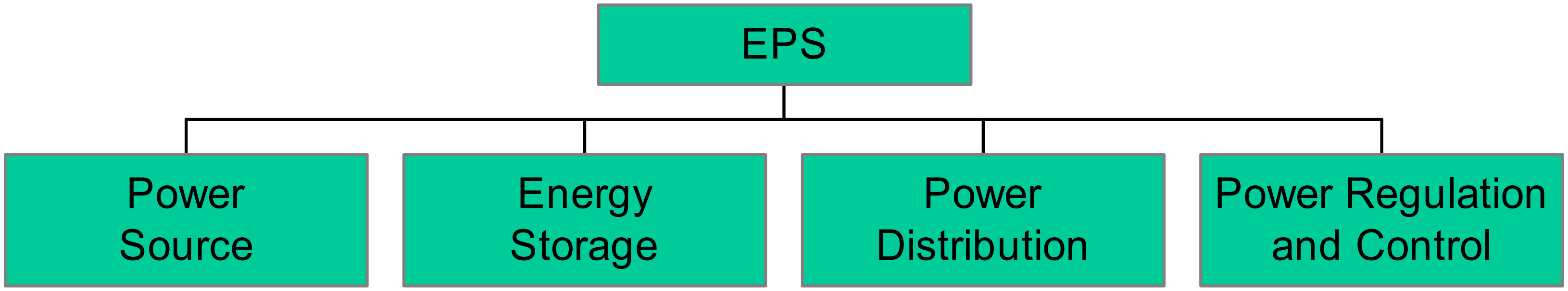
# Spacecraft Power Systems

David W. Miller
John Keesee

# Electrical Power System



EPS

Power Source

Energy Storage

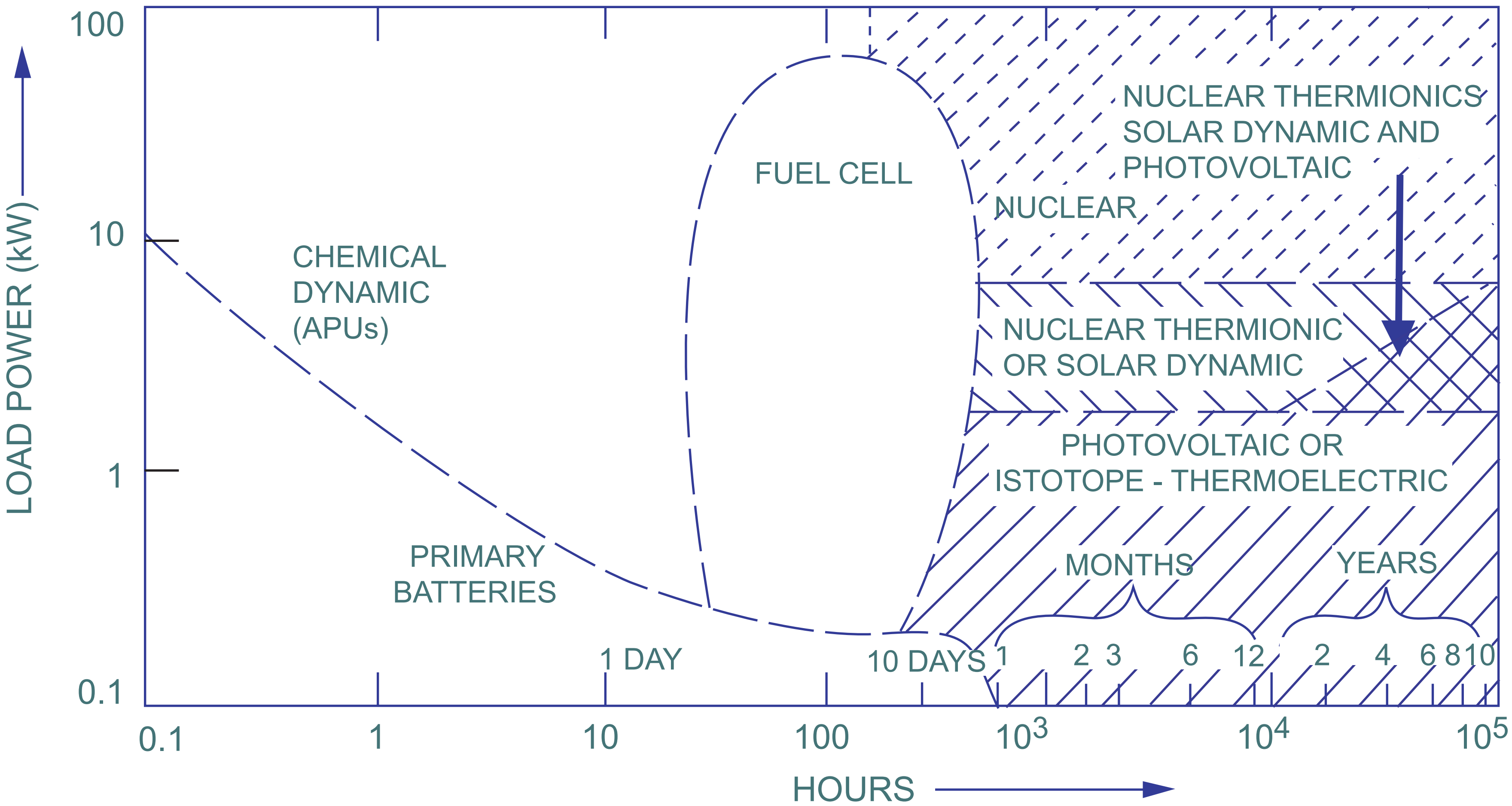
Power Distribution

Power Regulation and Control

# Power Sources

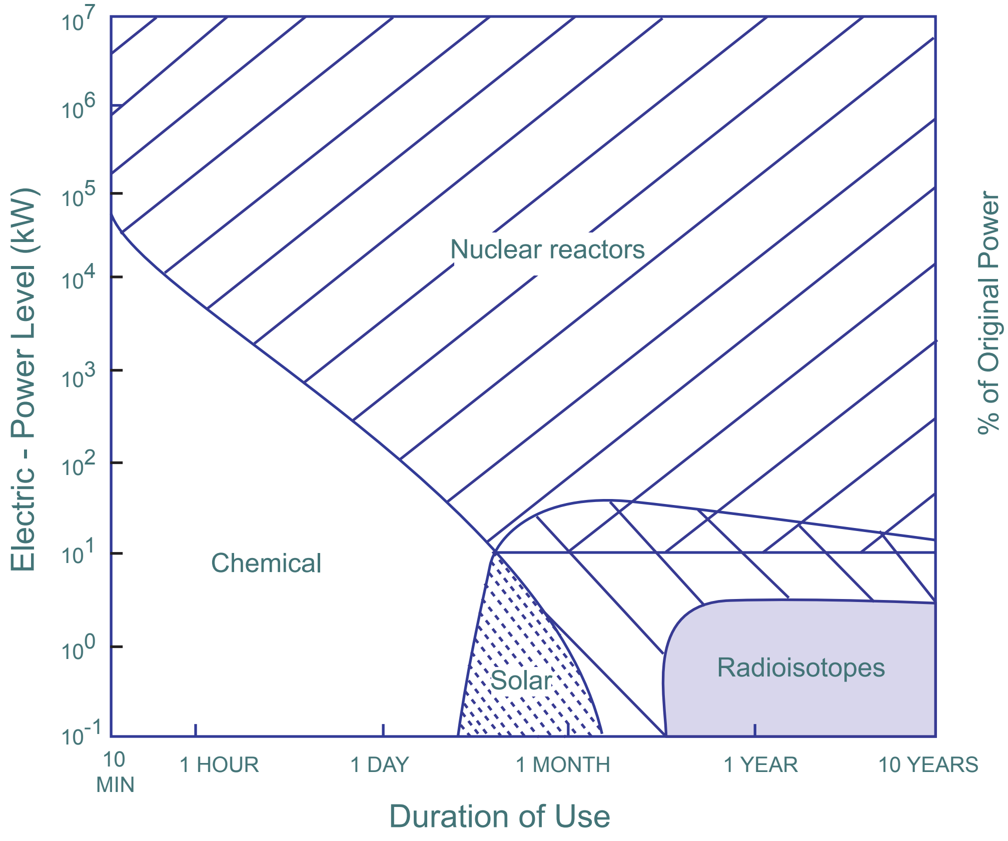
| | |
|---|---|
| Primary Batteries | Radioisotope |
| Secondary Battery | Thermionic converter |
| Fuel cell | Thermoelectric converter |
| Regenerative fuel cell | Photovoltaic |
| Chemical dynamic | Solar dynamic |
| Nuclear | Flywheel Storage |
| Electrodynamics Tethers | Propulsion-charged tether |

