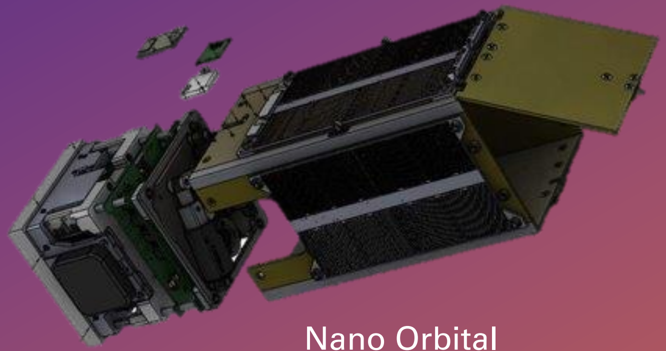
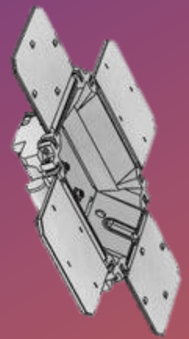
Nano Satellite Electrical Power Systems

HOW TO DESIGN, PLAN, AND IMPLEMENT AN EPS

Nano Orbital WorkshopTES-7

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NASA SILICON VALLEY AMES RESEARCH CENTER

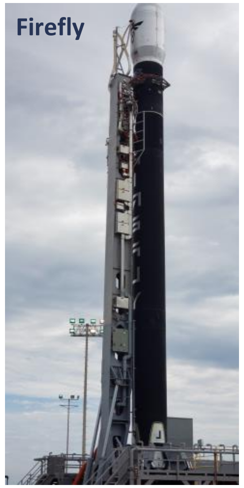
SPACEFLIGHT DIVISION NASA AMES RESEARCH CENTER

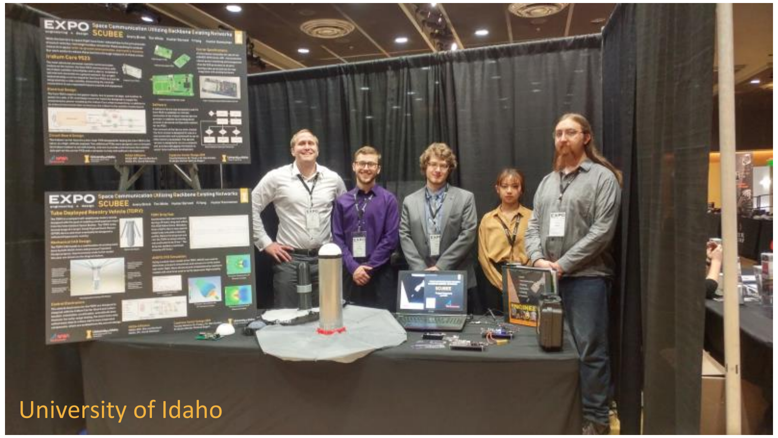
On behalf of the

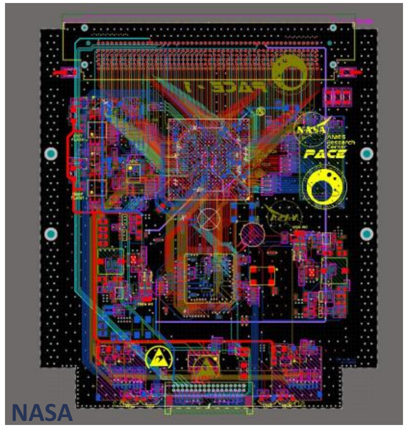
NASA Small Spacecraft Systems Virtual Institute (S3VI)

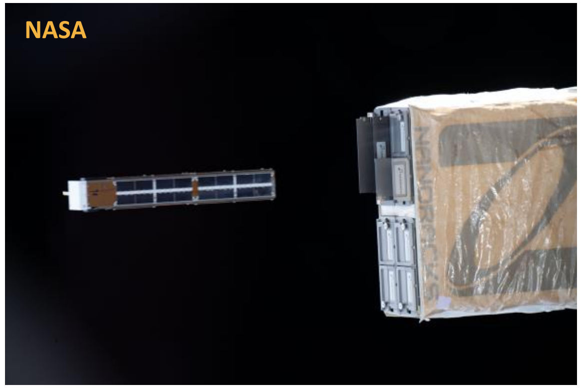
Speaker Background

University of Idaho BSEE, 2019
USIP Grant and Ames Capstone Design led to NASA
Small-Sat Program Electrical Design & Research Engineer
TechEdSat-6, 7, 8, 10, 11, 13, 15, 19, PACE-1
REV-TD Hypersonic Reentry Testbed





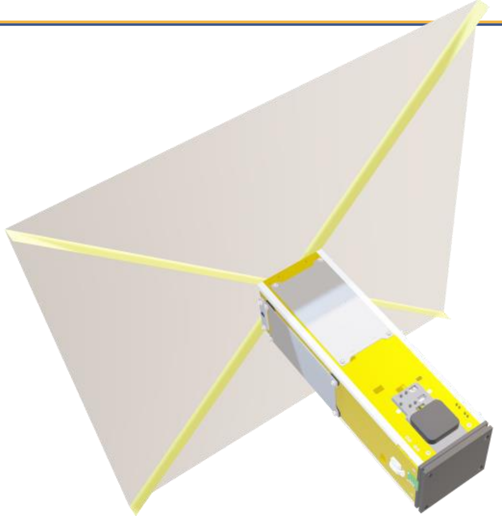




Speaker Background

NOW The Nano Orbital Workshop
Rapid Flight Development Group

Exploration Research and Technology Programs



TES13 Model:
NASA NOW

NASA SILICON VALLEY AMES RESEARCH CENTER

The Nano Orbital Workshop / TechEdSat:
Innovative flight project focused on rapid design & innovation
- 2-3 flights a year, low cost, ISS standards
- LEO, Lunar, & Mars exploration proposals
- Payload pathfinder(s) for new space launch providers (ISS, VO, Firefly)
- 100% In-house development, over 90% experiment success rate
    - *Rapid development group for technology and people*

Key Innovations:
Communication
- Iridium SBD for quick command and control
- Custom 'Lunar' and 'Mars' S-Band SDR radios
- Satellite-internal mesh Wi-Fi network

Exo-Brake
- Precision deorbit and reentry
- Space debris mitigation via EoM disposal

AI/ML Testbed
- Neuromorphic processing, cognitive communication, and health monitoring

TechEdSat Missions

Support:
Ames Research Center
Glenn Research Center
Goddard Space Flight Center
Air Force Research Laboratory
NASA STMD
NASA SST Program
NASA CSLI Program

University Partners:
San Jose State University
University of Minnesota
University of Idaho

Let's Revisit the UNP ShipSat

Exploration Research and Technology Programs

UNP Mission Design Course Example Project

Mission Statement

- Count ships in specific areas from a space-based platform to determine consumer traffic trends in order to assess parking needs [and traffic flow].

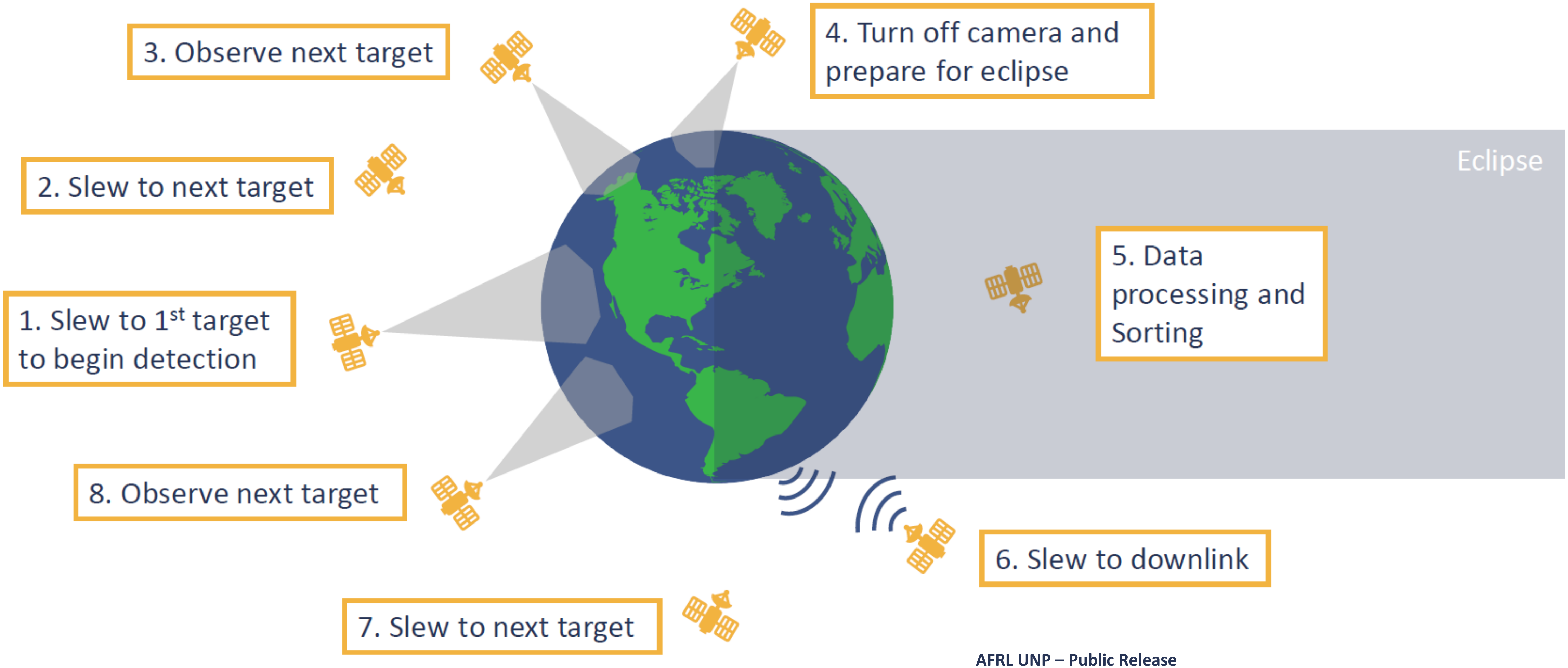
Mission Objectives

- MO-1: Identify ships within an image with 90% accuracy
- MO-2: Image same location at least once daily
- MO-3: Geolocate image to within 50 meters

Mission Success Criteria

- MSC: Obtain ship quantity for 1 location at the same time daily for 7 days
- FSC: Obtain ship quantity for 5 locations at the same time daily for 49 days

UNP ShipSat's Con-Ops



AFRL UNP – Public Release

ShipSat PDR Load Power Table

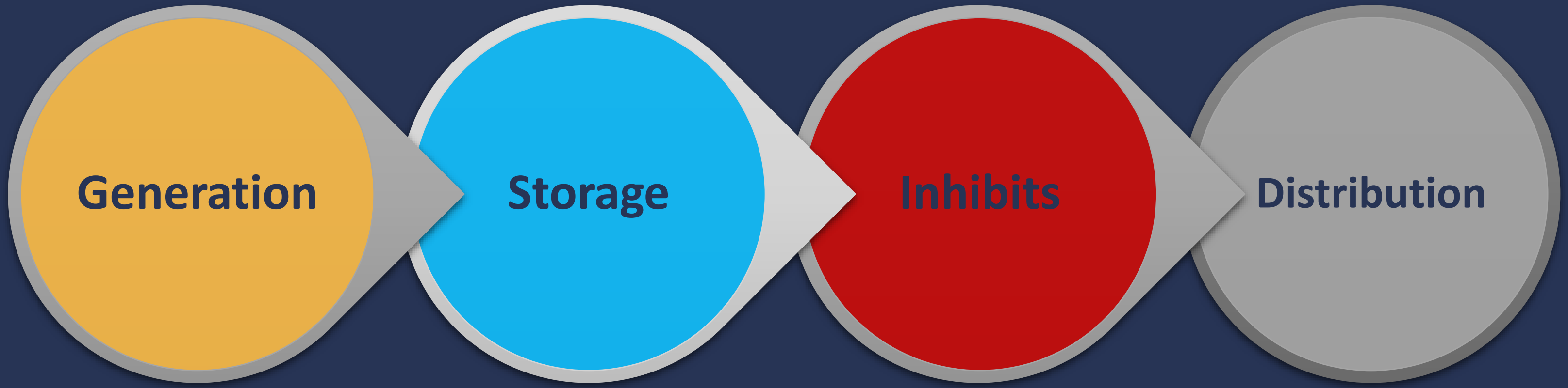
Let's say your System Engineers deliver you this table and ask for an EPS design

Component	Component Draw	Safe Mode		Standby Mode		Experiment Mode	
	(W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)
Power System	0.5	100%	0.5	100%	0.5	100%	0.5
Radio Tx	6	10%	0.6	10%	0.6	10%	0.6
Radio Rx	2	100%	2	100%	2	100%	2
ADCS	2	0%	0	100%	2	100%	2
CDH	1	50%	0.5	100%	1	100%	1
Heater(s)	2	50%	1	50%	1	50%	1
Payload Imager	5	0%	0	0%	0	60%	3
GPS	1	0%	0	100%	1	100%	1
	Power Draw Per Mode		**4.6 W**		**8.1 W**		**11.1 W**

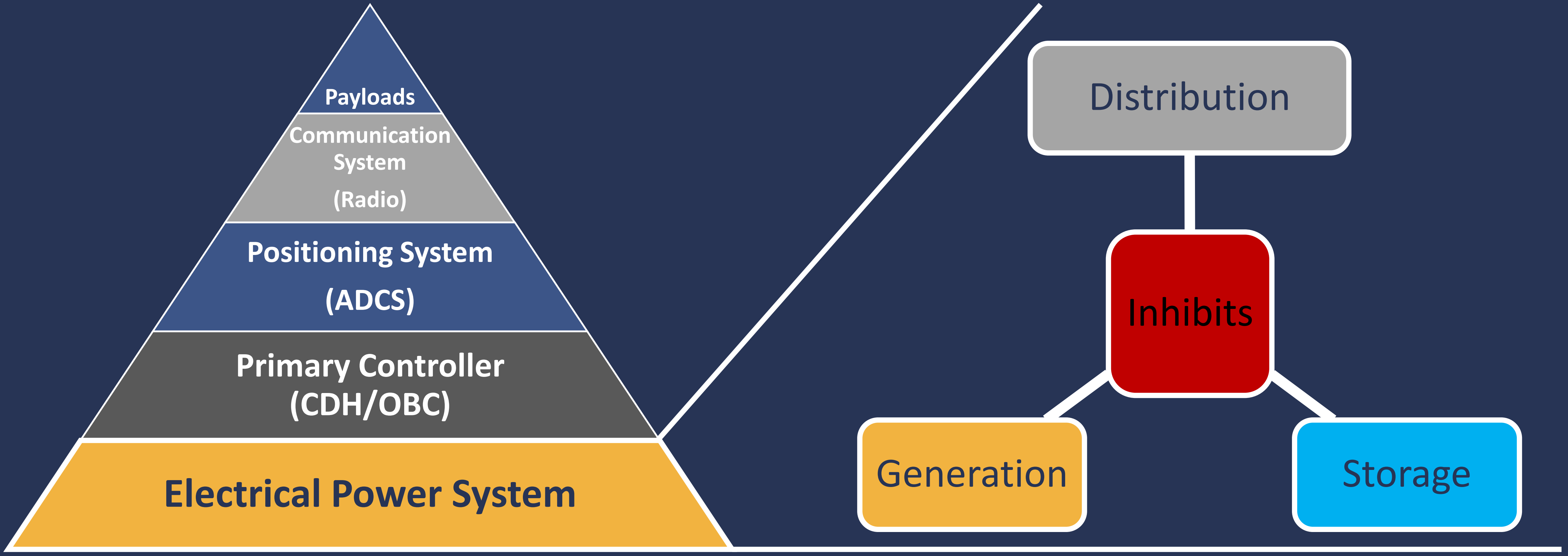
AFRL UNP – Public Release

What is an Electrical Power System?

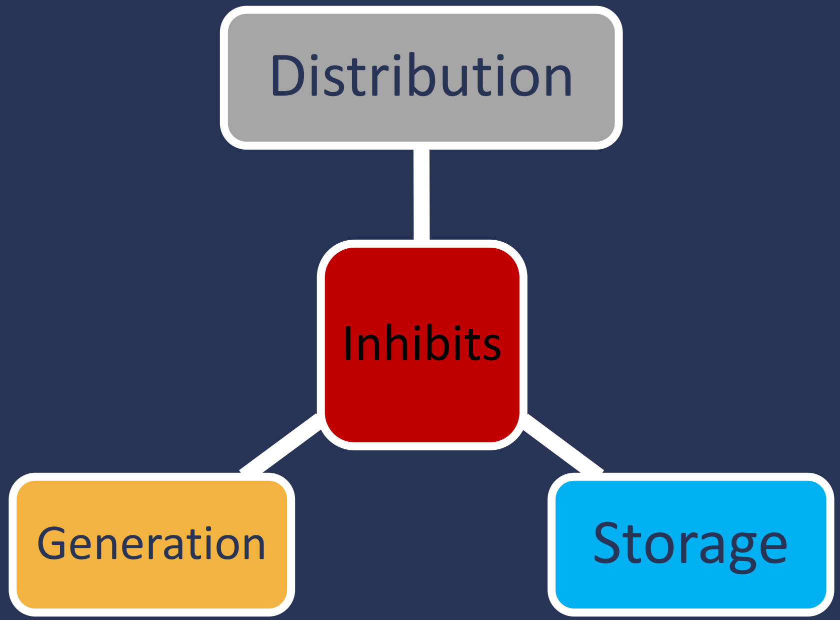
A system of four functions which together provide energy to the entire system, whether it be a small satellite, an electric vehicle, an appliance, or the entire power grid.

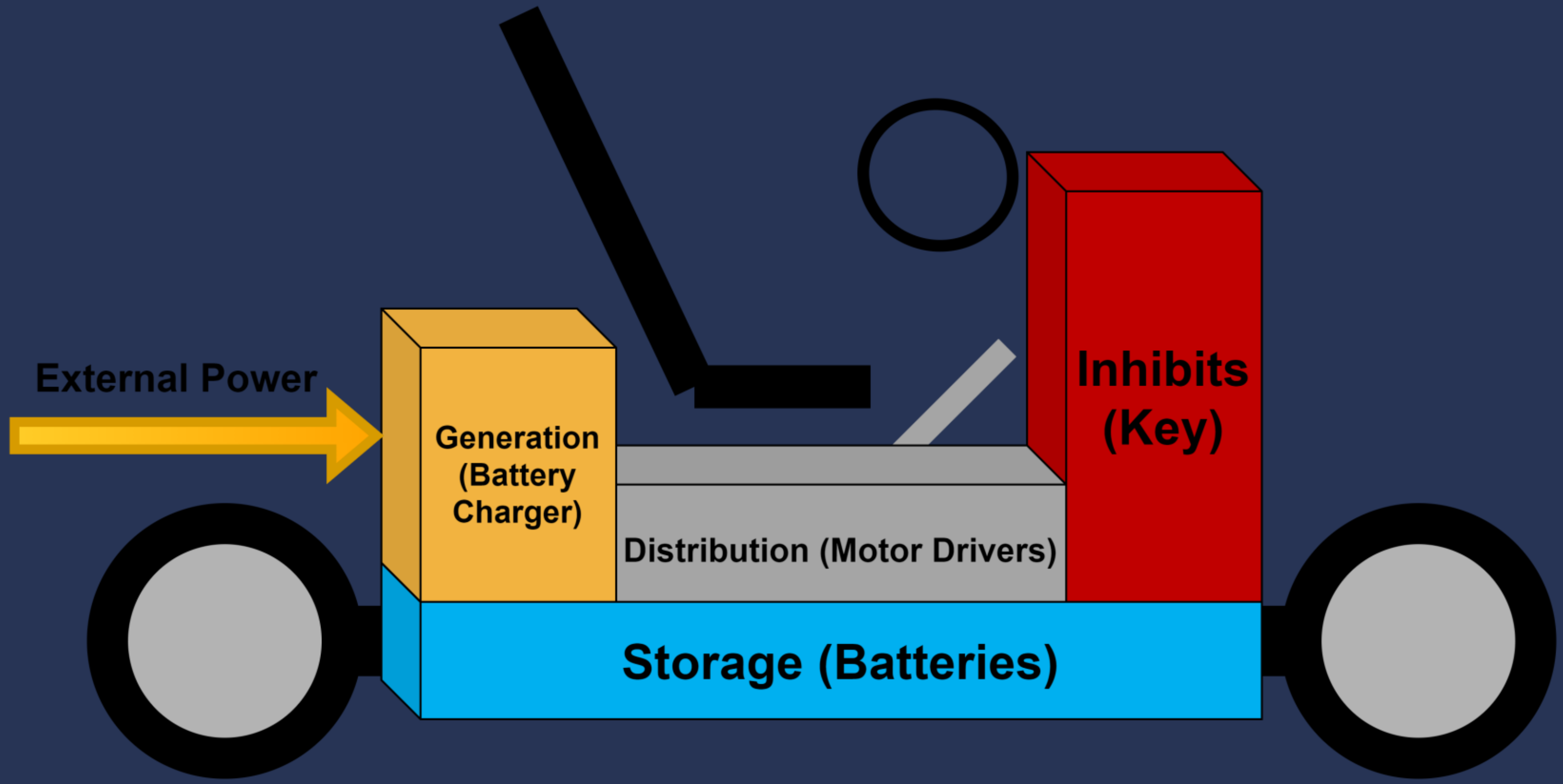


What is an Electrical Power System?



What is an Electrical Power System?





NASA Small Spacecraft Systems Virtual Institute (S3VI)

What is an EPS?

- **Electrical Theory to Know** ←
- Power Generation
- Power Storage
- Spacecraft Inhibiting
- Power Distribution System

So You Want to Design A Mission

- Developing A Power Budget
- EPS & PDS Design
- System Validation & Testing

Electrical Theory to Know

VOLTS

- Potential Energy of Electrons, a measure of the Electromotive Force pushing them along
- If you have low voltage, it is harder to get your electricity to flow around your circuit
- If you have very high voltages, it is harder to keep your electricity flowing only where you want it
- Water Analogy: Water Pressure

AMPS

- The amount of electrons flowing through an area per unit time (flow of current)
- If you have high current, you have a lot of electrons flowing though a point, but you may not have a high voltage. The converse is also true.
- High current requires large conductors
- Water Analogy: Water Flow Rate

RESISTANCE is a material property of a conductor's resistance to electric current flow

Volts are correlated to Amps by Resistance: Volts = Amps x Resistance

Larger conductor cross-sections reduce resistance

Electrical Theory to Know

WATTS

- A Watt is a measure of POWER, equal to a Joule/Second
- **Watts = Voltage x Current**
- A snapshot of **instantaneous** power consumption
- A rating of maximum or minimum power capability

WATT-HOURS

- Watt-Hours is a measure of ENERGY, equal to Joules
- **Watt-Hours = Watts x Time**
- A measurement of storage capacity or total energy delivery over a period of time
- Integral of Power over Time

With some algebra, Power = Current^2 x Resistance ($P=I^2R$)

As resistance is a material property, to increase power you must increase current

To increase current, you must increase voltage unless you can decrease resistance

HIGH SYSTEM POWER REQUIRES HIGH SYSTEM VOLTAGE

Electrical Theory – The Most Important Thing

DESIGN YOUR VOLTAGES TO STEP DOWN

Say we need 5V at 10W from a source that has 1-unit of internal resistance. We can select a source voltage of 3V (boost 2V) or 7V (buck 2V), what is the loss for each?

