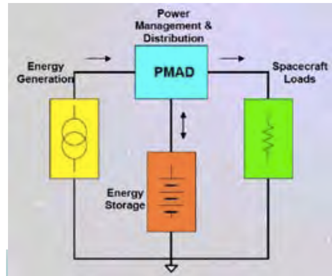
Electrical Power Systems

Space System Design, MAE 342, Princeton University

Robert Stengel

- Elements of the System
- Solar Cell Arrays
- Batteries
- Radioisotope Thermoelectric Generators
- Primary Power
- Secondary Power
- Management, Distribution, and Control
- Power Budget



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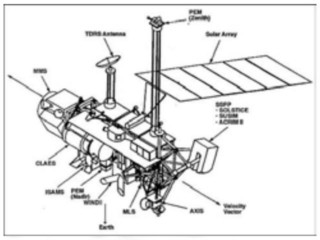
http://www.princeton.edu/~stengel/MAE342.html

Preliminary Design Process for Power System

Step	Information Required	Derived Requirements	References
1. Identify Requirements	Top-level requirements, mission type (LEO, GEO), spacecraft configuration, mission life, payload definition	Design requirements, spacecraft electrical power profile (average and peak)	Secs. 10.1, 10.2
2. Select and Size Power Source	Mission type, spacecraft configuration, average load requirements for electrical power	EOL power requirement, type of solar cell, mass and area of solar array, solar array configuration (2-axis tracking panel, body-mounted)	Secs. 10.1, 10.2 Table 10-9 Sec. 11.4.1 Table 11-34
3. Select and Size Energy Storage	Mission orbital parameters, average and peak load requirements for electrical power	Eclipse and load-leveling energy storage requirement (battery capacity requirement), battery mass and volume, battery type	Sec. 11.4.2 Tables 11-3, 11-4, 11-38, 11-39, 11-40 Fig. 11-11
4. Identify Power Regulation and Control	Power-source selection, mission life, requirements for regulating mission load, and thermal-control requirements	Peak-power tracker or direct-energy-transfer system, thermal-control requirements, bus-voltage quality, power control algorithms	Sec. 11.4.4

McDermott; Larson & Wertz, 1999



Effects of System Level Parameters

Parameter	Effects on Design
Average Electrical Power Requirement	Sizes the power-generation system (e.g., number of solar cells, primary battery size) and possibly the energy-storage system given the eclipse period and depth of discharge
Peak Electrical Power Required	Sizes the energy-storage system (e.g., number of batteries, capacitor bank size) and the power-processing and distribution equipment
Mission Life	Longer mission life (> 7 yr) implies extra redundancy design, independent battery charging, larger capacity batteries, and larger arrays
Orbital Parameters	Defines incident solar energy, eclipse/Sun periods, and radiation environment
Spacecraft Configuration	Spinner typically implies body-mounted solar cells; 3-axis stabilized typically implies body-fixed and deployable solar panels

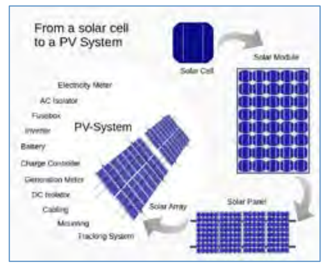
McDermott; Larson & Wertz, 1999

Typical Electrical Power Requirements

- **Generate electrical power for s/c systems**
- **Store power for "fill-in" when shadowed from Sun**
- **Distribute power to loads**
- **Condition power (e.g., voltage regulation)**
- **Protect power bus from faults**
- **Provide clean, reliable, uninterrupted power**

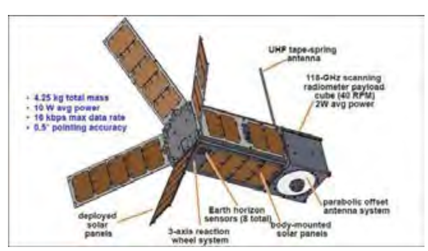
Power System Analysis

- **Power budget**
  - Payload, bus, and charge loads
  - Error margins
- **Energy balance**
  - Dynamic simulation over multiple duty cycles
- **Stability Analysis**
  - Small-signal AC stability
  - Bus impedance
  - Bus ripple
  - Transient response



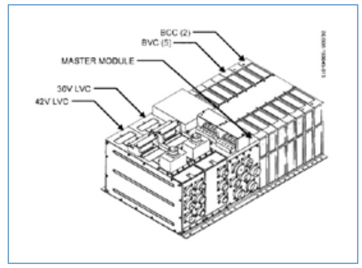
Power System Sizing

- **Power system must**
  - Support the spacecraft through entire mission
  - Recharge batteries after longest eclipse
  - Accommodate electric propulsion/attitude control
  - Accommodate failures to assure reliability
  - Account for margins and contingencies
- **Factors affecting size include**
  - Satellite orbit
  - Seasonal variation
  - Life degradation
  - Total eclipse load
  - Number of discharges

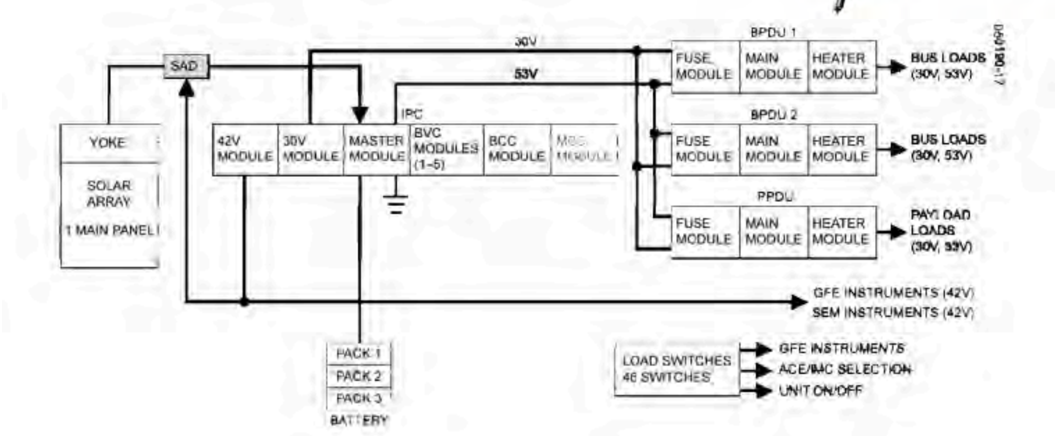


Power Management and Distribution

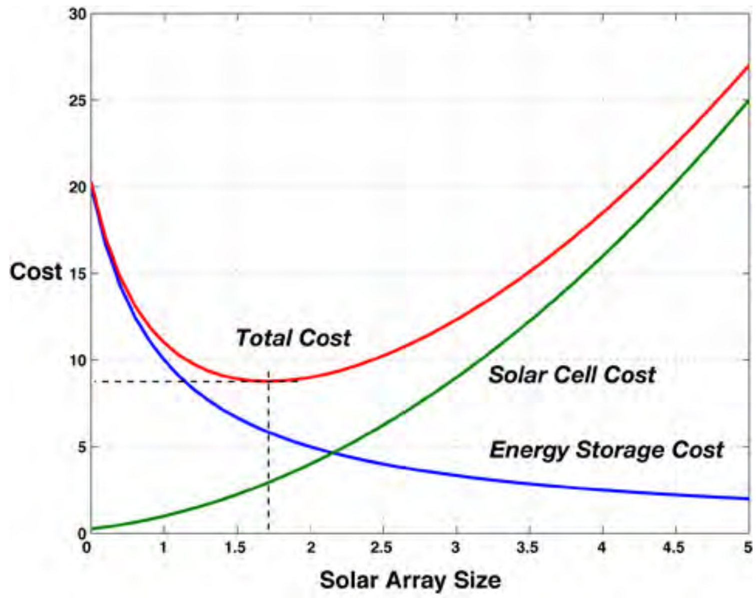
- Solar array control
- Battery charge control
- Battery discharge control
- Power distribution and protection
- Bus voltage regulation and conditioning
- Power switching
- Power telemetry
- Requirements driven by power system architecture, bus voltage, and power levels