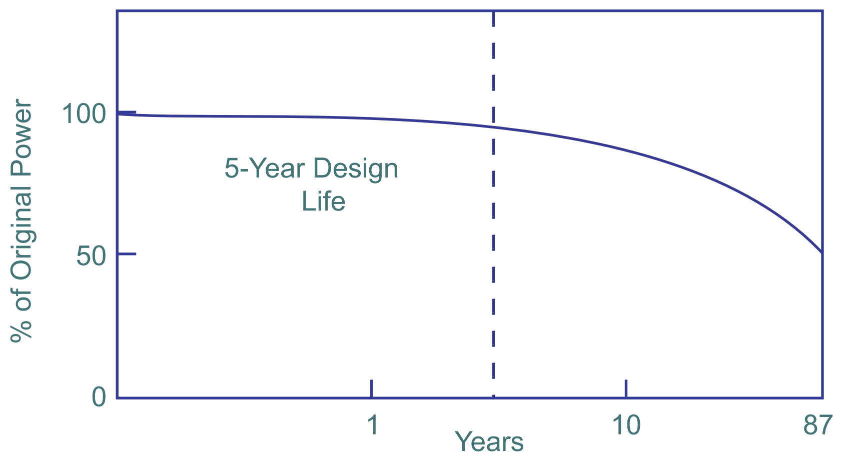
# Power Source Applicability



Approximate ranges of application of different power sources.

# Design Space for RTGs





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

# Primary Battery Types

| | **Silver zinc** | **Lithium sulfur dioxide** | **Lithium carbon monofluoride** | **Lithium thionyl chloride** |
|---|---|---|---|---|
| Energy density (W h/kg) | 130 | 220 | 210 | 275 |
| Energy density (W h/dm$^3$) | 360 | 300 | 320 | 340 |
| Op Temp (deg C) | 0-40 | -50 – 75 | ? – 82 | -40 – 70 |
| Storage Temp (deg C) | 0 – 30 | 0 – 50 | 0 – 10 | 0 – 30 |
| Storage Life | 30-90 days wet, 5 yr dry | 10 yr | 2 yr | 5 yr |
| Open circuit voltage(V/cell) | 1.6 | 3.0 | 3.0 | 3.6 |
| Discharge voltage(V/cell) | 1.5 | 2.7 | 2.5 | 3.2 |
| Manufacturers | Eagle Pitcher, Yardley | Honeywell, Power Conver | Eagle Pitcher | Duracell, Altus, ITT |

# Silver Zinc Cells

- Wide use in industry
- High energy density, high discharge rate capability, fast response
- Short lifetime
- Vent gas during discharge
- Potentially rechargeable but few cycles

# Lithium cells

- Higher energy density than silver zinc
- Wide temperature range
- Low discharge rate (high internal impedance)
  - Rapid discharge may cause rupture
- Slow response

# Secondary Battery Types

| | **Silver zinc** | **Nickel cadmium** | **Nickel hydrogen** |
|---|---|---|---|
| Energy density (W h/kg) | 90 | 35 | 75 |
| Energy density (W h/dm$^3$) | 245 | 90 | 60 |
| Oper Temp (deg C) | 0 – 20 | 0 – 20 | 0 – 40 |
| Storage Temp (C) | 0 – 30 | 0 – 30 | 0 – 30 |
| Dry Storage life | 5 yr | 5 yr | 5 yr |
| Wet Storage life | 30 – 90 days | 2 yr | 2 yr |
| Max cycle life | 200 | 20,000 | 20,000 |
| Open circuit (V/cell) | 1.9 | 1.35 | 1.55 |
| Discharge (V/cell) | 1.8 – 1.5 | 1.25 | 1.25 |
| Charge (V/cell) | 2.0 | 1.45 | 1.50 |
| Manufacturers | Eagle-Pitcher,Yardney Technical Prod | Eagle-Pitcher, Gates Aerospace Batteries | Eagle-Pitcher, Yardney, Gates, Hughes |

# Nickel Cadmium Cells

- Long space heritage
- High cycle life, high specific energy
- Relatively simple charge control systems
- Battery reconditioning necessary to counteract reduction in output voltage after 3000 cycles

# Nickel Hydrogen Cells

- Potentially longer life than NiCads
  - Hydrogen gas negative electrode eliminates some failure modes
- Highly tolerant of high overcharge rates and reversal
- Individual, common and single pressure vessel types

