SESA2024
Astronautics

Chapter 8:
Electrical Power Subsystem

Contents

Electrical Power Subsystem

Function of Power Subsystem

- Reliable, continuous operation of the spacecraft power subsystem is essential to the successful execution of the spacecraft mission.
  - a failure or brief interruption of the power subsystem can have catastrophic consequences for the electrical payload systems, and also for the spacecraft attitude control and thermal control.

What sources of power are available for satellite missions?

Solar arrays, Batteries, Fuel Cells, Solar dynamic devices, Radioisotope thermal generators (RTG's), Nuclear reactors

Primary power system:

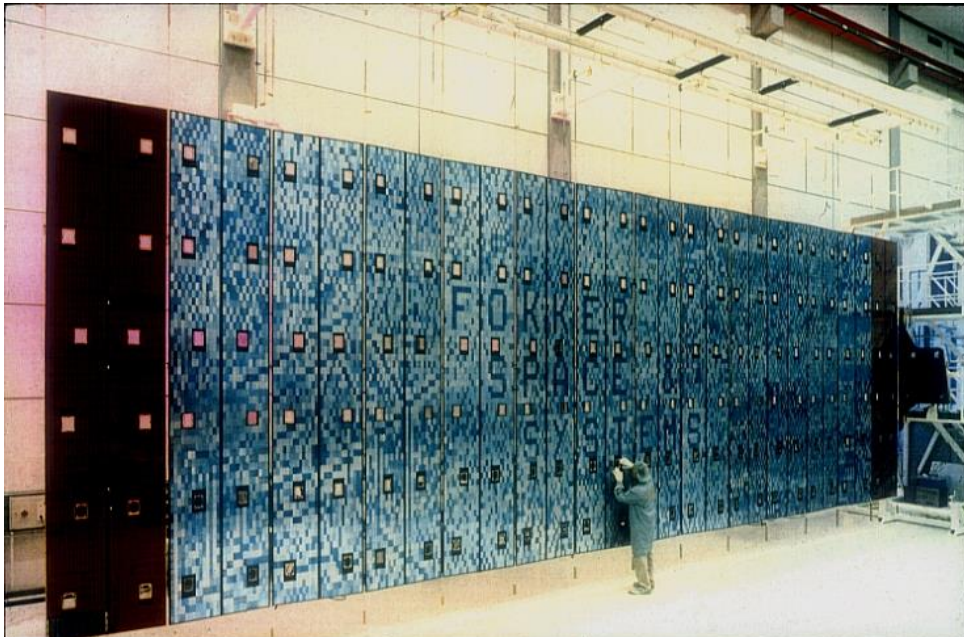
The main source of electrical energy (i.e. for an earth orbiting satellite this is often the conversion of sunlight into electrical energy using a solar panel).

Secondary power system:

An electrical storage device, which implies the use of a battery, although other possibilities exist.

Primary Power Sources

Solar Arrays



Convert the solar radiation (~1370W/m^2) into electrical power.

Efficiencies are generally low, resulting in ~100W/m^2 of useful electrical power.

Primary Power Sources

Batteries

Primary (unrechargeable) batteries are used for short duration missions, for example to power launch vehicles during the few minutes climb into orbit.

Fuel Cells

Essentially chemical engines that produce electrical power with water as a by product. They are therefore particularly suitable for manned missions but the duration of their operation is limited (by the requirement to fuel the reaction with oxygen and hydrogen).

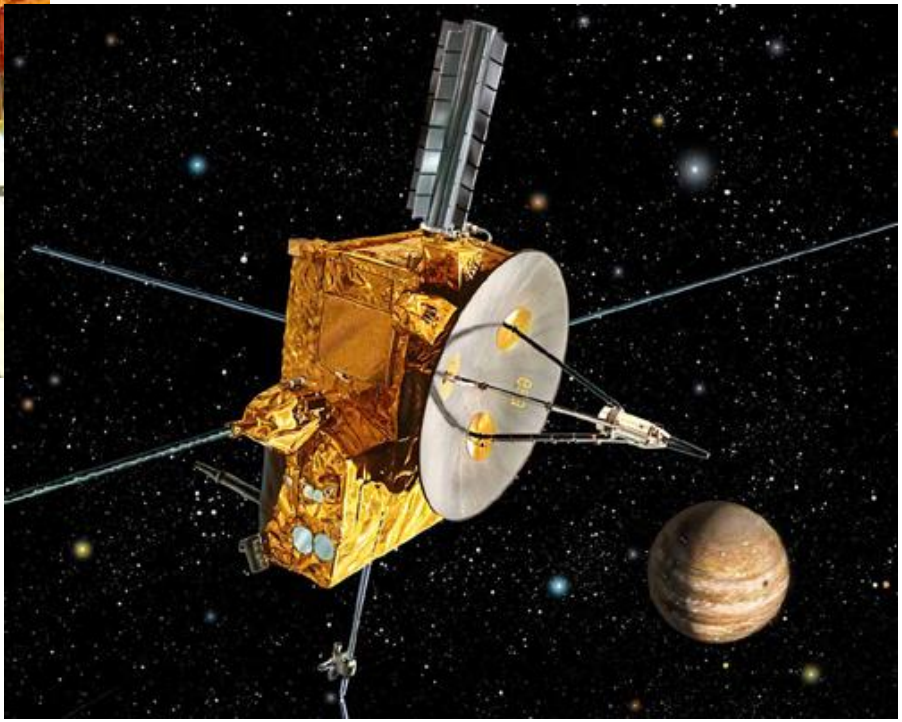
Solar Dynamic Devices

A solar concentrator, such as a parabolic mirror is used to focus the suns energy to heat a working fluid, i.e. water. The high pressure steam produced can then be used to drive a turbine generator
– More efficient than solar arrays but are generally much heavier.

Primary Power Sources

Radioisotope Thermal Generators (RTG)

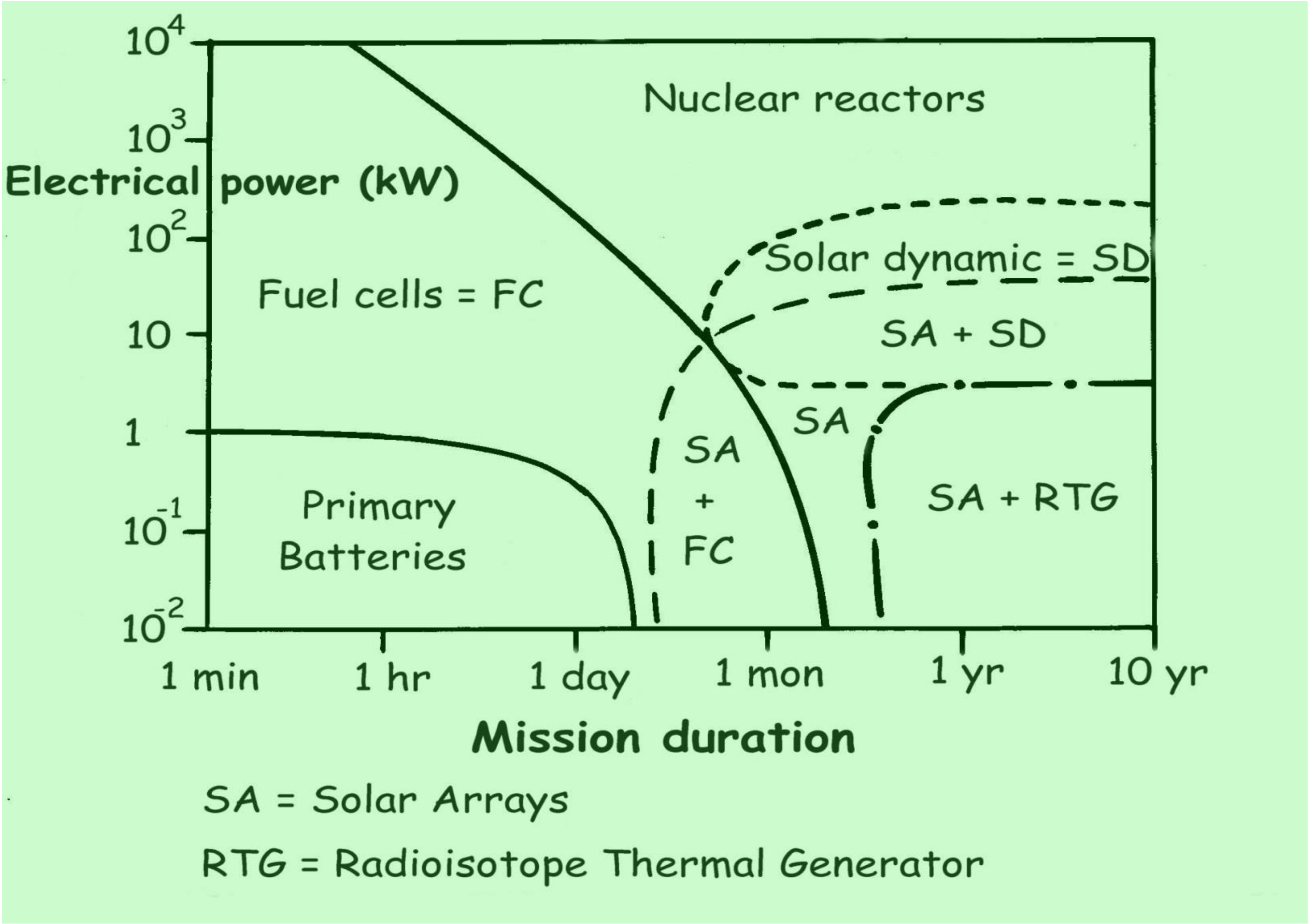
Ulysses, Voyager 1 and 2, Galileo (Jupiter orbiter), Cassini



