Power

MAE 4160, 4161, 5160

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Today's topics:

- Power system design process
- Power requirements
- Power subsystem elements
- Power technologies
    - solar cells
    - batteries
    - RTG's
    - fuel cells
    - tethers
    - flywheels
    - nuclear reactors

What is the power subsystem for?

- Supply a continuous source of electrical power to spacecraft/vehicle loads during mission lifetime
- Control/distribute electrical power to spacecraft/vehicle
- Support power requirements for average and peak electrical loads
- If necessary, provide converters for AC and regulated DC power buses
- Provide command and telemetry capability for Power health and status, as well as control by ground station or an autonomous system
- Protect the spacecraft against failures within the Power system
- Suppress transient bus voltages and protect against bus faults
- Provide ability to fire ordnance, if required

As always, we design the power system to meet *requirements*.

TABLE 11-32. Effects of System-Level Parameters on the Power Subsystem. Most aspects of the mission affect the power subsystem because so many other subsystems require specific power attributes.

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

Power system design process

Main Requirements:

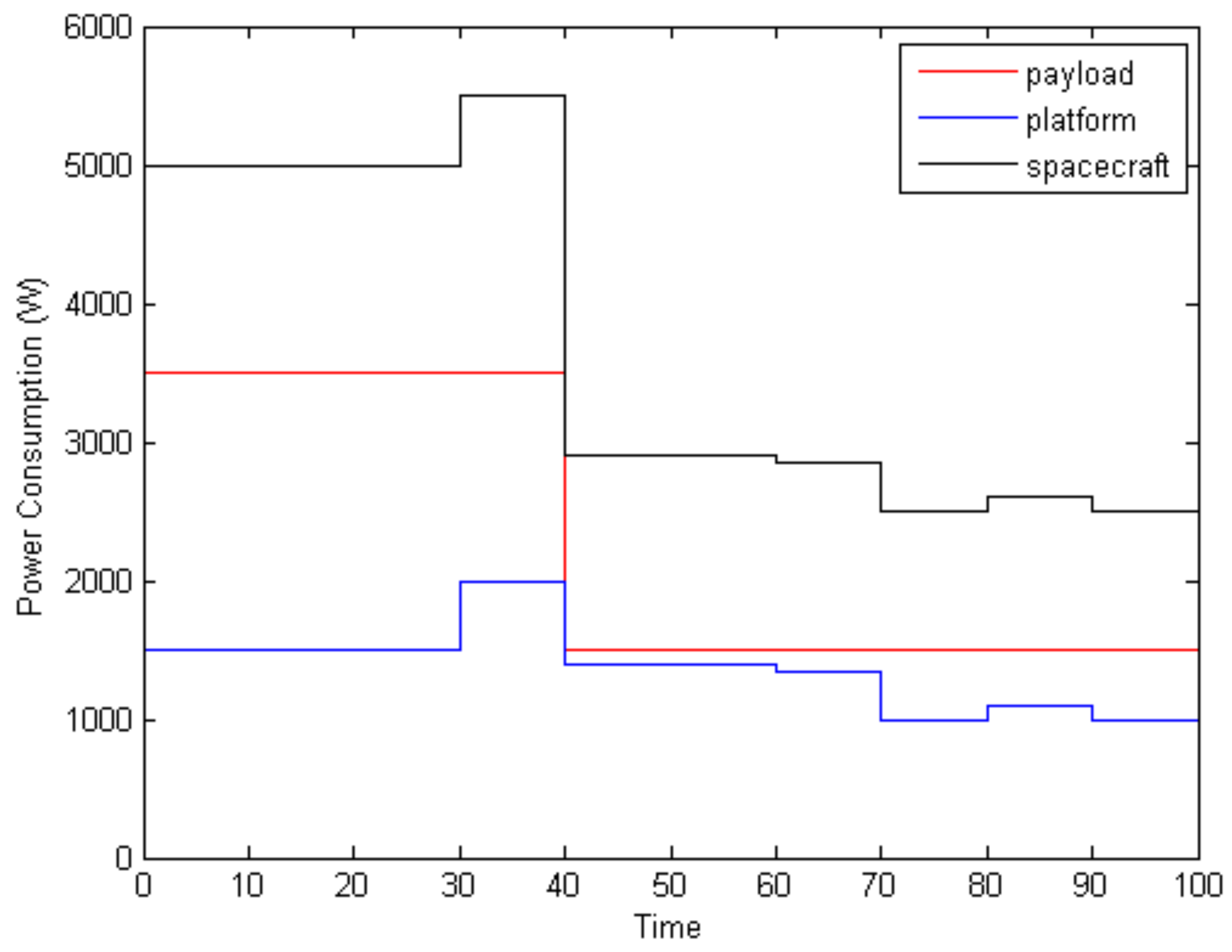
- Average and peak power requirements from payload+bus (at minimum) or distribution over time (better)
- Illumination: worst case sun angle, irradiance, and eclipse (at minimum), or distributions over time (better)
- Voltages and current requirements, including average values and max noise
- Lifetime (degradation)
- Mass, volume, reliability

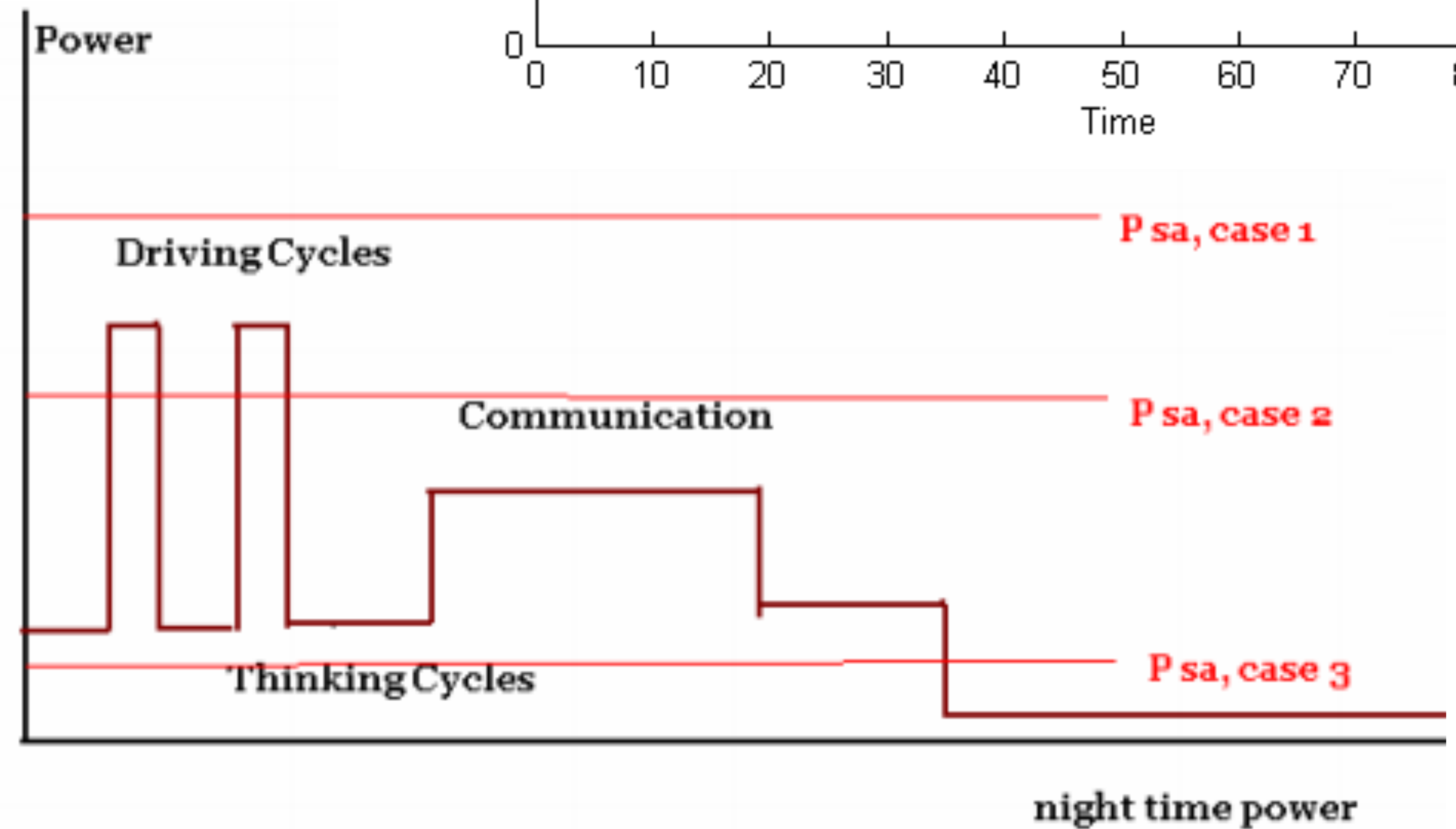
Main Functions:

- Power generation
- Energy storage
- Power regulation
- Power conditioning
- Power distribution
- Poser isolation (safety)

Power budgets

- Power requirement for a component/ subsystem is **not a single number in the power budget.** It changes with time
  - Instruments on/off (duty cycle)
  - Communications on/off
  - Thrusters on/off
  - Heaters on/off
- Power requirement descriptors:
  - Peak power (e.g., on transmitting)
  - Baseline power (e.g., on, no transmitting)
  - Dormant power (off)

