Modular Electric Power System for a Small Satellite Power Buffer

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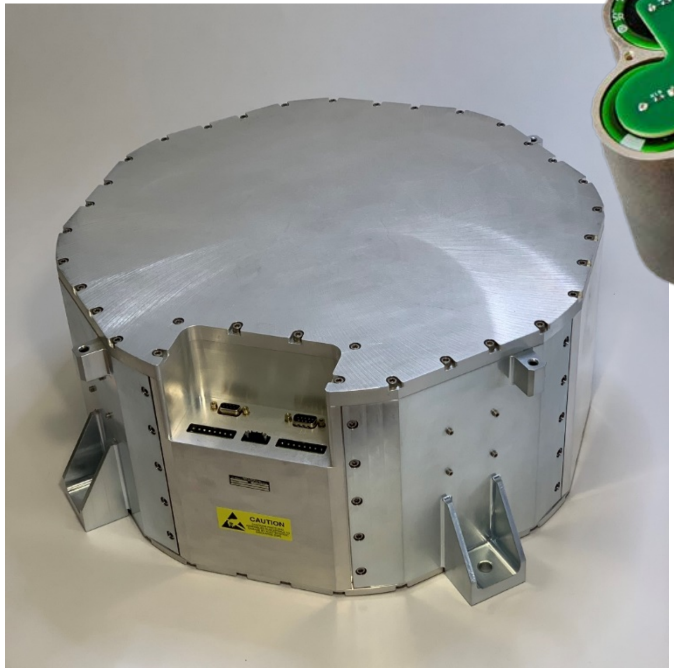
Overview

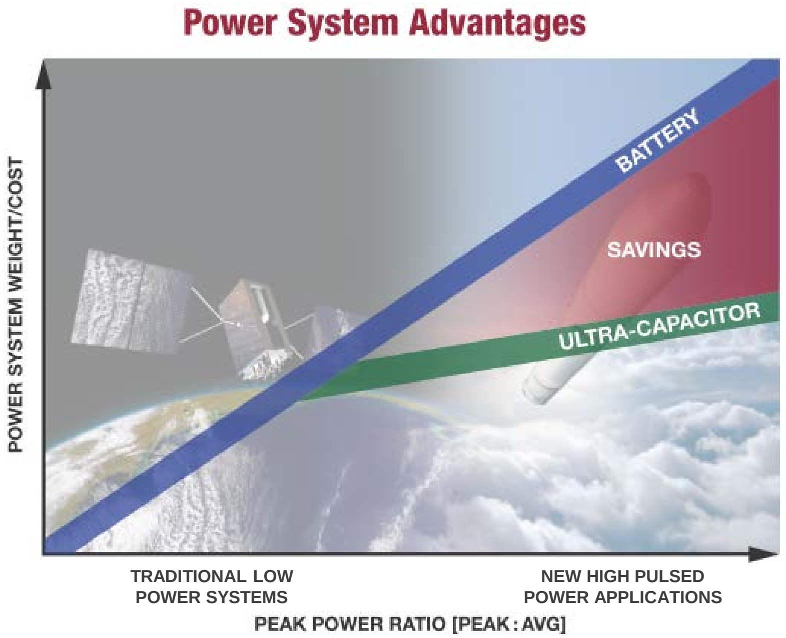
The purpose is to update the assembled group on:

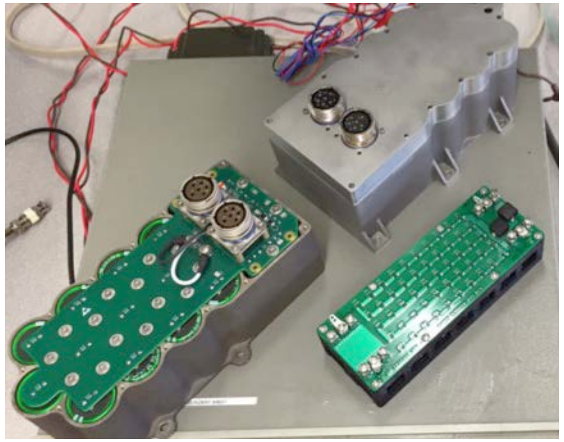
- Moog’s interest in power systems
  - Actuation systems are power-hungry
  - Adjacent high peak-power applications
- What MEPS is conceptually
  - Where it can be leveraged
  - Recent development efforts
  - System testing
  - Possible future instantiations



The passive hybridization of ultra-capacitors used in Moog MEPS is covered by US Patent US9230748

What is the Modular Electric Power System?

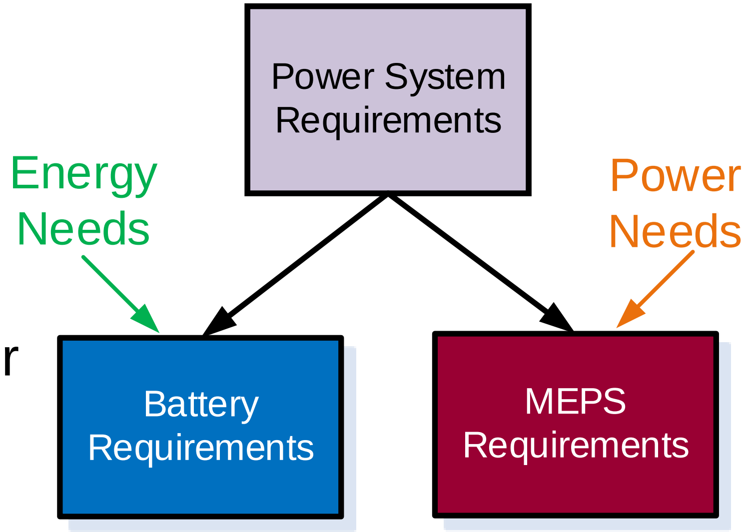




"High Power Density Modular Electric Power System for Aerospace Applications" JPC/IECEC 2014, G. Semrau

- MEPS is an electric power buffer utilizing Ultra-Capacitors for high power instantaneous use
- MEPS serves as an electric accumulator for an electric motion control system that can supply *power on demand* and can accommodate *all* regen power
- MEPS reduces the weight of the power system as it provides a more optimal solution space
  - Battery can be optimized to a higher energy density cell so capacity req. can be met with less cells comparatively
  - Peak power demand and higher frequency transients met by MEPS Ultra-Capacitors

Power System: Optimized Flow-down



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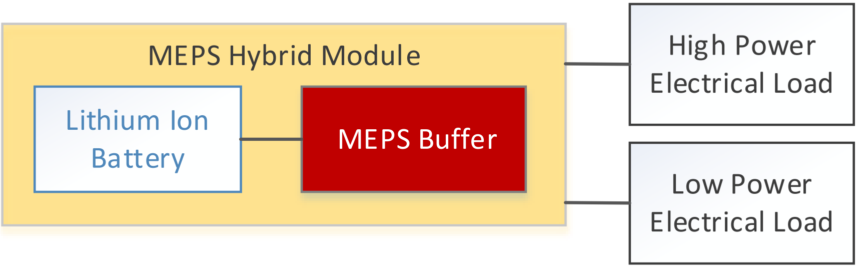
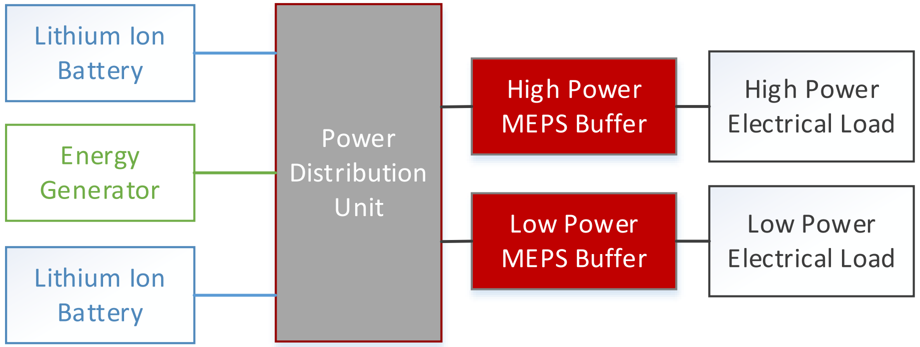
MEPS Architecture Implementation

Centralized Common Package MEPS Hybrid Systems Architecture



- Power dense point solution that is optimized for weight / volume
- Provides buffering action between the load(s) and the battery
- *Intended Launch Vehicle Application*

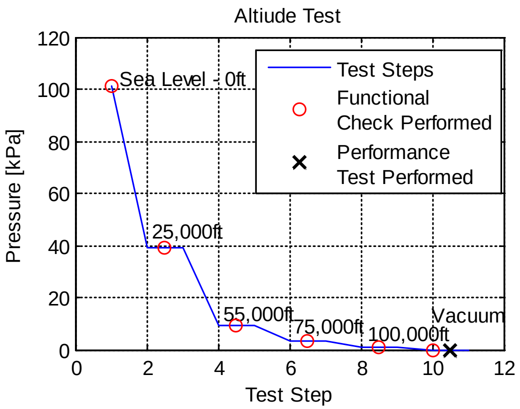
Decentralized MEPS Hybrid System in a Common Bus Architecture



