Development of a High Specific Energy Flywheel Module, and Studies to Quantify Its Mission Applications and Benefits

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Topics

- How Flywheels Work
- Flywheel Applications for Space
  - Energy Storage
  - Integrated Power and Attitude Control
- Flywheel Module Design
  - What are the major components of a flywheel?
  - GRC Flywheel Performance Progress
  - G3 Performance Metrics
- Flywheel Mission Study
  - International Space Station
  - Lunar 14 day eclipse energy storage system

Flywheels: How the Technology Works

A flywheel is a chemical-free, mechanical battery that **uses an electric motor to store energy in** a rapidly spinning wheel - with 50 times the Storage capacity of a lead-acid battery

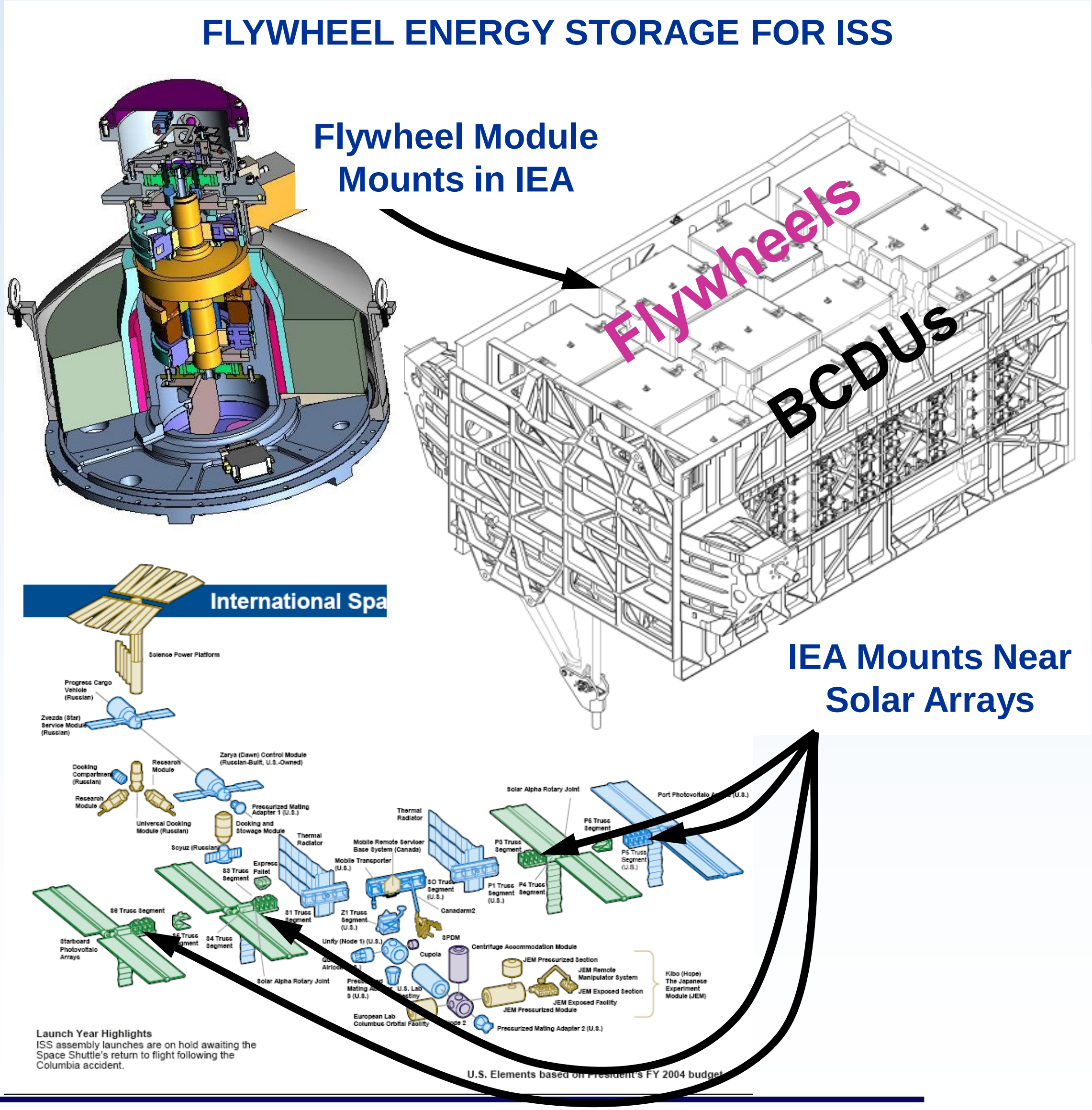
As the flywheel is discharged and spun down, the stored rotational energy is transferred back into electrical energy by the motor — now reversed to work as a generator. In this way, the flywheel **can store and** supply power where it is needed

Flywheel Applications For Space

Flywheels For Energy Storage

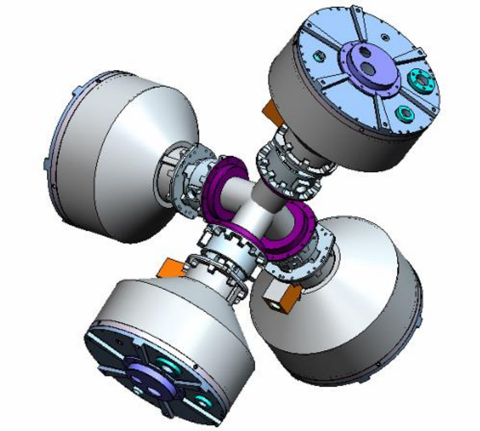
- Flywheels can store energy kinetically in a high speed rotor and charge and discharge using an electrical motor/generator.