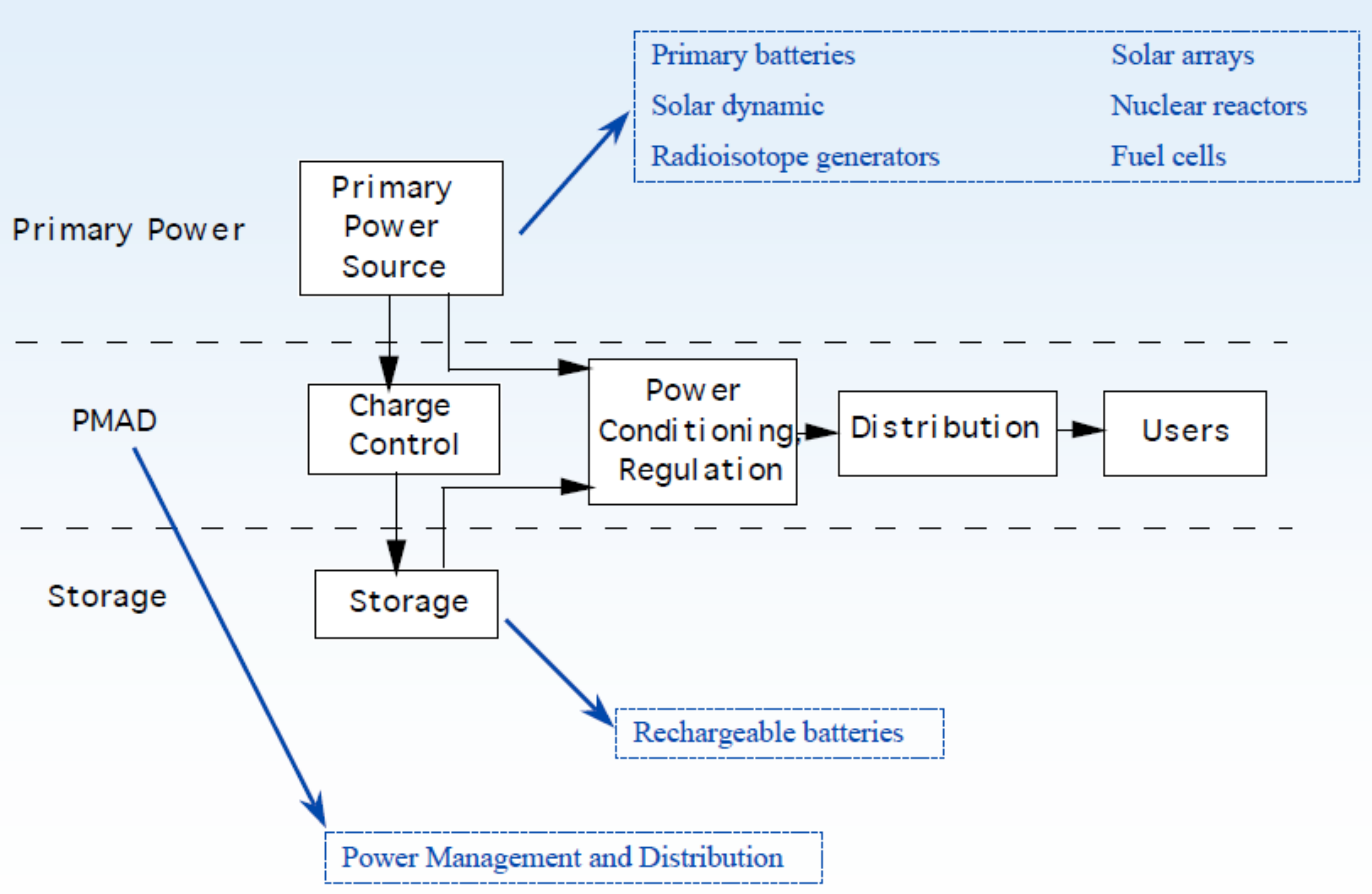




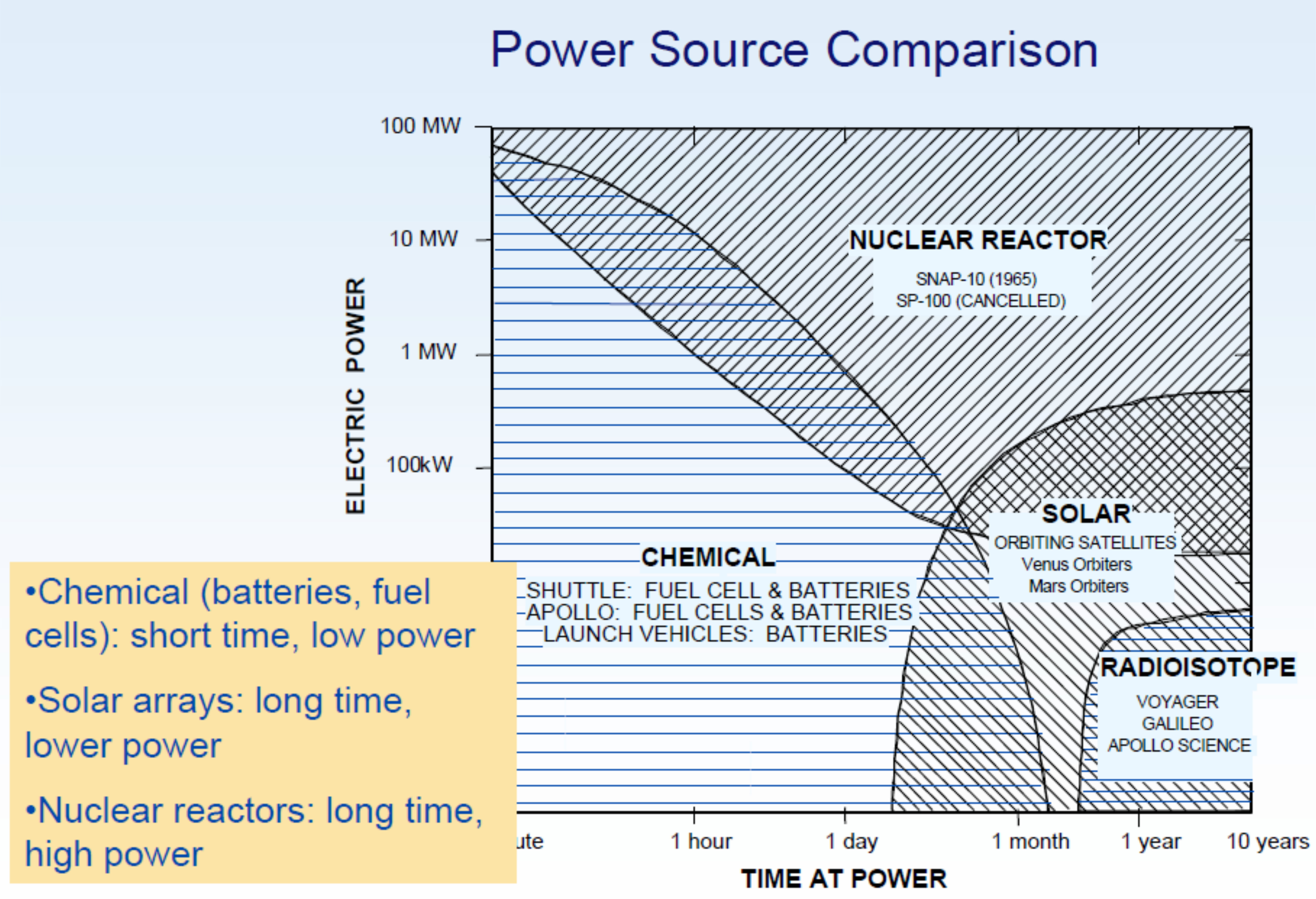
Subset of an ~SDR-level power analysis for a cubesat in LEO

	Peak Power (mW)	Duty Cycle	Average Power (mW)		
Flight Computer	150	100%	150		ATMega 2560
Sun Sensor	50	100%	50		Sinclair SS-411
Star Tracker	500	25%	125		Sinclair ST-16
Gyro	20	100%	20		ST Microelectronics L3G4200D
Radio	3000	10%	300		HopeRF RFM23BP
GPS Receivers	500	50%	750		Swift-Nav Piksi (3 units)
Thrusters	30000	0.1%	30		Moog Solenoid Valve
Reaction Wheels	75	25%	18.75		Faulhaber 2610B
		Total:	**1443.75**		
Solar Panels	4000	60%	2400		
		Margin:	**956.25**	**66%**	

Power subsystem elements



Power generation technologies

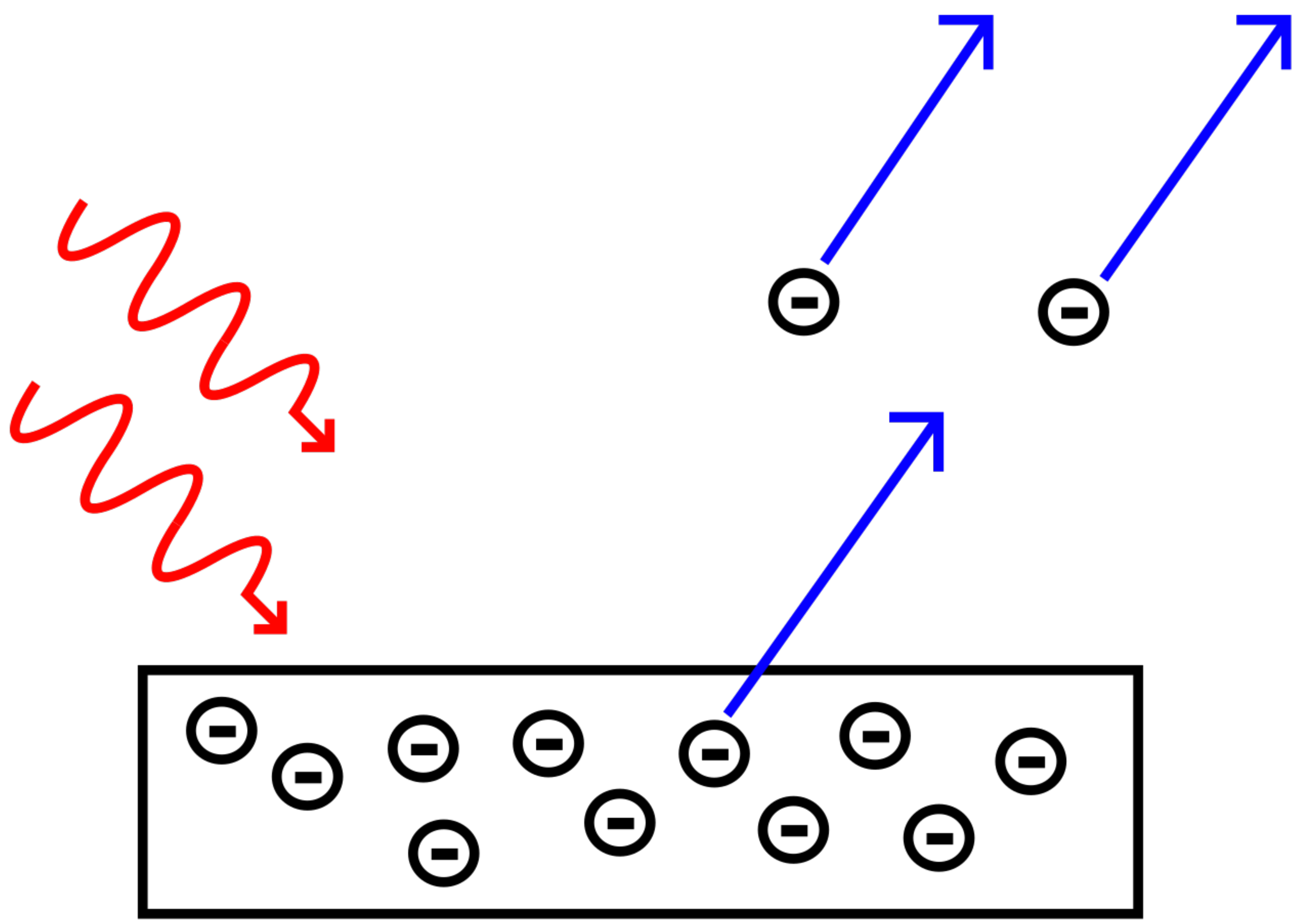


- Chemical (batteries, fuel cells): short time, low power
- Solar arrays: long time, lower power
- Nuclear reactors: long time, high power

Photovoltaic power generation

Converts energy from the Sun (photons) into a flow of electrons via the **photovoltaic effect**

- Photons in sunlight hit the solar panel and are absorbed by semi-conducting materials
- Electrons absorb enough energy from the photons to be knocked loose of their atoms. The structure of the solar cell ensures that the electrons may only move in a single direction.
- This flow of electrons is the DC current which powers the spacecraft, or which may flow into batteries for energy storage.
- Very similar to the photoelectric effect

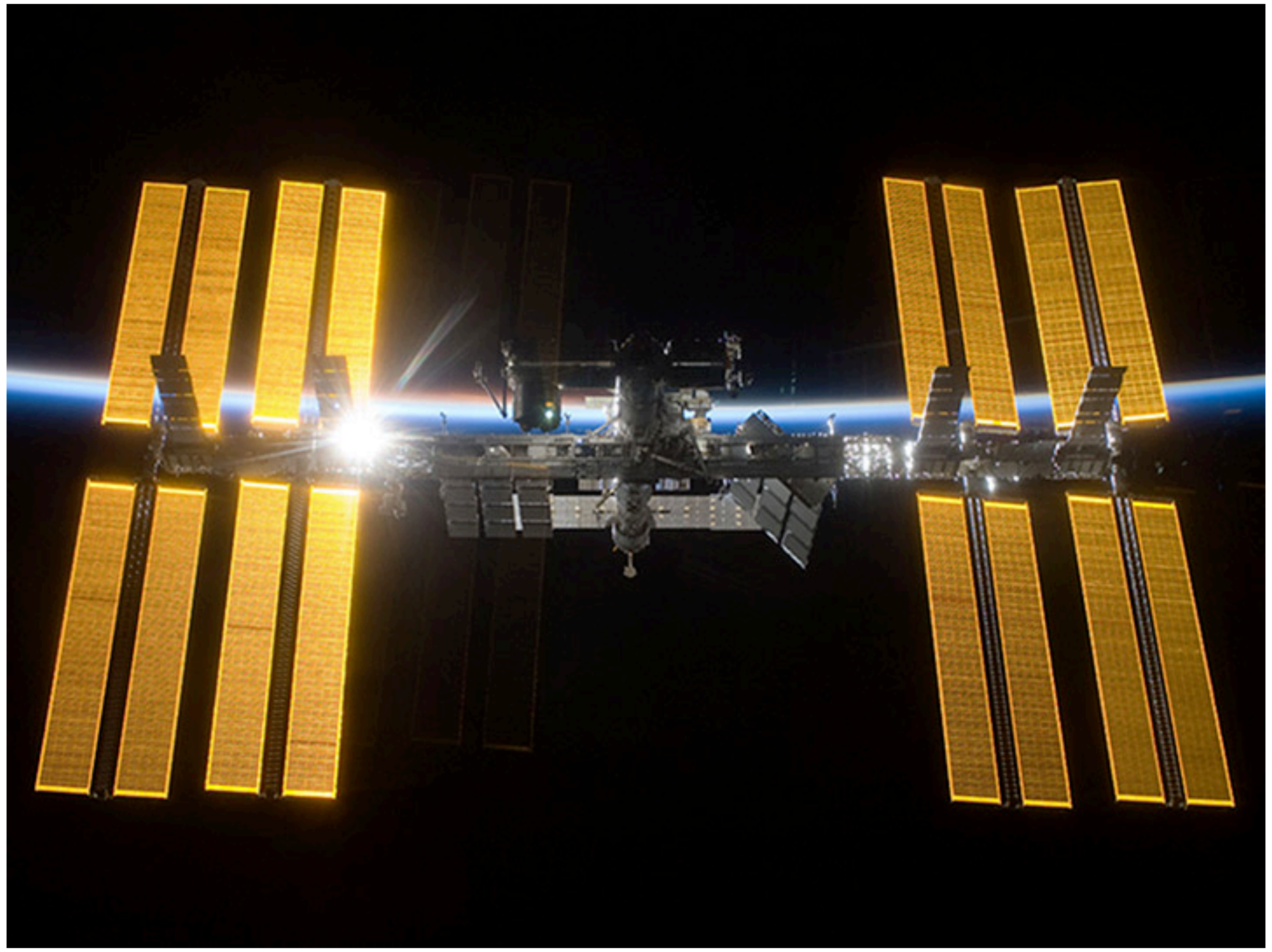


What variables affect power generated via the photovoltaic effect?