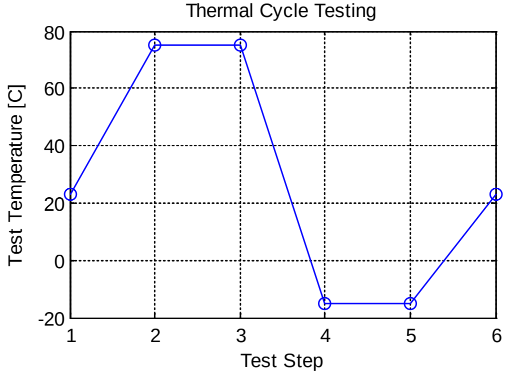
- Allows a flexibility to optimize the design of the power system
- MEPS Ultra-Capacitors can be modular to the application
  - One MEPS Package for multiple loads
  - Multiple MEPS, one per load
- Provides buffering action between the load(s) and the Vehicle Bus
- *Intended Exploration Vehicle or Satellite Application*

Prior MEPS Development Efforts

Altitude



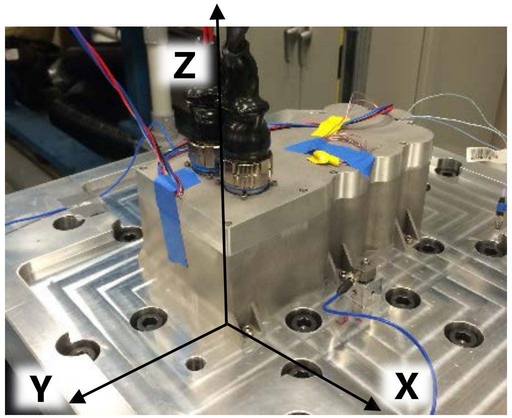
Thermal

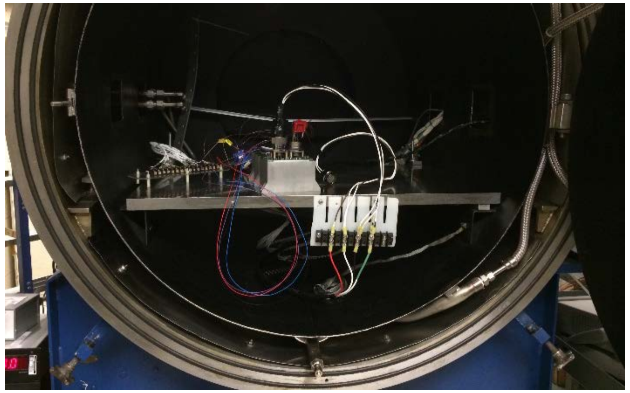


Vibration

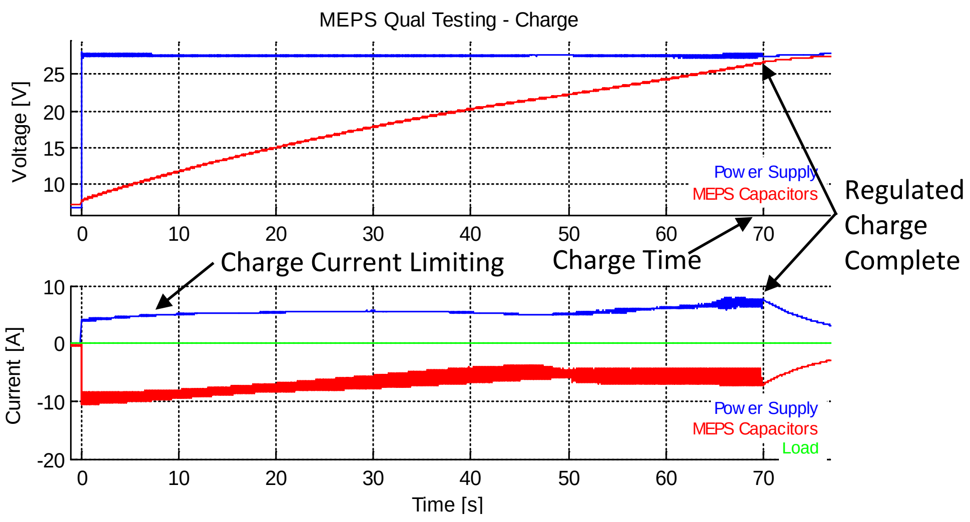
Vibration Test Results			
GRMS	X-Axis	Y-Axis	Z-Axis
9	Pass	Pass	Pass
19	Pass	Pass	Pass
27	Pass	Pass	Pass
38	Pass	Pass	Pass

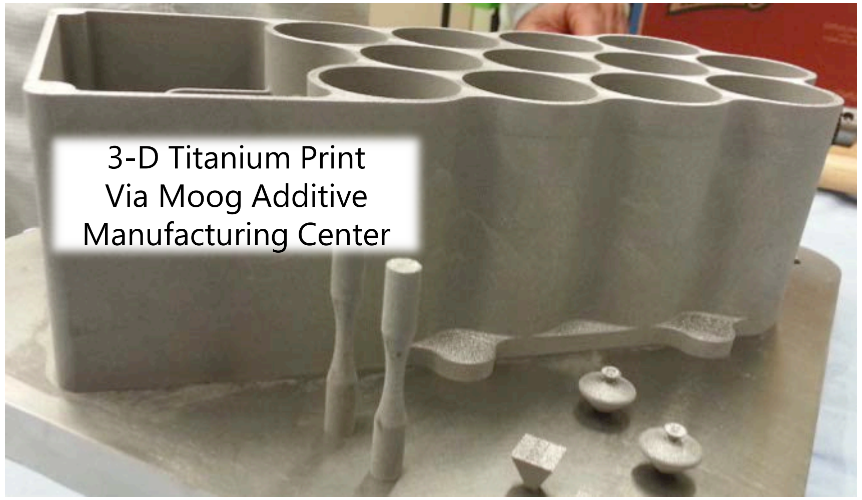
- Moog has developed a 28VDC 5kW MEPS solution to a TRL6 maturity level which has been through environmental screening
- Environmental Testing conducted to DO-160G and MIL-STD-1540B
- High Power System testing conducted at several voltages and power levels, five instantiations all between TRL4 through TRL6
  - Voltage Range [28V:270V]
  - Power Range [150W:50kW]
- Packaging allows components to survive environments
- Temperature rise in components is limited due to low ESR





MEPS Fundamental Architecture





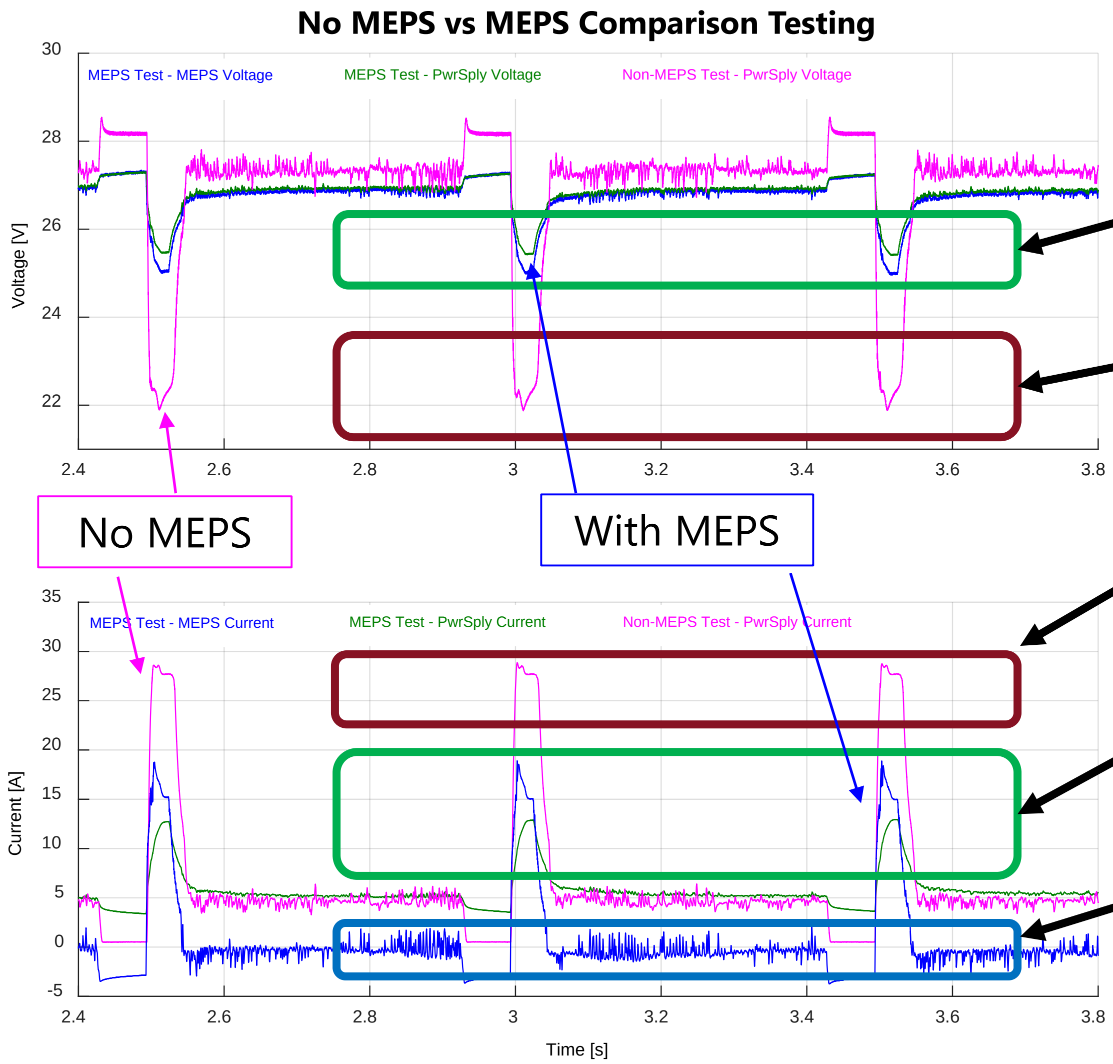
Initial Charge Regulation

- Without initial charge regulation the in-rush current would over-stress the connected electrical system
- Allows MEPS to be triggered on/off as needed
- Mitigates UC leakage current during storage