- Benefits
  - Flywheels life exceeds 15 years and 90,000 cycles, making them ideal long duration LEO platforms like ISS or national assets like the Hubble telescope
  - Flywheels have flexible charge/discharge profiles, so solar arrays are more fully utilized
  - Flywheels can operate over extended temperature ranges, reducing thermal control requirements
  - Flywheel state of charge is precisely known



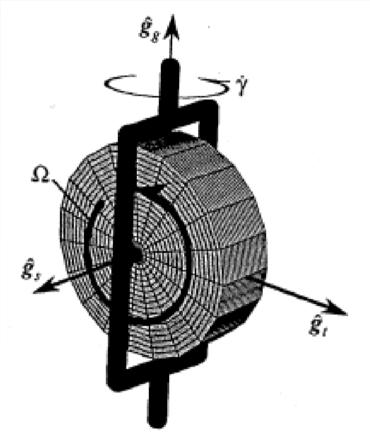
Integrated Power & Attitude Control System Options

- Body Mounted Reaction Wheel
  - Momentum vector of wheels are fixed w.r.t. spacecraft
  - Wheel speed is determined by simultaneously solving the bus regulation and torque equations.



Kascak, P.; Jansen, R.; Dever, T.; Kenny, B., "Demonstration of Attitude Control and Bus Regulation with Flywheels", Proceedings of the 39th IAS Annual Meeting; Seattle WA, Oct 2004.

- Variable Speed Control Moment Gyro.
  - Momentum vector of wheels are rotated w.r.t. spacecraft to produce torque
  - Wheel speeds are varied for bus regulation



Fausz, J.; Richie, D., "Flywheel Simultaneous Attitude Control and Energy Storage Using a VSCMG Configuration", 2000

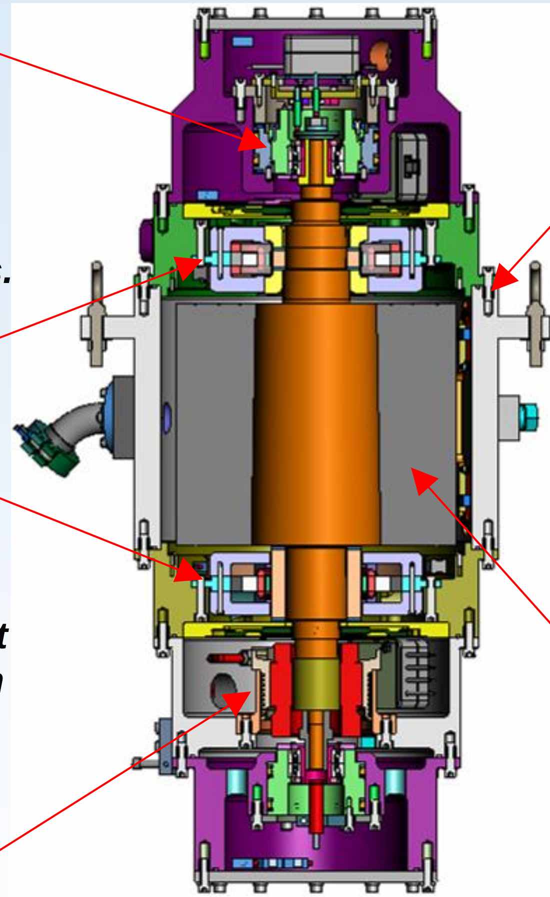
Richie, D; Tsiotras, P.; Fausz, J., "Simultaneous Attitude Control and Energy Storage using VSCMGs: Theory and Simulation", 2001.

Flywheel Module Design

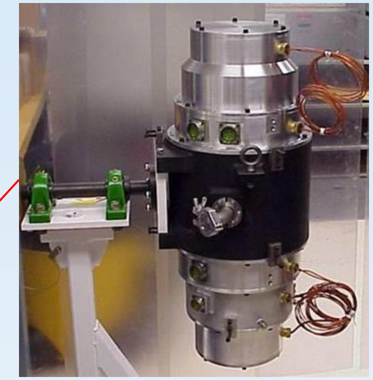
What are the major subcomponents of a flywheel?

Auxiliary Bearings – Capture rotor during launch and touchdowns.

Magnetic Bearings – Used to levitate rotor. These non-contact bearings provided low loss, high speeds, and long life.



Motor/Generator – Transfers energy to and from the rotor. High efficiency and specific energy is required.



Housing – A structure used to hold the stationary components together. Can also act as a vacuum chamber.

