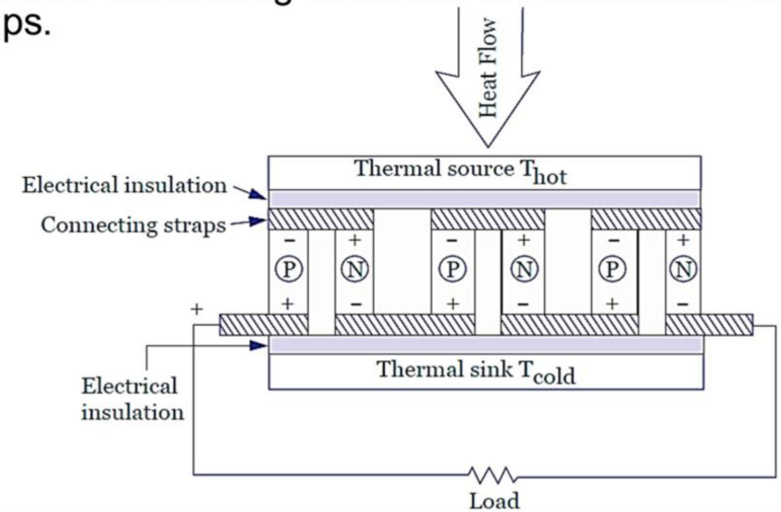
Comparing power sources

	Solar array	Solar dynamic	Radio-isotope	Nuclear reactor
Power (kW)	0.2-25	1-300	0.2-10	25-100
Specific power (W/kg)	26-100	9-15	8-10	15-22
Cost $/W	2500-3000	800-1200	16000-18000	400-700
Hardness to radiation	Medium	High	V high	V high
Manoeuvrability	Low	Medium	High	High

The different power sources have different qualities: total power, specific power, cost, radiation and how much they affect the manoeuvrability of the spacecraft.
100 W/kg will be triple junction cells (most efficient). In reality the dynamics of solar panels are a nightmare to calculate. You do not need to know the values in this table, but you do need to be able to compare and contrast the qualities of the sources, ie: solar array has very good sp. Power, medium cost, and low manoeuvrability, whereas…

Radioisotope thermoelectric generators

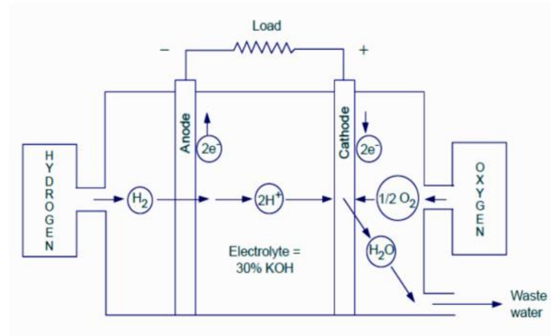
- The only technology suitable for the outer solar system
- "Seebeck" effect: current is produced when junctions of two dissimilar conducting materials are maintained at different temps.



RTGs work by converting the heat given off by a radioactive isotope into electricity. Radioisotopes release protons, neutrons, and energy in a process called decay. If one end of a thermocouple is placed next to a hot radioisotope and the other is connected to a heat sink in the cold, hostile void of space, a temperature difference is created, providing a continuous source of energy limited only by the isotope’s decay rate. What are the disadvantages of RTGs? RTGs are only 3-7% efficient. RTGs need to be kept away from IR instruments due to excess heat. You cannot switch them off, once on, they stay on, even if mission is delayed. The RTG must be robust to survive launch and launch failure, so is often encapsulated.

Fuel cells

- H_2 enters on anode side, O_2 on cathode
- H_2 splits into two H^+ ions and two electrons (e-).
- Electrons are conducted through anode then external circuit
- O_2 forms two negatively charged oxygen atoms.
- Charge attracts 2 H^+ ions through membrane ► H_2O.