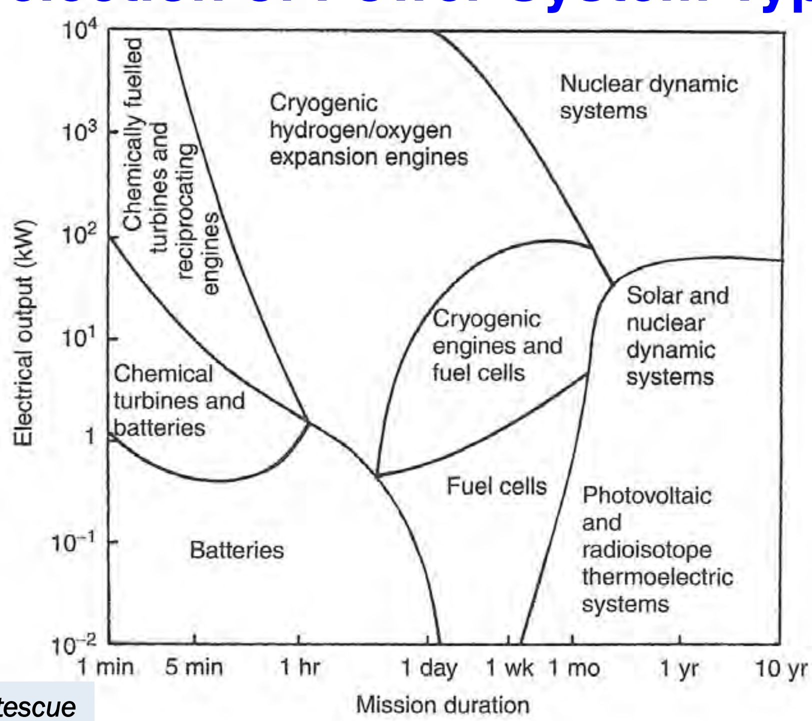
GOES-P Electric Power Sub-System



Power System Tradeoffs



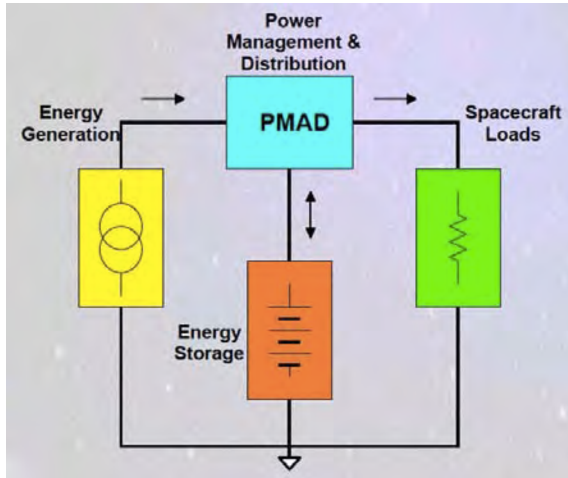
Selection of Power System Type



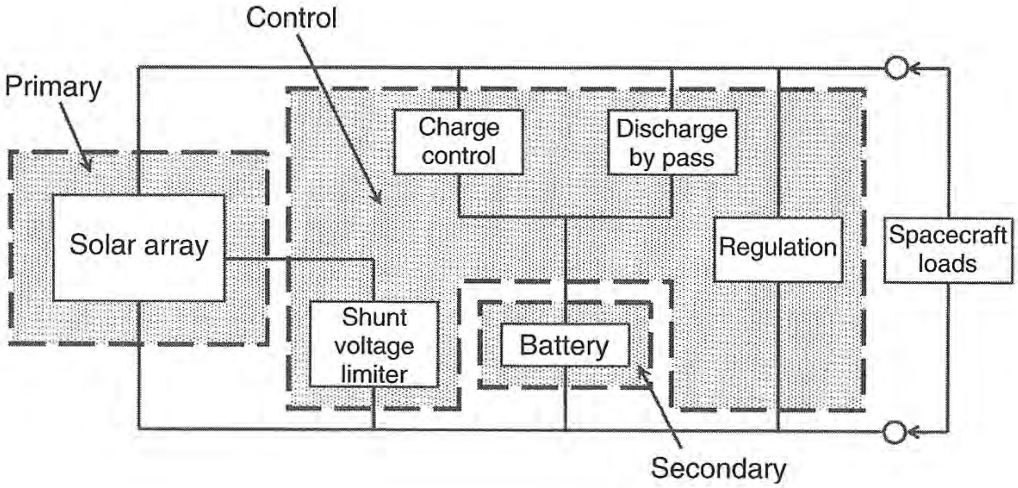
Fortescue

Functional Blocks of Electrical Power System

- **Energy generation**
- **Energy storage**
- **Power management and distribution**



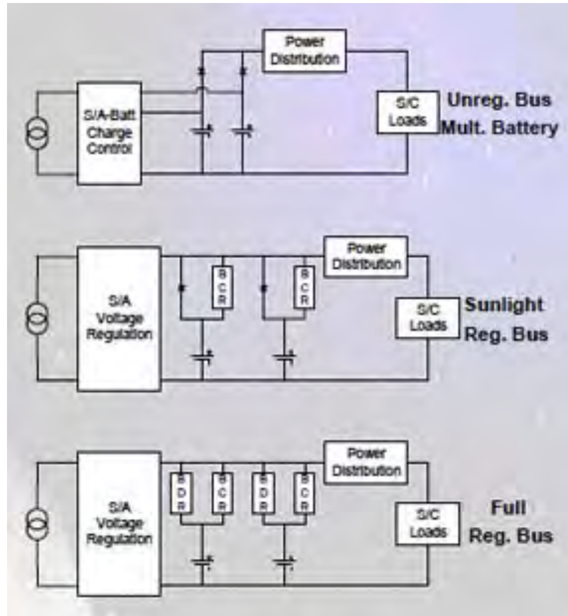
Functional Blocks of Solar Cell/ Battery Electrical Power System