Solar cells: advantages and disadvantages

- Assuming that incident photons have sufficient energy to dislodge electrons, the power generated then depends on the intensity of those photons.
- Intensity decreases with distance from the Sun *squared*, so only viable if close to the Sun (up to 1.5 AU)
- The exception to the above was **Juno**, which used $60m^2$ of solar cells at Jupiter (5 AU).
- High specific power (25-300 W/kg)
- Fixed vs. 1-axis vs. 2-axis gimbal
- Body mounted vs. deployable

“Photoelectric effect” - Nobel Prize for Einstein



~2500 m^2, 84-120 kW

> half the area of a football field

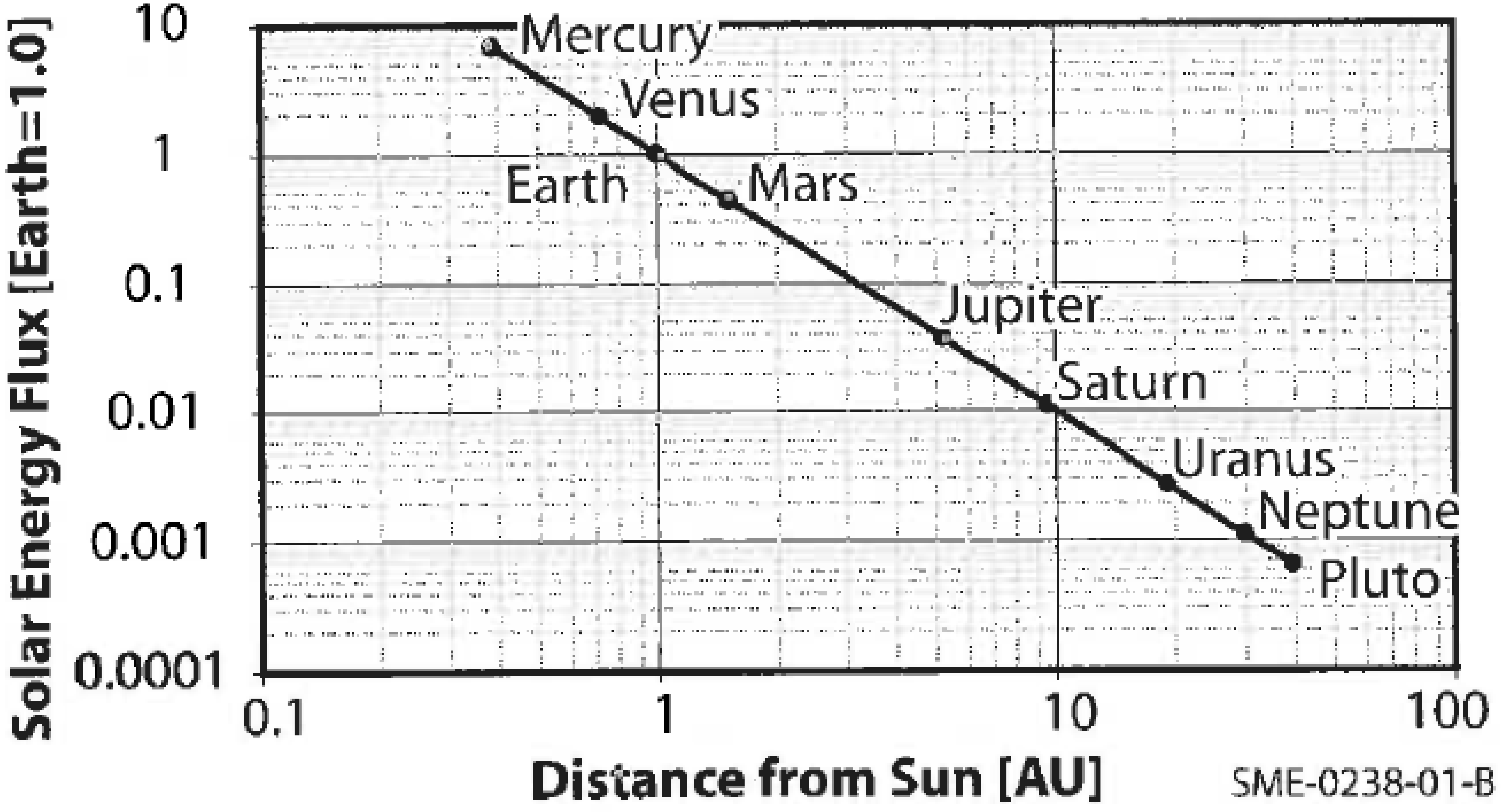
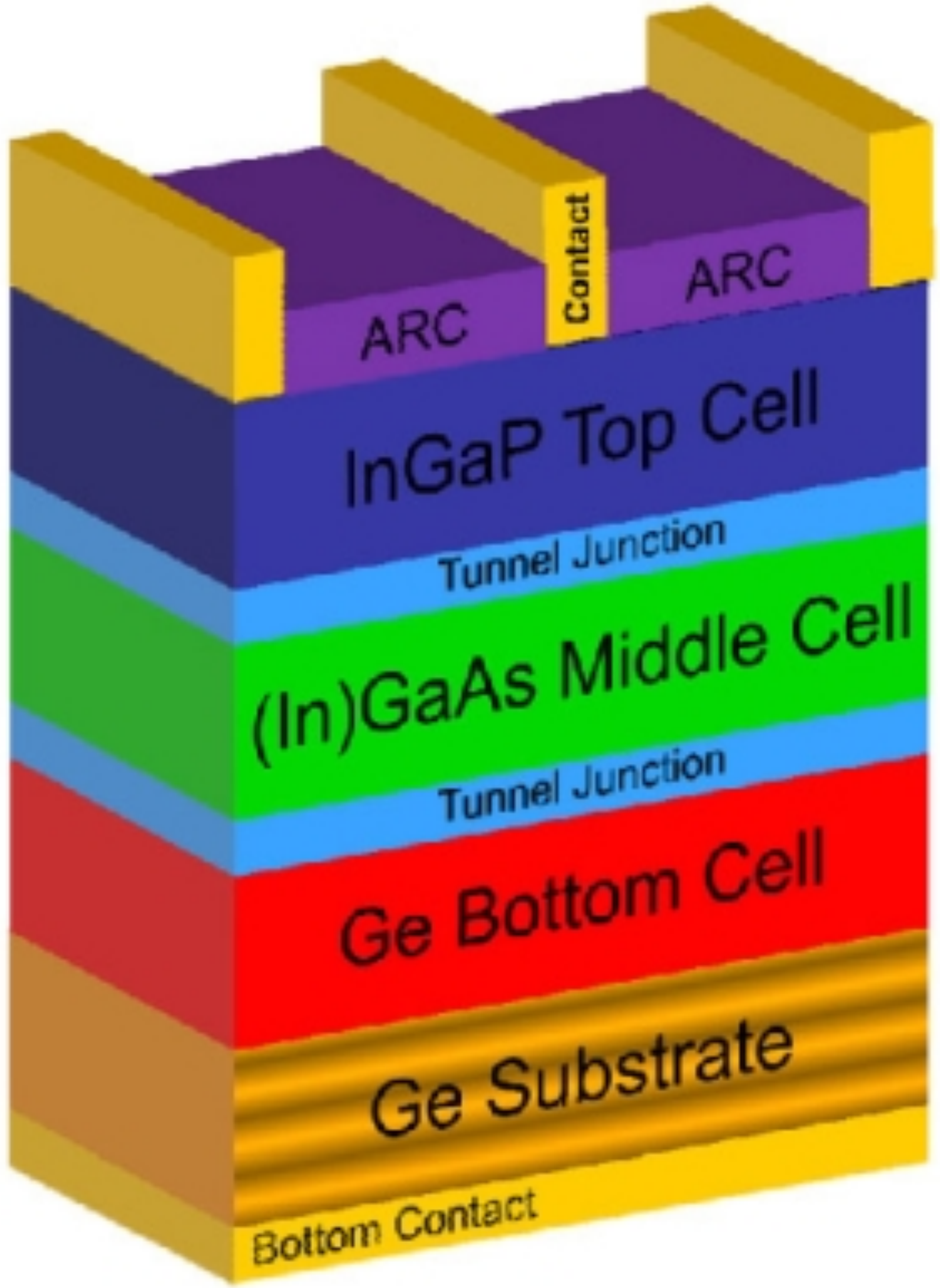


Fig. 21-24. Solar Energy vs. Distance from the Sun. The quick reduction of solar flux past Mars requires very large solar arrays, as shown for NASA's Juno spacecraft and its mission to Jupiter. Missions past Jupiter require a non-solar power source, such as a Radioisotope Thermoelectric Generator (RTG) based power source.

Solar cells: types and efficiency

- Theoretical solar cell efficiency: $\eta = \frac{P_{out}}{P_{in}}$
  - $P_{in} = 1386 W/m^2$ at 1 AU
- **Types:**
  - **Silicon**
    - Old, cheap, lots of heritage
    - $\eta \approx 15\,\%$
  - **Gallium Arsenide**
    - Slightly better than Is
    - $\eta \approx 20\,\%$
  - **Multi-junction**
    - State of the art
    - Several semiconductor layers
    - $\eta \approx 30\,\%$



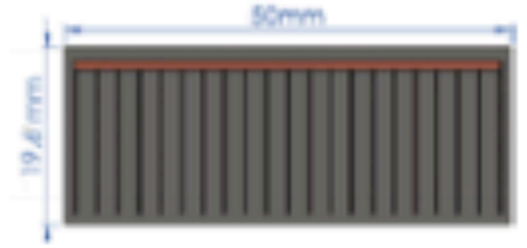
Triple-junction solar cell

An example

Dual-junction Ga-As cells from Alta Devices

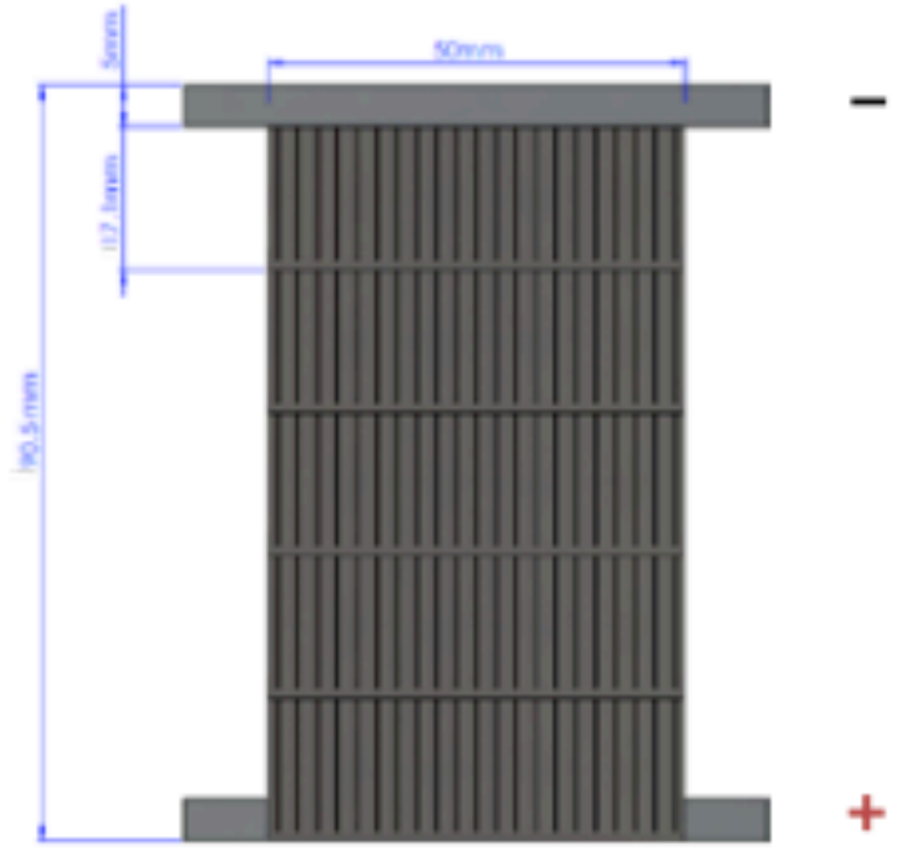
This technology performance brief is for the dual junction Gallium Arsenide photovoltaic product currently produced by Alta Devices. Cell-to-cell interconnect and cover lamination can be provided at customer's request.