Buck Step Down

7V at 10W requires 1.43A of current

$$P_{loss} = {I_{supply}}^2 \times R_{supply}$$

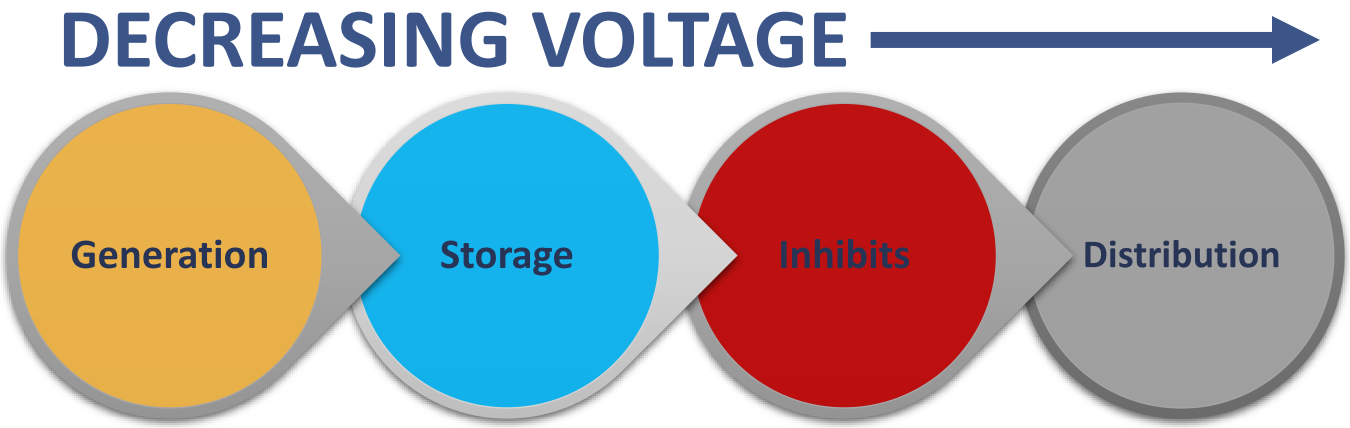
P_{loss} = 2.05W, **83% Efficient**

Boost Step Up

3V at 10W requires 3.33A of current

$$P_{loss} = {I_{supply}}^2 \times R_{supply}$$

P_{loss} = 11.09W, **47% Efficient**



In my experience, this is the main cause of systemic grief for SmallSat missions. One or two small subsystems that need a boost are okay, but not the whole bus.

Electrical Theory – Typical Values

Millivolts (mV)	0.001 Volts	Voltage measurement, supply tolerance	±500mV supply tolerance, 10mV supply ripple
Volts (V)	1 Volt	Most system voltages	SmallSat bus voltage is typically 28V CubeSats range from 3.3-12V typically
Kilovolts (kV)	1,000 Volts	High-Voltage; spacecraft charging protection, plasma research, physics payloads. High energy fun.	Ion thrusters operate at several kV Spacecraft charging in the dozens of kV
Milliamps (mA)	0.001 Amps	Discrete components, small systems	5mA LED, 750mA flight processor unit
Amps (A)	1 Amp	Larger systems, payloads, entire vehicles	3A Cryocooler, 20A Main Bus
Milliwatts (mW)	0.001 Watts	Discrete components and small systems, idle/standby power	250mW Microcontroller w/10mW sleep
Watts (W)	1 Watt	Systems and moderate spacecraft/vehicles	100W PDS, 3W solar panels, 5W heater
Kilowatts (kW)	1,000 Watts	Human-rated vehicles, large solar arrays, large intermittent loads	ISS Max Solar Generation: 90kW Current EV DC charging: 350kW
Watt-Hours (Wh)	1 Watt for One Hour	Individual battery cells, CubeSat power budgets	18650 Li-Ion cells average about 10Wh
Kilowatt-Hours (kWh)	1,000 Watts for One Hour (or 1 Watt for 1,000 Hours)	Large battery packs, large system power budgets	Most midsize EVs have a battery pack around 80kWh
Amp-Hours (Ah)	1 Amp for One Hour	Battery capacity at an electrochemical-level (more later)	18650 Li-Ion cells average about 3Ah

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Power Generation

Unless you are operating a very short mission, or can carry a lot of storage capacity, you will need a way to generate power throughout your mission.

Your selected power generation method will likely impact all other design considerations, especially thermal design, mechanical design, and mission operations. You will recursively design your power system as your mission requirements interact with design.

While solar is the standard go-to for most missions, it is important to remember is it not your only option, though it tends to be the easiest and most economical

Power Generation – A Few Options to Consider

Technology	Description	General Power Range	Benefits	Detriments	Notes
Solar Cells	Use photovoltaic cells (solar cells) to convert sunlight into electricity through electron excitement	Completely dependent on available area and solar exposure, mW to kW. Estimate 1 to 3 watts per square U in LEO.	Free energy source (Sun), easy to obtain solar cells, easy to use solar cells, relatively inexpensive, lots of literature	Must point towards the sun, large area needed, can become obstructed, may require deployable structure	The go-to for any near-Earth mission and even Mars. Just keep in mind pointing and large areas needing deployment.
Radioisotope Thermoelectric Generator (RTG)	Use the heat generated by a decaying radioactive isotope (Pu-238) to generate electricity via thermocouples	RHUs = 1W Thermal MSL RTG = 2kWT, 125WE (4.8kg Pu) Cassini RTG = 4.4kWT, 300WE (7.8kg Pu)	Provides constant thermal and electrical power over an extremely long duration. Decay is about 0.8% per year.	Incredibly if not impossibly difficult to procure due to radioactive nature and lack of Pu-238. Must be a critical mission.	Must be used for any deep-space mission or missions requiring constant heat or extended eclipse survival.
Beamed Power	Use beams of radio or optical frequency energy to transmit power to a receiver from a ground or space-based station	Research targets in the kW range, but current technology is very limited in distance and power (COTS is ~100W over mm)	Reduces mass needed for generation and storage onboard, can utilize a massive power source somewhere convenient	Very low TRL technology, requires a transmitter and power source somewhere with fine-pointing abilities, low efficiency	Of particular interest for electric aircraft (EVTOL) and electric vehicle charging in-motion/in-flight. Space upcoming.
Betavoltaic Cell	Use semiconductors to convert beta particles from radioactive decay into electricity	3V or less at 100 microwatts or less, very low power, ideal for standby/intermittent uses	Long-term standby power solution (20yr+ decay), small size, well-contained/safer materials	Requires radioactive material (usually Tritium), very low power output, very low SWaP efficiency	TRL and performance increasing. Mostly used to slowly charge larger devices.

Solar Generation – Solar Irradiance

- Cell performance is typically baselined in terms of 'AM' or 'Air Mass'
  - AM0 is for space-rated cells, indicating zero air mass
  - AM1 indicates a single atmosphere of mass, indicating sunlight directly overhead
  - AM1.5 is typical for terrestrial cells, indicating a sun angle

- This equates to about 1,000 Watts per square meter at AM1.0, and ~1,400W/m^2 in LEO at AM0

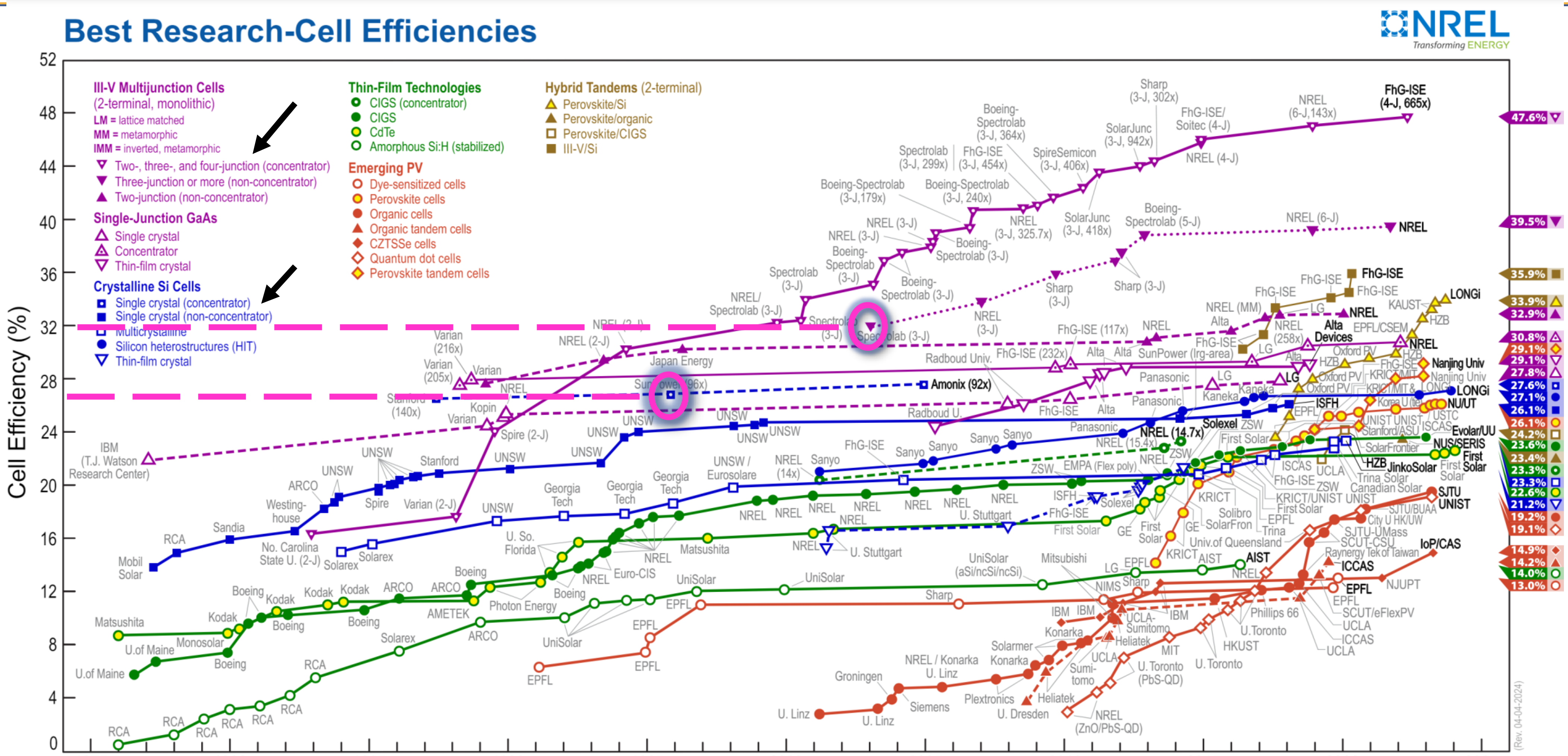
- Solar Irradiance decreases with the square of distance, see the table to the right…

Planet	Distance from Sun [AU]	Percent of Earth Solar Irradiance	Square-Meters needed to receive 1kW
Mercury	0.4	625%	0.16
Venus	0.7	204%	0.49
Earth	1	100%	1.0
Mars	1.5	44.5%	2.25
Jupiter	5.2	3.68%	27.2
Saturn	9.6	1.08%	92.6
Pluto	39.5	0.0625%	1,600 (130x130 feet)
Voyager	162.75	0.00378%	26,455 (4.95 football fields)

This is why deep-space missions must use RTGs, and power-beaming is of great interest

Solar Generation – Photovoltaic Technology

Exploration Research and Technology Programs



Top-of-the-line space-rated triple-junction solar cells are about 30-32% efficient and run around <u>$1k/watt</u>

Standard crystalline silicon cells are about 22-26% efficient and can be <u>$50/watt or less if COTS</u>

Generation | Storage | Inhibits | Distribution

Solar Generation – Solar Cells

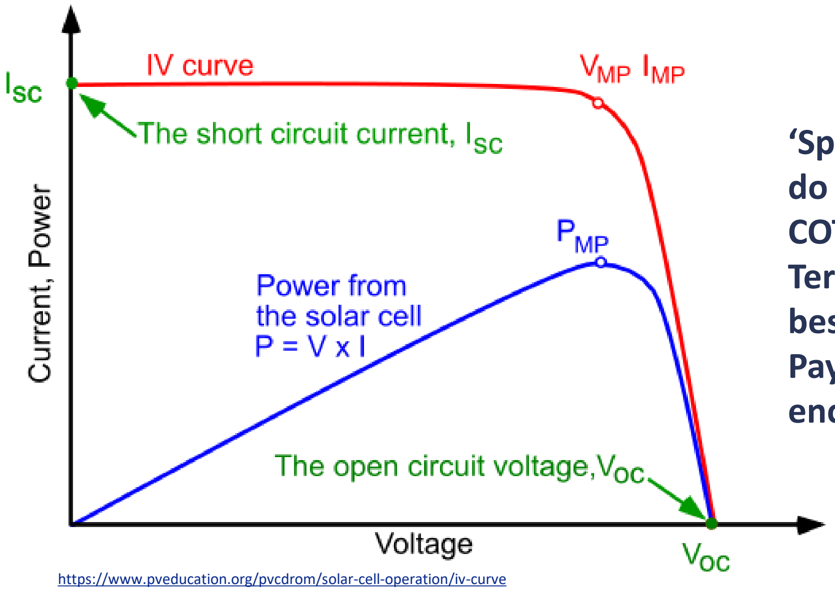
- Solar cell efficiency degrades over time, not enough to impact short-term LEO missions, but a serious consideration for deep-space or long-duration missions
- Solar cells operate along a current vs. voltage curve, or an 'IV curve'
- At a certain point of their IV curve, power can be maximized (P=IV)
- A specialized power converter circuit, called a 'solar optimizer' or Maximum Power Point Tracker (MPPT) regulates the output voltage of the solar array, so the panel stays at the Maximum Power Point (MPP).

XTE-SF Post 1 MeV e- Retention (US Standard AIAA S-111-2005)

Parameters*	BOL	1e14 (10-yr LEO)	5e14	1e15 (15-yr GEO)	1e16
$Efficiency_{mp}$	32.2%	0.93	0.88	0.84	0.66
V_{oc} (V)	2.750	0.92	0.88	0.86	0.78
J_{sc} (mA/cm^2)	18.6	1.00	1.00	0.99	0.94
V_{mp} (V)	2.435	0.92	0.88	0.86	0.76
J_{mp} (mA/cm^2)	17.9	1.00	0.99	0.98	0.88

* AM0 (135.3 mW/cm^2, 28ºC), for 27 cm^2 cell size (Fluence of 1 MeV electrons/cm^2)

Example cell data from Spectrolab



https://www.pveducation.org/pvcdrom/solar-cell-operation/iv-curve
Permission Granted by AFRL UNP

'Space-Grade' solar cells will do much better in orbit than COTS terrestrial cells. Terrestrial cells will try their best but will likely degrade. Pay careful attention to encapsulated cell materials.

Solar Generation – Cell Summary

- Estimate a maximum of 32% efficiency for solar designs, and keep in mind that number will be best-case generation
- Disregard degradation for LEO missions unless you are using cheap COTS cells
- Efficiency drops as cell temperature increases, keep things cool. **All incident power not converted to electricity or reflected is turned into heat.**
- Landers can suffer from dust buildup covering cells, 50% is a good estimate for Mars.
- MPPT conversion is not 100% efficient

Planet	Distance from Sun [AU]	Square-Meters needed to receive 1kw (100% Efficiency)	Square-Meters needed to receive 1kW (32% Efficiency)
Venus	0.7	0.49	0.82
Earth	1	1.0	1.68
Mars	1.5	2.25	3.78
Jupiter	5.2	27.2	45.7
Voyager	162.75	26,455 (4.95 football fields)	44,444 (8.32 football fields)

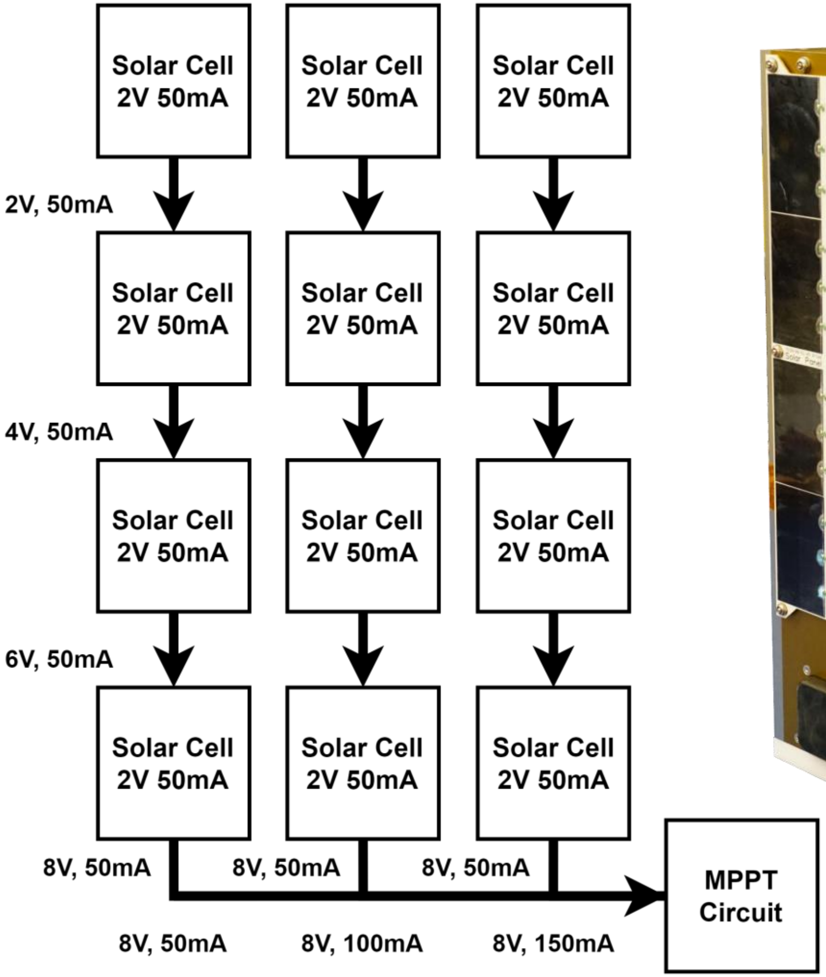
Solar Generation – Cell Strings and Arrays

- A singular solar cell is almost always insufficient to run a mission, they must be combined into arrays to increase power and output voltage

- A solar array is made of parallel-connected columns of series-connected strings.
  Series connections increase voltage
  Parallel connections increase current

- Array notation is in the form of xSxP, with S meaning 'series' and P being 'parallel'. For example, the diagram to the right of 3 columns of 4-cell strings would be 3S4P.

