X-57 Traction Power System

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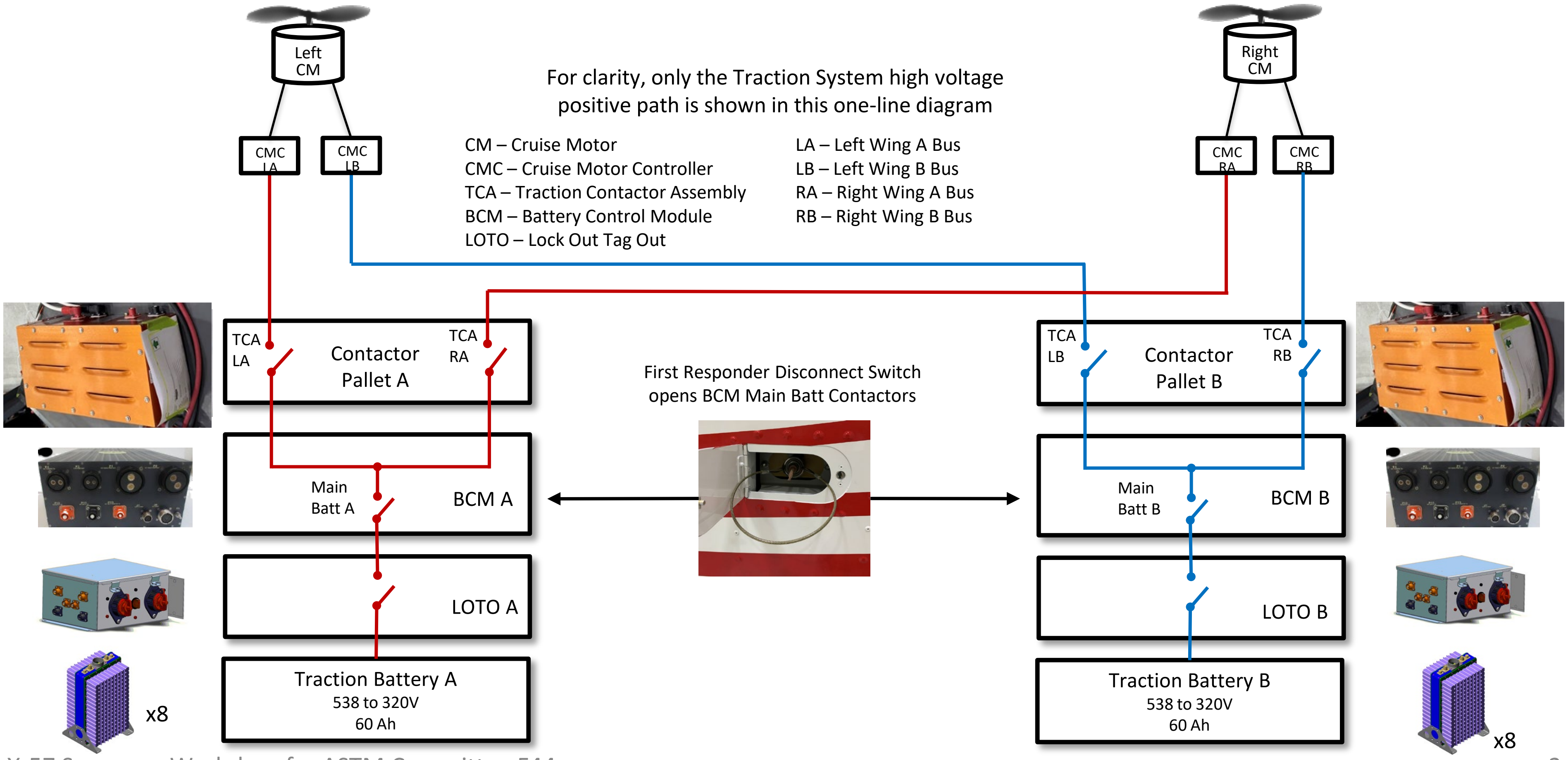
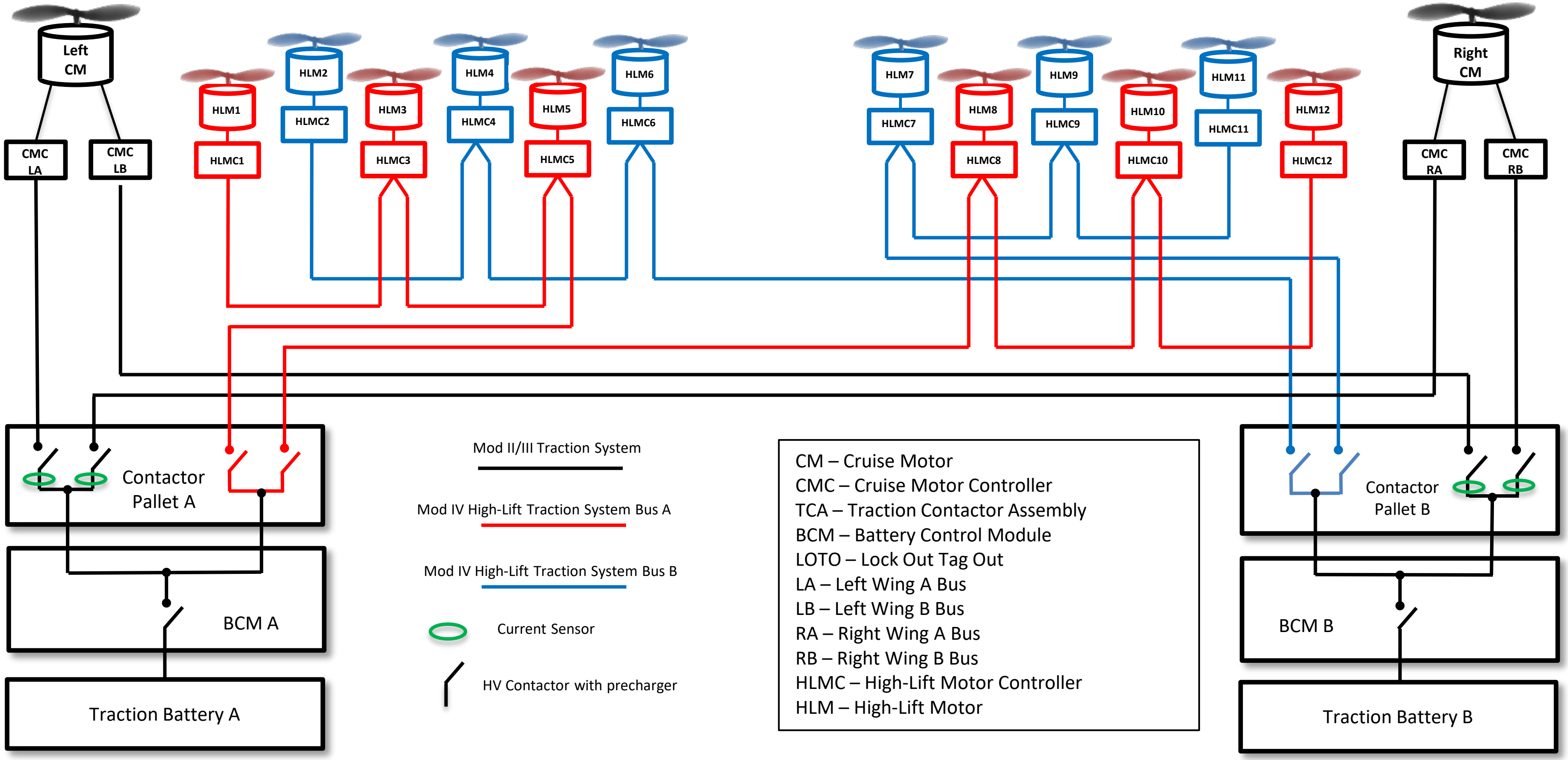
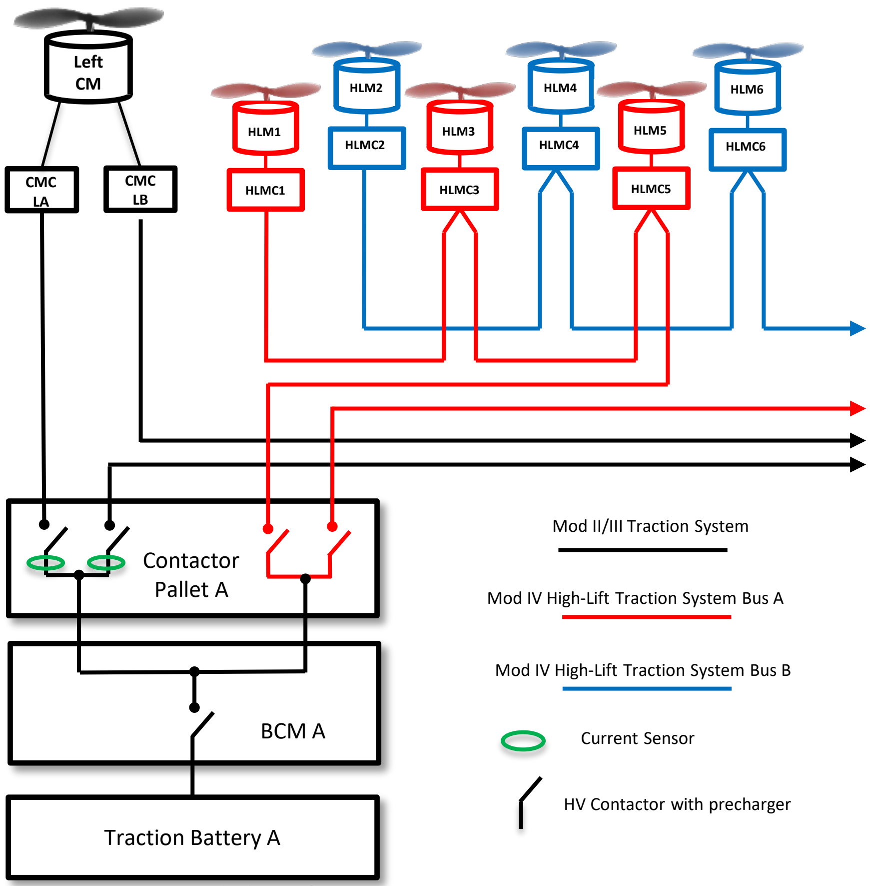
Traction Power System, Mod II and III