Composite Rotor – Stores energy. High energy density is achieved through the use of carbon composites.

System Metrics

The G3 Flywheel Module is the first module designed to meet the Near Term IPACS program metrics of the Aerospace Flywheel Technology Program

AFTP Near Term IPACS Metrics

Specific Energy – 25 Whr/kg

Specific Energy is at the system level. The system is defined to include the flywheel modules, power electronics, sensors and controllers.

Efficiency 85%

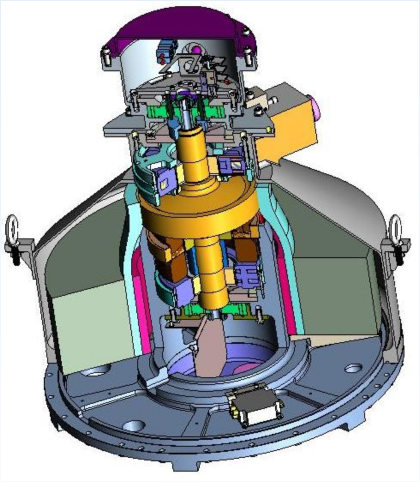
Efficiency is measured at the system level as the ratio of energy recovered in discharge to energy provided during charge.

15 Yr LEO Life

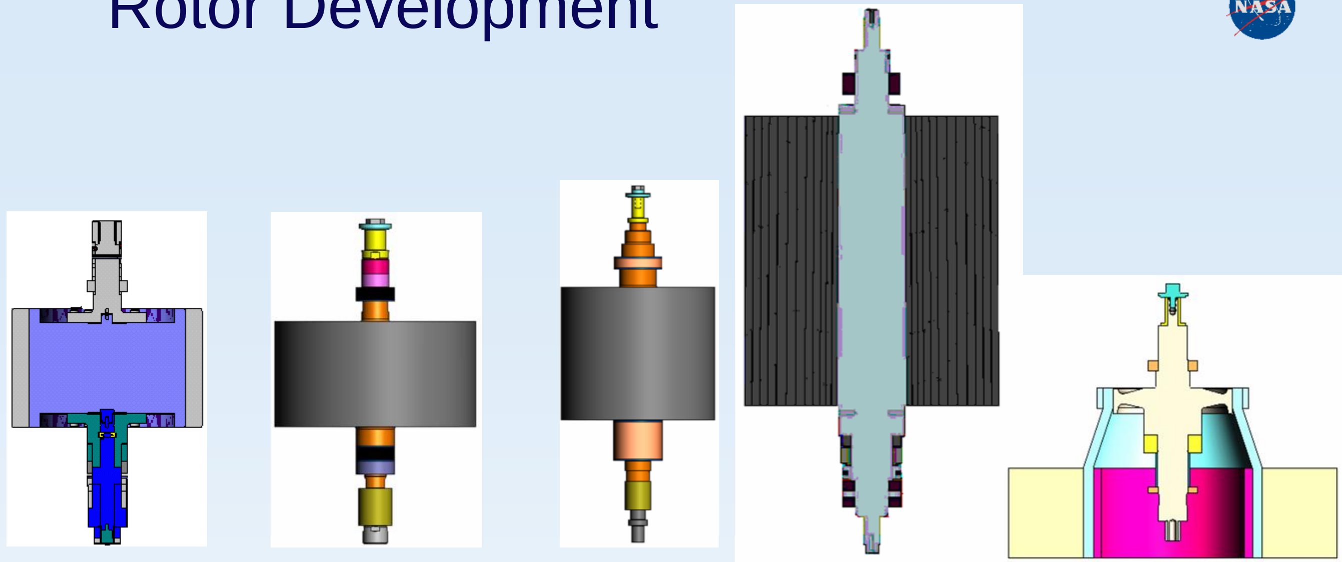
Fifteen year life is required in a Low Earth Orbit (LEO)

Temperature Range -45 to 45 °C

The ambient temperature range outside of the system is specified.

