

Capacity Fade Comparison Testing of LEO Cycling Using MEPS

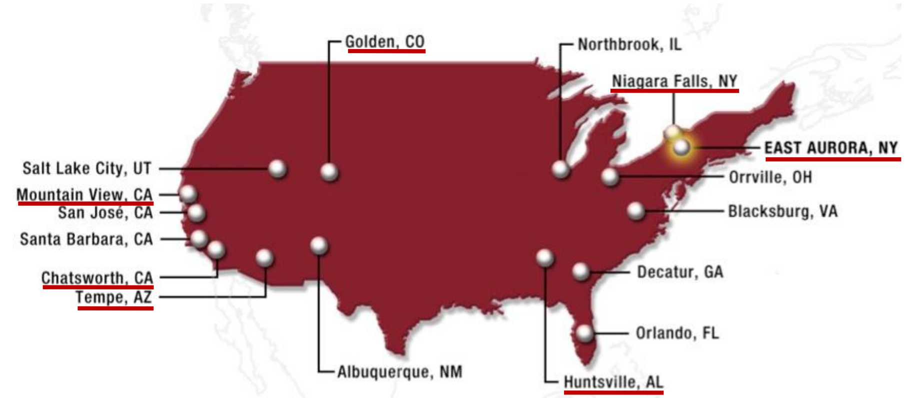
Presenter: Greg Semrau, Moog Space & Defense Group

*Thanks to: Thomas Miller NASA GRC,
Dan Muffoletto Moog & ABSL*

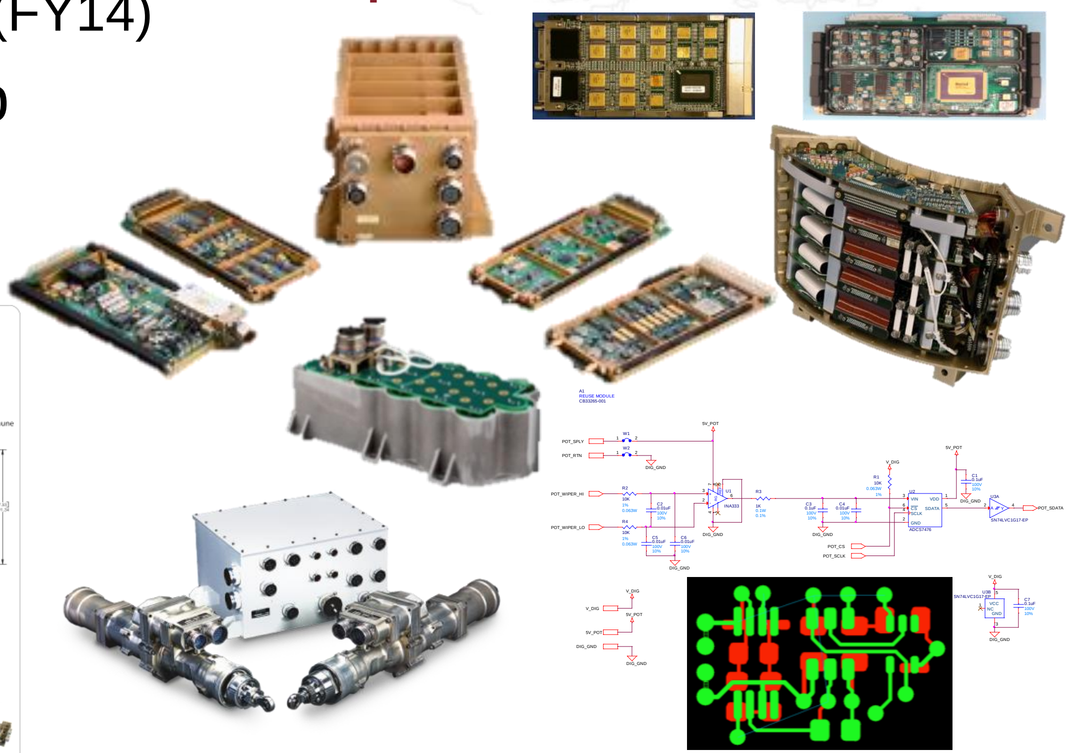
MOOG
SPACE AND DEFENSE GROUP

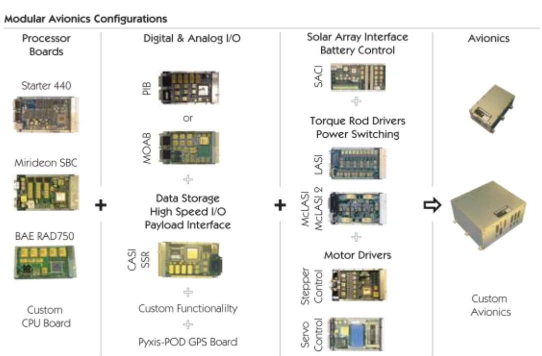
Moog Company Information

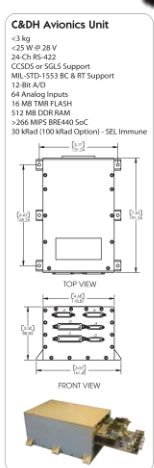
- Moog Incorporated in 1951 & headquartered in East Aurora, NY
  - Diversified supplier of motion control solutions
  - $2.65 Billion in Revenue (FY14)
- Space & Defense Group
  - Supply motion control & avionics to launch vehicles & satellites



Space Access Focus



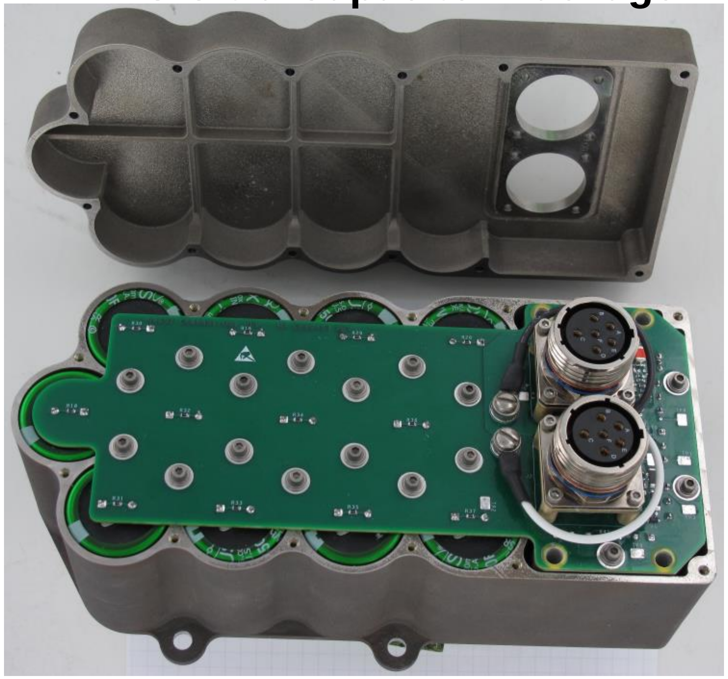


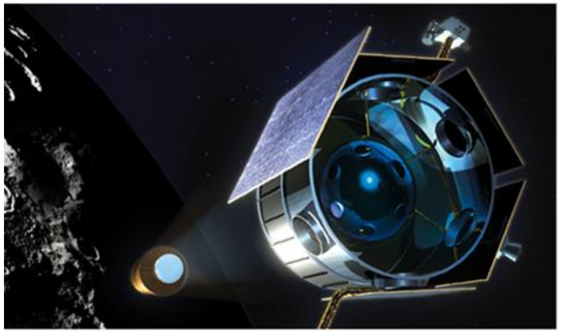


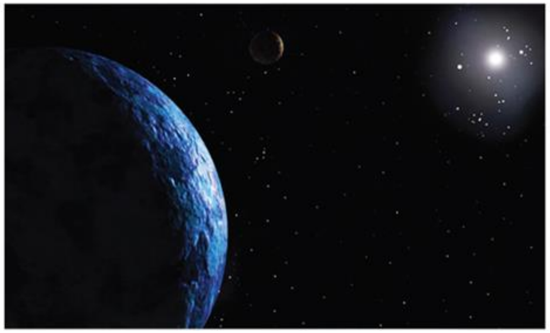
Overview

- MEPS Technology Overview
- Power System Architectures
- Update on Other Testing
- NASA GRC Capacity Fade Testing
  - Overview
  - Results Interpretation
  - Comparison of Results
  - Next / Future Steps
- Conclusions

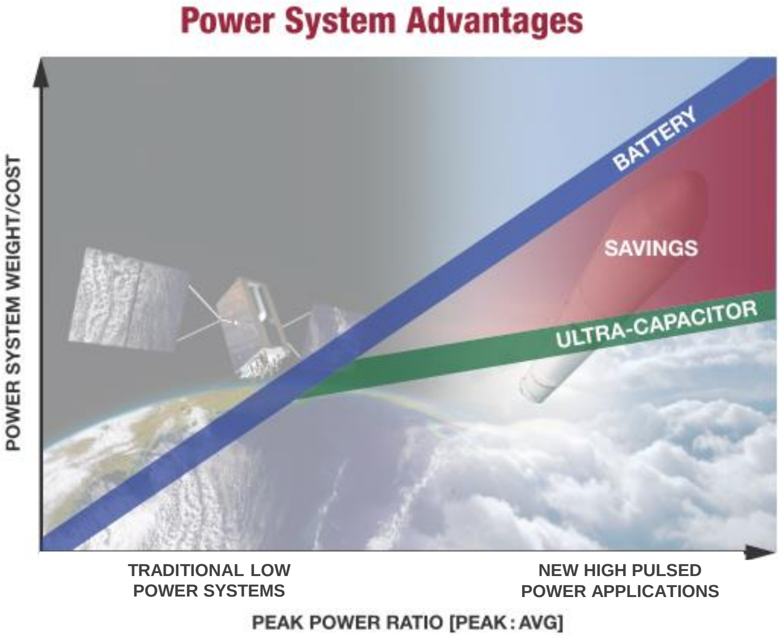
28VDC – 5kW
MEPS Ultra-Capacitor Package