Traction Power System, Mod IV



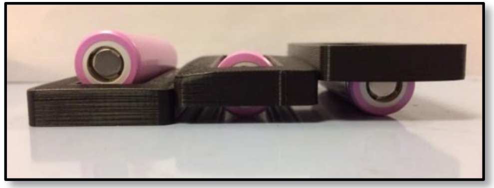
Traction Power System Thoughts



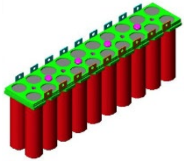
- Redundant design simplified hazard analysis
- First responder contactor control requirement not apparent until detailed con-ops were evaluated
- Contactor/precharger functionality somewhat redundant between BCMs and Contactor Pallets, but this was necessary to accommodate different development configurations (e.g., batt sim, batt load test) along with nominal modes (batt powered motors, batt charging)
- Split output from BCMs was a minor annoyance; High Voltage hazard if some components unpopulated.
- Individual control of traction buses (via Contactor Pallets) was useful for build-up test configurations.
- Relied on separate bus power (Voltage & Current) sensors instead of developmental components for both sense and display, but added another subsystem in need of development

Traction Battery Modules

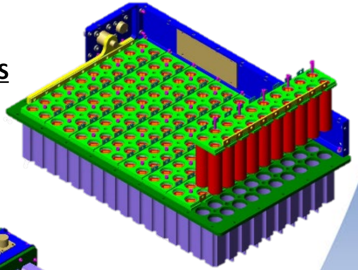
- Function: Energy Storage for vehicle traction (propulsion)
  - Each Brick has two temperature sensors and a voltage sensor monitored continuously
  - Each module is 60 Ah at 57.6 V nominal (3,456 Wh)
  - Pack is string of 8 modules 538 to 320V, 27.6 kWh, 2560 cells
- Cells are COTS from Samsung with established heritage on previous NASA and EPS contracts
- Large lots were purchased and then cells are screened for conformity in initial resting voltage, mass, resistance, and diameter (see JSC work guide for details)



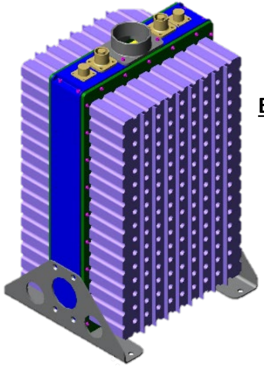
Mechanical Fixture pass-through test.



20P-1S Brick
20 Cells
3.6 Volts (Nominal)
60 Ah - 216 Wh (0.2C)



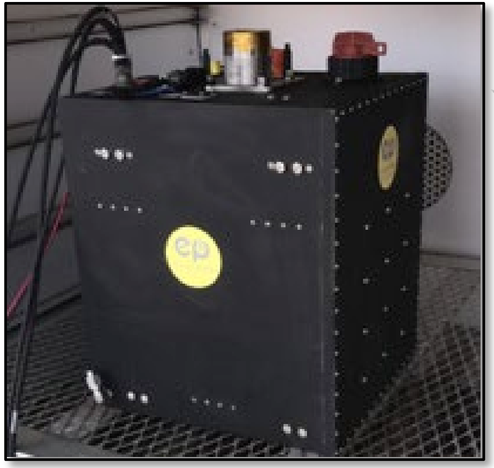
Sub-Module 20P-8S
8 Bricks
160 Cells



Battery Module 20P-16S
2 Sub-Modules
320 Cells
57.6 Volts
60 Ah - 3,456 Wh

X-57 Flight Batteries (Original Approach)

- Built to published best practice for cylindrical cell packaging, which at the time was an air gap of 2 to 4 mm
- Failed Thermal Runaway Propagation Prevention Test (cell venting is a higher risk for thin-wall cans).
- Full gas and particulate containment would drive sealed designs and increased weight (vehicle venting usually more appropriate)
- Gas-permeable caps to equalize pressure and prevent FOD ingress were not yet available. Membrane selection incorrect: during cell runaway did not either equalize pressure fast enough or burst (feature of current products)
- Cell cooling provisions in air-gap architecture were complex and negate mass savings



Original Battery Module (~110 lb)

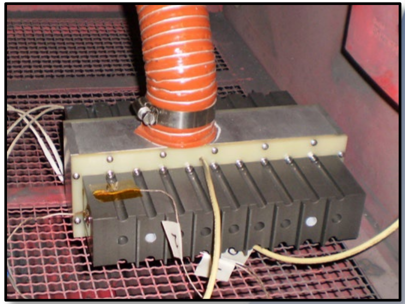
Battery Control Module (25 lb) contains BMS, contactors, HV distribution

X-57 Flight Battery Destructive Testing

Battery Module Development

- Driving requirement: high reliability pack that it does not present a hazard to the pilot and established a reference for public standards
- Development process included iterative prototype tests, capacity test, and mission profile test
- Parallel / series architecture highly dependent on system-level requirements (one size does not fit all)
- Dimensions and tolerances inspired by JSC ISS design, but required many rounds of iteration dial in the design for the 30Q cell
- Design tolerates failure of individual cells (opening, shorting, or thermal runaway) without full module runaway/fire
  - Cells can shed heat to surrounding structure and to neighboring cells. Design iterated through cell spacing (wall thickness) and cavity clearance to verify mechanical fit allowance before cell thermal runaway testing on full module
- X-57 Maxwell Battery From Cell Level To System Level Design And Testing (Presented at IEEE/AIAA EATS ntrs.nasa.gov/citations/20180005737)

NASA JSC Test Unit With Interstitial Barrier and Heat Spreader (Design Template)