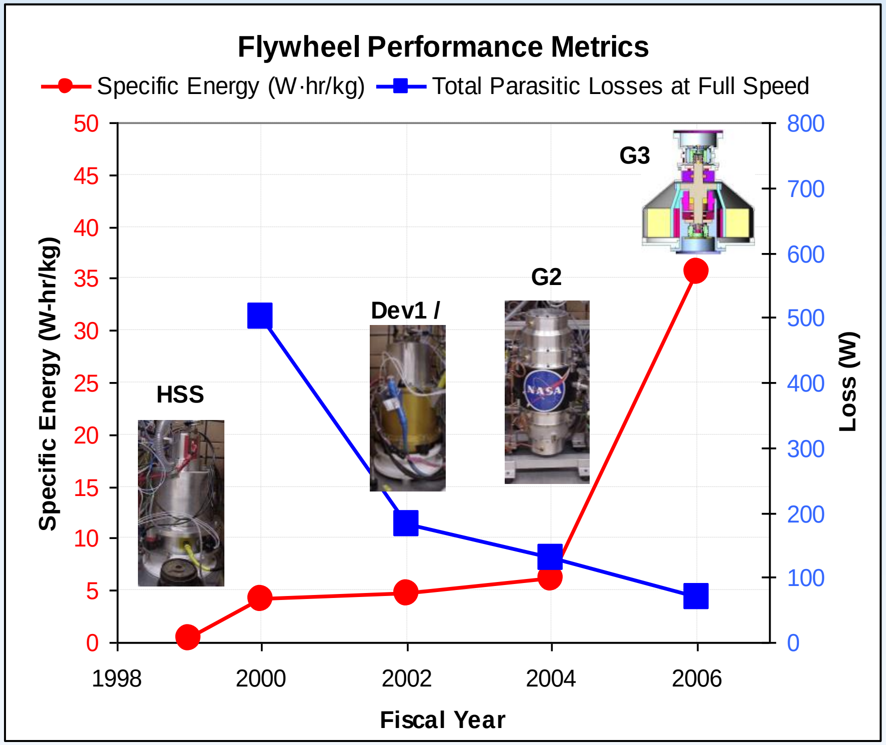


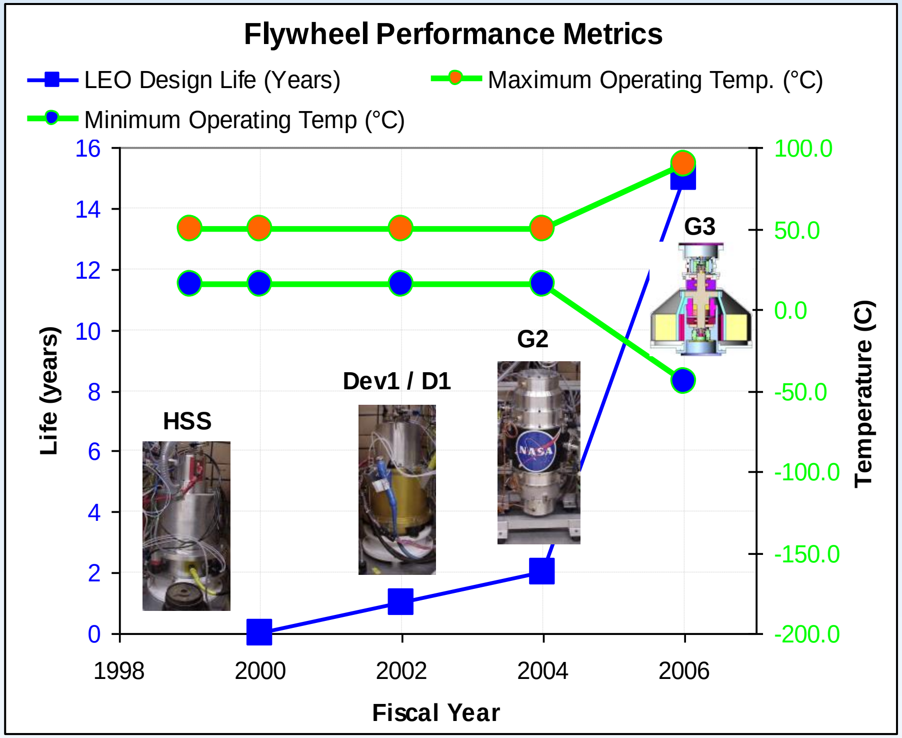
Rotor Development

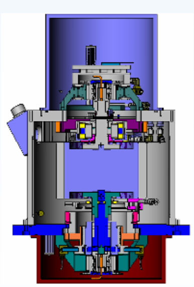


Flywheel	HSS	Dev1	D1	G2	FESS	G3
Features	Steel Hub	Single Layer Composite	Multilayer Composite 750m/s	Multilayer Composite 750m/s	Multilayer Composite 950m/s	Composite Arbor 1100m/s
Energy (W-Hr)	17	300	350	581	3000	2136
Specific Energy (W-Hr/kg)	1	23	20	26	40	**80**
Life	?	< 1 yr	1 yr	1 yr	**15** years	**15** years
Temperature)			+25 to +75	+25 to +75		**-45 to +90**

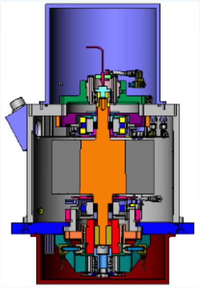
NASA Progress on Performance



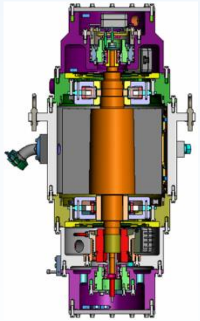




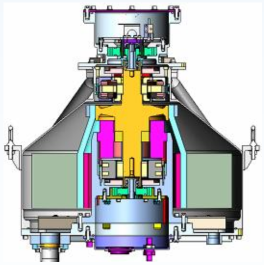
Dev 1 - 300 W-hr
4.1 W-hr/kg
Full Speed Once
USFS