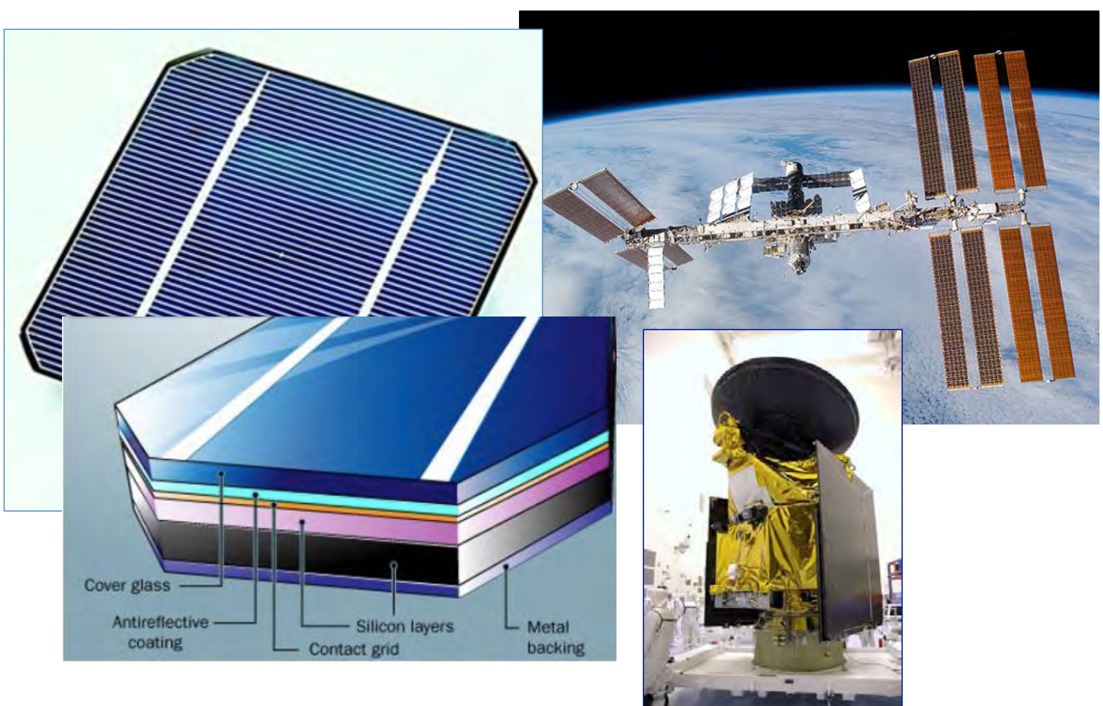
Fortescue

Power System Architectures

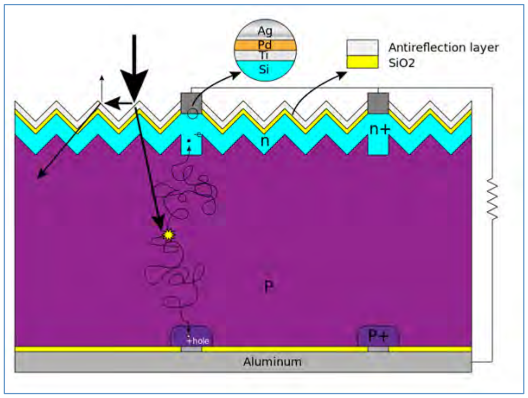
- Unregulated (battery-dominated) bus
  - Bus voltage determined by battery voltage
- Sunlight regulated bus
  - Bus voltage regulated during sunlit period
  - Bus voltage determined by battery voltage during eclipse
- Fully regulated bus
  - Bus voltage regulated in sunlight and eclipse
  - Power converter boosts variable battery voltage to bus voltage

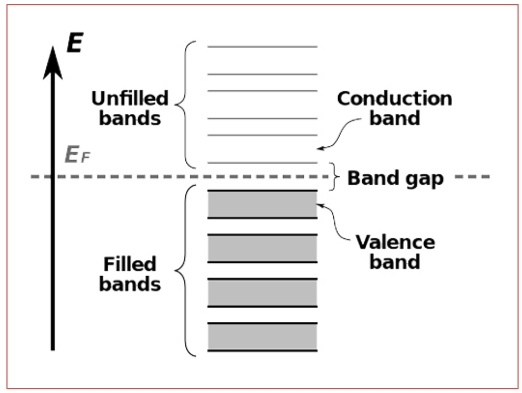


Solar Cells and Arrays



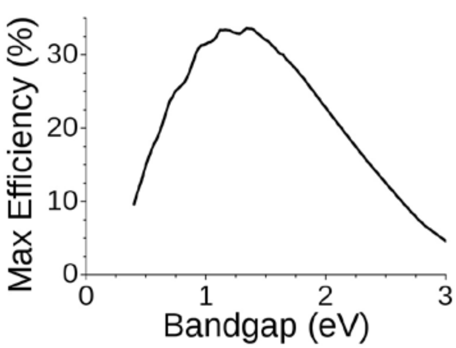
Solar Cells

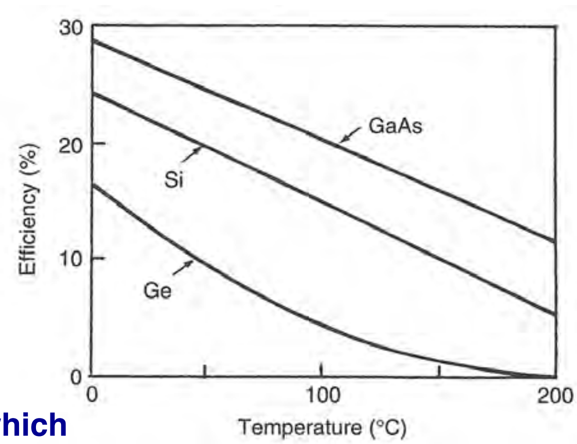




- Silver, palladium, titanium, silicon "sandwich"
- [p-n junction]
- Photons hit panel
- Electrons are excited, generating heat or traveling through material, e.g., boron or phosphorus, generating a current

Theoretical Single-Junction Solar Cell Efficiency

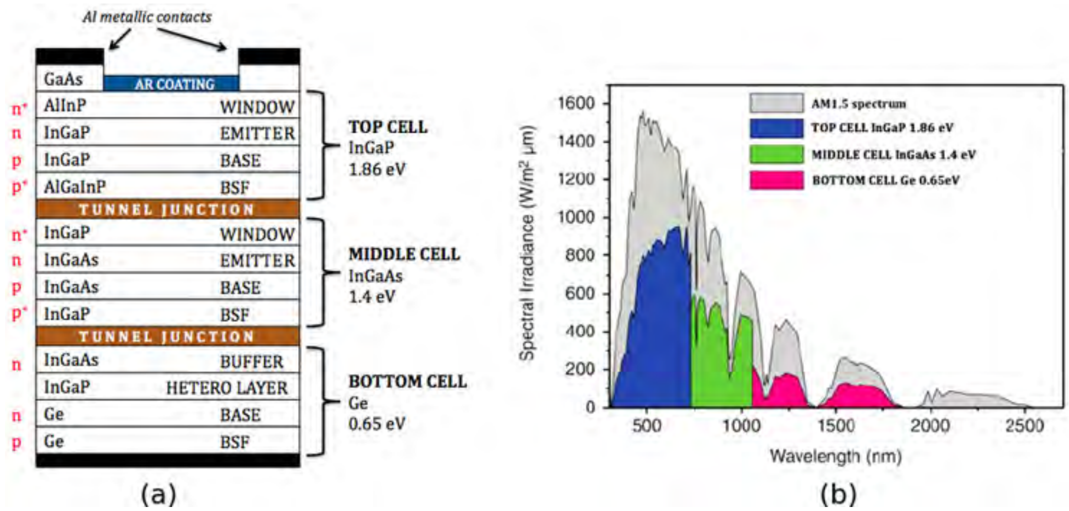




- Bandgap: Energy Range in which no electron states can exist
- Photon energy must exceed bandgap for current to flow across p-n junction