Unshingled Cell

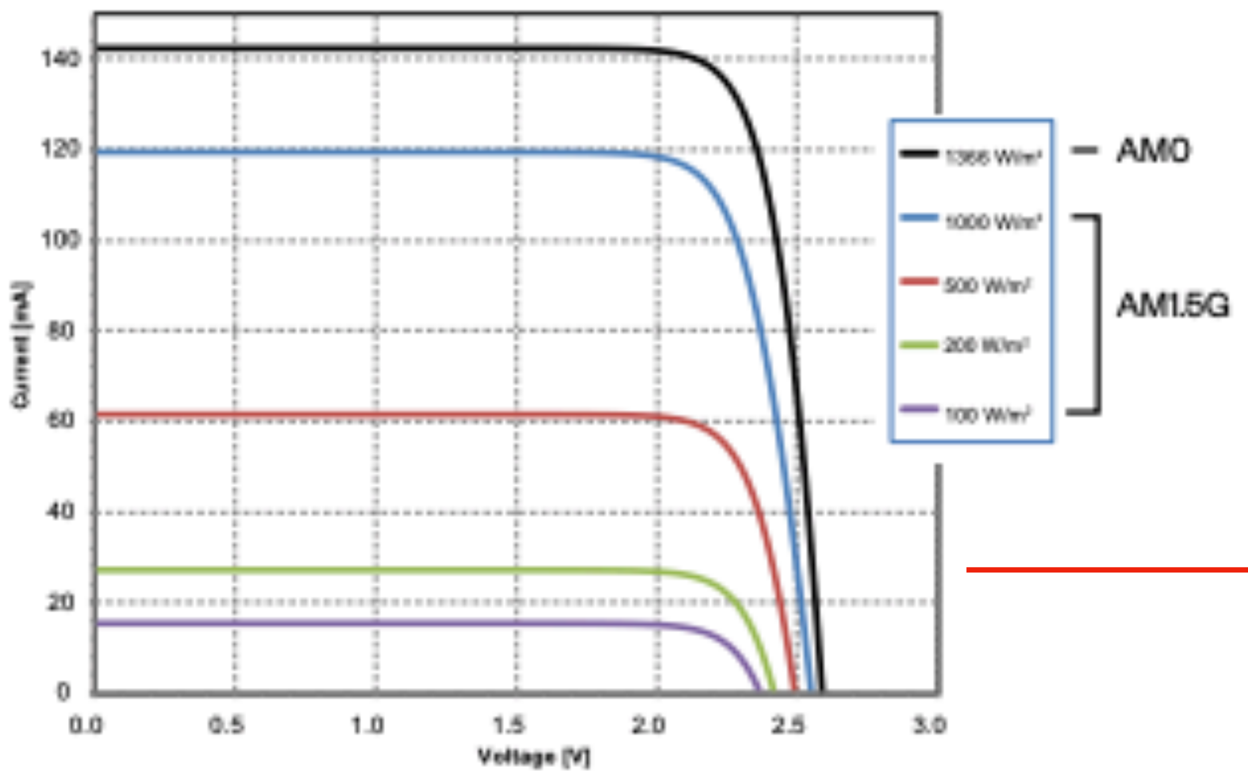


Example of 5x1: 5 Shingled Cells in Series

Assembly and Leads Provided by Alta Devices



Shingled IV Performance



I-V curves

Mechanical Characteristics		
Unshingled Area	mm	50 x 19.6
Shingled Area	mm	50 x 17.1
Density (Unshingled)	g/m²	114
Weight per cell (Unshingled)	g	0.112
Radius if Curvature	cm	> 5

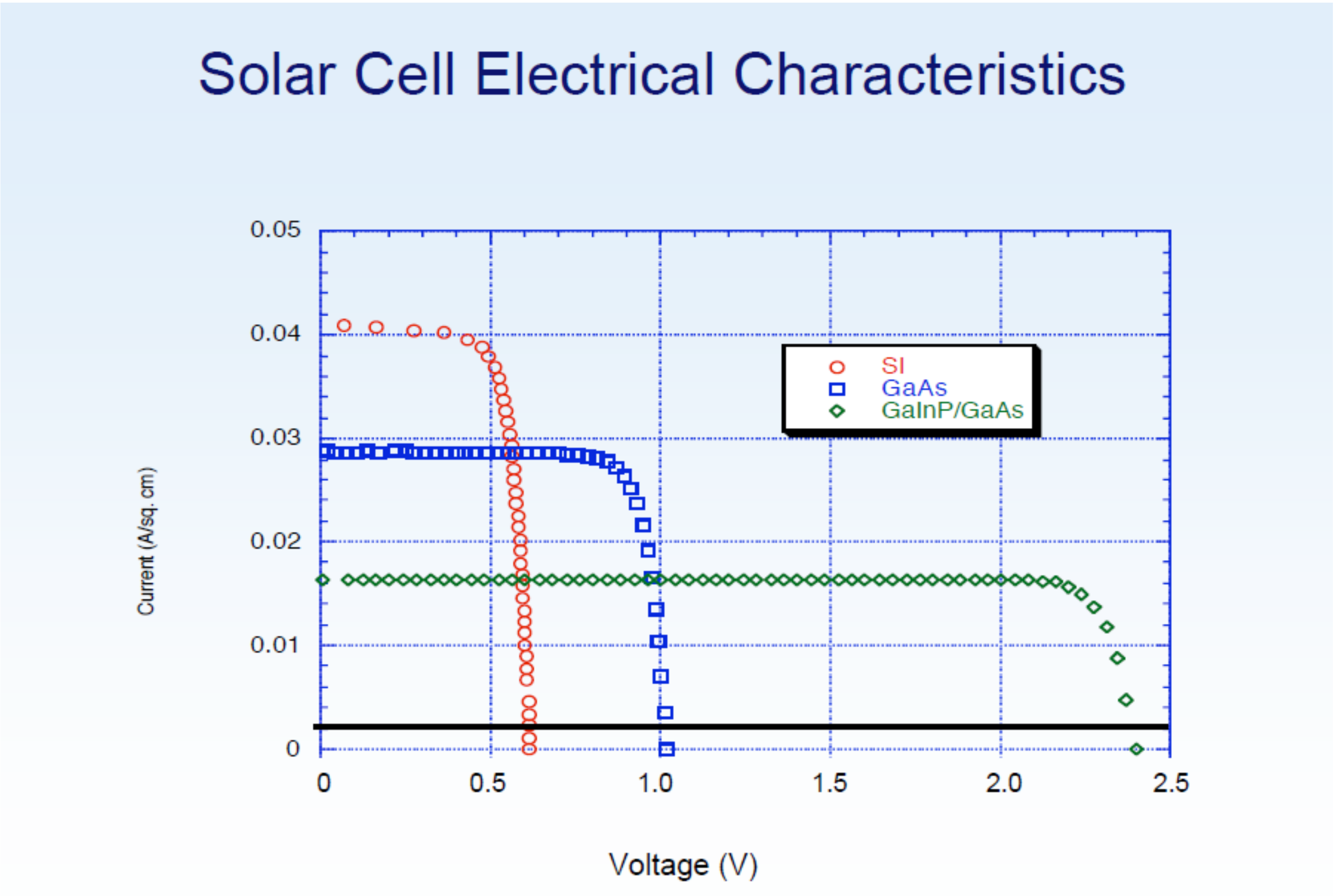
Electrical Characteristics		Typical at AM1.5, 1000W/m², 25°C	Estimated at AM0, 1366W/m², 25°C
Efficiency	[%]	29	25
Power per cell (Unshingled)	[W]	0.28	0.34
Power per cell (Shingled)	[W]	0.25	0.30
Power density	[W/m²]	290	345
Open Circuit Voltage (Voc)	[V]	2.54	2.59
Max Power Voltage (Vmp)	[V]	2.14	2.14
Short Circuit Current (Isc)	[mA]	119	142
Max Power Current (Imp)	[mA]	116	138

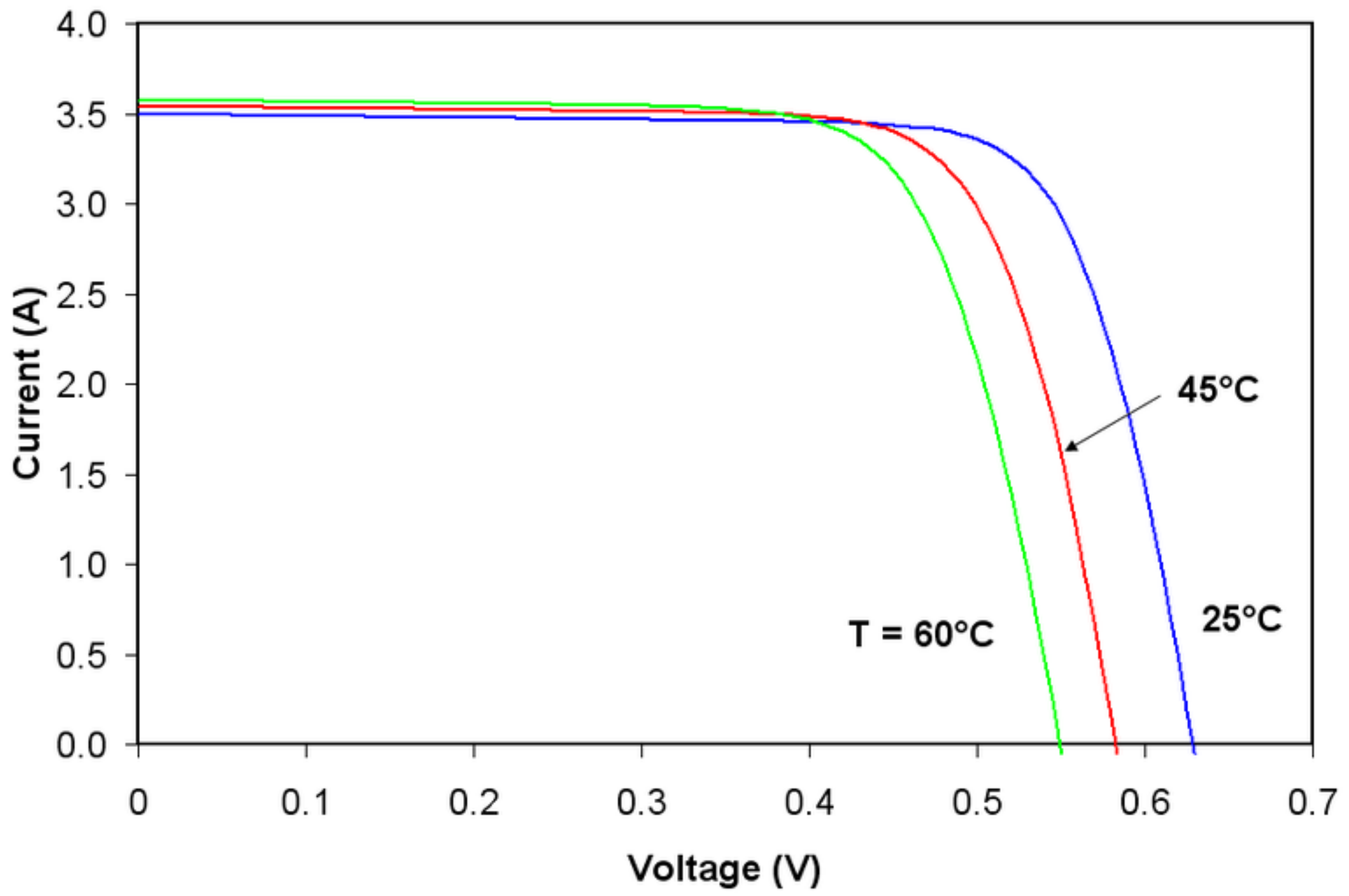
Values correspond to shingled cells and represent optimal performance unless otherwise stated. Actual performance depends on product size and encapsulation.