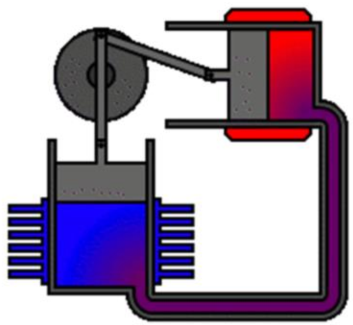
The pressurized hydrogen gas (H2) enters the fuel cell on the anode side. When an H2 molecule comes in contact with the platinum on the catalyst, it splits into two H+ ions and two electrons (e-). The electrons are conducted through the external circuit (doing useful work such as turning a motor).

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O2) which comes in forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H+ ions through the membrane, they combine with an oxygen atom and two of the electrons to form a water molecule (H2O).

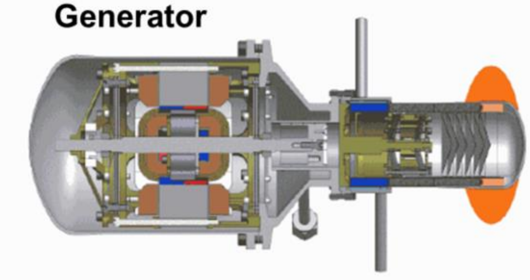
These are extensively used on the USA manned spacecraft including being used on the Space Shuttle. They use liquid hydrogen and oxygen and are 70% efficient.

Solar dynamic generators

- These use the Sun's heat to work a thermodynamic cycle.
- A collector focuses the sunlight onto a boiler to heat a working fluid, which is then used in a heat engine.



Infinia's Stirling Generator

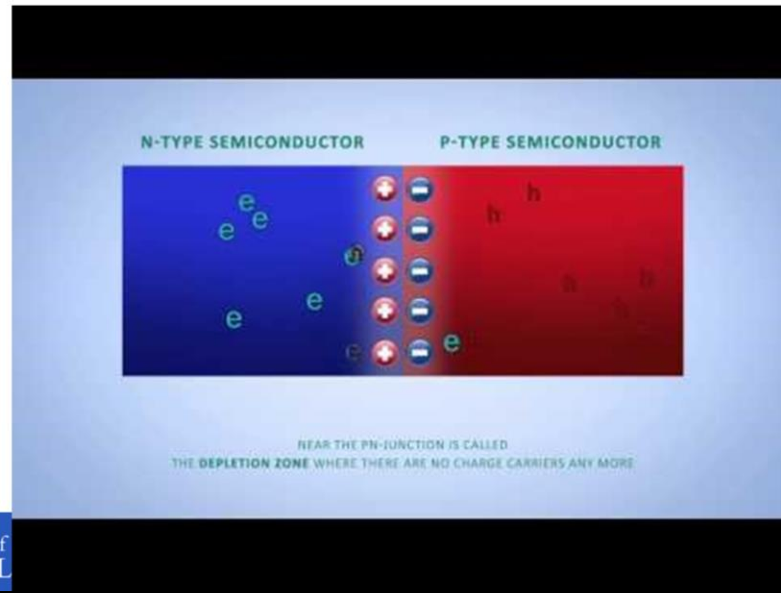


Three cycles have been explored on experimental systems: Rankine and Brayton Cycles (using turbines) and Stirling Cycle (using pistons). Dynamic generators are heavy and mechanically complex but suitable for higher power demands.
Helium is heated by radioisotope plutonium (or sun) then drives piston, then alternator converts motion into electricity.
Any mechanisms require lubrication, which is a huge issue in space.

Solar Cells

Long heritage, high reliability, high W/kg, low cost.