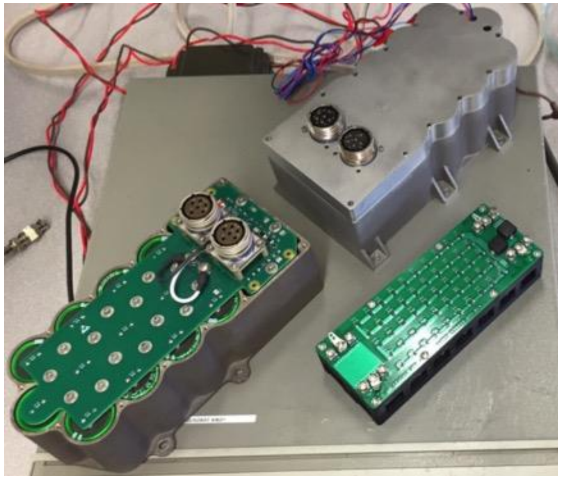






Overview on Modular Electric Power System (MEPS)



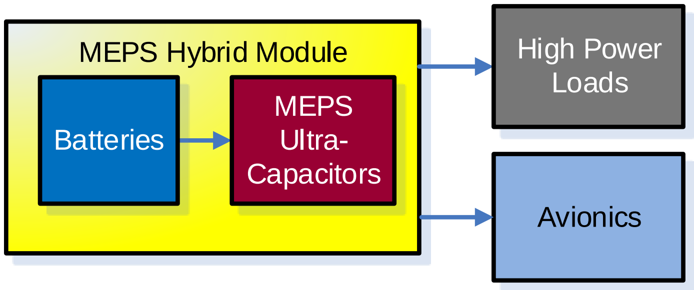


"High Power Density Modular Electric Power System for Aerospace Applications" JPC/IECEC 2014, G. Semrau

- MEPS is an architecture that hybridizes ultra-capacitors with batteries or an electrical bus
- The architecture is passive in nature allowing flexible configurations
- Benefits of this architecture are:
  - Increased system power density
  - Decreased capacity fade on Batteries
  - Increased regenerative energy capture capability
  - Reduced thermal impact
- Reduces need for electrical bus upgrade as MEPS can be placed at the load
  - Do not need to upgrade power system to supply high power loads
  - Decentralized approach reduces burden on energy generator/storage

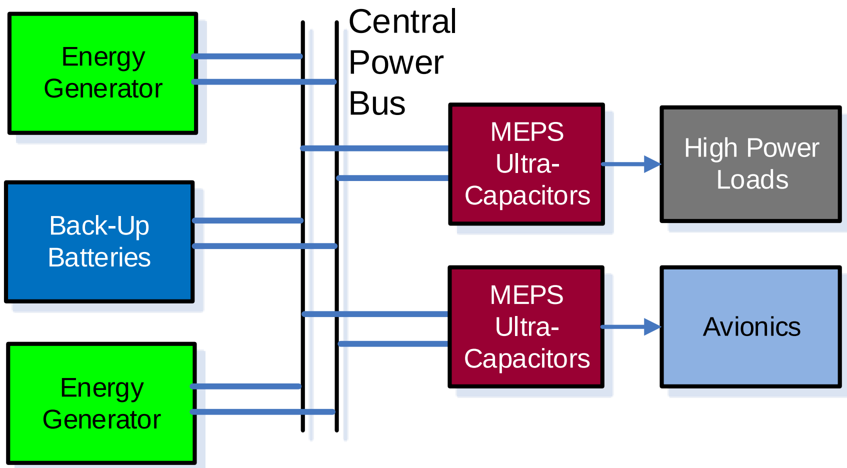
Power System Architecture

Centralized Common Package MEPS Hybrid Systems Architecture



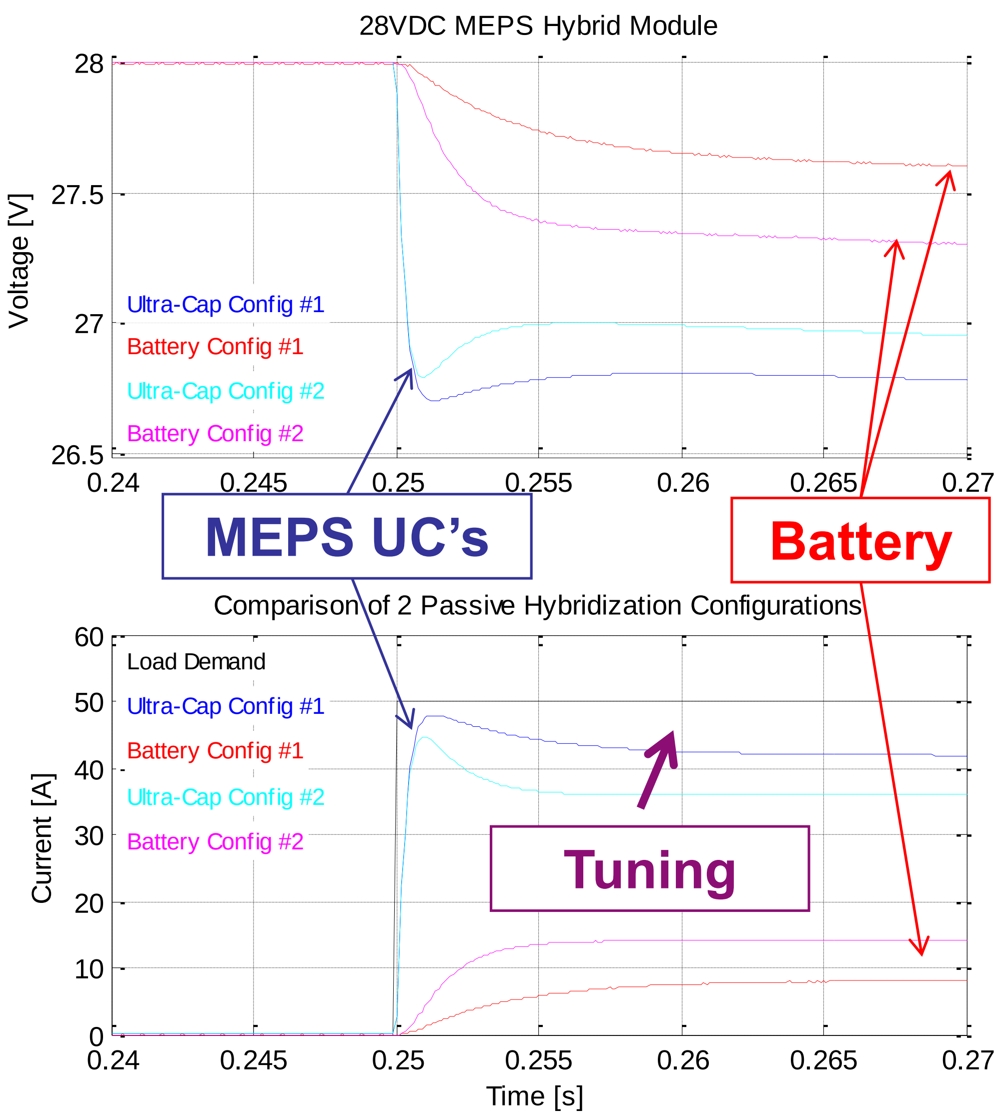
- Power dense point solution that is optimized for weight / volume
- Provides buffering action between the load(s) and the battery
- *Intended Small/Micro Sat Application*

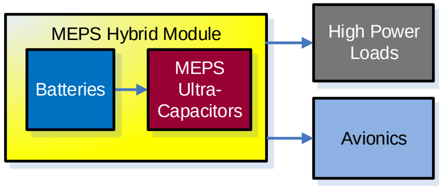
Decentralized MEPS Hybrid System in a Common Bus Architecture



- 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 MEA Application*

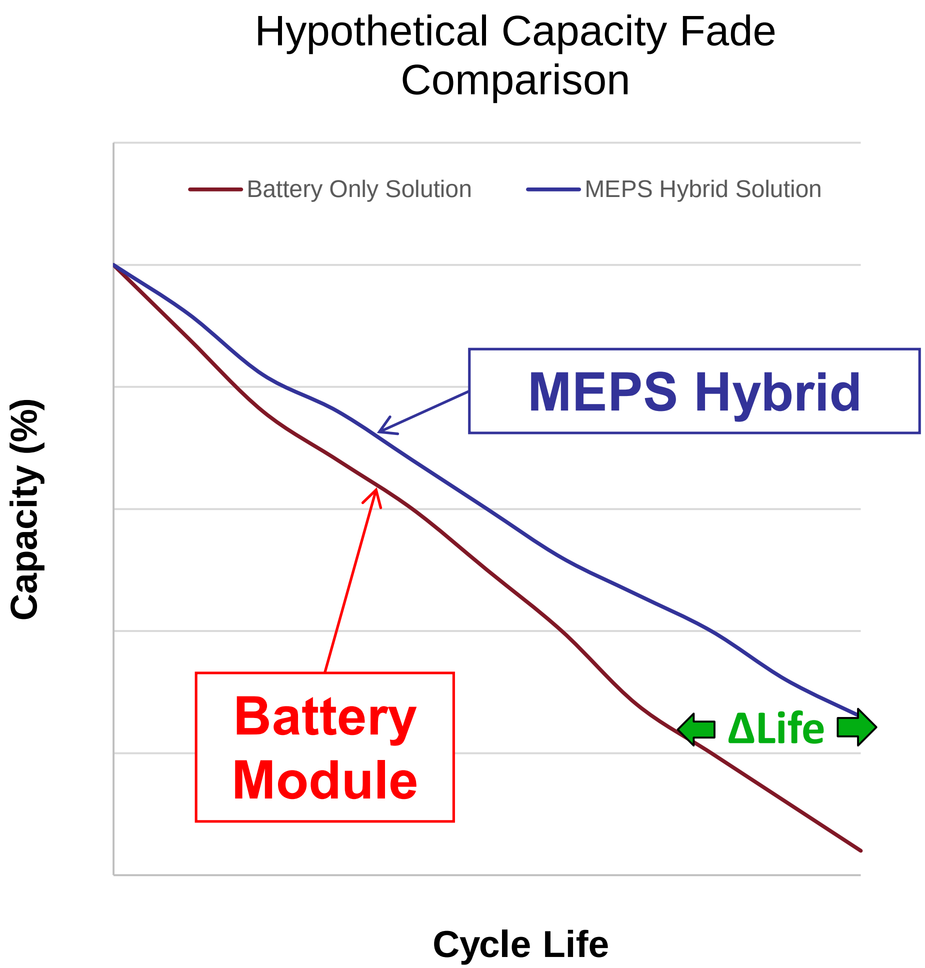
Passive Hybridization with Batteries





- The passive hybridization architecture can be tuned based on the desired implementation
- MEPS UC's can change the rate & magnitude of battery discharge altering the requirement placed on the battery
- MEPS enables the use of High Energy Density Batteries