Rauschenbach; Fortescue, 2011

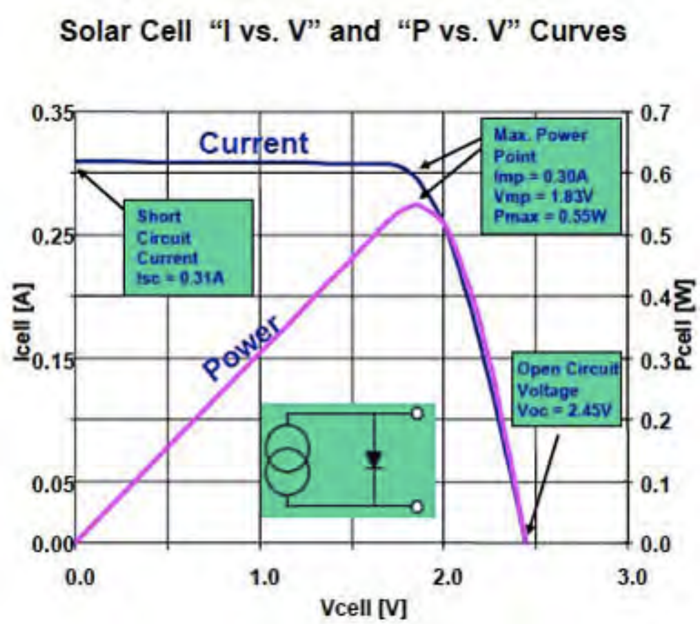
Multi-Junction Solar Cells

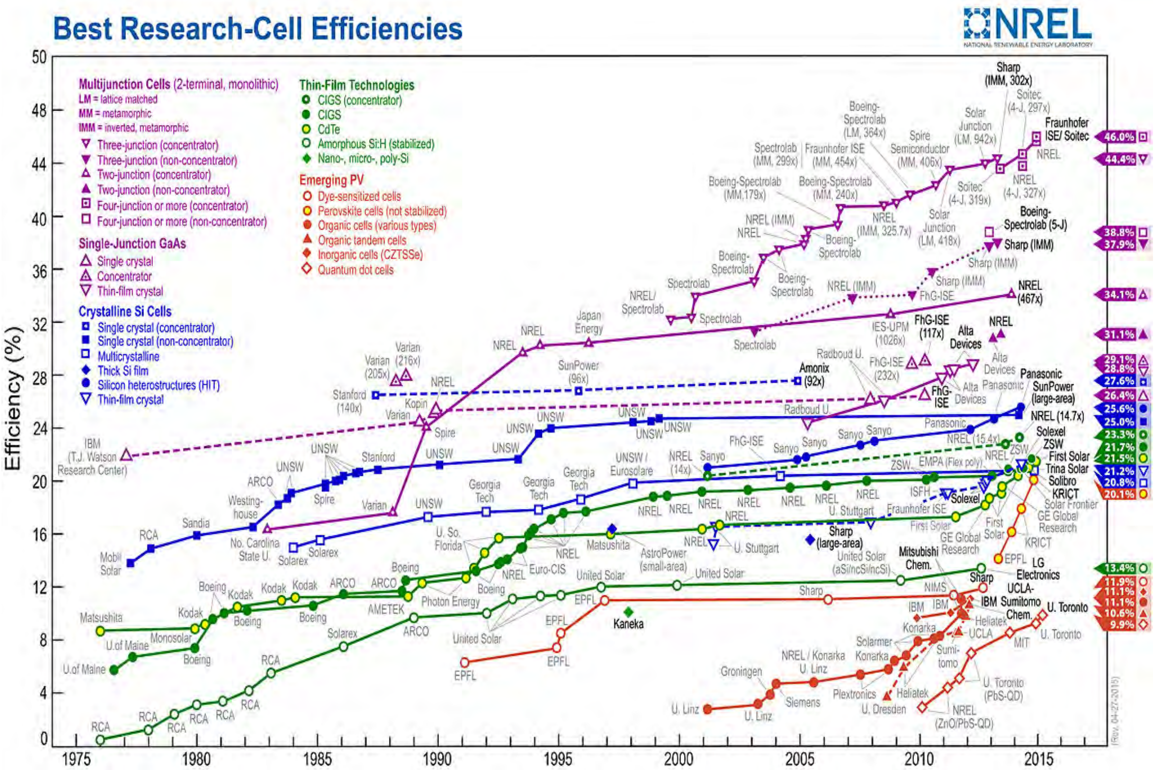


Material-dependent relationship between wavelength and bandgap

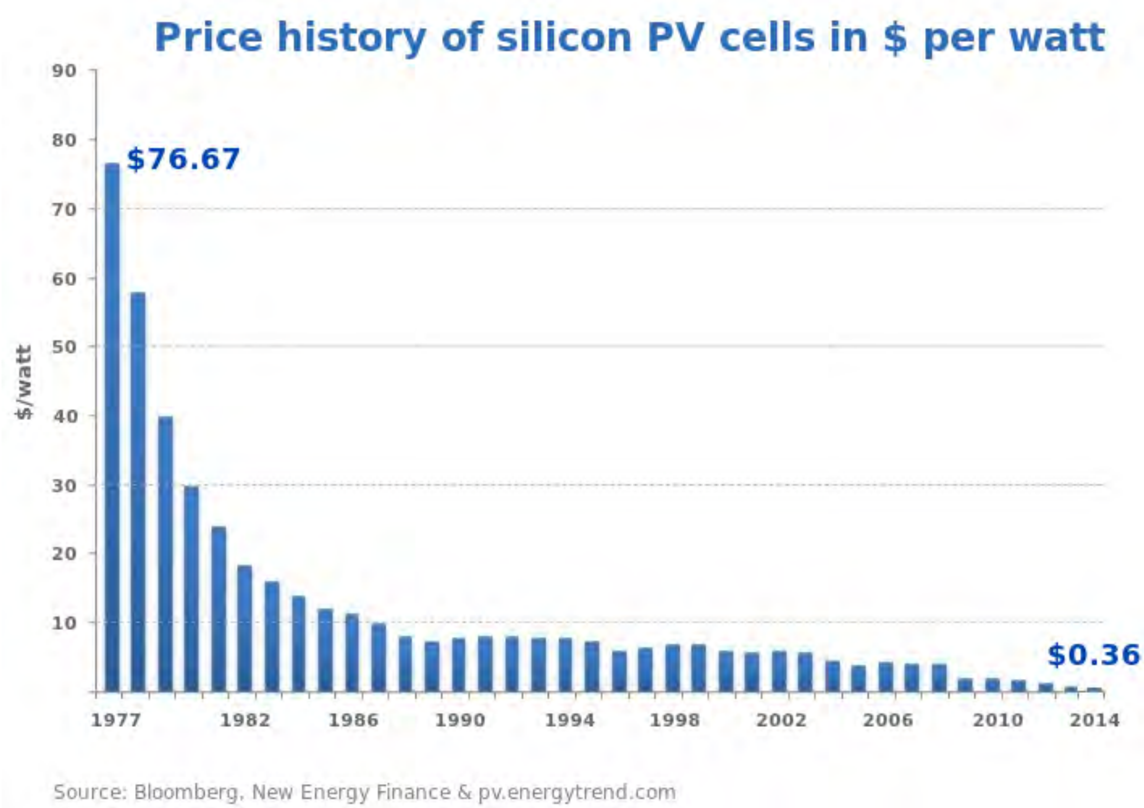
Current-Voltage-Power Characteristics of Typical Solar Cells

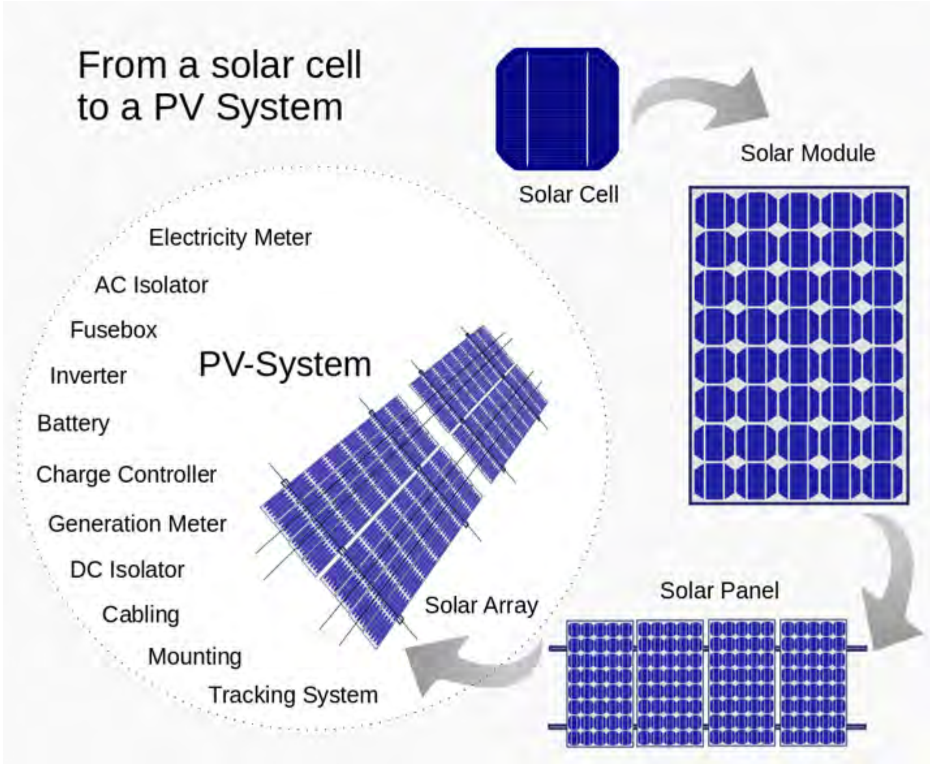
- **Silicon (Efficiency 15%)**
- **Gallium Arsenide (GaAs)**
  - **Dual Junction (~22%)**
  - **Triple Junction (~28%)**
  - **Quad Junction (>30%)**