Efficiency

Solar cells: I-V curves

- Solar cells are characterized by IV curves. These show all of the combinations of voltage and current that a cell can produce
  - Voltage at I=0 (open circuit voltage)
  - Current at V=0 (short circuit current)
  - Max power point
- IV curves for operational temperatures at 30C or so.
- As temperature increases, output voltage and efficiency decrease
  - ~0.5% efficiency loss per degree above operational temperature
- Most solar panels are hot (65-70C) ⟶ loss of 15% efficiency due to temperature!





Solar cells: inherent degradation

Element	Nominal	Range
Design/assembly	0.85	0.77-0.90
Temperature	0.85	0.80-0.98
Shadowing	1.00	0.80-1.00
Total I_d	**0.72**	**0.49-0.88**

- Theoretical efficiency of solar cells is determined by material properties (e.g. energy band gap)
- In practice, efficiency is lower due to:
  - Design and assembly (diodes, interconnections, transmission losses, etc)
  - Temperature
  - Shadowing
- All of these non-idealities are captured in a factor called inherent degradation I_d

Solar array sizing

1. Compute the power required from the payload and spacecraft bus and eclipse times at End of Life (EOL)

$$P_{sa} = \frac{\frac{P_d T_d}{X_d} + \frac{P_e T_e}{X_e}}{T_d} [W]$$

where:

- P_{sa} is the power required from the solar array
- P_d is the power required during the illuminated portion of the orbit, which lasts T_d seconds
- P_e is the power required during the eclipse portion of the orbit, which lasts T_e seconds
- X_e is the efficiency from the solar arrays → batteries → power distribution ($X_e \approx 0.65$)
- X_d is the efficiency directly from solar arrays → power distribution ($X_d \approx 0.85$)

Solar array sizing

2. Compute available power density $[W/m^2]$ at beginning of life (BOL)

$$P_{BOL} = \frac{S_0}{AU^2}\eta I_d \cos\theta \left[\frac{W}{m^2}\right]$$

where:

- S_0 is the solar irradiance at Earth's top of atmosphere (TOA) $\approx 1368 W/m^2$
- AU is the distance from the Sun in AU
- η is the theoretical solar cell efficiency
- I_d is the inherent degradation
- θ is the angle between the solar panel surface normal and the Sun-spacecraft vector

Solar array sizing

3. Compute available power density $[W/m^2]$ at end of life (EOL), taking into account cell degradation over time

$$P_{EOL} = P_{BOL}(1 - D)^t \left[\frac{W}{m^2}\right]$$

where:

- D is the degradation of performance of the solar cells per unit time (e.g. $D \approx 3\,\%/year$ for Si, $0.5\,\%/year$ for triple junction
- t is the spacecraft design lifetime (e.g. 5 years)

Solar array sizing

4. Compute the required solar array area

$$A_{sa} = \frac{P_{sa}}{P_{EOL}} \left[m^2\right]$$

e.g.

$$A_{sa} = \frac{P_{sa}}{P_{EOL}} = \frac{1946}{271} = 7.75m^2$$

Solar array sizing

5. Compute the required solar array mass

$$m_{sa} = A \cdot \rho_s = \frac{P_{sa}}{M_{sp}} \; [kg]$$

where

- ρ_{sa} is the surface density of the solar array (mass per unit area), typically 2.3-2.8 kg/m^2
- M_{sp} is the specific power of solar array (power per unit mass), typically 90-110 W/kg

Solar array sizing

In summary:

1. Compute the power required from the payload and spacecraft bus and eclipse times at End of Life (EOL)
2. Compute available power density $[W/m^2]$ at beginning of life (BOL)
3. Compute available power density $[W/m^2]$ at end of life (EOL), taking into account cell degradation over time
4. Compute the required solar array area
5. Compute the required solar array mass

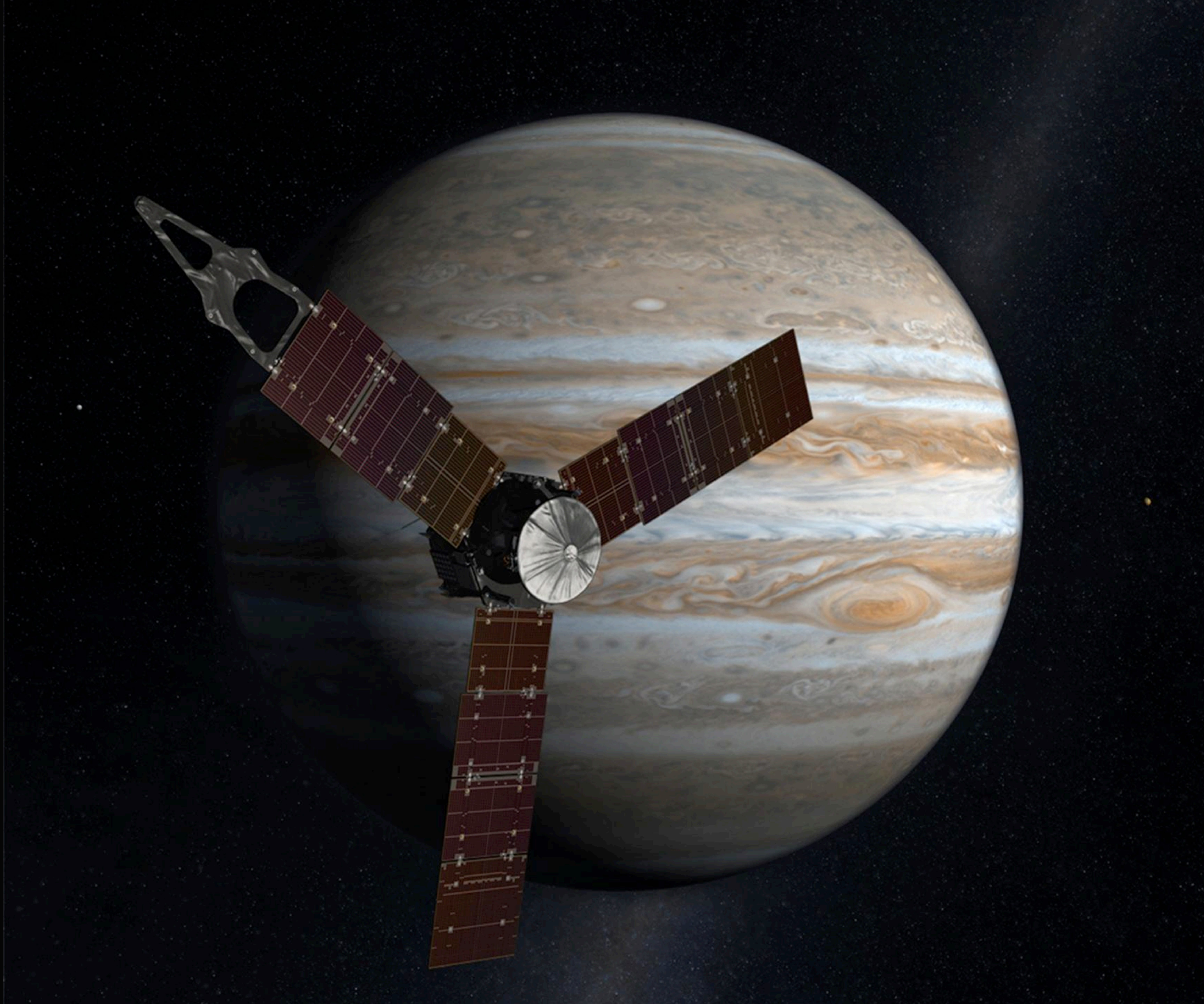
Practical considerations:

1. Sun angle and thus solar power change over time for most orbits
2. Part of the solar panel may be in the shadow of the bus, thus reducing effective solar area. So, spacecraft geometry and configuration must be considered.

Solar array concentrators and solar thermal dynamic

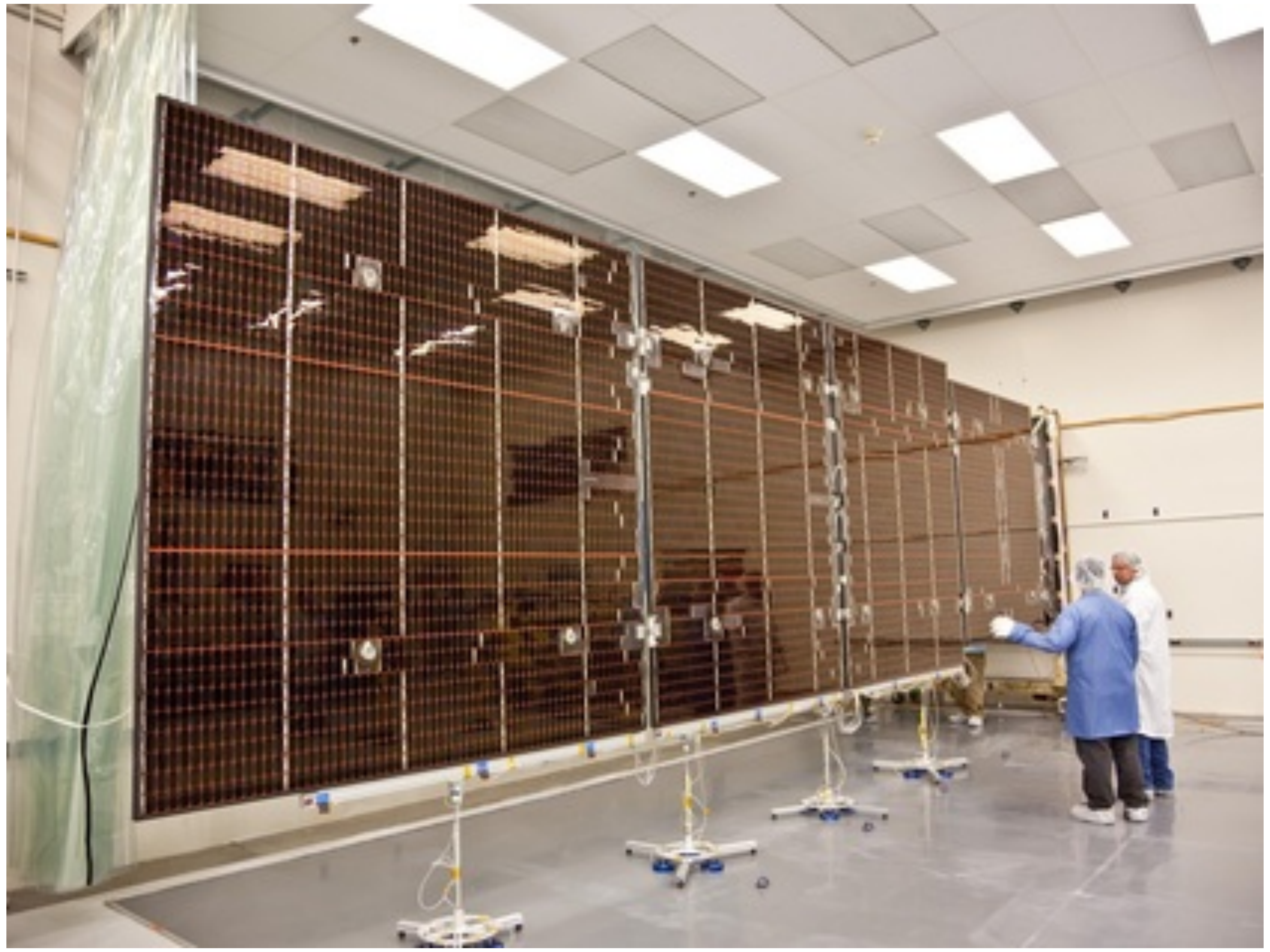
- Efficiency of photovoltaics can be improved using concentrators
    - Lenses and mirrors that focus sunlight onto cells
- They can also be used to generate heat that is then transformed into electricity (solar thermal dynamic)
    - Static: thermocouples, thermionic
    - Dynamic: heat is used to drive an engine in a thermodynamic cycle (Brayton, Rankine, Stirling)