Long Duration Capacity Comparison

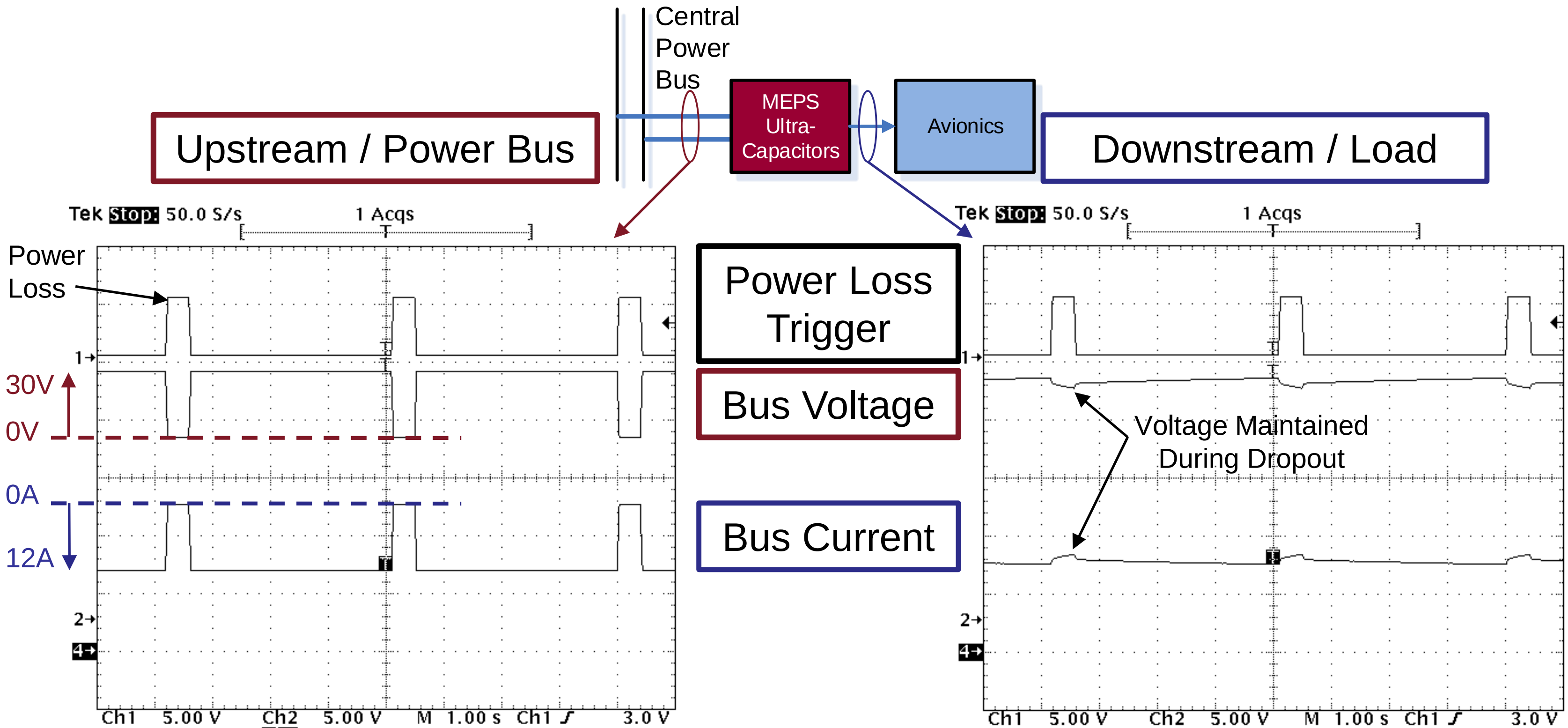


Ultra-capacitors serve as a peak shaving element for a battery, reducing the rate and magnitude of discharge.

- Extend the capability of the battery by reducing the capacity fade over multiple cycles
- Conversely can reduce # of batteries to achieve same desired mission timeline

** "Effect of ultracapacitor-modified PHEV protocol on performance degradation in lithium-ion cells", Clark G. Hochgraf, John K. Basco, Theodore P. Bohn, Ira Bloom. Journal of Power Sources, 2012.*

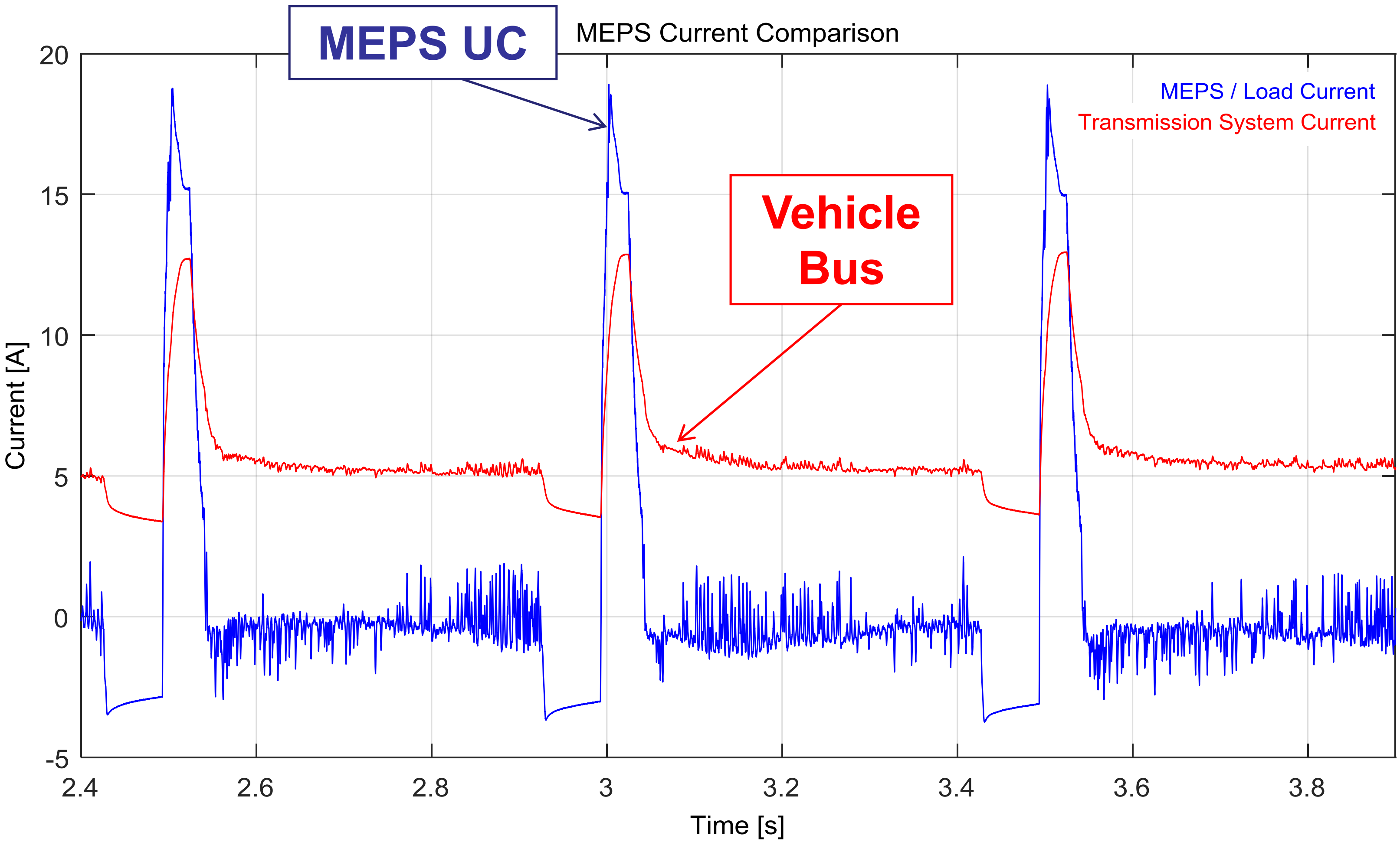
Low Power Transient Protection for Avionics



- Avionics place stringent requirements for “clean power” on electrical systems
- Sensitive Loads are more tolerant to voltage fluctuations due to excessive use
  - Inverting to 3Ø AC in motor control applications can pollute power bus
- Mitigates the effects of transients from the central power bus on sensitive electronics
- Adding a low power MEPS buffer between the delivery system and the Avionics allows the upstream delivery system power quality requirements to be relaxed

MEPS Test Data - 60% Pulse Power Output

Displacement



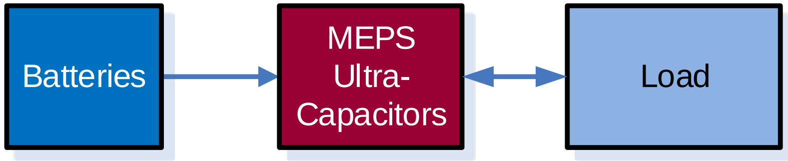
NASA GRC Capacity Fade Testing Overview

Test Methodology:

- Intent of the testing is to replicate as close as possible a Satellite Electrical Power System (EPS) undergoing LEO Power Profiles (40% DoD)
- Conducted on a Battery Only configuration & a MEPS Supplemented configuration
- All cells* screened & sorted, no BMS utilized

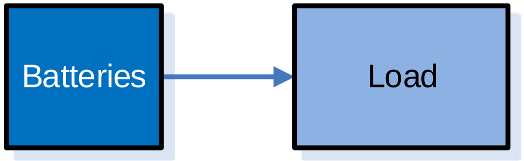
MEPS Based Test:

- Test on MEPS 12S1P 10F UC's & 8S3P battery configuration



Battery Only Test:

- Test on 8S3P battery configuration



Cells provided by ABSL for testing – E-Moli ICR18650J

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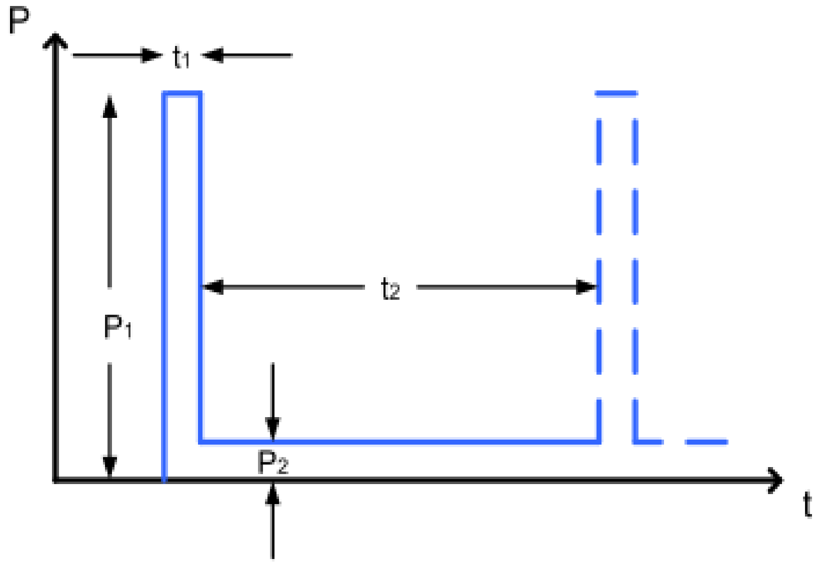
NASA GRC Capacity Fade Testing Overview

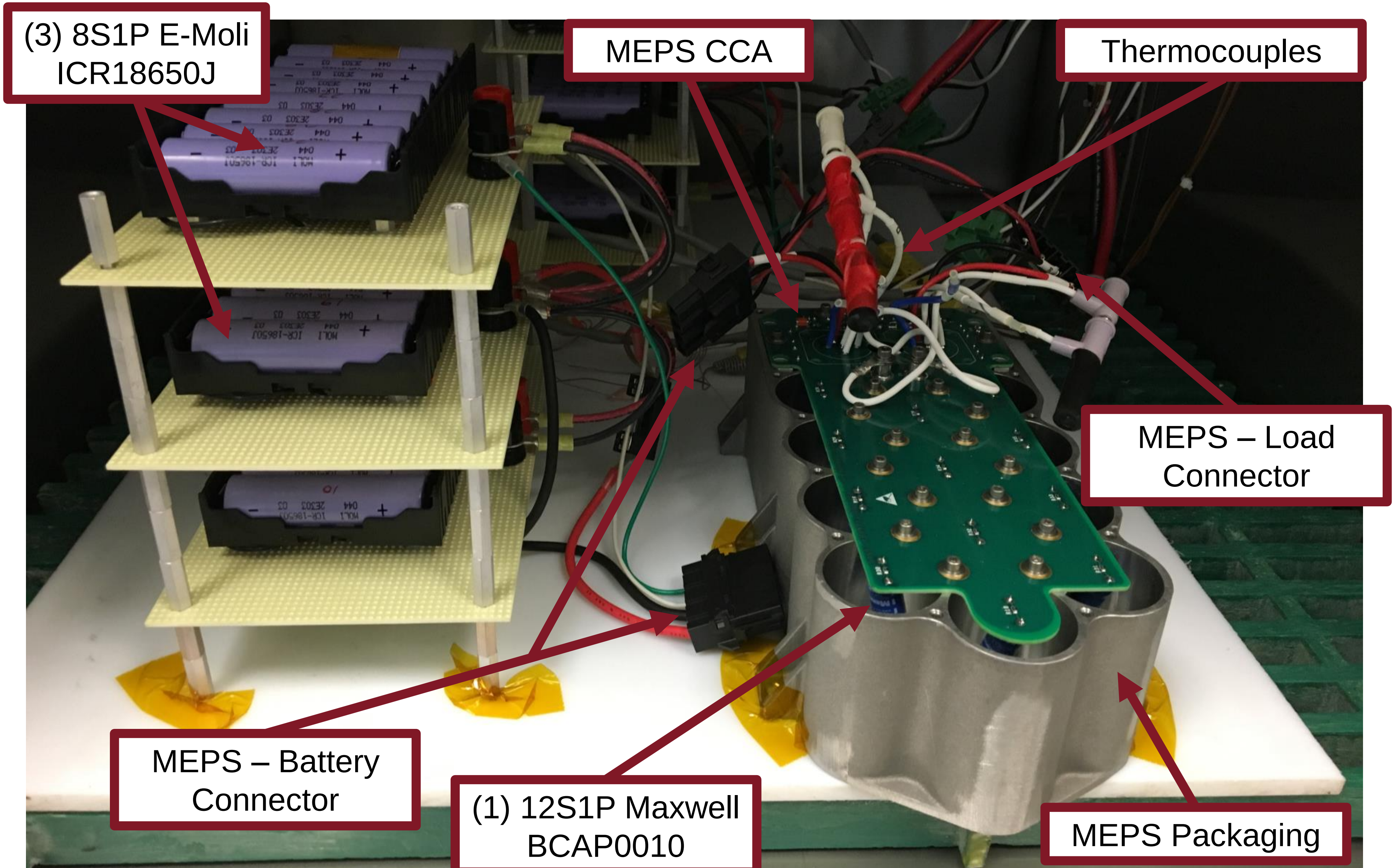


Variable	Value
t1 (s)	1
t2 (s)	59
P1 (W)	200
P2 (W)	100
Avg P (W)	101.6
Discharge Cutoff (Ah)	2.8944
Charge Rate (A)	3.6
Charge Voltage (V)	33.6

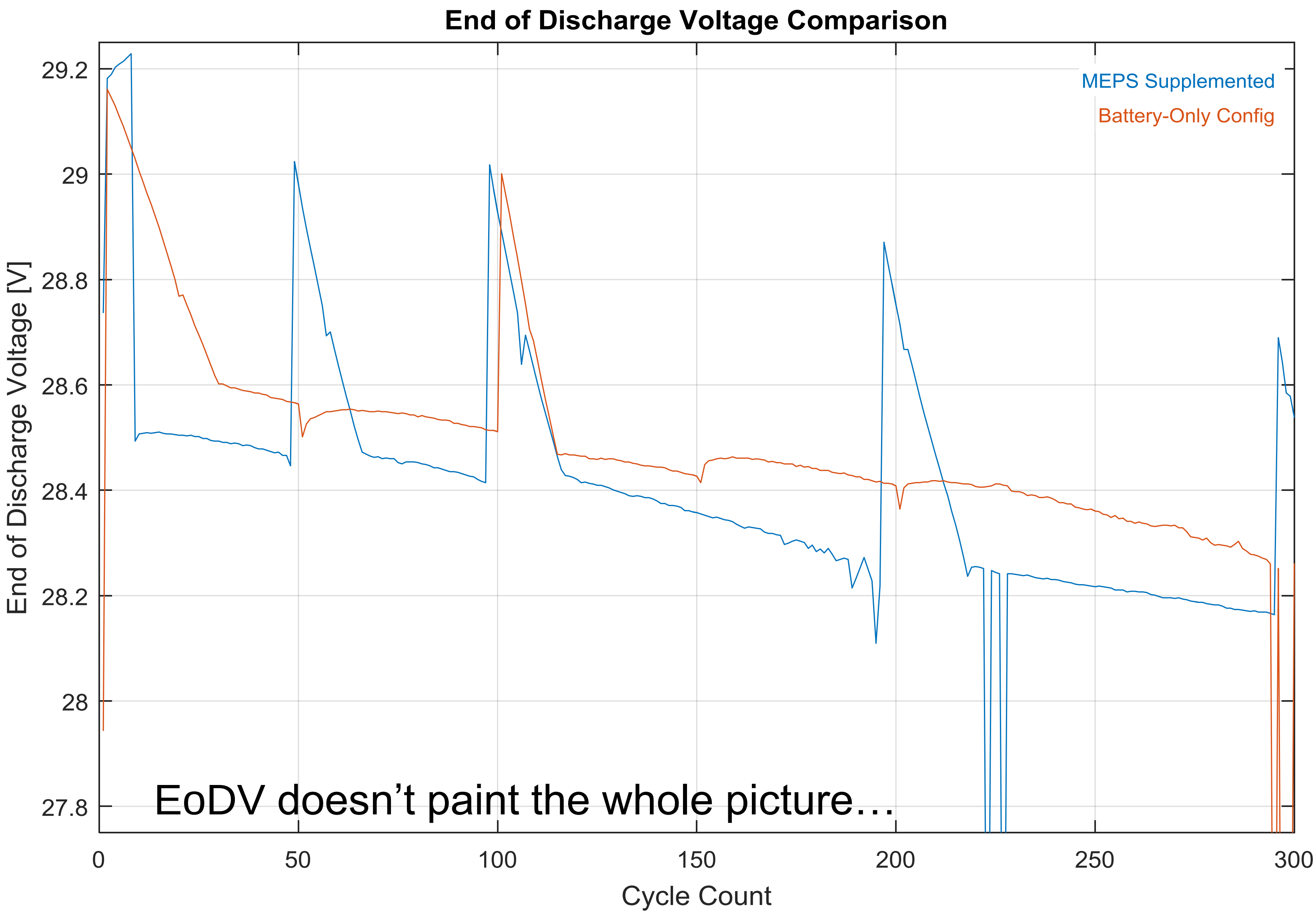
Test Specifics:

- Included in the $C/_2$ base rate of discharge is a 1s 1C discharge
  - This is meant to replicate peak discharges found in satellite EPS (Thruster/Valve/etc.)
- The charge was CC/CV to 33.6VDC tapered to $C/_{50}$ but capped at a specific capacity
- The discharge cut-off was based on capacity discharged (40% DoD)

NASA GRC Capacity Fade Test Picture

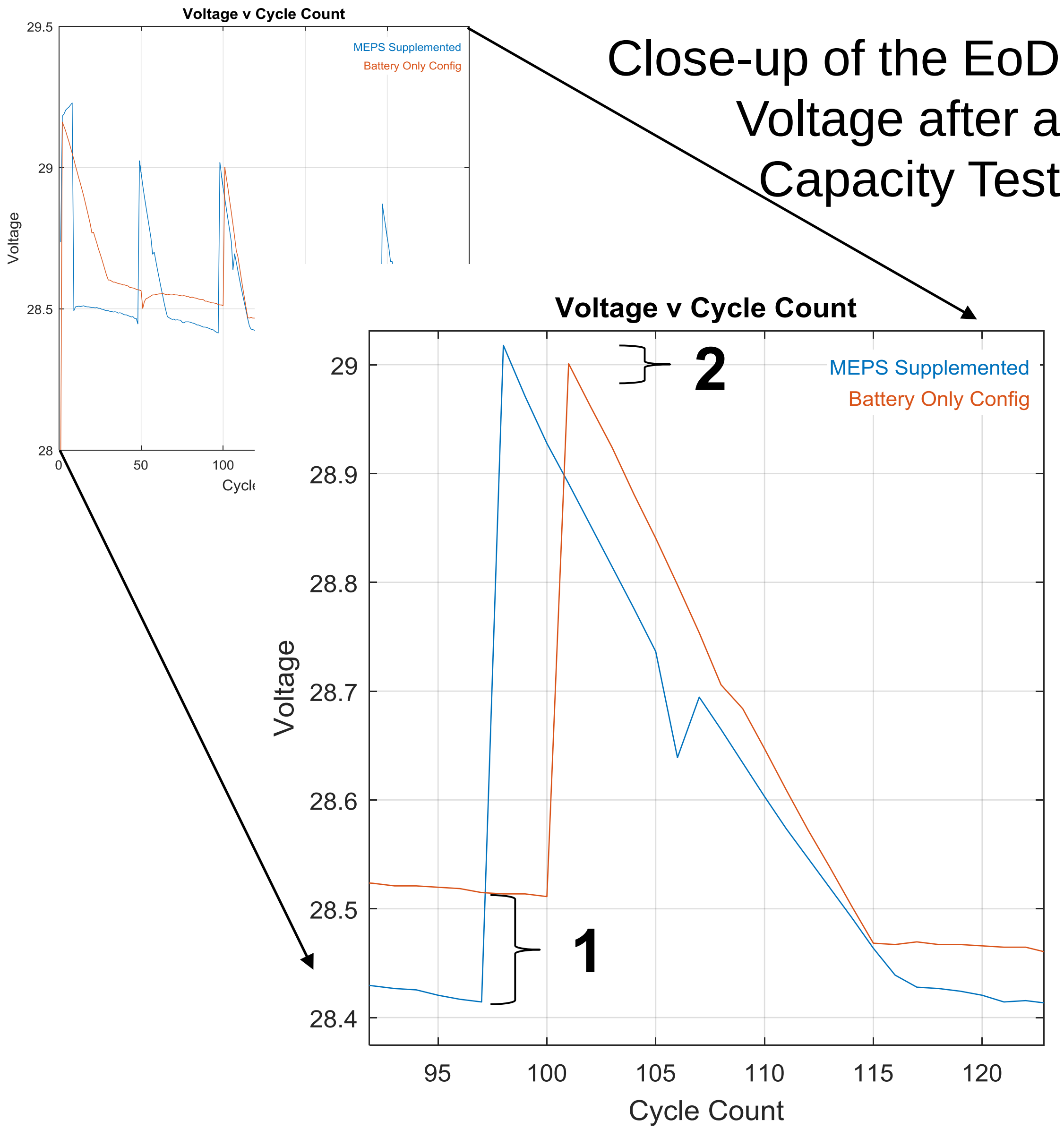


Cycle by Cycle Comparison

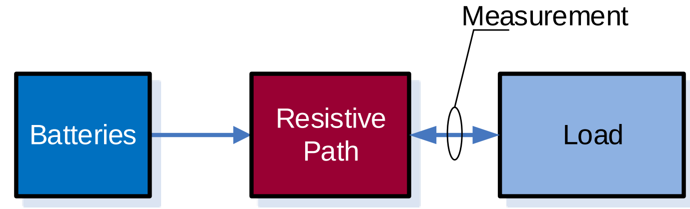


End of Cycle Voltage Comparison

Close-up of the EoD Voltage after a Capacity Test

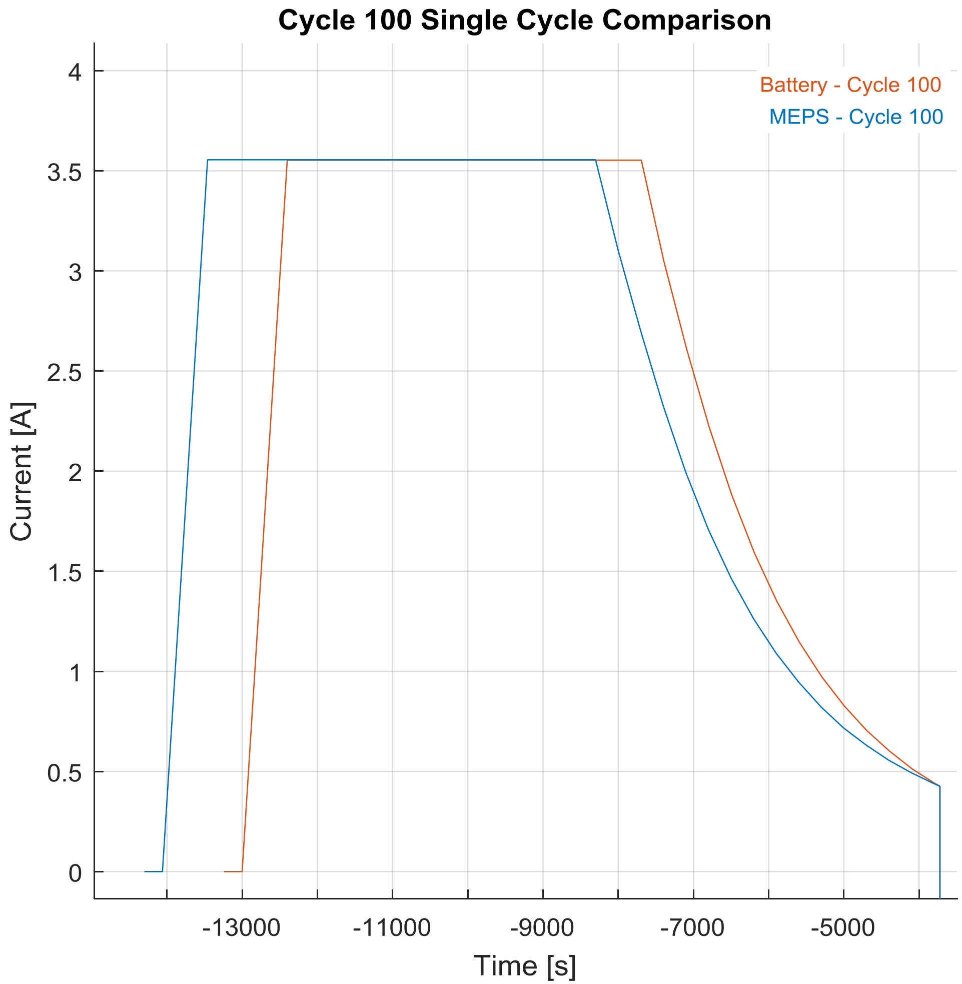


1. MEPS EoD Voltage is lower due to leakage/Ω



2. MEPS EoD Voltage after Residual Capacity Test shows that it recovers to similar voltage

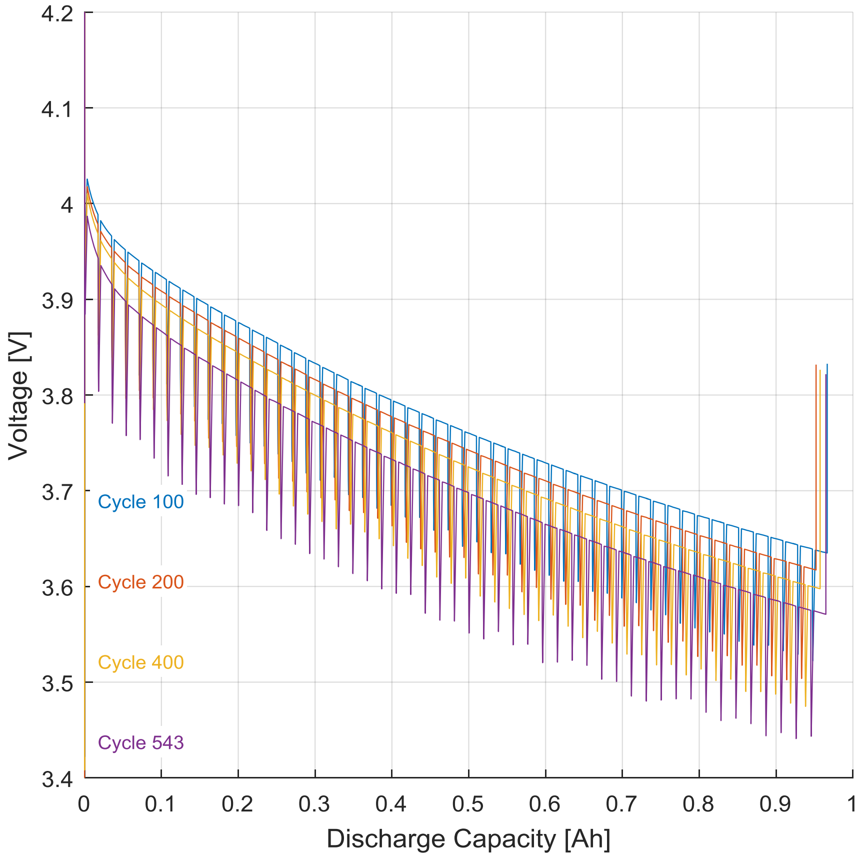
Charge Comparison



- More is charged into the MEPS configuration because of the resistive loss in the Balancing Ωs and leakage current that is present in the UC
  - Battery 2.89Ah
  - MEPS 3.03Ah
- Due to a “non-ideal” test asset that had safety circuitry
  - Soft-start
  - Switches

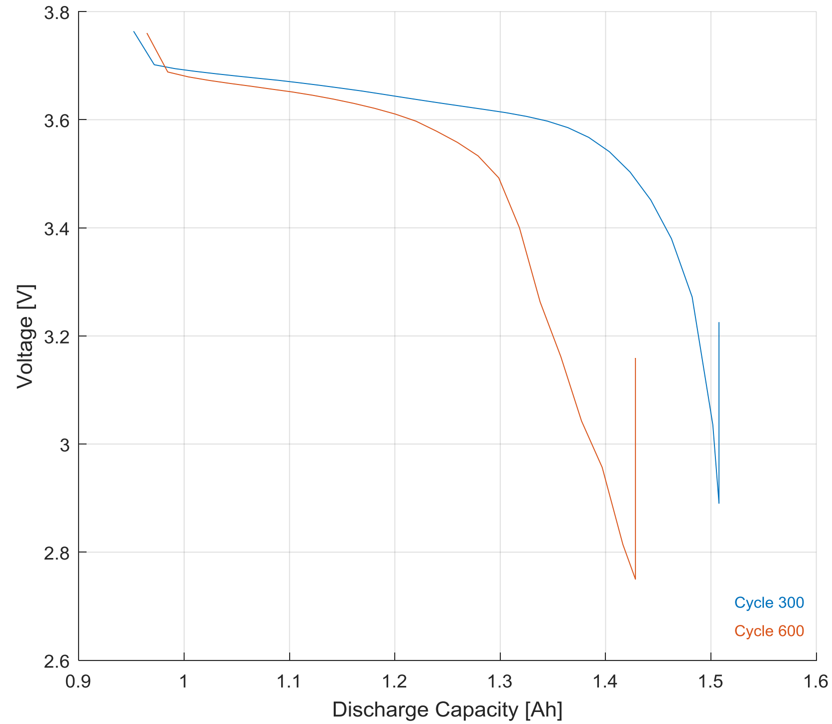
MEPS Supplemented Test Results

40% DoD LEO Cycle Test – Averaged Single Cell w/ MEPS



