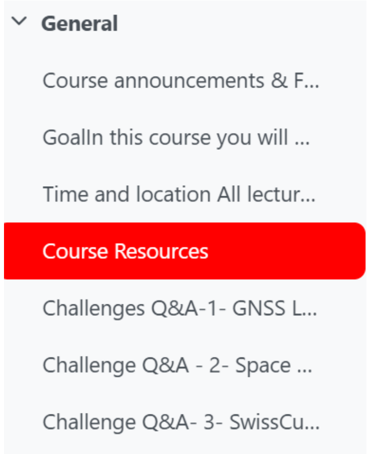
EE-584
Spacecraft Design & Systems Engineering

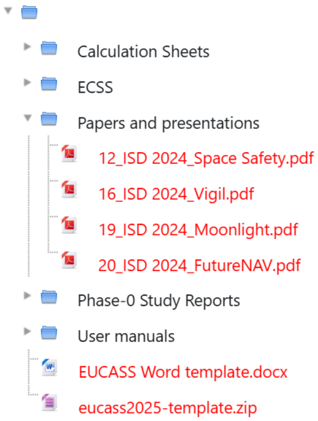
Lecture 6 - Electrical Power Systems

EPFL

Brief announcement

A set of **reference papers** have been uploaded to Moodle to support the preparation of your final papers.





For the writing of your papers, feel free to use Word or LaTeX but **make sure to follow the manuscript template**.

Reminder: due date for the initial submission of your manuscript is similar to MDR deadline (**15 December**)

After the MDR, feedback from the evaluation panel can be implemented in your report and a **camera-ready version** must be submitted by **14 January 2024, 23:59 CET**. (check Moodle for latest info)

Grading rubric

Published for MDR.

Soon the final report rubric will be published. It will be very similar to the MDR grading

Note: you may use your MDR presentation as a reference for your final paper → Feel free to add appendixes to the presentation!

Grading Rubric for the Mission Definition Review Presentation

Topic	Expected content	Grade: 1	2	3	4	5	6
Mission statement (weight = 5%)	Goal(s), Mission and (Science) Objectives	Goal, Mission and Objective(s) are not mentioned	Goal, Mission and Objective(s) are very vague or unclear	Goal, Mission and Objective(s) are mentioned but are not SMART	Goal, Mission and Objective(s) are SMART	Goal, Mission and Objective(s) are SMART and clearly flow down from one another. That is, the Goal indicates the overall ambitions, the Mission details how these ambitions will be met and the main (and secondary) Objective(s) show what should be done for the mission.	Goal, Mission and Objectives flow down clearly from customer requirements and from literature findings. Efforts have been made to show how the goal, mission and objectives compare to other similar missions
	Stakeholders	No mention is made of stakeholders	A vague mention of stakeholders is made	Some stakeholders are mentioned, but not the most important ones, or not in an extensive way	The key stakeholders and actors are summarised and their interest in the mission is explained	The key stakeholders and actors are listed, and their needs are well distinguished from one another and flow down into the requirements.	The students show a simple stakeholder value network (SVN) to indicate the interactions between stakeholders.
Mission design (weight = 5%)	CONOPS	CONOPS is not mentioned	CONOPS is unclear or vaguely discussed	Only some aspects of the CONOPS are mentioned	The CONOPS is discussed, with a list of key elements of the mission (e.g. duration, phases, trajectory and orbit, launch vehicle, launch windows etc)	The CONOPS is sufficiently detailed, showing that the mission is well designed and understood. The CONOPS follows well from the Mission Statement. The different mission phases are well explained along with their main activities and driving design constraints.	The students make an effort to make the CONOPS visually easy to understand, without overcrowding the infographic. The students make the links with the stakeholders and actors. It is clear that the CONOPS has been reviewed since the last presentation
	Project Timeline	The project timeline is not discussed	The project timeline is unclear or not well thought-through	The project timeline is clearly shown but does not make the link with any of the system engineering phases (Phases 0-A to E) discussed in class	A clear project timeline is given, from the earliest design phase to the end-of life	The project timeline is achievable and realistic. Where needed, links are made with the risk assessment.	The students look beyond the current project's timline and give an indication on extension or follow-up projects
	System modes	No modes are described	The system modes are poorly described (e.g. hey do not flow down from the CONOPS, their design implications are not given)	The modes are given but the link with the CONOPs is unclear.	The system modes are given in relation to the CONOPS	The system modes are detailed enough to indicate what design aspects they drive, in terms of (sub)system or componenent design	The students show that the system modes are used to define and update the budgets
	End-of-Life (EOL) Strategy	No EOL considerations were made or discussed	The EOL is not clearly shown.	The EOL considerations are included	The EOL strategy is logical and feasible	The EOL strategy follows from a tradeoff between technical considerations and sustainable guidelines	The students highlight what the technical implications, risks and sustainability advantages are of the chosen EOL strategy.
Systems engineering (weight = 10%)	Functionality analysis	The functionality analysis is not mentioned	A vague functionality analysis is shown or mentioned	The functionality analysis of the space mission has been presented clearly	The discussed mission's functionality follow from the Mission Statement	The mission's functionalities flow from an extensive functional breakdown	Special care has been put into explaining the reasoning behind certain functions, linking them with the CONOPS, customer requirements or other relevant aspects.
	Mission requirements	The requirements are not mentioned	Some requirements are mentioned, but they are not formulated in the correct way or clearly lack a reasoning	The key requirements are given and are mentioned. They are written in the correct way (i.e. using the verb " shall", and using an ID)	The requirements are SMART. The link with the functional breakdown is clear. A good reasoning for them is shown.	Relations between high-level and lower-level requirements are shown. The students show a good reflection of the requirements. That is, the students highlight for example the requirements which drive the design the most and their associated risks are discussed if relevent	The students provide an extensive list of requirements, detailing further the higher level-requirements. Each requirement has an ID which easily indicates from which parent it flows down. Each requirement has an associated rational (explaining why this requirement was drafted and why it was drafted this way)
	Mission constraints and limitations (environment)	Mission constraints and limitations are not discussed	A very vague discussion of mission constraints due to the spacecraft's environment is given	Key mission constraints and limitations are given and linked to the spacecraft's environments	Clear research on the spacecraft environments throughout its life cycle has been shown. The essential mission constraints and limitations have been distilled from them.	The listed mission constraints and limitations flow into the requirements and the risks.	The students make it clear how the environmental constraints are adressed in the mission design.
	Mission sucess criteria and measures of success	No success criteria or measures of success are mentioned	Unclear what the mission success criteria are or how the success is to be measured.	Mission success criteria are clearly mentioned and logical	Mission success criteria and measures of success are SMART and logical	The mission success criteria are clearly reflected in the requirements	The mission success criteria and measures of success are clearly mapped onto the CONOPS. That is, they are linked with the mission phases. Secondary mission success criteria are given, in case the primary ones cannot be met
	Verification and Validation	No V&V plan is presented	V&V is mentionned but not link to the requirements	V&V is mentionned and performed without any update of requirements	V&V plan is presented and performed for each requirements and flowed down to the subsystem. Requirements have been updated to be verifiable	V&V plan is performed and also the associated test plan	V&V plan is performed and the impact in the engineering models/ Qualification models philosophie as well as impact on developement timeline and costs
	Interface analysis	No interface analysis is done	A vague or rushed interface analysis is shown	The interfaces of few subsystems are analysed	An analysis is done of the most important interfaces between subsystems. The way each subsystem	The effect of the interface is discussed. Where relevant, risks associated with subsystems interfaces are discussed.	Requirements are derived from the interface analysis. For trhe most critical interface(s), a detailed analysis and design is shown
Mission Architecture (weight = 10%)	Budgets	No budgets have been shown or mentioned	Some budgets have been show without further explanations	All relevant budgets have been shown, but some are not quantified well	All relevant budgets have been shown and well quantified.	All relevant budget breakdowns are given, showing how the budget was computed. The breakdown is logical and based on research	The budgets are linked to the overall systems engineering process (requirements, etc). Some budget margins are shown and discussed. The technical implications of the most critical budgets are mentioned.
	Risk assessment	No risk assessments have been made	A vague risk asessment has been done	A clear risk assessment has been made	The risk assessment is well-explained and uses a system engineering methodology. Legends on any colour-coding, symbols and number ranges are provided.	The risk assesment methodology is chosen wisely, ensuring that the most mission-ending risks stand out. Mitigation are proposed for the most critical risks.	A detailed analysis is done for the most critical risks. The new level of risk after the mitigations are applied is discussed and it is shown how the mitigations affect the Mission Design. Moreover, it is clear that the students reviewed and improved the risk assessment from the previous presentation, if applicable.
Baseline Design (weight = 50%)	Payload components	No payloads have been mentioned	Some payloads have been mentioned in a very vague and unclear way	The types of payloads needed for the mission and how they will fill the mission's functions are presented	The types of payloads needed and specifics on some of the payload types is given (e.g. some comparisons with existing payloads, some requirements, etc)	Budgets for key payloads are given. Where possible, some comparable payloads are used as a source of information	The students show a critical mind regarding their choice of payloads. They indicate which ones are the most important, which ones are available as COTS components and which ones require most research and developments.
	Spacecraft configuration	No effort is made to show a breakdown of the spacecraft	A vague breakdown of the spacecraft is provided with no dimensioning.	A product tree or system breakdown is given partially or without much details. No effort is made to size any elements.	A clear product tree of the system breakdown is provided, showing the spacecraft's configurations throughout its mission. An initial volumetric sizing is done to ensure that all susbsystems fit within the spacecraft.	The system breakdown is clearly linked to the CONOPS, showing how the configurations or functions change per mission phase. It is visually shown that the susbsystems and mechanisms would fit within the various constraints (e.g. through 2D sketches).	Details is given on the operations and configuration of the spacecraft's subsystems during the most critical mission phases. This is also flown into the requirements A detailed look on the critical interfaces of one or more subsystems is given, or it is shown clearly that a mechanism would function properly (e.g. ensuring it does not get in conflict with other parts of the S/C during operations)
	EPS	No information on the spacecraft's EPS is given	Only some information on the spacecraft's EPS is given	The information provided on the EPS is vague or is missing key elements	All relevant information on the EPS is discussed. Most are detailed.	The EPS is sized and the relevant characteristics are highlighted following a more detailed analysis. The subsystem is compliant to the (high-level) requirements.	It is clear that the EPS subsystem was iterated upon. The students dive into detail on some more relevant elements for the mission. The key drivers for the subsystem design are clear and the most evident single-point of failures are highlighted
	Thermal subsystem	No information on the spacecraft's thermal subsystem is given	Only some information on the spacecraft's thermal subsystem is given	The information provided on the thermal subsystem is vague or is missing key elements	All relevant information on the thermal subsystem is discussed. Most are detailed.	The thermal subsystem is sized and the relevant characteristics are highlighted following a more detailed analysis. The subsystem is compliant to the (high-level) requirements.	It is clear that the thermal susbsystem was iterated upon. The students dive into detail on some more relevant elements for the mission. The key drivers for the subsystem design are clear and the most evident single-point of failures are highlighted and the most evident single-point of failures are highlighted
	Propulsion and AOCS	No information on the spacecraft's propulsion and AOCS is given	Only some information on the spacecraft's propulsion and AOCS is given	The information provided on the propulsion and AOCS is vague or is missing key elements	All relevant information on the propulsion and AOCS is discussed. Most are detailed.	The propulsion and AOCS subsystem is sized and the relevant characteristics are highlighted following a more detailed analysis. The subsystem is compliant to the (high-level) requirements.	It is clear that the propulsion and AOCS susbsystem was iterated upon. The students dive into detail on some more relevant elements for the mission. The key drivers for the subsystem design are clear and the most evident single-point of failures are highlighted
	CDH (Command and Data Handling)	No information on the spacecraft's CDH is given	Only some information on the spacecraft's CDH subsystem is given	The information provided on the CDH subsystem is vague or is missing key elements	All relevant information on the CDH is discussed. Most are detailed.	The CDH subsystem is sized and the relevant characteristics are highlighted following a more detailed analysis. The subsystem is compliant to the (high-level) requirements.	It is clear that the CDH susbsystem was iterated upon. The students dive into detail on some more relevant elements for the mission. The key drivers for the subsystem design are clear and the most evident single-point of failures are highlighted
	Spacecraft's and launcher's structure and mechanisms	No effort is made to show the structure or mechanism characteristics	The students only provide a vague description of the structure and mechanisms	Some aspects of the structure and mechanisms are detailed.	The key aspects of the structural components and mechanisms of the spacecraft and interface between the launcher and the spacecraft(s) are discussed	The key design drivers behind the spacecraft's and launcher's structure and mechanisms. These are linked with requirements	The students go in detail on some relevant aspects of the spacecraft's structure and mechanisms, including single points of failures. Where logical, students highlight risks and risk mitigations.
	Launch Segment	No effort is made to discuss the launch segment	The students only provide a vague description of the launch segment	Some aspects of the launch segment are detailed	The launch segment is discussed in sufficient detail	The key requirements for the launch segment are discussed, along with the requirements for the spacecraft due to the launch system (launcher and ground facilities)	The students go in depth on the effect of the launch segment choice for the spacecraft. Some of the driving aspects are discussed and it is shown how this is taken into account in the design and/or in the developement (testing & analysis requirements)
	Telecom and Ground Segment	No effort is made to discuss the ground segment	The students only provide a vague description of theground segment	Some aspects of the ground segment are detailed	The ground segment is discussed in sufficient detail	The key design drivers for the ground segment are discussed and linked with requirements	The students go in depth on the link budget and ground station requirements based on calculations and literature. It is clear that some iterations were performed
Presentation skill (weight = 20%)	Academic / Engineering Presentation skill	No presentation is given	The slides and presentation are given, but either (or both) the slides are messy or the presenters do not present clearly or know what to say	The presentation is given and its structure makes sense.	The presentation is well-structured and flowed nicely. The structure helps with getting the point accros and was made clear to the public at the start of the presentation. When figures or quotes are used from a third-party, this is clearly indicated.	Transitions (if any) between speakers were logical and smooth A good body language is displayed by the presenter. The slides are not overcrowded with text and are appropriately designed. The sources of external information are provided and shown clearly in the appropriate format	The presentation slides follow good scientific practices (i.e. indicating the sources of statements and quotes, ensuring the figures are readable and all the axes are labeled, etc). There are no noticeable typos in the slides It is clear to the public at any point how far along the presenters are in their presentation and how long it may still last (e.g. through indicators on the slides showing the current section in relation to past and future sections). Through intonation and pauses, the students made an effort to emphasise important information during the presentation
	Respect of time and speech speed	The presentation exceeded the maximum allowed time by more than 1 minute	The presentation exceeded the maximum time by 30 seconds to 1 minute	The presentation exceeded the maximum time by up to 30 seconds. Or, the pace of the presentation was rushed (or some sentences were unintelligible) to such an extent that it was difficult to follow the presentation.	The presentation within the maximum allowed time. The pace of the speech is acceptable. Transition between persons, slides or bullet points are easy to follow.	The presentation time was within the maximum allowed time. The pace of the speech is relaxed. The presentation is easy to follow for the listeners.	The presentation time was within the maximum allowed time. The pace of the speech was calm such that it was very easy to follow the presentation. It is clear that the presentation was well rehearsed