D1 - 330 W-hr
4.7 W-hr/kg
Full Speed Many Times
GRC/TAMU/USFS



G2 - 581 W-hr
6.1 W-hr/kg
Modular, Low Cost
GRC/TAMU



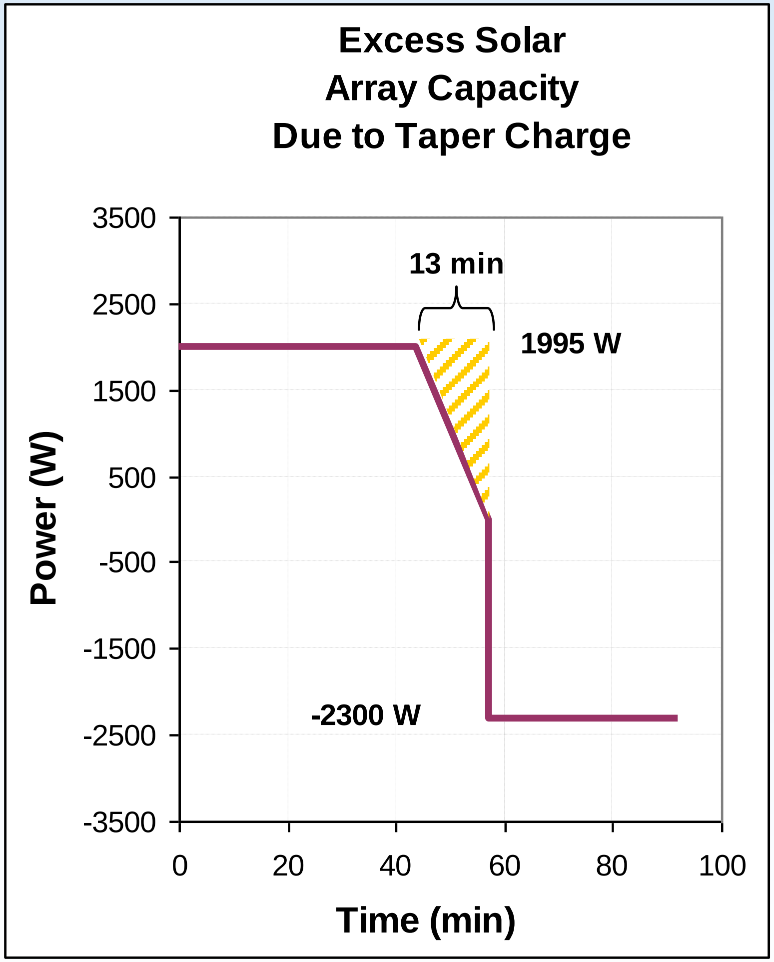
G3 - **2136** W-hr
35.5 W-hr/kg
High Energy, S.E., Life
GRC/TAMU/UT-CEM

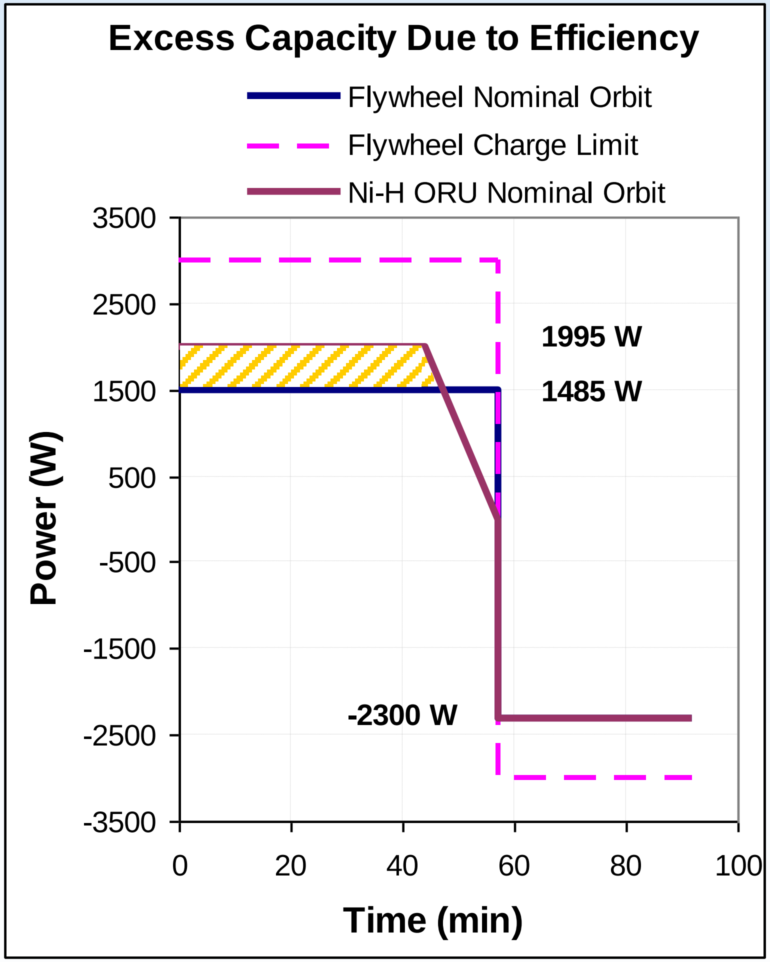
Flywheel Mission Study

Flywheel Mission Studies

- ISS
  - Efficiency and Charge Profile Effects
  - Mass Estimates
  - Proposed Configuration
  - Upmass Benefits
- Lunar 14 day eclipse energy storage system