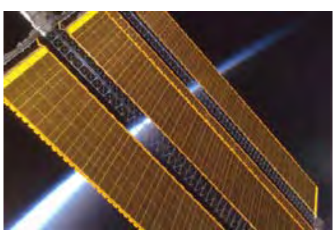



Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Thick Si film
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
46.0%
44.4%
38.8%
37.9%
34.1%
31.1%
29.1%
28.8%
27.6%
26.4%
25.6%
25.0%
23.3%
21.7%
21.5%
21.2%
20.8%
20.1%
13.4%
11.9%
11.1%
11.1%
10.6%
9.9%
1975
1980
1985
1990
1995
2000
2005
2010
2015

19


Price history of silicon PV cells in $ per watt
$/watt
$76.67
$0.36
1977
1982
1986
1990
1994
1998
2002
2006
2010
2014
Source: Bloomberg, New Energy Finance & pv.energytrend.com





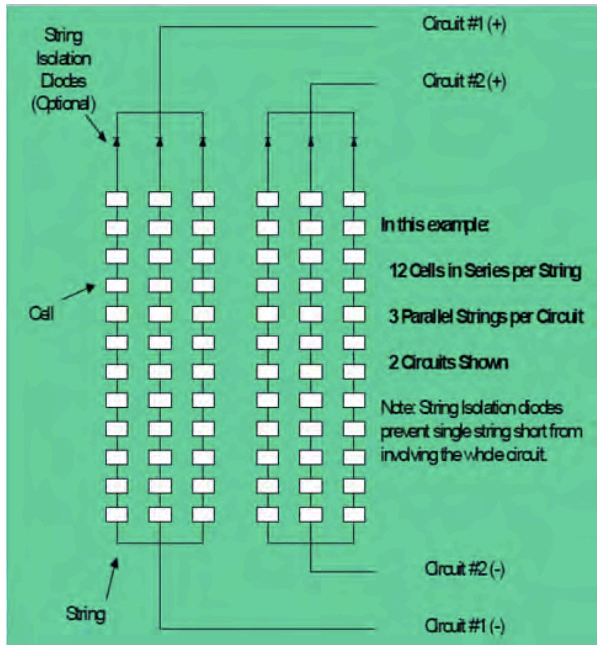
Solar Arrays

- **Generate power during sunlit periods for**
  - Payload
  - Operation of power bus
  - Charging batteries
- **Typical power output: 2kW – 15kW**

MAVEN Solar Array Deployment
https://www.youtube.com/watch?v=oxxUUO4tgWs

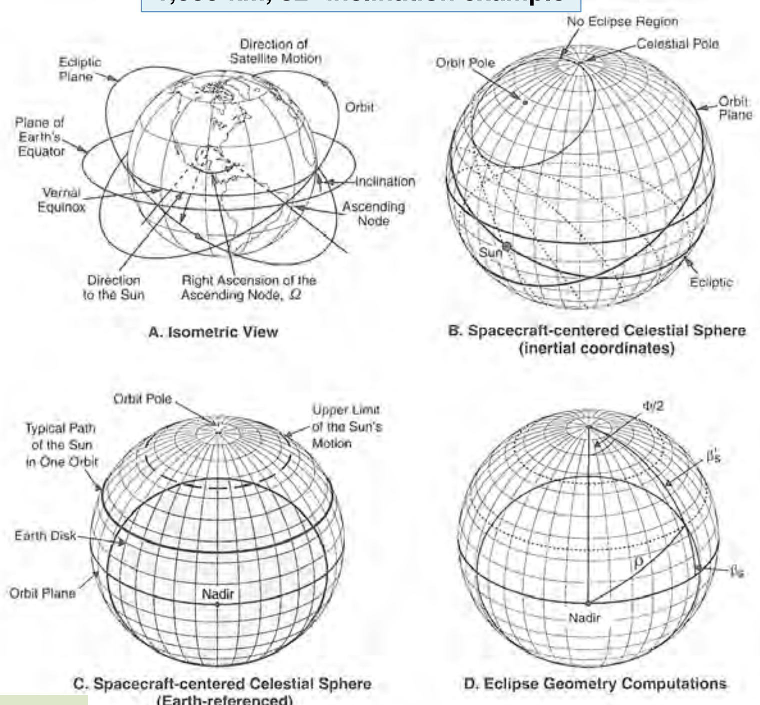
Solar Array Design

- **Each solar cell produces**
  - < 2 W
  - 0.7 – 3 V
- **Series arrangement to produce voltage**
- **Parallel arrangement to produce current**



Solar Cells Don't Function During Eclipse

1,000-km, 32° inclination example

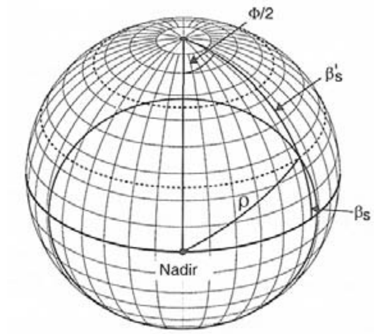


Larson & Wertz, 1999

Eclipse Duration

Orbit-Angle Segment of Eclipse

$$\Phi = 2\cos^{-1}\left(\frac{\cos\rho}{\cos\beta_S}\right) = 2\cos^{-1}\left(\frac{\cos\rho}{\sin\beta'_S}\right), \text{ rad}$$



Duration of Eclipse

$$T_{eclipse} = \frac{\Phi}{2\pi} P_{orbit}, \text{ min}$$

$\rho =$ Spherical angle of Earth disk, rad

$\beta =$ Spherical angle of Sun above the orbit plane, rad

$\Phi =$ Spherical angle of eclipse, rad

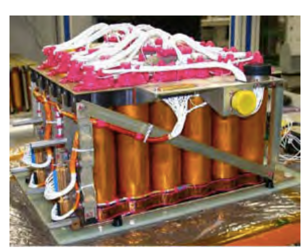
$T_{eclipse} =$ Duration of eclipse, min

Secondary power required during the eclipse

Larson & Wertz, 1999

Batteries

- **Nickel Cadmium (NiCd)**
  - **Heavier, older tech**
  - **Lower volume**
- **Nickel Hydrogen (NiH2)**
  - **High # of charging cycles**
  - **Pressurized vessels**
- **Lithium Ion (Li Ion)**
  - **State of the art**
  - **1/2 the mass, 1/3 the volume of NiH2**
  - **Extra care required in charging**



https://en.wikipedia.org/wiki/List_of_battery_types

Batteries

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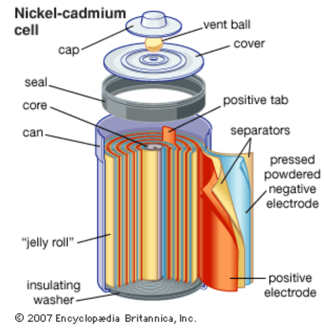
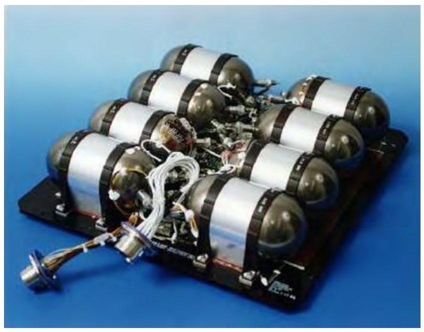
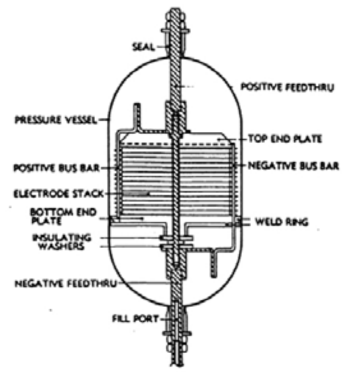