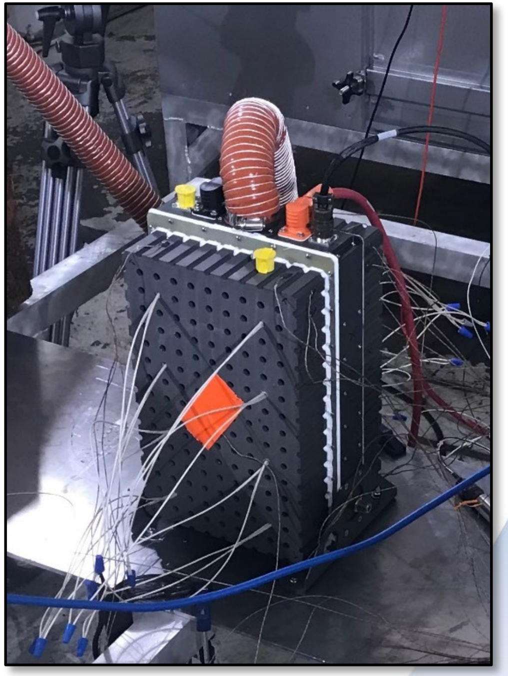


Thermal Runaway Plenum Containment Prototype

Traction Battery Module Testing

- Proto-qual and acceptance testing was successfully performed per the X-57 Environmental Test Plan (ETP-CEPT-007)
  - Thermal, Vibe, Shock, EMI/EMC, Short Circuit and thermal runaway containment test
  - Shipset 1 full proto-qual (1 module)

- Battery modules Acceptance Test Program (ATP) also included Hi-Pot and Functional tests, and the design was previously shown to contain thermal runaway.
  - Shipset 1 and 2 acceptance tests



Battery Module Thermal Runaway Containment Test

Battery Module Acceptance Test Program

High Pot
- 1500 Volts
- 15 kV/s ramp, 5 s dwell
- Leakage Current threshold: 3.0 mA

Functional
- Communications
- System Charge
- Capacity Check
- Mission Profile
- BCM Discharge Test
- Balancing to 20mV

Thermal
- 21 cycles
- -15C to +60C

Vibration
- X-57 Curve B1
- 20 mins/axis
- 4.13 Grms

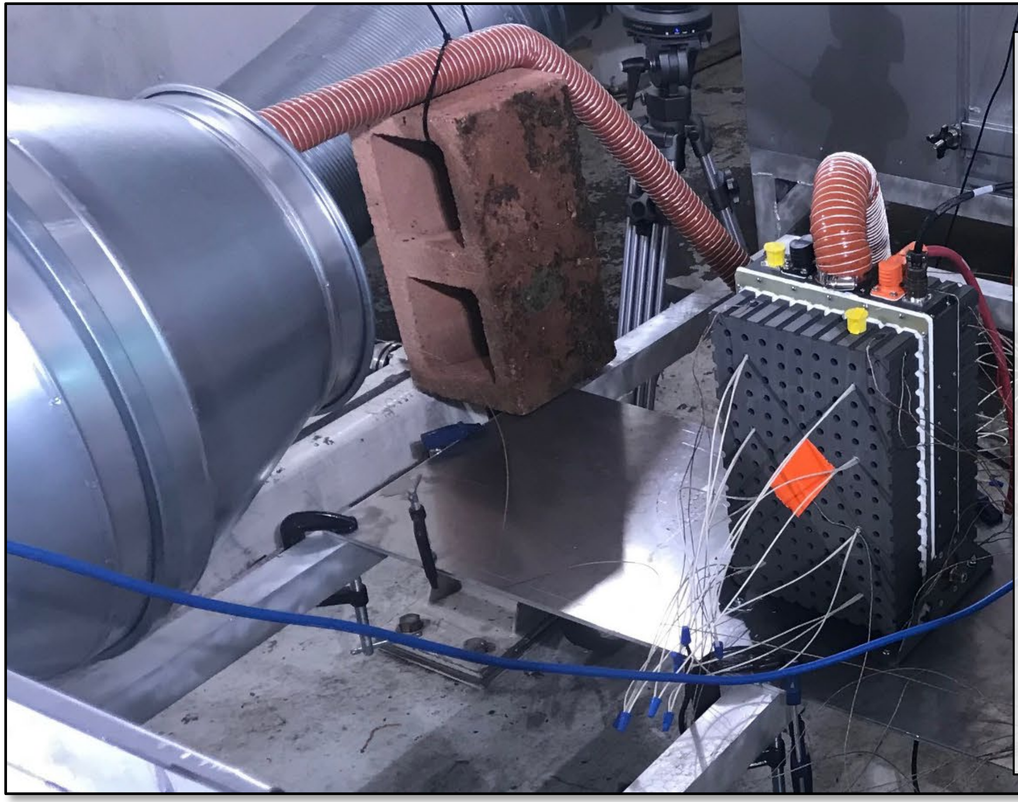
- 77-9008 Battery System Acceptance Test Procedure
- Flight Configuration of Eight battery Modules with single BCM
- Tested to Acceptance levels per DO-160D

Battery Module Qualification Test Program

Temp and Altitude	Vibration	Shock	EMC / EMI	Short Circuit	Thermal Runaway Containment
•12 cycles •-20C to +65C •15 kft press	•X-57 Curve B2 •60 mins/axis •5.84 Grms	•3 per axis •6g peak, 11ms	•Magnetic Effects (14.4 A/m) •AF Cond. Suscept. (Cat Z) •Induced Suscept. •RF Susceptibility •- CS and RS to Cat S •Emission of RF Energy (Cat B) •Electrostatic Discharge (Cat A)	•Single Unit tested •In Procedure 77-9004	•Single Unit tested •In Procedure 77-9004 •Details on next slide

- Single battery Module configuration
- Tested to Proto-qualification levels per DO-160D
- Temp & Altitude/Vibration/Shock also tested at NTS

Thermal Runaway Propagation Prevention

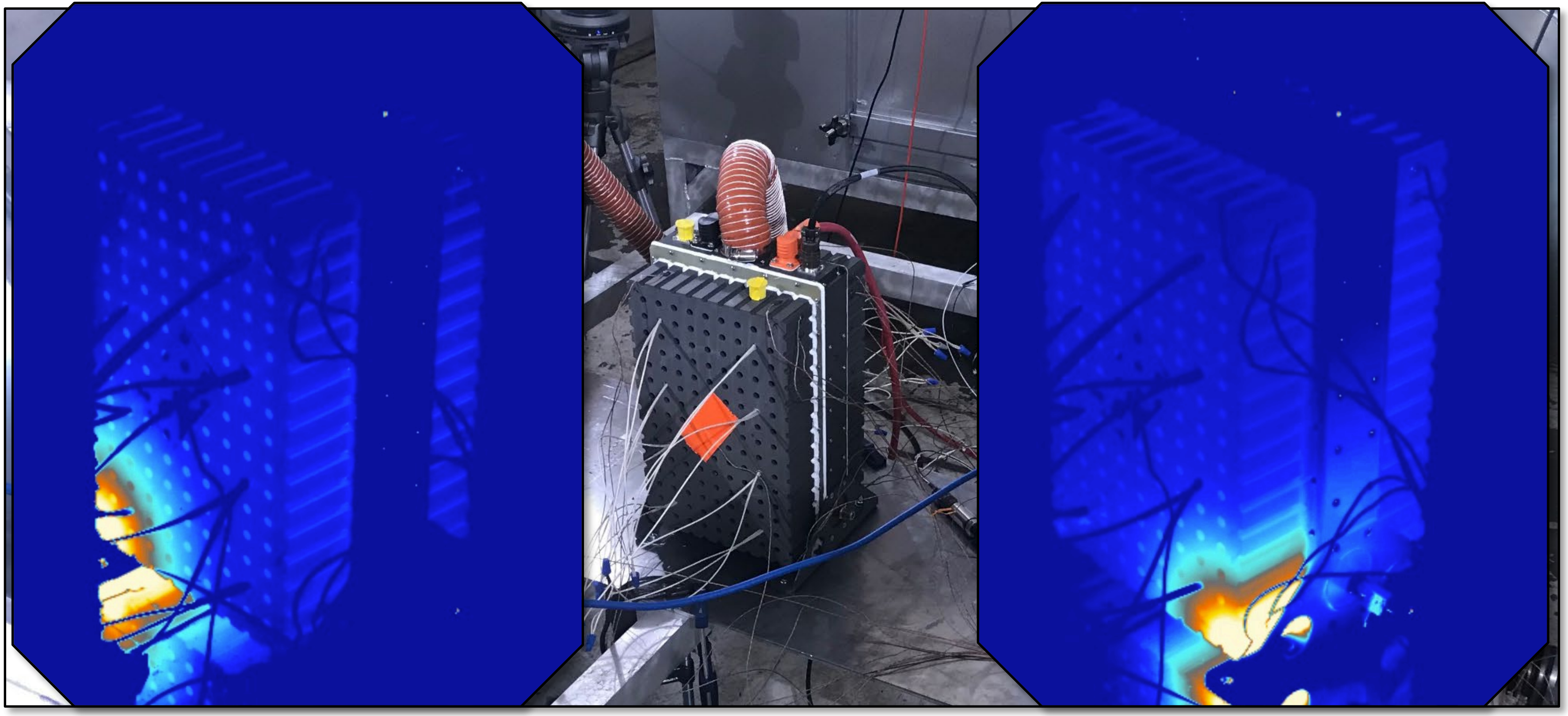


- One Test Module with 156 cells from the flight lot (30Q) and 4 corner cells with comparable energy (M36) but with internal short circuit devices
- Each M36 cell is wired independently (isolated from the rest of the battery)
- Rapid charge/discharge of the M36 cells used to trigger thermal runaway
- Vent temperature for cell at top of module peaked at 197℃; dropped below 100℃ in 6.1 seconds. Bottom cells runaway vent temp was <30℃
- Vent material is rated to 340℃