Efficiency and Charge Profile Effects

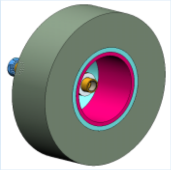




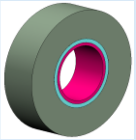
Flywheel Module Mass Estimates

- GRC has completed a detailed design of the G3 flywheel module which stores 2100 W-hr at 100% DOD and has a power rating of 3300W at 75% DOD.
- A sizing code has been designed which can be used to estimate the mass of a G3 type design as a function of energy stored and power.
- The five major components: rotor, motor, housing, and magnetic bearings are linearly scaled based on the requirements

G3 Rotor

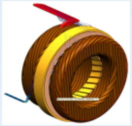


G3 ROTOR - CDR DESIGNED INFO		
Rotor Mass	27.3	kg
Rotor Inertia	0.560113	kg*m^2
Rim Mass	20.95	kg
Rim Inertia	0.540213	kg*m^2
Hub Mass	6.35	kg
Hub Inertia	0.0199	kg*m^2
Rim Length	0.1143	m
Rim Mass/Length	183.2896	kg/m
Rim Inertia/Length	4.726277	kg*m^2/m
Rim Mass/Inertia	38.78097	kg/kg*m^2



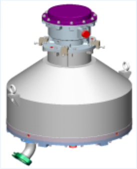
Rim Cross Section

G3 Motor



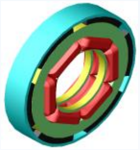
G3 MOTOR - CDR DESIGNED INFO		
Overall Mass	3.21	kg
Active Length	0.0185	m
Stator Active Mass	1.587	kg
Rotor Active Mass	1.15	kg
Mass/meter of Active Length	147.9	kg/m
Power @ 50,000 RPM	7600	W
Power/Active Length	410811	W/m
Mass in Non Active Area	0.473	kg
Active Mass / Power	0.000360	kg/W

G3 Stator



G3 STATOR - CDR DESIGNED INFO		
G3 Overall Mass	62.1	kg
Rotor Mass	27.3	kg
MB Stator Mass	4.897	kg
Stator Mass	29.903	kg
Stator Mass over Rim Length	2.43	kg
Rim Length	0.1143	m
Stator Mass not over Rim	27.473	kg
Stator Mass/Rim Length	21.25984	m

G3 Radial MB

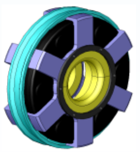


Radial Bearing

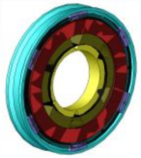
G3 RADIAL MB - CDR DESIGNED INFO		
Stator Mass	1.78	kg
Overall Length	0.035	m
Active Length	0.0147	m
Stator Active Mass	1.314	kg
Rotor Active Mass	0.53	kg
Mass/meter of Active Length	125.4	kg/m
Force Rating	285	N
Force / Active Length	19366	N/m
Mass in None Active Area	0.466	kg
Active Mass / Force	0.00648	kg/N

Active Length Cross Section

G3 Combo MB



G3 COMBO MB - CDR DESIGNED INFO		
Stator Mass	3.117	kg
Overall Length	0.049378	m
Active Length	0.014173	m
Stator Active Mass	1.746	kg
Rotor Active Mass	0.344	kg
Mass/meter of Active Length	147.5	kg/m
Force Rating	285	N
Force / Active Length	20086	N/m
Mass in None Active Area	1.371	kg
Active Mass / Force	0.00734	kg/N