The grade is calculated by rounding to the nearest quarter the outcome of the following formula:

Final grade = ROUND(Avg(Mission statement) * 0.05 + Avg(Mission design) * 0.05 + Avg(Systems Engineering) * 0.1 + Avg(Mission Architecture) * 0.1 + Avg(Baseline Design) * 0.5 + Grade(Presentation Skills) * 0.2)

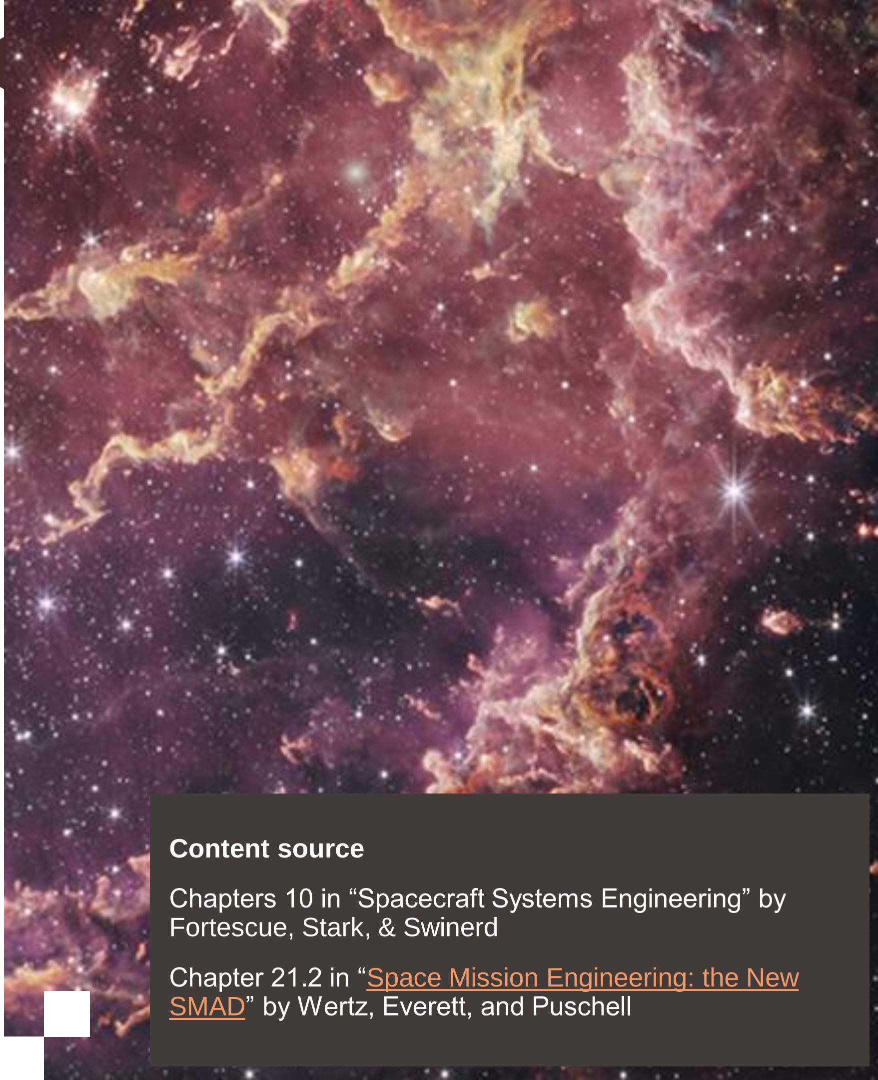
Note: "Avg" stands for "Average" and is composed of the average grade of a given topic

Learning Outcomes

By the end of this lecture you should be familiar with…

- Power system functions & its elements
- Primary power sources: solar arrays & RTGs.
- Secondary power systems: energy storage
- Power distribution, regulation and control
- Sizing your EPS and power budget

- Today's project work



Source: NASA

Content source

Chapters 10 in "Spacecraft Systems Engineering" by Fortescue, Stark, & Swinerd

Chapter 21.2 in "Space Mission Engineering: the New SMAD" by Wertz, Everett, and Puschell

Old reminder for the importance of EPS

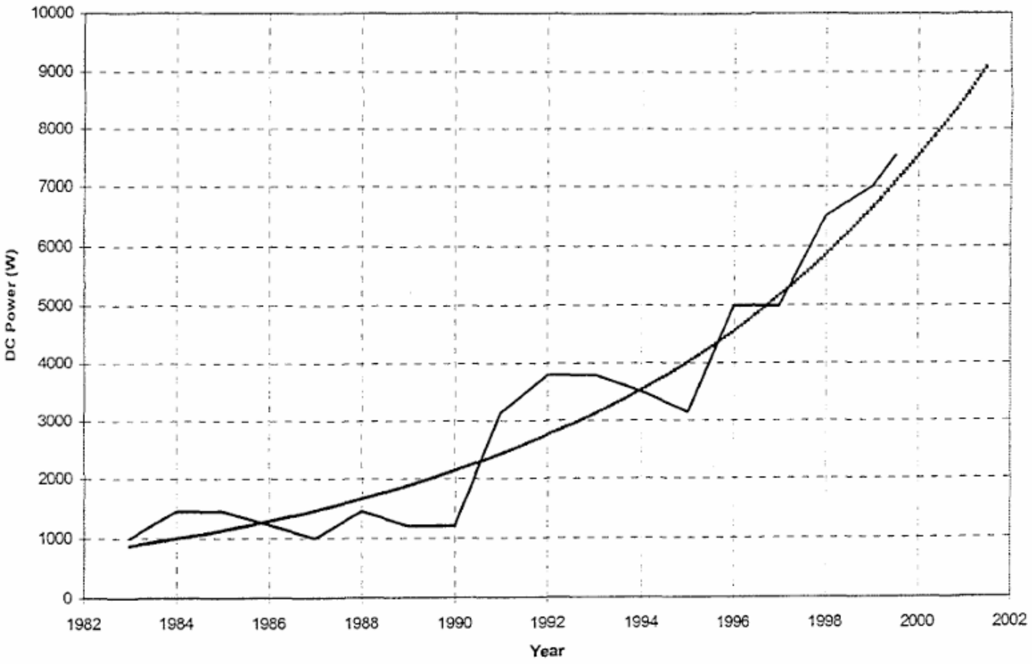


Figure 3 Evolution of Spacecraft End of Life Power

Dunbar, Neil. "Trends in communications satellite platform design." (1998). https://doi.org/10.1049/IC%3A19980881

How to size your EPS and power budget ?

Think in terms of "**mission modes**":

1. Initial sizing: Identify your average power needs
2. Define your mission phases (CONOPS)
3. Define the modes per mission phase
4. Identify which subsystems are active per mode
5. Estimate the power needs per mode
6. Identify the driving requirements
7. Size the EPS power and storage requirements accordingly
8. Define the EPS power source(s) (and storages)
9. Now, go in more details and re-iterate the design...

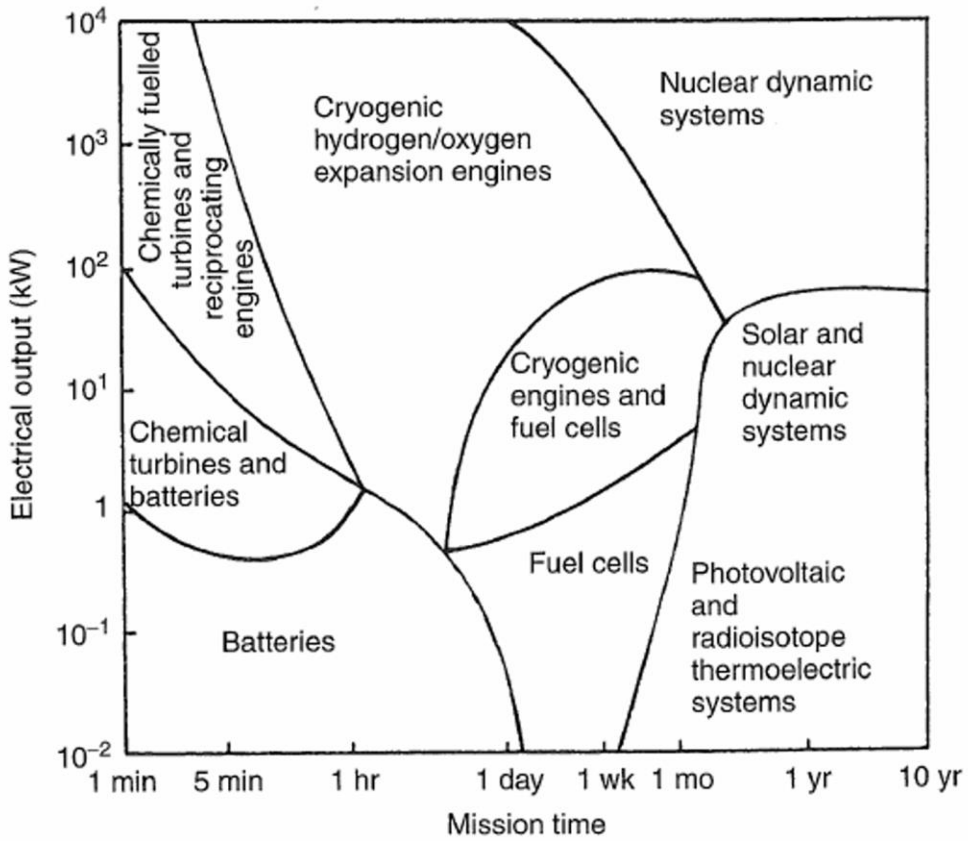
Modes depend on your mission type, CONOPS,

- Charging mode
- Science mode
- Deployment mode
- Communication mode
- Safe mode
- Standby mode
- Eclipse mode
- Re-entry mode
- ...

They influence your requirements, and have an effect on mission operations, planning etc.

Good examples of mission modes for AOCS: https://www.spacenavigators.com/post/attitude-and-orbit-control-system-aocs-modes-the-many-hats-a-spacecraft-wears

Which EPS technology to choose?



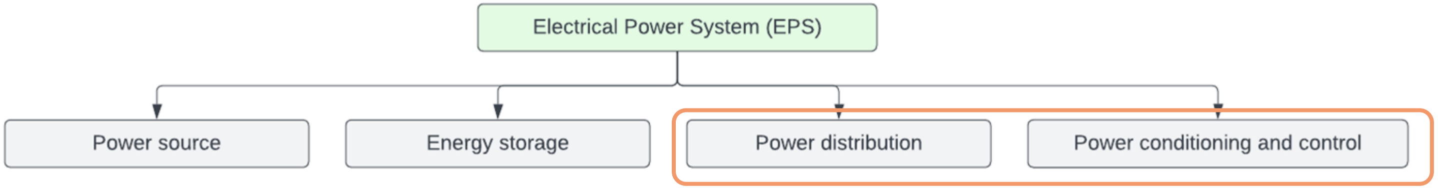
Taken from fig 10.1 of:
Fortescue, P., Swinerd, G., & Stark, J. (Eds.). (2011). Spacecraft systems engineering. John Wiley & Sons.

Note, the original source material dates from 1978!

Electrical Power System Intro

The **electrical power system (EPS)** provides, stores, distributes, and controls spacecraft power.