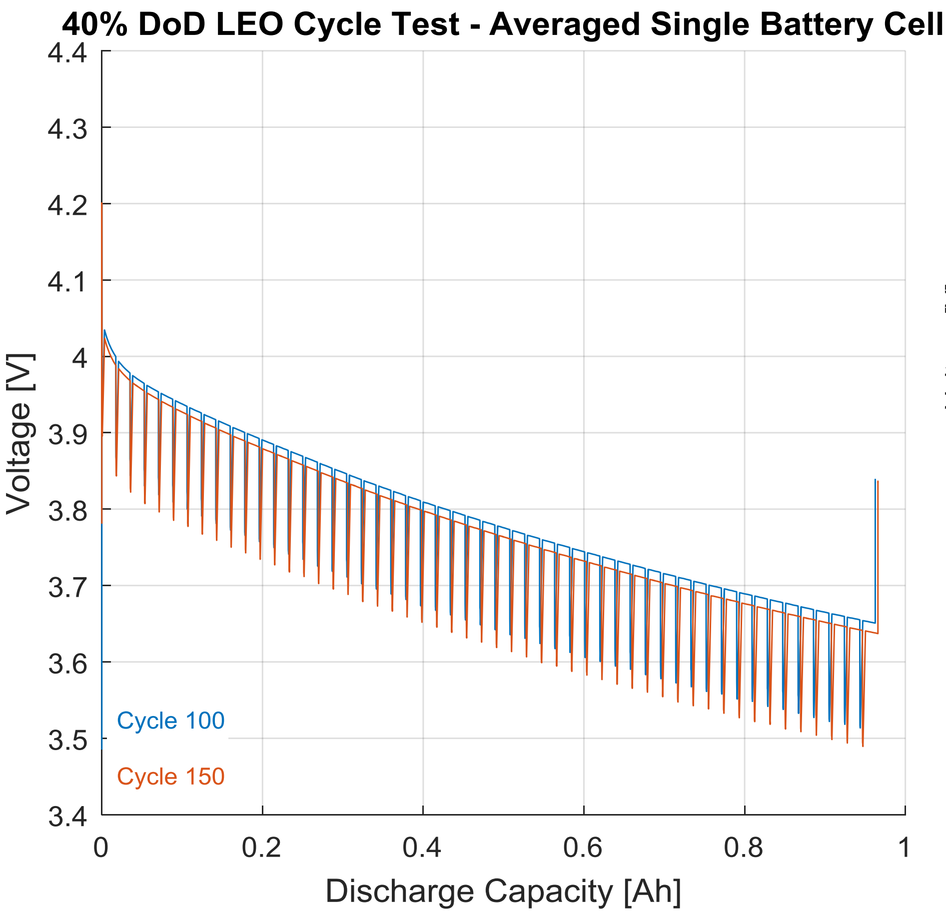
Cycle #	V Initial [V]	V Final [V]	ESR [Ω]	Charge Capacity [Ah]	Charge Energy [Wh]
100	4.2	3.64	0.103	2.5033	10.1790
200	4.2	3.62	0.107	2.4619	10.0455
400	4.2	3.60	0.120	2.3687	9.7117
543	4.2	3.57	0.128	1.3419	5.5993

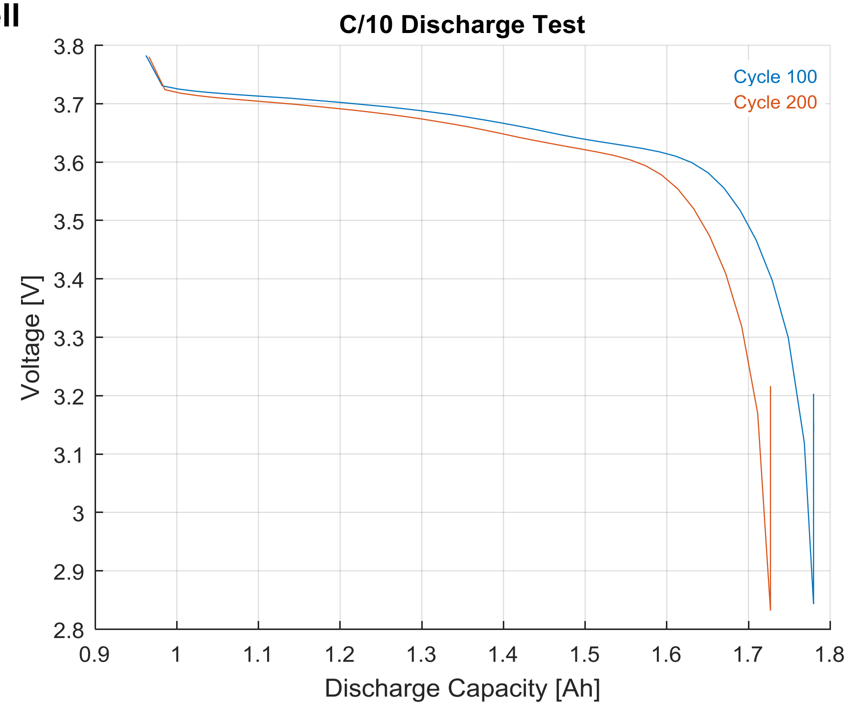
C/10 Discharge Test



- The aggressive LEO profile shows that there is a reduction in capacity
- MEPS displaces roughly 60% of the peak power from the battery
- MEPS buffers the output, reducing the rate and magnitude

Battery Only Test Results





Cycle #	V Initial [V]	V Final [V]	ESR [Ω]	Charge Capacity [Ah]	Charge Energy [Wh]
100	4.2	3.65	0.102	2.289	9.328
150	4.2	3.64	0.110	1.519	6.274

- More data needs to be accumulated (out to ~600 cycles) to make accurate comparisons

Next Steps

Inconsistencies in testing do not allow a fair comparison of the true impact of the ultra-capacitor buffer. What we need to still do…

- Perform a C/10 100% DoD discharge to characterize the MEPS supplemented battery
  - The cycle count is at 600 LEO cycles
- Continue testing the battery-only 8S3P module out to the same cycle count (600 LEO cycles)
- Perform a C/10 100% DoD discharge to characterize the battery only 8S3P module