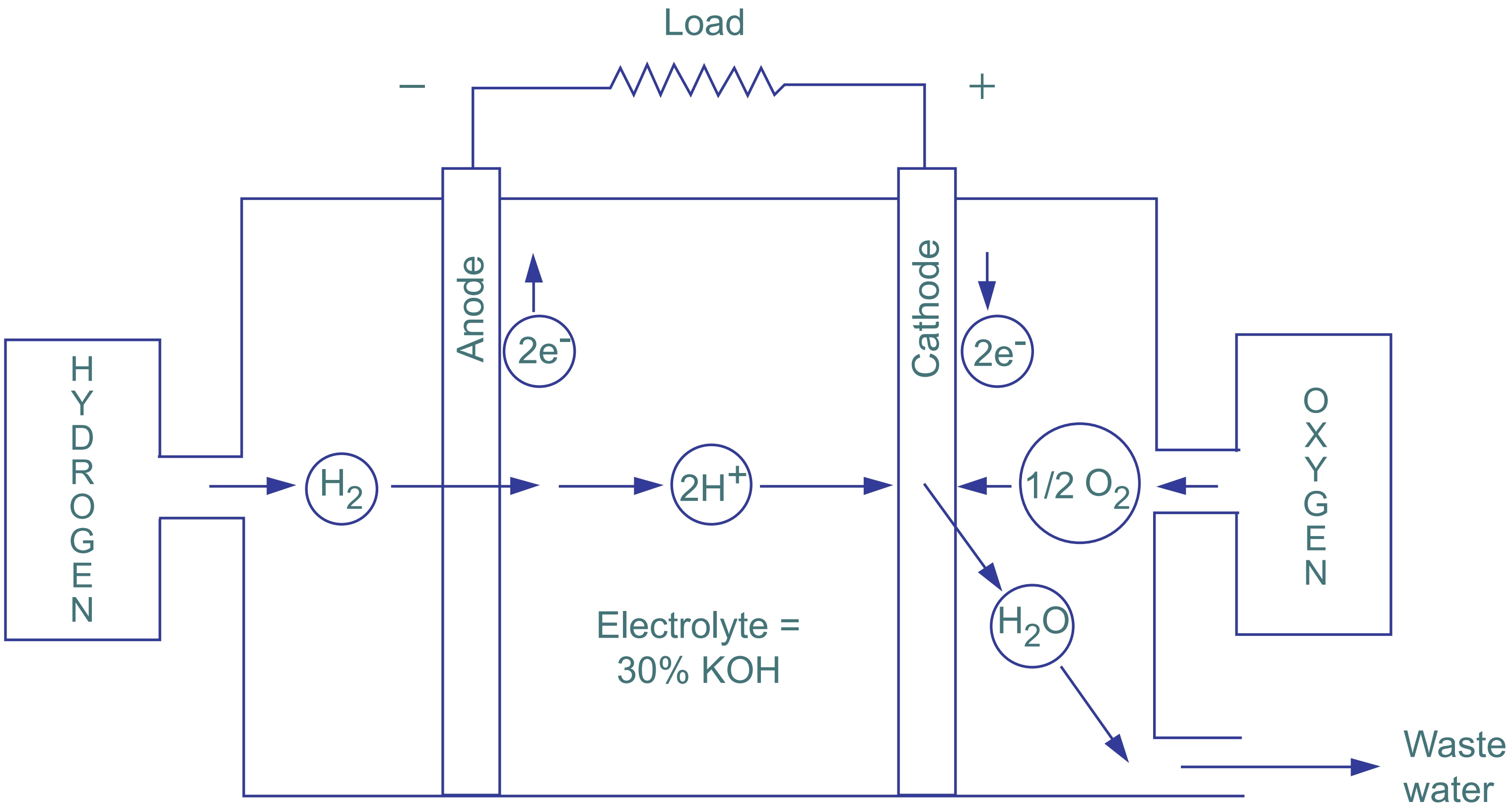
# Lithium Ion Cells

- Recently developed system, may provide distinct advantages over NiCd and NiH2
- Operating voltage is 3.6 to 3.9 v which reduces the number of cells
- 65% volume advantage and 50% mass advantage over state of the art systems

# Depth of Discharge

(Image removed due to copyright considerations.)

# Fuel Cells


Load
–
+
Anode
Cathode
2e⁻
2e⁻
HYDROGEN
$H_2$
$2H^+$
$1/2\ O_2$
OXYGEN
$H_2O$
Electrolyte = 30% KOH
Waste water

# Fuel Cell Characteristics

- Output voltage per cell 0.8 volts in practice
- Consumes hydrogen and oxygen, produces water as by-product (1 Pint/kW h)
- High specific power (275 W/kg)
- Shuttle fuel cells produce 16 kW peak
- Reaction is reversible so regenerative fuel cells are possible

# Radioisotope Thermoelectric Generators

- Used in some interplanetary missions
- Natural decay of radioactive material provides high temperature source
- Temperature gradient between the p-n junction provides the electrical output
- High temperatures
  - Lead telluride (300 – 500 deg C, silicon germanium >600 deg C
- Excess heat must be removed from the spacecraft

# (Dis) advantages of RTGs

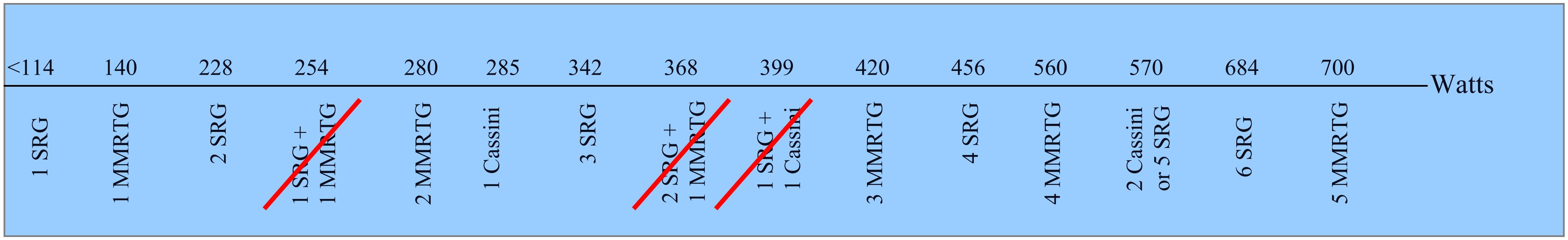
- **Advantages**
- Do not require sunlight to operate
- Long lasting and relatively insensitive to the chilling cold of space and virtually invulnerable to high radiation fields.
- RTGs provide longer mission lifetimes than solar power systems.
  - Supplied with RTGs, the Viking landers operated on Mars for four and six years, respectively.
  - By comparison, the 1997 Mars Pathfinder spacecraft, which used only solar and battery power, operated only three months.
- They are lightweight and compact. In the kilowatt range, RTGs provide more power for less mass (when compared to solar arrays and batteries).
- No moving parts or fluids, conventional RTGs highly reliable.
- RTGs are safe and flight-proven. They are designed to withstand any launch and re-entry accidents.
- RTGs are maintenance free..

- **Disadvantages**
- The nuclear decay process cannot be turned on and off. An RTG is active from the moment when the radioisotopes are inserted into the assembly, and the power output decreases exponentially with time.
- An RTG must be cooled and shielded constantly.
- The conversion efficiency is normally only 5 %.
- Radioisotopes, and hence the RTGs themselves, are expensive

# Subsystem: Power (RTG)

- Modeling, Assumptions and Resources:
  - RTG database
  - 3 RTG types used for modeling
  - General Purpose Heat Source (GPHS)
  - Batteries
  - Combinations of different types of RTGs

| Power Source | PBOL [We] | PEOL[We] | Mass [kg] | Dimensions [m] | Life[yrs] | Pu[kg] | Cost [M$] | TRL | Notes |
|---|---|---|---|---|---|---|---|---|---|
| Cassini RTG | 285 | 210 | 55.5 | D = 0.41,L=1.12 | 10.75 | 8 | 35.00 | 9 | 18 GPHS |
| New MMRTG | 140 | 123 | 32 | D = 0.41,L = 0.6 | 10 | 4 | 25.00 | 7 | 9 GPHS |
| SRG 1.0 | 114 | 94 | 27 | D = 0.27,L = 0.89 | 3 | 0.9 | 20.00 | 4 | 2 GPHS |