EPS is a critical subsystem; **no power = no mission**



*These tend to be combined into the **Power Conditioning & Distribution Unit (PCDU)***

EPS top-level functions

- Supply continuous electrical power to all spacecraft loads during the mission life
- Store, control, and distribute electrical power to the spacecraft
- Support power requirements for average and peak electrical load
- Regulate electrical power, protecting the spacecraft payload against failures within the EPS (and other subsystems)
- Provide TM/TC capability for the EPS health and status, as well as control by ground station or an autonomous system

Sizing your EPS and power budget

We must identify the electrical power loads for mission operations at BOL and EOL.

Design Drivers

The most important sizing requirements are the demands for **average and peak electrical power** and the **orbital profile** (inclination and altitude).

Average electrical power

- Sizes the primary power-generation system (number of solar cells or size of RTGs, primary battery size [given eclipse period and depth of discharge])
- The **average electrical power needed at EOL** determines de size of the power sources.

Peak electrical power

- Sizes the energy-storage system (number of batteries, capacitor bank size) and the PCDU.
- **We usually multiply average power by 2 or 3 to obtain peak power requirements** for attitude control, payload, thermal, and EPS (when charging the batteries).

Sizing your EPS and power budget

We must identify the electrical power loads for mission operations at BOL and EOL.

Design Drivers

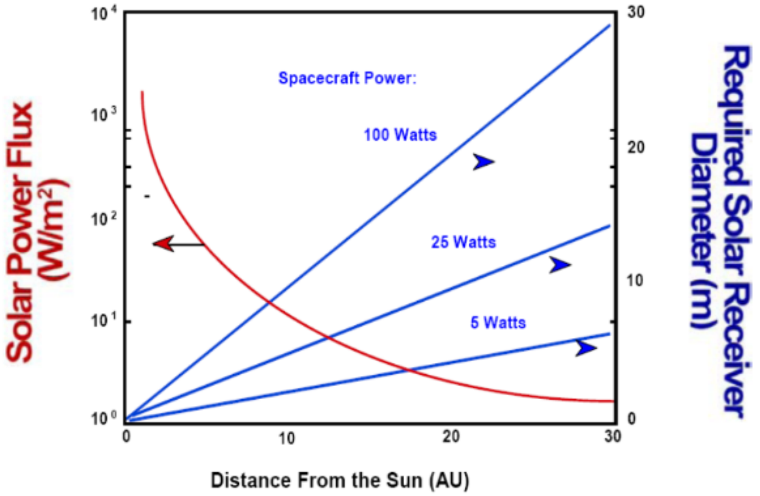
The most important sizing requirements are the demands for **average and peak electrical power** and the **orbital profile** (inclination and altitude).

Orbital profile

- Defines incident solar energy, eclipse/Sun periods, and radiation environment

Other design factors to consider include

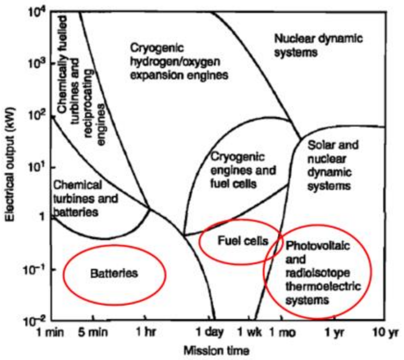
- Mission life: longer missions (>7 yr) often need extra redundancy design, independent battery charging, larger capacity batteries, and larger arrays.
- Spacecraft configuration: body-mounted solar arrays (spinner) vs deployable solar arrays (3-axis stabilized)



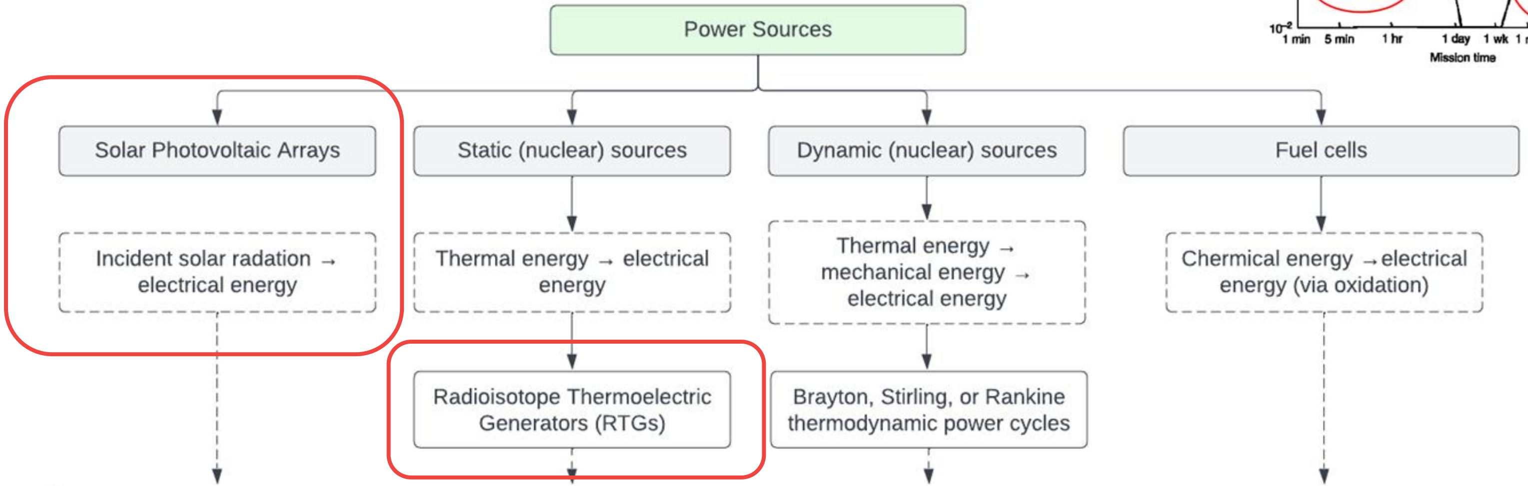
source: B. Foing (2022) EE584 EPFL

Primary power sources

From *Spacecraft Systems Engineering by Fortescue*, Stark, and Swinerd (Fig. 10.1)



We typically use **4 types of power sources** for spacecraft.

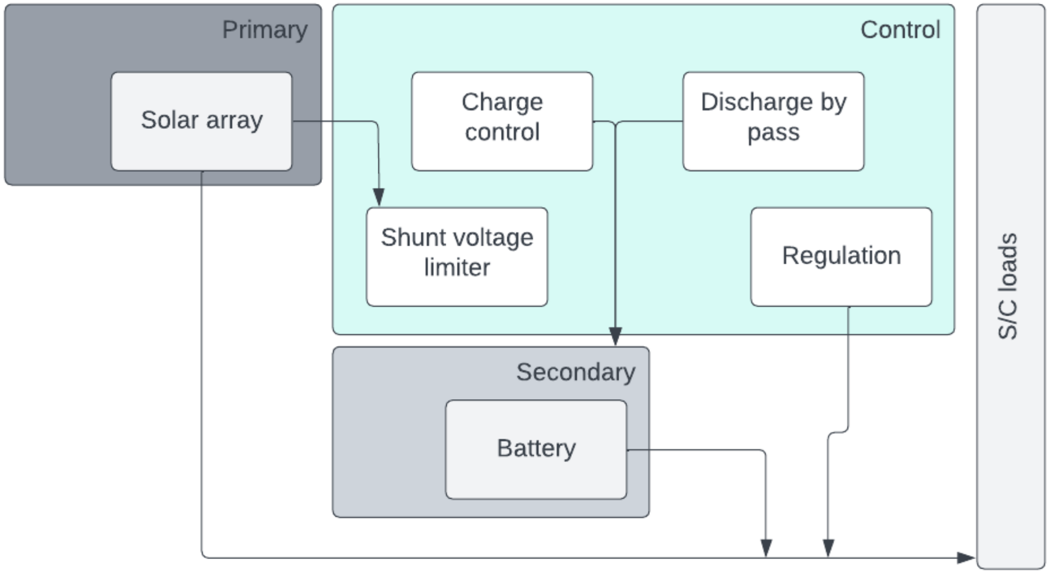


	Solar Photovoltaic Arrays	Static (nuclear) sources	Dynamic (nuclear) sources	Fuel cells
Efficiencies	**<10-25%**	**<5-20%**	**<15-35%**	**50-80%**
Power range (kW)	**0.2-300**	**0.2-10**	**5-300**	**0.2-50**
Specific power (W/kg)	**25-200**	**5-20**	**9-15**	**275**

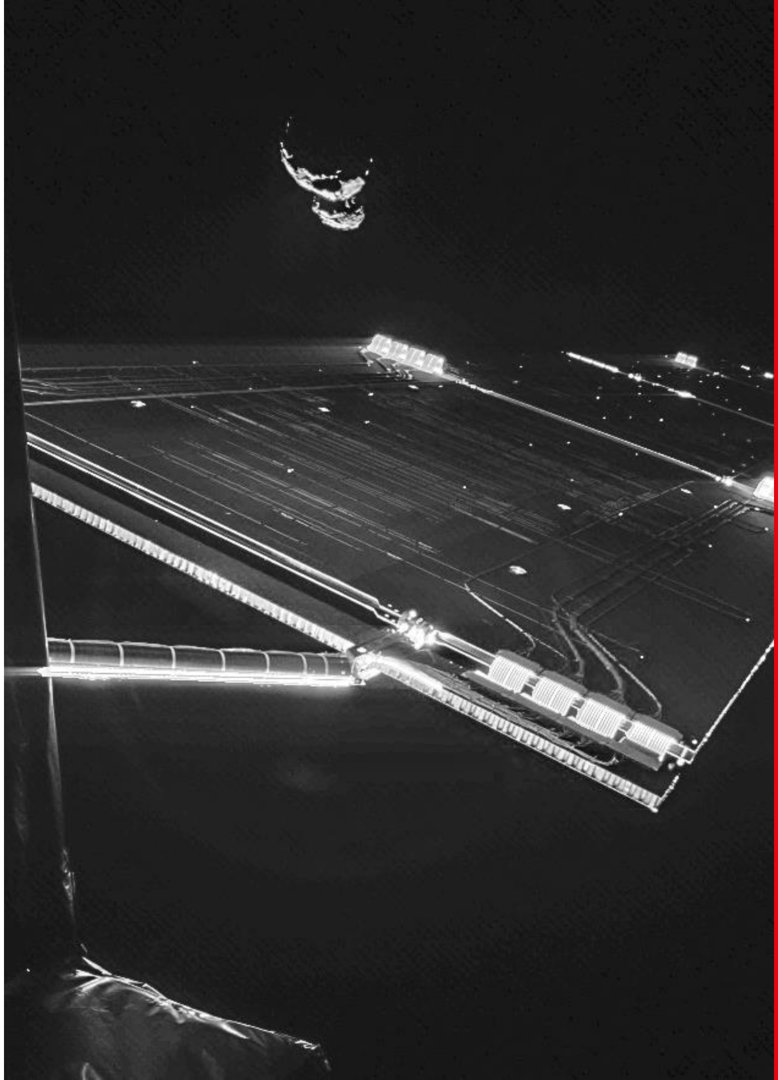
Check backup slides for an exhaustive list and comparison

Electrical Power System Intro

Below is an (extremely) simplified schematic of a typical spacecraft power system block elements



EPFL



Solar panels

- How they work
- Their expected efficiencies
- Design options
- Calculations

https://blogs.esa.int/rosetta/2014/09/10/rosetta-and-philae-snap-selfie-at-comet/

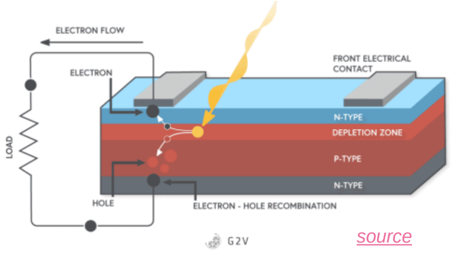
And bonus 3D render of Comet 67P/C-G: https://sci.esa.int/comet-viewer/

EPFL

Solar Photovoltaic Array

A solar photovoltaic (PV) array is made up of:

- 1000s of PV solar cells connected electrically in series-parallel configuration, which produce electricity (1s W to ~10s kW) when illuminated by sunlight.
- A structural substrate - rigid or flexible
- A deployment mechanism (or not)



source

Properties of semiconductor materials from Jean et al. Pathways for Solar Photovoltaics. Energy & Environmental Science 8(4):1200 (2015)