Each RTG is cylindrical in shape
~ 1m long, 30cm diameter
~ 40kg, ~200W

Primary Power Sources

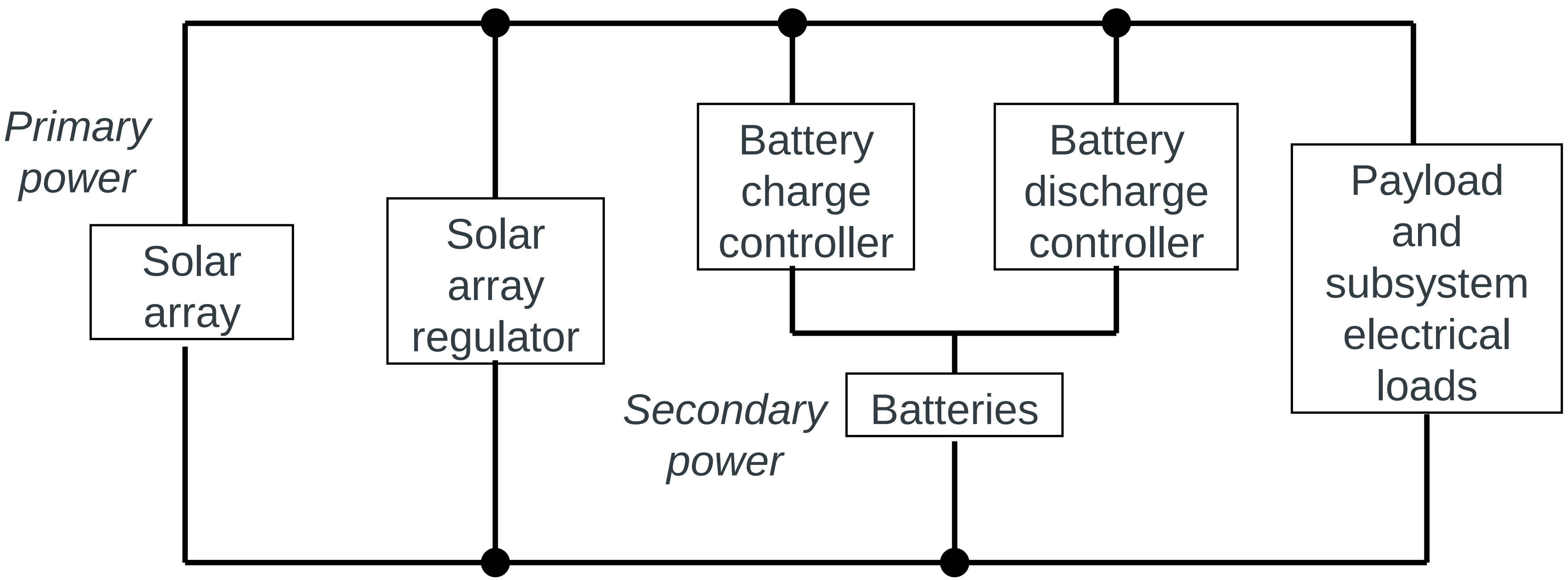
Mission usage



Power Systems Overview

The power bus - Fully regulated system

– 'Typical' system is based upon a solar array (power source) and battery (power storage) combination



Solar Arrays

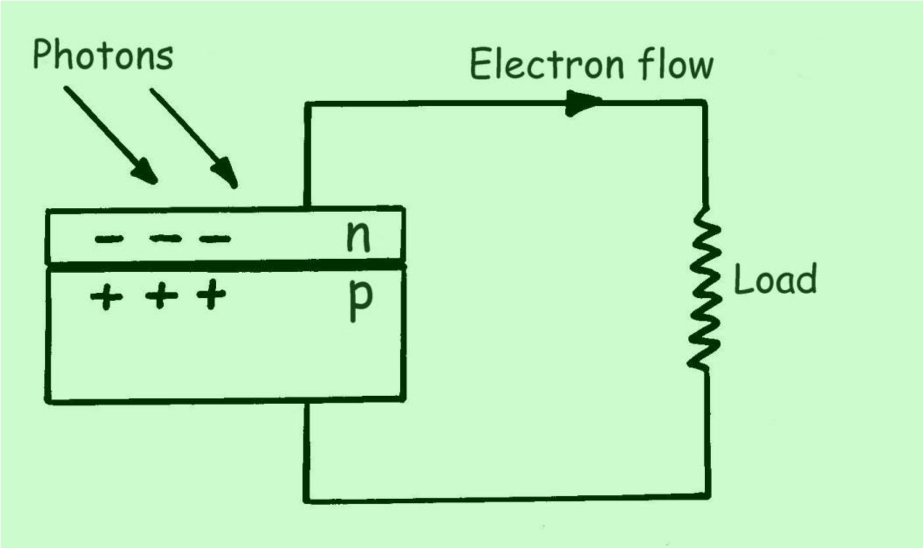
Photovoltaic effect

The electrical properties of materials depends on the ‘band gap’ between the (captured) valence electron energy and the (free) conduction electron energy:

- **Conductor:** Conduction band partially filled
- **Insulator:** Band gap is large (no free electrons)
- **Semi-conductor:** Band gap ~ 1 or 2 eV (electron-volts)
    - For example – Silicon has a band gap (valence energy to conduction band energy) of ~ 1.1 eV ($\lambda_{\mathbf{max}}$ ~ 1.1 μm)

Solar Arrays

The solar cell



– n = “n-type” semiconductor

  e.g. Silicon (4 valence electrons) doped with Phosphorous (5 valence electrons)

– p = “p-type” semiconductor

  e.g. Silicon doped with Boron (3 valence electrons)

Solar Arrays

Solar Cell Characteristics

- **Solar cell efficiency**

$$\eta = P_{out} / P_{in} \quad (8.1)$$

where P_{out} = electrical power output, and

P_{in} = solar power input (~ 1370 W/m^2 in Earth orbit)