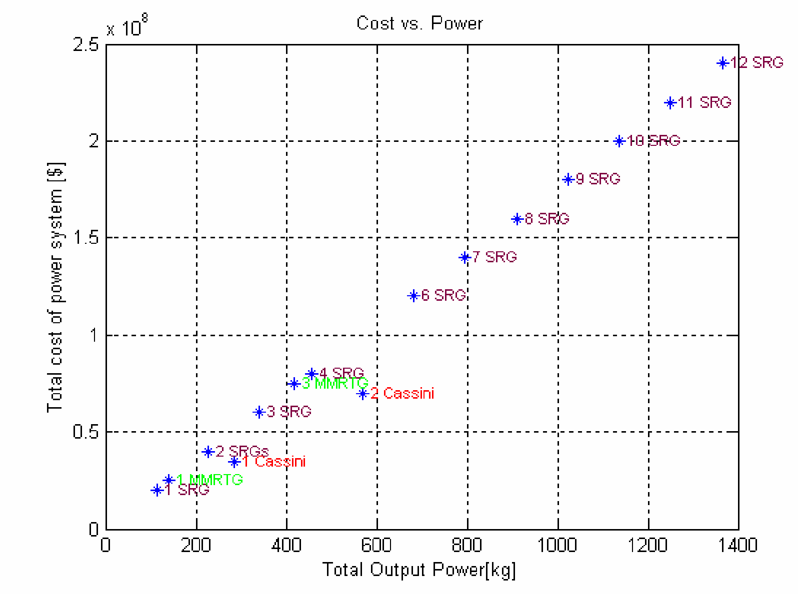


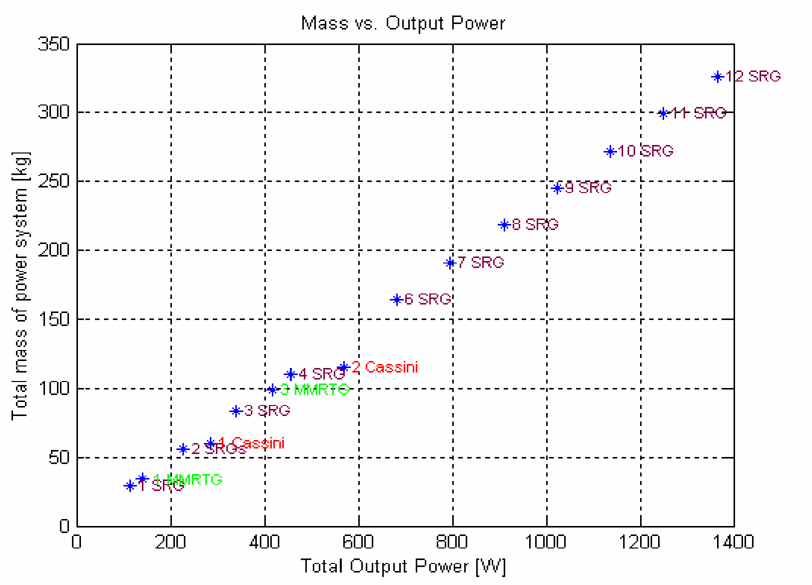
| Watts | |
|---|---|
| <114 | 1 SRG |
| 140 | 1 MMRTG |
| 228 | 2 SRG |
| 254 | ~~1 SRG + 1 MMRTG~~ |
| 280 | 2 MMRTG |
| 285 | 1 Cassini |
| 342 | 3 SRG |
| 368 | ~~2 SRG + 1 MMRTG~~ |
| 399 | ~~1 SRG + 1 Cassini~~ |
| 420 | 3 MMRTG |
| 456 | 4 SRG |
| 560 | 4 MMRTG |
| 570 | 2 Cassini or 5 SRG |
| 684 | 6 SRG |
| 700 | 5 MMRTG |

# Subsystem: Power (RTG)

- Validation of model:
  - Confirmation of data by multiple sources.
  - Tested ranges of variables:

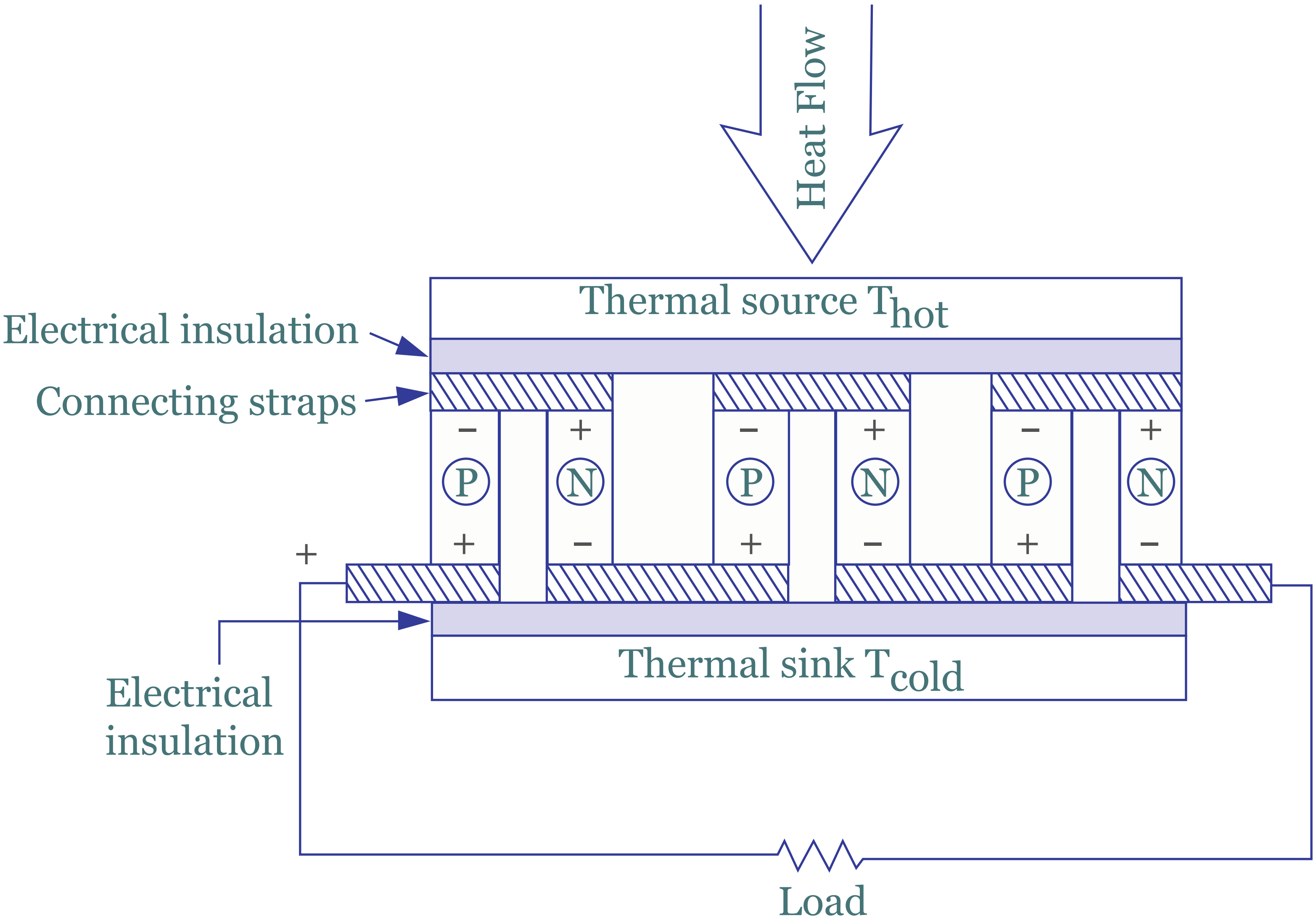
Hundreds of millions of $





KKG

# Thermoelectric Generator



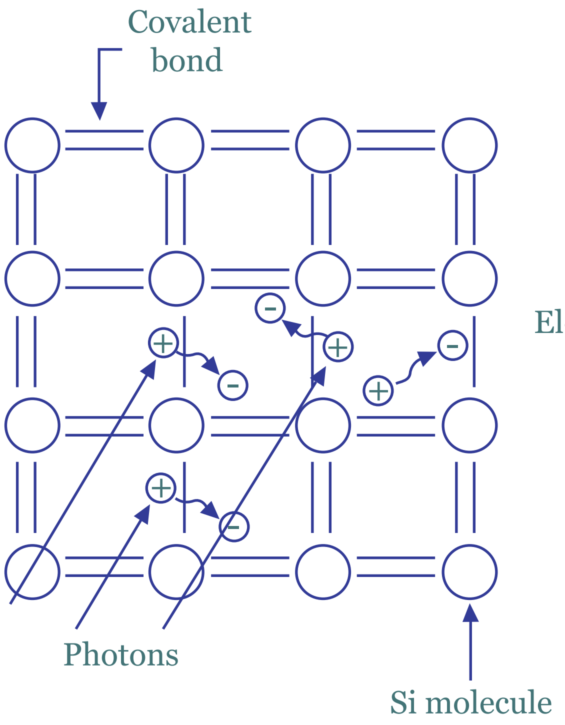
# Flywheel Energy Storage Modules (FESM) could replace batteries on Earth-orbit satellites.