Thermal Runaway Propagation Prevention

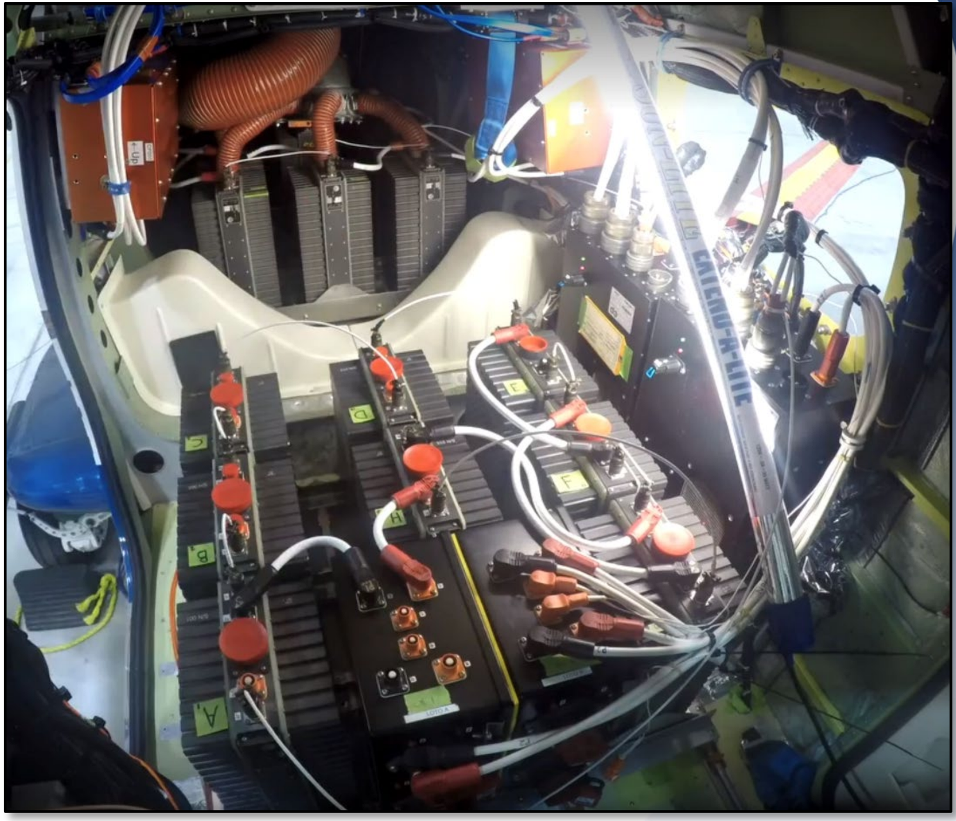
FLIR Video of Trigger Cell #4 Event (8x speed)

FLIR Video of Trigger Cell #3 Event (8x speed)



Traction Battery System Installation in Aircraft

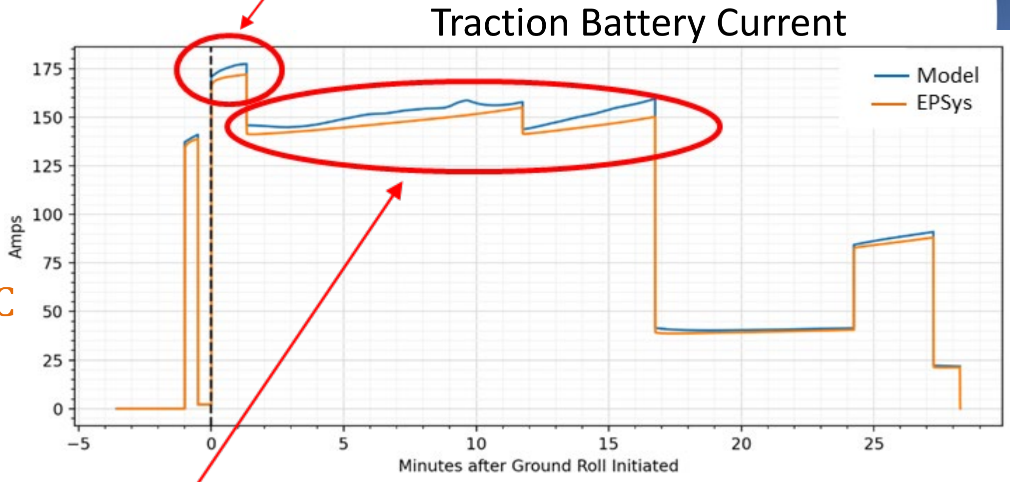
- Pack A in back seat area and Pack B in luggage area, each on reinforced rails
- "Octopus" vent system specified to match SCEET tube used in thermal runaway tests to contain ejecta during transient temperature extreme
- Vent not designed to forcefully exhaust cell gases, only provide expansion volume to prevent module case failure.
- Aerodynamic analysis of vent shows negative surface pressure coefficient at exit (will not impede exhaust)



LOTO Fuse Current Rating Margin

- The main purpose of fuse design is to protect against arc flash, which is a high current, short duration event, which can occur when the string of battery modules is being connected
- Modeling the Mod II reference mission predicts 150 A for 15 minutes
- The LOTO fuse is rating is 200 A, but derating for steady state reduces limit to 160 A at 25°C and 143 A at 50°C
- A higher rated fuse (e.g., 250 A or 300 A) provides insufficient arc flash protection
- More challenging in Mod IV, but thermal derating and mission length still acceptable given conservative cabin temperature model

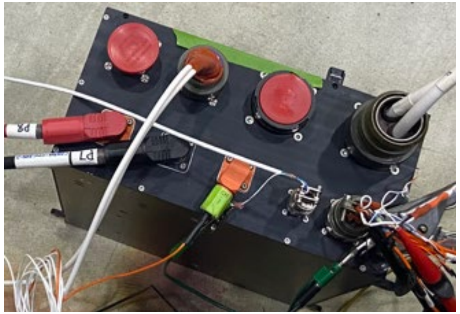
2-minute duration, which should be acceptable



15-minute duration, which should be acceptable at room temperature, but at 50°C, this is over the recommended current level.