How pn junctions work:
https://www.youtube.com/watch?v=2AX0qvnjSnM



ARC – anti reflection coating

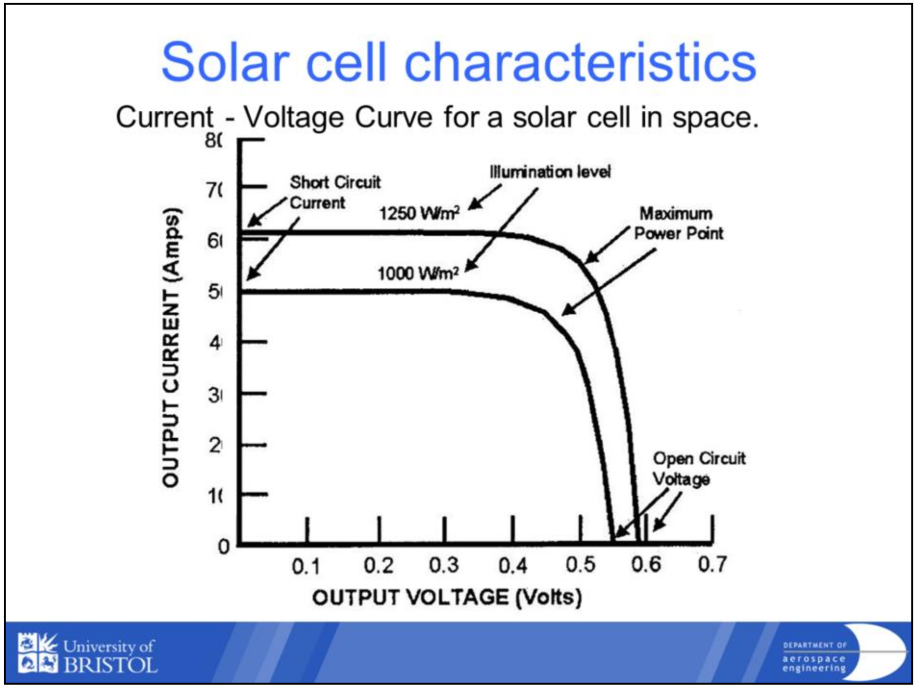
Disadvantages:

Need sun! No use beyond Mars. Need batteries for eclipses.

High temps and radiation reduce performance.

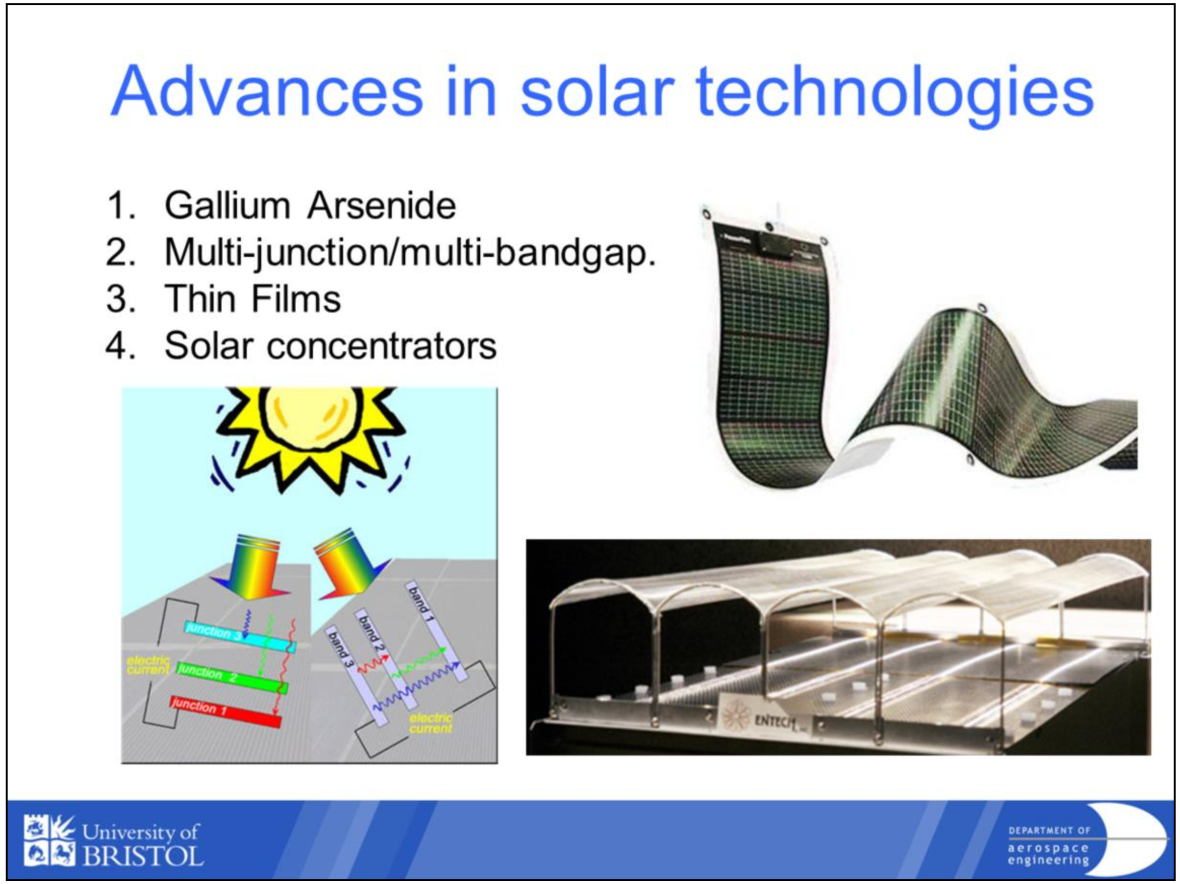
Silicon 14% efficient.