Packaging

- Packaging for extreme aerospace environments is not trivial
- Previous limitation to adoption

Unloaded EMA Low Voltage System Testing



System with MEPS Eliminates High-Duty Cycle Voltage Drops

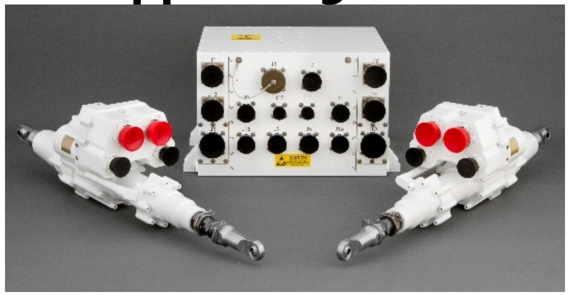
System without MEPS has High-Duty Cycle Voltage Drops

System without MEPS has high-current draw from Power Source

System with MEPS has significantly reduced current draw from Power Source

Upstream Power System has reduced high frequency/ amplitude noise, MEPS takes the load

Upper Stage TVC



- Initial testing anchors the claims made in simulation
- MEPS acts as a power buffer eliminating the peak pulse and high frequency / amplitude noise that is demanded by the motor inverter / actuator load
- System testing validates implementation architecture

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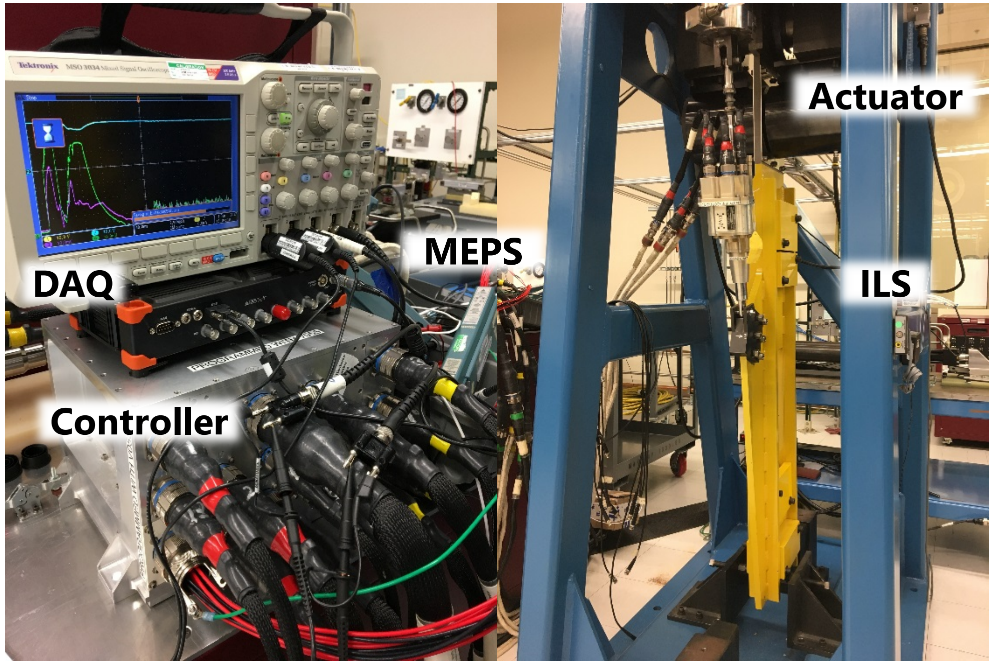
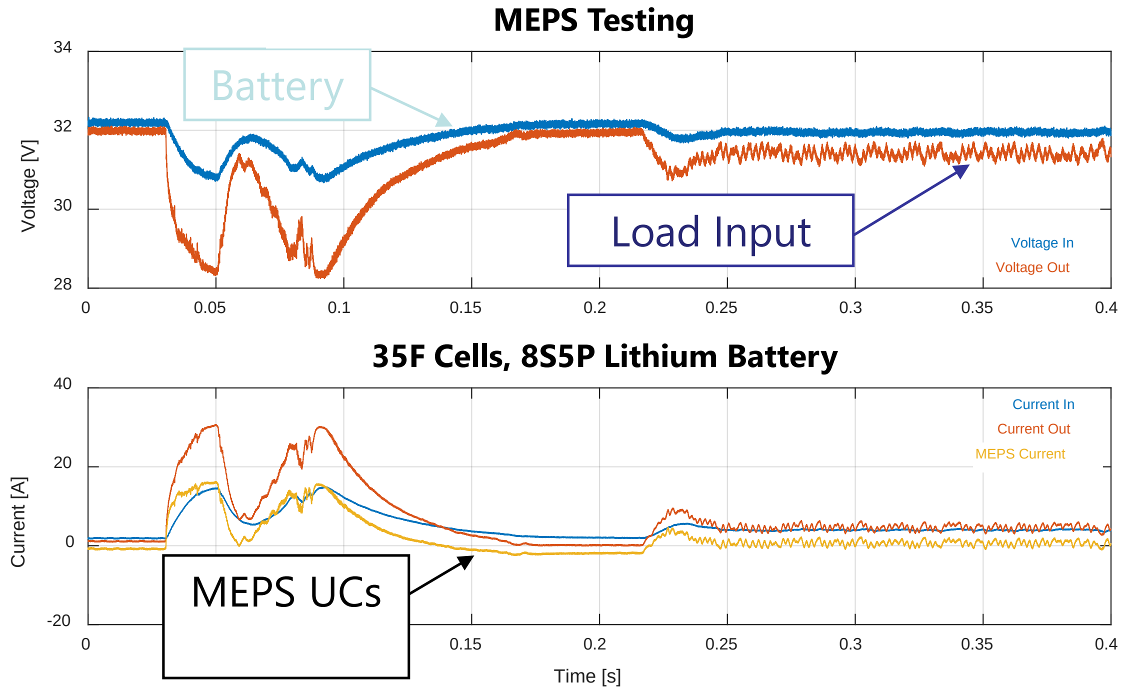
Loaded System Testing with Lithium Ion Battery

- A demonstration on a Upper Stage Nozzle EM Actuator was performed on a prototype CCA of the MEPS circuit utilizing 35F cells w/ 8S5P Li Battery
  (Frequency Response, Transient Response, Loaded Rate Response)

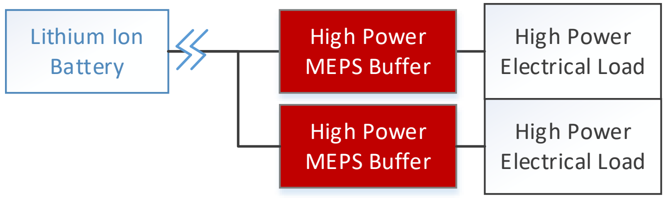


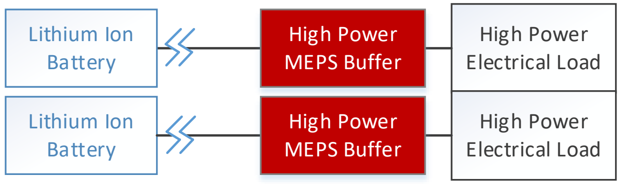


MEPS High Power Implementation

- What would be the High Power solution?
  - Use the Front End Circuit developed for Low Voltage as an interface
  - Develop a UC Package to house the UC's
  - Combine as a stand-alone system
- If a Lithium Ion Battery based solution MEPS can reduce mass by ~30%
- MEPS can enable a RPS or Fuel Cell solution because of the constant power nature of that energy system
- High Power/Voltage Solution would be based on larger format Ultra-Cap in modular package
- Solves Regen Power Issues