Battery Control System: BCM

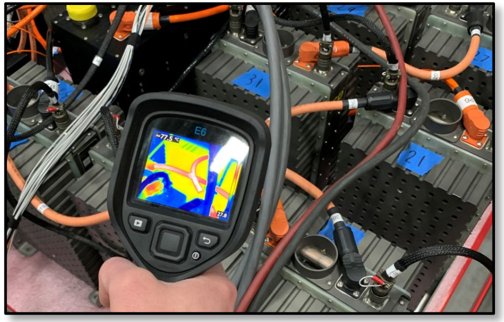
- Battery Control Module (BCM): Battery cell monitoring and telemetry, HV distribution, avionics power supply, discharge monitoring, charge control
- Routes HV from LOTO to Contactor Pallet for discharge and from GSE to LOTO for charging
- Avionics power (see Vehicle IPT): 13.8V,2A in for CPU; 13.8V,70A out to avionics; 28V,7A out to Contactor Pallet/instrument panel
- Input discrete control of traction contactors and 13.8V power supply. Output discrete to Annunciator system for battery fault.
- Isolation Detection Unit (IDU) constantly tests electrical isolation between HV bus and aircraft ground. Faults indicated at annunciator and in telemetry in all modes.
- Telemeters traction battery cell voltage & temperature, pack current, H&S to Command Bus (CAN). Data displayed on MFD, recorded on FDR, and downlinked to control room
- CSCI: Complex Programmable Logic Device (CPLD) for contactor control and annunciator multiplexing
- CSCI: Battery Management System (BMS) Software. Class 1S, monitors cell and system sensors, alerts (annunciator and telemetry) if limits exceeded. Can interrupt battery charge, but not discharge (flight)



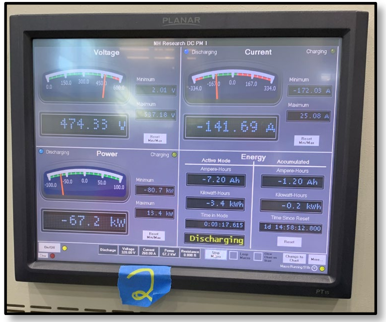
Battery Control Module (BCM) wired for compatibility tests with cruise motor and inverters.

Battery Control System Testing

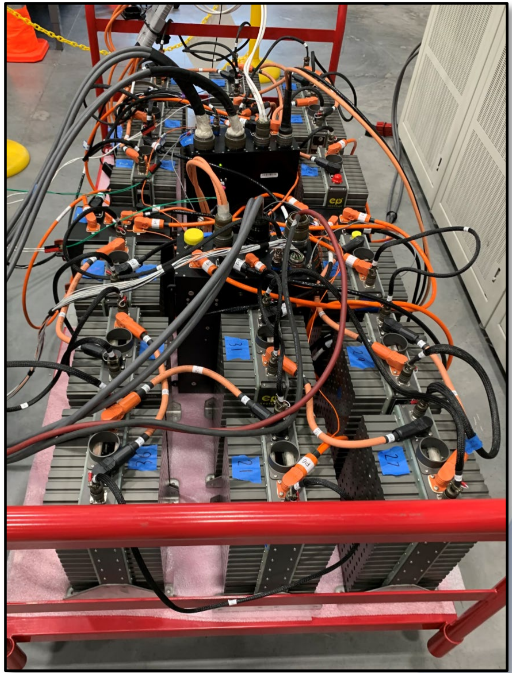
- BCMs and LOTOs proto-qual and acceptance tested by manufacturer. Acceptance Test Program (ATP) culminated in full mission profile
- Interface and assembly tests of each component incl. protection devices Environmental acceptance per the X-57 Environmental Test Plan (ETP-CEPT-007). Includes Thermal, Vibration, and Shock Acceleration
- Full charge/discharge with flight-like loads and flight battery pack
- End Item Data Package with Analyses, As-Run Test Procs, CDR, CofC's, Deviations/Waivers, Qual Procs, Non-Conformance Reports, Test Results



Battery Module Thermal Performance during Mission Profile Load Test



Programmable Load Bank Simulating Mission Profile Discharge



Battery Control System with Ship Set 2 Battery Modules in System Test Configuration

BCM & LOTO Acceptance Test Flow

Phase 1

- BCM & LOTO Build
- Battery Control Computer (BCC) Board Programming
- Complete BCM Build

Phase 2

- IDU Checks (Low Voltage)
- BCM & LOTO Megger
- BCM & LOTO Peak Load
- BRD-52 Stress test
- Protoqual: Open Contactor Under Load
- IDU Checks (High Voltage)
- Fault Checks
- Protoqual: Replace Contactor

Phase 3

- Protoqual: Functional Checks
- Protoqual: Peak Current Load
- Document BCM Assembly
- Seal BCM lid

Phase 4

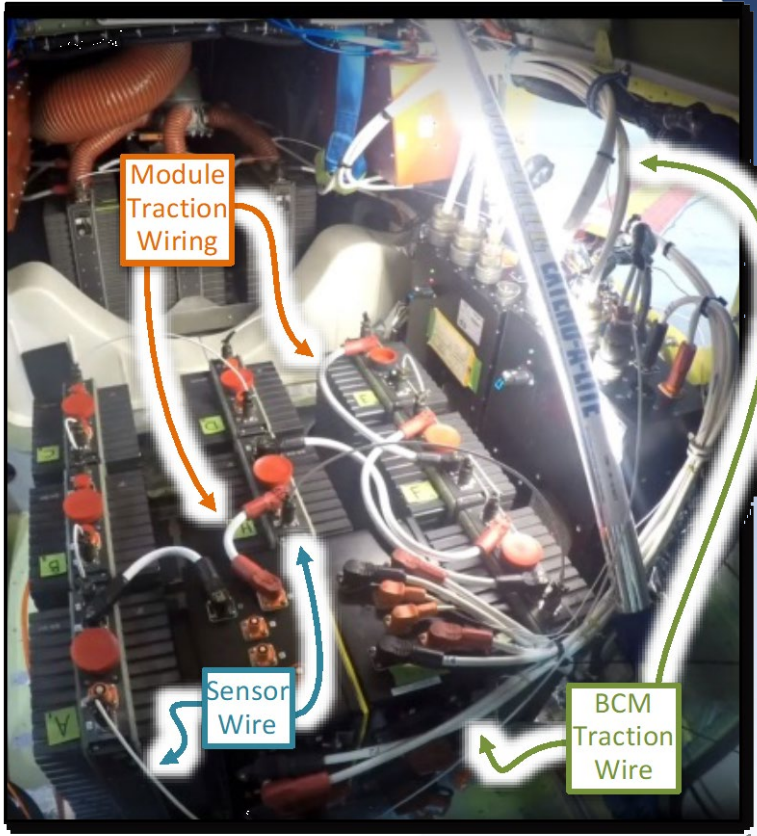
- Functional Checks
- Thermal Cycling
- Functional Test
- X, Y, Z Vibration
- X, Y, Z Shock
- Functional Test

Phase 5

- System Functional Test
- Mission Profile Test (Flight-like configuration)
- Peak Power test (78 kW for 3 minutes)
- Performed with BCM SN 14 & SN 15 and Shipset 2 battery modules

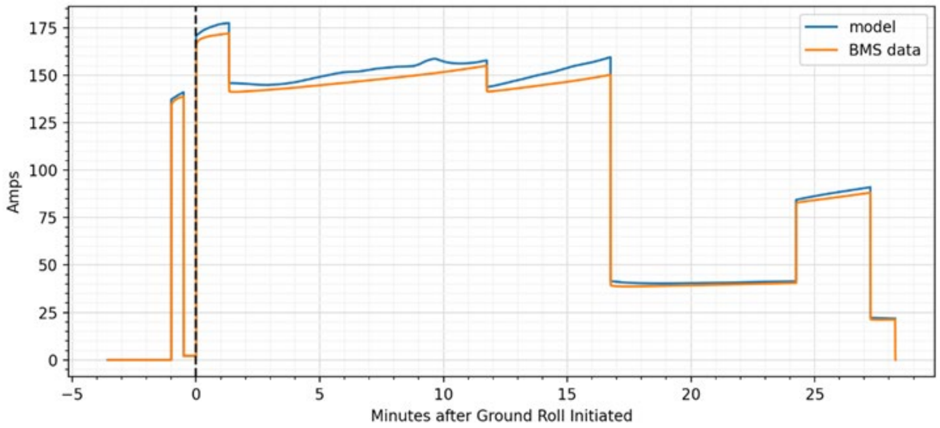
Battery System Wiring

- Wire sizing based on SAE Aerospace Std 50881 G, Sec 6.7 Wire Current Ratings
- Traction cable between Battery Modules and LOTO. Part №: M22759/16-01; 150C, 600 V, 1/0 AWG
- Traction cable between LOTO, BCM, and Contactor Pallet. Part №: SHF260-0113-2-9; 260C, 1000 V, #2 AWG
- Battery module sensor data is a daisy chained serial bus between battery modules and BCMs