Lithium-Ion Battery Modules

Choy Patent

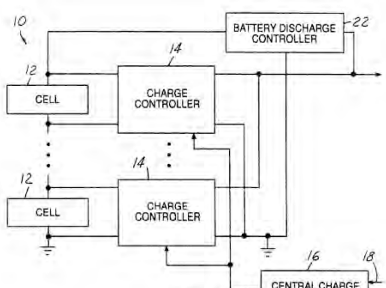


FIG. 1

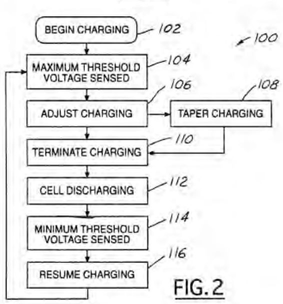
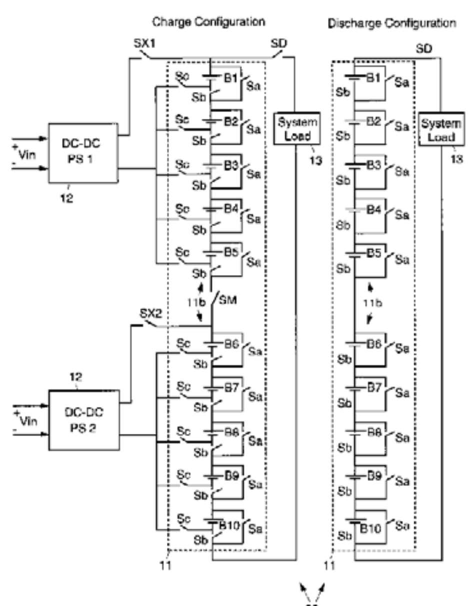


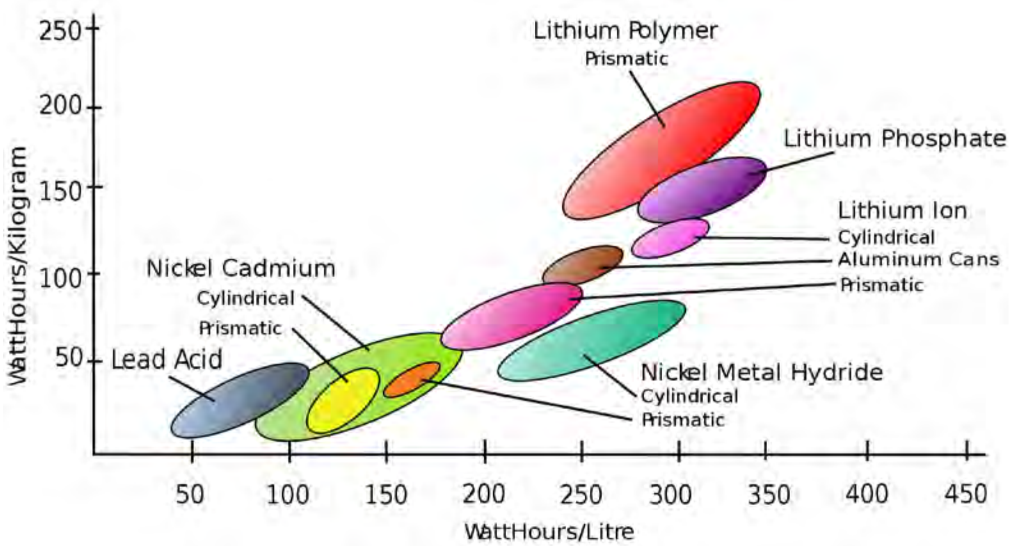
FIG. 2

Hall Patent



http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090023862.pdf

Battery Comparison



https://en.wikipedia.org/wiki/Comparison_of_battery_types

Performance of Spacecraft Batteries

Table 10.6 Performance of battery technologies for space use [23]

Type	Specific energy (W h/kg)	Mission examples
Ni-Cd	28–34	Sampex
Ni-H_2	30–54	Odyssey
Ag-Zn	100	Pathfinder
Li-Ion	90	MER Rover
Li-SO_2	90–150	Galileo
Li-$SOCL_2$	200–250	Sojourner

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https://en.wikipedia.org/wiki/List_of_spacecraft_powered_by_non-rechargeable_batteries

Three Spacecraft Examples

Table 10.7 Hubble space telescope (HST), Intelsat VII and Eurostar 3000 battery summary

Parameter	HST	Intelsat VII	Eurostar 3000
Technology	$Ni\text{-}H_2$	$Ni\text{-}H_2$	Li-ion
Specific energy (W h/kg)	57.14	61.26	175
Capacity (A-h)	96	91.5	50
Cell dimensions:			
Diameter (cm)	9.03	8.89	5.3
Length (cm)	23.62	23.67	25.0
Cell mass (kg)	2.1	1.867	1.1

Fortescue

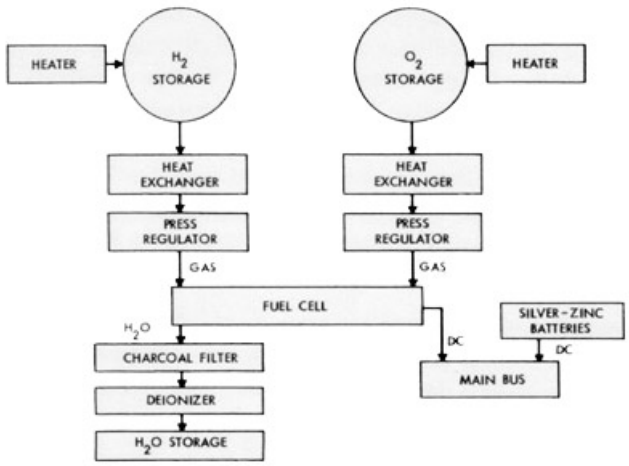
Definitions

- **Capacity: fully charged amount of energy**
- **State of Charge (SOC): How much charge remains in battery**
- **Depth of Discharge: How much charge is taken out of battery**
- **Charge Rate: Rate (current) at which charge (Ah) is put into battery**
- **Charge Efficiency: How much charge energy is stored**
- **Charge/Discharge Ratio: Charge required to restore beginning SOC following discharge**
- **Self Discharge: Low-level leakage**
- **Trickle Charge: Continuing charge to counter self-discharge**
- **Balancing: Equalizing the SOC of each cell in a battery**

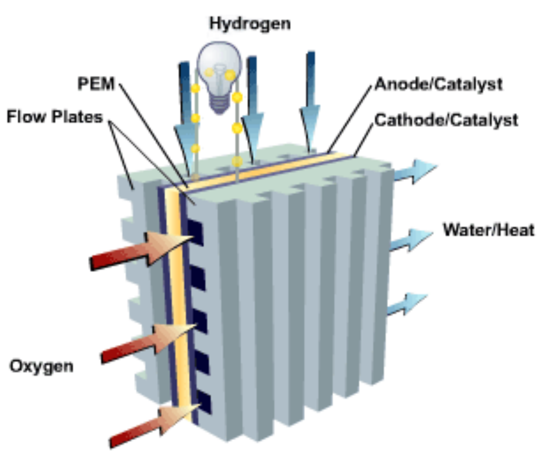
Fuel Cell

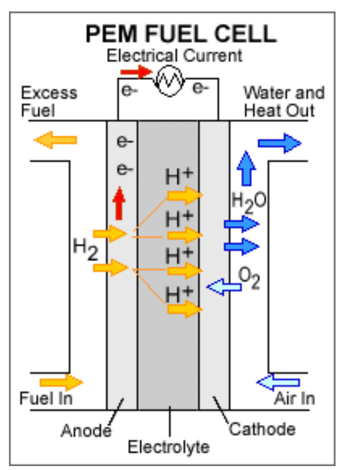
Produces electricity from hydrogen and oxygen