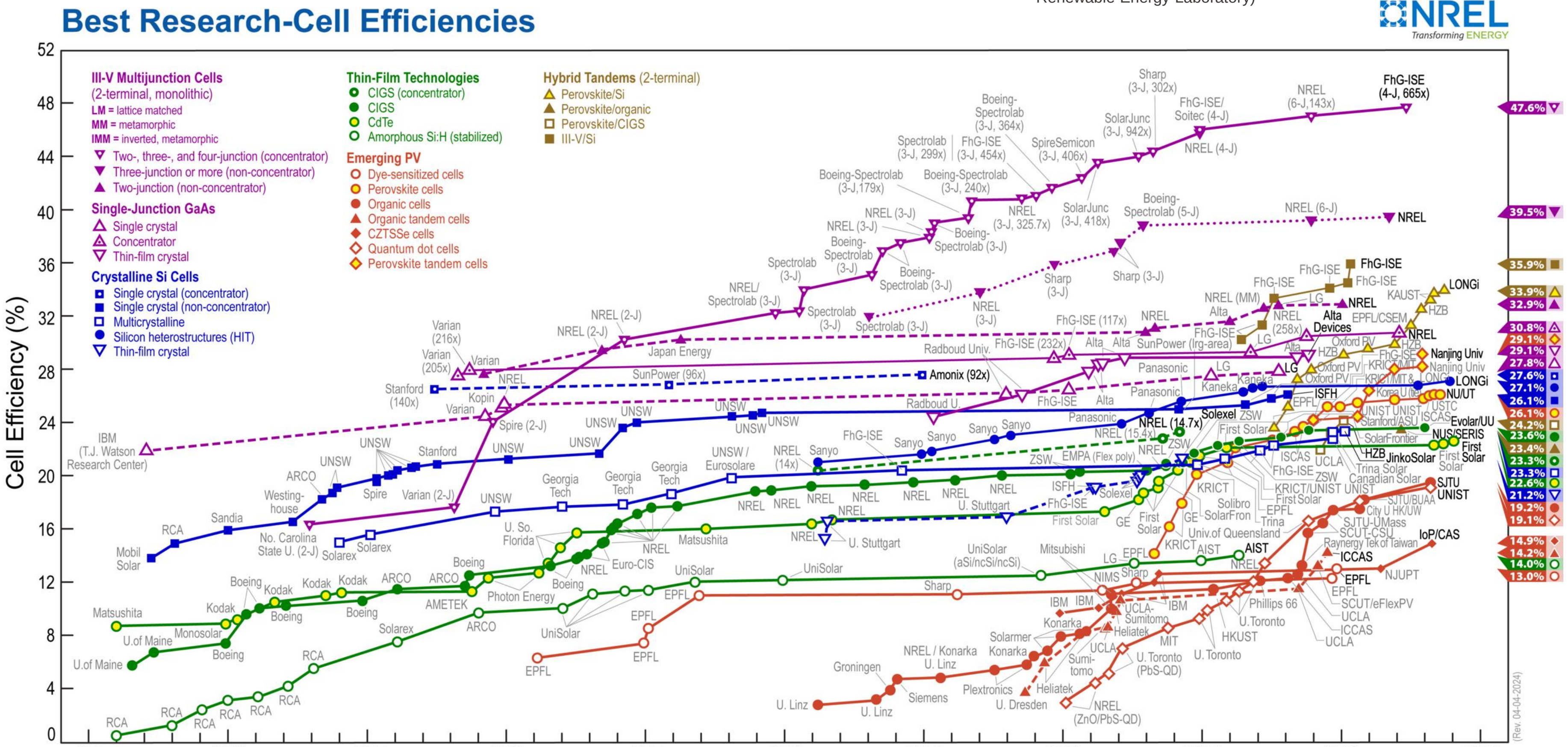
Material	Bandgap [eV]
Metals	0
PbS (lead sulfide)	0.4
Si (silicon)	1.1
CdTe (cadmium telluride)	1.4
CIGS (copper indium gallium diselenide)	1.0–1.7
C (diamond)	5.5
SiO_2 (silica glass)	~9
LiF (lithium fluoride)	13.6

Represents the minimum energy required to excite an electron in a semiconductor to a higher energy state

The ISS has the largest solar arrays ever built and deployed in space: 32800 cells of 8x8 cm = 210 m^2. ISS has eight of this arrays.

Most commonly used : Silicon (120-210 W/m2) or Gallium Arsenide (170-260 W/m2)

[Reported timeline of research solar cell energy conversion efficiencies since 1976](#) (National Renewable Energy Laboratory)



Solar Photovoltaic Array

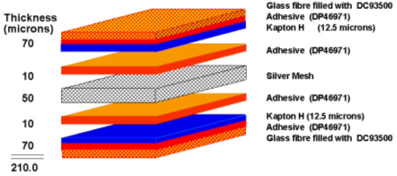
There are 3 primary configurations for solar arrays

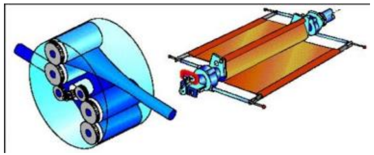
Fixed solar arrays	Deployable solar arrays (3-axis stabilized)	
Body-mounted arrays (spinner and cubesats)	Rigid-planar arrays	Flexible arrays

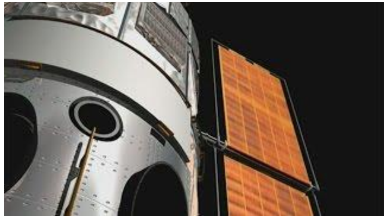
INTELSAT-603

Most other missions…

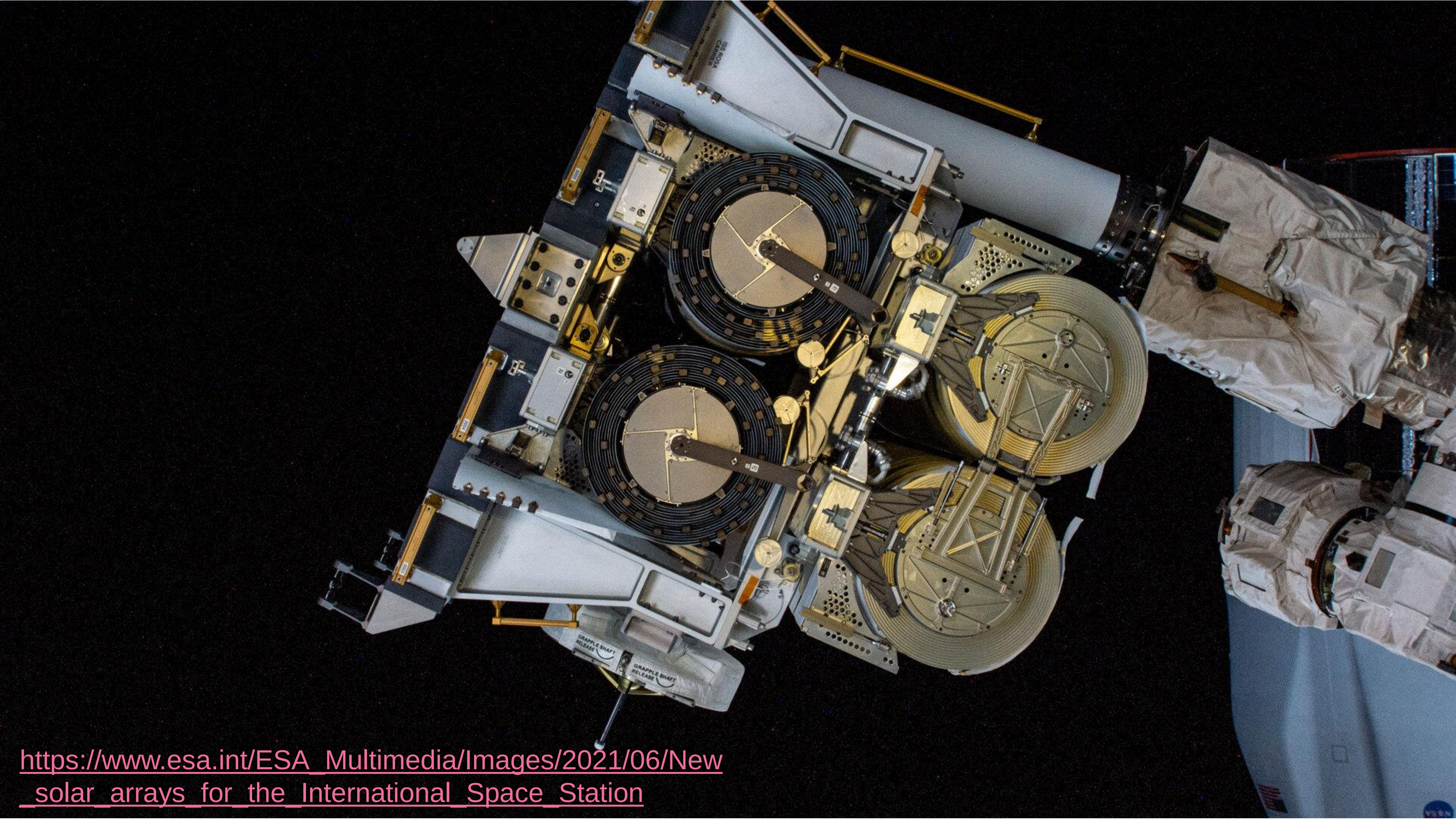
Hubble Telescope, ISS, ...







Read more: *How Hubble got its wings by ESA*



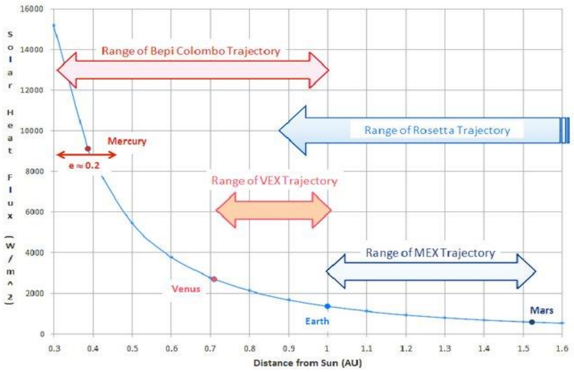
https://www.esa.int/ESA_Multimedia/Images/2021/06/New_solar_arrays_for_the_International_Space_Station

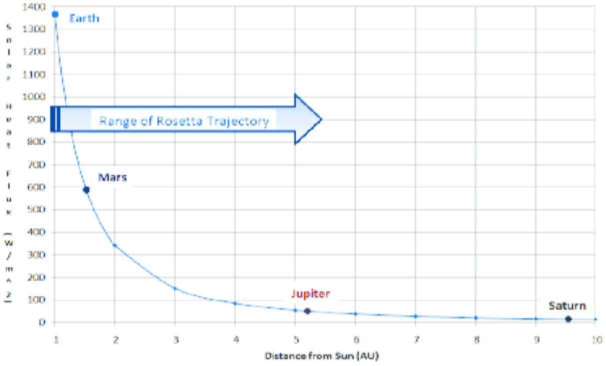
Solar Photovoltaic Array

Effect of solar distance on performance

Solar arrays are, however, only useable **inside the orbit of Jupiter**.

Beyond this distance from the Sun, the intensity of the solar radiation becomes too low to produce useful amounts of electricity.





Planet	Distance from Sun (AU)	Relative solar intensity
Mercury	0.387	6.68
Venus	0.723	1.913
Earth	1.000	1.000
Mars	1.524	0.431
Jupiter	5.203	0.0369
Saturn	9.539	0.0110
Uranus	19.189	0.00272
Neptune	30.060	0.00111
(Pluto)	39.439	0.00064

*assuming solar flux in Earth orbit of 1371 W/m^2

Solar Energy Flux as Function of Solar Distance (Inner (left) and Outer (right) Solar System) from J.C.Van der Har et al., *Thermal Radiation Effects on Deep-Space Trajectories*, Advances in the Astronautical Sciences, 136:1861-1880 (2010)

Solar Photovoltaic Array

Effect of Sun angle on performance

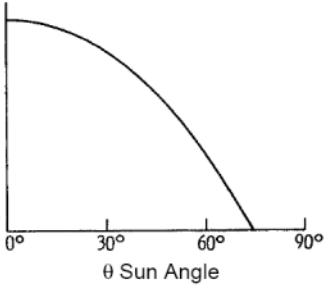
The amount of power provided **declines** as the Sun moves off the normal to the panel.

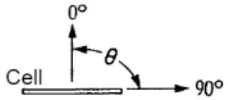
Cosine curve decline until about 45 deg, then falls rapidly.

Typically no power generated above 70 deg to normal.

Watch for **shadows**! → deployables, antennas, etc.

- Shadowing considerations are important because a cell will go into open circuit (become high resistance) when not illuminated.
  - This means that in a series-connected string of cells, the shadowing of one results in the loss of the entire string.





$$P_{out} = P_{in}\eta\cos\theta$$

P_{out}: output power (W/m^2)
P_{in}: solar flux (W/m^2)
η: cell efficiency
θ: angle of incidence

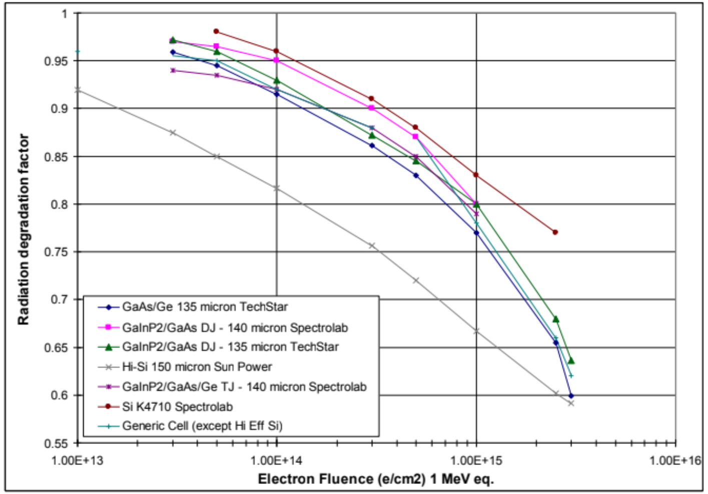
Solar Photovoltaic Array

source: B. Foing (2022)

Other effects on performance

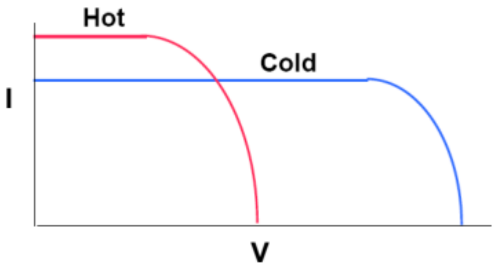
<u>Radiation effects</u>

- Reduces available power voltage and current
- Degradation of the cells
- UV damage to glue



<u>Temperatures</u>

- Changes the I-V curves of the cells
- High temperatures
  - Reduces power and voltage
- Low temperatures
  - Increases power and voltages



Note:

- a solar array often provide max. Power coming out of an eclipse period
- you may need to protect your spacecraft against transient voltage excursions when coming in and out of eclipses.