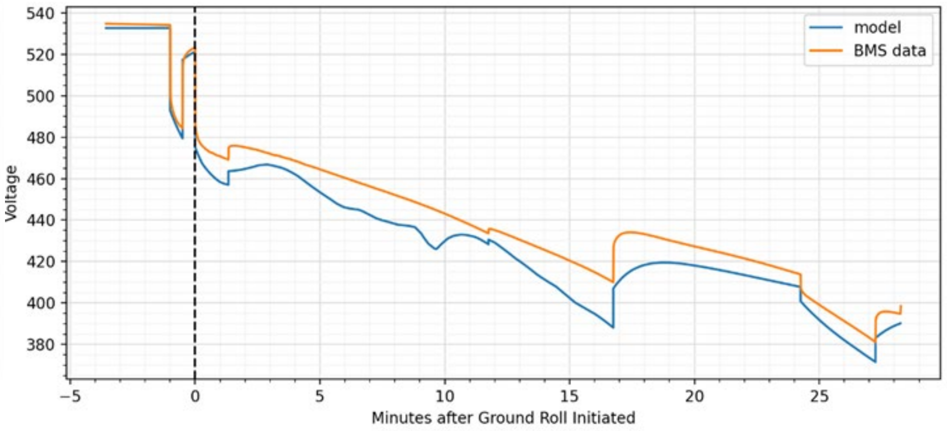


Battery Model vs Phase 5 Test Data

Traction Battery Current



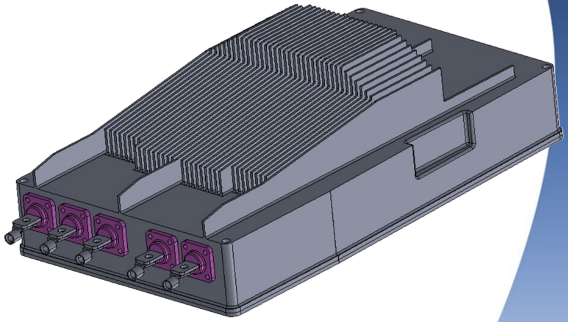
Traction Battery Voltage

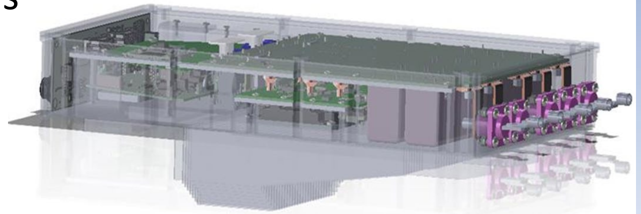


- Test performed at EPS as part of the Acceptance Test (Phase 5) using the Mod II Standard Mission Profile in the Mod II X-57 Cruise Motor and High Lift Motor Mission Profile Power Requirements Analysis (ANLYS-CEPT-018)
- NASA developed a traction battery performance model based on parametric cell performance tests at GRC battery lab and evaluated Mod II Mission Profile (from ANLYS-CEPT-018 Rev-D)

CMC Functional Overview

- Motor Controller/Inverter that converts DC input from battery to 3-phase AC to power the X-57 Cruise Motor
- Controller uses a current feedback loop to apply pilot-commanded torque control independent of speed, battery voltage, and operating conditions
- Inverter functionality relies on high power Silicon Carbide (SiC) Metal Oxide Semiconductor Field Effect Transistor (MOSFET) module
- The final version of the CMC uses Cree CAB400M12XM3 ("XM3") modules. The earlier generation CAS300M12BM2 ("BM2") modules did not meet flight vibration requirements
- Operating Voltage: 320-538 VDC (tested to 600 V)
- 39 kW nominal output in peak operating condition (per CMC), and each can supply 55 kW output in emergency overdrive mode
- Each Cruise Motor driven by two independent controllers for redundancy
- Completely Air-cooled

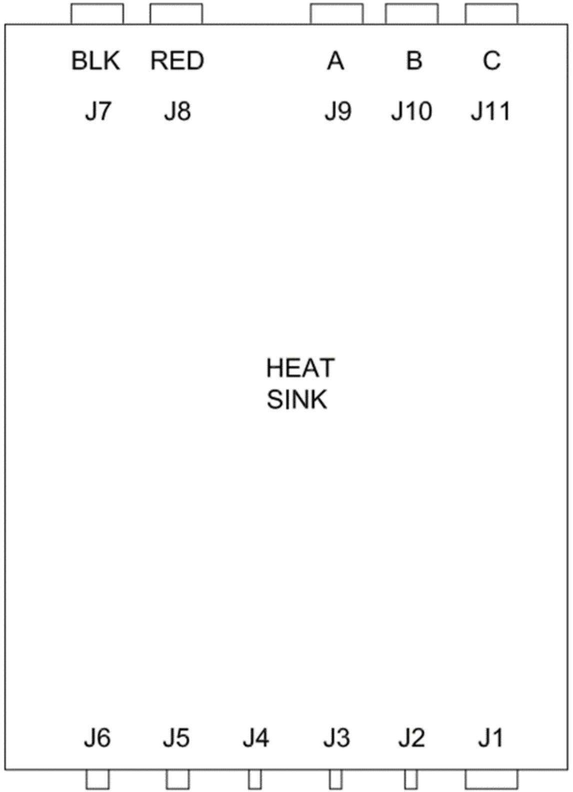




CMC Overview/Interfaces

Each of these documents represent features that were needed and took time to design, build, analyze, and test (multiple revisions in many cases).

- **Traction Bus / DC Link Power (J7, J8):** REQ-CEPT-026 Rev A; ICD-CEPT-002 Rev -, p17; X57-37011 Rev F, Sht 2,5; ANLYS-CEPT-018 Rev D;
- **Motor Phase Power (J9, J10, J11):** REQ-CEPT-026 Rev A; ICD-CEPT-002 Rev -, p17; X57-37011 Rev F, Sht 3,6; ANLYS-CEPT-018 Rev D
- **Avionics Power (J2)**: REQ-CEPT-026 Rev A; ICD-CEPT-002 Rev -, p17; X57-47008 Rev D, Sht 1-5; ANLYS-CEPT-020 Rev C
- **Arm Switch / Address Discretes (J2, J3, J4):** REQ-CEPT-026 Rev A; X57-47008 Rev C, Sht 1-5; X57-45001, Rev -; REQ-CEPT-012, Rev B
- **Annunciator / Fault Status Discrete (J1)**: REQ-CEPT-026 Rev A; X57-47003 Rev E, Sht 1-5; X57-45006, Rev -; X57-47003 Rev E, Sht 2, REQ-CEPT-012, Rev B
- **Command Bus (J5):** ICD-CEPT-002 Rev -, p43-44; X57-47008 Rev D, Sht 1-5; ISO 11898-2; REQ-CEPT-012, Rev B; ICD-CEPT-005, Rev F;
- **Maintenance Bus (J6):** X57-90008 Rev -; IEEE 802.3ab
- **Ext. Temp. Sensors, Rotor Encoder, Rotor Resolver, External Gate Kill (J1):** Not used in X-57 application; no connection



Electrified Powertrains are mechanically simplified, but power, control, telemetry interfaces are complex and require extensive testing and fault tolerance

Traction Wire Margin Analysis

Wire Characteristics				Environment		Voltage			Current		
Wire Location	Part Number	AWG	Insulation Temp Rating (°C)	Wires per bundle	Ambient Temp (°C), Altitude (Ft)	Voltage Rating (VDC)	Maximum Expected Voltage[1]	Voltage Margin	Continuous Current Rating[2] (Amps)	Maximum Peak Current[3] (Amps)	Current Margin
Cables from Battery Module to LOTO	M22759/16-01	#1/0	150	1		600		10%	325	183	44%
LOTO Internal Wire	M22759/16-2	#2	150	1		600		10%	240	183	24%
Cables between LOTO and BCM	SHF260-0113-2-9	#2	260	2		1000		46%	284	183	36%
BCM Input Internal Wires	M22759/16-2	#2	150	1		600		10%	240	183	24%
BCM Output Internal Wires	M22759/16-01	#1/0	150	1	50°C 15,000 MSL	600	538 VDC	10%	325	183	44%
Cables from BCM to Contactor Pallet	SHF260-0113-2-9	#2	260	4		1000		46%	232	91.5	61%
Contactor Pallet Internal Cables	M22759/16-2	#2	150	1		600		10%	240	91.5	62%
Cables from Contactor Pallet to CMCs	W-5590-100	#4	200	2		1000		46%	177	91.5	48%
Cables from CMCs to Motor	SHF260-0113-6-9	#6	260	1		1000		46%	186	89	52%

1) Represents the maximum theoretical fully charged battery voltage (128 cells x 4.2 VDC). Actual fully charged voltage will between 520 VDC and 530 VDC. Voltage will decrease as mission progresses.
2) Continuous current rating defined by SAE Aerospace Standard 50881 Rev G, Section 6.7 Wire Current Rating.
3) Maximum Peak Current defined by Mission Profile Power Analysis Rev D, ANLYS-CEPT-018. Maximum current is for approximately 90 seconds.

