Power System Components and Design

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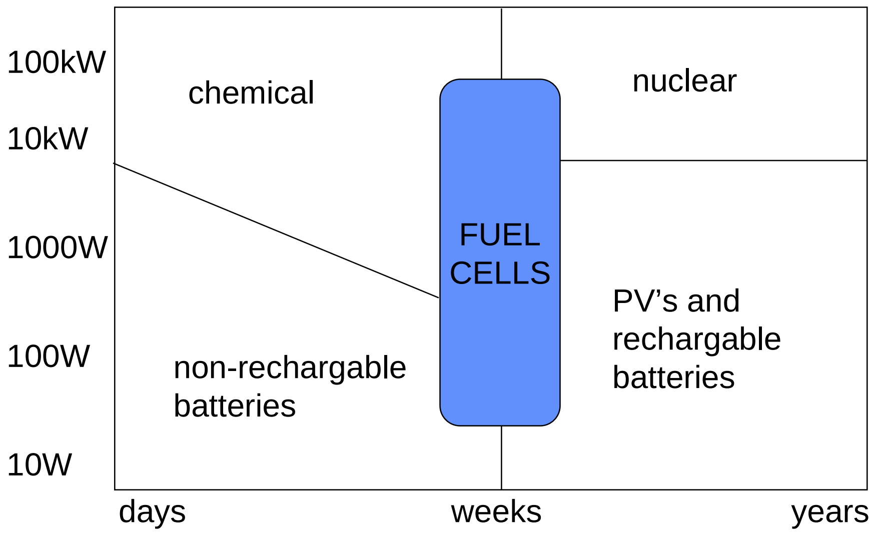
AA420 Space Design

Outline

- Power Generation
- Solar Cells
  - types
  - characteristics
- Batteries
  - types
  - characteristics
- Power system distribution and control
- Power system design approach

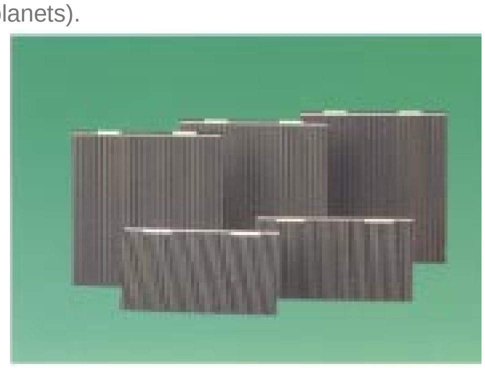
- References:
  - Larson and Wertz
  - Prof. Mattick

Power Generation



Solar Cells

- Solar cells convert solar radiation into useable electrical energy.
- Works well for LEO and GEO
- Does not work well for missions away from the sun because the energy degrades as $1/(\text{distance})^2$
  - (such as to the outer planets).



Solar Cell Issues

- Type of solar cells
  - Si (14% efficient)
  - GaAs (18-24% efficient)
  - higher efficiency cells currently being developed
- Eclipse periods
- Characteristics as a function of
  - temp
  - voltage/current/size
  - lifetime
- Integration
  - cover glass
  - epoxy
  - diodes
  - stringing cells to generate a bus voltage

Eclipse Periods

- Solar energy is can only be utilized while the cells are illuminated.
- The number and length of the eclipse period is a function of the orbital elements (such altitude)
  - see back cover of Larson and Wertz for worst case eclipse period for typical orbits

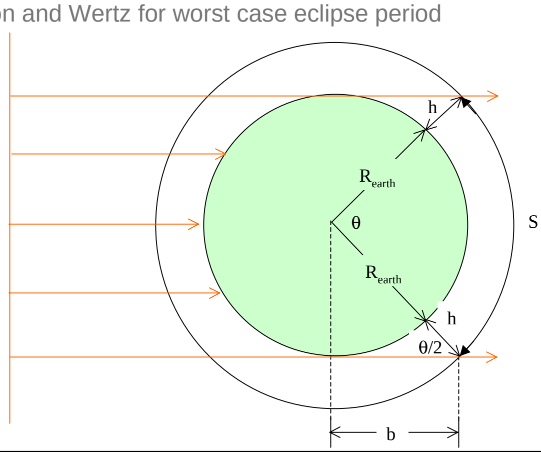
$$\theta = 2 * \sin^{-1}\left(\frac{R_{earth}}{R_{earth}+h}\right)$$