Water is a by-product



Proton Exchange Membrane Fuel Cell



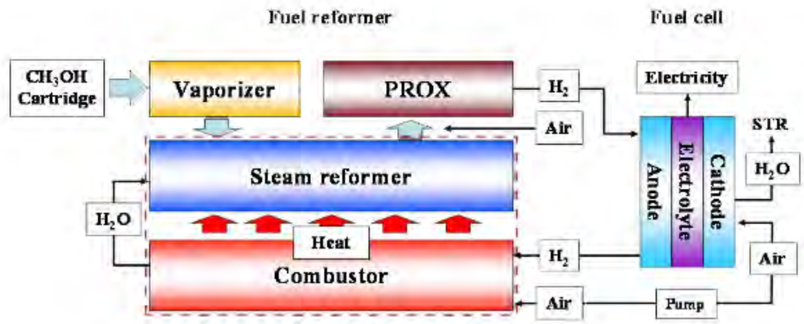


Gemini Fuel Cell

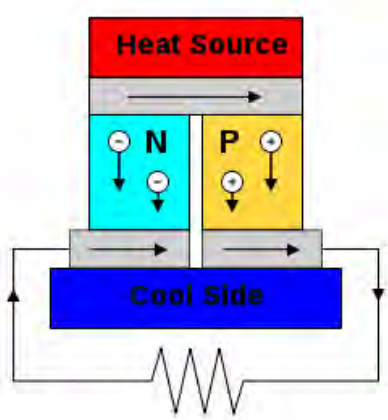
47 x 37.5 x 63.5cm

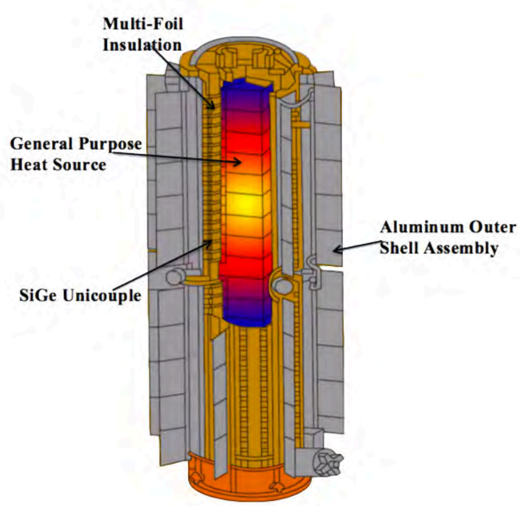
Reformed Methanol Fuel Cell

- **Methanol: source of hydrogen**
  - Partial oxidation (hydrogen-rich gas)
  - Autothermal reforming (steam treatment)
  - Water-gas-shift (“water gas’)
  - Preferential oxidation (removal of CO, which “poisons” the fuel cell catalyst)

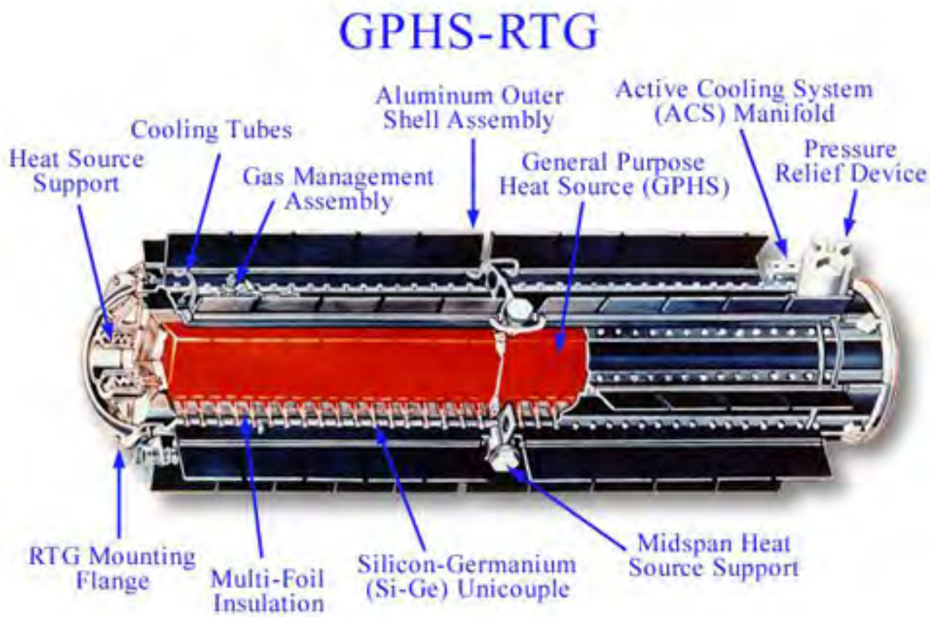


Thermoelectric Power Generation



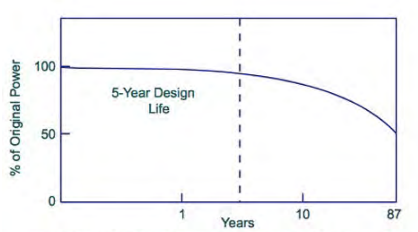


Radioactive Isotope Thermoelectric Generator (Cassini Spacecraft)



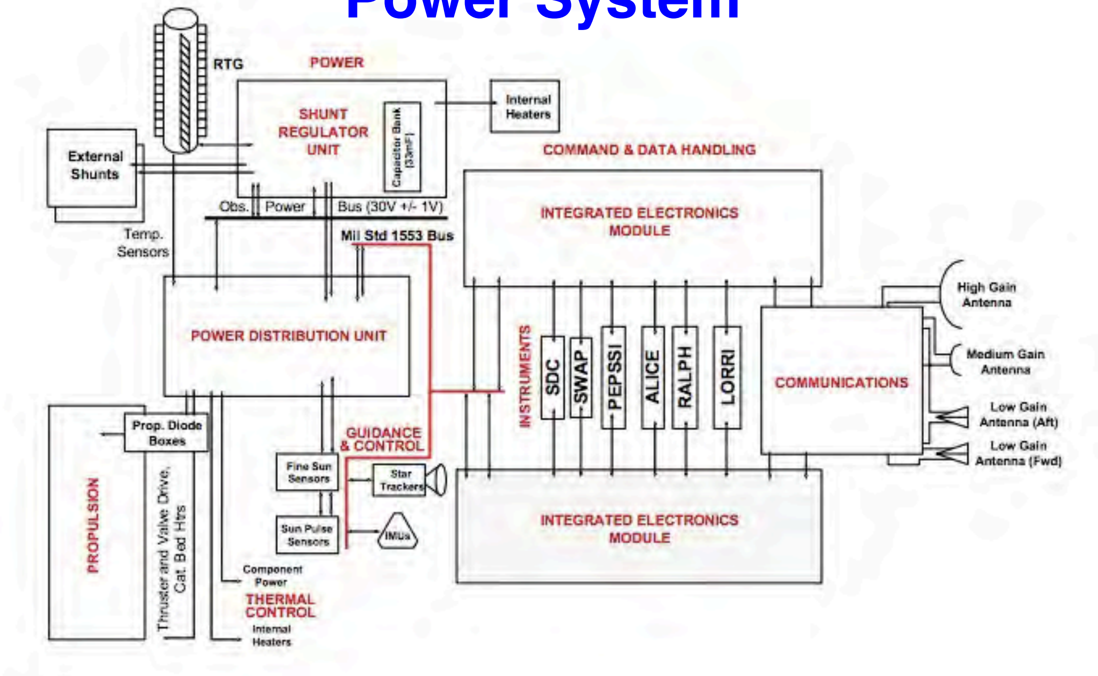
Radioactive Isotope Thermoelectric Generator