Traction Component Margin Analysis

Components		Voltage			Current		
Component	Part Number	Voltage Rating (VDC)	Maximum Expected Voltage[1]	Margin	Continuous Current Rating (Amps)	Maximum Peak Current[2] (Amps)	Margin
Battery Module Connectors	SLP with 8 MM contact	1000	538 VDC	46%	200	183	9%
LOTO Fuses	A100P200-4	750		28%	200/160/143	183	Slide 16
LOTO Switches	HBD41	1000		46%	400	183	54%
LOTO Connectors	SLP with 8 MM contact	1000		46%	200	183	9%
BCM Discharge Contactors	KHR500	1000		46%	600	183	70%
BCM Precharge Contactors	CAP120	600		10%	150	0	100%
BCM Precharge Resistor	LPS800	5000		89%	2.5	0	100%
BCM Input Connectors	SLP with 8 MM contact	1000		46%	200	183	9%
BCM Output Connectors	GTC030/GTC06	1250		57%	250	91.5	63%
Contactor Pallet TCAs	CAP120	600		10%	150	91.5	39%
Contactor Pallet Connecotrs	SLP with 8 MM contact	1000		46%	200	91.5	54%
CMC Connectors Input Connectors	SLP with 8 MM contact	1000		46%	200	91.5	54%
CMC Connectors Output Connectors	SLP with 8 MM contact	1000		46%	200	33	84%

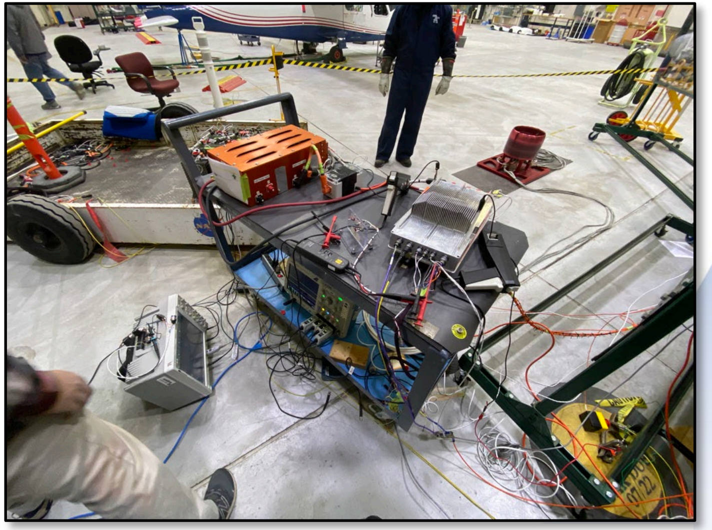
1) Represents the maximum theoretical fully charged battery voltage (128 cells x 4.2 VDC). Actual fully charged voltage will between 520 VDC and 530 VDC. Voltage will decrease as mission progresses.
2) Maximum Peak Current defined by Mission Profile Power Analysis Rev D, ANLYS-CEPT-018. Maximum current is for approximately 90 seconds.

Inverter & Battery Compatibility

- Perfect storm for incompatibility
  - SiC-based inverter with "instant" switching rise/fall and wideband DC bus capacitance
  - DC distribution bus uses "flat" ribbon-like cable resulting in extremely low inductance
  - Battery module sensor boards are coupled to the cells without filtering or a drain to ground
- Resulted in loss of battery module comms when inverters were active (even while power delivery was good)
- Fix is tuned to the flight hardware
  - Measured noise on actual flight units
  - Developed custom T-filter to absorb switching transients between inverter and battery

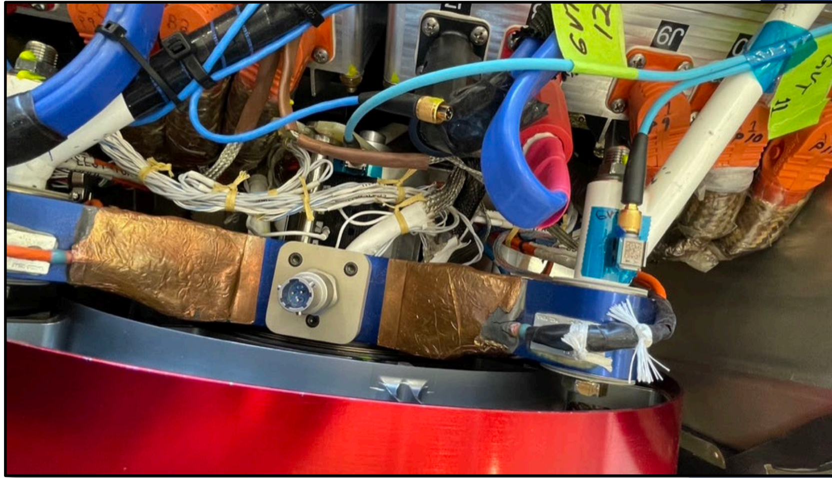

Custom Flat Cable


Common-mode T-Filter


Hardware test setup using X-57 batteries, inverter, motor

Conducted Interference from Inverter/Motor

- Grounding design vs reality
  - Battery, Inverter, Motor were intended to be isolated from vehicle structure and other system grounds
  - Tight clearances between case/heatsink, mounting structure, baffles, vibration mounts resulted in multiple rounds of 'surprise' ground paths
- Inverter/motor act as a system and must be solidly bonded
  - EM coupling between rotor and stator induced current to flow through bearings and into vehicle structure
  - Spare slipring channel is used to drain rotor currents to CMC chassis/T-filter

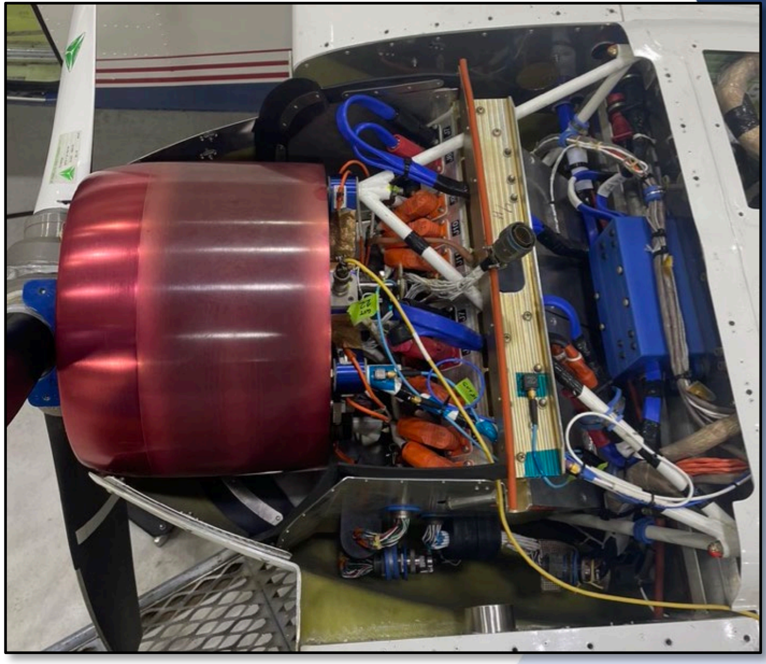


Close quarters in the nacelle resulted in unintentional grounding

Slip ring must be rugged and provide reliable rotor-stator coupling to drain induced current