Solar Photovoltaic Array

NASA [State-of-the-Art of Small Spacecraft Technology](#) [Ch.3 Power](#)

Table 3-2: Solar Array/Panel Products

Company	Product	Panel Type	Specific Power (W/kg)	Peak BOL Solar Array Power (W)	TRL	Ref
AAC Clyde Space	Photon	Body Mount + Deployed Rigid	*	9.25W / 3U-12 Face	7-9	(11)
Blue Canyon Technologies	BCT Solar Array	Body Mount + Deployed Rigid	*	28 – 42 (3U) / 48-118 (6U-12U)	7-9	(12)
DHV Technologies	Solar Panels for CubeSats Set	Body Mounted (Polyimide)	50	2 (1U) Face	9	(13)
	Solar Panels for CubeSats Set	Body Mounted (Polyimide)	49	4 (2U) Face	9	
	Solar Panels for CubeSats Set	Body Mounted (Polyimide)	75	8 (3U) Face	9	
	Solar Panels for CubeSats Set	Body Mounted (Polyimide)	68	18 (6U) Face	9	
	Solar Panels for CubeSats Set	Deployed Rigid (Polyimide)	42	12 (3U) Double Deployable and Body Mounted	9	
	Solar Panels for CubeSats Set	Deployed Rigid (Polyimide)	69	57 (6/12U) Double Deployable and Body Mounted	9	
	Solar Panels for CubeSats Set	Deployed Rigid (Polyimide)	108	34 (3U) Quadruple Deployable	8	
	Solar Panels for CubeSats Set	Deployed Rigid (CFRP)	69	68 (6U) Quadruple Deployable	6	
	Solar Panels for CubeSats Set	Body Mounted (Polyimide)	50	2 (1U) Face	9	
	Solar Panels for CubeSats Set	Body Mounted (Polyimide)	49	4 (2U) Face	9	
	Body mounted solar array panel	Sandwich CFRP substrate	84	179	9	
	Body mounted solar array panel	Sandwich CFRP substrate	90	171	9	
	Body mounted solar array panel	Low thickness monolithic CFRP substrate	140	96	8	
	Multiple deployable solar array wing	Sandwich CFRP substrate	57	697	8	
Exoterra	Fold Out Solar Arrays (FOSA)	Deployed Flexible	140	150	5-6	(14)
MMA Design	Hawk	Deployed Rigid (PCB)	121	36-112	7-9	(15)
	zHawk	Deployed Rigid (PCB)	95	36	7-9	(16)
Airbus Defense and Space Netherlands	Sparkwing Solar Panel	Deployed Rigid	165	66	5-6	(17)
Agencia Espacial Civil Ecuatoriana	DSA/1A	Deployed Rigid	107	7.2	7-9	(18)
GomSpace	Nanopower DSP	Deployed Rigid	*	1.2	7-9	(19)
ISISPACE	Smallsat Solar Panels	Body Mount + Deployed Rigid	46	2.3W / U	7-9	(20)
Redwire Space	ROSA	Flexible PV blanket	100	1000	5**	(21)
	Aladdin SmallSat Array	Hybrid Array: Flex Rigid	80	300	5-6	
EnduroSat	1U Solar Panel	Deployed Rigid	50	2.4	7-9	(35)
	1.5U Solar Panel	Deployed Rigid	55	2.4	7-9	
	3U Solar Panel/Array	Deployed Rigid	66	8.4	5-6	
	6U Solar Panel/Array	Deployed Rigid	64	19.2	5-6	
Nanoavionics	CubeSat GaAs Solar Panel	Deployed Rigid	Unk	Unk	7-9	(89)

* Available with inquiry to manufacturer
** For SmallSat use

Game Time!!

Name the top-5 missions with the largest solar arrays!

1 …

2…

3…

4…

5…

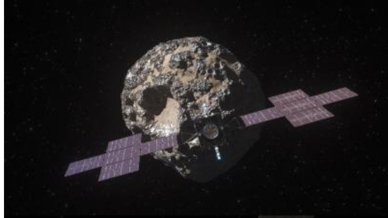
EPFL

Solar Photovoltaic Array

Game Time!!

Name the top-5 missions with the largest solar arrays!

1. Psyche 75 m^2
2. Juno 72 m^2
3. Rosetta 61.5 m^2
4. Lucy 51 m^2
5. Dawn 38.5 m^2



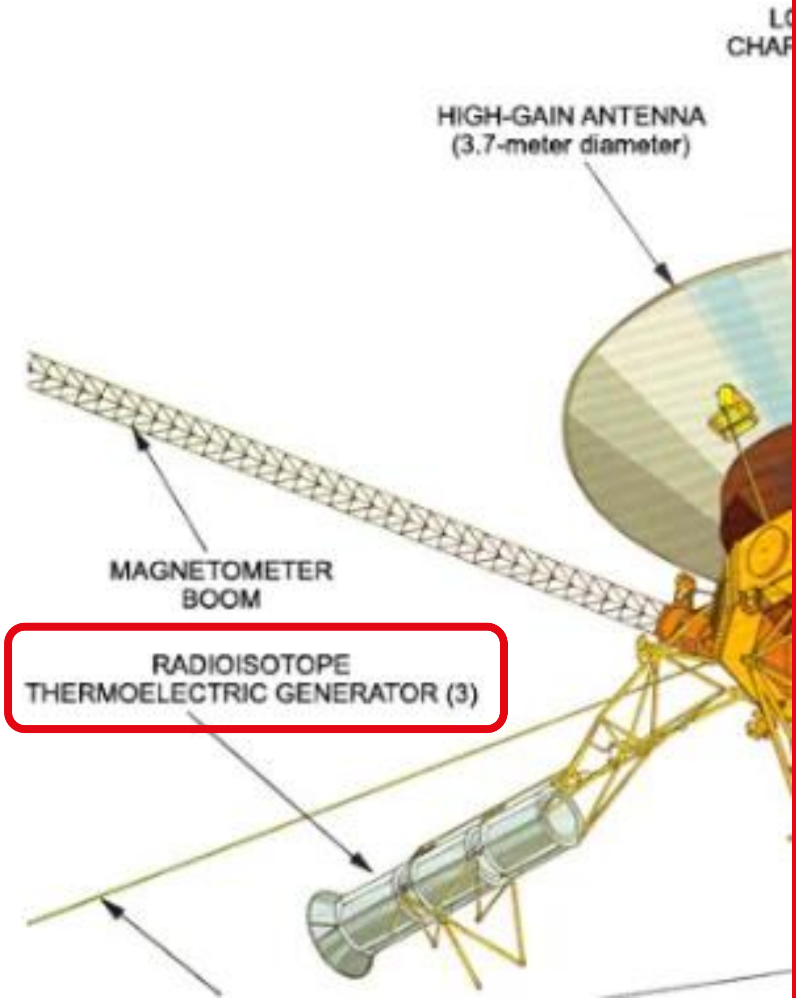


Get an idea of the size...

http://www.youtube.com/watch?v=fh6DlEFjR1M

A link with the Thermal Subsystem…

https://www.youtube.com/watch?v=aQaCY7wlQEc&pp=ygUuVGhlIFBhcmtlciBTb2xhciBQcm9iZSAtIFNtYXJ0ZXIgRXZlcnkgRGF5IDE5OA%3D%3D



Radioisotope Thermoelectric Generators (RTGs)

- Use in real missions
- How they work

Radioisotope Thermoelectric Generators (RTGs)

RTGs are independent of the Sun and are used most commonly for deep space missions to the outer solar system.

Sun

Ulysses (1990-2009)

Venus

Galileo (1990 flyby)

Cassini-Huygens (1998 flyby)

Earth's Moon

Apollo Lunar Surface Experiment Package (Six missions 1969-1977)

Earth

Transit 4A (1961-1971)

Nimbus III (1969-1972)

Galileo (1990 flyby, 1992 flyby)

Cassini-Huygens (1999 flyby)

Mars

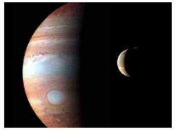
Viking 1 and 2 landers (1976-1982)

+Mars Pathfinder (1997)

+Mars Exploration Rovers (Opportunity: 2004-2018; Spirit: 2004-2011)

Mars Science Laboratory (2012-present)

Mars 2020 (2021-present)



Jupiter and Its Moons

Pioneer 10 & 11 (1972 & 1973 flybys)

Voyager 1 and 2 (1979 flyby)

Ulysses (1991 flyby, 2004 flyby)

Galileo (1995-2003) | +Galileo atmospheric probe (1995)

Cassini-Huygens (2000 flyby)

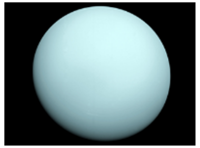
New Horizons (2007 flyby)

Saturn and its Moons

Pioneer 11 (1973 flyby)

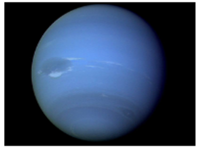
Voyager 1 and 2 (1980 flyby)

Cassini-Huygens (2004-2017) | +Huygens Titan probe (2005)



Uranus

Voyager 2 (1986 flyby)

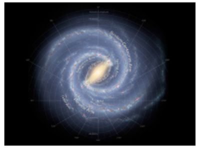


Neptune

Voyager 2 (1989 flyby)

Pluto and the Kuiper Belt

New Horizons (Pluto flyby 2015, KBO flyby 2019)



Interstellar Space

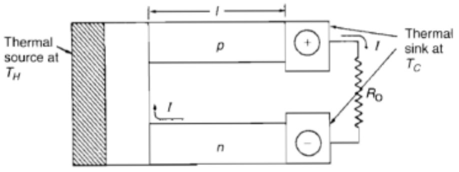
Voyager 1 (2012)

Voyager 2 (TBD)

Note: Pioneers 10 and 11 and New Horizons also are on interstellar trajectories.

Read more: *What is radioisotope power and why does NASA use it?*

Radioisotope Thermoelectric Generators



Working principle

RTGs work by radioactive decay of an isotope, which generates heat that is converted into electricity (thermoelectric effect).

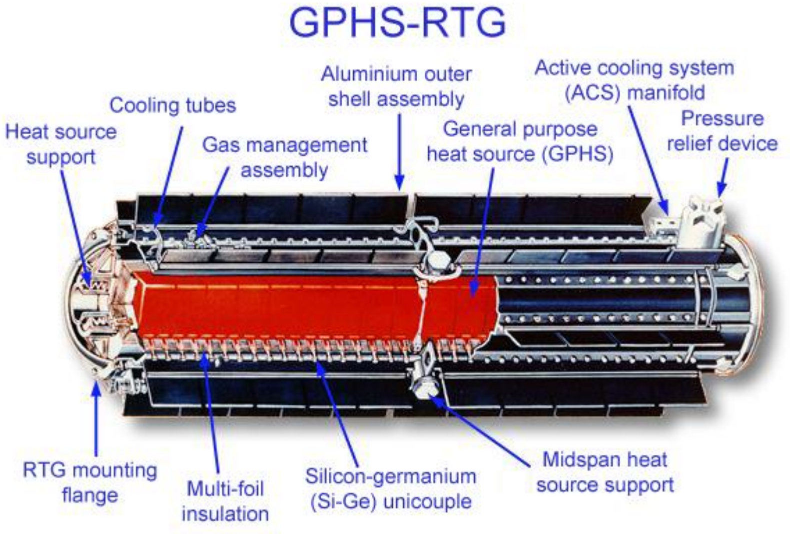
Plutonium 238 is the most common isotope used → it has lowest shielding requirements and longest half-life (87.4 yr) of suitable fuels.