- Cell combining may be done at the panel or solar power converter, or both



NASA-NOW

TES-6, equipped with four 4S2P panels, each with an MPPT converter, then combined in parallel at the battery charger

Solar Generation – Designing for a Mission

1. Determine the key parameters your solar array needs
   - Total generation capacity needed
   - Target operating voltage
2. Select a cell to use as a design reference starting point
3. Determine the number of cells you need by dividing total power by generation per cell
4. Determine the number of cells you need per string by dividing your target voltage by cell MPP voltage
5. Calculate square area & performance parameters

1. Requirements: 20W maximum generation at 10V

2. Reference Cell Data:

Solar Cell Manufacturer	MicroLink Devices (MLD), Niles Illinois, USA
Solar Cell Type	Triple-Junction Gallium Arsenide
Solar Cell Efficiency	~30% at AM0 prior to lamination
Solar Cell Dimension	66mm x 31mm x <40µm
Solar Cell Maximum Power Point	823mW @ 2.64V, 311mA
Solar Cell Test Parameters	Isc = 325mA, Voc = 3.0V

3. Cells Needed:

$$\frac{20W\ Target}{0.823W_{cell}} = \mathbf{25\ cells\ total}$$

4. Series String length:

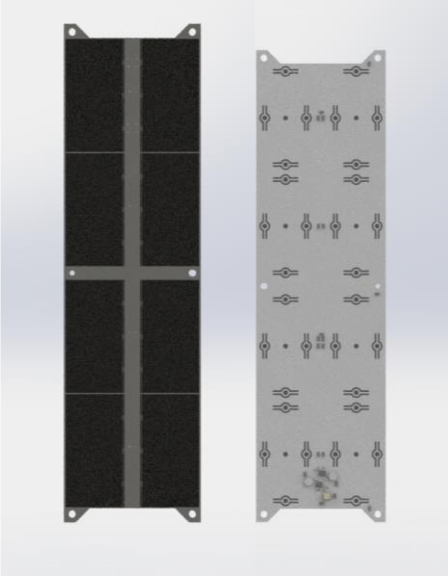
$$\frac{10V\ Target}{2.64V_{mpp}} = \mathbf{4\ cells\ in\ series, 7\ columns\ needed}$$

5. Array Statistics:

4S7P Array (no partial strings), 28 cells, 572.88cm^2, ~5.7U

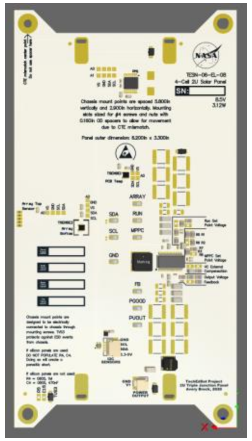
Isc = 2.275A, Voc = 12.0V, Impp = 2.18A, Vmpp = 10.56, **MP = 23W**

Solar Generation – Example Array Comparison



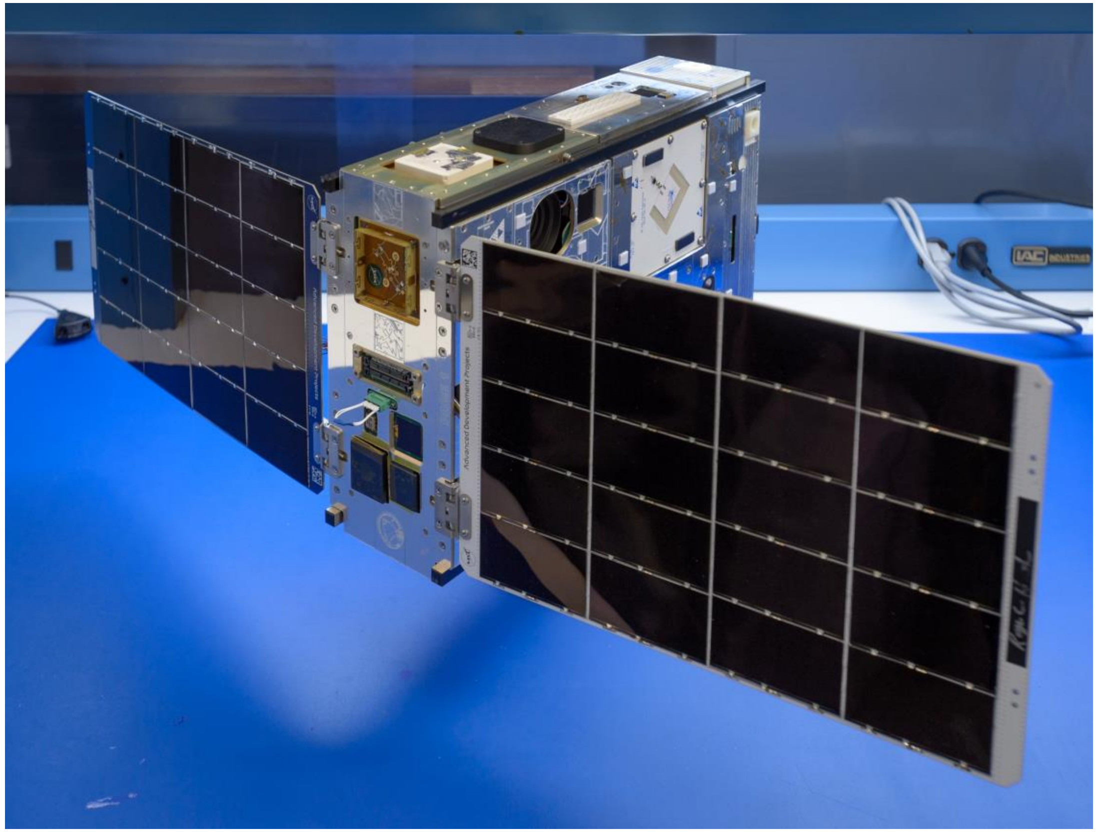
TechEdSat Solar Panel Upgrade

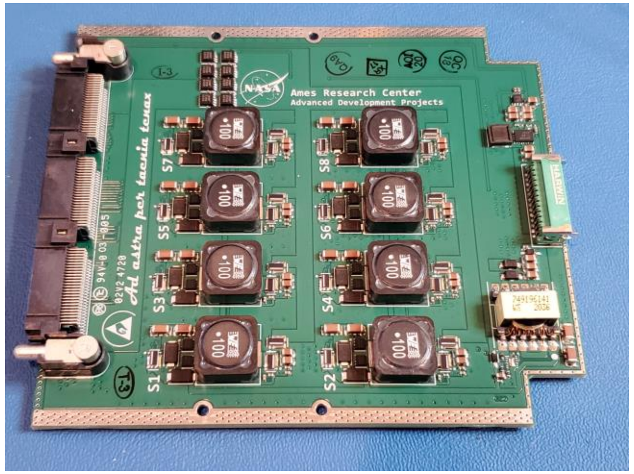
	TES-4 to TES-10	TES-N (2020→)
Cell Type	Crystalline Silicon, Single-Junction	Gallium Arsenide ELO, Triple-Junction
Cell Specs	69x36mm **18.5%**, 0.46W: 0.52V, 880mA	66x31mm **31%**, 0.78W: 2.51V, 311mA
'U' Panel Power at AM0	**2U: 1.84W** 3U: 3.68W	**2U: 3.12W** 2.5U: 3.90W
Panel Topology: 2U (2.5/3U)	2S(4S)2P MPPT Boost SPV1040 Based	4S(5S) MPPC 4-SW Buck/Boost LTC3119 Based
Panel Limits	4-10.4Vout, 1.8A, 100kHz	0.8-18Vout, 5A, 400kHz-2MHz
Sensors	None	Array: voltage, current, power, back and top temperatures PCB: temperature



Images Credit NASA Nano Orbital Workshop

Solar Generation – Example 47W System





Two 5S4P 6U Deployable Panels with 27cm^2 Spectrolab XTE-SF Cells

String: 13.75V_{oc} , 12.175V_{mp}, 502mA_{SC}, 483mA_{MP}

MPPT Converter per string, strings are parallelized at MPPT converter outputs, converter output set at 4.126V

Images Credit NASA PACE/SST

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Power Storage

Power storage serves two main functions:

1. Storage allows you to retain generated **energy** so you have it when your generation stops
2. Storage allows you to augment your available **power** if your load needs exceed your generation capability

Like your selection of generation technology and power capacity, your selection of storage technology and capacity will be a recursive interaction with your mission design, both physically and in concept of operations development

Power Storage – A Few Options to Consider

Technology	Description	General Storage Range	Benefits	Detriments	Notes
Batteries (Lithium-Ion)	Lithium-based electrolyte electrochemical cell, usually packaged in a standardized metal tube. Liquid/paste/gel electrolyte is current with solid electrolyte upcoming	259-276Wh/kg for 18650 (metal can) cells, 3.7V nominal cell voltage, can have discharge exceeding 10A/cell. Solid Li-Ion may improve power density.	Very easy to get, have significant spaceflight heritage and testing, very good power density, relatively radiation tolerant, very good charge retention.	Explosive thermal runaway failure mode, relatively small operating temperature range, highly nonlinear behaviors, can quickly loose capacity if over-stressed	18650 cells or similar are the go-to standard for cubeSat missions and even Artemis and Europa Clipper. Very robust and long-lived when treated properly.
Super Capacitors	Electric Double Layer Capacitors (EDLC) utilizing graphene or other nanoporous solid electrodes	~5Wh/kg, but 10,000W/kg specific power. Cells max out around 5.5V but the rating is slowly increasing.	Able to support incredibly high charge/discharge rates over hundreds of thousands of cycles, very safe high-power storage	Poor storage density and very poor charge retention, can degrade quickly in high temperatures or voltages	Not suitable for primary long-term storage, but great for suppling high pulsed-loads or energy harvesting
Flywheels	Spinning mass storing rotational inertia. Energy is added during generation and bled off when needed	Entirely depends on flywheel size and rotational velocity. Proposed for lunar base eclipse storage.	Very safe and more environmentally robust compared to charge storage	Mechanical wear mechanisms, imparts rotational inertia on space vehicles	Not practical as primary storage for spacecraft, but can be used with ADCS reaction wheels
Thermal Mass	Heated mass used to store power via thermocouples and heaters	Entirely depends on specific heat and amount of mass and operating temperature	Very safe and very robust, wide operating temperature range	Efficiency is entirely dependent on design and specific heat of mass	Molten salt for terrestrial applications, also phase-change materials

Battery Terms to Know

'C' charge/discharge rate

- A 1C charge/discharge rate means the cell or pack will be fully charged/discharged in 1-hour. For example, a 10Ah pack would have a 1C rate of 10A.

Amp-Hours (Ah)

- Not a measure of stored energy but electric charge, used to more accurately measure battery capacity as the electrochemical process stores charge, not energy

Watt-Hours (Wh)

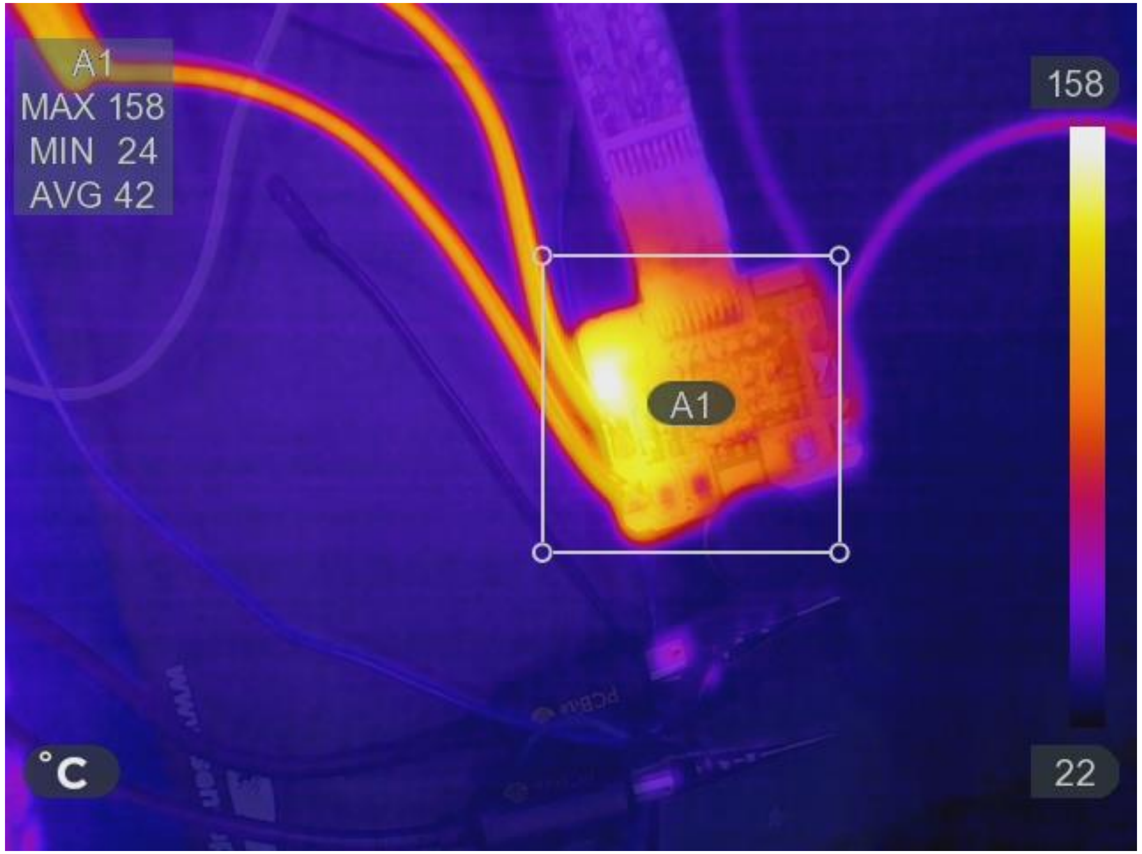
- Sometimes used to measure batteries and is relatively accurate if associated with a reference current, for example 1C

State of Charge (SoC)

- Usually reported as a percent of total capacity based on monitoring charge/discharge current integral and some reference capacity

Depth of Discharge (DoD)

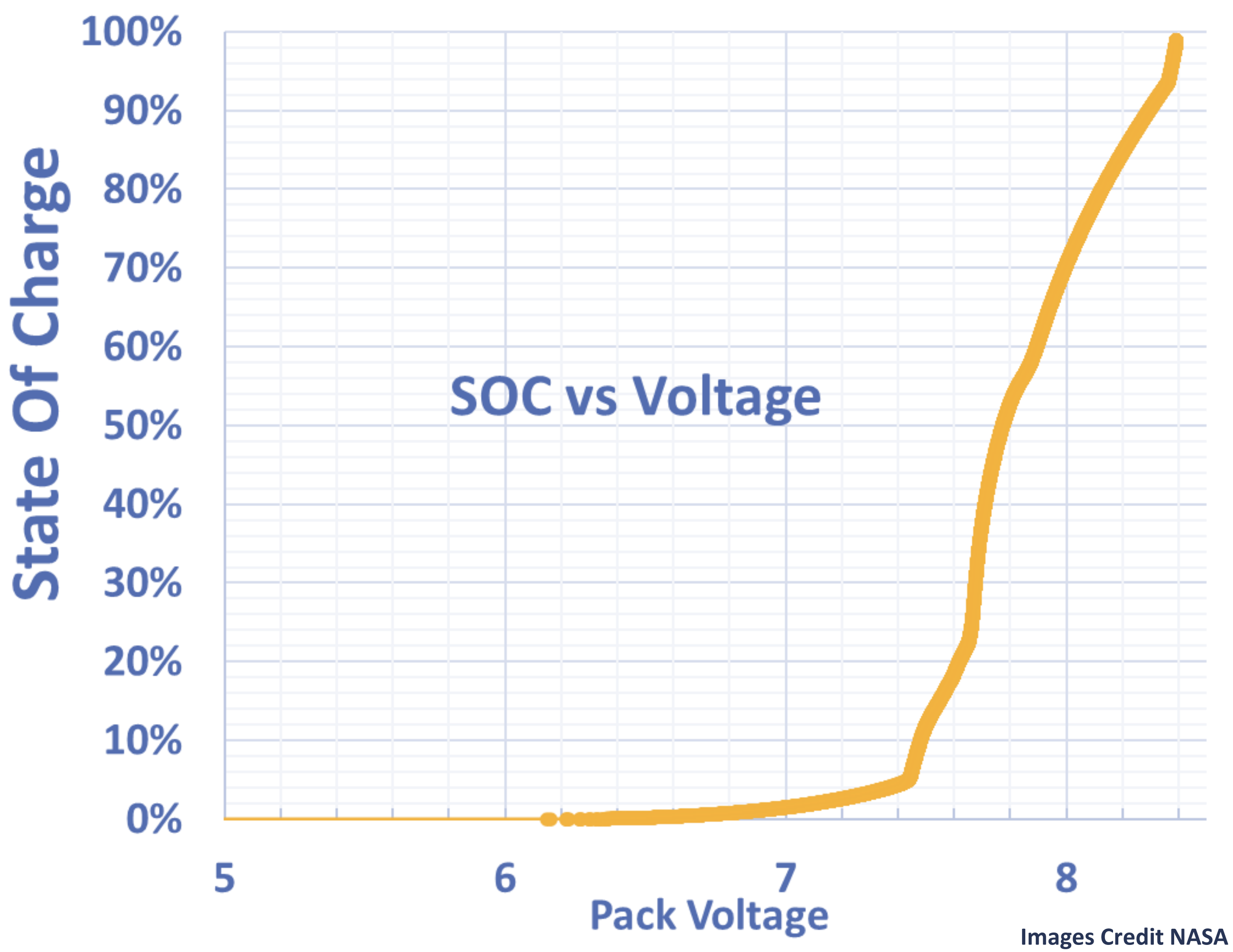
- Usually reported as a percent of total capacity, used to set a discharge limit or measure lifecycle stress



Images Credit NASA NOW

Lithium-Ion Batteries – Things to Know

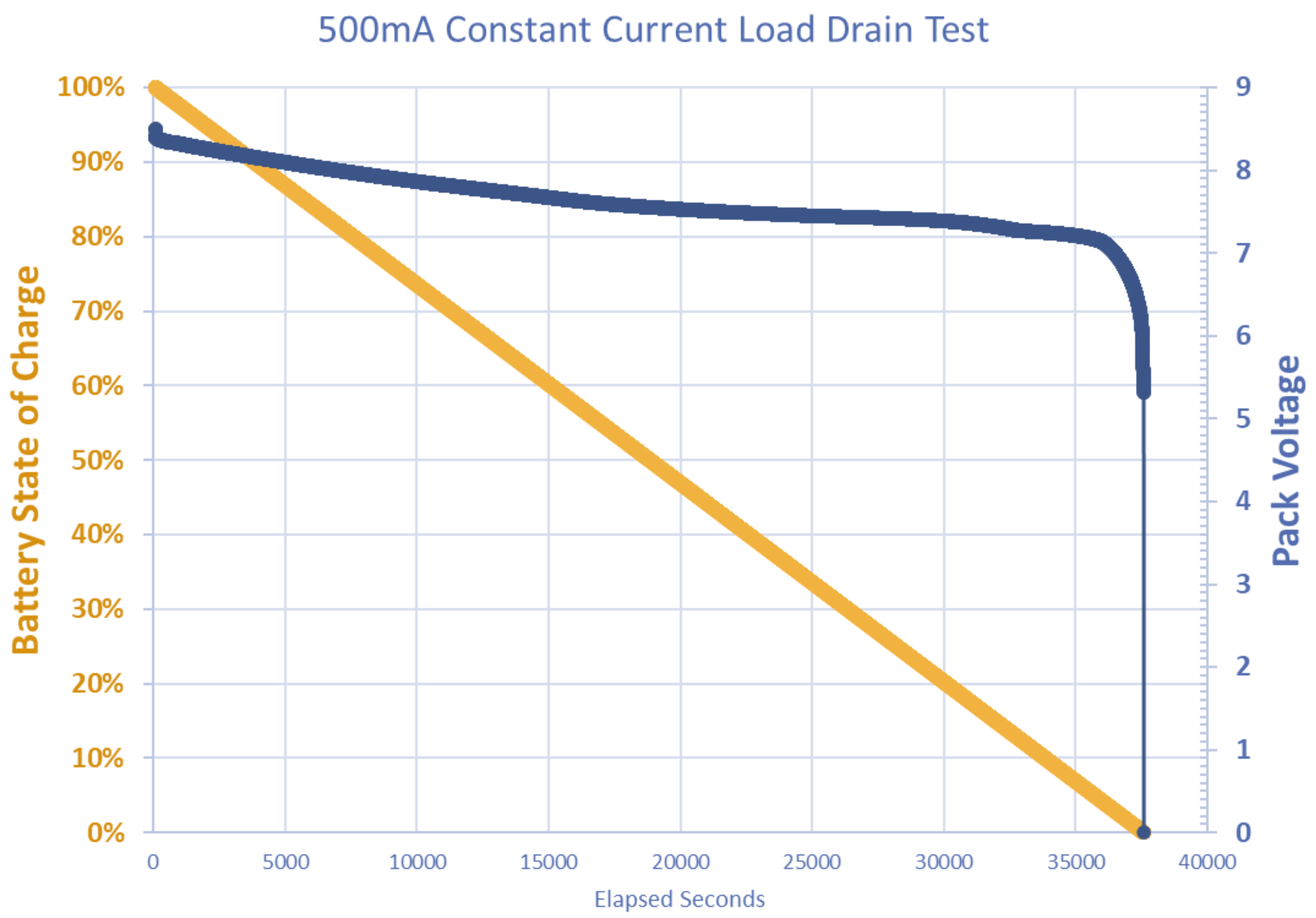
- Lithium-Ion (Li-Ion) batteries offer exceptional performance with little charge memory and low self-discharge
- Li-Ion exhibits a highly non-linear relationship between cell voltage and state of charge (SoC), requiring the use of advanced models or ‘coulomb counter’ current sensors to accurately monitor SoC
- Cells can boil their electrolyte if they get too hot, usually from an internal short, which releases hydrogen gas, causing documented explosions
- Cells can grow dendrites between anode and cathode over time or if charged too quickly when too cold, reducing capacity or causing internal shorting



Images Credit NASA NOW

Lithium-Ion Batteries – Things to Know

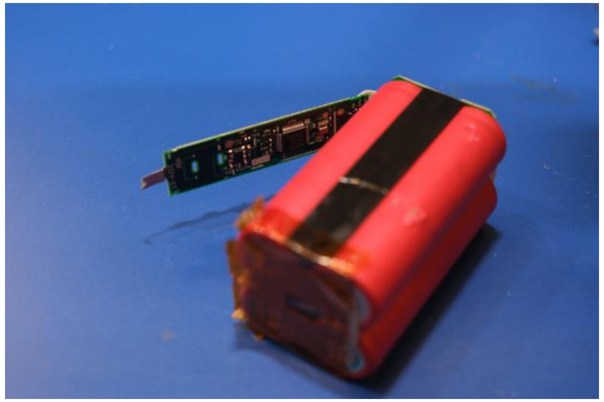
- Cell voltage should be maintained **between 2.5V to 4.1V or 4.2V**, or even lower to increase lifespan.
- Over-discharge and over-charge are very bad for Li-Ion cells, charge control circuitry is required
- Cell temperature should be maintained between **0°C to 45°C during charging and -20°C to 60°C during discharge**
- As cells age, their internal resistance increases, reducing their output power and increasing thermal waste
- Most COTS batteries contain physical thermal fuses in the anode to stop current flow if cell temperatures exceed the melting point



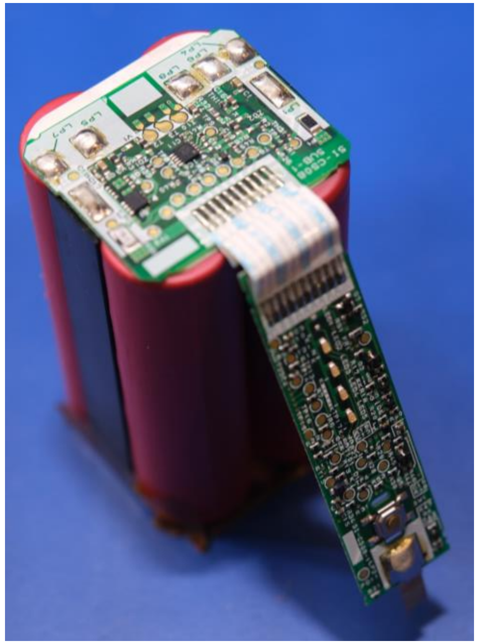
Images Credit NASA NOW

Lithium-Ion Batteries – 18650 Cells

- Most spacecraft use 18650 Li-Ion cylindrical cells as they are robustly packaged, well tested, and mass produced.
- LG Chem MJ1 cells are a NASA standard per extensive testing from JPL, offering “the most favorable combination of energy, cycling stability, and high rate capability up to 10A”.
- If using raw 18650 cells, a battery protection circuit must be designed to safely operate the cells
- Several COTS battery packs are approved for ISS flight by NASA, for example Canon BP-955 2S2P packs
- **ALWAYS RESEARCH AND TEST YOUR CELLS AND PACKS.** JPL has extensive cell testing reports, and the ISS program has approved multiple commercial packs for onboard use.