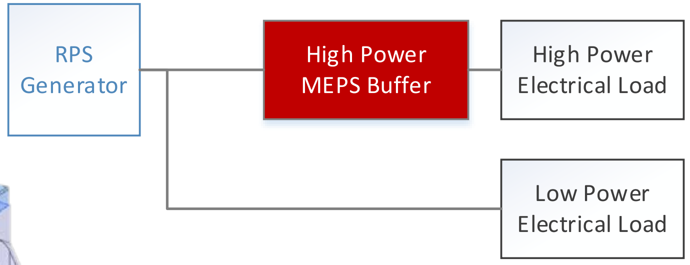
Central Storage →

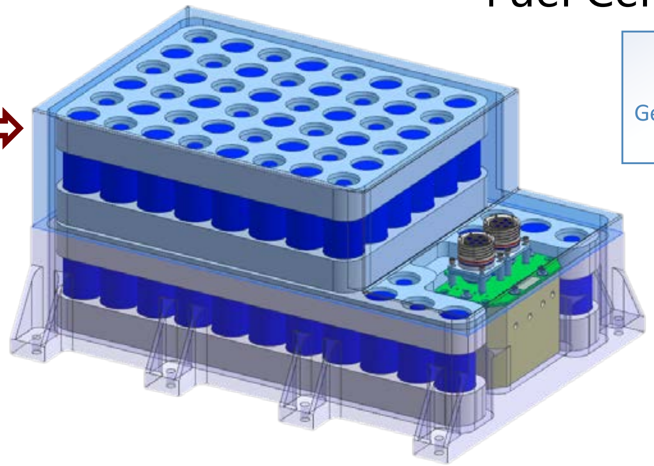




← Discrete LRU's

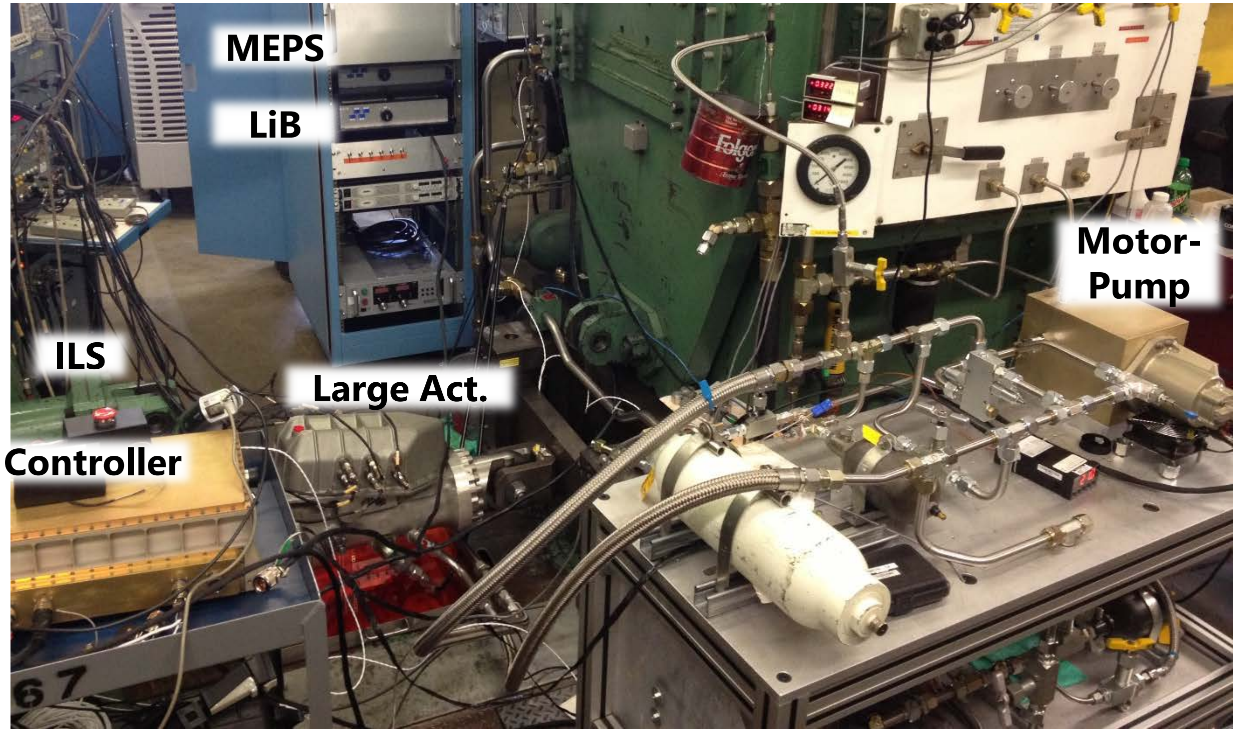
Fuel Cell or RPS System Augmentation



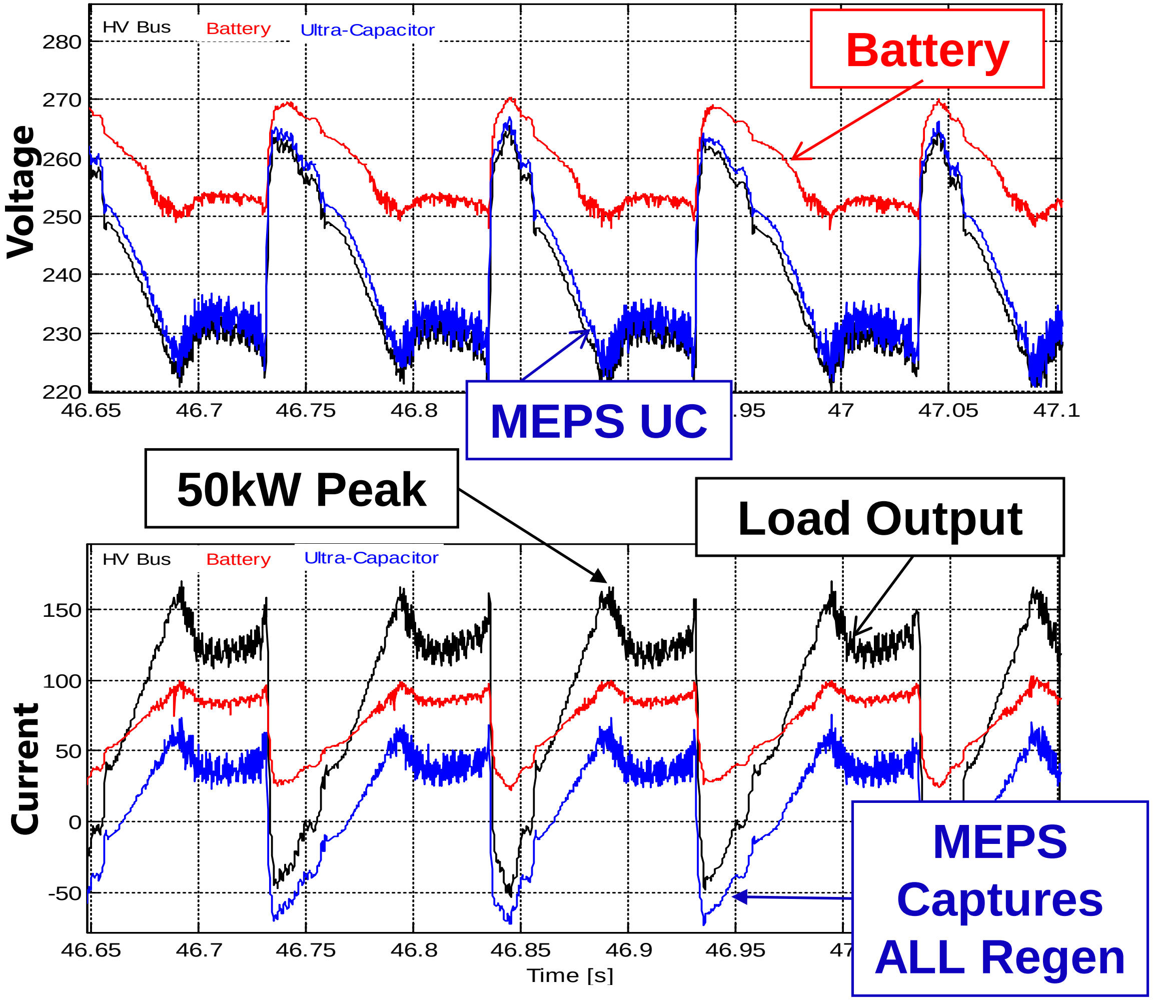


High Power Lower Stage Nozzle Demonstration

- System maintains an acceptable level of voltage during pulsed discharge
- Battery output is kept to a more steady level
  - Advantageous for battery selection
- Ultra-Capacitor is taking a significant amount of the current loading – can be sized for ALL regen current