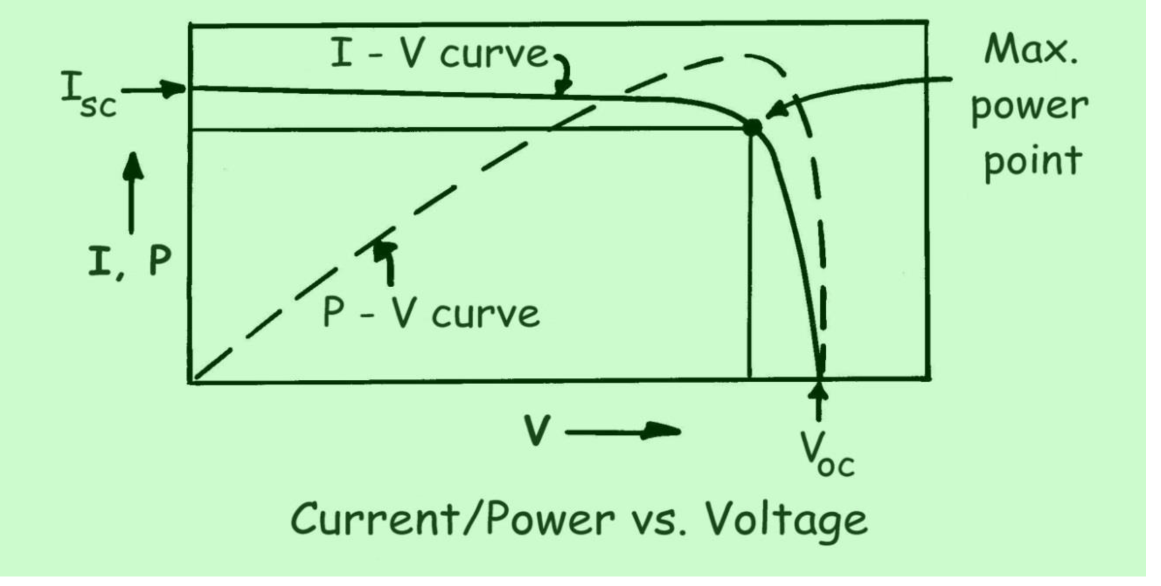
Typically η ~ 0.10 to 0.30

– depending upon semi-conductor material used, temperature of cell, Sun incidence angle, radiation degradation, etc.

Solar Arrays

Solar Cell Characteristics

- **Electrical output**



- For typical silicon cell (30° C with solar flux ~ 1400 W/m²)
  - Open circuit voltage V_{oc} ~ 0.55 V
  - Short circuit current I_{sc} ~ 35 mA/cm²
  - Max. power P_{max} ~ 14 mW/cm²

Solar Arrays

Solar Cell Characteristics

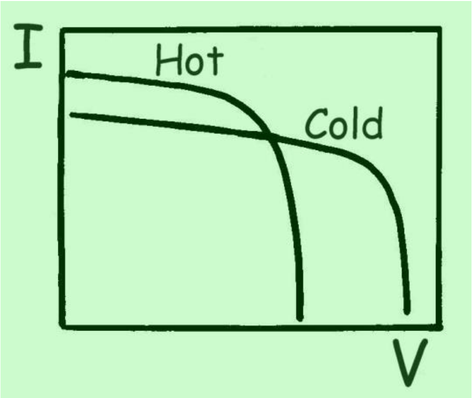
- **Temperature effect**

  High temperature – reduces P

  Low temperature – increases P

  – eclipse exit can cause power surge

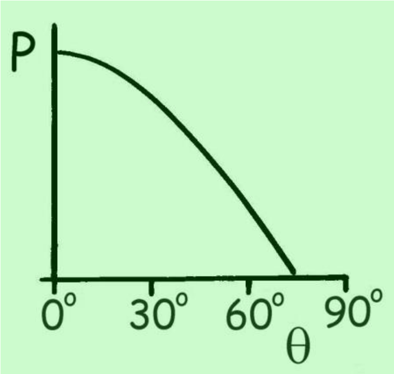
  – power loss per ^{o}C (silicon) ~ - 0.004



- **Sun angle effect**

  P decreases as sun-line moves away from surface normal

  – approximates to a cosine law

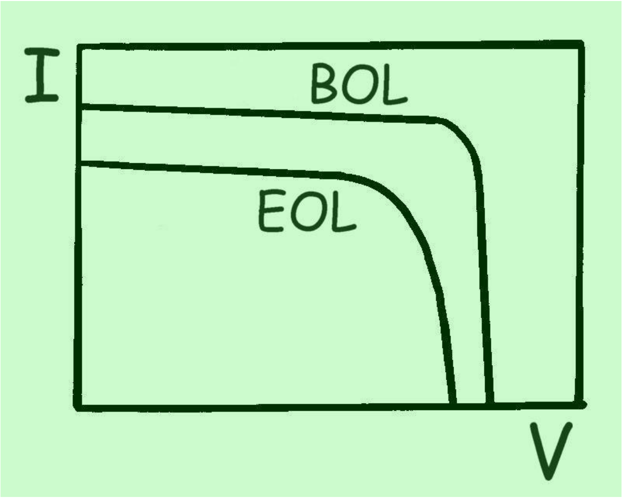


Solar Arrays

Solar Cell Characteristics

- **Radiation effect**

  BOL: Beginning of life
  EOL: End of life



Radiation exposure:

- reduces available power
- reduces V_{oc} and I_{sc}
- depends on thickness of cell and cover glass
- n-type semiconductor upper-most increases resistance to radiation damage
- EOL power may be predicted from radiation environment

Solar Arrays

Solar Cell Characteristics

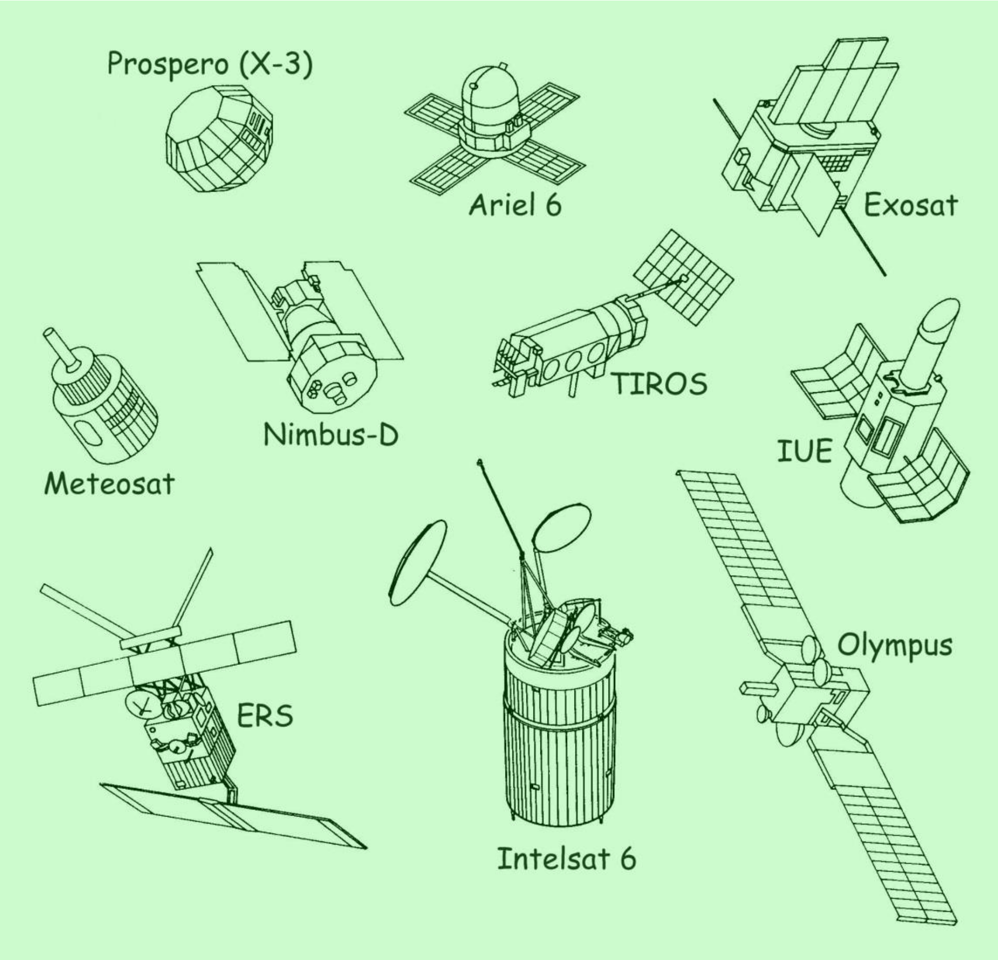
- **Solar cell material comparisons**

Cell material	Si silicon	GaAs gallium arsenide	InP indium phosphide
Efficiency η - theoretical - production	0.18 0.14	0.23 0.19	0.22 0.13
Power loss % per °C	-0.44	-0.16	-0.21
Radiation degradation* % of BOL efficiency	67	78	94
Relative density	1	2.3	2.1
Relative cost	1	~15	~35