2S2P 18650 COTS Pack Approved for ISS Flight



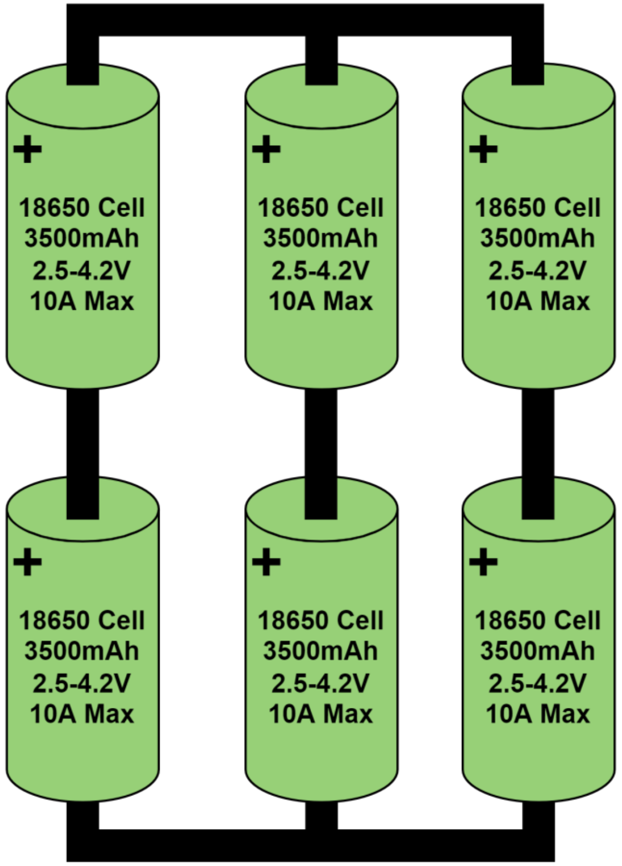
Battery pack approval can break your mission with Space-X or ISS deployments. You will likely need to partner with a NASA center or a professional laboratory to validate the safety of your packs.

Images Credit NASA NOW

Designing and Using Packs

- Just like solar cells, a single Li-Ion cell is almost always insufficient to run a mission, they must be combined into packs to increase capacity and operating voltage. All the same parallel and series combining rules hold true.
- For advanced designs, series cells may be ‘balanced’ by ensuring each cell is charged to the same voltage, distributing load equally between cells
- Long duration missions may slowly lower their maximum charge voltage to reduce risk of sudden failure and slow aging processes
- Recommended DoD can be as little as 40% for conservative missions, or up to 80% for higher-risk or shorter missions

Type	2S3P
Min Voltage	5V
Max Voltage	8.4V
Nominal Storage	10.5Ah
Peak Discharge	30A



Li-Ion Packs– Designing for a Mission

1. Determine the key parameters your pack needs to meet
   - Total storage capacity needed
   - Target operating voltage
   - Expected discharge current (sustained vs peaks)
2. Select a cell to use as a design reference starting point
3. Determine the number of cells you need in series by dividing the target pack voltage by the cell's nominal voltage (usually 3.6V)
4. Determine the number of parallel strings you need by selecting the greater of:
   A) Storage capacity divided by cell capacity
   B) Peak discharge current divided by cell peak current
5. Calculate mass and performance parameters

1. Requirements: 12V Pack with 40Ah Capacity, 5A Sustained

2. Reference Cell Data:

18650 Cell Manufacturer	LG Chem Ltd, Seoul, South Korea
18650 Cell Type	INR18650 MJ1
Cell Capacity	3500mAh NOM, 3350mAh MIN
Cell Voltage	2.5V MIN, 3.635V NOM, 4.2V MAX
Discharge Rate	0.2C 670mA NOM, 2.85C 10A MAX
Mass	49g

3. Series Cells Needed:

$$\frac{12V\ Target}{3.635V_{cell}} = \mathbf{4\ series\ cells}$$

4. Parallel Cells Needed:

A) $$\frac{40Ah\ Target}{3500mAh_{cell}} = 12$$

B) $$\frac{5A\ Target}{670mA_{cell\ NOM}} = 8$$

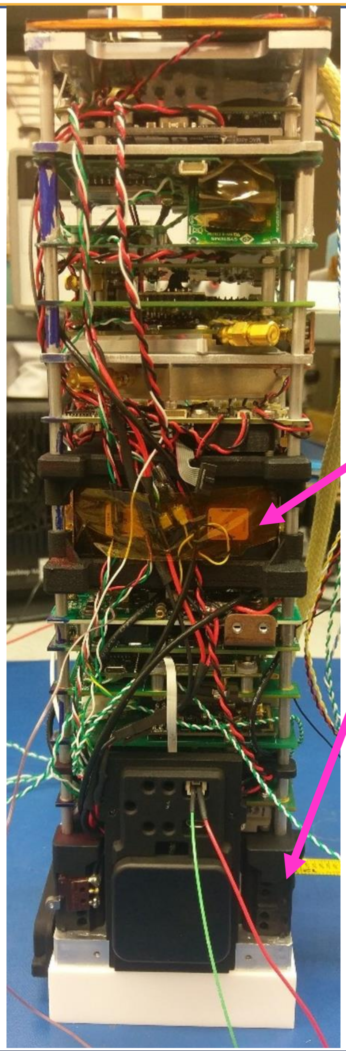
5. Pack Statistics:

4S12P, 48 cells, 2.35kg

Vmin = 10V, Vmax = 16.8V

Nominal Storage = 42Ah, **Peak Discharge = 120A – CAUTION**

Battery Packs– Example CubeSat Systems

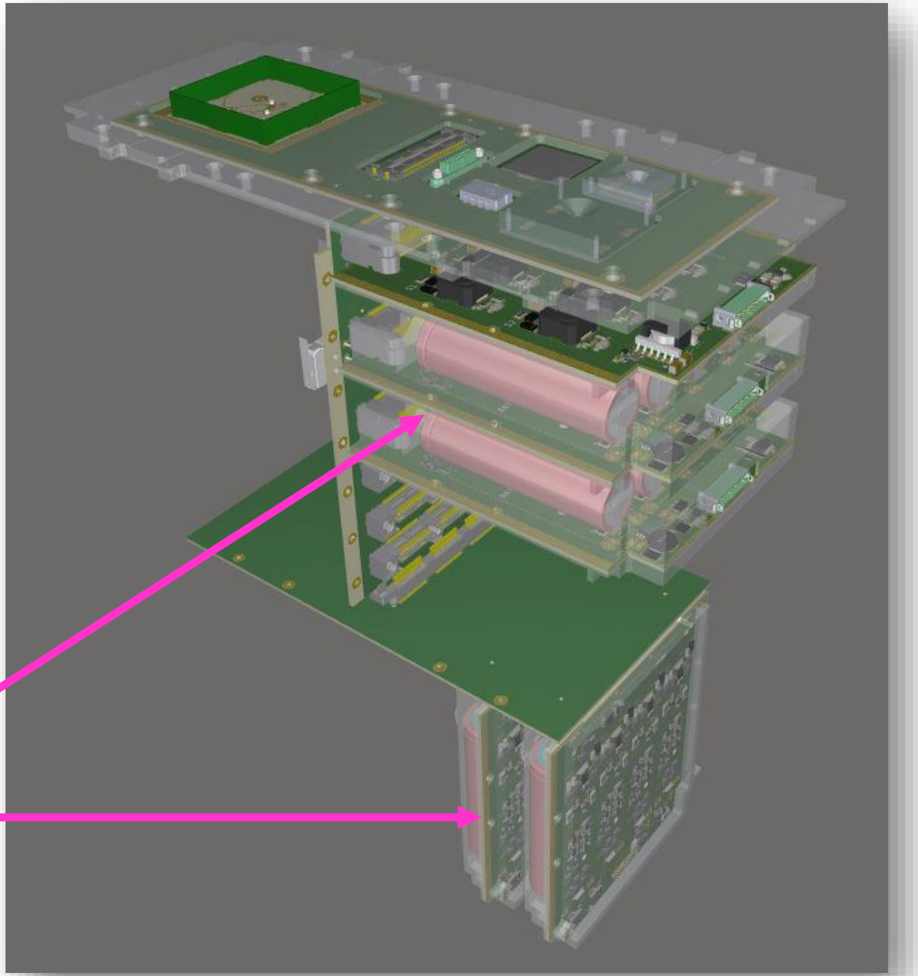


6U 'PC-104' Spacecraft:

- COTS BP-955 2S2P Packs
  - 30Wh/pack, 35W peak output
  - 5-8.4V Pack voltage
- 4-packs per bus, 2S8P
  - 120Wh S/C storage
  - 140W peak S/C output

6U Backplane Spacecraft:

- Custom-Designed 1S4P Packs
  - 51.8Wh/pack, 168W peak output
  - 2.5-4.2V Pack voltage
- 4-packs per bus, 1S16P
  - 207Wh S/C storage
  - 670W peak S/C output



Images Credit NASA NOW & PACE/SST

NASA Small Spacecraft Systems Virtual Institute (S3VI)

What is an EPS?

- Electrical Theory to Know
- Power Generation
- Power Storage
- Spacecraft Inhibiting ←
- Power Distribution System

So You Want to Design A Mission

- Developing A Power Budget
- EPS & PDS Design
- System Validation & Testing

Spacecraft Inhibits

Inhibits are critical for both safety and mission execution:

- Inhibits prevent your spacecraft from operating while it is being integrated, stored, launched, and deployed by **inhibiting the flow of power in the EPS and/or PDS**.
- Ensuring your spacecraft stays off **protects people** from RF exposure from your radios, protects your single-use actuators from early firing, and helps ensure your power system will still have energy stored when the spacecraft is deployed.

As this is not a circuit design lecture, we will keep things at the high-level with some example systems and general recommendations

Spacecraft Inhibits

Your inhibits MUST be approved by your launch service provider (LSP):

- In general, at a minimum, inhibits must be two-fault tolerant and prevent the flow of current into or out of storage devices, and prevent radios and deployables from operating.

- Ideally, your inhibits should completely prevent current from flowing between EPS elements and keep the PDS completely unpowered.

- UNP Requirements are designed to meet all LSP requirements

Fault tolerance and failure-modes needs to be accounted for in mission design and inhibit design. A poorly designed or understood inhibit system can **easily** cause total mission failure

Inhibit Types – CubeSat Focus

Nested Inhibits – A Good Idea

1. **Mechanical Inhibits/Switches**
   - **Mechanical switches to detect deployment**
   - **Will include Remove-Before-Flight (RBF) pin that overrides all other inhibits to ‘OFF’**

   <- ALWAYS REQUIRED IN SOME FORM BY LSP

2. Solid-State EPS/PDS Switches
   - Silicon switches actuated by mechanical switches

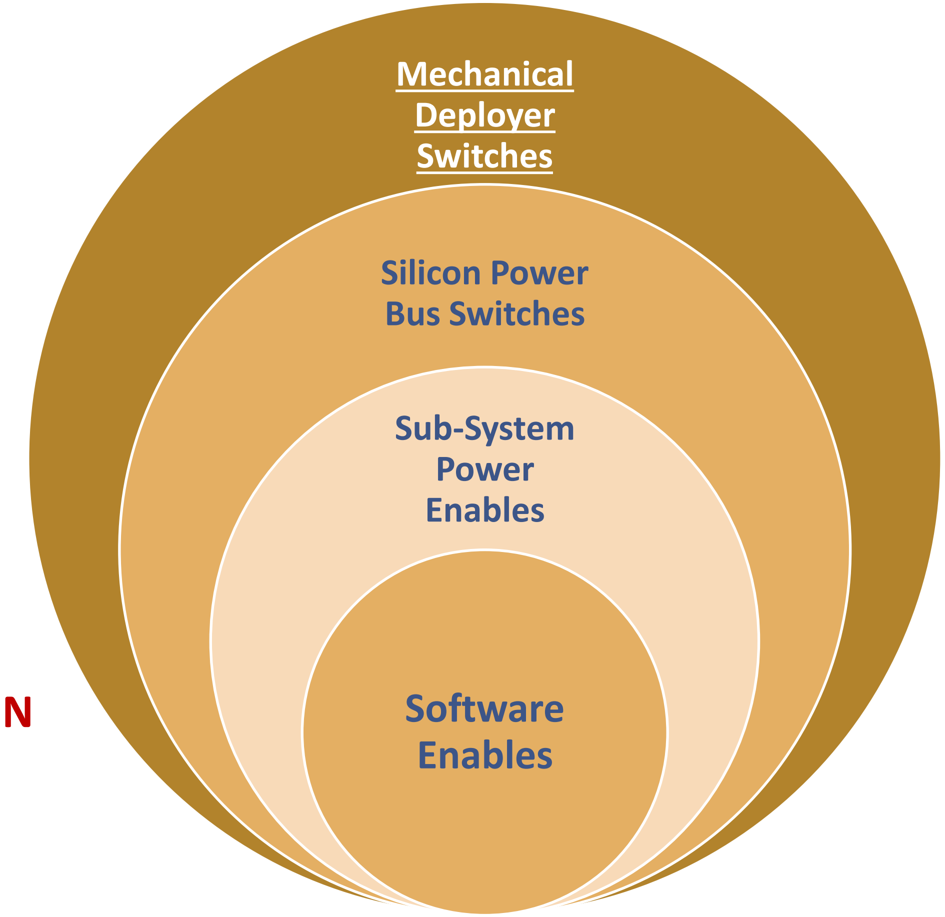
   <- GOOD POWER ENGINEERING

3. Sub-System Enables
   - Silicon power switches embedded in the PDS and/or each sub-system

   <- GOOD FAILURE MITIGATION DESIGN

4. Software Enables
   - Software command instructions or dedicated signal lines that initiate an external interaction

   <- ALWAYS REQUIRED IN PRACTICALITY

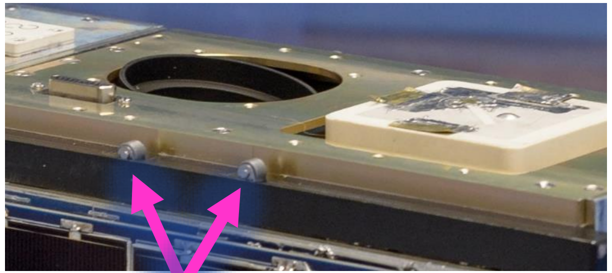


Inhibit Types – Mechanical Inhibits

Mechanical Inhibits

- **Mechanical switches to detect deployment, switches are open when depressed by dispenser**
- May directly switch the batteries into the EPS, or may trigger silicon solid-state switches to do the same
- Hard to get switches rated at more than 5A DC that can be easily integrated into CubeSat rails

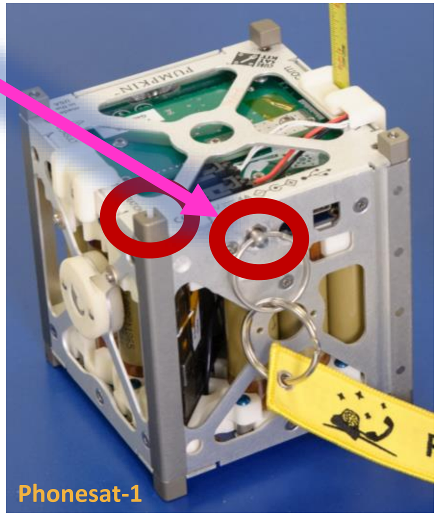
- Benefits: **Simple**
- Cautions: Mechanical actuation can jam, contacts can wear during vibe, can limit total system power if used as sole inhibit scheme, latent failure
- **Warning:** Foot switches tend to be much more temperamental than rail switches



Rail roller-leaf switches (top) vs Foot pushbutton switches (below)

Images Credit NASA

Connector vs Pin RBF



Mechanical Deployer Switches

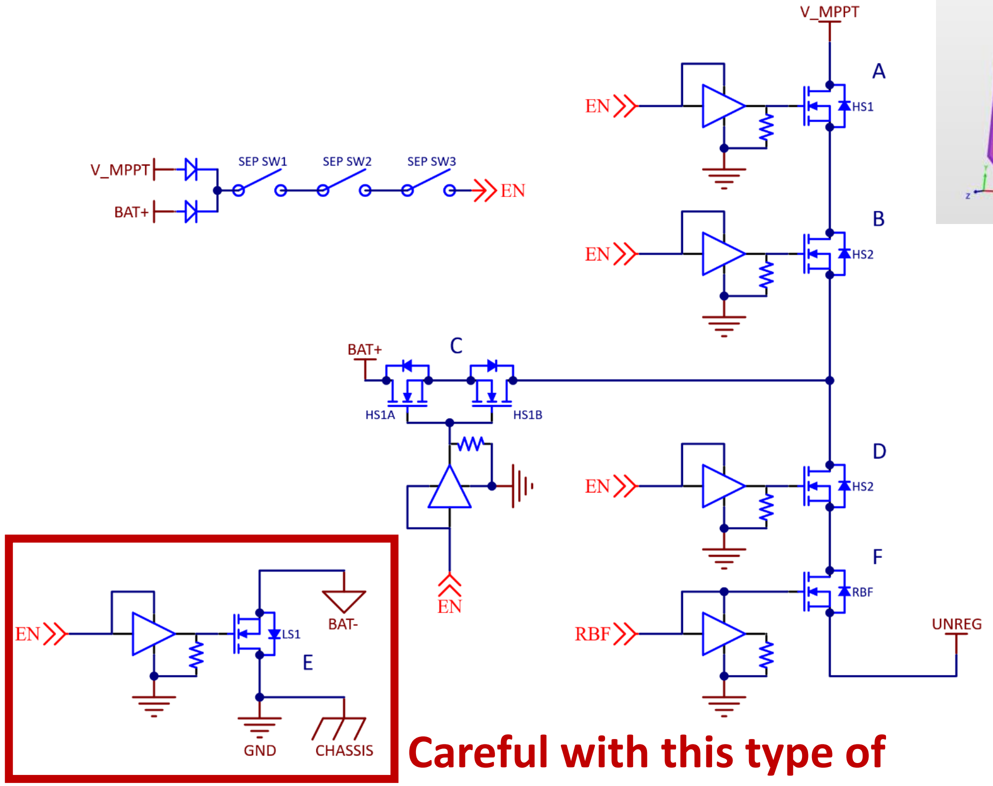
Inhibit Types – Solid-State PDS/EPS

Solid-State PDS/EPS Switches

- **Using solid-state switches triggered by mechanical switches increases bus power efficiency at the cost of electrical complexity**
- Allows for increased switch redundancy and lower resistance, and allows for switches to be located at each source, generator, and load
- P-Channel MOSFETS are radiation-robust, inherently vibration immune, and do not mechanically wear

- Benefits: **Increased power handling and efficiency**
- Cautions: Can quickly over-complicate EPS/PDS system design or introduce odd behaviors at low system voltages
- **Warning:** Do not use solid-state switches to ground-inhibit anything unless you have a very good engineer

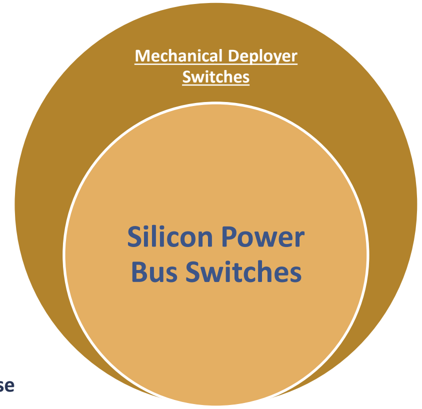
1.7sq-in majority-voting with debounce filtering & nA standby Inhibit Board, 56W



Careful with this type of ground inhibit

Diagram: AFRL UNP Public Release

NASA-NOW

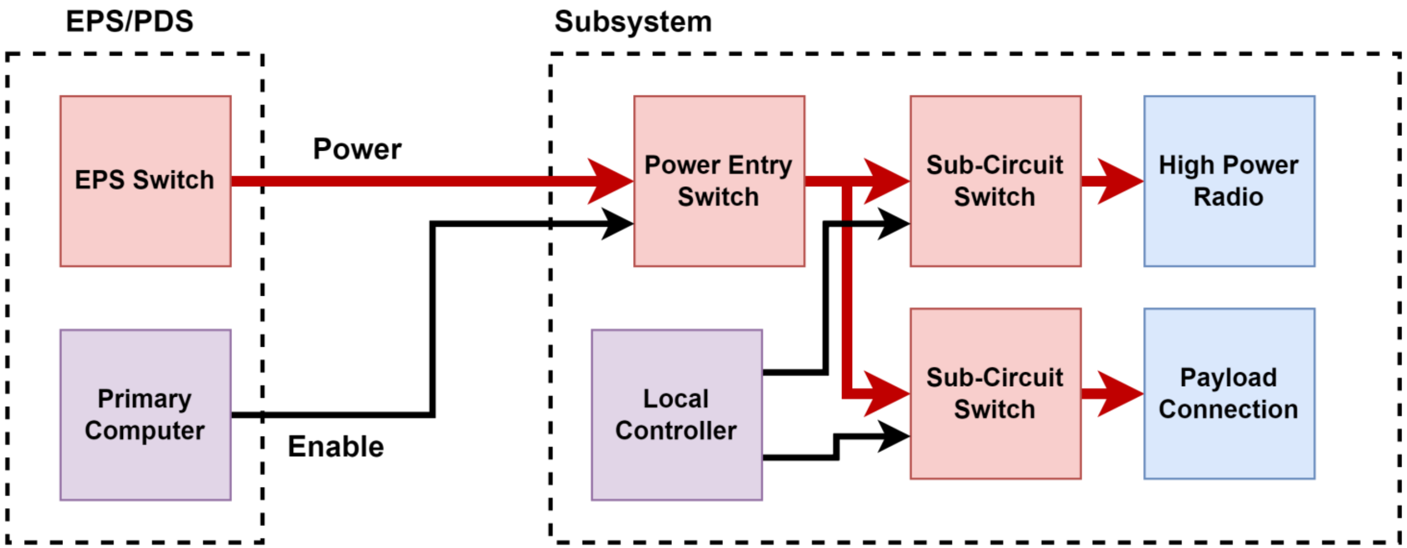


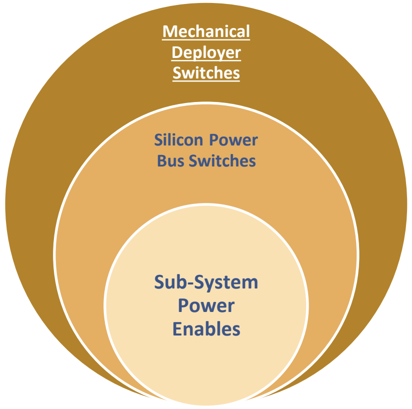
Inhibit Types – Sub-System Enables

Sub-System Enables

- **It is good practice to have each subsystem enact board-level inhibits/enables so faults can be contained or low-power modes can be entered**
- MOSFET switches activated by an external signal, or the onboard controller to enable a high-power subcircuit
- Reduces criticality of PDS response and keeps idle systems powered off to reduce radiation Single-Event Effects such as latch-up.