Need deployment mechanisms and cosine law for incidence means may need pointing mechanism.



The cell delivers maximum power *Pmax* when operating at a point on the characteristic where *IV* is maximum.The characteristics of the IV curve alter with the material used, the size (area) of the cell and the level of illumination.

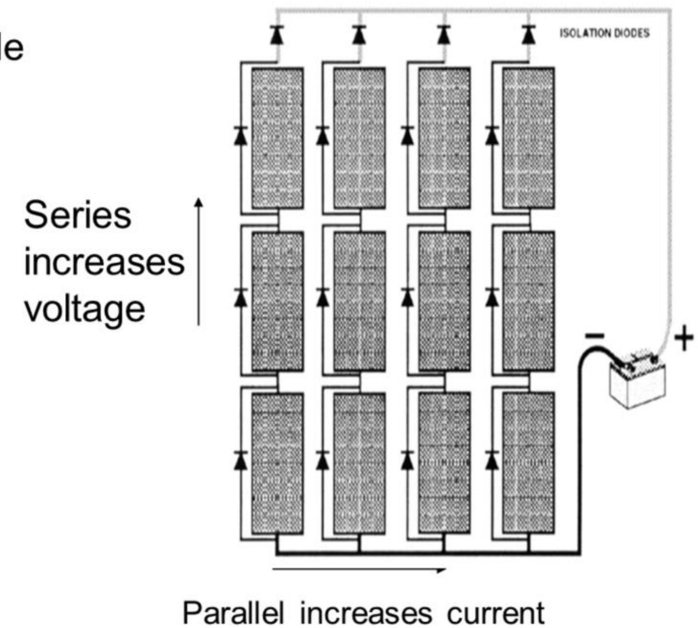
Heat makes voltage and power drop. Voc is when there is infinite resistance and circuit is open/broken. Short circuit is electrical opposite (little resistance). The cell generates no power in short-circuit (when current *Isc* is produced) or open-circuit (when cell generates voltage *Voc*). This is shown graphically where the position of the maximum power point represents the largest area of the rectangle shown.



Gallium Arsenide – more efficient, costly and 33% more radiation hard. Efficiency is max 28%
Multijunction - multiple band gaps allow response to a range of different frequencies of light. Efficiency is max 40%.
Thin Films – low mass, 7-10% efficiency
Solar concentrators – Fresnel lenses concentrate light 10x onto cells.

Solar array design

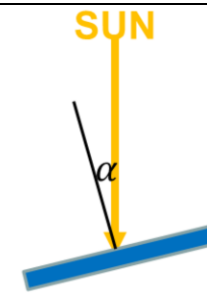
- Cells in series provide bus voltage.
- Number of parallel strings determines current
- Power = Vbus x Nparallel x Icell



Construct arrays with cells in series to provide the required voltage eg: 28 or 50V
Then stack up the parallel strings to provide required current (and hence power)
Must plan for minimum performance requirements at EOL during max temperature conditions

Cells that are not illuminated become open circuits. So isolation diodes prevent current from circulating uselessly through shaded cells and damaging them.