*** Assuming an electron fluence of 10^{15} 1 Mev electrons/cm^2 – equivalent to approximately 7 years in GEO.**

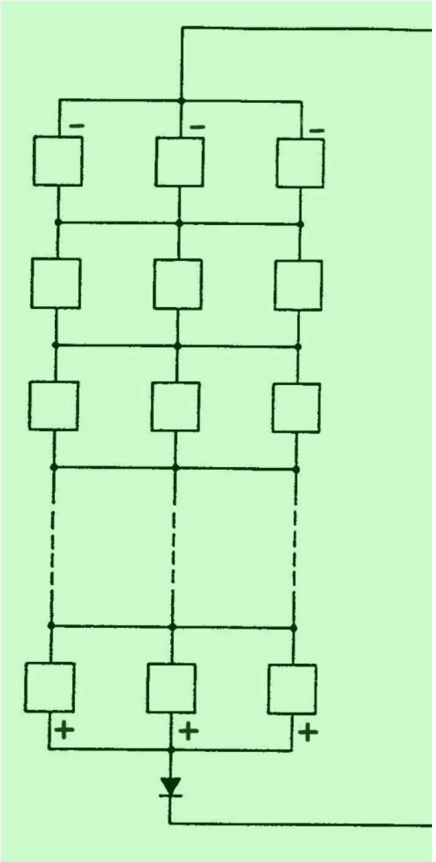
Array Configurations and Construction

Array Configurations



Array Configurations and Construction

A series – parallel solar cell circuit



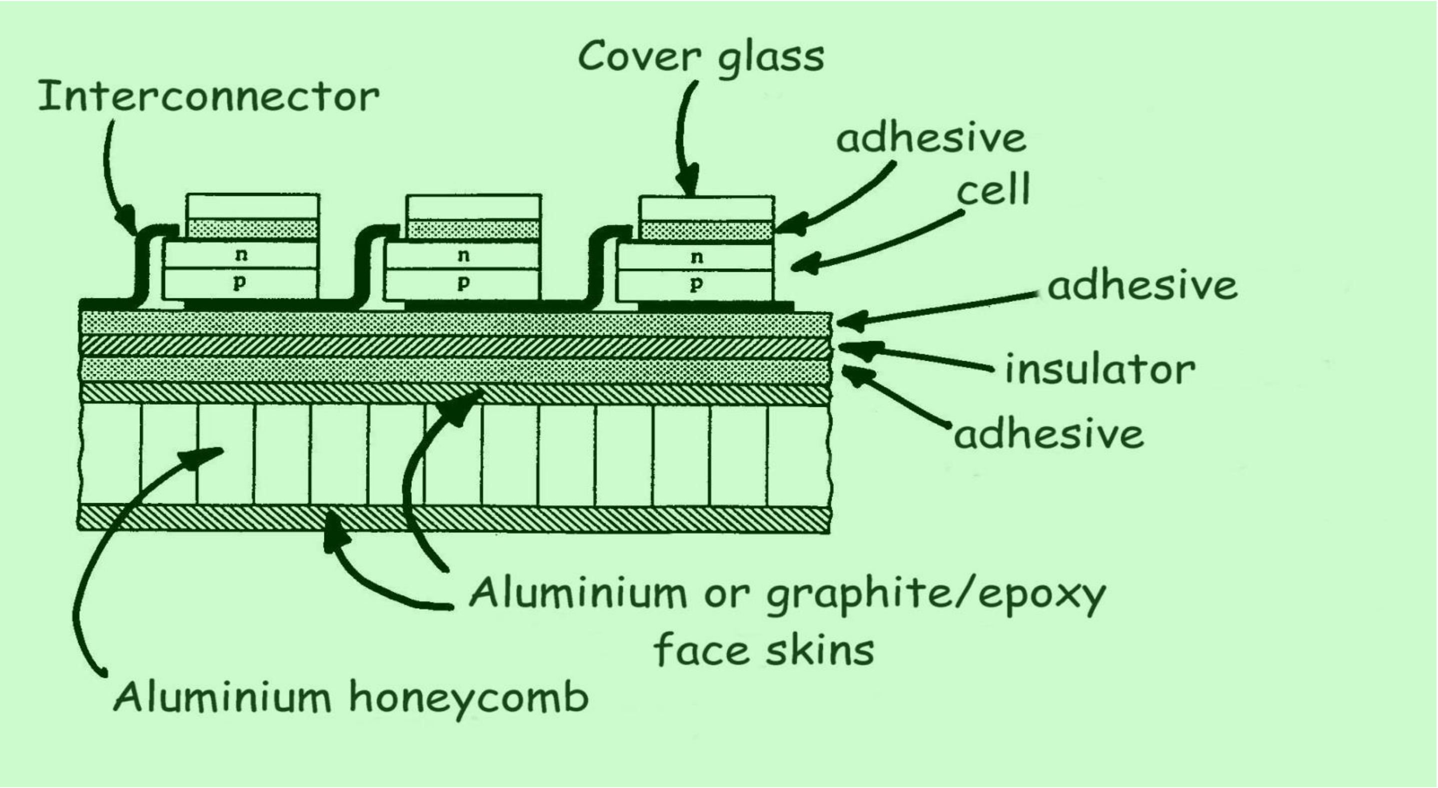
Individual cells are arranged:

– in series ➡ desired V

– in parallel ➡ desired I

Array Configurations and Construction

Typical Solar Array Construction



Power Storage - Batteries

- Terminology

  Arrays: primary power system

  Batteries: secondary power system

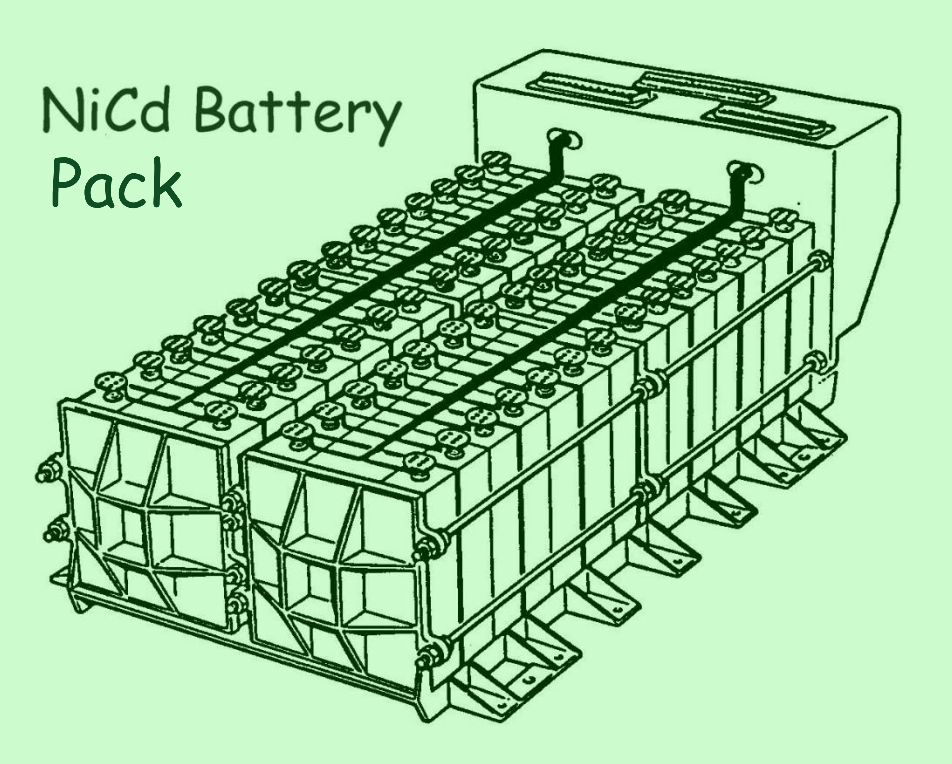
  Primary battery cells: not rechargable