These extra steps will allow the fair comparison to be made

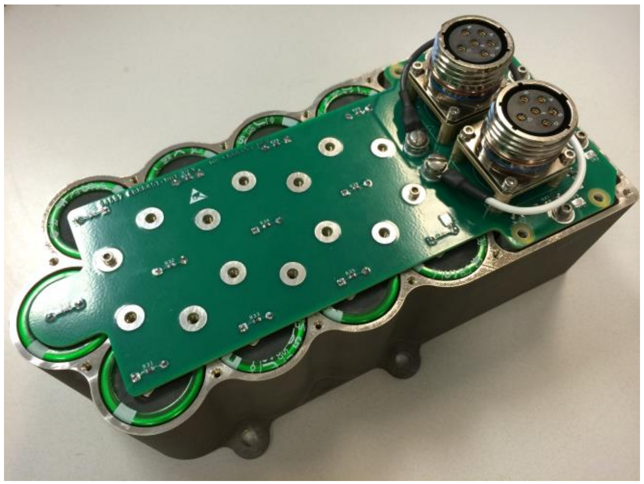
Testing Conclusions

- This altered LEO cycle represents a hypothetical test that exercises a more realistic duty cycle beyond a steady state discharge duty cycle
- The buffering action of MEPS plausibly leads to a reduction in capacity fade
  - *Testing is not yet completed!*
- The MEPS circuit was originally designed to be “lab safe” as there is a master safety transistor on the input and output to protect from accidental short circuit
  - This leads to a ~26mA leakage through these components
  - This is an unnecessary component that ***WOULD NOT*** be included in a final design – test artifact only
- The 1C pulse may be too low to take full advantage of the MEPS supplemented EPS

MEPS: Modular Product & Future

Product:

28VDC – 5kW
MEPS Ultra-Capacitor Package



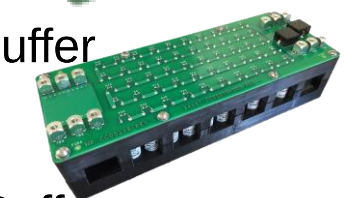
- Weight: 3.2 kg
- Volume: 4.3” x 9.5” x 3.5”
- Peak Power: 5 kW
- Voltage Range: 22VDC to 36VDC
- Technology Readiness Level Attained ➔ 5~6
- Agnostic to Battery Chemistry
- Can connect directly to Vehicle Bus
- No external charge circuitry necessary
- Tested to DO-160G / MIL-STD-1540b
  - 38GRMS/All Axes

Future:

Modular building blocks are key to sizing *Flexibility*

Small Power Buffer – Satellite Pwr Sys
- 28VDC – 150W
- ½U to 1U form factor

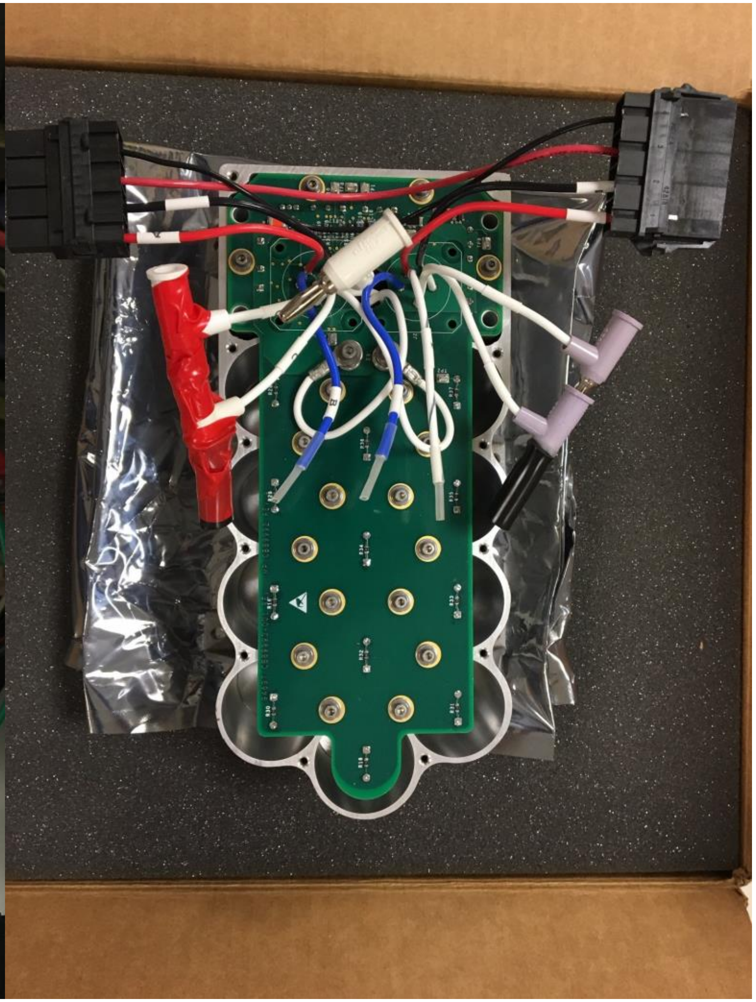
High Voltage Low Power Buffer
- 280VDC – 2000W



High Voltage High Power Buffer
- 280VDC – 50kW

Multiple Configurations & Possibilities
- Moog Power System Designers can conduct a Trade Study on Vehicle Power Systems to recommend architectures
- Agnostic to Battery Chemistry
- Can connect directly to Vehicle Bus
- No external charge circuitry necessary

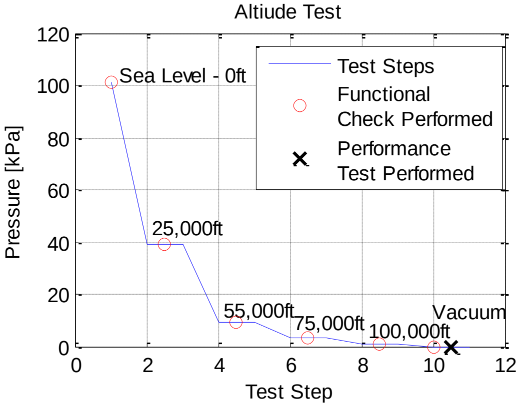
Questions & Comments?



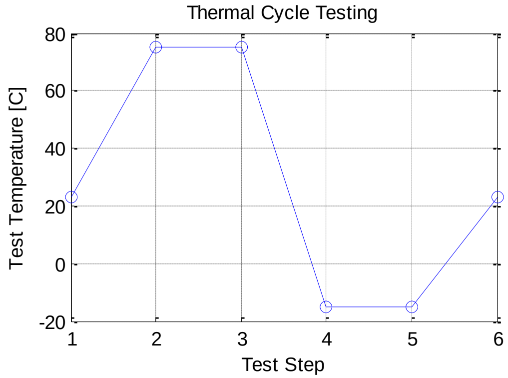
Testing funded under Space Act Agreement No. SAA3-1412 between NASA Glenn & Moog, Inc. for Ultra Capacitor Battery Testing