Main advantages

+ Sun independence
+ Unaffected by S/C orientation
+ Unaffected by shadows

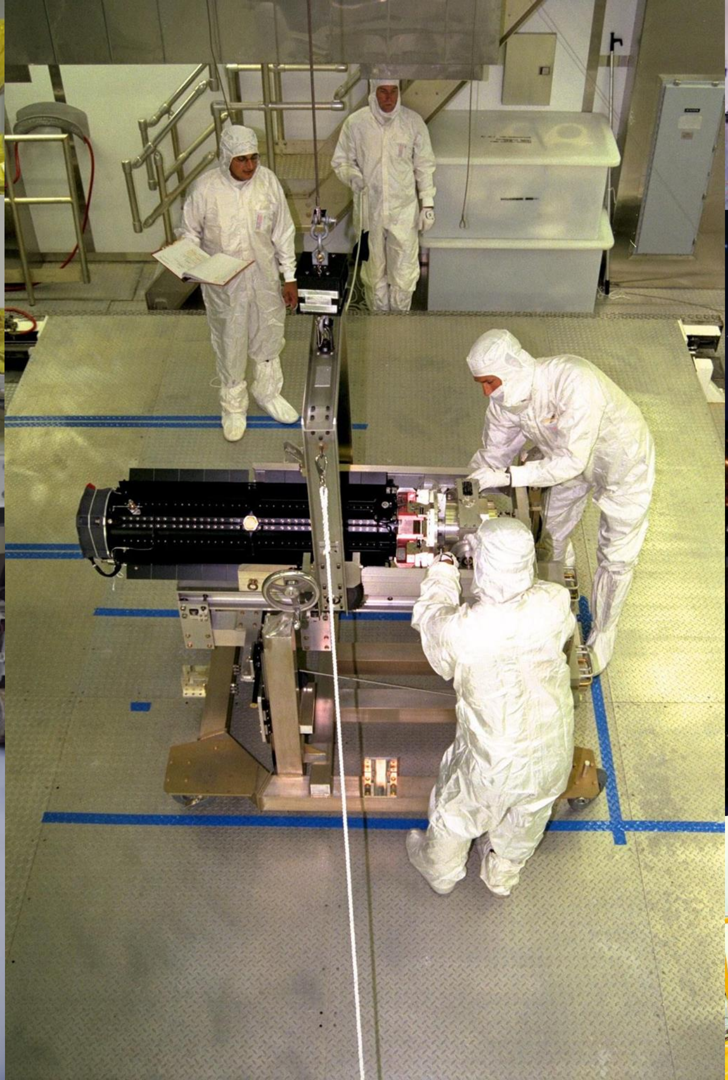
Main disadvantages

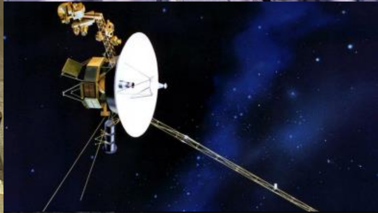
- Low efficiencies (~8%)
- Removal of waste heat is required (via fins)
- Power decrease due to to nuclear decay
- Radiation emission (so often boom-mounted)
- High safety/compliance requirements
- Pu availability is limited

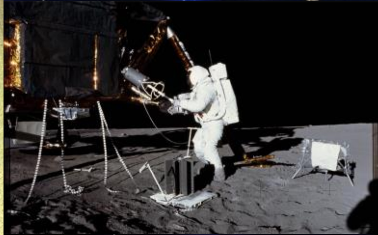


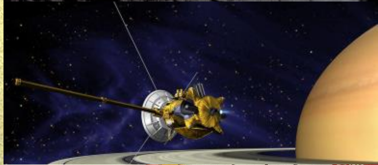
- RTGs are used to provide low power levels for long periods of time

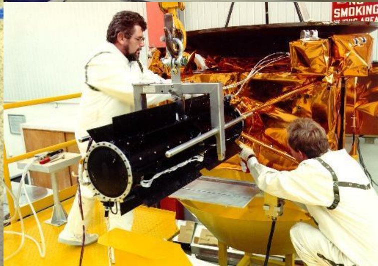

FLAMMABLE
EMERGENCY
EXIT
ONLY











How do RTGs work?

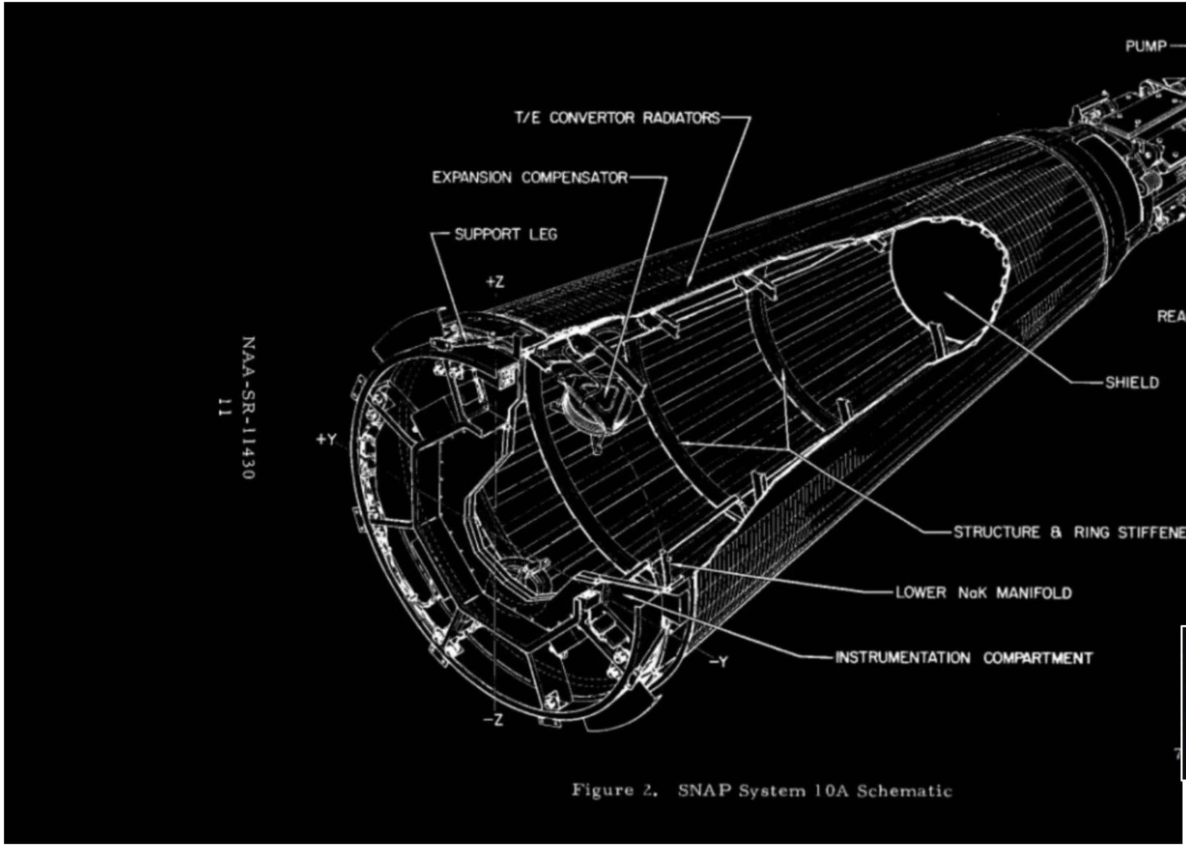
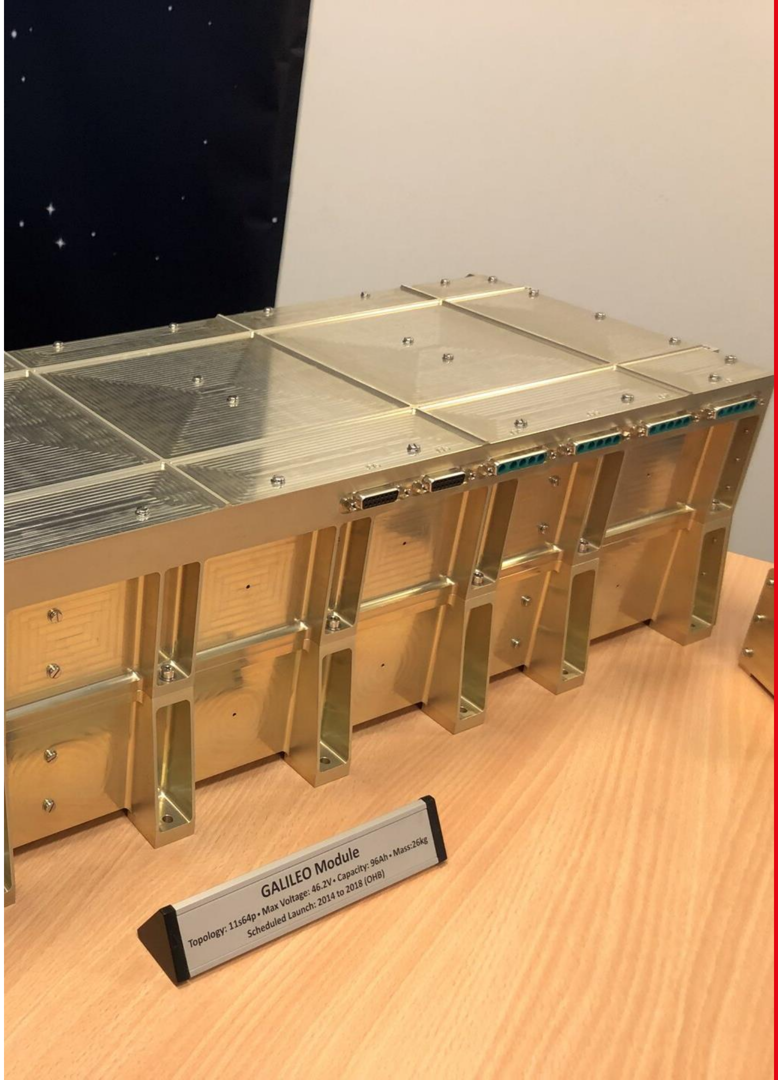


Figure 2. SNAP System 10A Schematic

https://www.youtube.com/watch?v=1oS-BmoSBtQ



Batteries and Power Distribution & control

- Technologies
- Important parameters

https://www.esa.int/ESA_Multimedia/Images/2019/10/Galileo_lithium-ion_battery

Batteries: energy storage

Rarely are batteries used as primary energy source (one shot, no recharge) → launch vehicles.

That's why they are often referred to as secondary power systems.

Most space power subsystems need energy storage when not illuminated by the Sun (unless nuclear powered).

In almost all cases, this energy storage is performed by **chemical batteries**.

Multiple battery technologies have been used in space

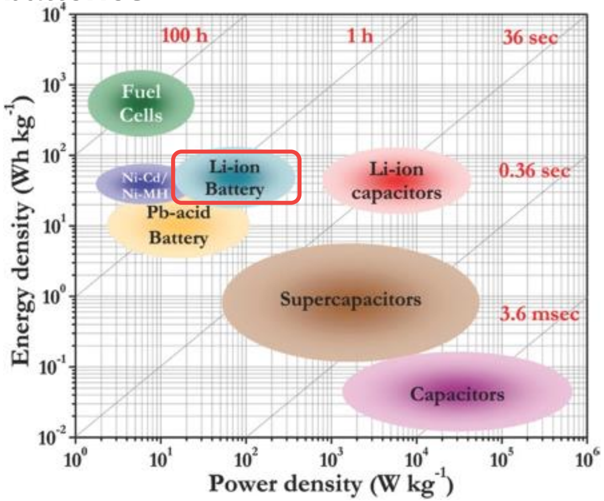
Lithium-Ion is starting to replace most Nickel-Cadmiun and Nickel-Hidrogen batteries

In some cases Lithium-Polymer are used

Table 10.6 Performance of battery technologies for space use [14]

Type	Specific energy (W h/kg)
Ni–Cd	39
$Ni–H_2$	52
Ag–Zn	60
Ni–MH	60
Li–Ion	80
$Li–TiS_2$	125
Na–S	150

NASA State-of-the-Art of Small Spacecraft Technology Ch.3 Power

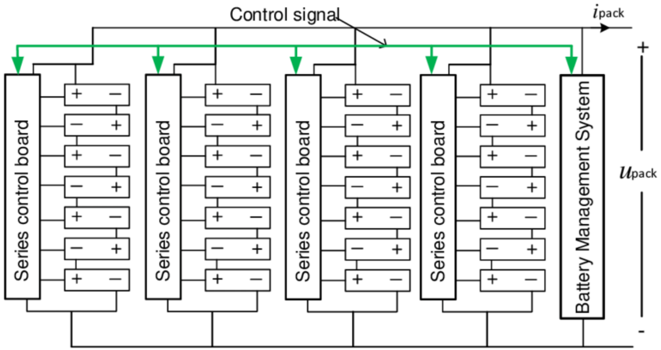


Read more: A review on battery technology for space application

Batteries: energy storage

Three **parameters to keep in mind** when it comes to batteries

- Capacity (Ah) [C(EOL)= Capacity End of Life]
- Depth of discharge: how much of the battery's capacity (in Ah) is removed from the charged battery on a regular basis (in %).
- Total number of cycles: number of charge-discharge cycles a battery can complete before losing performance.