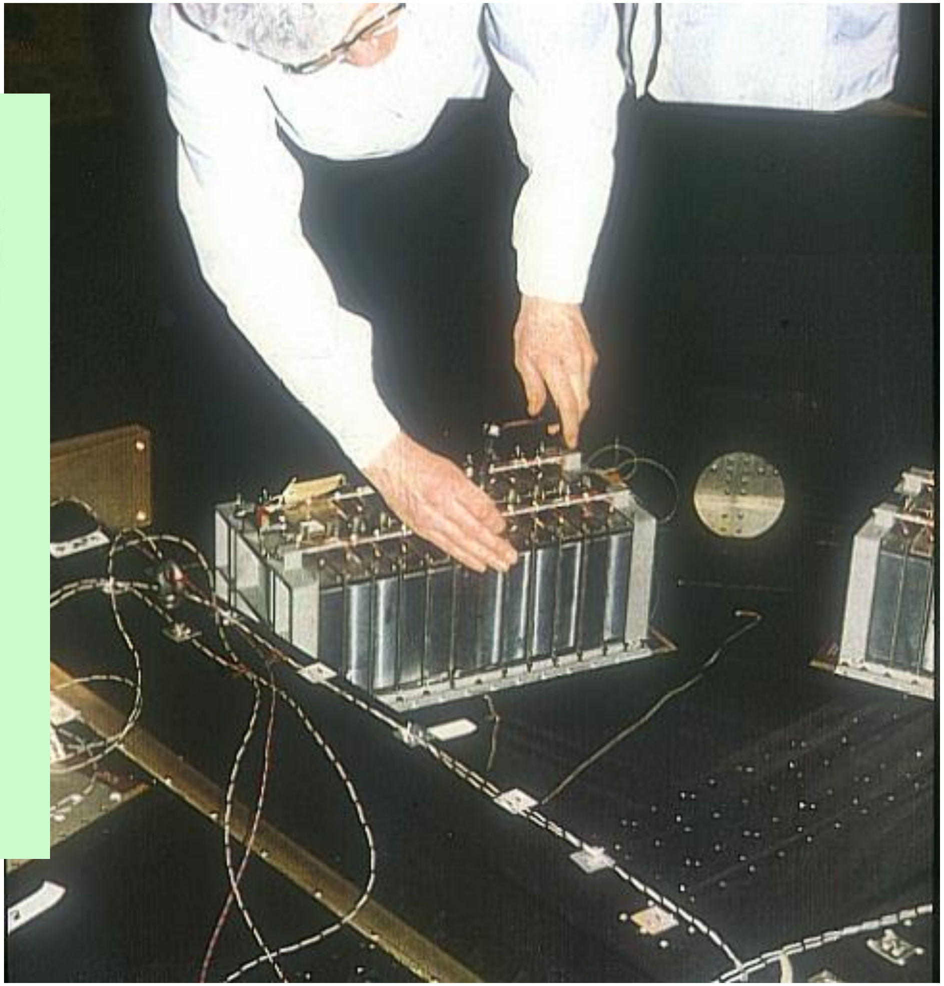
  Secondary battery cells: rechargeable

- (almost) universal application of batteries is for secondary power systems
- The rechargeable systems are predominantly either:
  - Nickel Cadmium (NiCd) – now obsolete (used in older spacecraft)
  - Nickel Hydrogen (NiH_2) – being phased out (still used in some comsats)
  - Lithium Ion (Li-ion) – todays choice
  - Lithium-polymer – going through ESA approval

Power Storage - Batteries

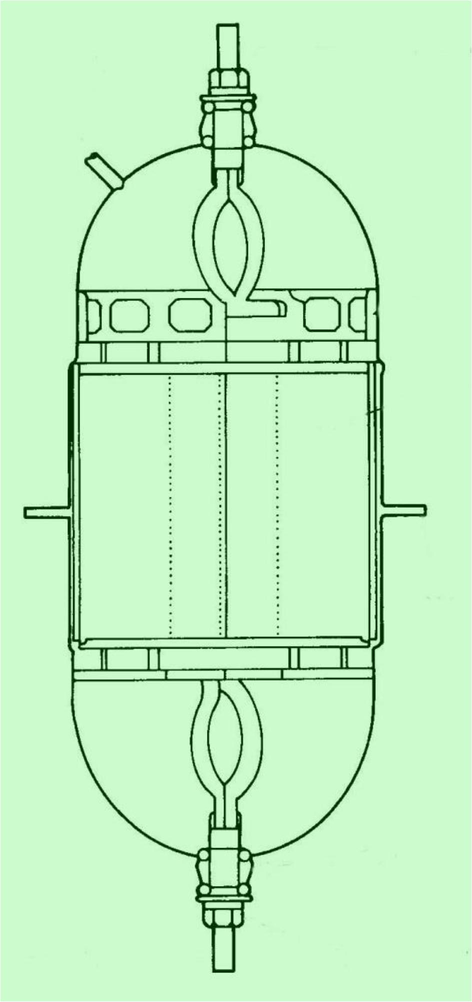
Nickel Cadmium Batteries





Power Storage - Batteries

Nickel Hydrogen Batteries



NiH_2 cell

NiH_2 battery pack

Power Storage - Batteries

Lithium Ion (Li-ion) Batteries

Currently used widely in terrestrial applications: i.e. for mobile phones, laptops etc.

Was initially used for small satellite missions due to their low cost and high performance.

The current choice for satellite manufacturers – was first used on a commercial satellite in 2004 (Eutelsat W3A communications satellite).

Power Storage - Batteries

Key Battery Characteristics

- Total battery capacity (C) – *Unit:* Ampere-hour (e.g. 40 A for 1 h = 40 A-h)
- Number of battery charge/discharge cycles
- Depth of Discharge *DoD* – Percentage of battery capacity used in discharge

  (e.g. *DoD* = 40% mean 60% capacity remaining)
- Total stored energy of battery $\varepsilon = C$ times average discharge voltage

  Unit: Watt-hour
- Energy density $\bar{\mathcal{E}}$ Stored energy per unit mass – *Unit:* W-h/kg

Power Storage - Batteries

– Charge rate R, Rate at which battery can accept charge – *Unit:* Ampere

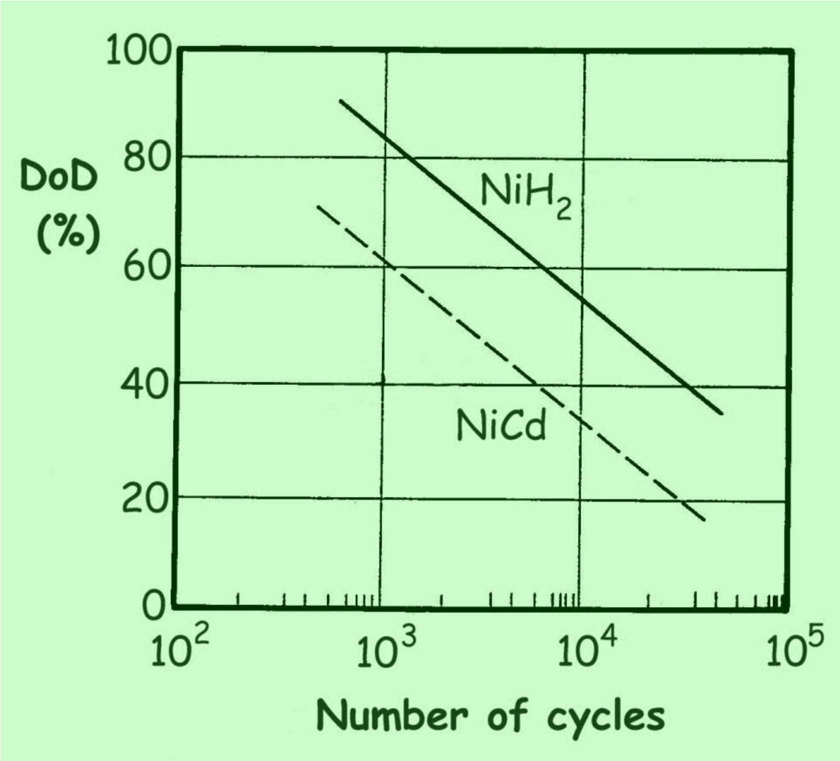
– Average battery discharge voltage V_B, Number of cells in series times cell discharge voltage – *Unit:* Volt

Performance of Space Qualified Batteries

	NiCd	NiH_2	Li-ion
Energy density (W-h/kg)	25 – 30	50 – 80	120 – 150
Operating temp (^oC)	-10 to +40	-10 to +40	0 to +45
Discharge cell voltage (V)	1.25	1.30	4.1
Cycle lifetime	Dependent on use…		

Power Storage - Batteries

Performance of Space Qualified Batteries



... Cycle lifetime

NiH_2 can be discharged to a greater depth than NiCd for the same lifetime

offers an improvement in mass.