Juno



Juno case study

- Three solar wings placed symmetrically about spacecraft bus
- At Jupiter (~5AU), Juno receives ~1/25 the sunlight that it would at Earth
- Benefits from advances in solar cell design with modern cells that are 50 percent more efficient and radiation tolerant than silicon cells available for missions 20 years ago
- Wings are 2.9 meters wide, 8.9 meters long, consist of 11 individual solar panels
- Low, medium, and high string of solar arrays activated as the vehicle increases its distance from the Sun
- Juno can tolerate solar cell failures, which are expected when going through Jupiter's radiation belts and failures have been calculated so that the power system has adequate margin
- 460-490W at Jupiter. EOL mission power is planned to be 420 W



Batteries

- Transform chemical energy into electrical energy
- Arrays of electrochemical cells connected in series/parallel
- Each cell has a cathode and an anode connected by a conductive electrolyte containing anions and cations
- Electrons travel from anode → cathode through redox reactions
- Example for a Ni-Cd battery, using KOH as electrolyte, during discharge:
  - Anode (oxidation):
    $$Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^-$$
  - Cathode (reduction):
    $$2NiO(OH) + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$$

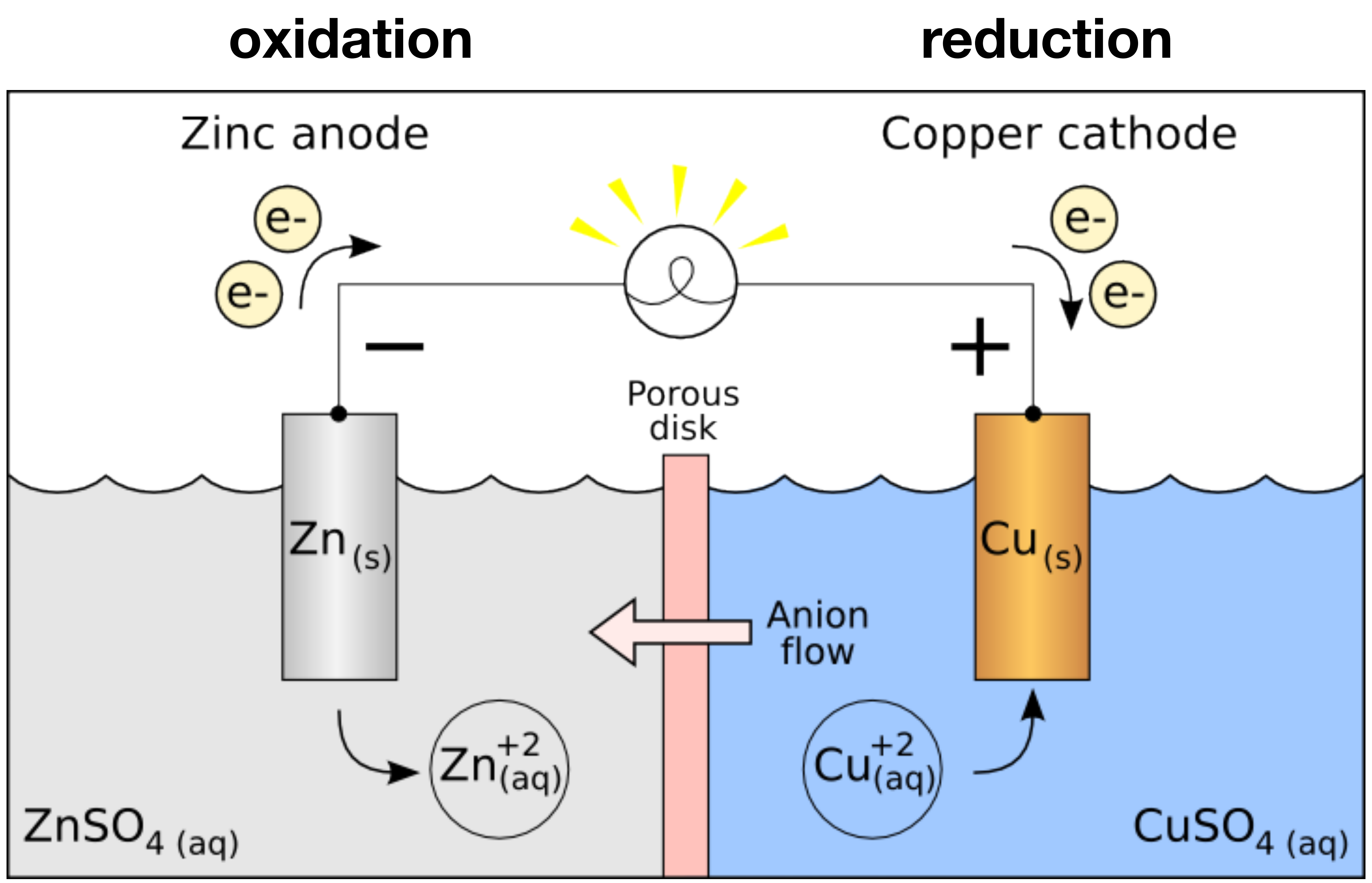


TABLE 11-40. Steps in the Energy Storage Subsystem Design. To obtain the required battery capacity in Amp-hr, divide by the required satellite bus voltage.

Step	Consider	FireSat Example
1. Determine the energy storage requirements	• Mission length • Primary or secondary power storage • Orbital parameters – Eclipse frequency – Eclipse length • Power use profile – Voltage and current – Depth of discharge – Duty cycles • Battery charge/discharge cycle limits	• 5 yrs • Secondary power storage • 16 eclipses per day • 35.3 min per eclipse (T_e) • Eclipse load 110 W (P_e) – 26.4 V, 4.2 A (max) • 20% (upper limit) • TBD—depends on observations taken and downlinked during eclipses
2. Select the type of secondary batteries	• NiCd (space qualified) • NiH_2 (space qualified) • Li-ion (under development) • NaS (under development)	• NiCd or NiH_2—both are space-qualified and have adequate characteristics
3. Determine the size of the batteries (battery capacity)	• Number of batteries • Transmission efficiency between the battery and the load	• $N = 3$ batteries (nonredundant) • $n = 0.90$ • $C_r = 119$ W-hr • $C_r = 4.5$ Amp-hr (26.4 V bus)

Battery Capacity: $C_r = \dfrac{P_e T_e}{(DOD) N n}$ W-hr (for battery capacity in Amp-hr, divide by bus voltage)

Energy storage design process

Day-in-the-life analysis

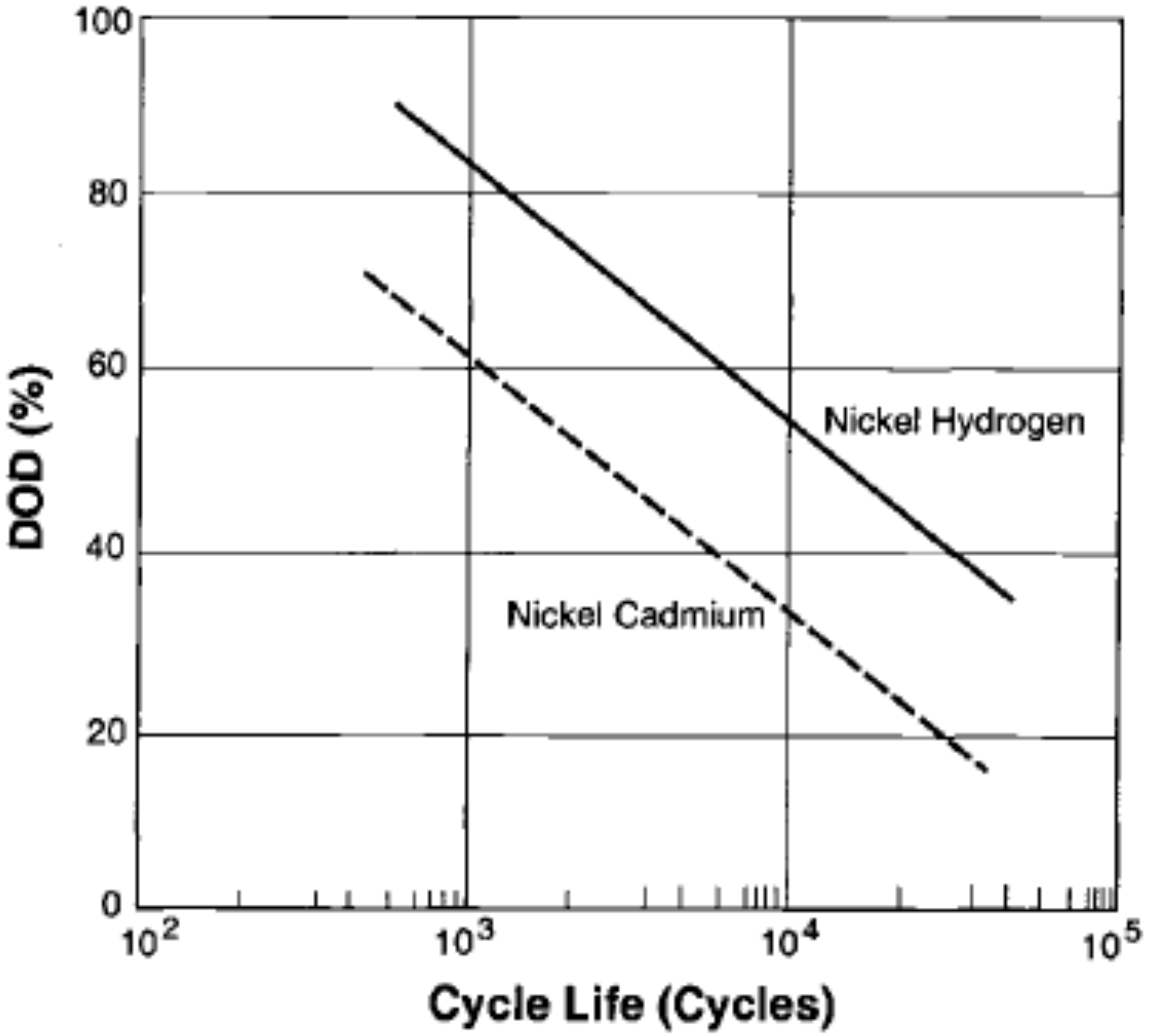
- Create a statistically representative timeline
    - one or many orbits
    - requires a concept of operations
    - requires some sense of attitude-control approach and orbit behaviors
- Average power used
- Size batteries for this average (EOL performance)
    - keep in mind depth of discharge
    - keep in mind solar cell degradation
- Note the peak: design harness and discharge rates for this value
- Incorporate margins that vary with design maturity

TABLE 11-39. Characteristics of Selected Secondary Batteries. Though secondary batteries have much lower specific energy densities than primary batteries, their ability to be recharged makes them ideal for backup power on spacecraft powered by solar cells.