Tolerating Residual Radiated Interference

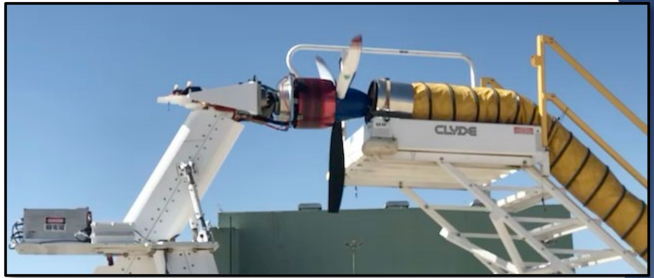
- Electric Engines have many adjacent systems
  - Prop governor (actuator and speed pickup), tachometer, blade angle sensor, motor and air duct temperature sensors, accelerometers, and strain gages are all within inches of the inverter/motor
  - Remote aircraft systems also saw switching noise including instrumentation throughout the vehicle, annunciator, audio comms, flap indicator / controller
- Contain and absorb the noise at the nacelle
  - Common-mode chokes were installed on all wiring bundles that entered the electric engine bay
  - Grounding improvements were made to stock systems: don't use structure for power return path, route return with supply and use shields with drains



Electric Engine Nacelles includes many proximate subsystems, and this one includes many common-mode chokes

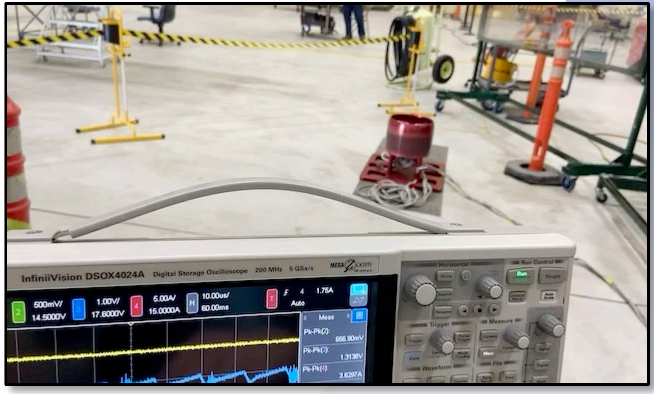
Lessons Learned: System Development and Testing

- Planned to use Mod II vehicle as integration testbed, but we needed an Iron Bird/hardware-in-the-loop lab
  - Unexpected degree of component development
  - Aircraft less flexible than a lab
  - Iron Bird lab with would have enabled faster design iteration
  - Dynamometer would have improved HW and SW development.
- Propulsion system testing and qualification requires multifaceted approach
  - Dynamometer critical for effective power envelope testing
  - Static propeller stand exercised some thrust and vibration loads
  - Battery ops had significant overhead
  - Offline Inspection and direct measurement are useful and cheap



Airvolt static propeller test stand with cooling duct

Battery, Inverter, Motor compatibility testing



Lessons Learned: Battery System Features

- Cell imbalance impacts available energy. Charge shuttling or an imbalance derating needed
- Continuous isolation detection reduced hazard but interfered in various non-flight/temporary grounding configurations
- Battery Support System was sized for battery simulation but oversized for 0.5C charging
- Aircraft architecture reconfigured for various development and test modes, but support cable harnesses were complex
- Storage module installation and removal poses highest risk of arc flash

Ground Support Equipment "Battery Support System" charges, simulates, and tests aircraft traction batteries

Battery maintenance and operations are higher workload than traditional aircraft fueling until battery management and control systems become more complex

Lessons Learned: Traction/Command Architecture

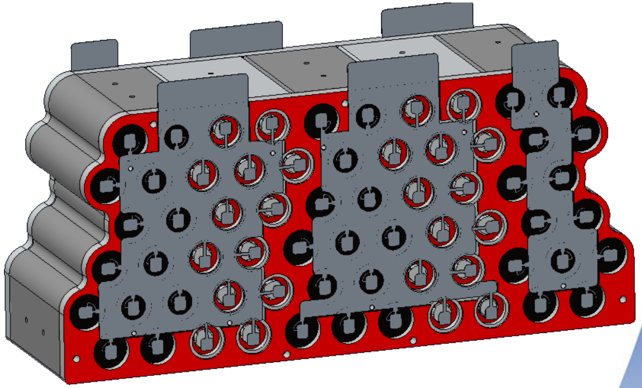
- Subsystem architecture was relatively stable during the project lifecycle
  - Lockout/Tagout boxes added for better access to maintenance/isolation switches
  - Operations crew relied on maintenance lockout switch for daily activities
  - First Responder Disconnect was a relatively simple addition
- This redundancy design is simple but primitive. More complex redundancy design would offer improved failover modes but with additional losses/heat rejection and failure modes.

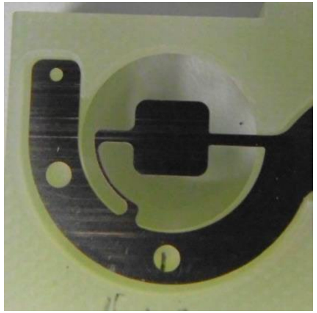
Backup / Supplementary Material

Battery Module Cell Fuses

- Individual cell thermal runaway cannot be fully mitigated with state-of-the-art cells (Civil Aviation Authorities assume Probability=100%)
- Individual cell “fusible links” mitigate some failure modes and impacted Hazard Analysis
- These fuses don’t have the same heritage as commercial protection devices, so reliability was discounted in Hazard Analysis
- Especially needed for parallel-first pack designs, although subsequent JSC research prefer series-first strings
- Requires highly parallel module design (20p chosen for these modules) to ensure failed cells will isolate; adjacent cells supply the overload current

NASA “Safe, High Power Li-ion Battery” cell module





NASA “Safe, High Power Li-ion Battery” cell fusible link

The “Safe, High Power Li-ion Battery” project followed the X-57 design and incorporated X-57 lessons for HV lithium cell packaging (funded by NESC, ARMD/FDC, and others) [https://ntrs.nasa.gov/citations/20180004170]

Traction Contactor Assembly

- Traction Contactor Assemblies (TCA): Enables individual isolation of traction buses
  - TE CAP120, 150 A @ 600 V continuous, can interrupt 100 A for 1000x, or up to 600 A 5x. Mission requires up to 125 A.
- Traction Contactor Controller (TCC): Modified COTS microcontroller manages precharge and contactor timing
  - Pre-charges traction bus before contactor closure to eliminate contact wear
  - Software comparator checks that the bus is not shorted or open and that capacitance is within limits; will only energize a bus with motor controllers presenting large capacitance
  - No software is used to open contactors; simply remove power.

Traction Contactor (TE CAP120)

Traction Bus

- **Traction Bus Cable**: Custom design cable with high stranding for flexibility, flat profile for low inductance and Mod 3/4 integration constraints
- **Conductor**: 4x 10 AWG 7 x 3 x 50/40 silver plated copper
- **Jacket**: Extruded silicone 0.61" X 0.22". Rated for -55C TO 200C, 1000 V_{RMS}
- **Flammability**: FAA 25.869/25.853
- Wire sizing based on SAE Aerospace Standard 50881 G, Sec 6.7 Wire Current Ratings
- Traction Bus Cable was tested at GRC and the following report (X-57_Thermal_SSVP_02_01_17) was produced showing compatibility with Subproject requirements

Flat Cable Custom X-57 Design for Electric Propulsion Systems

CMC HW/SW Operation Overview

- CMC start-up and operation initiated by the pilot. MOSFET driver circuit and SW mode sequence locked out until cockpit switch set to Armed
- Torque command calculated from throttle lever position messages
- CMC health and status information output on the Command (CAN) bus for consumption by the instrumentation system and the cockpit MFD
  - Instrumentation system archives and telemeters CMC H&S data
  - MFD displays subset of CMC H&S data to aid in ground ops and for pilot situational awareness
- CMC triggers annunciator system whenever the motors will not respond to throttle inputs as expected. CMC will annunciate only in the instance of a hardware failure, does not protect against exceeding limits (pilots manage limits manually).
- Can (re)arm whenever motor speed is less that 1,000 rpm. Limited by inner-loop motor control logic.
- Torque Control setpoint include protection for over-speed and under-voltage conditions. Motor speed may be high due to windmilling, but CMC will not add torque. If battery voltage is less than 340 V, torque at full speed is not possible (back EMF overcomes forward EMF), so CMC limits current command to avoid faulting.