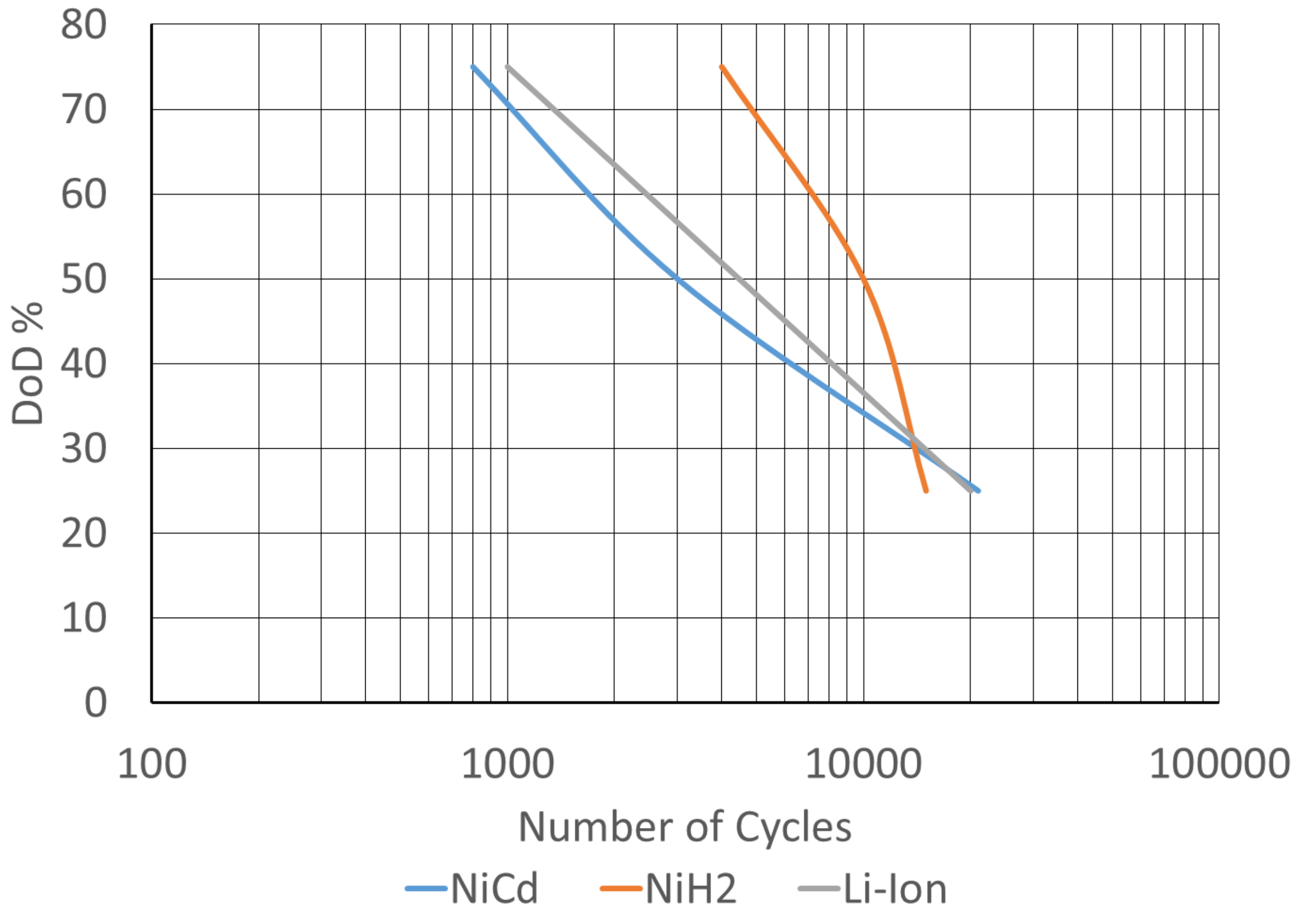
But NiH_2 are volumetrically inefficient.