MEPS: Conclusion

Altitude



Thermal

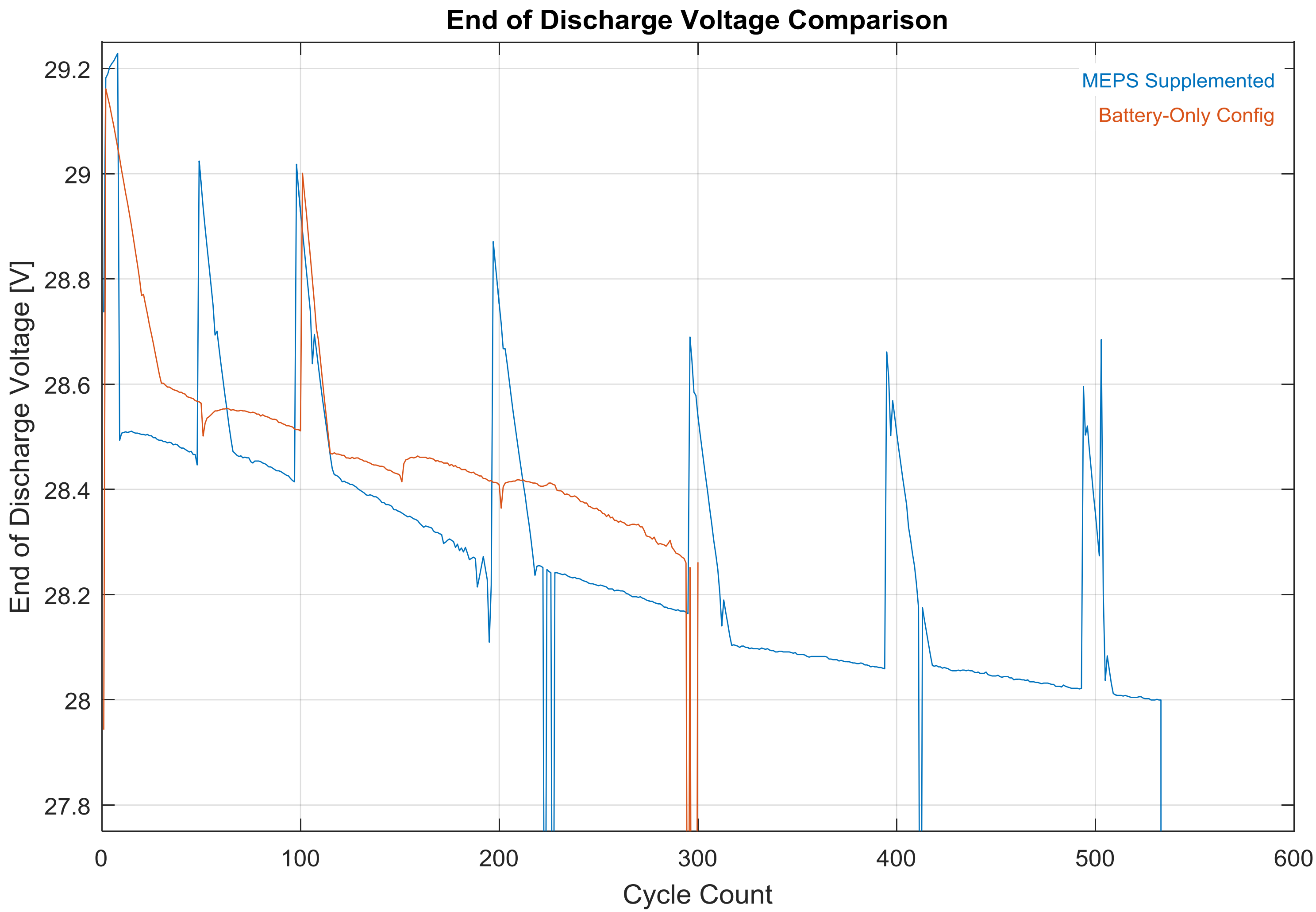


Vibration

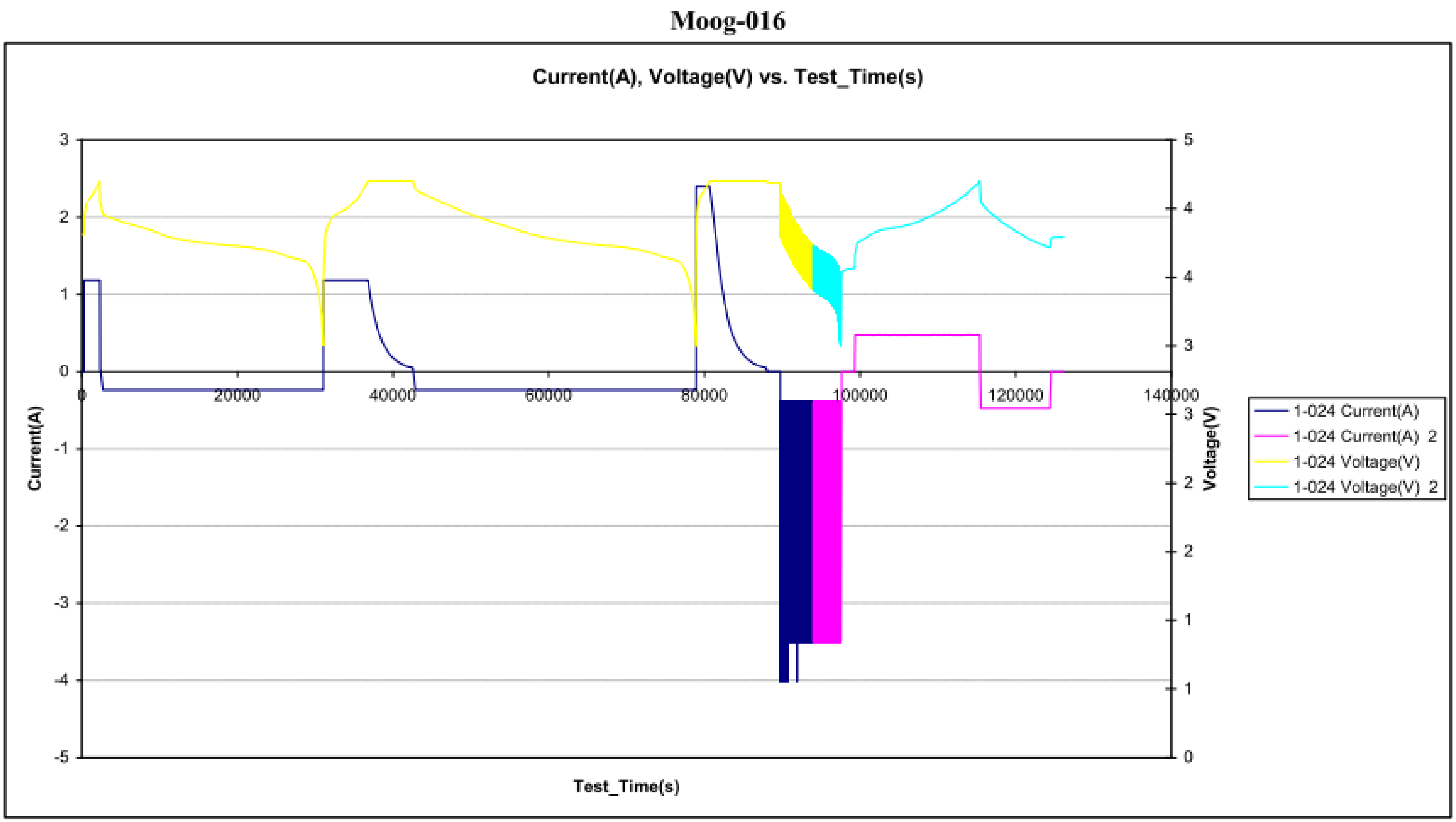
Vibration Test Results			
GRMS	X-Axis	Y-Axis	Z-Axis
9	Pass	Pass	Pass
19	Pass	Pass	Pass
27	Pass	Pass	Pass
38	Pass	Pass	Pass

- Hybridization of (*High Energy Density*) Batteries and Ultra-Capacitors is possible
  - *Harness advantages of individual technologies to optimize on a flexible high energy / power density solution*
- MEPS reduces the peak power demand on the central vehicle electrical system by providing a “buffer” action to the central circuit
  - *Reduced weight in central generator & back-up system*
- MEPS removes the need for a regen circuit / regen resistor by capturing & reusing the energy
  - *Reduced thermal control burden on system architect*
- MEPS along with an optimized battery module can be the building blocks for the entire vehicle’s power needs
  - *Reduced dynamic requirement on High Energy Density Batteries reduces burden and complexity (& Schedule/$)*
  - *Intelligent design yields simplistic results*
  - *One part number, one qualification, high quantity*

Full Picture of EoD Voltage Comparison

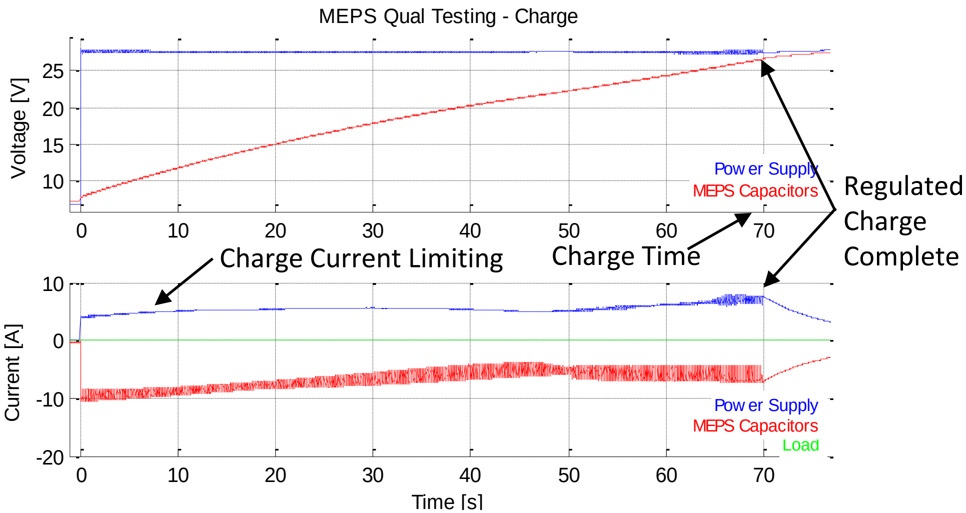


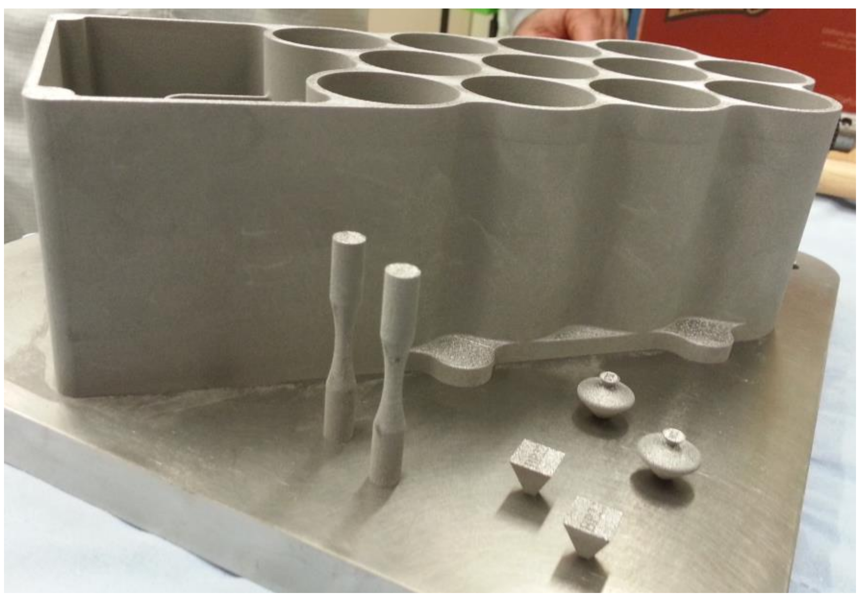
Sort & Screening Data Capture



Cycle_Index	Test_Time(s)	Date_Time	Current(A)	Voltage(V)	Charge_Capacity(Ah)	Discharge_Capacity(Ah)	Charge_Energy(Wh)	Discharge_Energy(Wh)	Charge_Time(s)	DisCharge_Time(s)
1	31059	07/24/15 22:56:08	-0.237	3.000	0.682	1.885	2.798	7.061	2098.676475	28660.52904
2	78983	07/25/15 12:14:56	-0.237	3.000	2.409	2.396	9.734	9.122	11508.33491	36415.27899
3	97523	07/25/15 18:03:44	-3.498	2.999	2.396	1.467	9.949	5.331	8977.722043	7658.64574

Novelty Beyond Ultra-Capacitors





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

Packaging

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