- Benefits: **Enhances fault-response and power conservation**
- Cautions: Increases electrical complexity
- **Warning:** Introduces communication bus back-power or latch-up risk if not designed properly





Inhibit Types – Software/Analog Enables

Software Enables

- **It may seem obvious, but throughout a mission you will want to turn various subsystems and subcircuits on and off**
- How these systems are enabled and the level of power control granularity needed is a requirement driven by mission design and operations
- These choices significantly impact hardware design

- Benefits: **Enables power conservation & dynamic spacecraft control**
- Cautions: Increases electrical complexity
- **Warning:** Introduces communication bus back-power or latch-up risk if not designed properly

ShipSat State Machine

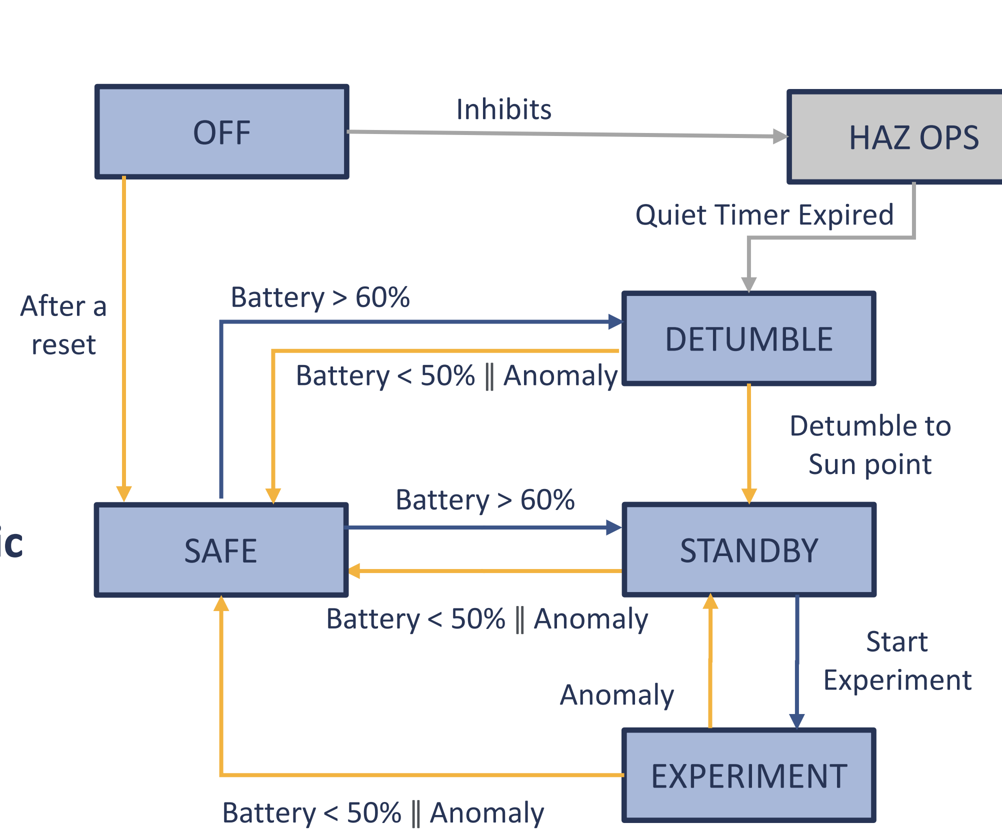
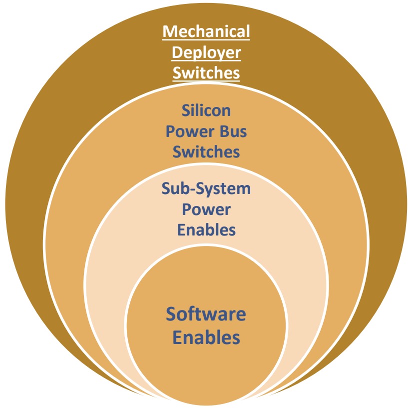


Diagram: AFRL UNP Public Release



Inhibit System - Simple

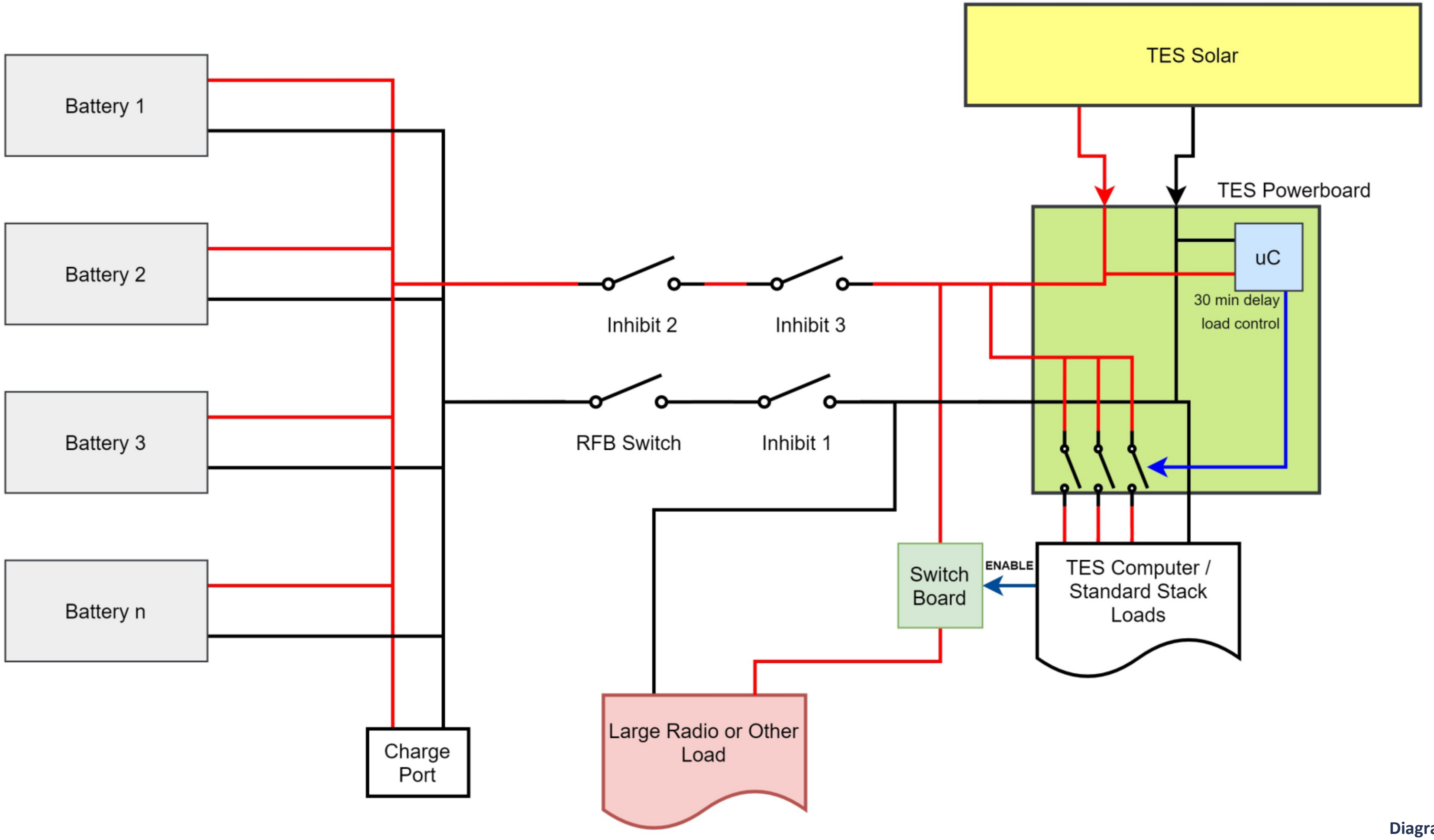


Diagram: NASA Nano Orbital Workshop

Inhibit System - Complex

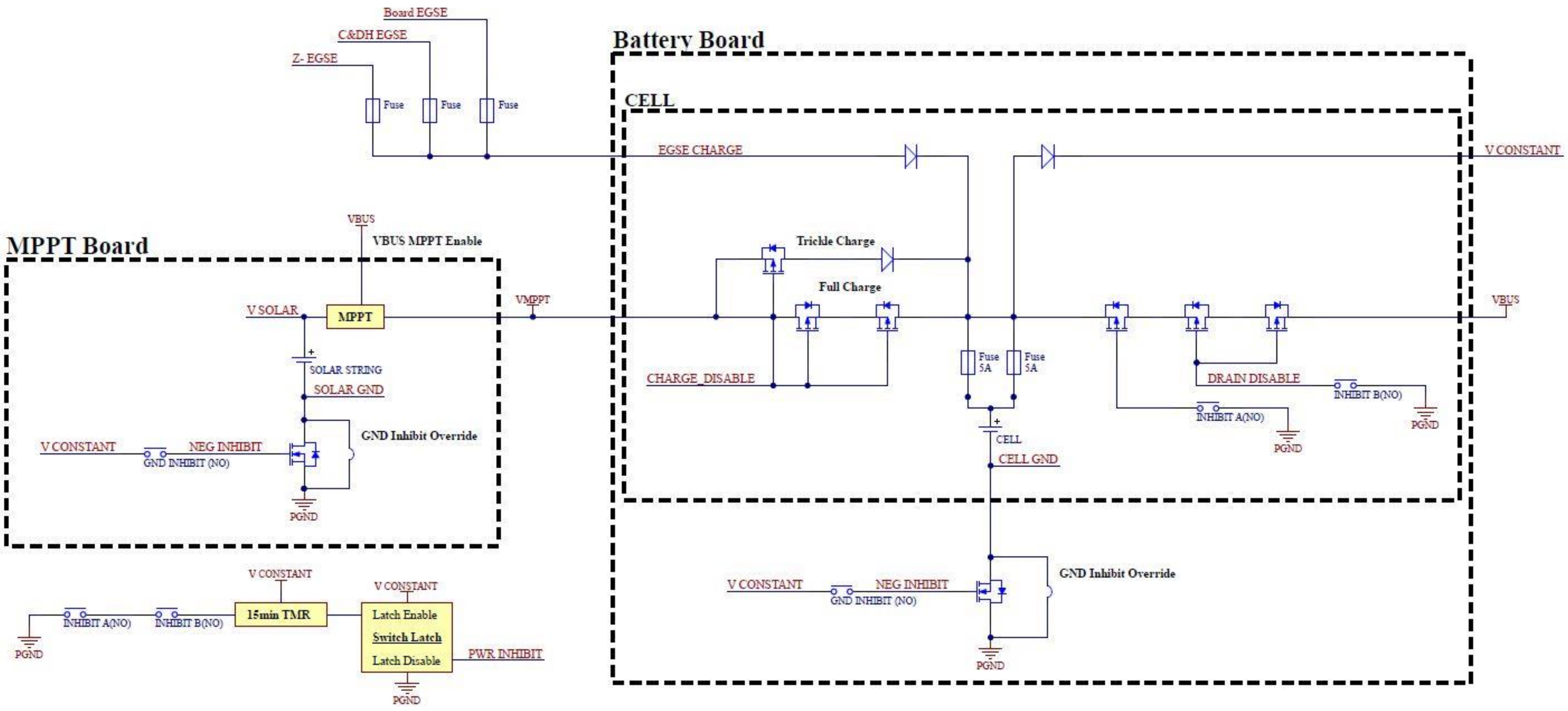


Diagram: NASA PACE/SST

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Power Distribution

Generation → Storage → Inhibits → Distribution

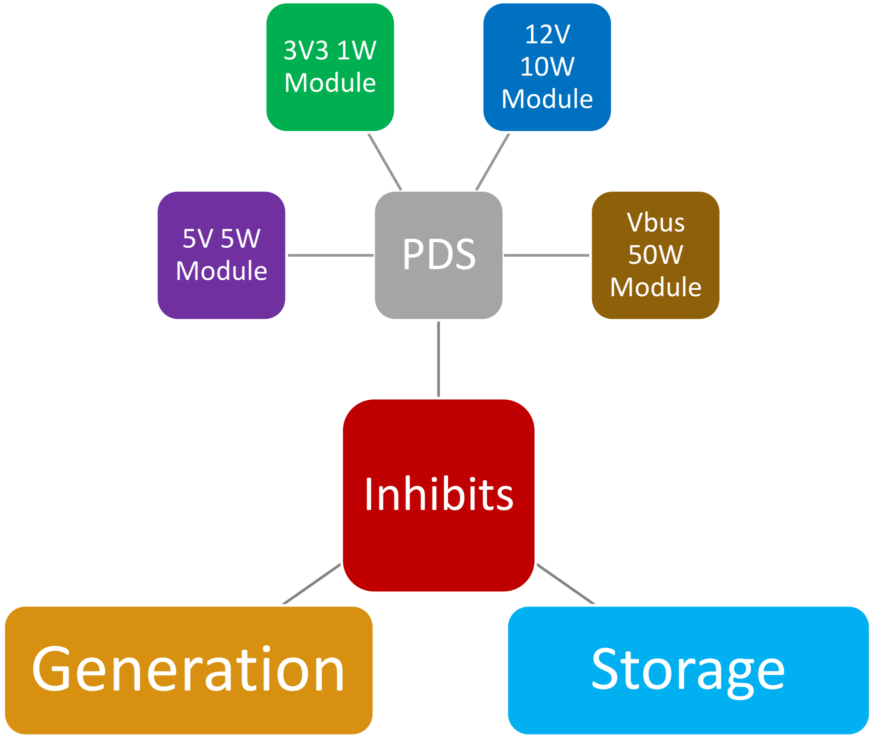
Directly connecting sub-systems (loads) to your generation and storage isn't a great idea:

- It is very unlikely all your payloads and subsystems will require the same voltage, and nearly all sub-systems should require less than your battery voltage, if you followed the most important lesson.
- Your storage system will likely be able to output an extremely high peak power (see the battery design example) that could cause catastrophic failure in the event of a short.
- Your storage and generation system will produce a variable, unregulated voltage, something most sub-systems are not designed to handle (see example designs)

Power Distribution System - PDS

A Power Distribution System (PDS) connects your EPS to the rest of the system:

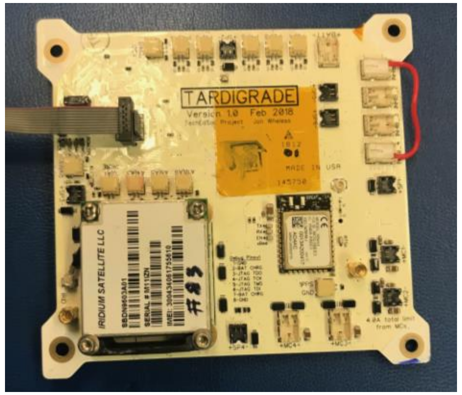
- A PDS should produce regulated, monitored, and switched power channels for each attached sub-system
- A PDS can be a single module or distributed across sub-system modules
- A PDS almost always needs to be modified to fit a specific mission's system requirements

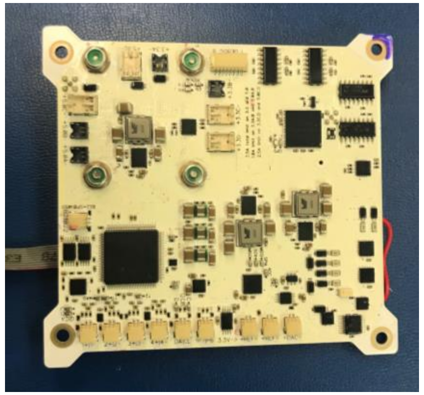


Power Distribution Topologies

Like generation and storage systems, a PDS may be purchased or custom made:

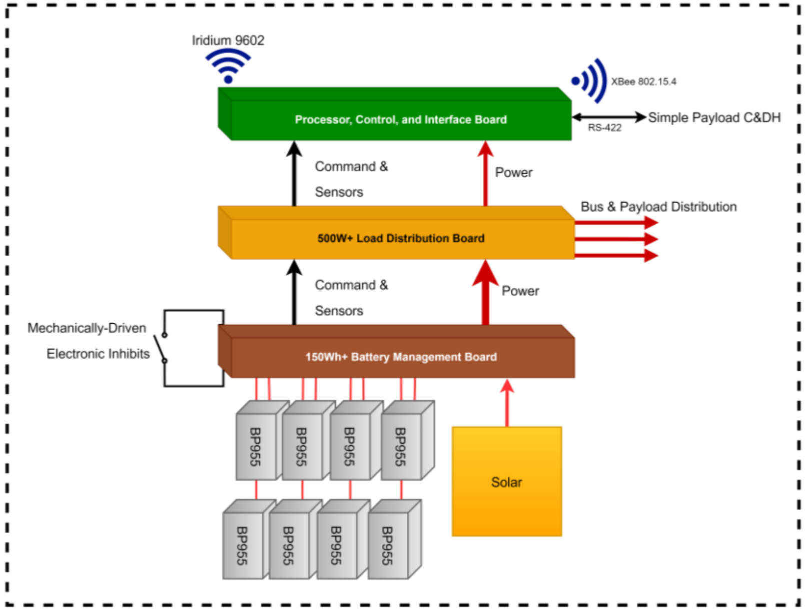
- For small missions, a PDS integrated into a battery pack or primary computer is usually the best way to go
- For modular busses supporting a series of various payload missions, a central PDS unit is usually best
- For a repeated design with only a few payloads, a distributed, system-integrated PDS may be best





40-Watt All-In-One Board

Combines PDS with battery and solar management, inhibits, and primary flight computer and radio



Modular EPS with Separate PDS

Top-level block diagram with hybrid PDS where voltage regulation is done at the sub-system

Images: NASA Nano Orbital Workshop

Power Distribution – Generating Requirements

In just about any case, you will need to generate an electrical requirements table listing each module to be connected to the PDS

- This table will likely arise somewhere in the middle of mission design, after you have finalized what your subsystems are, your mass budget for storage, and your area budget for solar.
- You will want the following basic values for each module to be able to start design:

System Rating	ADCS Unit	X-Band Radio
Minimum Input Voltage	11V	8V Standby 11.5V Active
Maximum Input Voltage	14V	12.5V
Nominal Input Voltage	12V	12V
Nominal Operating Power / Current	10W	2W Standby 25W TX, 6W RX
Maximum Sustained Power/Current	15W	50W TX
Inrush Power/Current	2.5A Limited	5A 50ms pulse per TX
Communication Protocol	RS-422	Ethernet / Spacewire

Power Distribution – Generating Requirements

Voltage below which the system won't operate properly or could generate errant data. AKA: Undervoltage Lock Out (UVLO)

Voltage above which the system is designed to operate and could be permanently damaged. AKA: Overvoltage Lock Out (OVLO)

Usually for transmitting radios, things that have a 'standby' or 'idle' state vs. a periodic but sustained 'active' state

The current something takes when power is first applied to it, usually from charging internal capacitance. This can be **very** substantial unless limited by the device or PDS.

System Rating	**ADCS Unit**	**X-Band Radio**
Minimum Input Voltage	11V	8V Standby 11.5V Active
Maximum Input Voltage	14V	12.5V
Nominal Input Voltage	12V	12V
Nominal Operating Power / Current	10W	2W Standby 25W TX, 6W RX
Maximum Sustained Power/Current	15W	50W TX 5A 50ms pulse per TX
Inrush Power/Current	2.5A Internally Limited	25A 1ms (can be limited)
Communication Protocol	RS-422	Ethernet / Spacewire

Not usually part of an EPS, but sometimes needed when using a highly-integrated EPS system

Power Distribution – Matching Requirements

Chances are a COTS PDS won't exactly match your load requirements

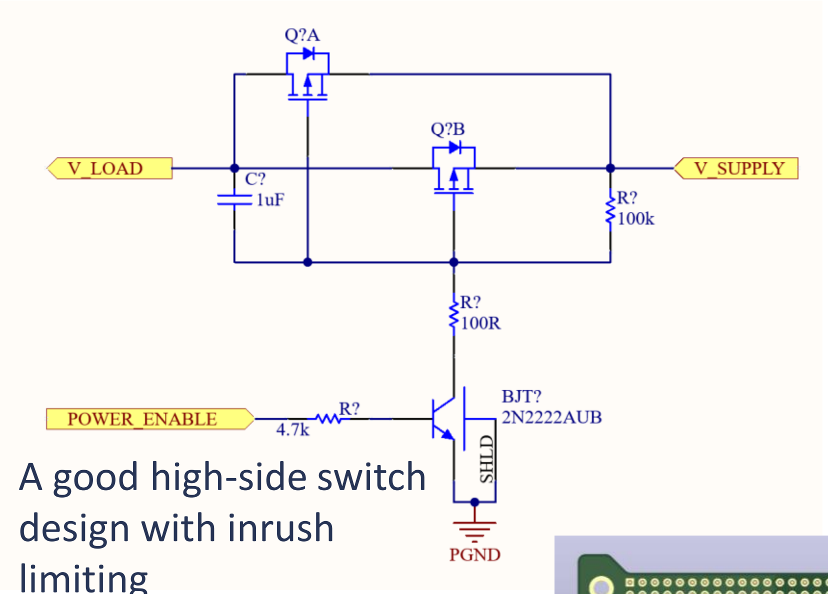
	Requirements	PDS 1	PDS 2
Voltage Rails:	3V3 @ 3A x2 5V0 @ 1A x2 12V @ 1A x1 Vbus @ 5A x1	3V3 @ 2A x4 5V0 @ 5A x1 Vbus @ 2.5A x 4	3V3/5V0 Configurable 5A x 8 0.8V – 18V Configurable Buck/Boost 2A x4 Vbus @ 10A x 4
Battery Pack Voltage:	2S8P Li-Ion (~7.2V)	2S-4S Li-Ion, constant-voltage charging/monitoring only	2S Li-Ion, CC/CV charger w/SoC monitoring
Solar Capacity:	10W, MPPT needed	25W Diode-Mux Single-MPPT	40W (10W MPPT x4)
Rail/Regulator Protections	COTS sub-systems have protection, custom sub-systems do not	Over-current/Over-temperature on all rails	Configurable over-current/over-temperature/voltage excursion on rails
Rail Switching	Majority of sub-systems need a switched power rail to enable power-saving operations	Only Vbus rails can be switched, other rails are always-on	All outputs can be switched
Inhibits	Series rail-inhibit switches required between batteries and bus	None integrated	Integrated electronic inhibits w/rail switch input
Communication Protocols*	RS-232 UART, RS-422, SPI, I2C	SPI x2, I2C x2	RS-422/CAN