Motor-Pump Driven Large EH Actuator DC Transmission System Test



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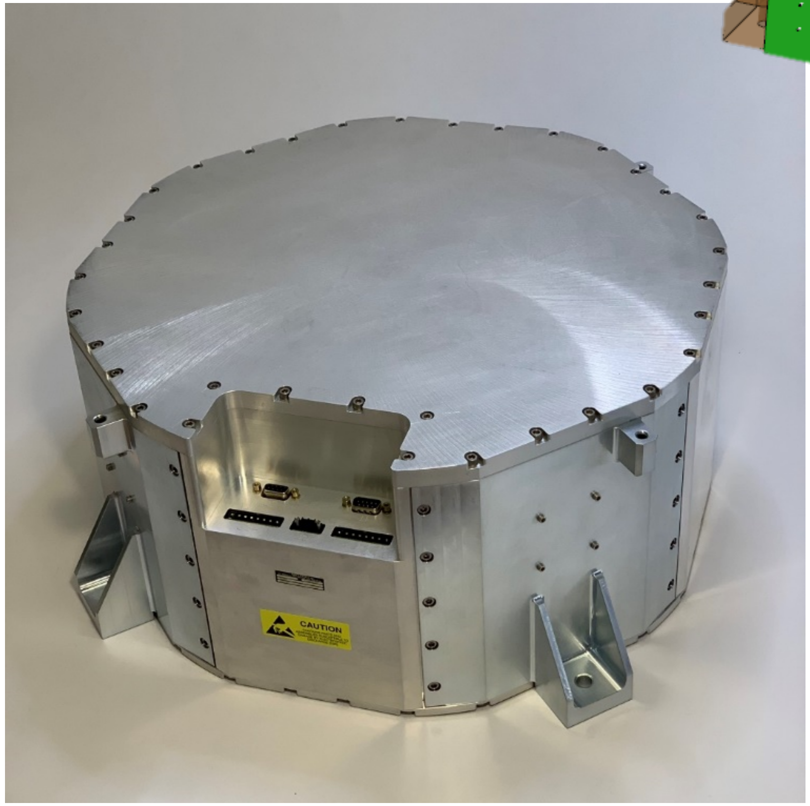
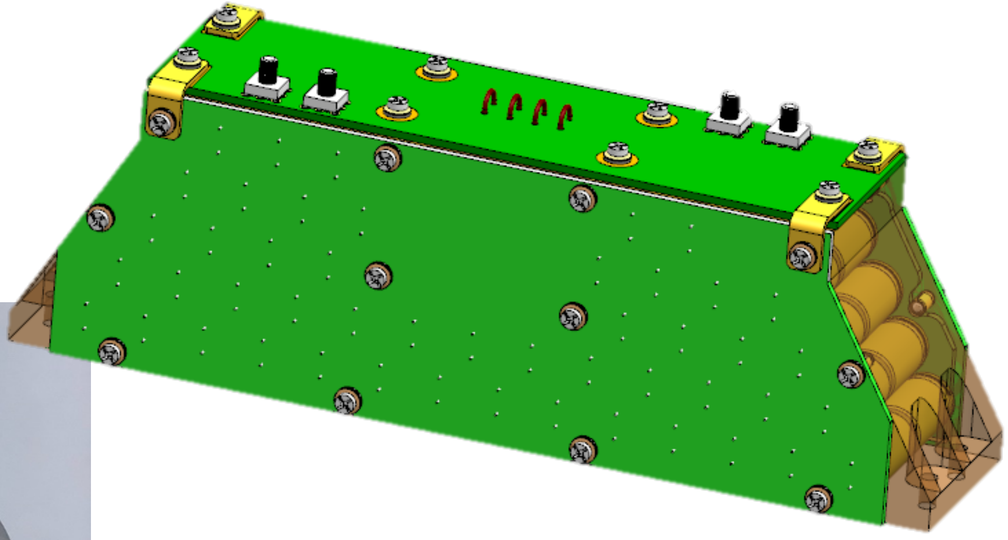
MEPS Development Activities

Power Filter
260mF Application
270VDC Bus Line
±8A Buffer





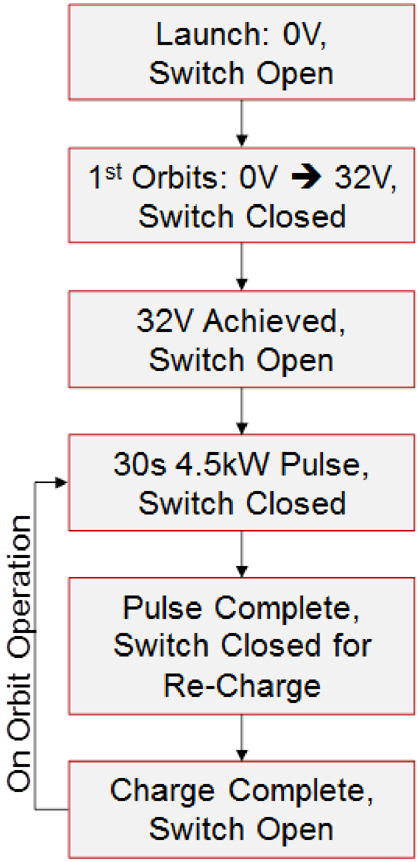
High Power Energy Storage module
533F Application
28VDC Bus Line
150kJ Accumulator
Flight in CY19
(SAR Application)

Capabilities & ConOps Overview

- High Power Buffer for Small Spacecraft applications
  - Regulated Input
    (<4A draw for 28V to 34V input)
  - Unregulated Output
    (>200A, voltage function of SoC & ESR drop)
- Performance
  - 533F Nominal Capacitance
  - Buck or boost input to 32V
  - ESR <10mΩ
- Testing & Environments

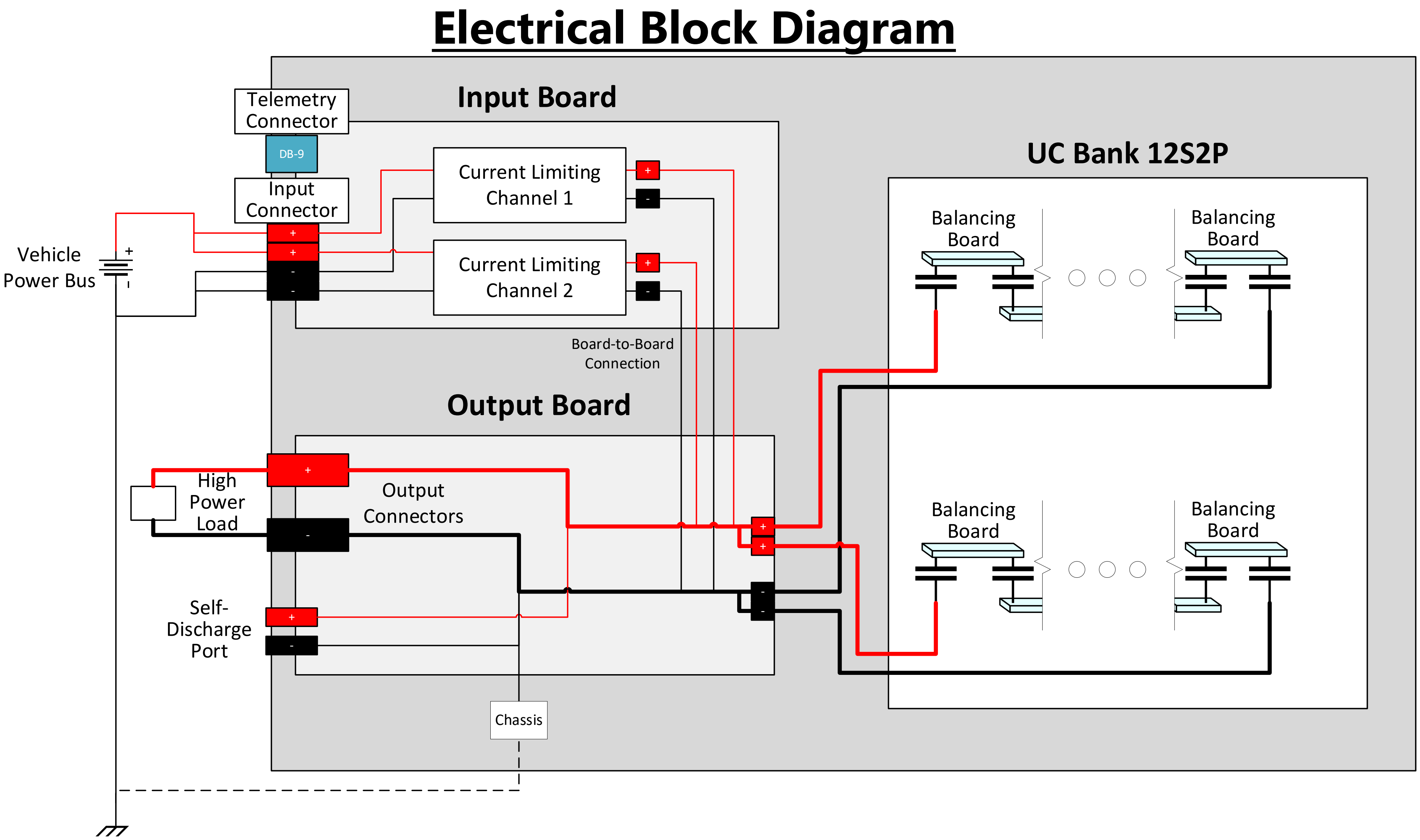
Test	Level(s)	Pass/Fail
Mass	<28kg	Pass
Performance	4.5kW Pulse, 30s	Pass
Vibration	6.8Grms, 3 Axes	Pass
Altitude	1 Cycle @ Vacuum	Pass
Temperature	-29C to 66C	Pass
Cycle Life (@ Cell Level)	1000 Cycles	Pass