Calculating array area



Solar flux 'S' at array in W/m^2: S$= \frac{1370}{R^2} k_{atmos}$

$$Array\ area = \frac{Power}{S L_p \eta_{Cell} \eta_{packing} \left(1 - D\right)}$$

S = 1370 W/m^2 at earth
R = distance of s/c from Sun in AU (astronomical units)
k_{atmos}= atmospheric transmission factor
For a body-mounted spin stabilised spacecraft: L_p= 1/π
For flat arrays: L_p = cosα
α = angle of incident sun from normal
D = radiation degradation factor over spacecraft lifetime

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Radiation degradation factor is typically 0.9 and $\eta_{packing}$ can be 0.7 to 0.9 depending on the environment (this is a much more complex subject which we cannot treat here but see also space environment lecture).

Solar array sizing example

Q: A Mars lander requires 35 watts to operate on the surface. The requirement is for the lander to operate when the sun is 45 degrees or higher in the Martian sky, which at the landing site is for 20% of the Martian day.

a) Using photovoltaic cells with an efficiency of 12% that can be packed on to the array panel surface with an efficiency of 90%. If the Martian atmosphere stops 20% of the light from the sun reaching the surface what area of panel is needed to supply the power? [6 Marks]

S at Mars' surface (1.52 AU and only 80% of light gets through atmosphere) = $1370*0.8/(1.52)^2 = 474\ W/m^2$

If cell efficiency is 12% and packing is 90% (and no D) then…
Array area = Power / [474*cos(45deg)*0.12*0.9] = $35/36\ m^2$

Array area ≈ $1m^2$

Energy storage

- Batteries, flywheels, fuel cells, …
- Battery = individual cells in series
- Batteries can be connected in series to increase voltage or in parallel to increase current
- Bus voltage determines number of cells (as with solar cells)
- Energy stored described by ampere-hour or watt-hour capacity
- Sized to provide power during eclipse or during peak loading.

- http://www.youtube.com/watch?v=8hwLHdBTQ7s

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Storage units are built up the same way as solar cells, in series to increase voltage, in parallel to increase current

LEO: batteries are needed every orbit 16x a day, equivalent to 6000 discharge/recharge cycles per year. Max time: 36mins.

GEO: eclipse season is 45days, equivalent to 90 cycles per year. Max eclipse time 1.2hrs.

Energy storage terms

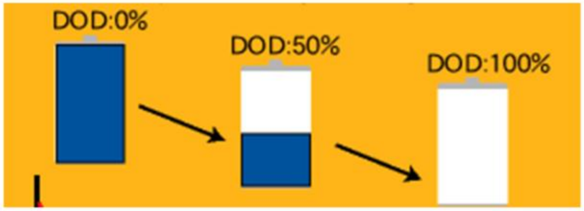
Specific Energy Density or SED - W hr/kg

Primary Batteries

- non-rechargeable batteries

Secondary Batteries

- rechargeable batteries



Depth-of-Discharge

- % of capacity used/available during discharge
- 100% would mean you were able to use full battery (ideal case)

Charge Rate

- rate at which battery can accept charge
- higher charge rate leads to shorter cycle life

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Primary Batteries – short missions with medium to high power load. Long-term, low-power tasks
Secondary Batteries – provide power during eclipse or peak loading
Depth-of-Discharge – higher DOD leads to shorter cycle life

Secondary battery types

Battery type	Cycle life	DoD %	Abusability	Memory effect?
NiCd	20000	10-20	High –can be fast charged/ discharged, left for long and still recover. Trickle charging poss.	Yes
NiMH	20000	40-60	Med – can charged/discharged fairly fast, can be left for long, but cannot be trickle charged.	Low
Lithium-Ion	3000	80	Low – Charge/discharge fairly fast, but must not overcharge or go below 3V when discharging, risk of explosion or fire.	No

These are 3 types of secondary (ie: rechargeable) batteries used in spacecraft. Which batteries do you think would be suited to LEO and which to GEO? (think about the number of cycles each would have to submit to). The memory effect influences the level of discharge for NiCadmium batteries: the battery remembers the last level it was discharged to and can only be discharged to this level so needs a full discharge regularly.