Generation Storage Inhibits Distribution

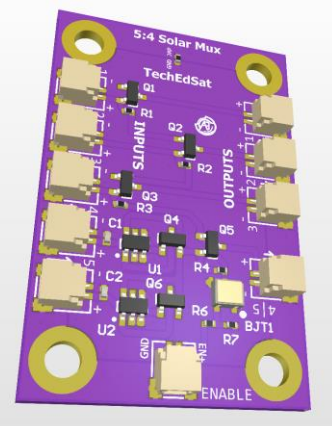
Power Distribution – Core Notes

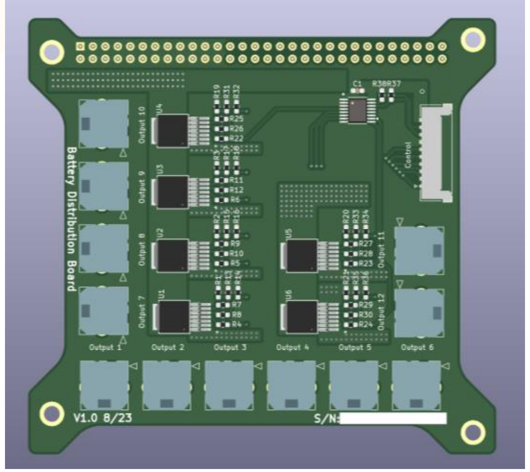
Keeping a PDS simple can keep your development and testing simple, and remember these core rules:

- The most important lesson: **Always Lower a Voltage, Only Boost if you Must**
- Avoid low-side (ground/return path) switches and PDS systems that use them. Floating returns can cause issues more easily.
- COTS to Custom adapter boards are common, most research spacecraft are a Frankenstein of parts



A good high-side switch design with inrush limiting





Images: NASA Nano Orbital Workshop

Custom boards to augment existing PDS systems for specific missions
Top: Add more solar panels and inhibits
Bottom: Add more bus-voltage loads

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An EPS Supports the Mission

As such, Mission Design should be well underway before it is worth starting EPS design

(coming from an electrical engineer)

<u>ShipSat designs the power budget LAST when drafting the mission</u>

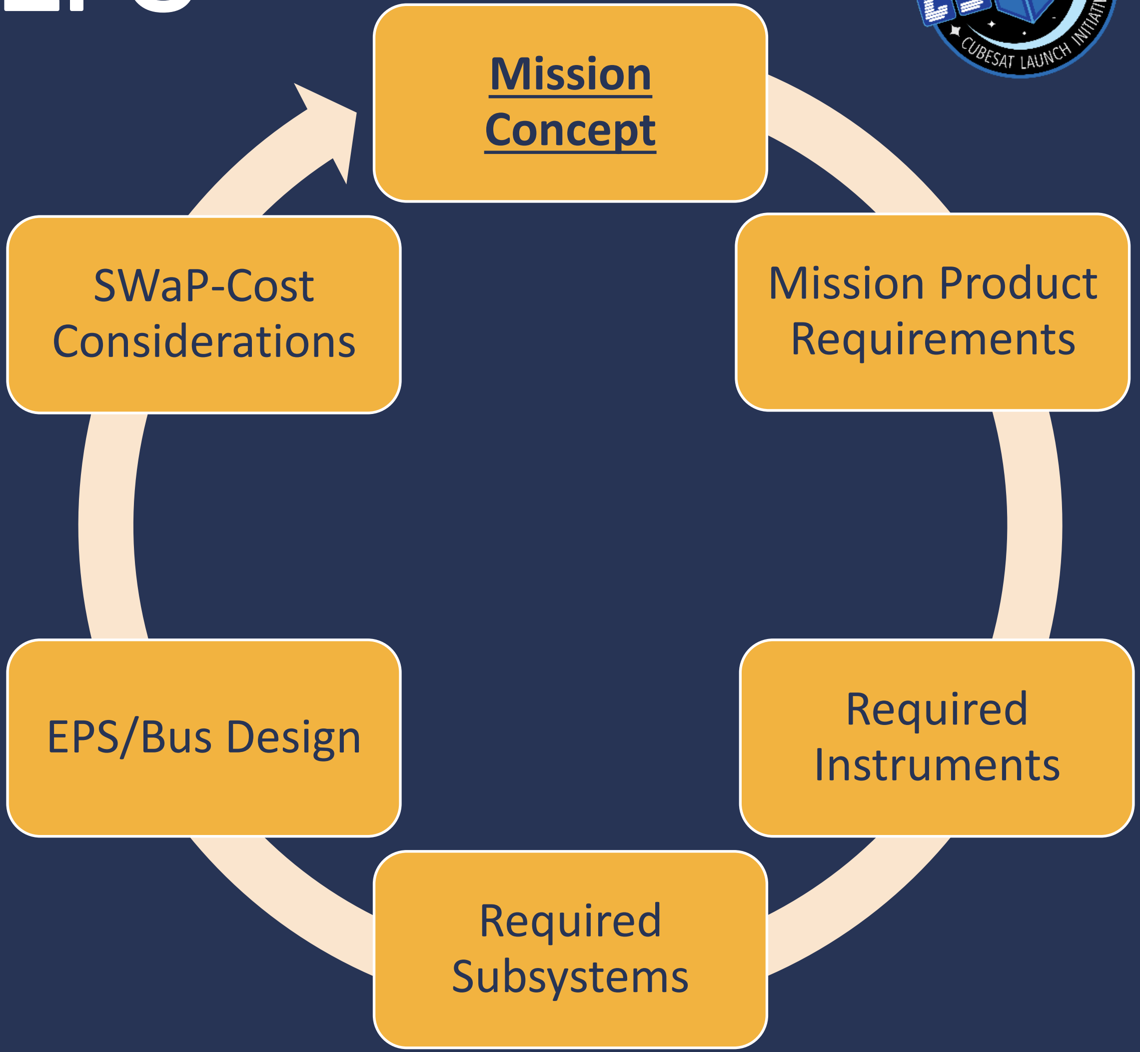
That being said, don't forget to keep things realistic. Don't design a solar-powered Neptune-bound CubeSat with 12% efficient solar to power a 2kW ion thruster in a 1U.

We won't get into requirements writing, operational modes drafting, or mission-operations level work. That will be left for the mission design classes and to our Systems Engineers.

The Phases of EPS Design

EPS design tends to be recursive as ideas solidify, and the real world will significantly impact mission design, and especially impact concept of operations

Spreadsheets are your friend!

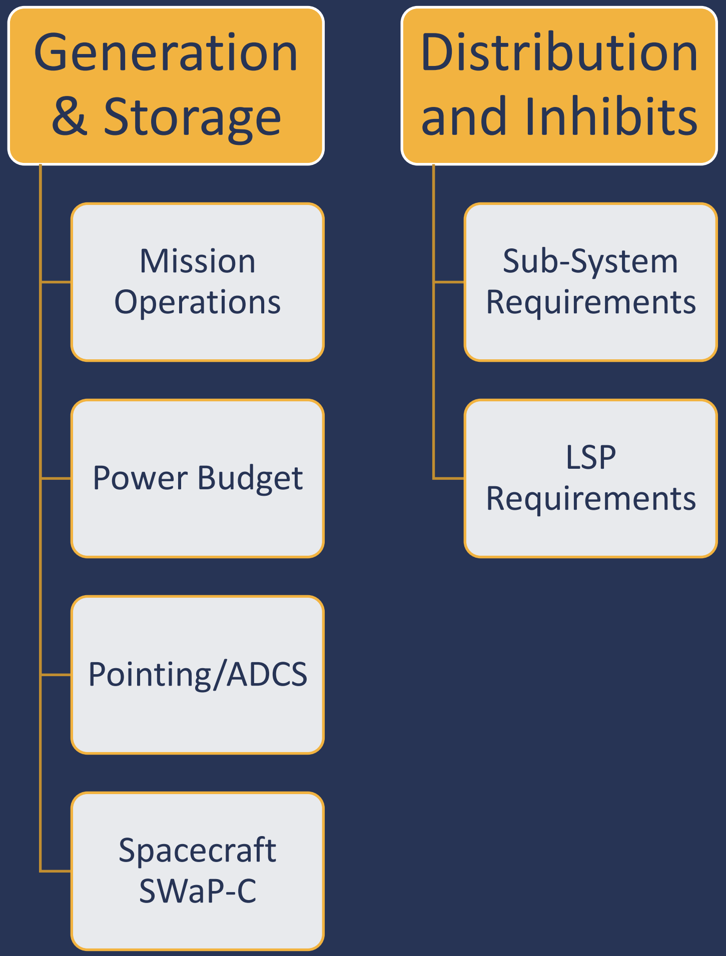


EPS Engineering Requirements

EPS Requirements fall into two categories:

1. Generation and Storage
2. PDS/Inhibit Requirements

Preliminary design will usually only address generation and storage, with distribution requirements coming in for a detailed review when specific hardware starts taking shape



The Steps of EPS Design

Load Table
- Sub System Estimates
- Per-Orbit Operations

EPS System
- Load Table + Operations = Power Budget
- Balancing Power Budget Yields Generation and Storage Requirements

PDS System
- Sub-System Hardware Requirements
- System Design Requirements

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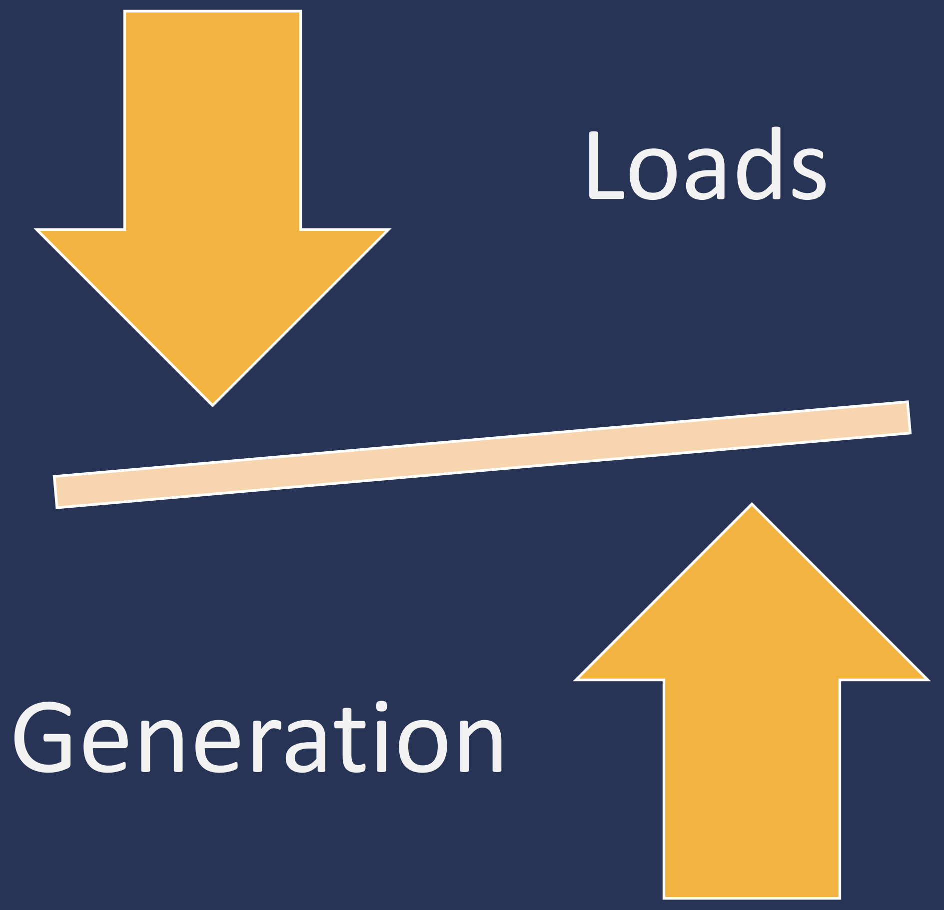
Power Budget

Unless you are running a short-duration one-and-done mission, you need to make sure you will be generating at least as much power as you are using, and that you will have enough energy stored to bridge generation gaps (eclipse periods)

Sun-Synchronous Orbits (SSO) are becoming more popular with rideshares as traditional LEO orbits become filled with commercial constellations. SSO orbits usually do not have eclipse periods but may have less available incident sunlight.

I am going to show more of an Engineer's approach to power budgeting rather than a mission designer's approach



ShipSat Load Table

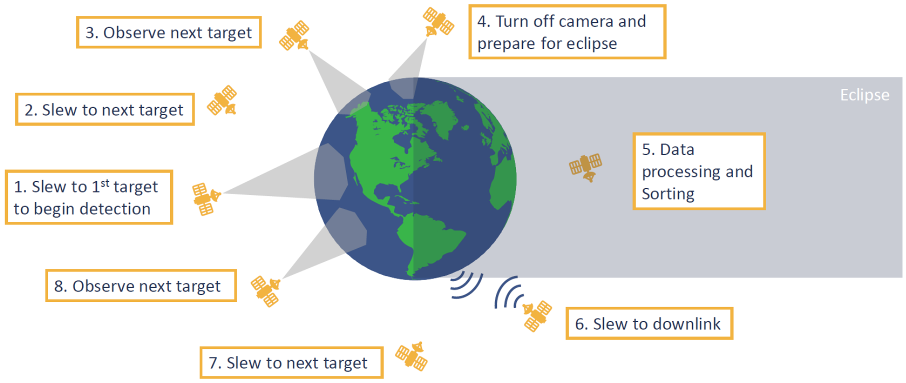
Component	Component Draw	Safe Mode		Standby Mode		Experiment Mode	
	(W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)
Power System	0.5	100%	0.5	100%	0.5	100%	0.5
Radio Tx	6	10%	0.6	10%	0.6	10%	0.6
Radio Rx	2	100%	2	100%	2	100%	2
ADCS	2	0%	0	100%	2	100%	2
CDH	1	50%	0.5	100%	1	100%	1
Heater(s)	2	50%	1	50%	1	50%	1
Payload Imager	5	0%	0	0%	0	60%	3
GPS	1	0%	0	100%	1	100%	1
	Power Draw Per Mode		**4.6 W**		**8.1 W**		**11.1 W**

AFRL UNP – Public Release

Turning a Load Table into a Power Budget

Component	Component Draw	Safe Mode		Standby Mode		Experiment Mode	
	(W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)
Power System	0.5	100%	0.5	100%	0.5	100%	0.5
Radio Tx	6	10%	0.6	10%	0.6	10%	0.6
Radio Rx	2	100%	2	100%	2	100%	2
ADCS	2	0%	0	100%	2	100%	2
CDH	1	50%	0.5	100%	1	100%	1
Heater(s)	2	50%	1	50%	1	50%	1
Payload Imager	5	0%	0	0%	0	60%	3
GPS	1	0%	0	100%	1	100%	1
	Power Draw Per Mode		**4.6 W**		**8.1 W**		**11.1 W**

AFRL UNP – Public Release



Let's change a few mission design parameters:

- Use an orbital network radio (Iridium Modem) for command uplink so commands can be given regardless of S/C orientation and orbital location
- Use a dedicated high-speed transmit-only radio for image downlink
- Only downlink data during eclipse periods so sunlight time can be fully used for imaging
- Utilize current advanced processors to enable AI/ML recognition of boats and cars to reduce downlink data size

And baseline some real hardware for estimation purposes:

- Iridium SBD modem and TES S-Band downlink radio
- AAC Hyperion 1U Integrated ADCS Unit
- 4K CameraLink Imager (Teledyne Genie Nano-CL)
- Novatel OEM GNSS Unit
- Nvidia Jetson Orin GPU Primary Processor

UNP Turning a Load Table into a Power Budget

Exploration Research and Technology Programs

Component	Component Draw	Safe Mode		Standby Mode		Experiment Mode	
	(W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)	Duty Cycle	Power Draw (W)
Power System	0.5	100%	0.5	100%	0.5	100%	0.5
Radio Tx	6	10%	0.6	10%	0.6	10%	0.6
Radio Rx	2	100%	2	100%	2	100%	2
ADCS	2	0%	0	100%	2	100%	2
CDH	1	50%	0.5	100%	1	100%	1
Heater(s)	2	50%	1	50%	1	50%	1
Payload Imager	5	0%	0	0%	0	60%	3
GPS	1	0%	0	100%	1	100%	1
Power Draw Per Mode			4.6 W		8.1 W		11.1 W

AFRL UNP – Public Release

Let’s make some assumptions to get load estimates:

- Point and Transmit to one ground station each eclipse
- Heaters needed primarily during eclipse, otherwise sun and radio transmitter will keep S/C warm (probably don’t need heaters)
- Don’t need to do a ton of math during eclipse periods, just data packaging

Equipment	Operational Power [W]	Nominal Operating Voltage [V]	Imaging Mode Duty Cycle	Eclipse Mode Duty Cycle
Core Bus EPS	0.5	5	100%	100%
Radio - Transmit	20	12	0%	N/A
Radio - Receive	1	5	100%	100%
ADCS - Slewing	30	12	75%	25%
ADCS - Station Keeping	8	12	100%	100%
Primary Computer	25	5	100%	50%
Payload Imager	7	12	25%	0%
GPS	1.5	5	100%	100%
Bus Heater	5	12	25%	75%

Turning a Load Table into a Power Budget

- Baselining a 100-minute orbital period lets us add run-time
- Estimate a 12-minute ground station radio pass

Duty Cycle -> Run Time per Orbit Operation

Equipment	Operational Power [W]	Nominal Operating Voltage [V]	Imaging Mode Duty Cycle	Eclipse Mode Duty Cycle	Imaging Mode Run Time (minutes)	Eclipse Run Time (minutes)
Core Bus EPS	0.5	5	100%	100%	50	50
Radio - Transmit	20	12	0%	N/A	0	12
Radio - Receive	1	5	100%	100%	50	50
ADCS - Slewing	30	12	75%	25%	37.5	12.5
ADCS - Station Keeping	8	12	100%	100%	50	50
Primary Computer	25	5	100%	50%	50	25
Payload Imager	7	12	25%	0%	12.5	0
GPS	1.5	5	100%	100%	50	50
Bus Heater	5	12	25%	75%	12.5	37.5

Duty Cycle % * Operational Period = Run Time

Operational Period = Orbital Period /2 (for this example)

Turning a Load Table into a Power Budget

Now knowing duration and power consumption, calculate energy use

Run Time x Power -> Energy per Orbit Operation

Equipment	Operational Power [W]	Nominal Operating Voltage [V]	Imaging Mode Run Time (minutes)	Eclipse Run Time (minutes)	Imaging Energy [Wh]	Eclipse Energy [Wh]	Per-Orbit Total [Wh]
Core Bus EPS	0.5	5	50	50	0.42	0.42	0.83
Radio - Transmit	20	12	0	12	0.00	4.00	4.00
Radio - Receive	1	5	50	50	0.83	0.83	1.67
ADCS - Slewing	30	12	37.5	12.5	18.75	6.25	25.00
ADCS - Station Keeping	8	12	50	50	6.67	6.67	13.33
Primary Computer	25	5	50	25	20.83	10.42	31.25
Payload Imager	7	12	12.5	0	1.46	0.00	1.46
GPS	1.5	5	50	50	1.25	1.25	2.50
Bus Heater	5	12	12.5	37.5	1.04	3.13	4.17

(Minutes/60)*Power = Watt-Hours

Always total things up to check consistency

Turning a Load Table into a Power Budget

Equipment	Operational Power [W]	Nominal Operating Voltage [V]	Imaging Energy [Wh]	Eclipse Energy [Wh]	Per-Orbit Total [Wh]
Core Bus EPS	0.5	5	0.42	0.42	0.83
Radio - Transmit	20	12	0.00	4.00	4.00
Radio - Receive	1	5	0.83	0.83	1.67
ADCS - Slewing	30	12	18.75	6.25	25.00
ADCS - Station Keeping	8	12	6.67	6.67	13.33
Primary Computer	25	5	20.83	10.42	31.25
Payload Imager	7	12	1.46	0.00	1.46
GPS	1.5	5	1.25	1.25	2.50
Bus Heater	5	12	1.04	3.13	4.17

Column Totals:

Need **51.3Wh** During Imaging Sessions

Need **33Wh** During Eclipse

84.2Wh Total Per Orbit
50.5W Nominal Power Draw

So, we need to enter eclipse with at least 33Wh of stored energy, which means during sunlit imaging sessions we need to generate at least 33Wh of energy **plus** 51.3Wh for the imaging operations themselves, or 84.2Wh if we want to maintain **constant** operations.

Making a Power Budget into EPS Requirements

Exploration Research and Technology Programs

Constant Operations EPS Minimums		
Sunlit Load [Wh]	51.3	Power Budget Data and Orbit Parameters
Eclipse Load [Wh]	33.0	
Per-Orbit Generation Needed [Wh]	84.2	
Sunlit Time [Minutes]	50	
Solar Power Needed [W]	101	<- Per-Orbit Generation Wh ÷ Sunlit Time (hrs) = Watts Solar
Incident Solar Energy Req [W]	337	<- 30%η solar panel baseline, Watts Solar x 1/η
Solar Area Estimate [Sq m]	0.241	<- AM0: 1,400 Watts/Square Meter, Watts Incident ÷ Watts/Square Meter
Solar Area Estimate [Sq U]	**24**	<- 0.01 square meters per square U (10x10cm)
Energy Storage Required [Wh]	**33**	<- 100% of Eclipse Load (no generation)
1860 Cell Count Estimate [cells]	**4.0**	<- 10Wh per 18650 Cell, round up
Battery Mass (g)	200	<- 50g per 18650 Cell

Making a Power Budget into EPS Requirements

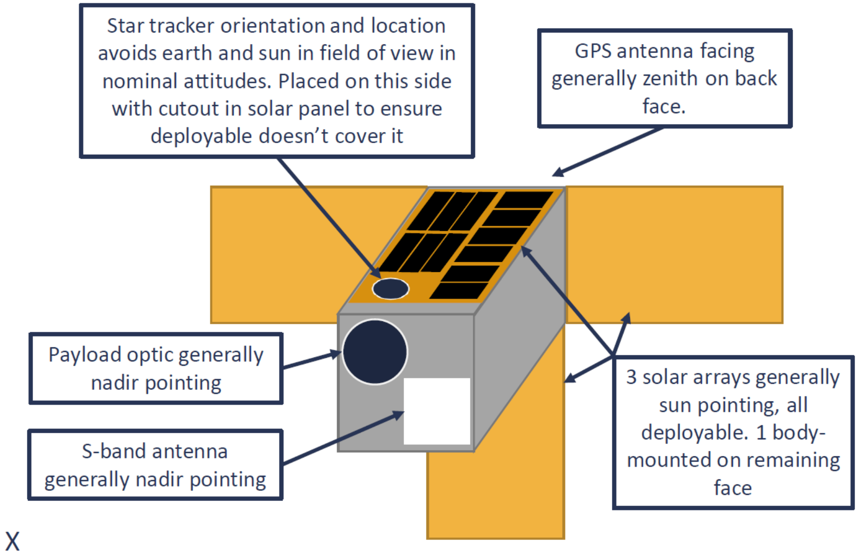
Constant Operations EPS Minimums	
Sunlit Load [Wh]	51.3
Eclipse Load [Wh]	33.0
Per-Orbit Generation Needed [Wh]	84.2
Sunlit Time [Minutes]	50
Solar Power Needed [W]	101
Incident Solar Energy Req [W]	337
Solar Area Estimate [Sq m]	0.241
Solar Area Estimate [Sq U]	**24**
Energy Storage Required [Wh]	**33**
1860 Cell Count Estimate [cells]	**4.0**
Battery Mass (g)	200

24U worth of solar panels is a lot, will they fit on the proposed 12U ShipSat?