When batteries are used and how often

In LEO, during eclipses → 40% of each orbit (depending on inclination) → 5000/6000 charge-discharge cycles per year → large number of low depth discharges → Ni-Cd or Ag-Zn

In GEO, during 2 equinoctial periods → eclipse seasons lasting ~45 days at each equinox → from minutes to 1.2h for a total of ~90 eclipses → few depth discharges → Ni-H2

Nickel-Hydrogen batteries for Hubble

Read more: *A review on battery technology for space application*

Batteries: energy storage

Table 3-3: Battery (Pack) Product Table

Company	Product	Volumetric Energy Density [Wh L^{-1}]	Specific Energy [Wh kg^{-1}]	Typical Capacity [Ah]	Max Discharge Rate [A]	Cells Used	TRL	Ref
EaglePicher Technologies	NPD-002271	271	153.5	14.5	15	EaglePicher Li-ion	7-9	(39)
GomSpace	Nanopower BPX (4S-2P)	228.7	150	5.2	2.5	GomSpace NanoPower Li-ion	7-9	(42)
GomSpace	Nanopower BP4 (2S-2P)	211.9	149.2	5.2	2.5	GomSpace NanoPower Li-ion	7-9	(43)
AAC Clyde Space	Optimus	169.5	119	4.84	2.6	Clyde Space Li-Polymer	7-9	(44)
Ibeos	28V Modular Battery	151.1	109.8	9.82	20	*	N/A	(45)
Saft	VES16 4S1P	109.2	91	4.5	4.5 – Cont. 9 - Pulse	SAFT Li-ion	7-9	(46)
Vectronic Aerospace GmbH	VLB-X	101.96	74.6	12	10 – Cont. 20 - Pulse	SAFT Li-Ion	7-9	(47)
Berlin Space Technologies	BAT-110 Modular Battery (Nominal 3 strings)	69.73	57.75	7.5	3	Li-Fe	7-9	(48)
GUMUSH AeroSpace	n-ART BAT	184.5	155.1	6.01	8	Li-Ion	7-9	

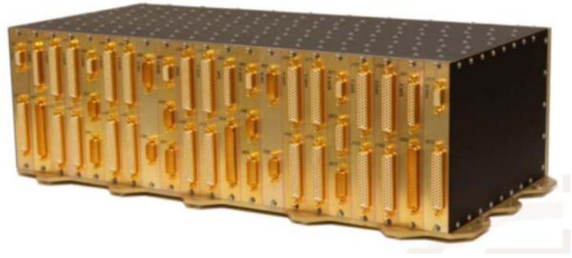
* Available with Inquiry to Manufacturer

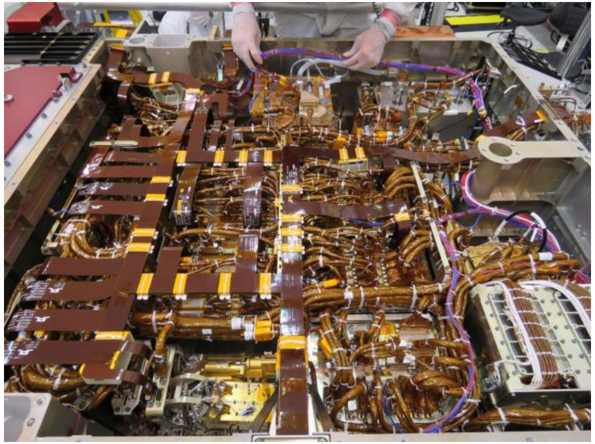
NASA State-of-the-Art of Small Spacecraft Technology Ch.3 Power

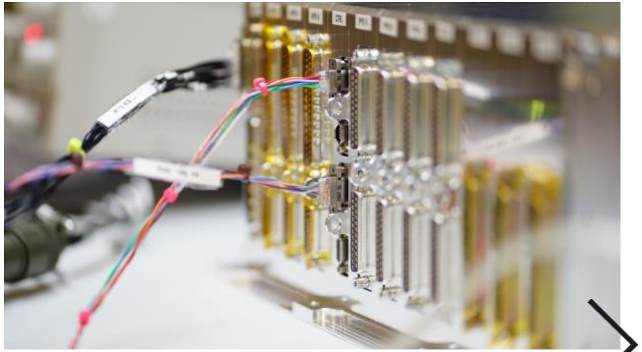
Power distribution, regulation, and control

Most often simply called **Power Conditioning and Distribution (PCDU)** or **Power Management and Distribution (PMAD)**

- <u>Conditioning</u> → manage power generation and supply the bus with the requested power at the requested voltage
  - The S/C EPS must be designed to operate with both primary and secondary power systems whose characteristics are changing with time.
  - Prevent overcharging the batteries and undesired heating to the s/c
- <u>Distribution</u> → distribute the conditioned power to all "users" (typical 28 or 50 V buses)



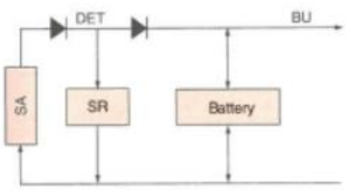




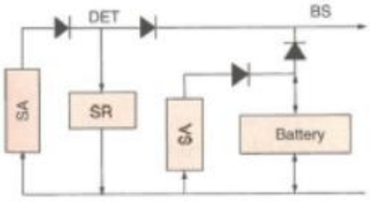
Power distribution, regulation, and control

There are 2 main ways to **control** the power generated:

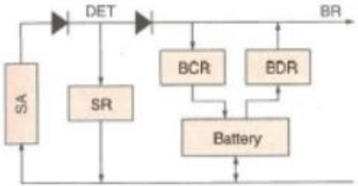
- Direct energy transfer (DET) with shunt dumps
    - Dissipates power not used by the loads (into “shunts” = resistors)
    - High efficiency, few parts. low mass



Unregulated bus (BU) with DET

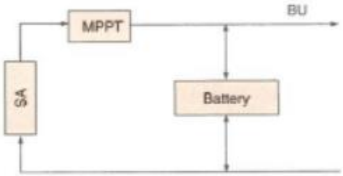


Semi-regulated bus (BS) with DET

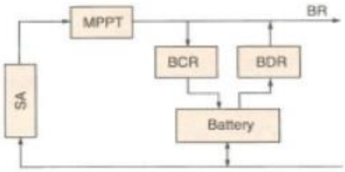


Regulated bus (BR) with DET

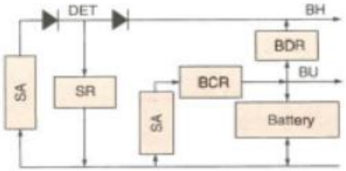
- Maximum power point tracking (MPPT) (most used in interplanetary)
    - DC-DC converter operating in series with the solar array
    - Dynamically changes the operating point of the array to its max. Power
    - Permits to extract large amount of power when the array is cold
    - PPT uses 4-7% of total power.



Unregulated bus (BU) with MPPT



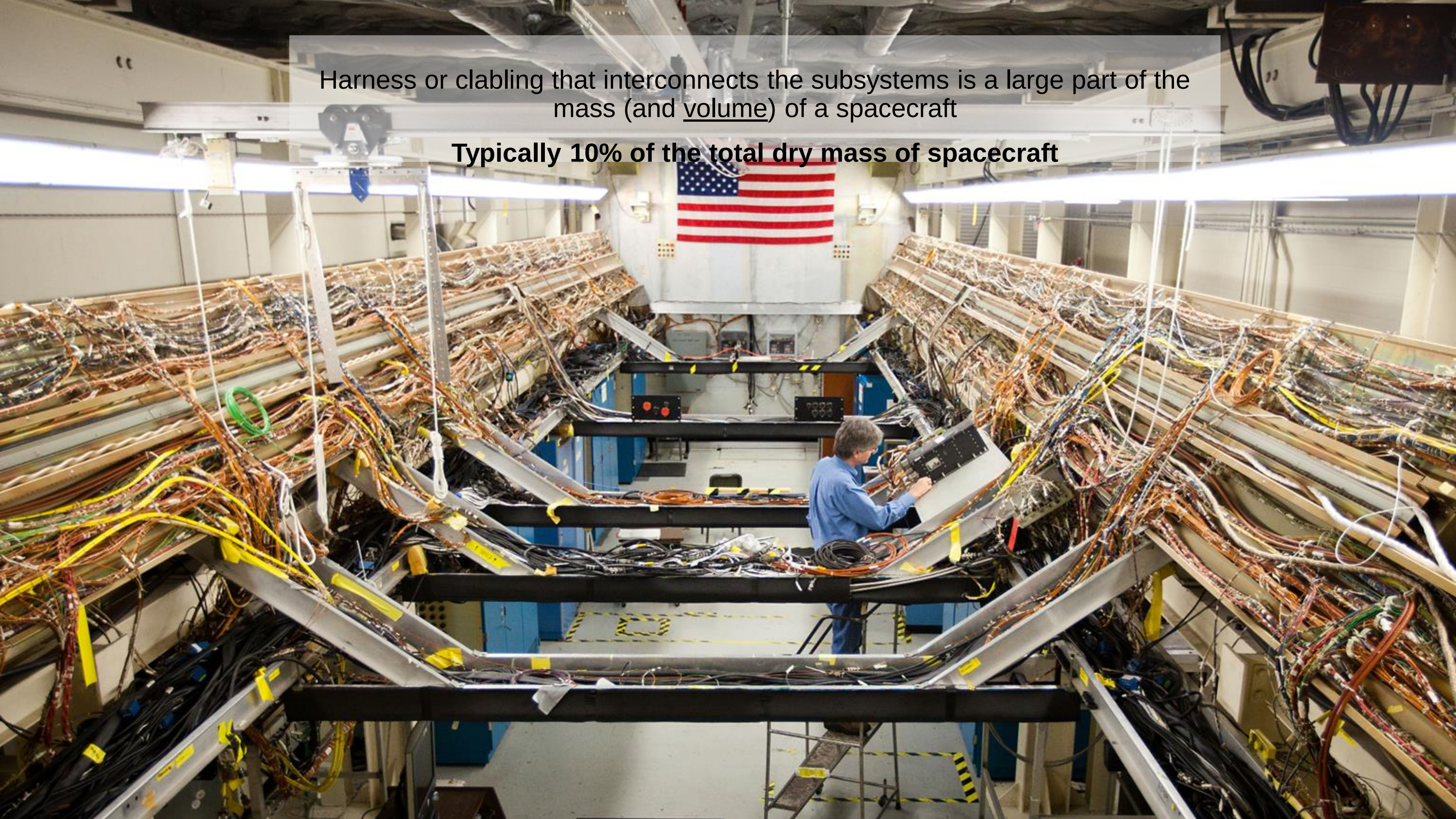
Regulated bus (BR) with MPPT

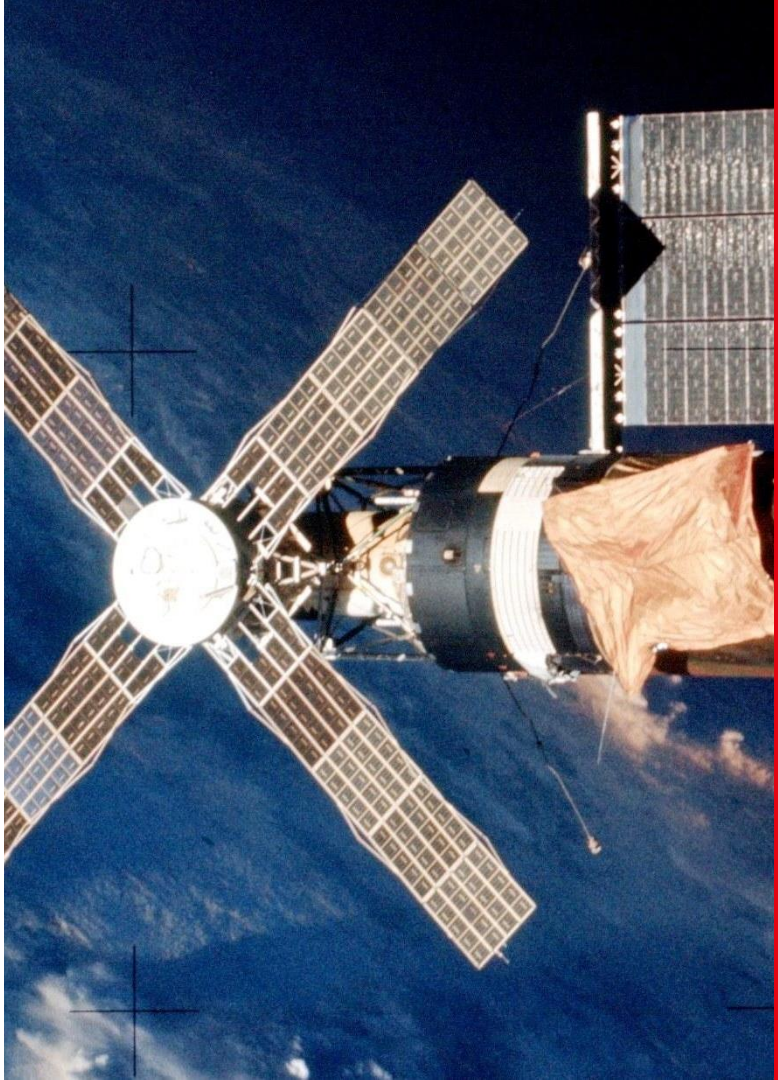


Hybrid bus (BH) with DET

Harness or clabling that interconnects the subsystems is a large part of the mass (and volume) of a spacecraft

Typically 10% of the total dry mass of spacecraft





Sizing your EPS

- Equations

Sizing your EPS and power budget

FireSat example

1. Prepare operating power budget
   a. Estimate power requirements for payload and each s/c bus subsystem
      i. Average power required during daylight/eclipse (110 W during d/e)
      ii. Orbit altitude and eclipse duration (700 km, 35.5 min)
      iii. Design lifetime (5 yr)
2. Size primary power source
   a. If **solar arrays…**
      i. Calculate amount of power that must be produced by the solar arrays (239.4 W)

$$P_{sa} = \frac{\left(\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}\right)}{T_d}$$