Concept of Operations

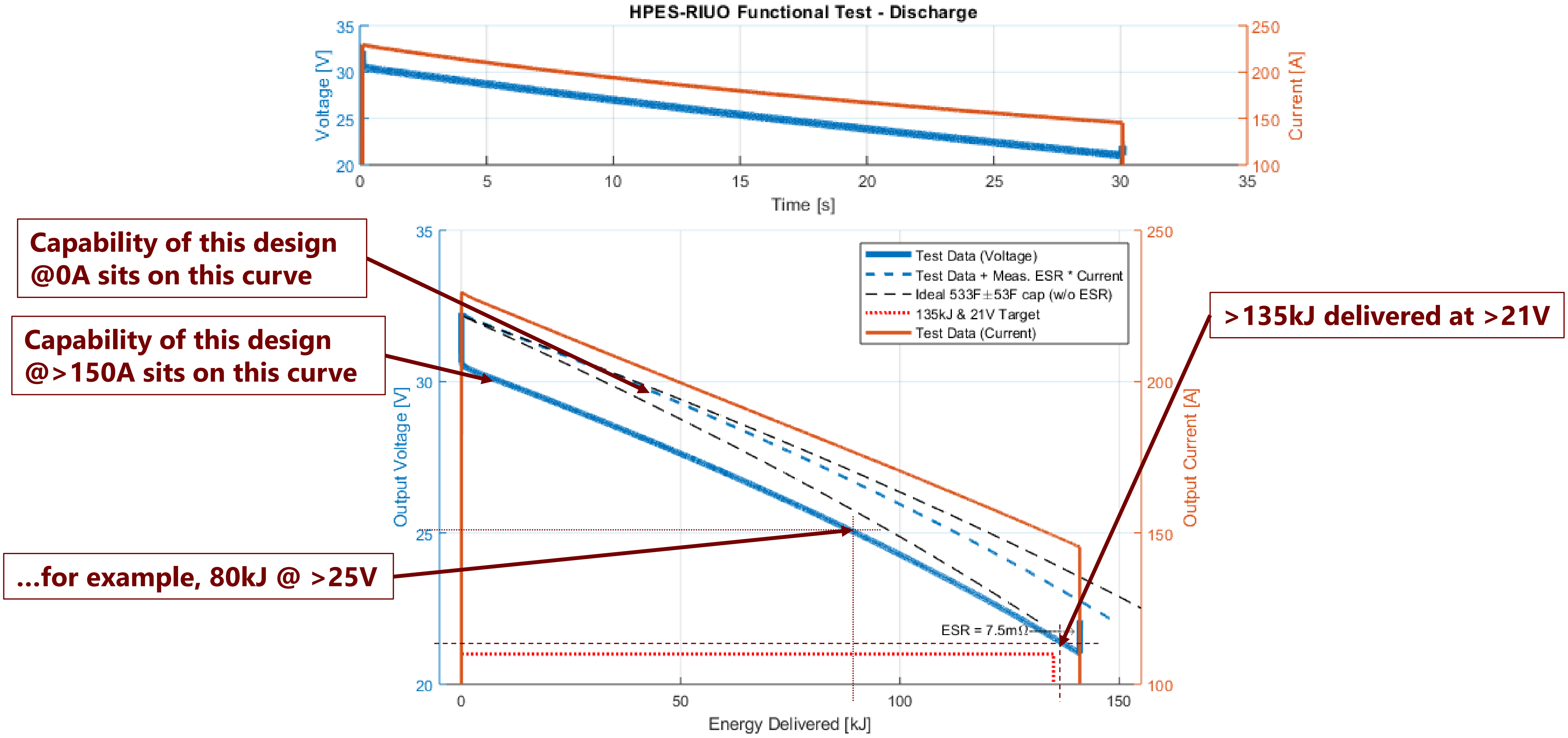


- HPES provides a buffer between low and high power portions of Satellite Bus
- Will remain at 0VDC during Launch & Separation
- Front end circuit will boost EPS voltage to HPES voltage (~32V) and will limit charge current below 4.0A
- When not in charge state, EPS switch interface can open switch to eliminate power consumption
  (Open Switch dictated by flight computer)

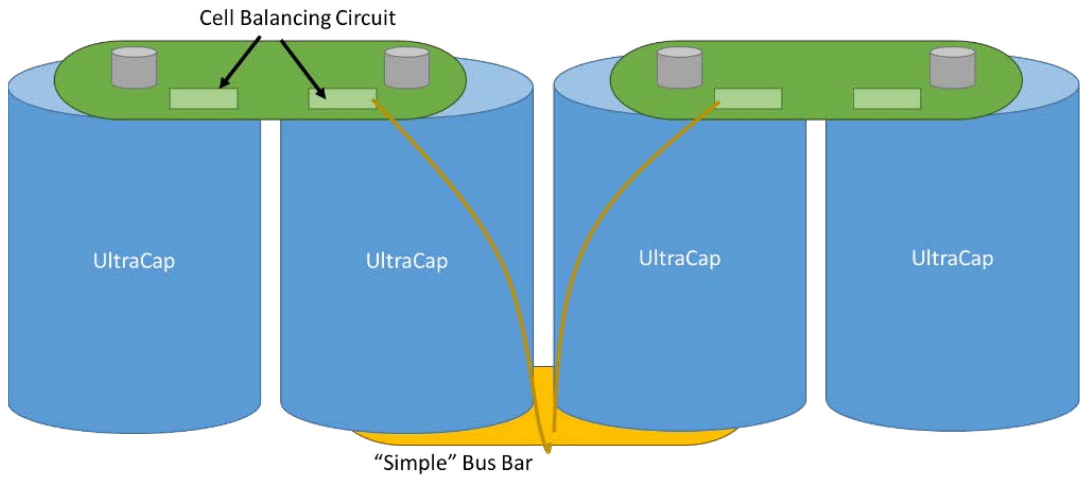
Block Diagram



Nominal Discharge & Design Capability



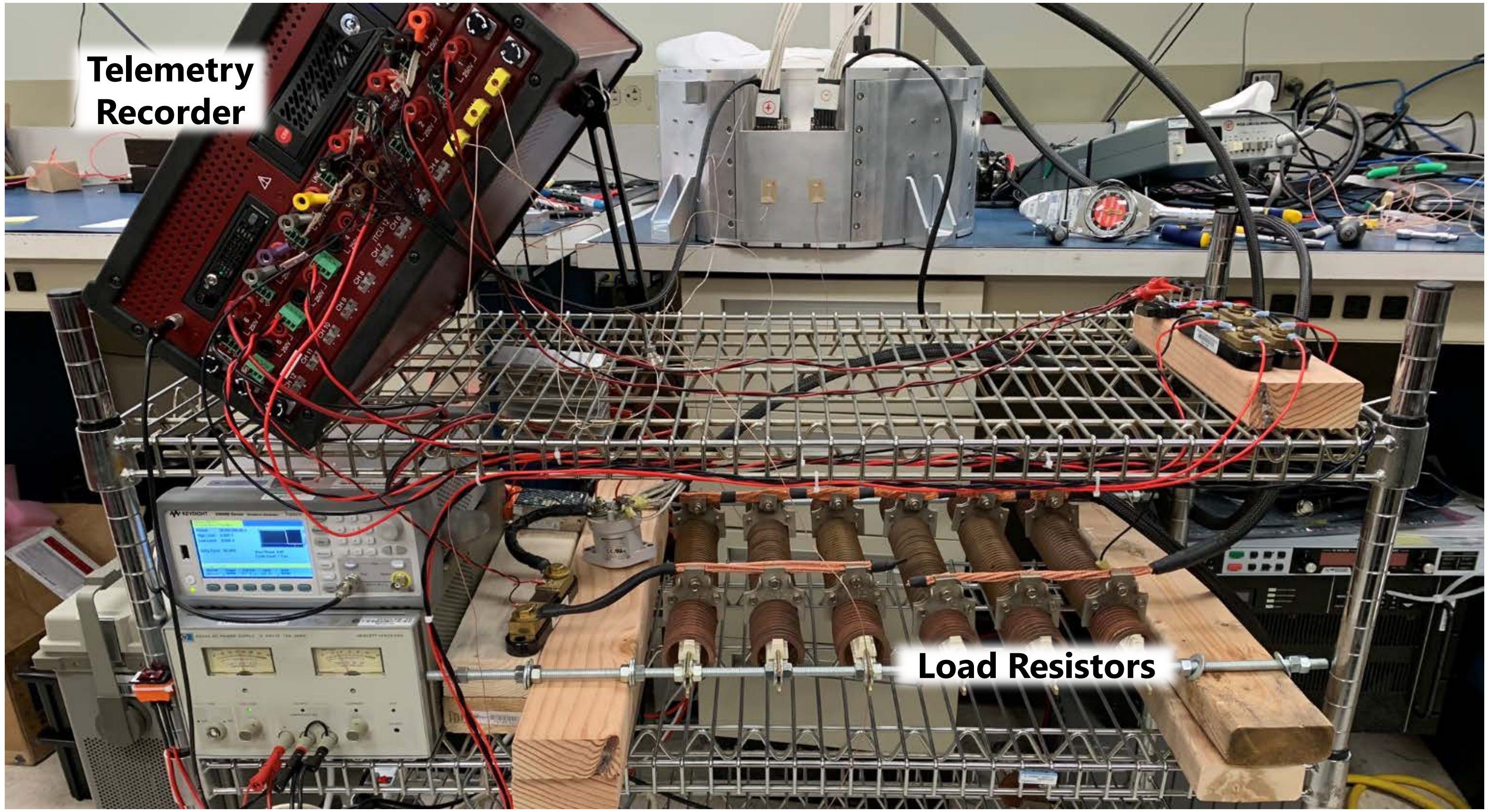
Balancer Board Overview



- Passive, non-linear balancing circuit across each cell
- Integrated into bus bar between cells