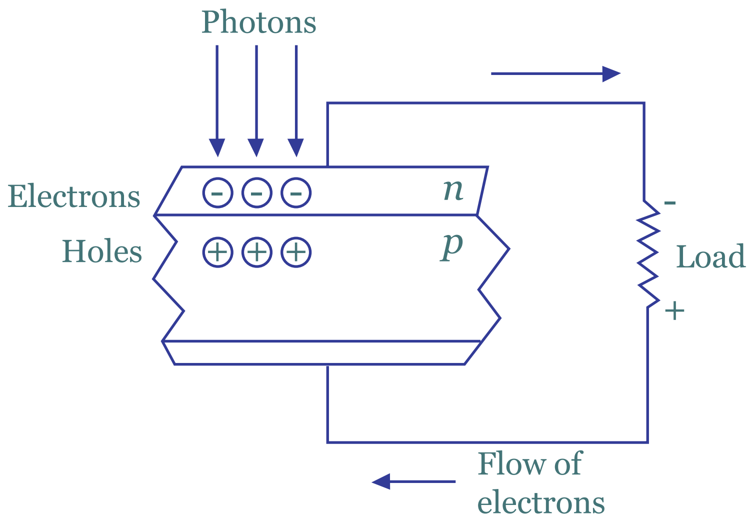
- While in sunlit orbit, the motor will spin the flywheel to a fully charged speed
  - generator mode will take over to discharge the flywheel and power the satellite during the eclipse phase
  - present flywheel technology is about four times better than present battery technology on a power stored vs. weight comparison.
- Weighing less than 130 lbs, the FESM is 18.4-in. in diameter by 15.9-in. in length
  - Delivers 2 kW-hr of useful energy for a typical 37-minute LEO eclipse cycle
  - high speeds of up to 60,000 rpm
- the current average for commercial GSO storage is 2,400 lbs of batteries, which is decreased to 720 lbs with an equivalent FESM.
- Honeywell has developed an integrated flywheel energy storage and attitude control reaction wheel
  - Energy stored in non-angular momentum change mode

# Solar Cell

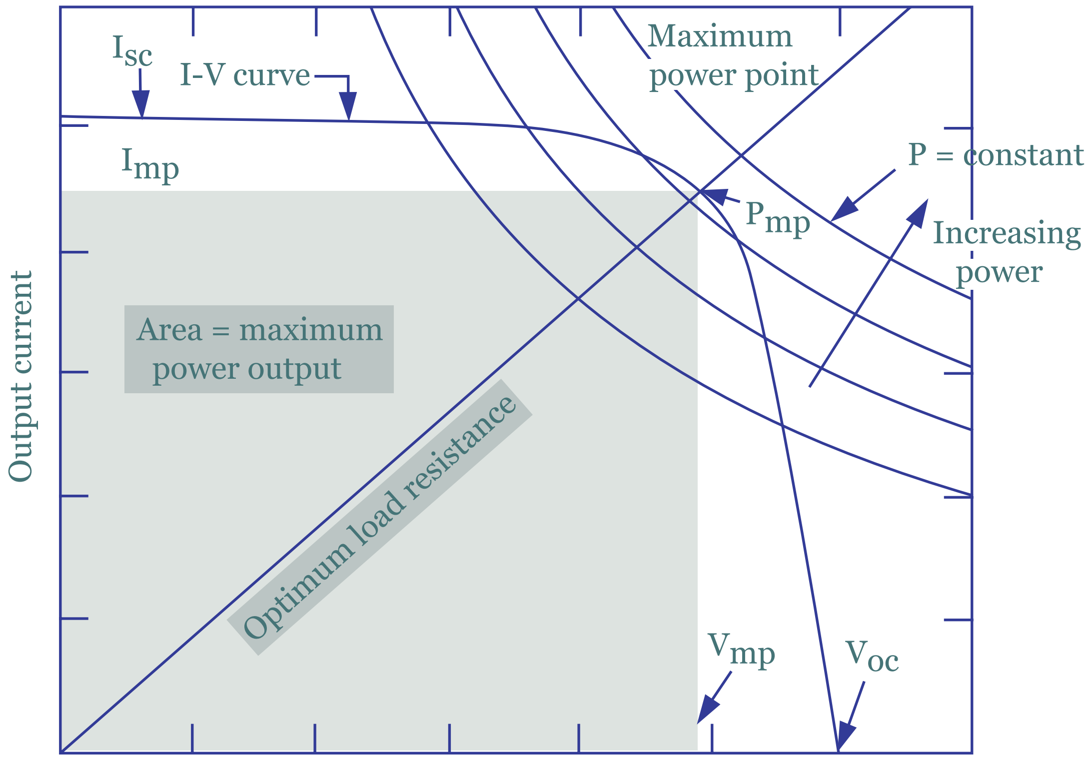
- Long heritage, high reliability power source
- High specific power, low specific cost
- Elevated temperature reduce cell performance
- Radiation reduces performance and lifetime
- Most orbits will require energy storage systems to accommodate eclipses