$$S = (R_{earth}+h) * \theta$$

$$V_{CS} = \sqrt{\frac{\mu}{R_{CS}}} = \sqrt{\frac{\mu}{R_{earth}+h}}$$

$$t_{total} = \frac{2\pi(R_{earth}+h)}{V_{CS}} \qquad t_{eclipse} = \frac{S}{V_{CS}}$$

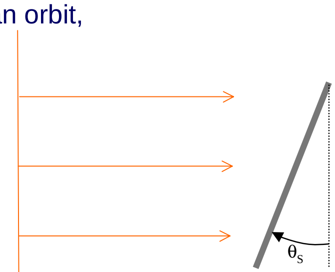
$$t_{light} = t_{total} - t_{eclipse}$$



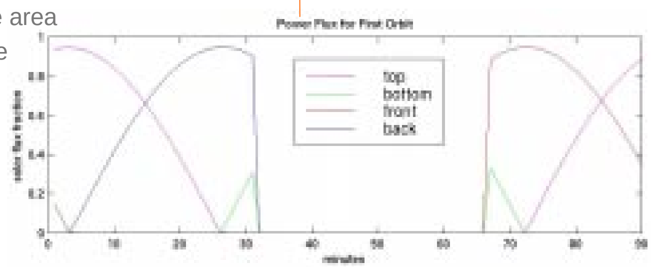
Sun Angle

- The sun angle must be used to find the power generation
- Unfortunately it always changes over an orbit, unless the satellite is sun pointing
- The sun angle is just the power for the projected area

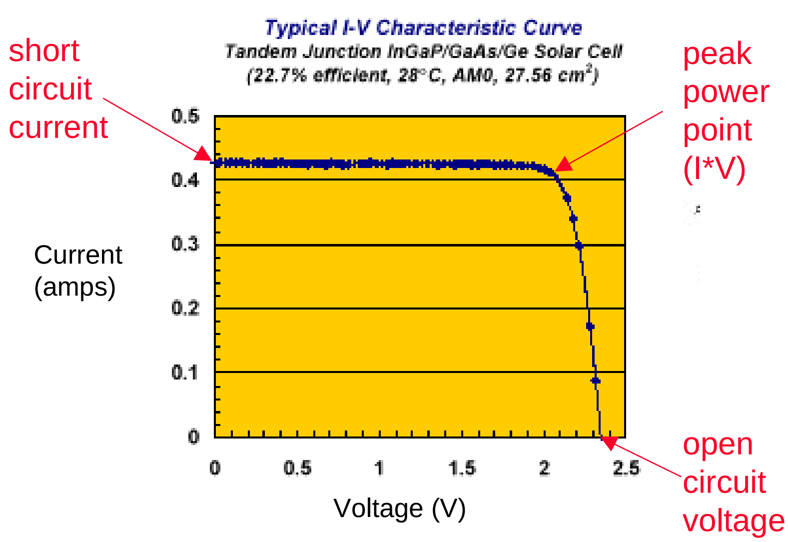
$$P_{SAT} = P_{AREA} \sin(\theta_S)$$



- Approaches:
  - Approximate area
  - Find average using STK or FreeFlyer



Solar Cells Characteristics



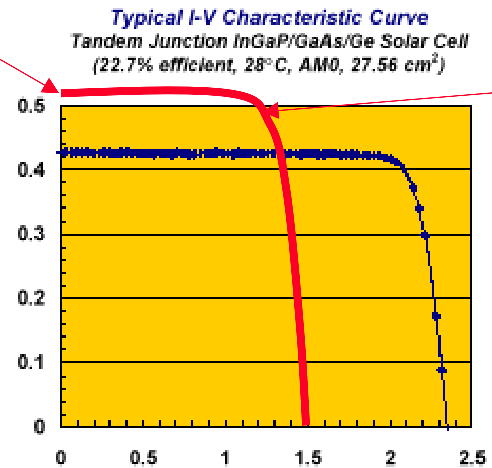
- When the cell is NOT illuminated, it acts as an open circuit (high resistance)