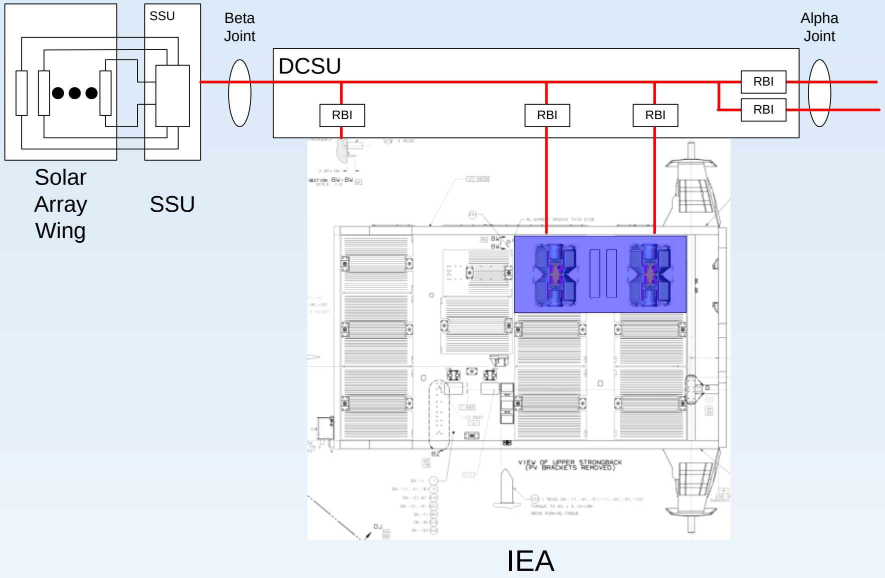


Active Length Cross Section

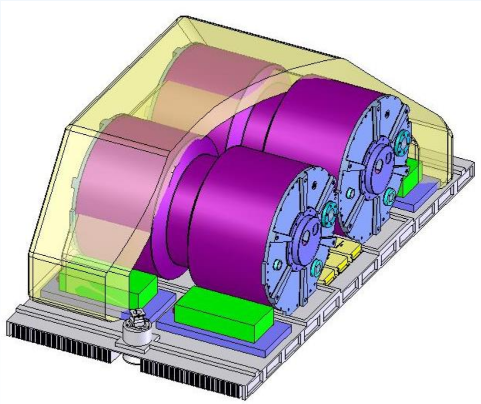
Proposed Configuration

- A single flywheel system will replace three strings of Ni-H batteries on the IEA
- This configuration allows three options after the flight demonstration phase
  - Flywheels only
  - Flywheels paralleled with Ni-H to extend life (rotor size reduced)
  - Flywheels paralleled with Li-Ion (rotor size reduced)
- The flywheel system will interface with the existing mounting hardware.