$T_e = time\ interval\ during\ eclipse\ per\ orbit\ [min]$ (35.3 min)

$T_d = time\ interval\ during\ daylight\ per\ orbit [min]$ (63.5 min)

$P_e = s/c\ power\ required\ during\ eclipse\ [W]$ (110 W)

$P_d = s/c\ power\ required\ during\ daylight\ [W]$ (110 W)

$X_e = efficiency\ of\ power\ distribution\ during\ eclipse$ (0.6)

$X_d = efficiency\ of\ power\ distribution\ during\ daylight$ (0.8)

Depends primarily on the type of regulation (DET vs PPT)

      i. Select type of solar cell and estimate power output, P_o, with the Sun normal to the array (Si cells, $P_o = 0.148 \times 1367\ W/m^2 = 202\ W/m^2$)
      ii. Determine the BOL power production capability, P_{BOL}, per unit area of the array (worst case θ=23.5 deg, $P_{BOL} = 143\ W/m^2$)

$$P_{BOL} = P_o I_d cos\theta$$

$I_d = inherent\ solar\ array\ degradation$ → use 0.77

Sizing your EPS and power budget

FireSat example

1. Prepare operating power budget
2. Size primary power source (5 yr)
   a. If **solar arrays…**
      iv. Determine the EOL power production capability, P_{EOL}, for the solar array (performance degradation is 3.75%/yr for Si cells, L_d=0.826 for 5 yr mission, P_{EOL}=118.1 W/m^2)

$$P_{EOL} = P_{BOL} L_d \qquad L_d = actual\ lifetime\ degradataion = (1 - degaradation/yr)^{s/c\ life}$$

      iv. Estimate solar array area required to produce the necessary power, P_{sa}, based on P_{EOL} (A = 2.0m^2)

$$A = P_{sa}/P_{EOL}$$

      iv. Estimate the mass of the array (for planar arrays m= 0.04*P_{sa})(m = 9.6 kg)

Sizing your EPS and power budget

FireSat example

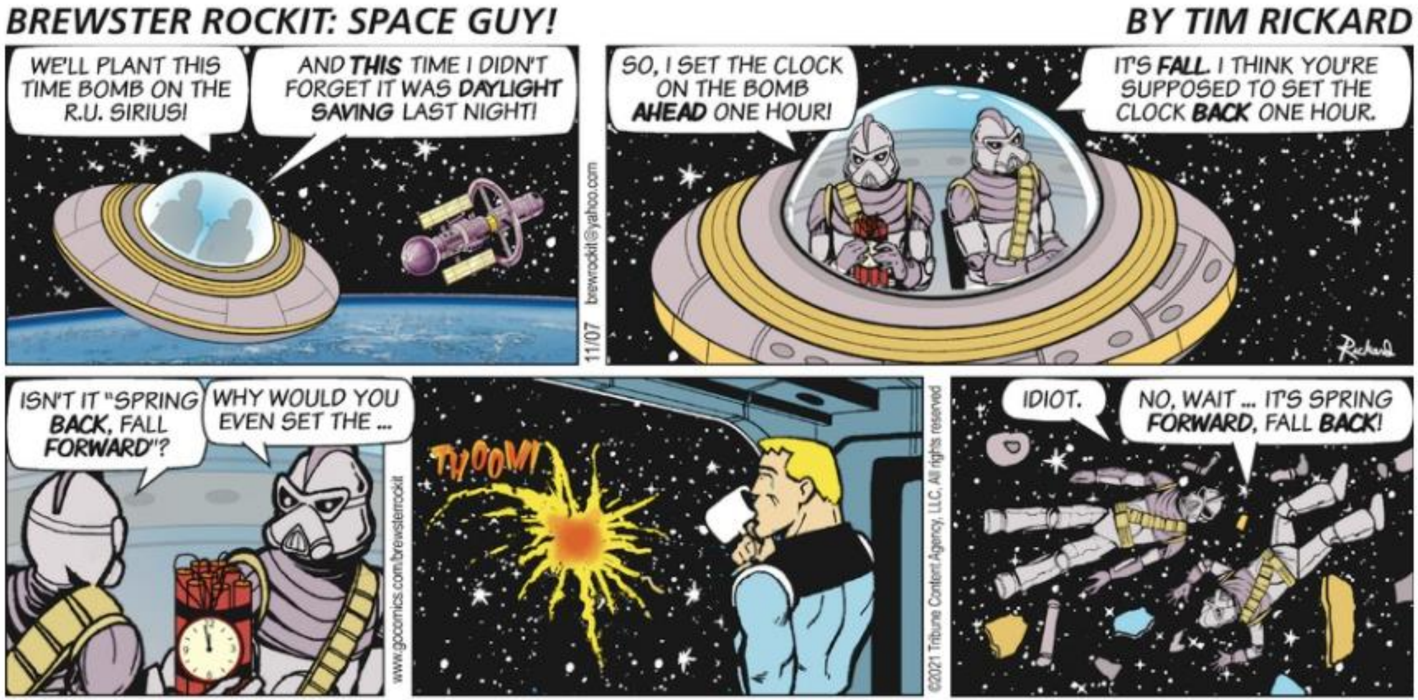
1. Prepare operating power budget
2. Size primary power source (5 yr)
   a. If **RTGs…**look for reference documentation on existing reactors.

1. Size the battery
   a. Determine energy storage requirements considering
      i. Mission length (5 yr)
      ii. Primary or secondary power storage (secondary)
      iii. Orbital parameters (eclipse frequency and length) (16 eclipses/day at 35.3 min/eclipse)
      iv. Power use profile (eclipse load 110 W (P_e) [26.4 V, 4.2 A max], DOD of 20% (upper limit))
      v. Battery charge/discharge cycle limits (TBD)
   b. Select type of batteries (NiCd or NiH2, both are space qualified and have adequate characteristics)
   c. Determine the size of the batteries (battery capacity) (C_r=119 Whr = 4.5Ah [26.4 V bus])
      i. Number of batteries (N = 3, nonredundant)
      ii. Transmission efficiency between the battery and the load (n = 0.9)

$$C_r = \frac{P_e T_e}{(DOD)Nn}\,[Whr](*\,for\ Ah\ divide\ by\ bus\ voltage)$$

EPFL

Time for a 15-min break!



Your turn...

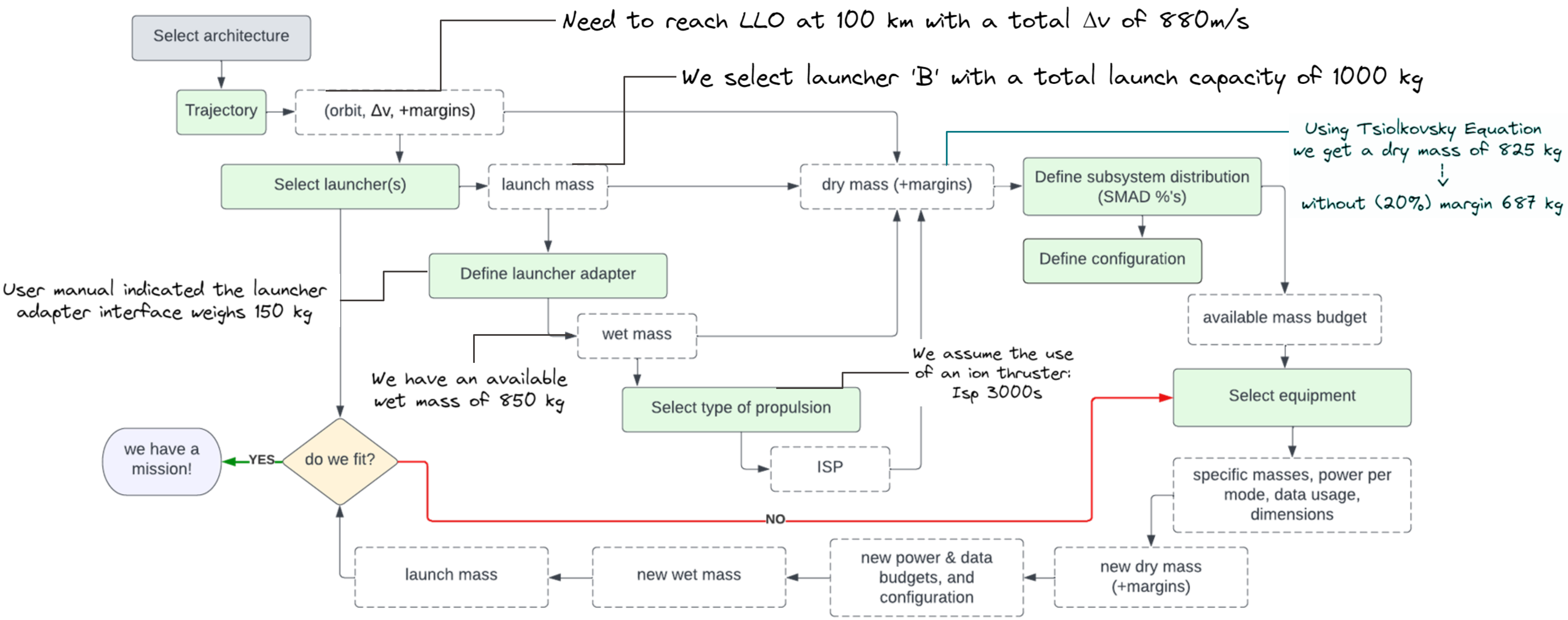
Today’s Project Work:

- Continue drafting out the details of your mission.
- It would be a good time to start working on your **final paper** (if you haven’t done so already)
- Today you need to start:
  - Select and size your electrical power system (solar arrays or other)
    - Calculate overall mass and dimensions
  - Define power distribution scheme
    - Estimate power consumption and mass
  - Size your batteries
    - Calculate overall mass and dimensions
  - Size your Thermal subsystem

Backup slides

Backup slides

Defining your spacecraft concurrently (more on this in ENG411)



Backup tables

TABLE 11-33. **Matrix for Comparing Most Common Spacecraft Power Sources.** We may use different factors to select the correct power source but specific power and specific cost are used extensively.

EPS Design Parameters	Solar Photovoltaic	Solar Thermal Dynamic	Radio-isotope	Nuclear Reactor	Fuel Cell
Power Range (kW)	0.2–300	5–300	0.2–10	5–300	0.2–50
Specific Power (W/kg)	25–200	9–15	5–20	2–40	275
Specific Cost ($/W)	800–3,000	1,000–2,000	16K–200K	400K–700K	Insufficient Data
Hardness					
– Natural Radiation	Low–Medium	High	Very high	Very high	High
– Nuclear Threat	Medium	High	Very high	Very high	High
– Laser Threat	Medium	High	Very high	Very high	High
– Pellets	Low	Medium	Very high	Very high	Medium
Stability and Maneuverability	Low	Medium	High	High	High
Low-orbit Drag	High	High	Low	Medium (due to radiator)	Low
Degradation Over Life	Medium	Medium	Low	Low	Low
Storage Required for Solar Eclipse	Yes	Yes	No	No	No
Sensitivity to Sun Angle	Medium	High	None	None	None
Sensitivity to Spacecraft Shadowing	Low (with bypass diodes)	High	None	None	None
Obstruction of Spacecraft Viewing	High	High	Low	Medium (due to radiator)	None
Fuel Availability	Unlimited	Unlimited	Very low	Very low	Medium
Safety Analysis Reporting	Minimal	Minimal	Routine	Extensive	Routine
IR Signature	Low	Medium	Medium	High	Medium
Principal Applications	Earth-orbiting spacecraft	Interplanetary, Earth-orbiting spacecraft	Inter-planetary	Inter-planetary	Inter-planetary

TABLE 11-41. **Steps in the Power Distribution Subsystem Design.**

Step	Consider	Possibilities
1. Determine the electrical load profile	• All spacecraft loads, their duty cycles, and special operating modes • Inverters for ac requirements • Transient behavior within each load • Load-failure isolation	• Low-voltage dc: 5 V • High-voltage dc: 270 V • High-voltage 1-phase ac: 115 V_{rms}, 60 Hz • High-voltage, 3-phase ac: 120/440 V_{rms}, 400 Hz
2. Decide on centralized or decentralized control	• Individual load requirements • Total system mass	• Converters at each load—for a few special loads • Centralized converters control voltage from the main bus (no specialized power requirements)
3. Determine the fault protection subsystem	• Detection (active or passive) • Isolation • Correction (change devices, reset fuses, work around lost subsystem)	• Cable size (length and diameter) and excess current-carrying ability • Size of power storage in case of a short circuit • Location of fuses and their type

From *SMAD 3d Edition* (Ch 11)

TABLE 11-42. **Steps in the Power Regulation and Control Subsystem Design.**

Step	Consider	Possibilities
1. Determine the power source	• All spacecraft loads, their duty cycles, and special operating modes	• Primary batteries • Photovoltaic • Static power • Dynamic power
2. Design the electrical control subsystem	• Power source • Battery charging • Spacecraft heating	• Peak-power tracker • Direct-energy transfer
3. Develop the electrical bus voltage control	• How much control does each load require? • Battery voltage variation from charge to discharge • Battery recharge subsystem • Battery cycle life • Total system mass	• Unregulated • Quasi-regulated • Fully regulated • Parallel or individual charging – < 5 yrs—parallel charge – > 5 yrs—independent charge