Solar Cells as a Function of Temperature

hotter than normal

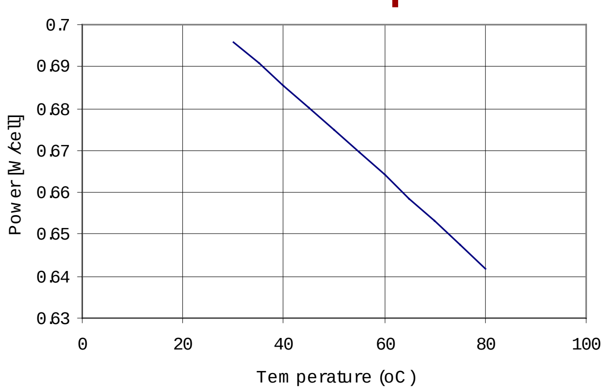
peak power point is smaller

Current (amps)



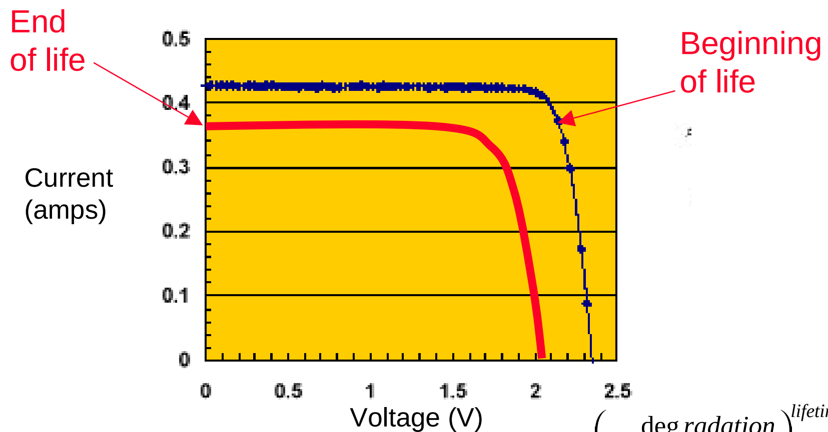
Voltage (V)

Solar Cells as a Function of Temperature



- Solar cells like to be cold!
- Environmental temperatures can vary from -80 deg C to 100 deg C in LEO
- cell efficiency is greatest just after eclipse

Solar Cells as a Function of Lifetime



- Typical degradation over time:
  - Si: 3.75%/year
  - GaAs: 2.75%/year

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

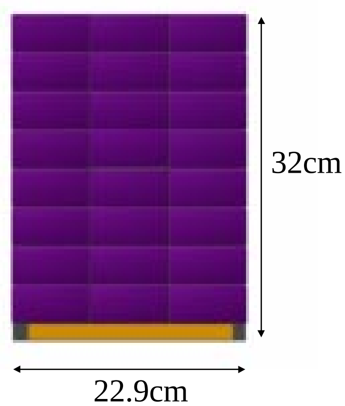
$$P_{EOL} = P_{BOL} * L_d$$

from radiation, thermal cycling, plume impingement, out-gassing

- Usually design based on End of Life

Solar Cell Integration

- Solar Cell configuration
  - 24 cells on six sides and top.
  - No cells on the bottom.
  - 12 cells/string.
  - If operating at maximum efficiency, the average power is 39W during illumination.
- Specifications:
  - Size: 76X32mm
  - Efficiency: 23%
  - Peak values at 28ºC:
    - Imp = 0.407 A/cm2
    - Vmp = 2.06 V/cm2
    - Max Power = 0.82 W