Note: DoD/cycle data is very dependant on temperature and can very significantly

Power Storage - Batteries

Performance of Space Qualified Batteries

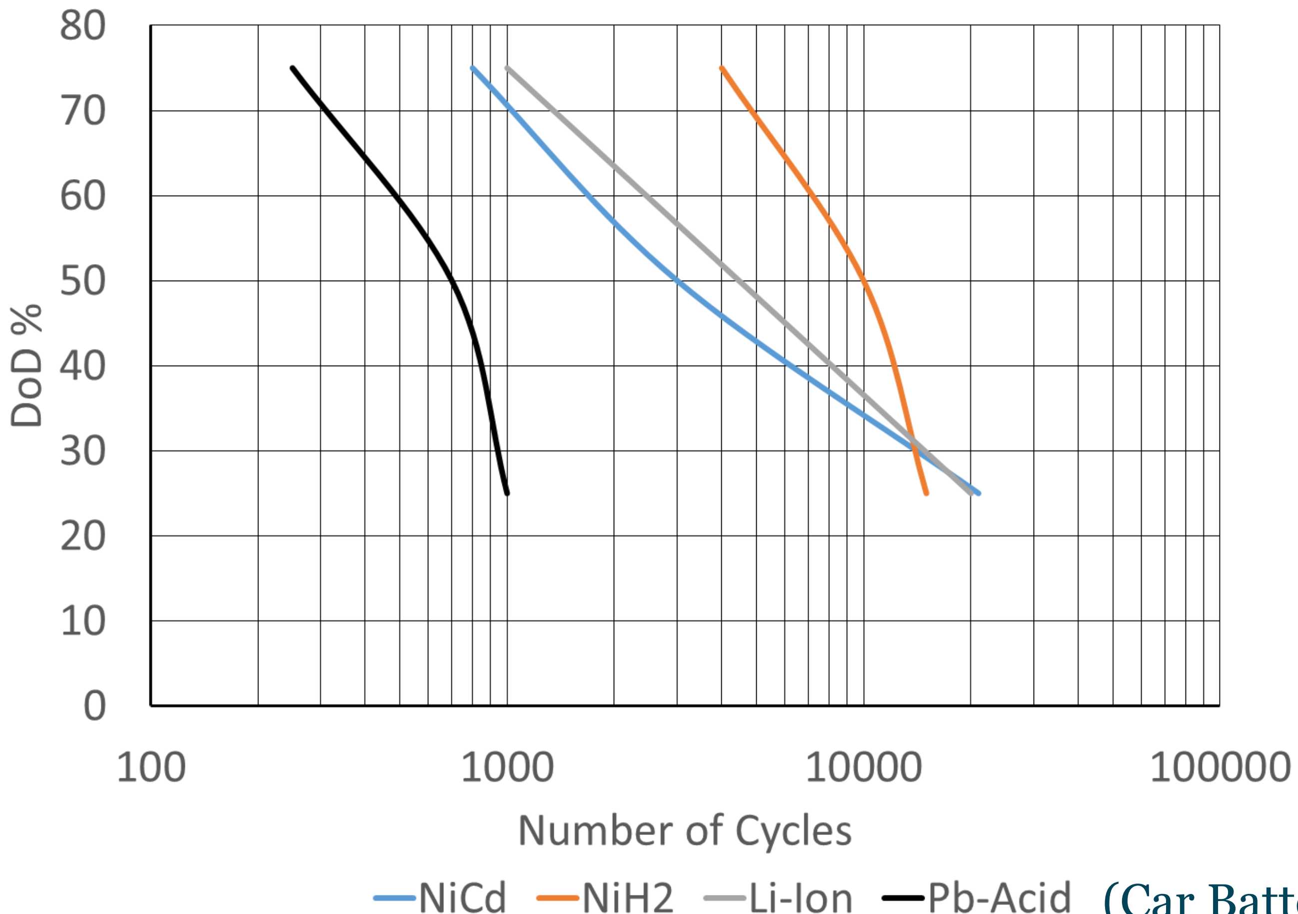
Comparative Li-ion Lifetime Performance



Power Storage - Batteries

Performance of Space Qualified Batteries

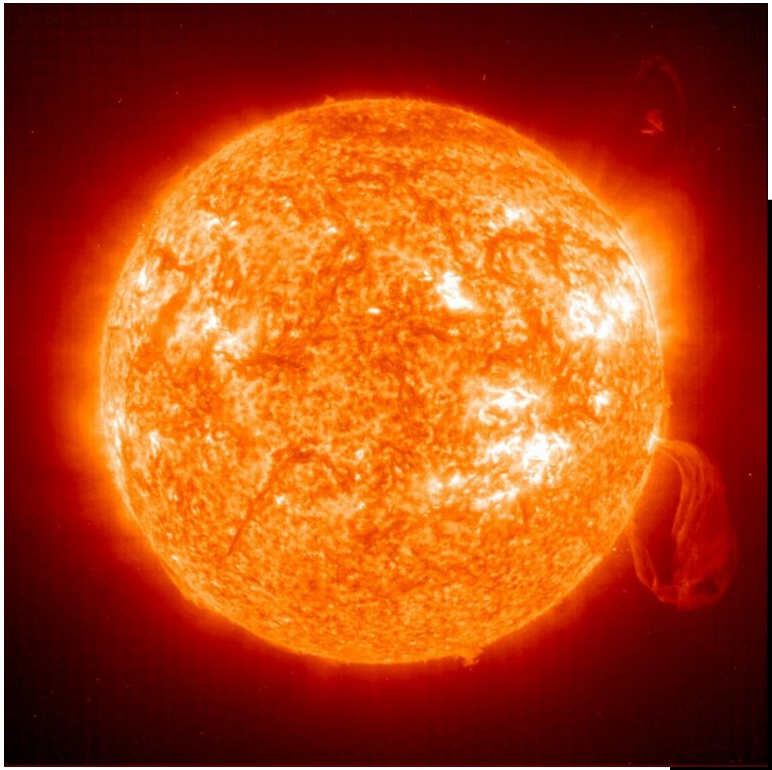
Comparative Li-ion Lifetime Performance

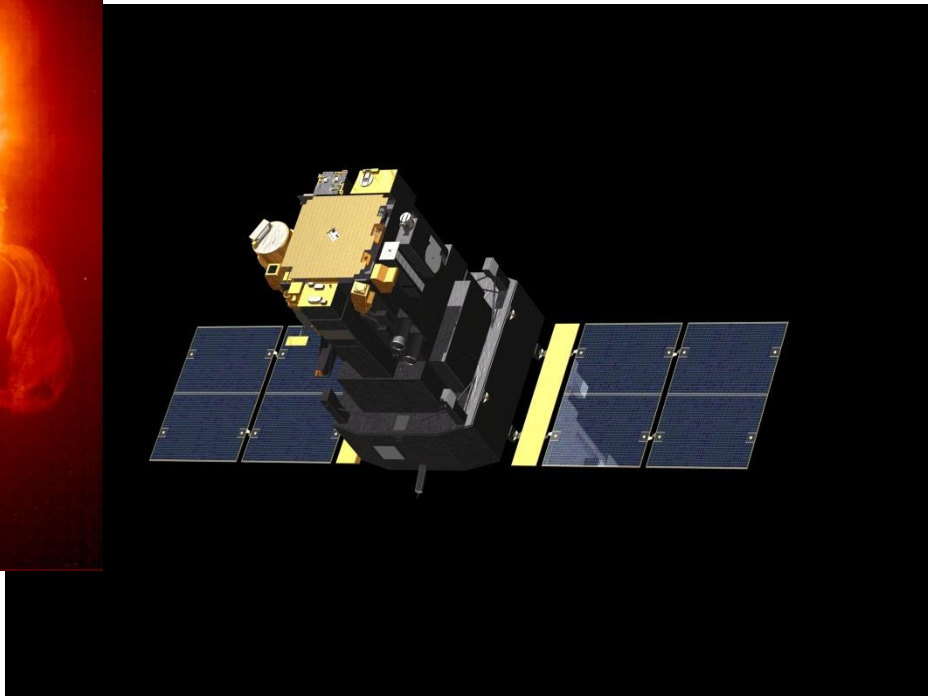


(Car Battery)

Power Budgets

Example – SOHO (Solar Heliospheric Observatory) spacecraft





Power Budgets

Example – SOHO spacecraft

SOHO spacecraft power Budget

	MISSION PHASE POWER (W)					
	Pre-launch	Ascent	Parking orbit	Transfer orbit	Cruise	On-station
1. Service module total	87.5	102.9	127.3	161.3	239.5	279.5
2. Service module total (15% margin)	101	119	147	186	276	322
3. Payload total	0	0	0	0	427	427
4. Payload total (15% margin)	0	0	0	0	491	491
TOTAL (Sum of 2. + 4.)	**101**	**119**	**147**	**186**	**767**	**813**

Preliminary Battery and Array Sizing

Example

- Estimate the battery and array size for a LEO spacecraft in a 800 km altitude circular orbit, given an average power requirement for payload and subsystems of 1 kW over a mission lifetime of 2 years.

- **Spacecraft draws** on array power in sunlight and on battery power in eclipse ⇒ there will be an increment of power (in excess of the 1 kW) required to charge batteries during sunlit part of the orbit.

Preliminary Battery and Array Sizing

Example – Mission parameters

- **Maximum eclipse period**
  - Time in eclipse is

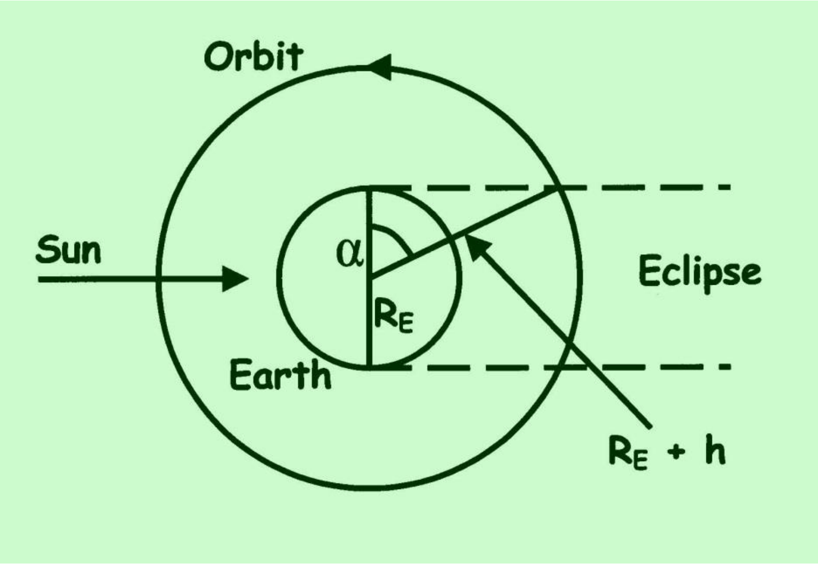
$$t_e = \left(\frac{180^\circ - 2\alpha}{360^\circ} \right) \tau \qquad (8.2)$$

where $\cos\alpha = R_E / (R_E + h)$

and τ is the orbit period from equation (5.9)