# Solar Cell Physics





# Solar Cell Operating Characteristics



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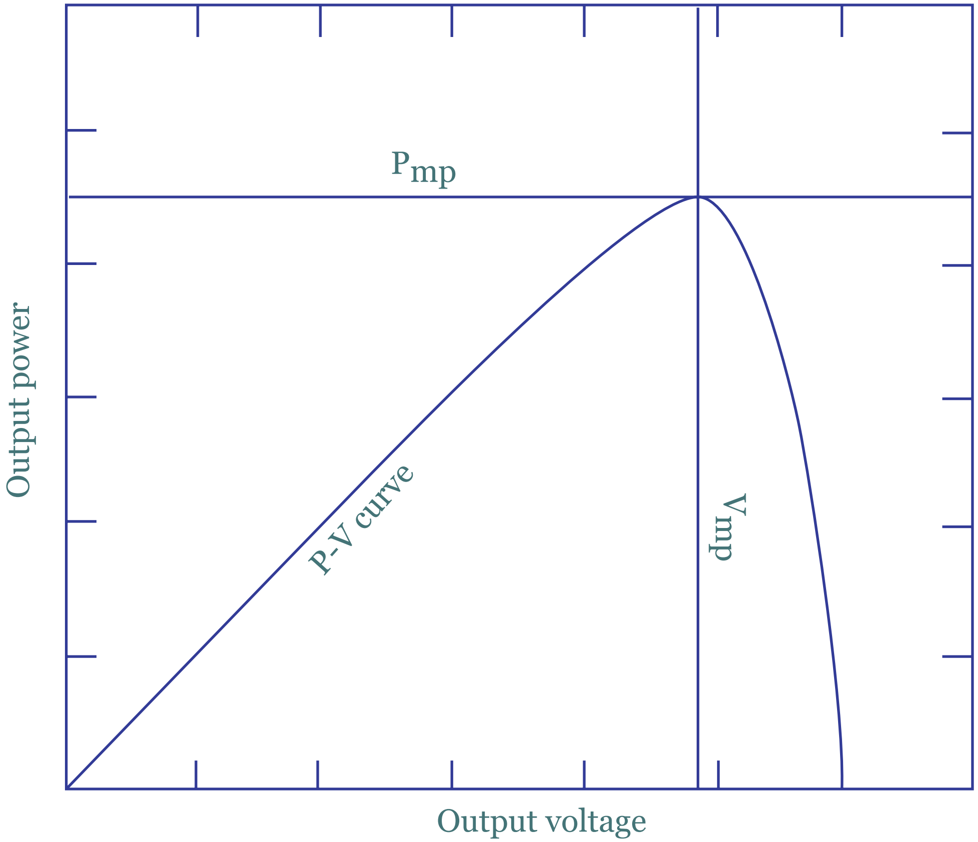
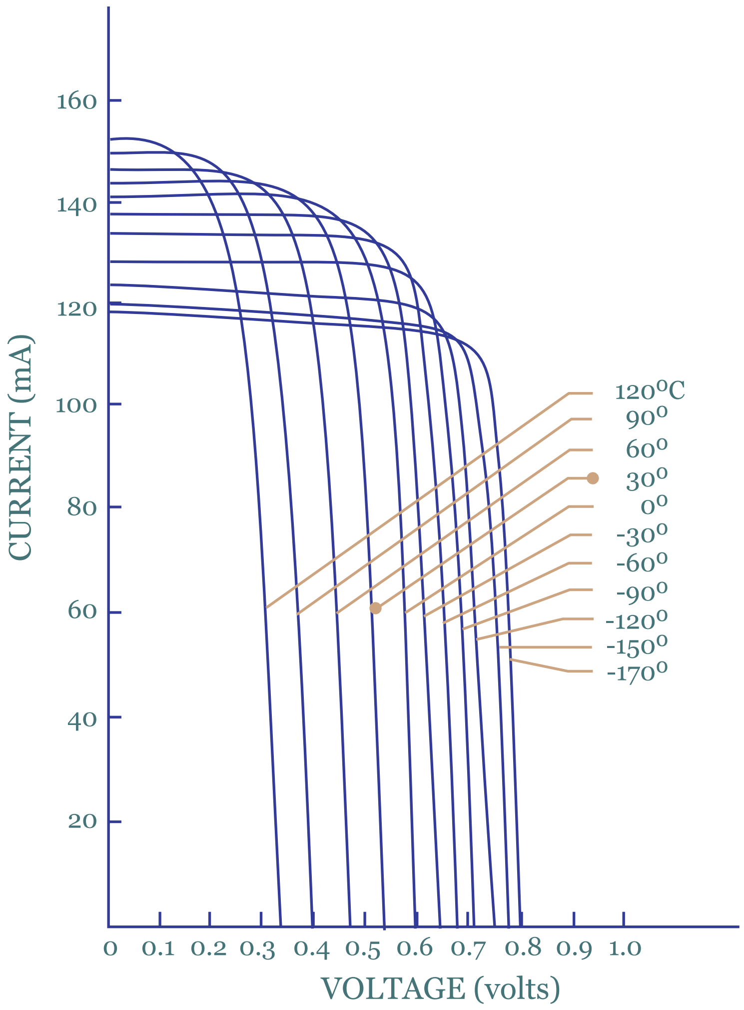
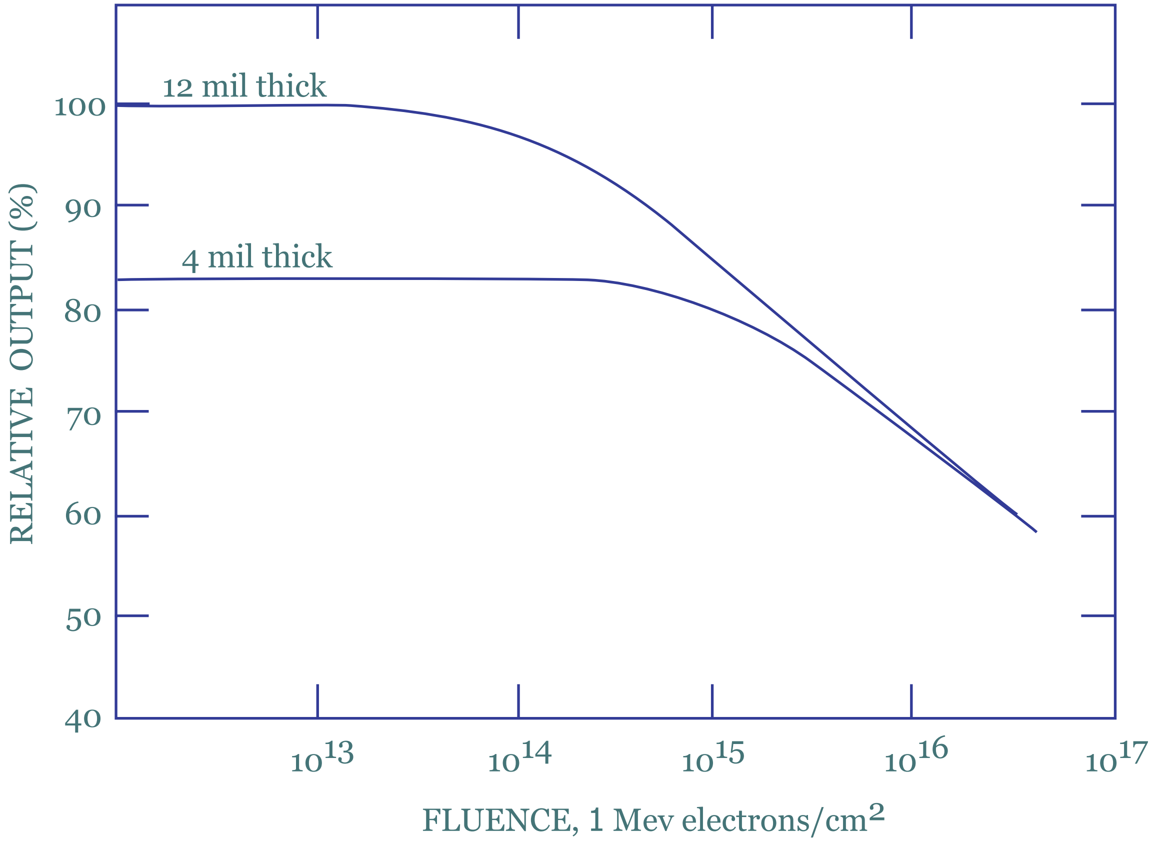


# Temperature Effects



Voltage - current characteristics vs cell temperature
for 2 x 2 cm 10 ohm cm N/P solar cell
Silicon thickness 0.012 inch, active area 3.9 cm$^2$
Spectrosun solar simulator = AMO
Balloon calibration