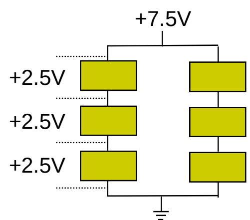


Solar Cell Integration

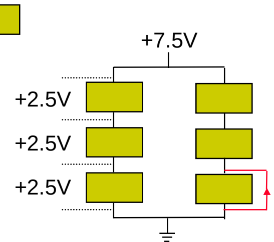
- A cover glass is usually used to help with degradation over time.
  - It creates an hermetic seal that allows sunlight through and allows heat rejection
- Usually very strong epoxies are used
- Cell stringing:

$$V_{BUS} = nV_{cell}$$

$$I_{BUS} = \sum_{n} I_{cell}$$



- Shadowing: if one cell is not illuminated, the entire string is out because the cell creates and open circuit
  - caused by appendages
- Solution: bypass diodes



Batteries

- Batteries convert chemical energy to electrical energy
- Batteries come in several forms:
  - non-rechargable, sometimes called primary
  - rechargable, sometimes called secondary
- Works well for LEO and GEO
- Does not work well for longer missions because of lifetime

Rechargable Battery Issues

- Type of batteries
  - NiCd
  - NiMH
  - NiH
  - Li
  - Li polymer and other batteries currently being developed
- Important characteristics
  - energy storage
  - DOD
  - lifetime
  - charging and discharging
  - memory
- Integration
  - safety (boxes)
  - sizing correctly for mission and lifetime
  - stringing batteries to generate a bus voltage

Batteries

- NiCd batteries
  - most common, a lot of flight heritage, rapid charge rate
  - memory effects, low cell voltage, lower energy density
- NiMH
  - higher energy density, non memory effects
  - little flight heritage, low cell voltage, heat problems requiring complex charge
- Li
  - high energy density, no memory effects, high cell voltage, good thermal
  - slow charge rate, no flight heritage, susceptible to overcharge

	NiCd	NiMH	Li-Ion	Li-Polymer
Energy Density (W-Hr/Kg)	40-60	60-80	100	140
Cell Voltage (V)	1.2	1.25	3.6	3
Temperature Range (^{o}C)	-10 to +50	-10 to +50	-20 to +60	-30 to +55
Rapid charge times (Hrs)	½ to 1	2 to 3	3 to 6	8 to 15
Discharge curve	Sloped,falls off @ 60-80%	Sloped,falls off @ 60-80%	Relatively flat 20 - 80%	Relatively flat 20 - 80%
Memory effect	Yes	No	No	No

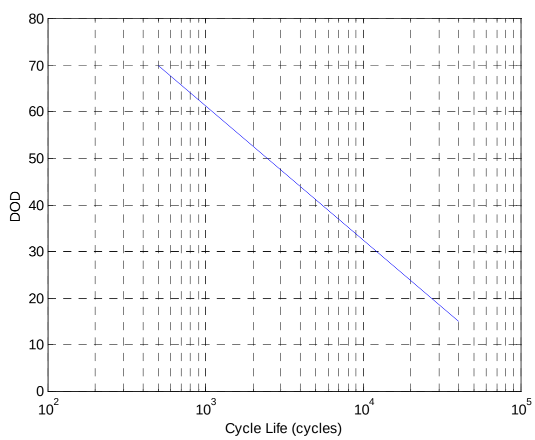
Energy Storage and Memory

- Energy storage is usually in Watt-hours, or
  - Power * Time
- An analysis of the loads and duty cycle will help to size the battery - later
- Some batteries have memory effects:
  - if they are charged to only 25% continually, at some point that is all that they will discharge to
- Solution: discharge fully every few months

Depth of Discharge and Lifetime

- The lifetime of rechargeable batteries is very dependent the Depth of Discharge (DOD) and Number of Cycles
- Example:

  NiCd

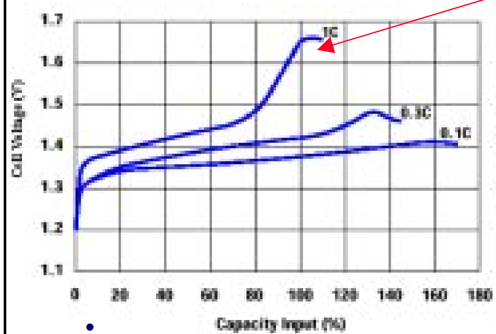


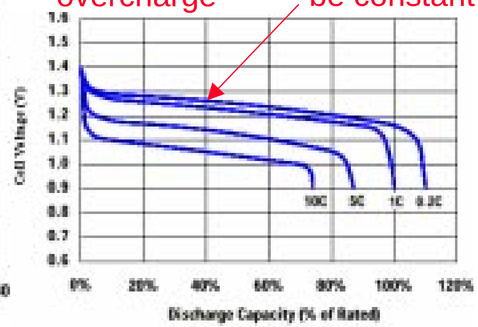
Charge/Discharge rate

- The discharge curve is fairly consistent through most of its discharge cycle and can be recharged at 0.5 C to virtually full capacity within the time allowed
- Typical NiCd curves @ 23º C:

want little overcharge

want to be constant





charging

discharging

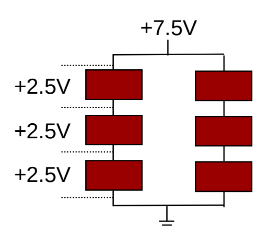
- Want discharge voltage to be as constant as possible for loads
- 1C - charge in one hour, 0.1C - charge in 1/10th of an hour

Battery Integration

- Most batteries are pressure vessels with corrosive materials
  - a big hazard for shuttle missions
- Usually have to use a special battery box to prevent leakage
- Battery stringing:

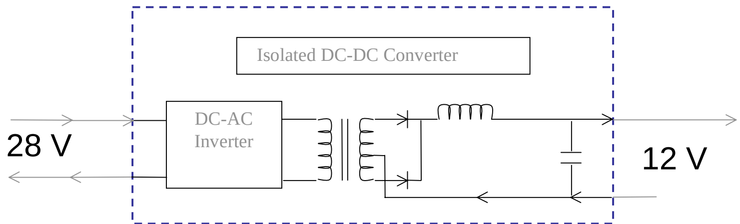
$$V_{BUS} = nV_{battery}$$

$$I_{BUS} = \sum_n I_{battery}$$



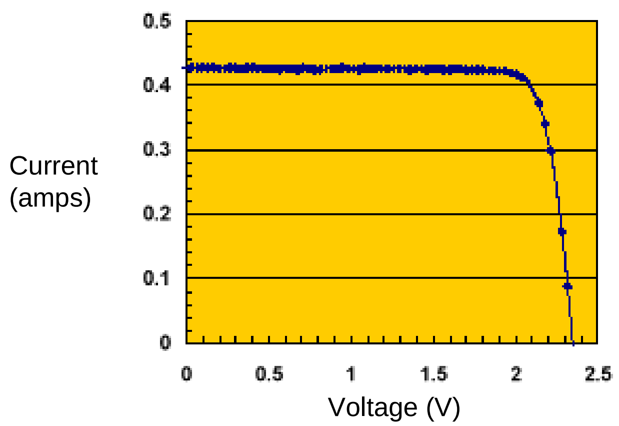
- Sizing of the batteries is a function of
  - lifetime (number of cycles, orbit)
  - depth of discharge
  - power (peak and average) required during eclipse and in the sun

Power Distribution System: DC to DC converters



- DC to DC converters are used to step voltages down
- They are usually 85-90% efficient
- Can use one to step down to all components are each voltage or can use individual DC to DC converters