  - Time in sunlight is

$$t_s = \tau - t_e \qquad (8.3)$$



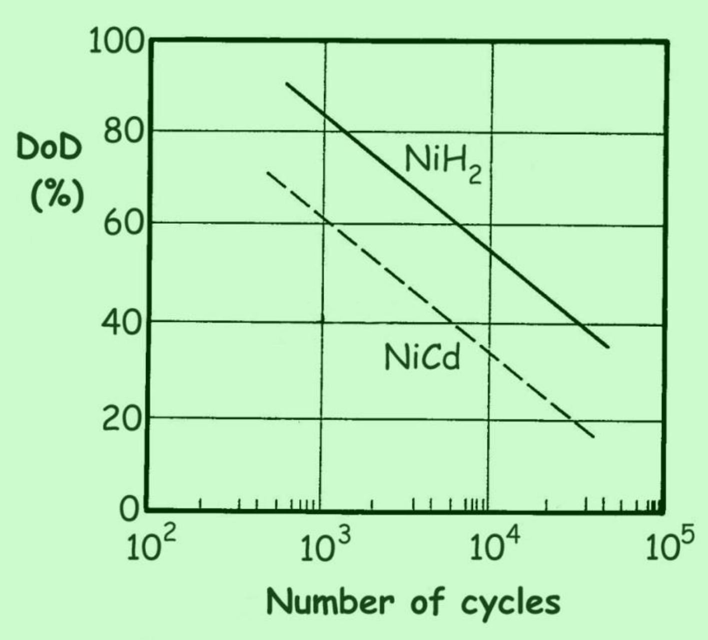
Preliminary Battery and Array Sizing

Example – Mission parameters

- In this example, we find $\tau = 1.68$ h, $t_e = 0.59$ h, $t_s = 1.09$ h (using $R_E = 6378$ km and $\mu_E = 398{,}600$ km³/sec²)

- **Number of charge/discharge cycles**
  - This is the number of orbits over 2 year lifetime ~ (2 years)/τ = 10,420 cycles

If we assume NiCd batteries, then DoD = 30% (with margin)



Preliminary Battery and Array Sizing

Example – Battery sizing

- **We now size NiCd battery** to support an EOL power of P_{EOL} = 1000 W (payload and subsytems) in eclipse (t_e ~ 0.6 h)

Sytem/Battery data:
- Bus voltage V_{BUS} = 28 V dc
- Energy density $\bar{\mathcal{E}}$ = 30 W-h/kg for 100% discharge
- Average cell voltage V_C = 1.25 V

Preliminary Battery and Array Sizing

Example – Battery sizing

- Number of cells $N_c = V_{BUS} / V_c$ (8.4)

$$= 28 / 1.25 = 22.4$$

- Choose $N_c = 22$ → $V_B = N_c V_c$ (8.5)

$$= 22(1.25\text{V}) = 27.5 \text{ V dc}$$

- Total capacity, $C = P_{EOL}\, t_e / (DoD\ \ V_B)$ (8.6)

$$= \frac{(1000\text{W})(0.6\text{h})}{0.3(27.5\text{V})} = 72.7 \text{ A - h}$$

Preliminary Battery and Array Sizing

Example – Battery sizing

– Total stored energy $$\varepsilon = CV_B \quad (8.7)$$

$$= (72.7 \text{ A-h})(27.5\text{V}) = 2000 \text{ W-h}$$

– Battery mass, $$M_{Battery} = \varepsilon / \bar{\varepsilon} \quad (8.8)$$

$$= \frac{2000 \text{ W-h}}{30 \text{ W-h/kg}} = 67 \text{ kg}$$

Preliminary Battery and Array Sizing

Example – Array sizing

- **Size array for** $P_{EOL} = 1000\ \mathrm{W} + (\mathrm{battery\ charge})$

Assume: - BOL cell efficiency of $\eta = 11.5\%$

- Degradation factor, due to radiation damage, over 2 year lifetime $D = 0.1$

- Sun angle (max. off-normal) $\theta \sim 3^\circ$

- Solar intensity $S = 1350\ \mathrm{W/m^2}$

- Packing efficiency $\eta_p = 90\%$

Preliminary Battery and Array Sizing

Example – Array sizing

– For charge $V_A > V_B$, where $V_A =$ array voltage

Assume: $V_A \approx 1.2\, V_B$

$$= 1.2\,(27.5 \text{ V}) = 33 \text{ V dc}$$

– Battery charge rate $R = \dfrac{(DoD)C}{t_s}$ (8.9)

$$= (0.3)(72.7 \text{ A - h})/(1.09 \text{ h}) = 20.0 \text{ A}$$

Preliminary Battery and Array Sizing

Example – Array sizing

– Total power required of the array

$$P_{EOL} = P(\text{payload} + \text{subsystems}) + RV_A \qquad (8.10)$$

$$= 1000\ \text{W} + (20\ \text{A})(33\ \text{V}) = 1660\ \text{W}$$

– Solar array area

$$A_{SA} = \frac{P_{EOL}}{S \cos\theta\, \eta\, \eta_p\, (1 - D)} \qquad (8.11)$$

$$= \frac{1660}{1350 \cos 3^\circ (0.115)(0.9)(0.9)}$$

– Finally, $A_{SA} \approx 13.2\ \text{m}^2$

Impacts of Power on S/C System

- Power subsystem interfaces with all other electrical subsystems and payload

- Spacecraft mission $\Longleftrightarrow$ choice of primary power source

- Power raising pointing requirements $\Longleftrightarrow$ impact on spacecraft configuration

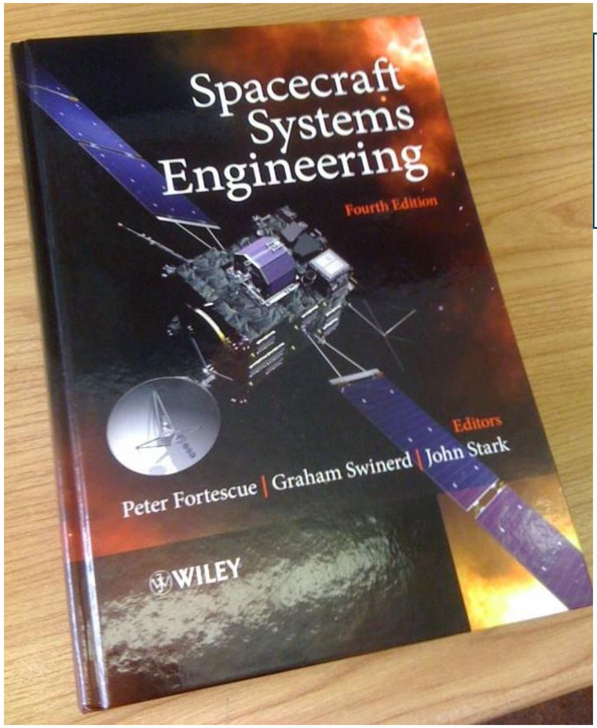
Chapter 8 Summary

Key points:

Electrical Power Subsystem	• Function of the subsystem, power sources and key definitions
Primary Power Sources	• Introduction into all the main primary power sources and their main mission usage
Power System Overview	• Introduction of the typical system, its components and layout, using solar arrays and batteries
Solar Arrays	• The basics of solar cells, solar cell characteristics (performance and their sensitivity to different effects) • Using solar cells to create arrays
Power Storage	• Terminology, battery types • Battery characteristics • Performance of space qualified batteries
Power Budgets	• Introduction to power budgets using SOHO as an example • Overview into how budgets are used to guide the design
Preliminary Battery and Array Sizing	• Example demonstrating the sizing calculations for an Earth orbiting spacecraft using solar arrays and batteries
Impacts of Power on S/C System	• The impacts of the power subsystem design on the spacecraft system

Chapter 8 Summary

UNIVERSITY OF Southampton



Read Chapter 10 of Fortescue, Stark & Swinerd