# Radiation Effects



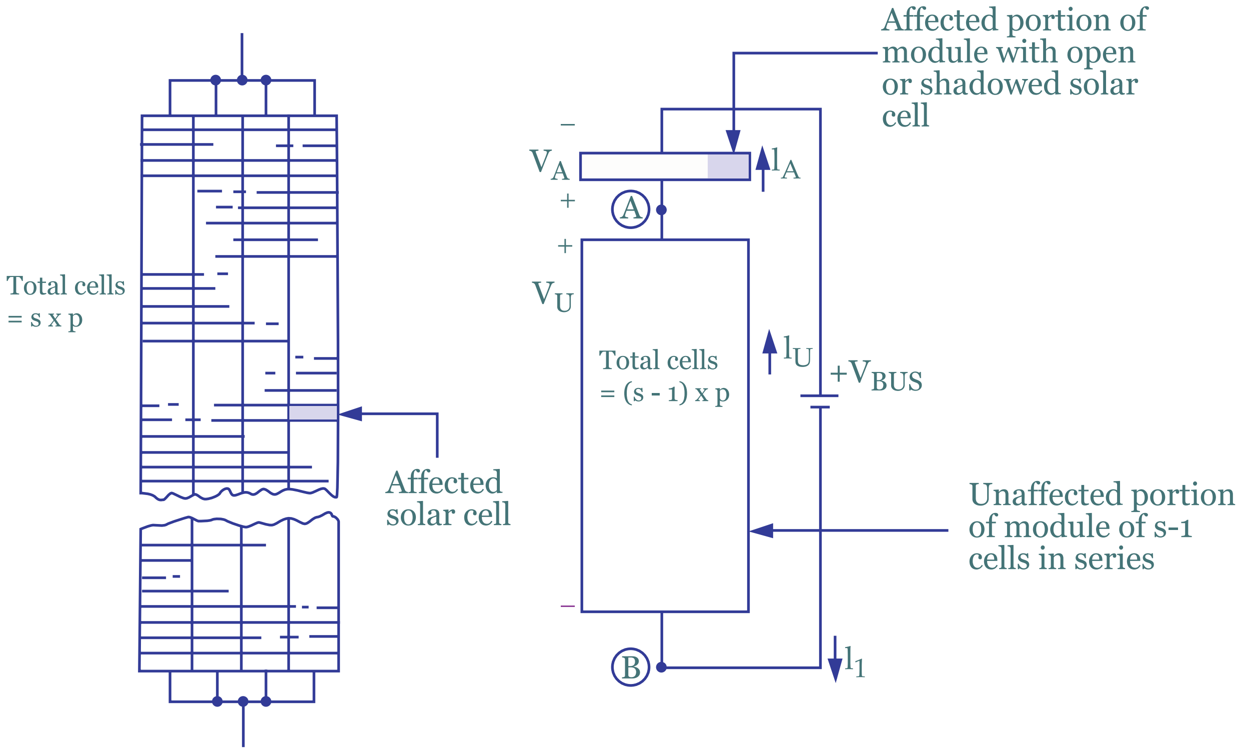
# Alternate Solar Cell Technologies

| **Cell type** | **Silicon** | **Thin sheet amorphous Si** | **Gallium Arsenide** | **Indium Phosphide** | **Multijunction GaInP/GaAs** |
|---|---|---|---|---|---|
| Planar cell theoretical efficiency | 20.8% | 12.0% | 23.5% | 22.8% | 25.8% |
| Achieved efficiency: | | | | | |
| Production | 14.8% | 5.0% | 18.5% | 18% | 22.0% |
| Best laboratory | 20.8% | 10% | 21.8% | 19.9% | 25.7% |
| Equivalent time in geosynchronous orbit for 15% degradation | | | | | |
| - 1 MeV electrons | 10 yr | 10 yr | 33 yr | 155 yr | 33 yr |
| - 10 McV electrons | 4 yr | 4 yr | 6 yr | 89 yr | 6 yr |

# Solar Array Construction

- Construct arrays with cells in series to provide the required voltage
- Parallel strings provide required current
- Must plan for minimum performance requirements
  - Radiation affects at end of life, eclipse seasons and warm cells
- Shadowing can cause cell hot spots and potentially cascading failure