Peak Power Tracker



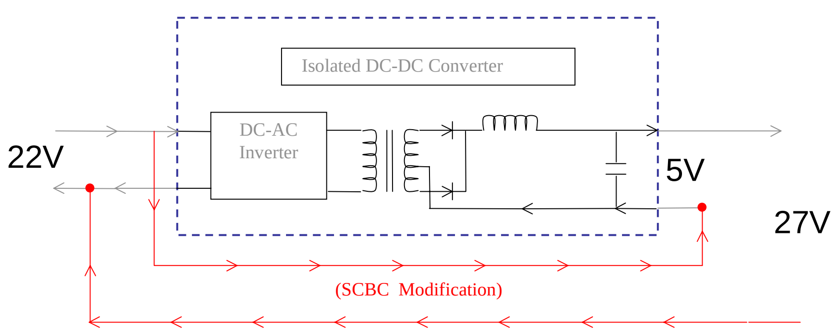
- He peak power tracker allows the system to get the maximum power from the solar cells
- It is a traditional feedback loop:
  - sensor: power (V*I) coming from the solar cells
  - actuator: battery charger, which can change the charging current

Shunted Power Distribution System

- Excess power may come when:
  - the batteries are fully charged and the loads are less than the power generated by the solar cells
  - the power generated by the solar cells is greater than the power required for battery charging and the loads
- Solution: run excess current through a shunt (resistor) to dissipate as heat.

Series Connected Boost Converter

- Series Connected Boost Converter (SCBC) is an alternative to a shunted system
  - Based on a standard isolated step-down DC-DC converter
- Instead of dissipating energy, it is pumped back in
- Efficiency is then only a function of the DC-DC converter



Power System Design Approach

1. List all of the design drivers
2. Develop a table of the design loads (sensors, actuators)
3. List the duty cycle for each mode of operation, including eclipse and sun operation
4. Find average and peak power requirements
5. Using the orbital information, simulate the facing area power flux (or approximate at first)
6. Find the average power generated in the sun and per orbit
7. Size the batteries based on required power during eclipse, DOD, lifetime, and number of cycles
8. Select a power distribution approach based on complexity, mass, cost, and power requirements
9. Calculate the power generated for system loads based on efficiencies
10. If 4 and 9 do not match, then iterate with systems engineers

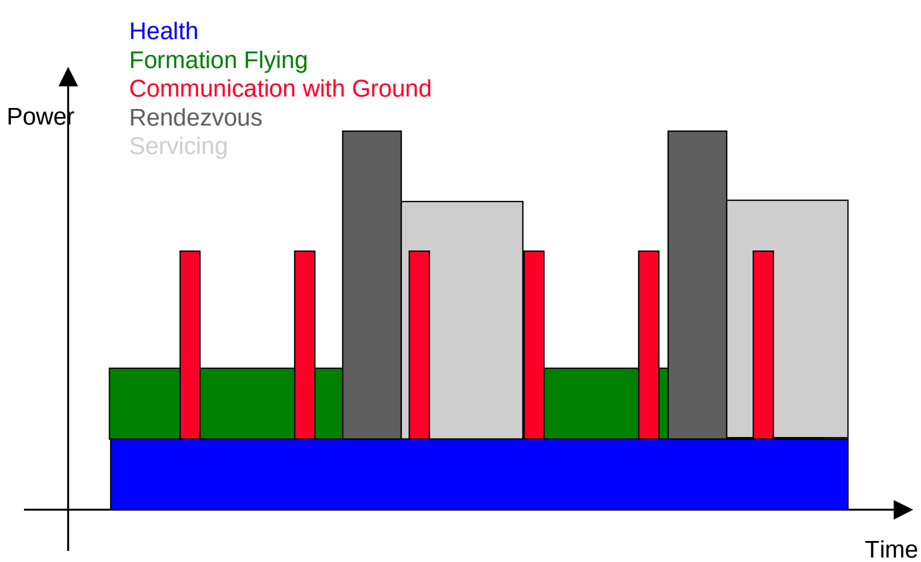
Power System Drivers

- Mass
  - batteries
  - cells
  - electronics
- peak power
- average power (for different modes of operation)
- lifetime
- number of cycles
- time of eclipse, time in sunlight
- Power required from the loads
  - sensors
  - actuators
  - duty cycle