Name	Used on (# of RTGs)	Electrical Output (W)	Heat Output (W)	Radioisotope	Max fuel used (kg)	Mass (kg)	Power/Mass (W/kg)
MMRTG	MSL/Curiosity rover	~110	~2000	^{238}Pu	~4	<45	2.4
GPHS-RTG	Cassini (3), New Horizons (1), Galileo (2), Ulysses (1)	300	4400	^{238}Pu	7.8	55.9–57.8	5.2-5.4
MHW-RTG	LES-8/9, Voyager 1 (3), Voyager 2 (3)	160	2400	^{238}Pu	~4.5	37.7	4.2
SNAP-3B	Transit-4A (1)	2.7	52.5	^{238}Pu	?	2.1	1.3
SNAP-9A	Transit 5BN1/2 (1)	25	525	^{238}Pu	~1	12.3	2
SNAP-19	Nimbus-3 (2), Pioneer 10 (4), Pioneer 11 (4)	40.3	525	^{238}Pu	~1	13.6	2.9
SNAP-19 (modified)	Viking 1 (2), Viking 2 (2)	42.7	525	^{238}Pu	~1	15.2	2.8
SNAP-27	Apollo 12–17 ALSEP (1)	73	1,480	^{238}Pu	3.8	20	3.65
Buk (BES-5)	US-As (1)	3000	100,000	^{235}U	30	~1000	3
SNAP-10A	SNAP-10A (1)	600	30,000	Enriched uranium		431	1.4

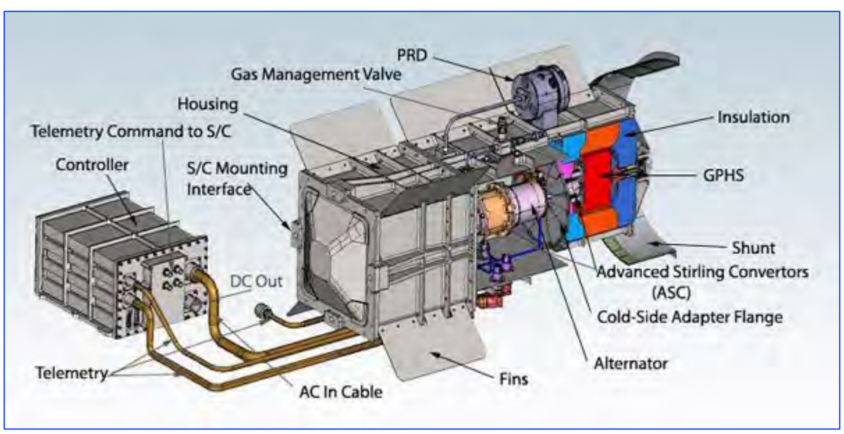


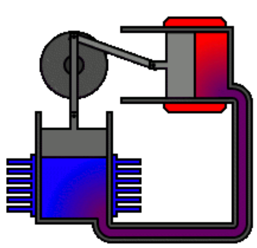
The 87-year half-life of Pu-238 results in 96% of the original heat output even after five years

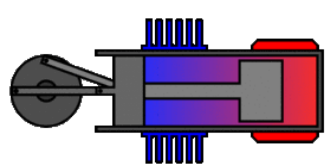
New Horizons Electrical Power System



Stirling Cycle Radioactive Isotope Thermoelectric Generator



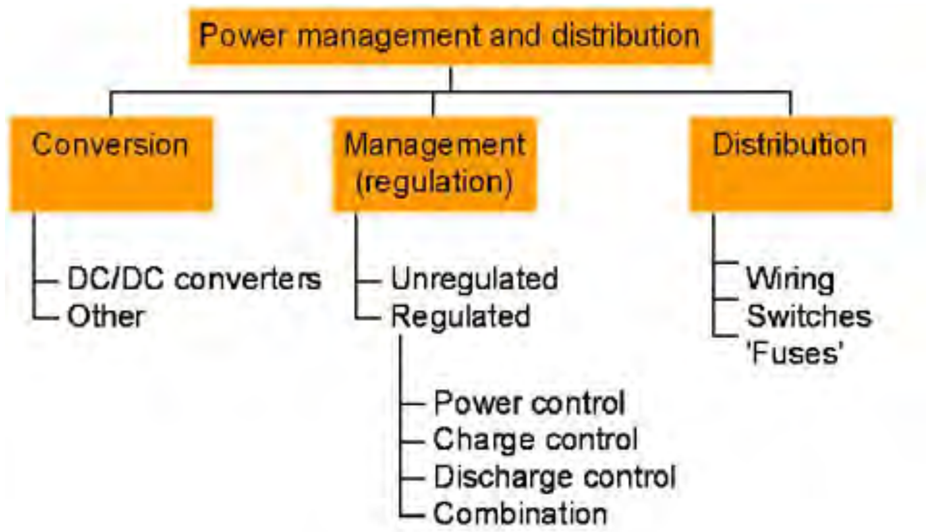




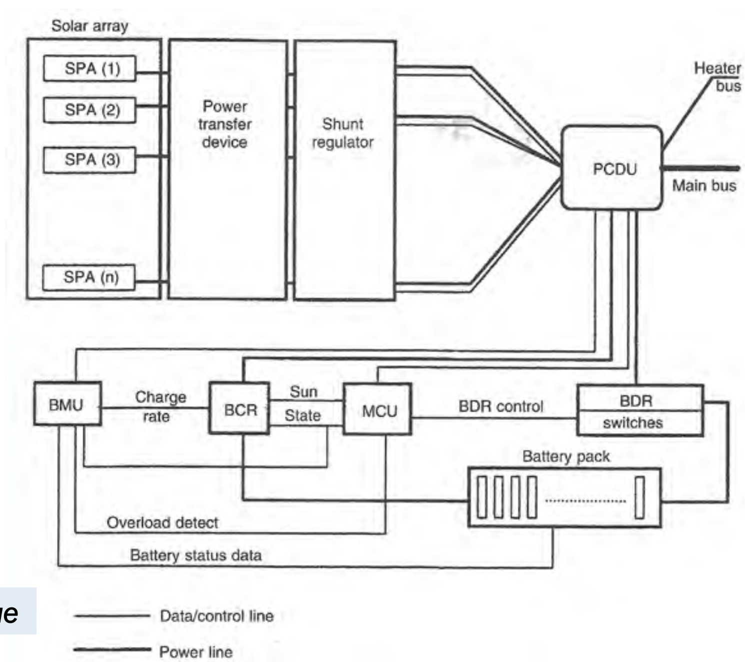
Next Time:
Thermal Control Systems

Supplemental Material

Power Management and Distribution

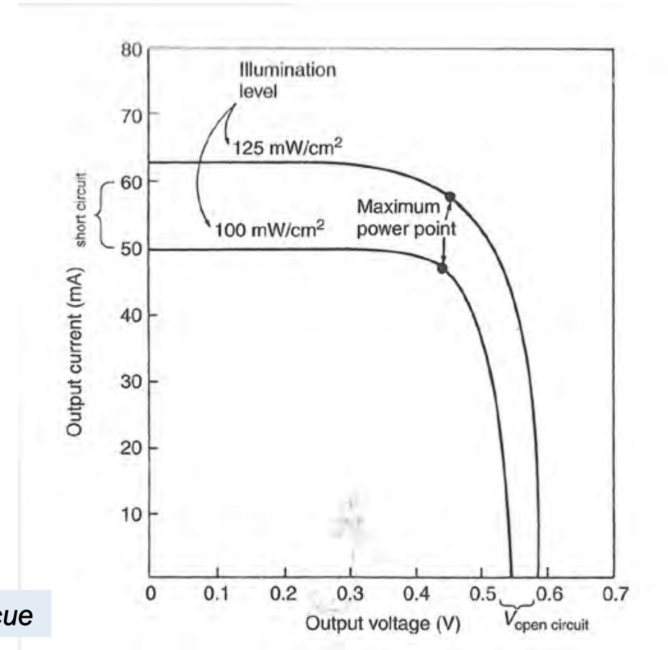


Power System Layout



Fortescue

Current-Voltage Characteristic of a Typical Solar Cell



Fortescue