# Cell Shadowing



Total cells = s x p

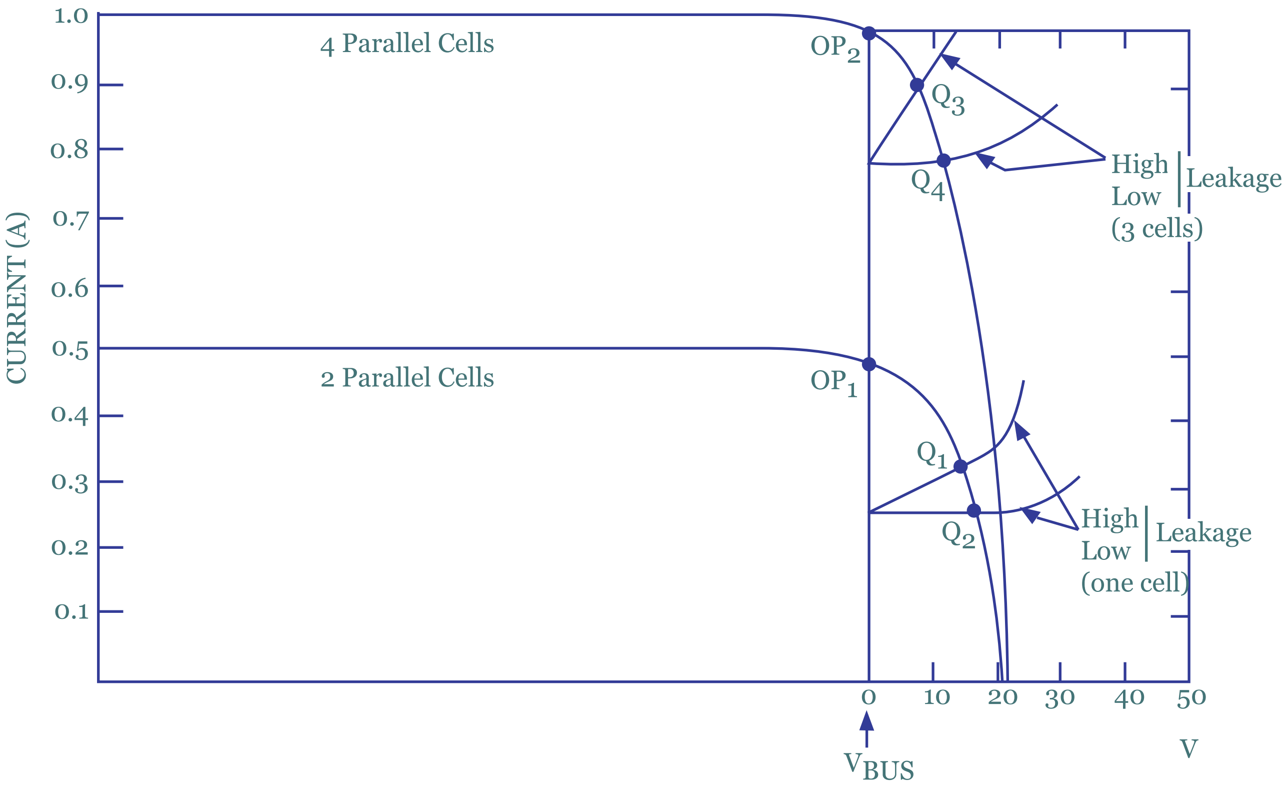
Affected solar cell

Affected portion of module with open or shadowed solar cell

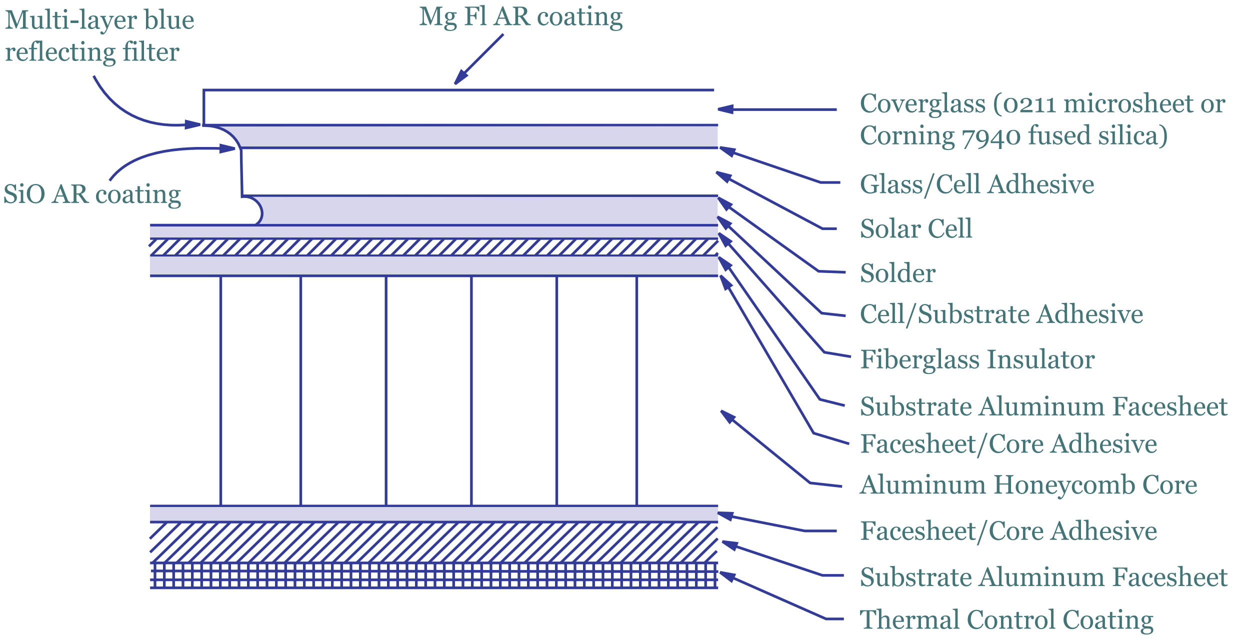
Total cells = (s - 1) x p

Unaffected portion of module of s-1 cells in series

# Cell Shadowing



# Solar Array Construction



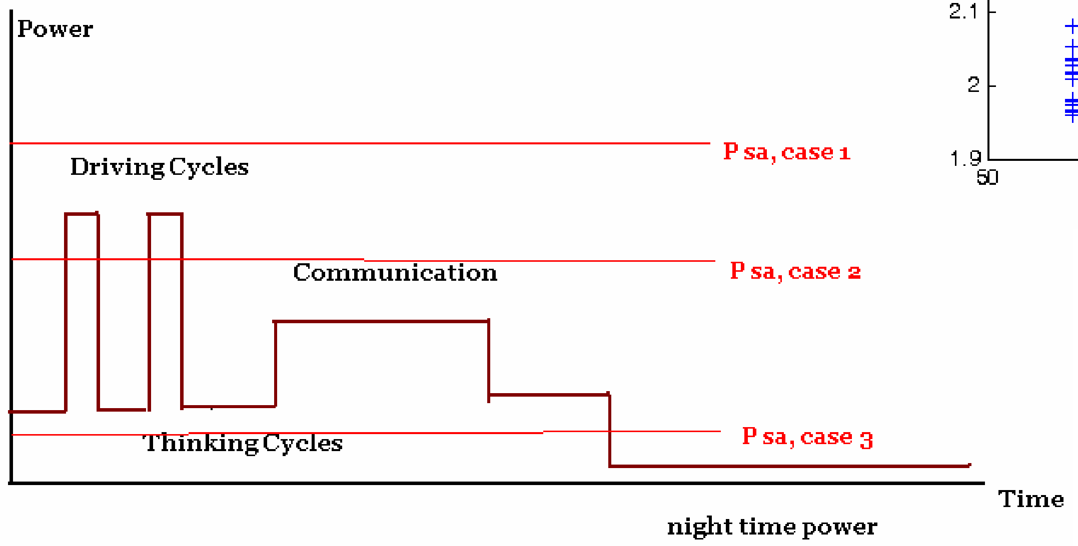
# Power Supply-Demand Profiling

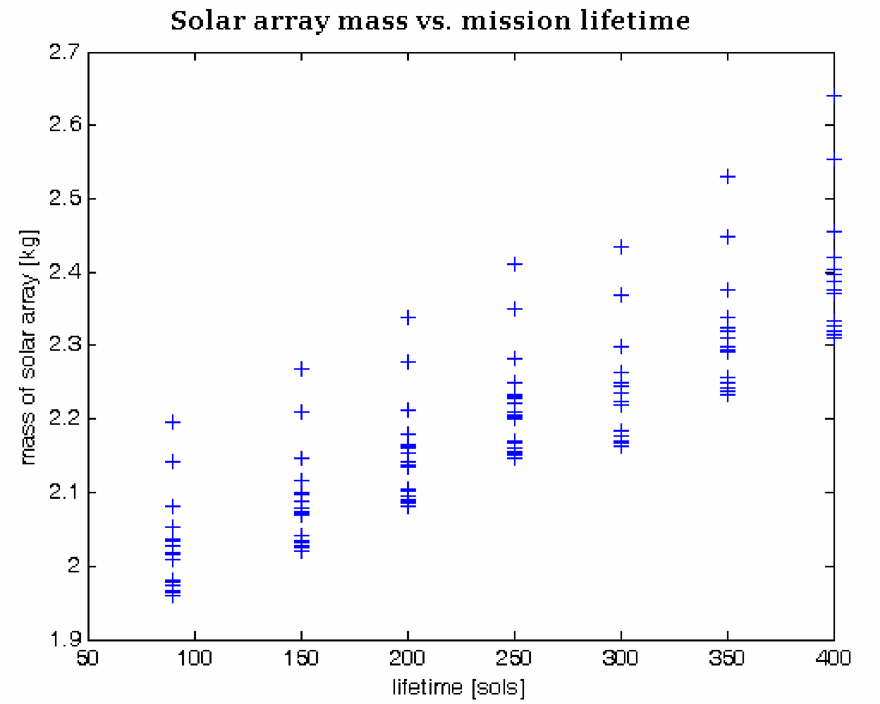
- Solar array:

Silicon GaAs Multi junction

- Batteries:

| Secondary Battery | Specific energy density (W-hr/kg) |
|---|---|
| Nickel-Cadmium | 25-35 |
| Nickel hydrogen | 30 |
| Lithium-Ion | 70 |
| Sodium-Sulfur | 140 |





$$L_d = \left(1 - \frac{\deg radation}{year}\right)^{Rover's lifetime}$$

RN

# Power Distribution Systems

- Power switching usually accomplished with mechanical or solid-state FET relays
- Load profiles drive PDS design
- DC-DC converters isolate systems on the power bus
- Centralized power conversion used on small spacecraft
- Fault detection, isolation and correction

# DET Power Regulation Systems

- Direct Energy Transfer (DET) systems dissipates unneeded power
  - Typically use shunt resistors to maintain bus voltage at a predetermined level
  - Shunt resistors are usually at the array or external banks of resistors to avoid internal heating
- Typical for systems less than 100 W

# PPT Power Distribution Systems

- Peak Power Trackers (PPT) extract the exact power required from the solar array
  - Uses DC to DC converter in series with the array
  - Dynamically changes the solar array's operating point
  - Requires 4 - 7% of the solar array power to operate

# Other Topics

- Lenses are sometimes used to concentrate solar energy on cells
  - Higher efficiency
  - Some recent evidence of premature degradation
- Tethers
  - $F_{electron}$=e(vxB), decay orbital energy to produce electricity
  - Use high $I_{sp}$ propulsion to spin up tethers over many orbits
  - Discharge tether rapidly using it as a slingshot to boost payloads into higher orbits or Earth escape