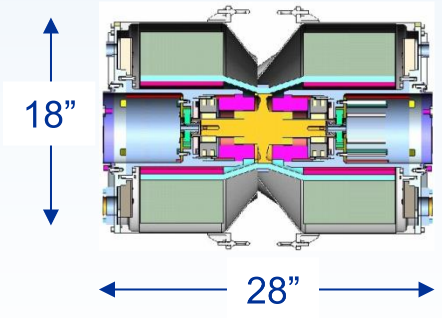
Channel Configuration



Flywheel ORU



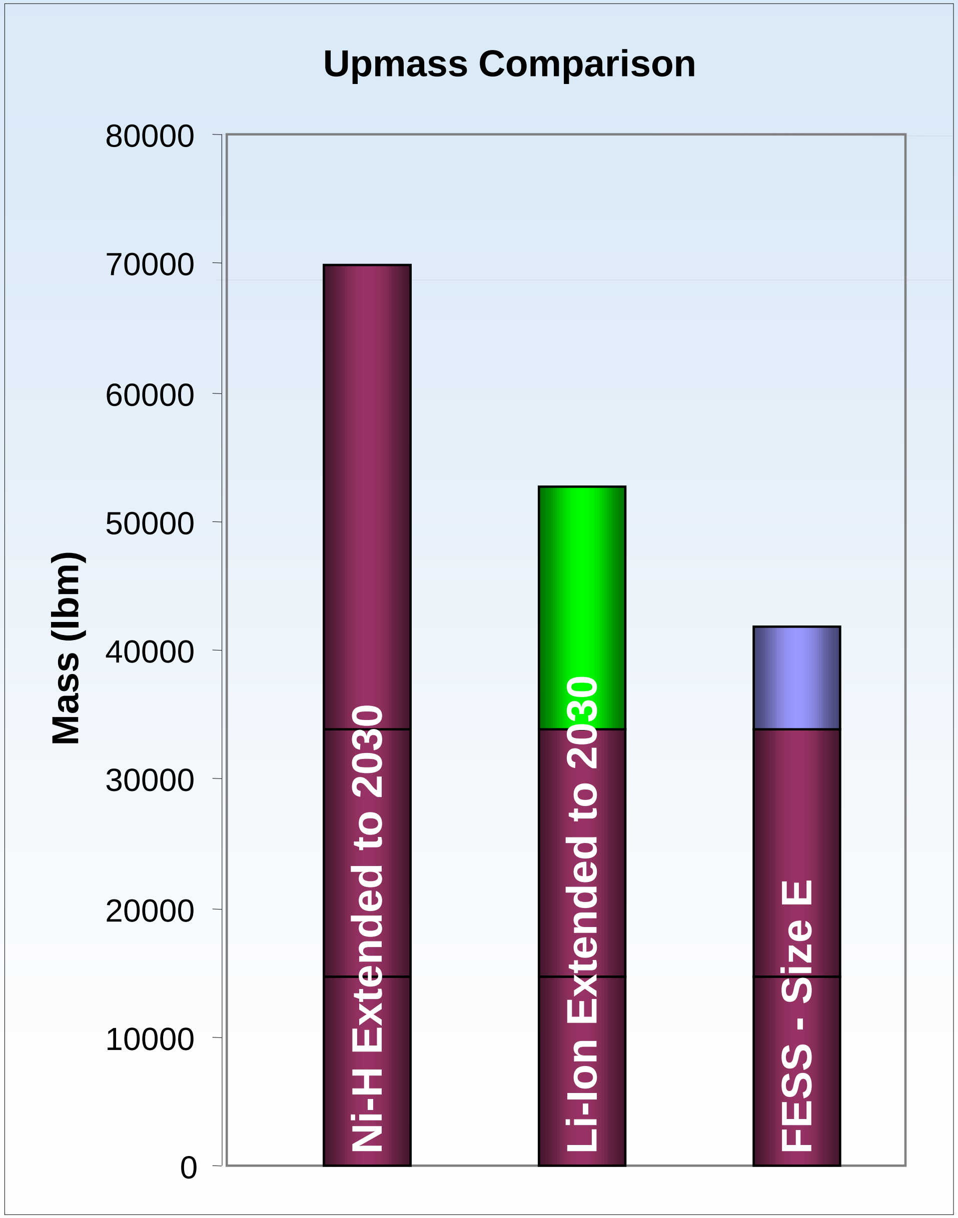
Flywheel Module



G3 Heavy - Size E

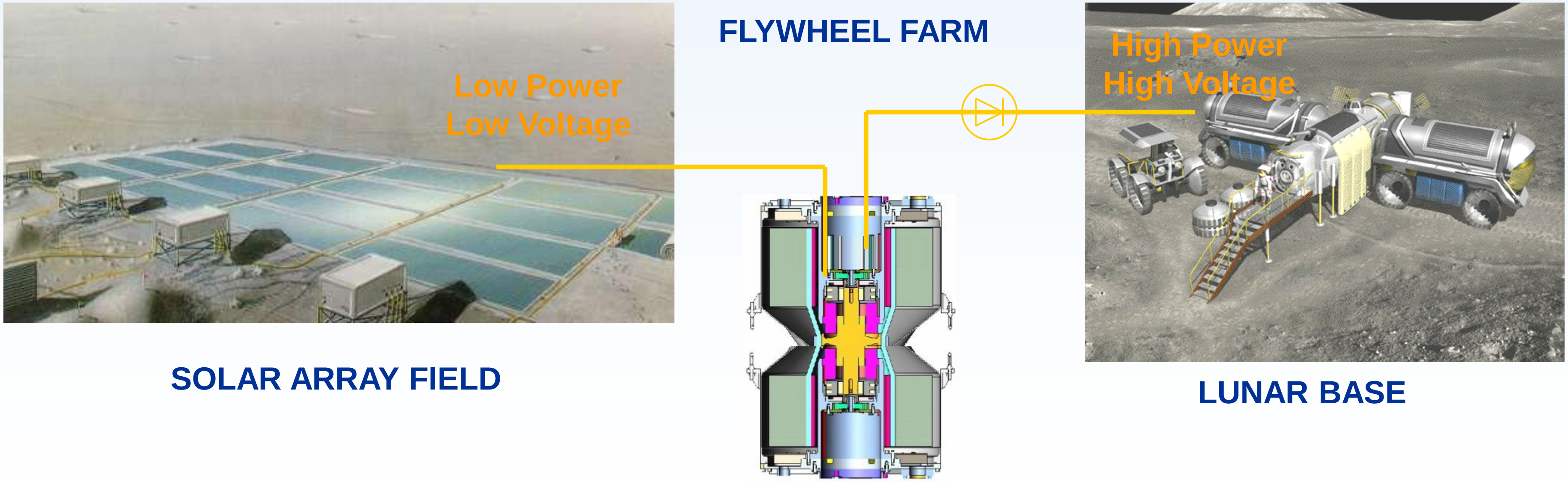
Upmass Benefit To ISS

- General Assumptions
  - One flywheel ORU replaces six Ni-H ORUs
  - One Li-Ion replaces two Ni-H ORUs
  - No BCDU replacements for Li-Ion
  - All BCDUs launched prior to flywheel flight demo
- Life Assumptions
  - Flywheel Life = 15 years
  - Ni-H & Li-Ion Life = 7 years
- Mass Assumptions
  - Li-Ion ORU – 394 lbm
  - Ni-H ORU – 375 lbm
  - BCDU – 235 lbm
  - FESS-E – 993 lbm



Benefits of 14 day Lunar Eclipse Flywheel System

- **Safety, Reliability, and Redundancy**
  - Flywheel infrastructure will not need to be replaced during the first 15 years of lunar exploration
  - Flywheels do not degrade when not in use. If program milestones slip, the deployed hardware will not suffer.
  - Flywheels can provide complete **electrical isolation** between a power source and load. A low voltage motor charges the flywheel from the solar array and a separate high voltage motor provides power to the lunar base.
  - Since reliability is achieved at the component level within a flywheel module, a system with 100 flywheel modules would provide tremendous redundancy.
- **Performance**
  - Flywheels can charge and discharge quickly and can be used as outposts for rover or EVA suit recharging.
  - Flywheels can accommodate very high peak loads, reducing constraints and planning requirements for operations.
  - Flywheels can operate over extreme temperature ranges without maintenance



Summary

- Flywheels have been experimentally shown to provide bus regulation and attitude control capability in a laboratory.
- The G3 flywheel can provide 25W-hr/kg system specific energy, 85% round trip efficiency for a 15 year, LEO application
- A sizing code based on the G3 flywheel technology level was used to evaluate flywheel technology for ISS energy storage, ISS reboost, and Lunar Energy Storage with favorable results.