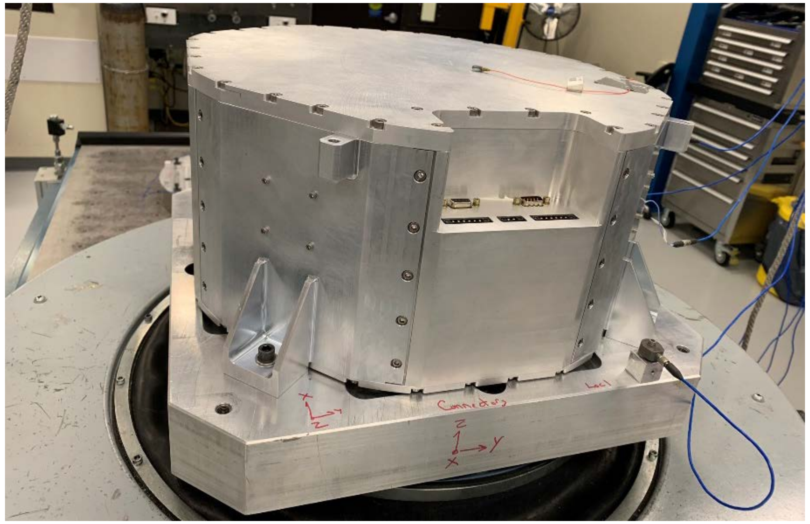
System Functional Testing

- Charge from 0V to 32V (i.e.: initial charge on orbit)
- Discharge into resistive load for 30s
  - Verify >135kJ delivered
- Recharge to 32V
  - Verify <30min recharge
- Repeat discharge
  - Verify >135kJ delivered
- Recharge to 32V
  - Verify <30min recharge
- Discharge to 0V

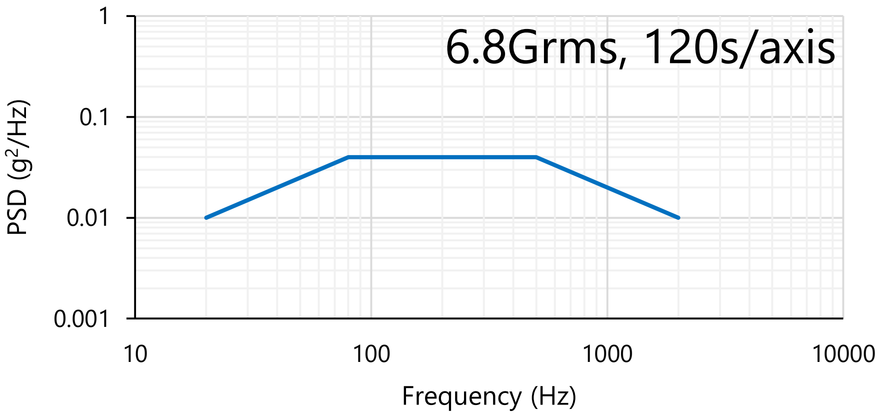


Environments

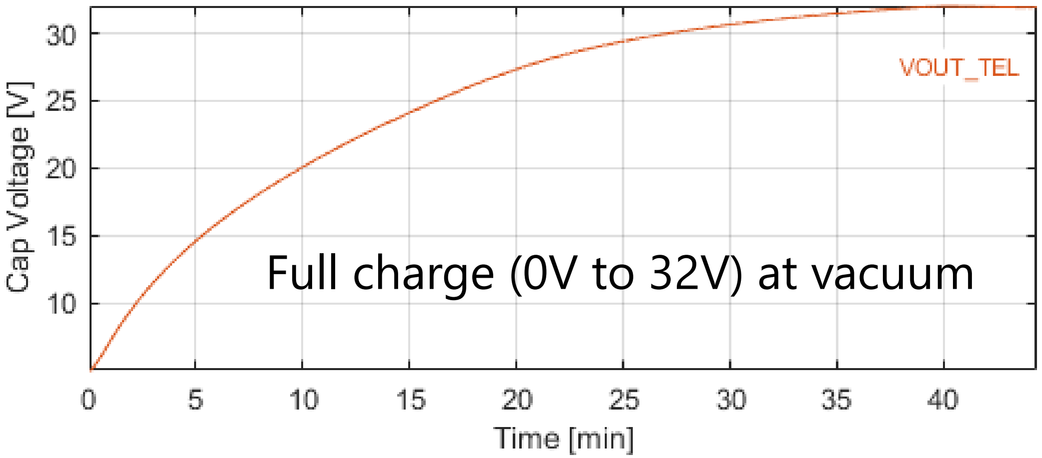
Vibration



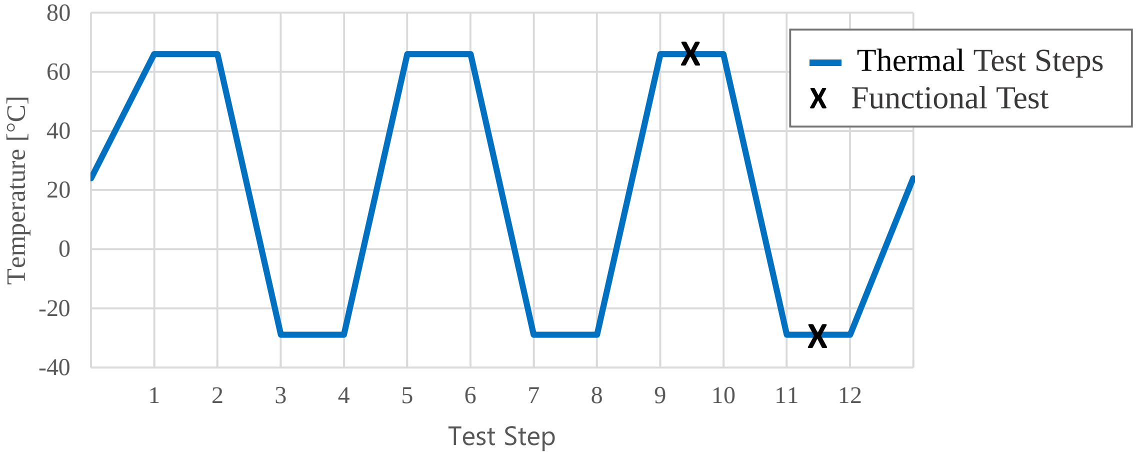
Random Vibration Input Spectrum (All Axes)



Altitude

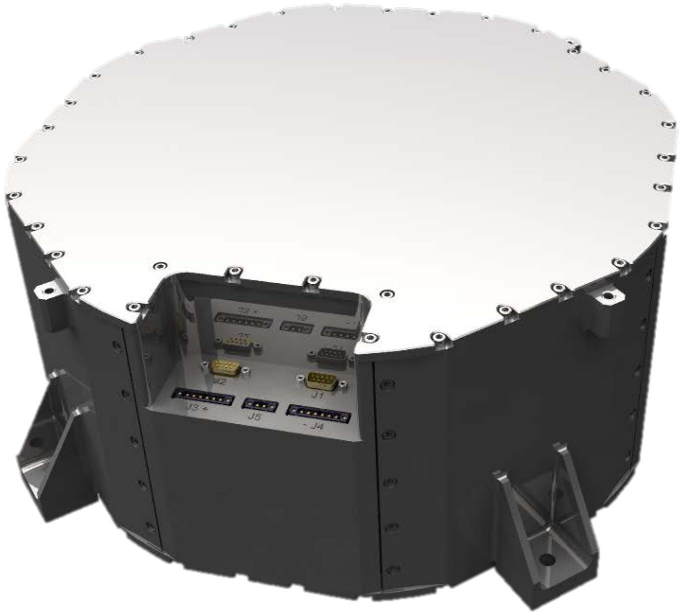


Thermal Cycling



Closing Remarks

- Moog is continuing to develop power storage and distribution solutions to increase power system architecture flexibility
  - Launch actuation systems (i.e.: TVC)
  - In-space systems with high peak-power (i.e.: SAR)



<u>Advanced Technology</u>

- MEPS Supplemented Power System will further decrease the total Mass of the Vehicle by lowering the power demand of the Loads as sensed by the Storage/Delivery System
- Decoupling power & voltage requirements between the loads and delivery system lead to flexibility in PMAD architecture
- Mass reductions and increased efficiency lead to cost savings

Thank you for your attention

Questions?