If ShipSat is 4x3U, we can have four 2x3U Panels that deploy, with an aft 4U panel, providing 28U of total solar area

YES, in fact if we take the original design and make the last panel also deploy, we are set!

UNP PDR 12U ShipSat



Improving EPS Design Requirements

Constant Operations EPS Minimums	
Sunlit Load [Wh]	51.3
Eclipse Load [Wh]	33.0
Per-Orbit Generation Needed [Wh]	84.2
Sunlit Time [Minutes]	50
Solar Power Needed [W]	101
Incident Solar Energy Req [W]	337
Solar Area Estimate [Sq m]	0.241
Solar Area Estimate [Sq U]	**24**
Energy Storage Required [Wh]	**33**
1860 Cell Count Estimate [cells]	**4.0**
Battery Mass (g)	200

This estimate carries no margin for solar cell failure or battery capacity reduction, and assumes the batteries are 100% discharged each eclipse (which would be horrible for them).

Let's add safety margins and see what happens ->

Constant Operations EPS Margin	
Minium Generation Req [W]	101
Solar Generation Margin	20%
Generation Req [W]	121
Incident Solar Energy Req [W]	404
Solar Area Estimate [Sq m]	0.289
Solar Area Estimate [Sq U]	**29**
Minimum Storage Req [Wh]	33
Battery Depth of Dischage	40%
Nominal Storage Req [Wh]	82
Storage Margin	20%
Battery Capacity Needed [Wh]	99
18650 Cell Count Est [Cells]	**10**
Battery Pack Mass (g)	500

Estimation Assumptions Return

Constant Operations EPS Margin	
Minium Generation Req [W]	101
Solar Generation Margin	20%
Generation Req [W]	121
Incident Solar Energy Req [W]	404
Solar Area Estimate [Sq m]	0.289
Solar Area Estimate [Sq U]	**29**
Minimum Storage Req [Wh]	33
Battery Depth of Dischage	40%
Nominal Storage Req [Wh]	82
Storage Margin	20%
Battery Capacity Needed [Wh]	99
18650 Cell Count Est [Cells]	**10**
Battery Pack Mass (g)	500

With only 28U of area available for panels, we will have to either buy more expensive, more efficient cells, or accept less margin

If we enter a safe mode, or lose pointing, we will lose solar generation. **Is this acceptable?**

Ten 18650 Cells will consume about 2U of volume, what if we can't fit that in the 12U? **What are our design options?**

If we can't have all our solar panels in one 'pointing basket' due to **risk posture**, what could we do?

If we deploy tumbling, how much energy do we need to recover? Will this pack estimate satisfy that requirement?

The Phases of EPS Design

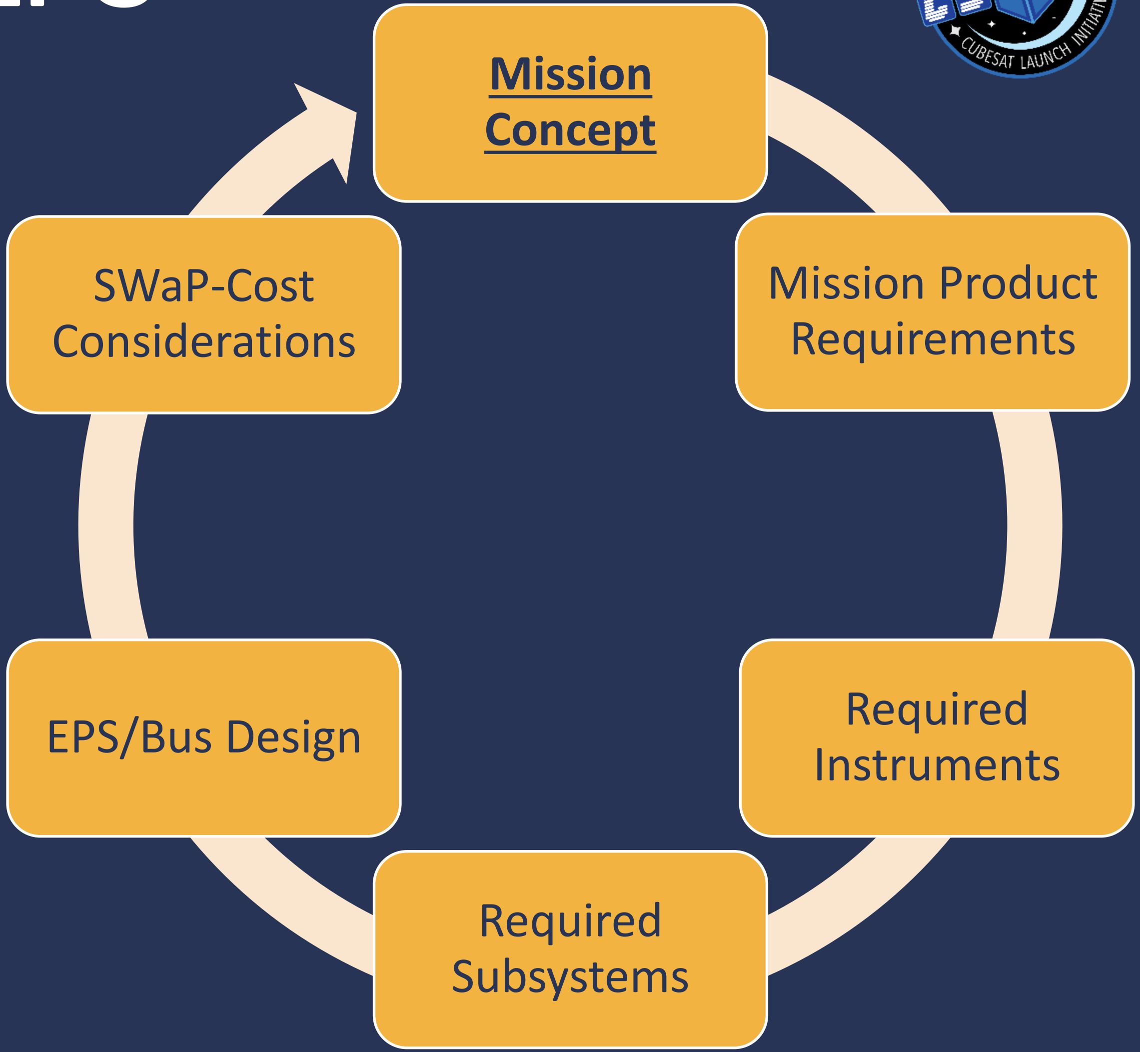
Maybe your 12U launch slot turns into a 6U

Maybe you don’t have the budget for deployable panels

Maybe you can’t get authorization for S-Band and have to use VHF

Maybe in testing your 3U imager needs another 1U of lensing

Maybe you find you don’t need heaters but a radiator



NASA Small Spacecraft Systems Virtual Institute (S3VI)

What is an EPS?

- Electrical Theory to Know
- Power Generation
- Power Storage
- Spacecraft Inhibiting
- Power Distribution System

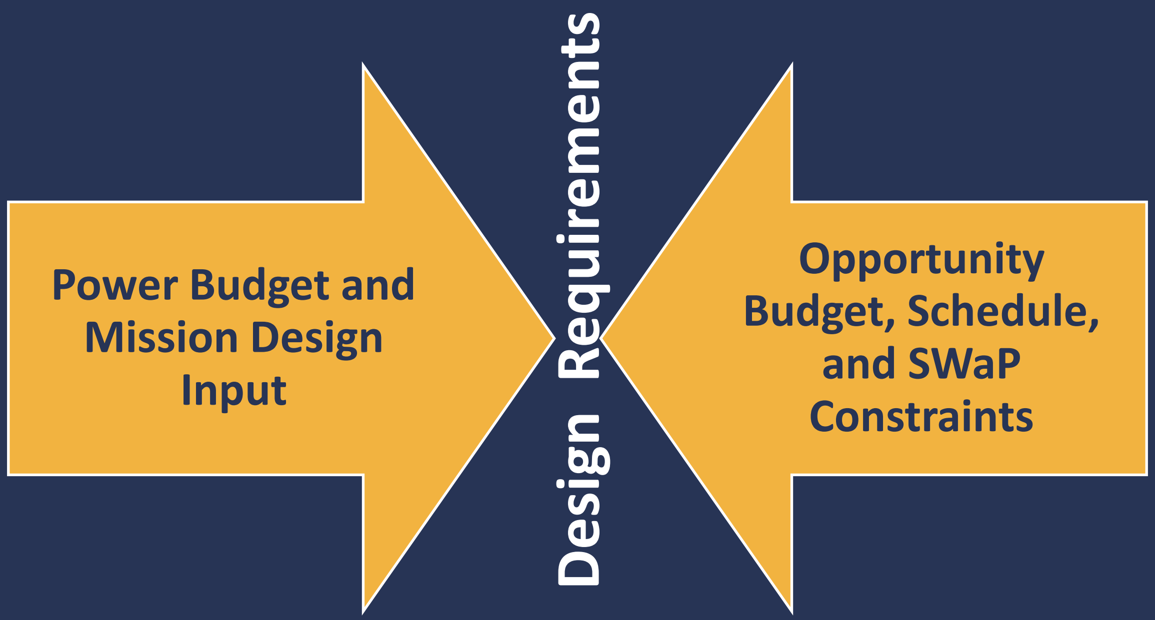
So You Want to Design A Mission

- Developing A Power Budget
- EPS & PDS Design ←
- System Validation & Testing

EPS & PDS Design

With the draft power budget completed and showing a power-positive system with margin, let’s develop the specifications for ShipSat’s EPS and PDS.

Again, we are not going to delve into safe-modes, detumbling, pointing risks and budget, etc. I’ve got to keep this to two hours as it is.



EPS & PDS 'Requirements'

Let's pull in our equipment list and the EPS specifications we just created

Equipment	Operational Power [W]	Nominal Operating Voltage [V]
Core Bus EPS	0.5	5
Radio - Transmit	20	12
Radio - Receive	1	5
ADCS - Slewing	30	12
ADCS - Station Keeping	8	12
Primary Computer	25	5
Payload Imager	7	12
GPS	1.5	5
Bus Heater	5	12

Constant Operations EPS Margin	
Generation Req [W]	121
Solar Area Estimate [Sq U]	**29**
18650 Cell Count Est [Cells]	**10**

First, we need to determine the optimal battery pack voltage for our EPS, so let's start with battery pack design

UNP Battery Pack Design

Equipment	Operational Power [W]	Nominal Operating Voltage [V]
Core Bus EPS	0.5	5
Radio - Transmit	20	12
Radio - Receive	1	5
ADCS - Slewing	30	12
ADCS - Station Keeping	8	12
Primary Computer	25	5
Payload Imager	7	12
GPS	1.5	5
Bus Heater	5	12

Constant Operations EPS Margin	
Generation Req [W]	121
Solar Area Estimate [Sq U]	**29**
18650 Cell Count Est [Cells]	**10**

A majority of our equipment needs 12V to operate, so remembering the most important rule of EPS design, we want a system voltage of at least 12V

Assuming Li-Ion Cells, which have a nominal voltage of 3.6V, lets look at a table of series cell voltage ranges:

Cells	Min	Nom	Max
1S	2.5	3.6	4.2
2S	5	7.2	8.4
3S	7.5	10.8	12.6
4S	10	14.4	16.8
5S	12.5	18	21
6S	15	21.6	25.2

Since all our solar panels face the same direction, we MUST have ADCS running until the bitter end, which pushes us to a 5S design. If no 12V systems were potentially needed in a 'Safe' mode, 4S would probably be fine

UNP Li-Ion Packs– Designing for a Mission

1. Determine the key parameters your pack needs to meet
   - Total storage capacity needed
   - Target operating voltage
   - Expected discharge current (sustained vs peaks)
2. Select a cell to use as a design reference starting point
3. Determine the number of cells you need in series by dividing the target pack voltage by the cell's nominal voltage (usually 3.6V)
4. Determine the number of parallel strings you need by selecting the greater of:
   A) Storage capacity divided by cell capacity
   B) Peak discharge current divided by cell peak current
5. Calculate mass and performance parameters

1. Requirements: 18V Pack with 10 Cells

2. Reference Cell Data:

18650 Cell Manufacturer	LG Chem Ltd, Seoul, South Korea
18650 Cell Type	INR18650 MJ1
Cell Capacity	3500mAh NOM, 3350mAh MIN
Cell Voltage	2.5V MIN, 3.635V NOM, 4.2V MAX
Discharge Rate	0.2C 670mA NOM, 2.85C 10A MAX
Mass	49g

3. Series Cells Needed:

$$\frac{18V\ Target}{3.635V_{cell}} = \mathbf{5\ series\ cells}$$

4. Parallel Cells Needed:

A) $$\frac{\boldsymbol{99Wh\ Target}}{\boldsymbol{10Wh_{cell}}} = \boldsymbol{10\ total\ cells \rightarrow 2\ parallel\ cell\ strings}$$

5. Pack Statistics:

5S2P, 18V, 10 cells, 500g, ~2U

Vmin = 12.5V, Vmax = 21V

Nominal Storage = 7Ah, **Peak Discharge = 20A**

UNP Battery Pack Design

Exploration Research and Technology Programs

Equipment	Operational Power [W]	Nominal Operating Voltage [V]
Core Bus EPS	0.5	5
Radio - Transmit	20	12
Radio - Receive	1	5
ADCS - Slewing	30	12
ADCS - Station Keeping	8	12
Primary Computer	25	5
Payload Imager	7	12
GPS	1.5	5
Bus Heater	5	12

Constant Operations EPS Margin	
Generation Req [W]	121
Solar Area Estimate [Sq U]	**29**
18650 Cell Count Est [Cells]	**10**

EPS Battery Pack Statistics:
5S2P, 10 cells, 500g
Vmin = 12.5V, Vmax = 21V
Nominal Storage = 7Ah, 100Wh, **Peak Discharge = 20A**

Now that we know cell configuration and **charge** storage, we can better refine a more detailed power budget down the road and start estimating pack performance vs. temperature and SoC.

Now, lets design a solar array to charge this pack

Keep in mind, our pack will be at **21V fully charged**, so the solar array needs to have a **MPP voltage of at least 21V**

Solar Array Design

1. Determine the key parameters your solar array needs
   - Total generation capacity needed
   - Target operating voltage
2. Select a cell to use as a design reference starting point
3. Determine the number of cells you need by dividing total power by generation per cell
4. Determine the number of cells you need per string by dividing your target voltage by cell MPP voltage
5. Calculate square area & performance parameters

1. Requirements: 121W maximum generation, at least 21V

2. Reference Cell Data:

Solar Cell Manufacturer	MicroLink Devices (MLD), Niles Illinois, USA
Solar Cell Type	Triple-Junction Gallium Arsenide
Solar Cell Efficiency	~30% at AM0 prior to lamination
Solar Cell Dimension	66mm x 31mm x <40µm
Solar Cell Maximum Power Point	823mW @ 2.64V, 311mA
Solar Cell Test Parameters	Isc = 325mA, Voc = 3.0V

3. Cells Needed:

$$\frac{121W\ Target}{0.823W_{cell}} = \mathbf{148\ cells\ total}$$

4. Series String length:

$$\frac{24V\ Target}{2.64V_{mpp}} = \mathbf{9\ cells\ in\ series, 16\ columns\ needed}$$

5. Array Statistics:

9S16P Array (no partial strings), 148 cells, 3,028cm^2, ~30U

Isc = 5.2A, Voc = 27.0V, Impp = 4.976A, Vmpp = 23.76, **MP = 118W**

Solar Array Design – Margin Loss

Equipment	Operational Power [W]	Nominal Operating Voltage [V]
Core Bus EPS	0.5	5
Radio - Transmit	20	12
Radio - Receive	1	5
ADCS - Slewing	30	12
ADCS - Station Keeping	8	12
Primary Computer	25	5
Payload Imager	7	12
GPS	1.5	5
Bus Heater	5	12

Constant Operations EPS Margin	
Generation Req [W]	121
Solar Area Estimate [Sq U]	**29**
18650 Cell Count Est [Cells]	**10**

EPS Battery Pack Statistics:
5S2P, 10 cells, 500g
Vmin = 12.5V, Vmax = 21V
Nominal Storage = 7Ah, 100Wh, **Peak Discharge = 20A**

EPS Solar Array Statistics:
9S16P Array (no partial strings), 148 cells, 3,028cm^2, ~30U
Isc = 5.2A, Voc = 27.0V, Impp = 4.976A, Vmpp = 23.76, **MP = 118W**

We don't have 30U of solar panel area available, and even then we will only get 118W… We need to cut down to 28U:

9S15P Array (no partial strings), 135 cells, 2,762cm^2, ~28U
MP = 111W

Our minimum generation to stay in equilibrium is 101W, so 111W will give 9% margin vs. the original target of 20%.

Which is more important? Fitting the solar cells, or maintaining generation margin?

ShipSat EPS Design

Battery design for ShipSat yielded a 5S2P 18V 100Wh pack that will fit in 2U and meet design margins

Solar Array design yielded a deployable array of four 2Ux3U petals with a 2Ux2U core hosting 111W of generation across 135 9S15P 30% cells.

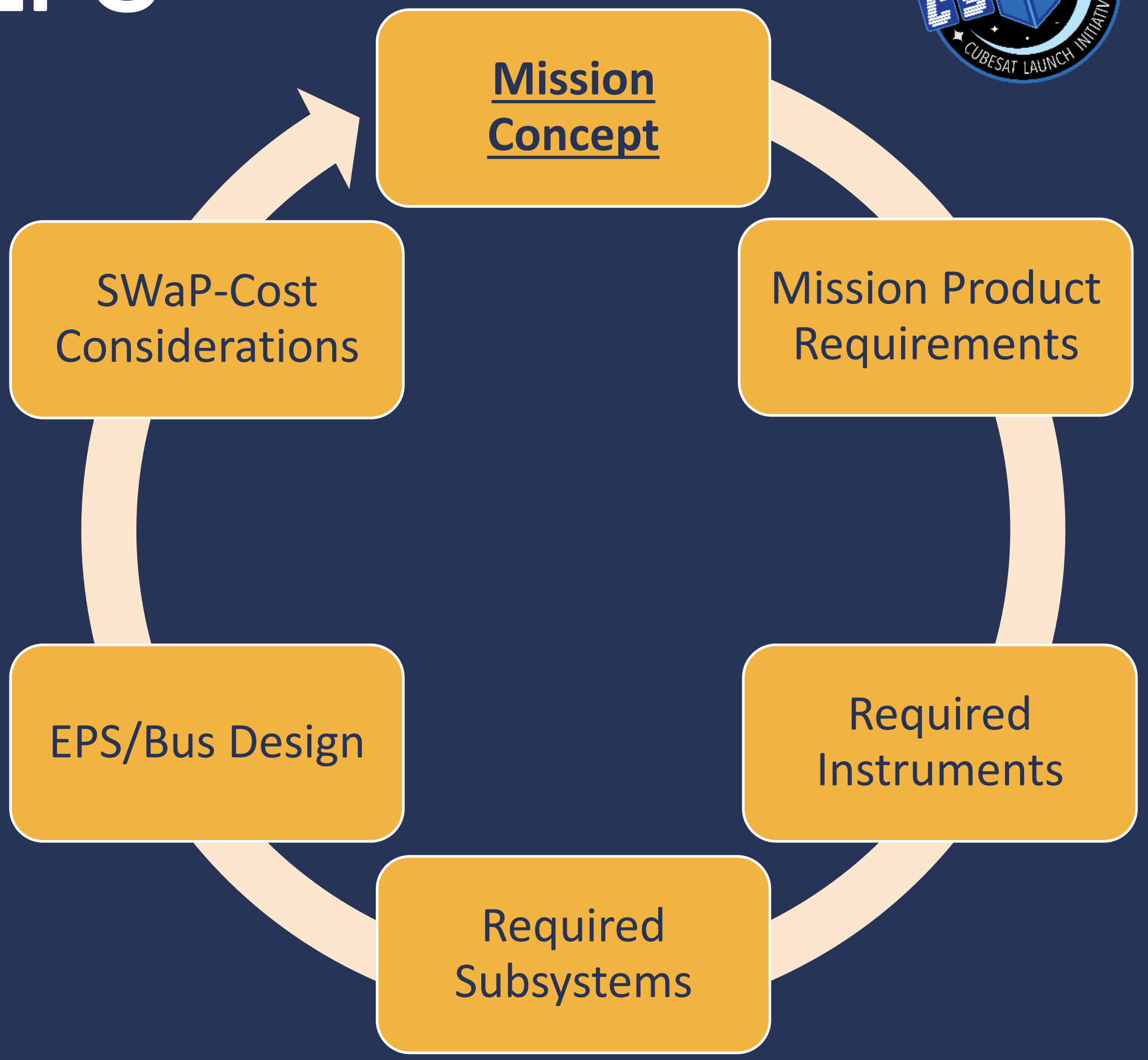
Solar design can meet the minimum needs for a positive power budget, but cannot meet mission design power margin without increasing the available solar panel area

The Phases of EPS Design

Do you reduce margin, increase area, or reduce power use?

Do you find more efficient, more expensive cells?

Does the mission need to operate 24/7, or can it recharge over multiple orbits?