System Loads for Dawgstar

Subsystem	Component	Power rating (mW)	Voltage (V)	Battery Load (mA)	Duty-cycle (Hrs / day)
C&DH	Microcontroller board	3.3	12	0.17	24
	Communication board	3.3	12	0.17	24
	Memory	2.0	12	0.10	24
	I/O Board	0.01	12	0.00	24
	Contingency	1.0	12	0.05	24
ADCS	ADCS Tempsensors (4)	1	5	0.05	24
	Horizon Sensor (2)	60	5	3.10	24
	Micro-gyro (1)	30	5	1.55	24
	Magnetometer	30	5	1.55	24
Propulsion	2 micro PPT	12500	28	548.25	24
	Micro PPT propellant sensors (0.25x8)	2	28	0.09	24
	Capacitor voltage sensor (0.25x4)	1	28	0.04	24
	Discharge Initiator sensor (0.25x8)	2	28	0.09	24
GN&C	GPS	2000	5	103.20	24
	Downlink Transmitter	3000	12	154.80	0.44
	Downlink Standby	200	12	10.32	23.56
	Receiver	700	12	36.12	24
	Xlink	1800	12	92.88	24
Science Payload	PIP	1500	5	77.40	24
Thermal Control	TBD				
	Average total current load on battery (mA-Hr)			1029.92	

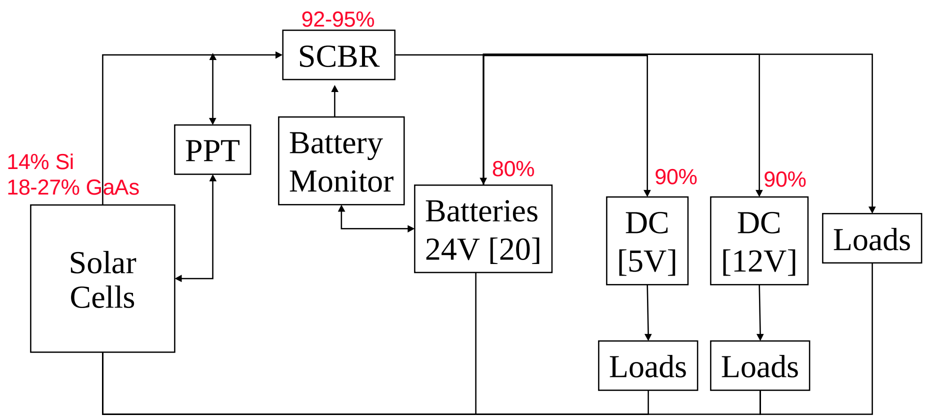
Duty Cycle and Modes of Operation



Power: Requirements

Number	Heading	Value	Unknown	Met	Not Met
6.1.01	Mass	1.5 Kg		A,S	
6.4.01	Power Supply Voltage	5,12,28V		S	
6.6.01	Orbit Average Power Generation	19.5 W			X
6.6.02	Maximum Peak Power Generation	27 W		S	

Power: Functional Diagram



- Example of the typical efficiencies for a power distribution system

Calculation of Power Generation

Solar Flux [W/m^2]
1353

Solar Cell Definition

Cell Efficiency	Cell Size [m]	
0.23	0.076	0.032

Solar Cell Layout	Top	Bottom	Side1	Side2	Side3	Side4	Side5	Side6
#of Cells	22	0	22	22	22	22	22	22
Area [m^2]	0.054	0.000	0.054	0.054	0.054	0.054	0.054	0.054

Face	Average % Flux		Average power over orbit [W]		Average power in sunlight [W]
Top	0.31		5.16		8.60
Bottom	0.02		0.00		0.00
Front	0.2		3.33		5.55
Back	0.21		3.50		5.83
Front-right	0.19		3.16		5.27
Front-left	0.32		5.33		8.88
Back-right	0.04		0.67		1.11
Back-left	0.18		3.00		4.99
Total			24.14		40.24

% Flux can be an approximation or calculated from STK/FreeFlyer/MATLAB

Those numbers to change are given in red

Useable Power		24.14		40.24
Power Dist Efficiency	90%			
Battery Charge Efficiency	80%			
% Power on lowerV (DC-I	20%			
DC-DC Efficiency	90%			
		17.03		28.39

Average Power Over an Orbi	17.03
Average Power in Sunlight	28.39