Calculating the capacity C_r of secondary batteries

$$C_r = \frac{P_e T_e}{DoD.N.n} Whr$$

Parameter	Example
Pe = avg. eclipse load (W)	500
Te = max. eclipse time (hr)	0.5
DoD= limit on battery's depth of discharge (20% is 0.2)	0.2
N = number of batteries (non-redundant)	3
n = transmission efficiency between battery and load	0.9
Cr = required battery capacity in Whrs per battery	463
Or Cr = required battery capacity in Ahrs (for a 26.4V bus)	*17.5*

Example

A Mars lander requires 35 watts to operate on the surface. The requirement is for the lander to operate when the sun is 45 degrees or higher in the Martian sky, which at the landing site is for 20% of the Martian day (a Martian day is 24.62hrs). When the sun is not above 45 degrees the lander goes into hibernation mode that requires 5 watts to sustain it. This is supplied by nickel cadmium cells with a SED of 39 Whr / kg used to 25% depth of discharge.

Q: What mass of batteries are required?

Answer:

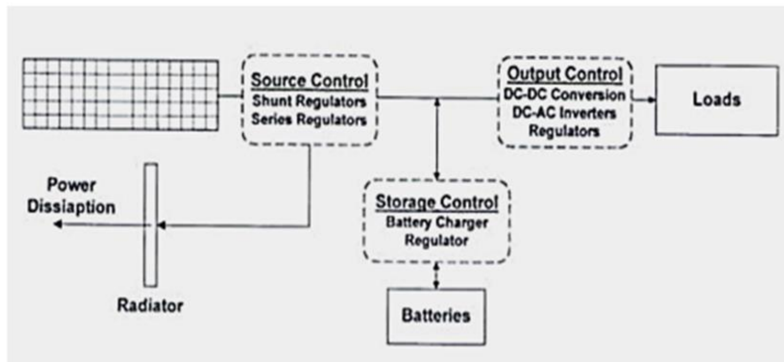
- Time for which batteries required = 24.62 hrs * 0.8 = 19.7 hr
- $C_r = \frac{P_e T_e}{DoD.N.n} = \frac{5*19.7}{0.25*1} = 394Whr$
- If cells have SED of 39 Whr/kg, then mass needed is ~10 kg

SED = specific energy density
Note that we have to assume a transmission efficiency here, as it is not specified, so we assume 1 for simplicity’s sake.

Power regulation and control

Power control electronics performs the following functions:

1. Source control (array management)
2. Storage control (battery management)
3. Output control (power distribution and regulation)



Source control: usually the array generates more power than required and the excess power needs to dumped in some manner
Storage control : conditions output from batteries, prevents undervoltage and overcurrent, charge regulator allows charging at different rates (trickle charge), discharge regulator controls depth of discharge.
Output control : can be unregulated, sun-regulated or fully regulated (where the output voltage from solar panel and battery is controlled fully by the power control electronics).

Summary

1. Space power is usually provided by solar cells, RTGs, solar dynamic generators, fuel cells or batteries.
2. RTGs use the Seebeck effect and are used far from Sun
3. Fuel cells require H2 and O2 to be supplied
4. Solar cells have a peak power point and degrade
5. Secondary batteries are used for eclipses.
6. To calculate solar array area we use:

$$Area_{array} = \frac{Power_{array}}{SL_p \eta_{cell} \eta_{packing} (1-D)}$$

7. To calculate battery size we use:

$$C_r = \frac{P_e T_e}{DoD.N.n} Whr$$

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Test Yourself! (Feedback)

1. How many cells and strings are needed for a bus voltage of 28V and power of 112W if each cell is 0.5V and 0.05A? (Assume no losses)
2. Explain how a fuel cell works.
3. What is the Seebeck effect?
4. What are the disadvantages of RTGs? And solar dynamic generators?
5. How can we improve the specific efficiency of photovoltaics?
6. Is 80% DoD better or worse than 50% DoD?