PDS Requirements Drafting

Let's pull in our equipment list and the EPS we created:

Equipment	Operational Power [W]	Nominal Operating Voltage [V]
Core Bus EPS	0.5	5
Radio - Transmit	20	12
Radio - Receive	1	5
ADCS - Slewing	30	12
ADCS - Station Keeping	8	12
Primary Computer	25	5
Payload Imager	7	12
GPS	1.5	5
Bus Heater	5	12

EPS Battery Pack:
5S2P, 10 cells
Vmin = 12.5V, Vmax = 21V
Nominal Storage = 7Ah, 100Wh, Peak Discharge = 20A

EPS Solar Array:
9S15P, likely with some strings divided between panels
Voc = 27V, Max Power = 111W

Nominal system power = 50W (orbit energy / time)
Maximum system power = 98W (all systems on)

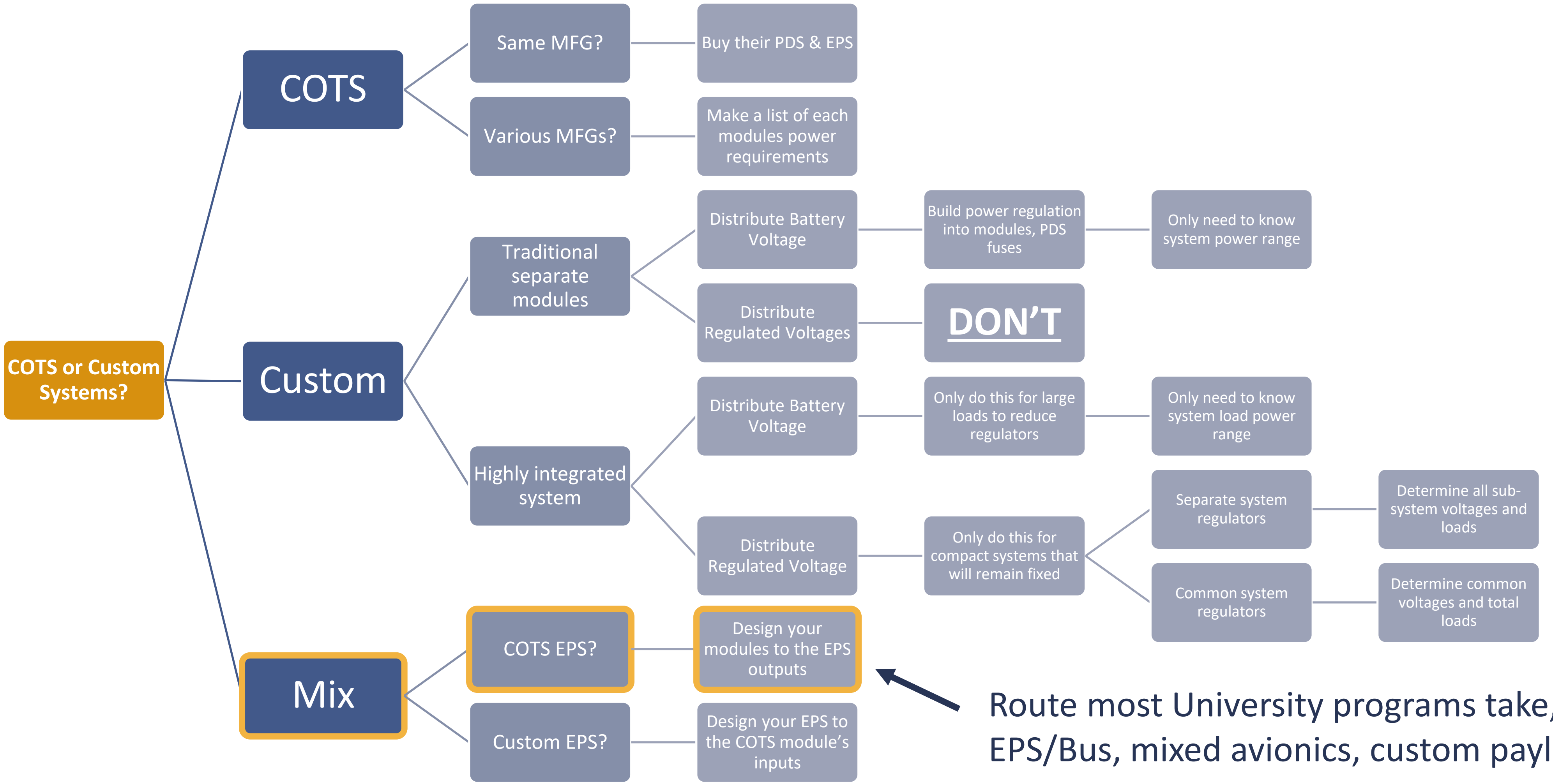
So, we need to specify an EPS that can handle all this so we can either build it, buy it, or augment it.

ShipSat PDS Starting Criteria

What are your resources for the PDS?

	PDS Criteria	Option 1	Option 2
Voltage Rails:	**5V0 @ 5A x4 12V @ 2.5A x4**	5V0 @ 5A x4 12V @ 2.5A x4	3V0 @ 3A x4 5V0 @ 5A x4 12V @ 2.5A x4 Vbatt @ 10A x4
Battery Pack Voltage:	**5S2P Li-Ion (~18V)**	Constant-voltage charging using MPPT step-down converter, 1S-6S range.	Cell-balancing charger with SoC estimator for 2S-8S.
Solar Capacity:	**111W 9S15P, MPPT needed**	Single solar array hookup point, 50V 150W maximum.	16 parallel-combined MPPT circuits each handling a 40V 20W string
Rail/Regulator Protections	**All rails need active monitoring and protection**	Over-current/Over-temperature on all rails set to maximum allowable current and voltage	Configurable over-current/over-temperature/voltage excursion on rails
Rail Switching	**All rails need independent switching, with PWM control for heaters**	No independent rail switching capability, all 5V and 12V rails are grouped together	All outputs can be switched with PWM capability
Inhibits	**Series rail-inhibit switches required between batteries and bus**	Place in series with battery pack, 100W @ 18V will require large switches but doable	Integrated electronic inhibits w/rail switch input

PDS Planning Paths



Route most University programs take, COTS EPS/Bus, mixed avionics, custom payloads

NASA Small Spacecraft Systems Virtual Institute (S3VI)

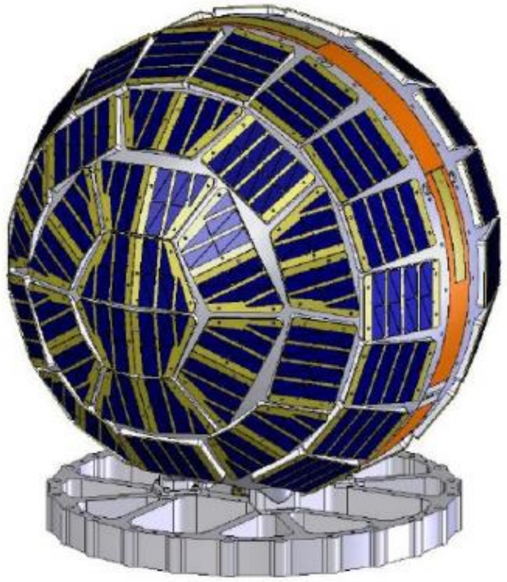
What is an EPS?

- Electrical Theory to Know
- Power Generation
- Power Storage
- Spacecraft Inhibiting
- Power Distribution System

So You Want to Design A Mission

- Developing A Power Budget
- EPS & PDS Design
- System Validation & Testing ←

DANDE Example – Mission Design Course



AFRL Images

DANDE Mission Example from UNP Mission Design Course

- 43kg Nano-Sat for Thermosphere wind and density variability study
- Sphere covered in solar panels deployed from ring, no ADCS

Assume DANDE is covered in 120-watts worth of solar panels, which satisfies the power budget and keeps the mission power positive with 40% margin.

Thoughts?

This mission won't be power positive as designed, as only 50% of the solar panels will have light exposure at any given time

ShipSat Mass Budget, What's Wrong?

Component Identification	Mass	Contingency	Total mass
Power System	100g	25%	125g
Radio	450g	25%	563g
ADCS	1100g	25%	1375g
CDH	250g	25%	313 g
Heater(s)	50g	25%	63g
Payload Imager	1600g	25%	2000g
GPS	250g	25%	313g
Solar Arrays	300g	25%	375g
Structure	10kg	25%	12500g
		Total Mass	17627g

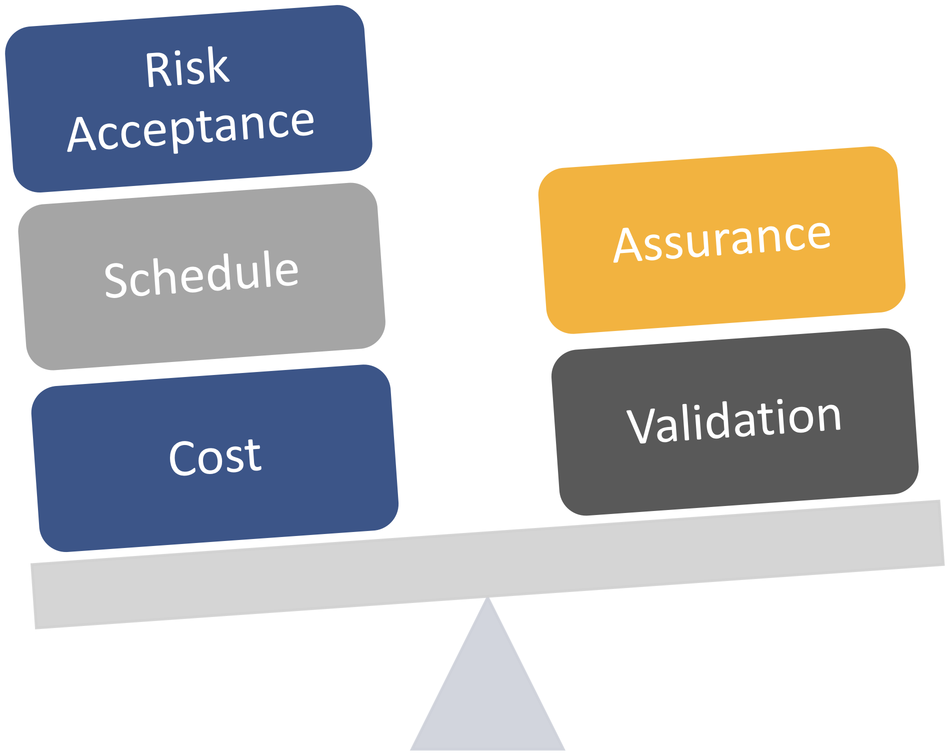
NO BATTERIES INCLUDED!

Validation and Test

Validation and Testing is critical for all systems and all missions, but testing your EPS is especially critical

EPS are notorious for having odd edge-case behaviors, and as the backbone of the whole system can easily cause difficult to source problems

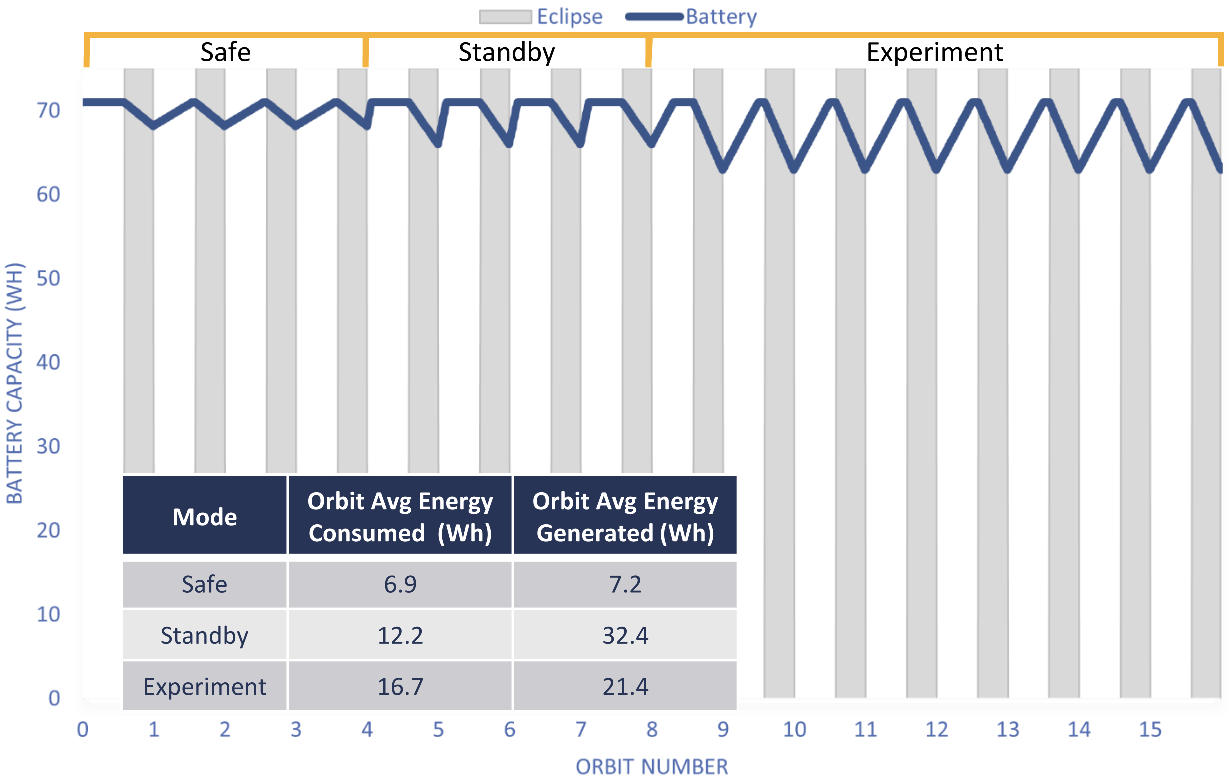
Testing is always a balance of thoroughness and project constraints. We want to test every possible variable, but usually don't have the time or budget to do so.



UNP ShipSat CONOPS Modeling

- Assumed realistic mode sequence (mission dependent)
  - 4 orbits safe
  - 4 orbits standby
  - 8 orbits experiment
- Results
  - Power positive across all modes
  - Initial design closes, future work should critically evaluate assumptions

Battery Capacity in One Day



Mode	Orbit Avg Energy Consumed (Wh)	Orbit Avg Energy Generated (Wh)
Safe	6.9	7.2
Standby	12.2	32.4
Experiment	16.7	21.4

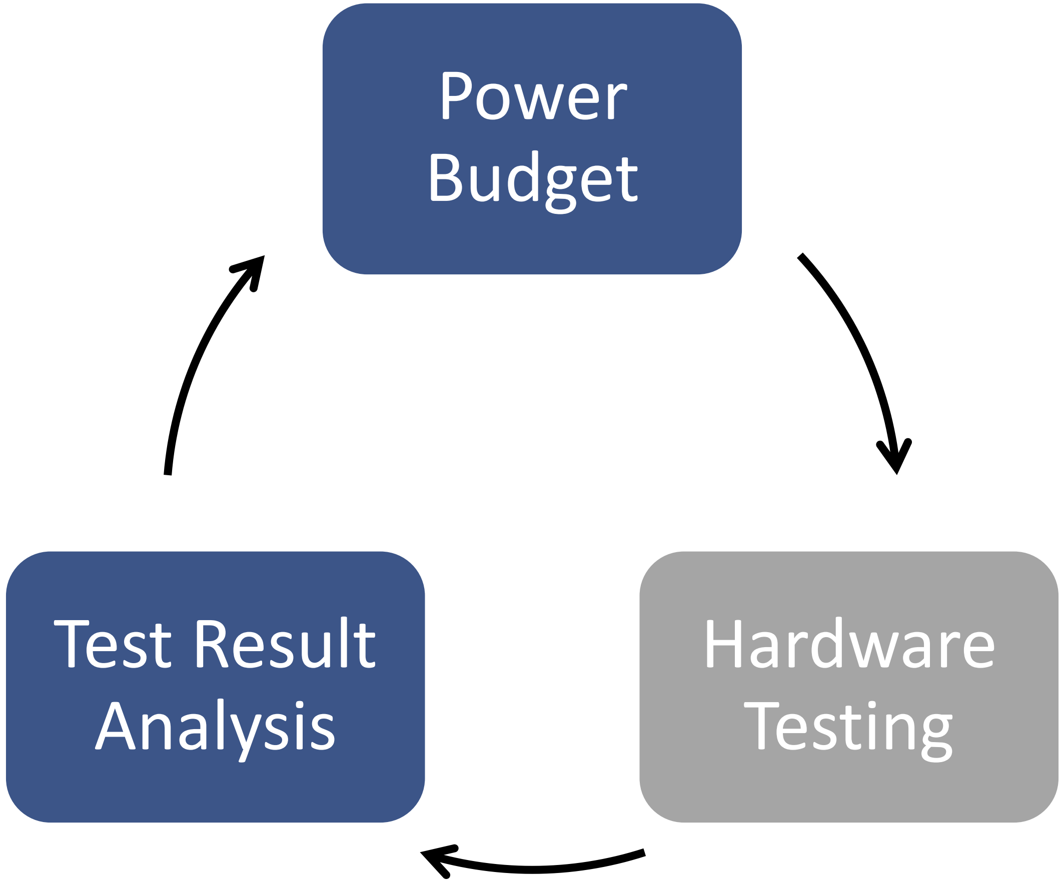
How can we refine and add more fidelity?

AFRL UNP – Public Release

Hardware-In-The-Loop Testing

- Datasheet values and cutsheet estimates will only get you so far
- Measuring the actual flight-hardware in a flight-like configuration is the best way to accurately finalize a power budget
- Powered Thermal-Vacuum testing is the best and usually only way to truly evaluate how hardware will perform on orbit

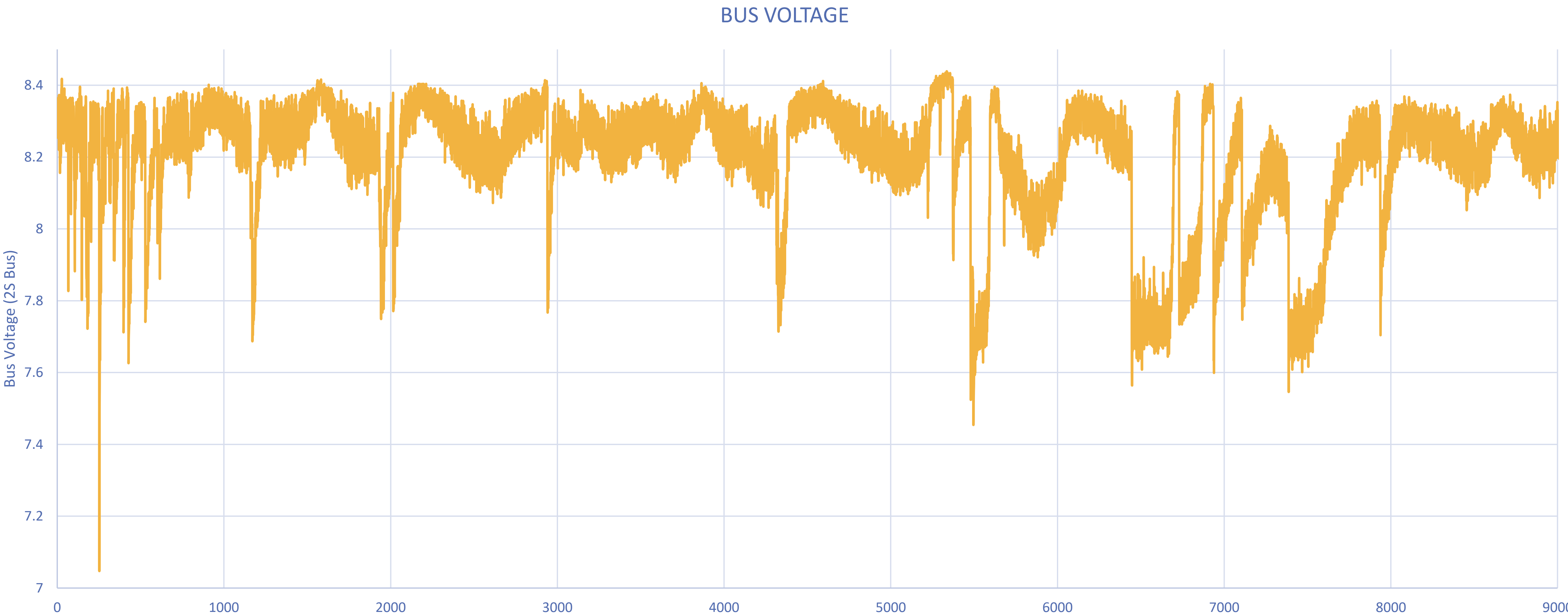
Design margin helps cover unexpected power, but testing and especially TVAC testing will let you know if your margin is enough



Critical Testing Questions

Solar Array Testing	• If we take this spacecraft outdoors for testing, are we going to be net power positive? • If something damages individual cells, or a panel doesn't deploy, what is the impact?
Battery Testing	• If the launch is delayed and the spacecraft sits in a dispenser for three months, will the mission still be successful? • If one cell fails, what is the impact to the pack?
Regulation Load Testing	• What happens if the whole spacecraft boots at its coldest temperature and lowest SoC? • What happens as the spacecraft warms and SoC increases? • What happens if an active subsystem is accidentally shut off during operations?
Inhibit Testing	• If the inhibits vibrate, how will the spacecraft respond? • If one of the inhibits has a latent failure, what will happen?

Example Mission Data Plot – TES13



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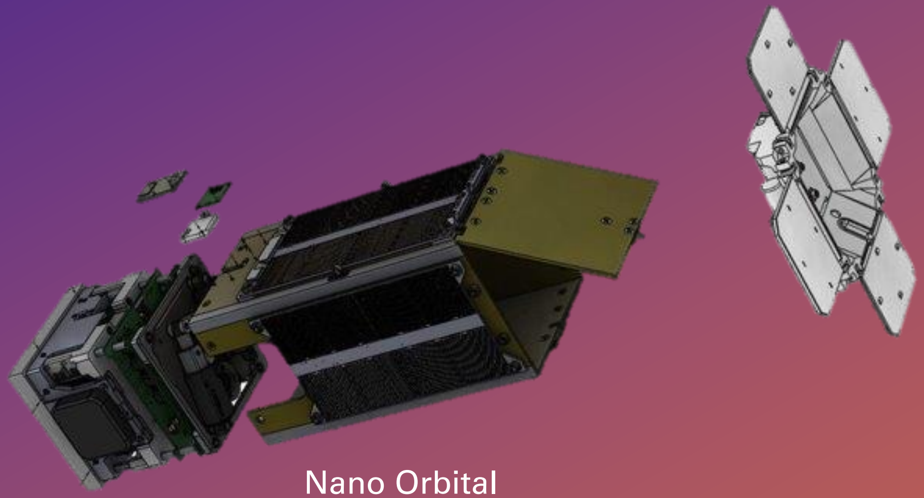
So, after 90 slides, where do you start?

1. Develop a list of the **critical** sub-systems you will need to achieve your mission goals
2. Lookup load **estimates** from either actual hardware datasheets or publicly available PDRs (the NASA CubeSat 101 Handbook and the NASA State-of-the-Art Small Spacecraft Technology Report are great resources)
3. Develop a load table, then develop a **rough** power budget with only your **key** equipment
4. Estimate the solar area needed and battery pack needed, and compare to your available resources
5. **Ask yourself if the mission now needs to be driven by loads, or driven by EPS restrictions**
6. Revisit your mission goals and concept of operations
7. Iterate through another power budget
8. Repeat

Just having realistic design that feasibly closes is a major accomplishment

Nano Satellite Electrical Power Systems

HOW TO DESIGN, PLAN, AND IMPLEMENT AN EPS



Nano Orbital WorkshopTES-7

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