Backup Slides

High Level Review of the Testing on MEPS

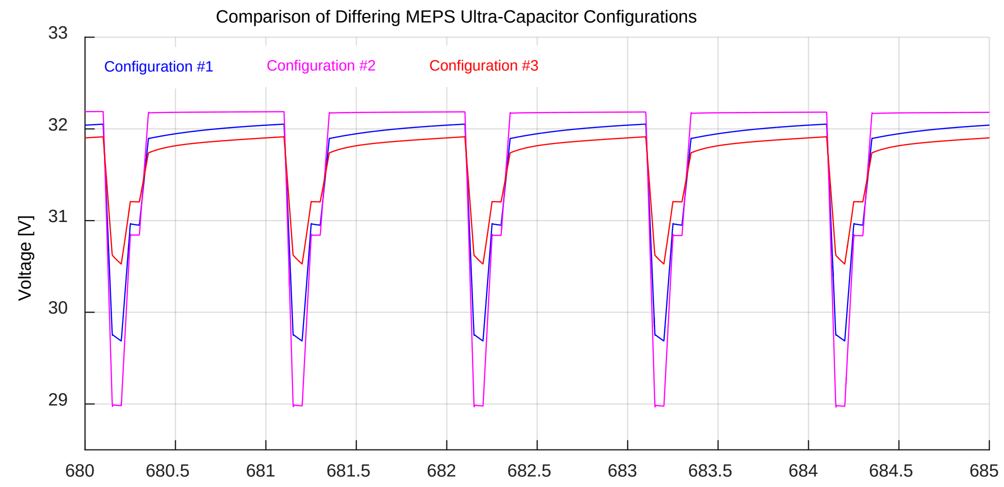
Completed Testing to-date:

- Low Power & Low Voltage – Regulated input, Unregulated output
  - Functional Test w/ Unloaded EMA = Pass
  - Functional Test w/ Loaded EMA = Pass
  - Functional Test w/ Loaded EMA & Lithium Ion Battery = Pass
  - Life Testing w/ Lithium Ion Battery (NASA GRC) = Pass
- High Power & Low Voltage – Regulated input, Unregulated output
  - Functional Test w/ Controlled DC Load = Pass
  - Environmental Test (Vibration, TVAC) = Pass
- High Power, High Voltage Module – Unregulated input, unregulated output
  - Functional Test w/ Loaded EHPU & Lithium Ion Battery = Pass
  - Functional Test w/ Loaded EHA = Pass

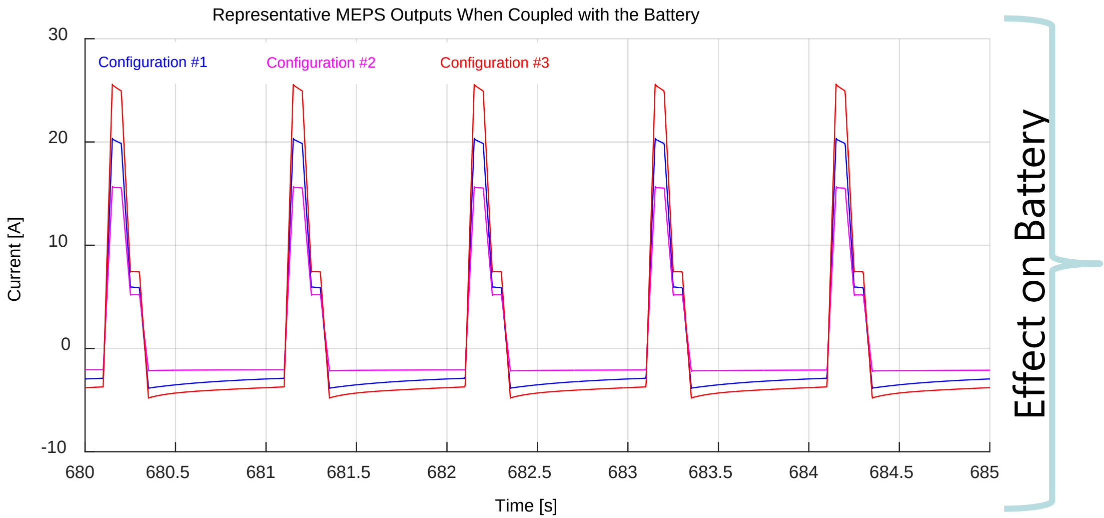
Application Specific Testing:

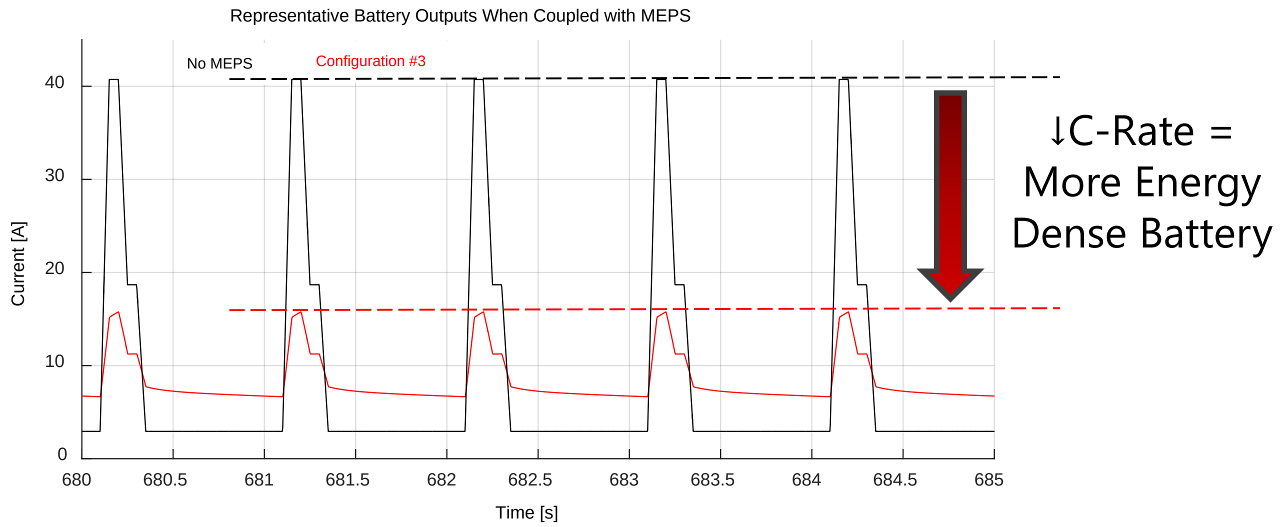
- Functional Test w/ Loaded EHA/EMA & Lithium Ion Battery
- Environmental Test (Vibration, Shock, TVAC)

Sizing Trades



- Different configurations of MEPS have varying “strengths” of buffering against peak power demand periods
- With the MEPS supplemented Power System, output power of the Battery can be reduced which leads to an optimization of the Battery as a sub-system
- The reduction of the peak output power may be enough to reconfigure the power system architecture





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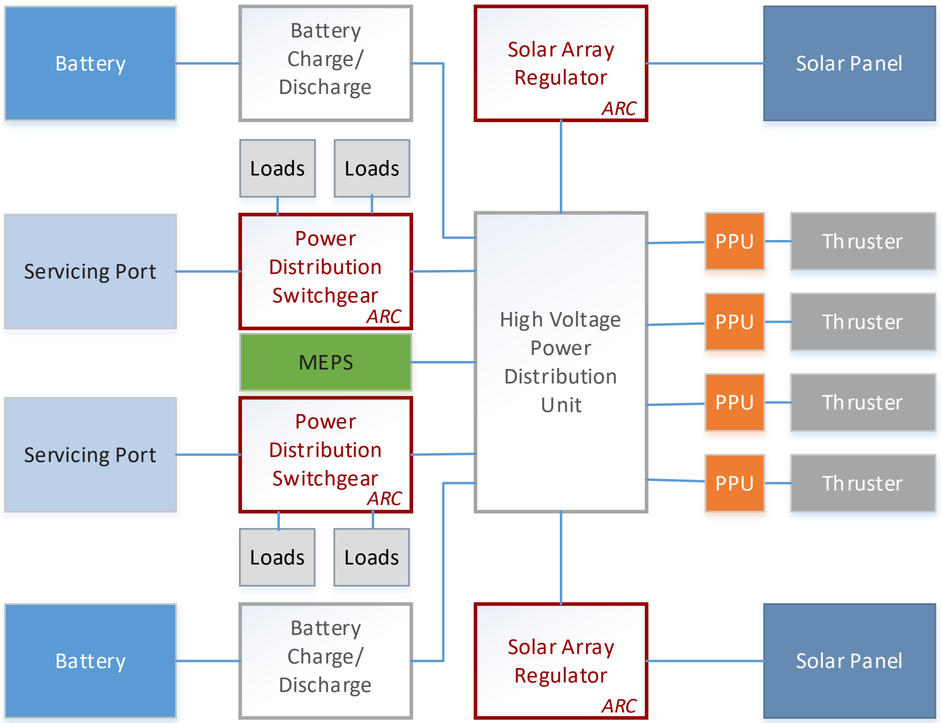
Look Ahead – Joining Storage and Conversion

- Moog is working in augmenting power storage as well as power distribution
- Key issues involved in some proposed future architectures:
  - Electric Propulsion is driving towards high power
  - Mass efficiency will drive towards higher voltage
  - EEE parts will restrict modular sizing of conversion & distribution equipment

Potential Exploration Vehicle PMAD Architecture



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