Secondary Battery Couple	Specific Energy Density (W·hr/kg)	Status
Nickel-Cadmium	25 – 30	Space-qualified, extensive database
Nickel-Hydrogen (individual pressure vessel design)	35 – 43	Space-qualified, good database
Nickel-Hydrogen (common pressure vessel design)	40 – 56	Space-qualified for GEO and planetary
Nickel-Hydrogen (single pressure vessel design)	43 – 57	Space-qualified
Lithium-Ion ($LiSO_2$, LiCF, $LiSOCl_2$)	70 – 110	Under development
Sodium-Sulfur	140 – 210	Under development

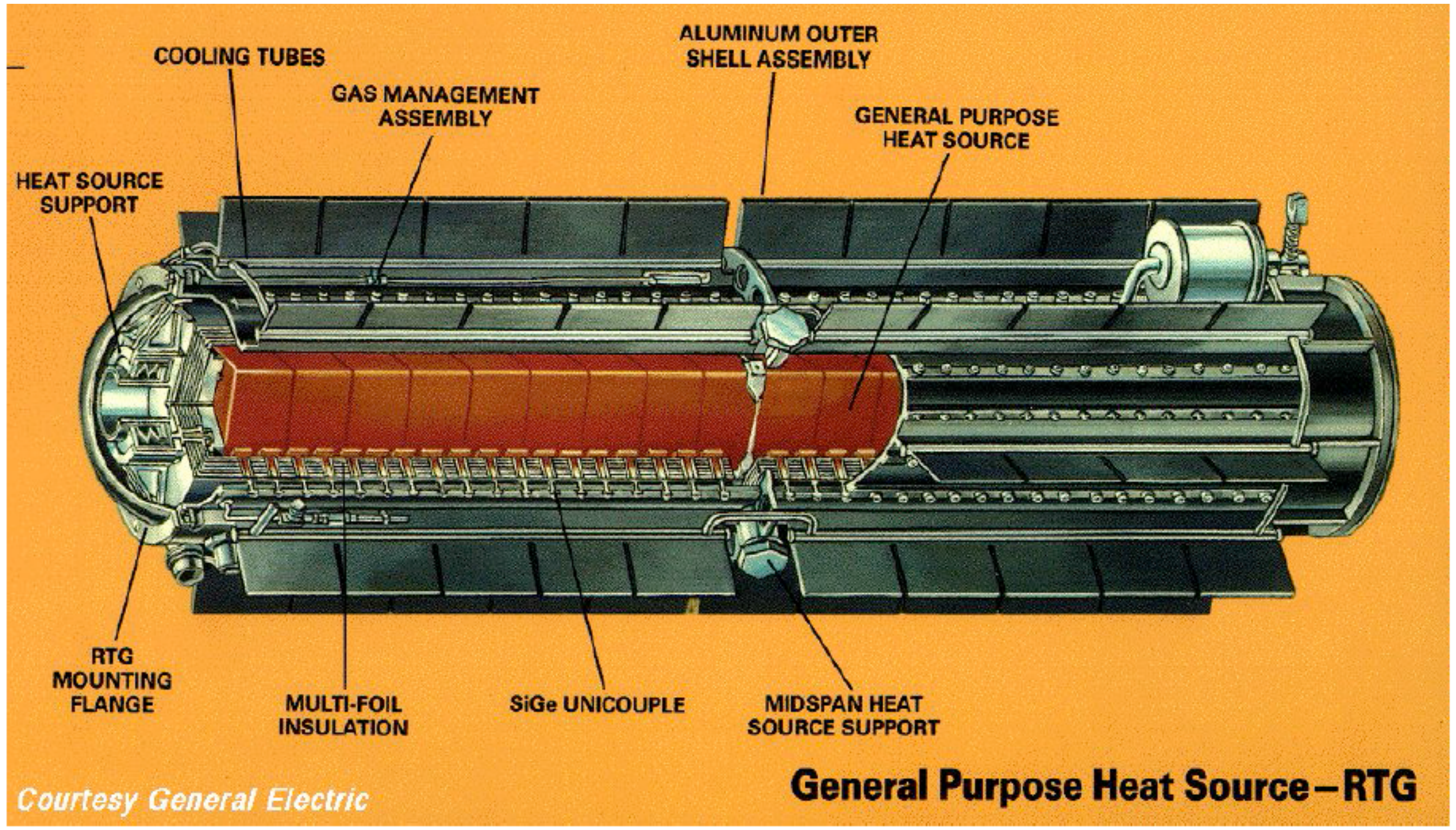
Estimating battery capacity

- The capacity of a battery is the total energy stored
  - typically measured in Wh or Ah
  - sized to power the spacecraft during eclipse
- Depth of discharge of a battery is the percentage of the capacity that is used in each charge/discharge cycle
- Battery life (#cycles) decreases with depth of discharge
  - GEO (few cycles): 60% DOD
  - LEO (many cycles): 30% DOD
- Total battery capacity needed: $C_r = \dfrac{P_e T_e}{DOD \cdot n}$ where $n \approx 90\,\%$ is the battery efficiency



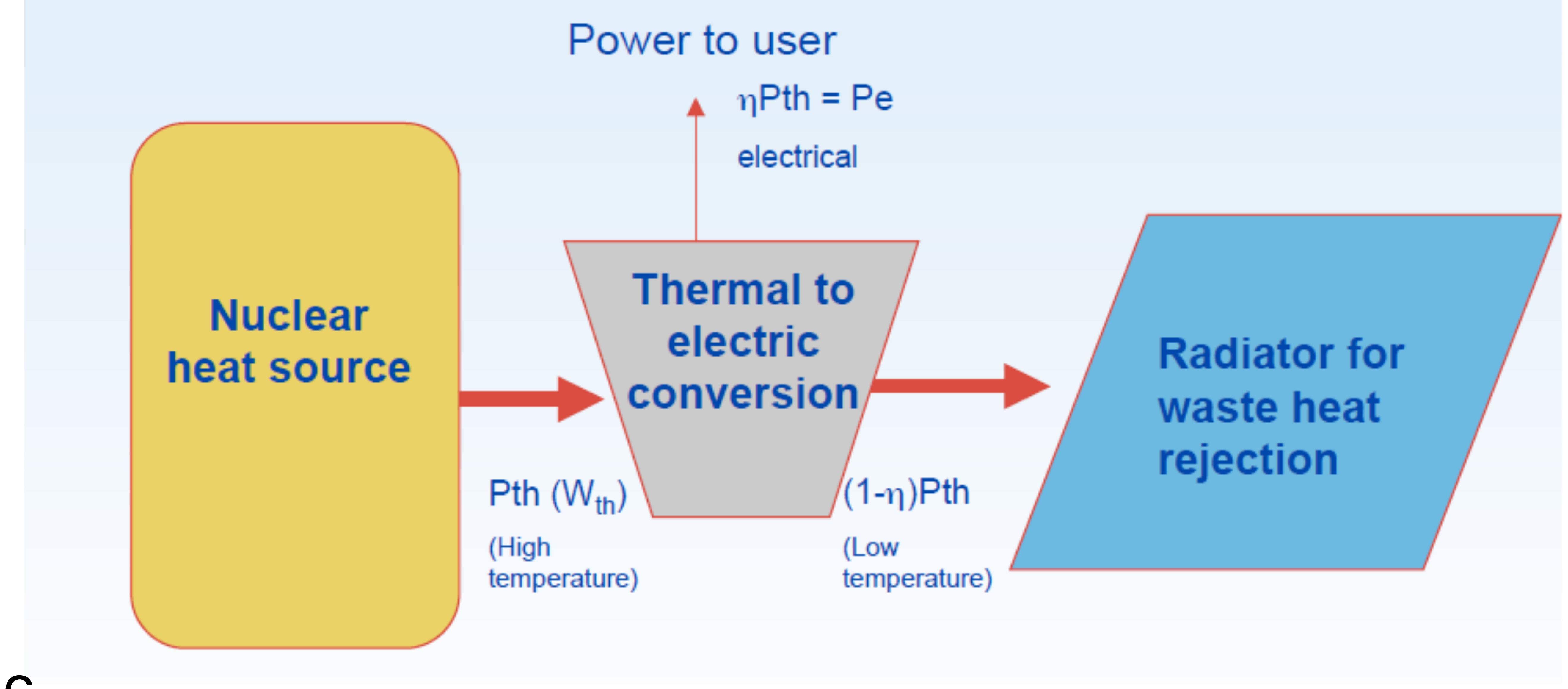
Radioisotope Thermoelectric Generators (RTG's)

- Use natural decay of a radioisotope as a heat source
  - 238Pu, 90Sr, 210Po, . . .
  - reach temperatures ~500C
- Use array of thermocouples for heat → electricity conversion
- Temperature gradient at PN junction is transformed into electricity
- Can only provide up to a few hundreds of Watts, but last for a very long time
- Used for outer solar system missions
  - Cassini, Galileo, New Horizons



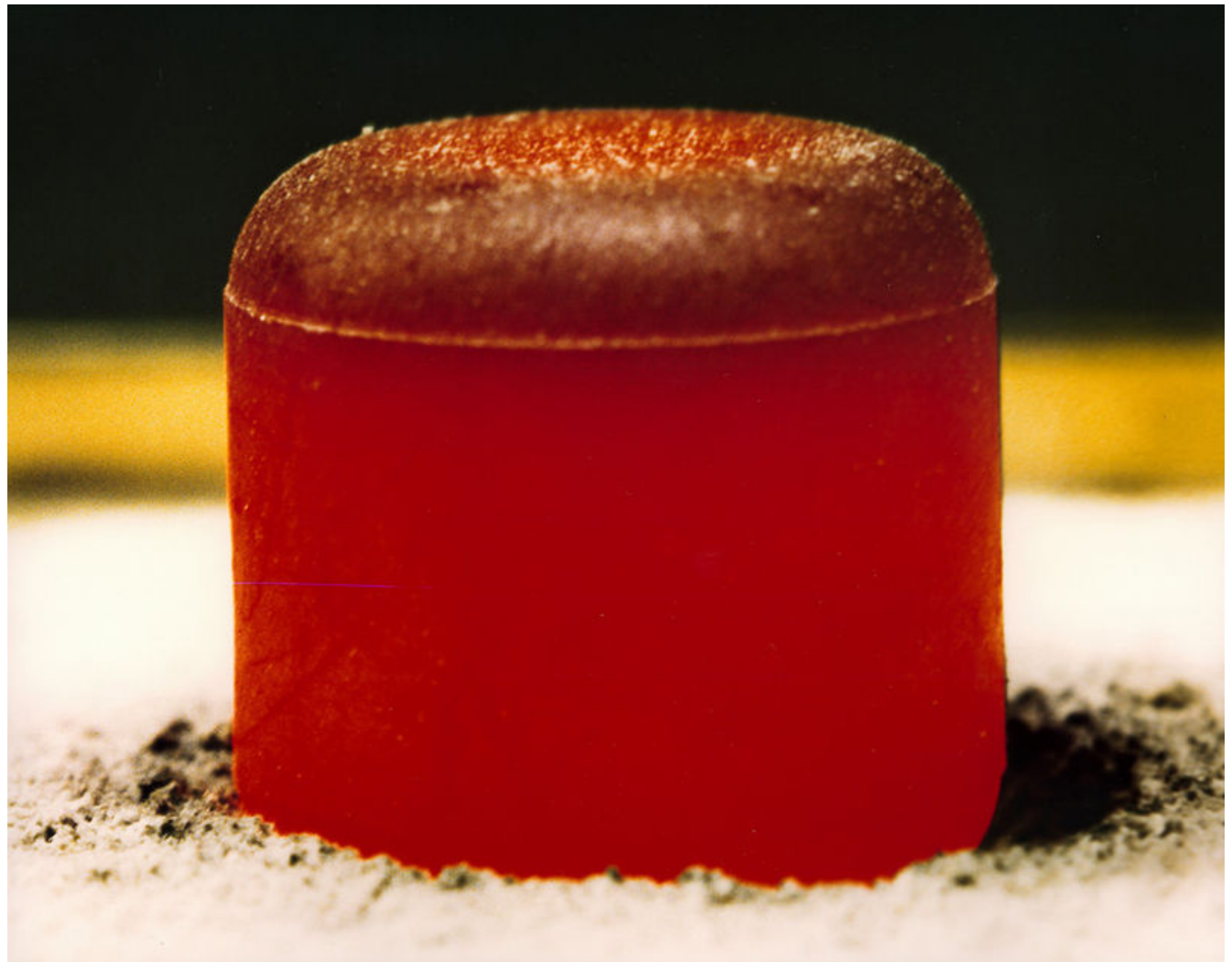
Nuclear power generation

- Requires 3 main functions:
  - generate heat (nuclear source)
  - transform heat into electricity
  - radiate excess heat
- Heat source could be:
  - natural decay of a radioisotope
  - nuclear reactor
- Transformation of heat → electricity
  - static: thermocouples
  - dynamic: drive an engine in a thermodynamic cycle
- Radiation is done through thermal subsystem



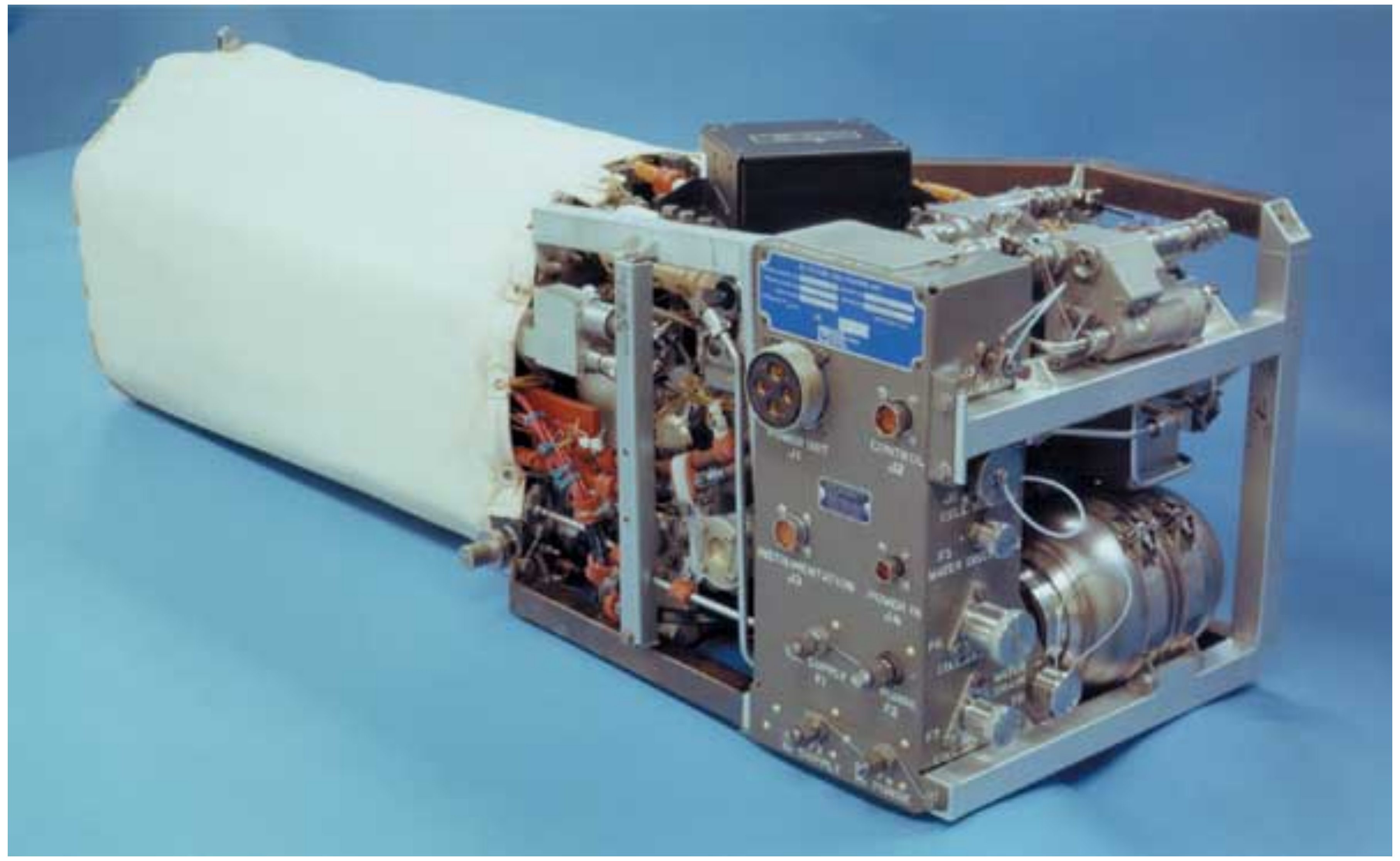
Radioisotope generators

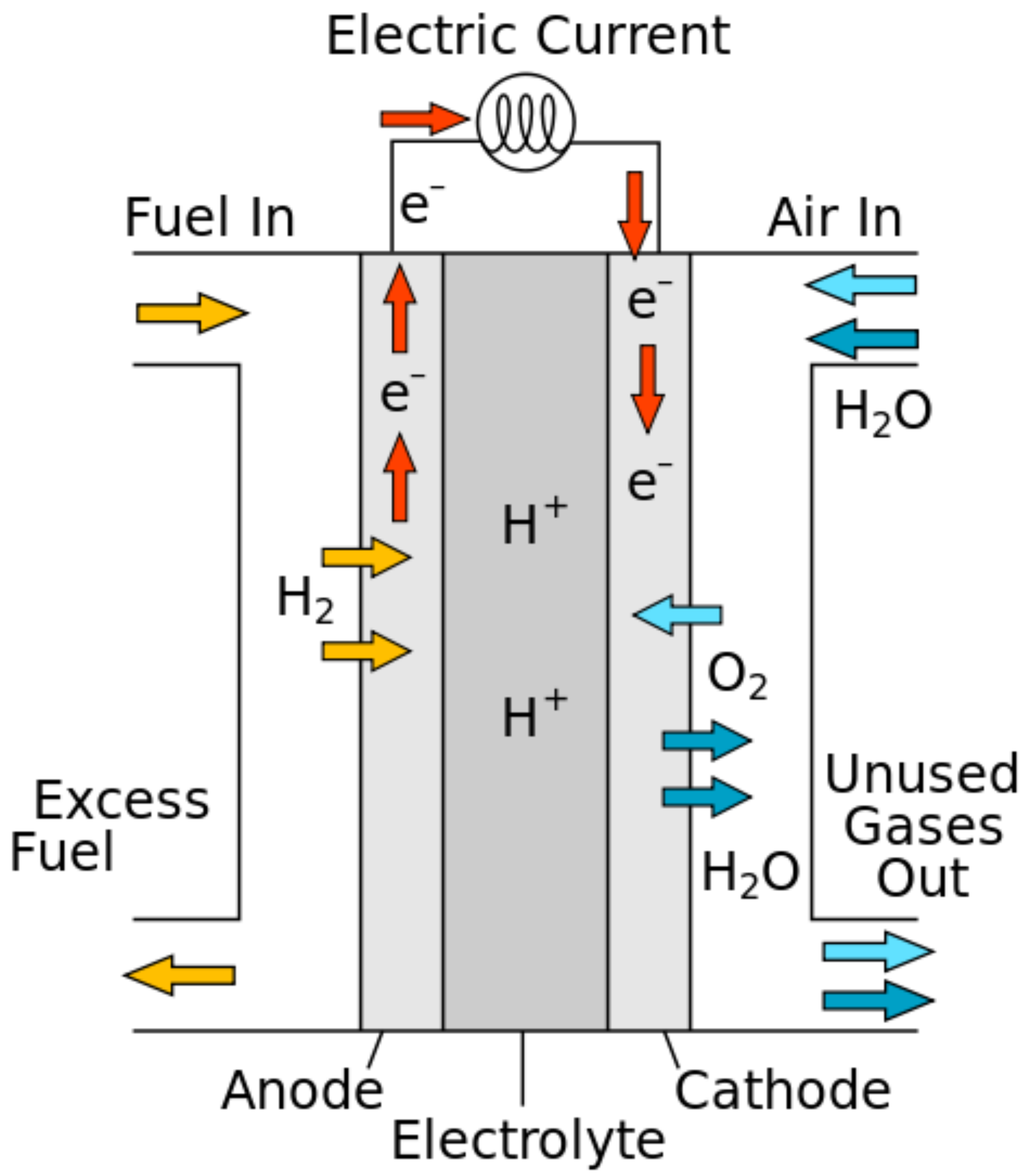
- Choice of radioisotope based on
  - Half-life (~1-100 years)
  - Power density (~1-100 kW/kg)
  - Type of radiation (mostly want α)
- RTG's generate radiation that adds to the total radiation dose and could harm electronics → coupling with structures system
- They also have implications for the thermal system, since excess heat must be dissipated



Fuel cells

- Combine oxygen and hydrogen to create water and electricity (and heat)
- Similar to batteries, redox reactions:
  - Anode: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$
  - Cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$
- High power density (~10kW/cell)
- Short time, high-power applications
- Need a continuous supply of fuel
  - About 0.33kg of fuel per kWh
  - Shuttle: 1727 kg of cryo = 5.2MWh
- Water must be used (useful for manned missions) or disposed of
- Extra heat must be dissipated



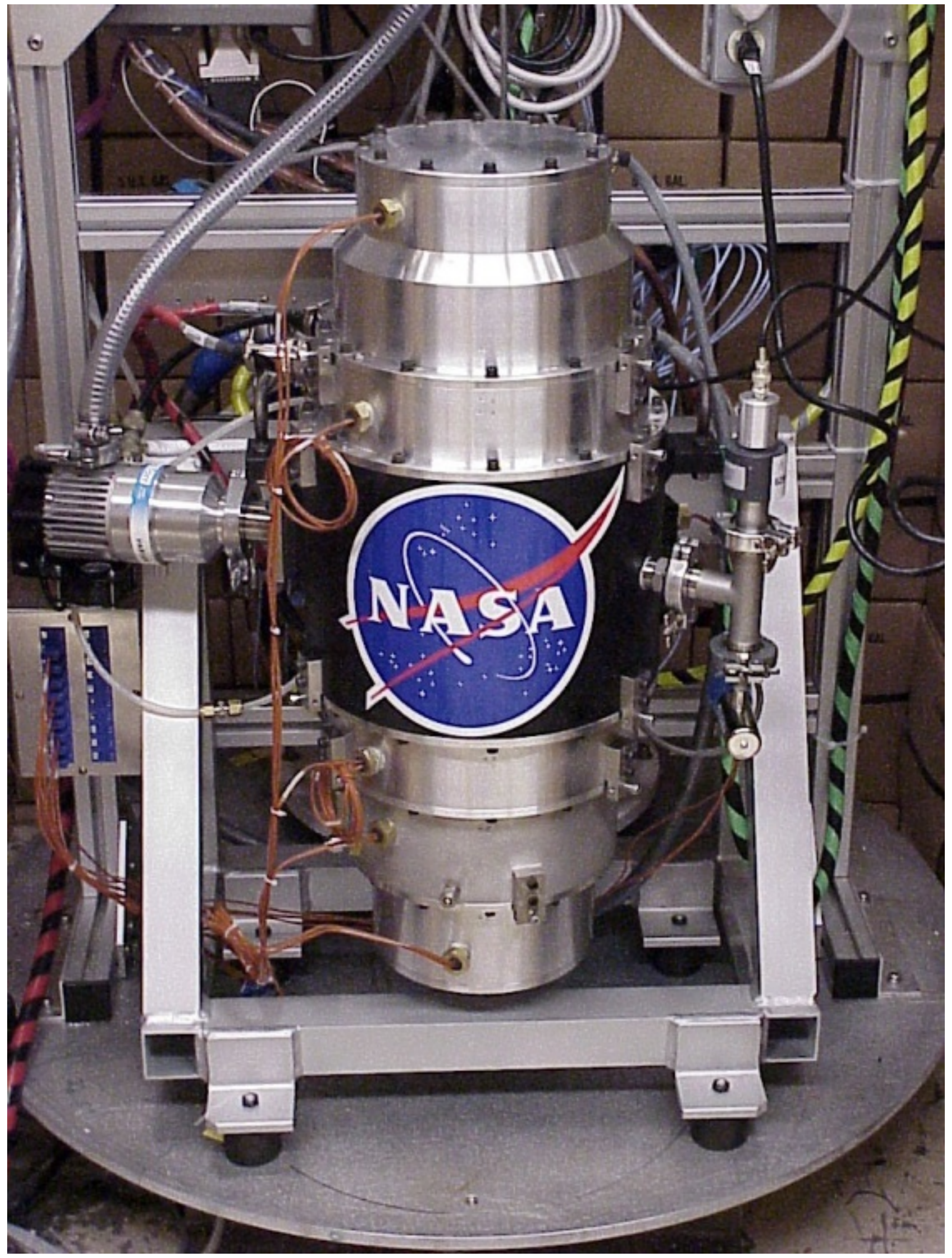


Electrodynamic tethers

- Long conducting wires
- Convert kinetic energy into electricity using magnetic fields
- Electric field: $E = vB$
  - B is the magnetic field
  - v is velocity perpendicular to the magnetic field
- Voltage: $V = E \cdot L$
  - L is the length of the wire

Flywheels

- Store energy as rotational energy
- G2 flywheel
    - 60,000 rpm
    - 525 Why
    - 250 lbs
- Coupled attitude and power subsystem?
- Similar energy storage to Li-Ion/Li-Po (~80-100 W/kg currently)



Nuclear reactors

- Nuclear fission-powered satellite launched in 1965
- Stopped working after 43 days due to a non-nuclear electrical failure
- Contained 37 uranium-zirconium-hydride fuel rods
- Thermal power output of 30 kW
- Led to the inception of the Aerospace Nuclear Safety Program

SNAP-10a

Power distribution and management

- Ensures that all loads receive the voltage and current that they need
- Main functions
  - Voltage converter: Generate all necessary voltages from main bus voltage (e.g. 55V, 28V, 12V, 5V) typically using DC-DC converters
  - Power regulator: Ensure voltage and current levels are constant over time to avoid equipment damage
  - Power distribution: Wiring needed to bring power to equipment
  - Excess power disposal: Dispose of excess power generated by solar arrays (e.g., using shunts)
  - Fault protection: Isolate power lines of components so that a problem in one component doesn't affect other components (e.g., switches, relays, circuit breakers)