Envisioning Urban Air Mobility Panel
Enabling Technologies

AHS Aeromechanics Design for Transformative Vertical Flight

Technical Meeting

The Vertical Flight Technical Society

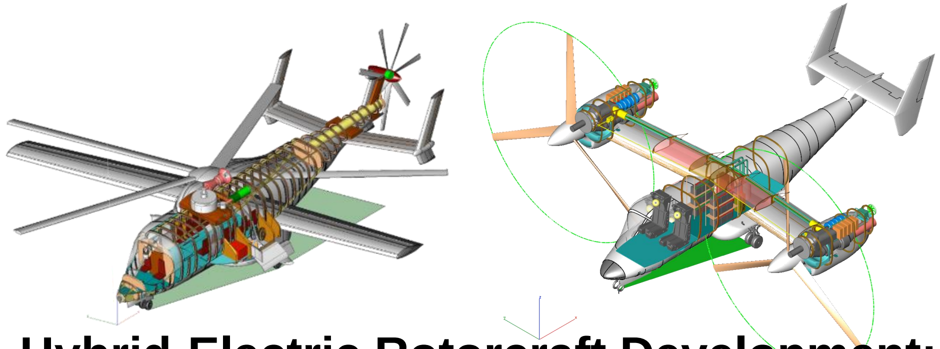
Why is ESAero here with the Billion Dollar Companies?

10 Years of *"eAirplane"* Development

- Design AS an Enabling Technology

- NASA/ESAero X-57 *"Maxwell"*

ECO-150R



Hybrid-Electric Rotorcraft Development; "Unique Configurations"

ECO-150

AFRL TeDP Dual-Use

LEAPTech

X-57 "Maxwell"

Timeline Approximate & Not to Scale

2008 | **2012** | **2013** | **2014** | **2015** | **2018**

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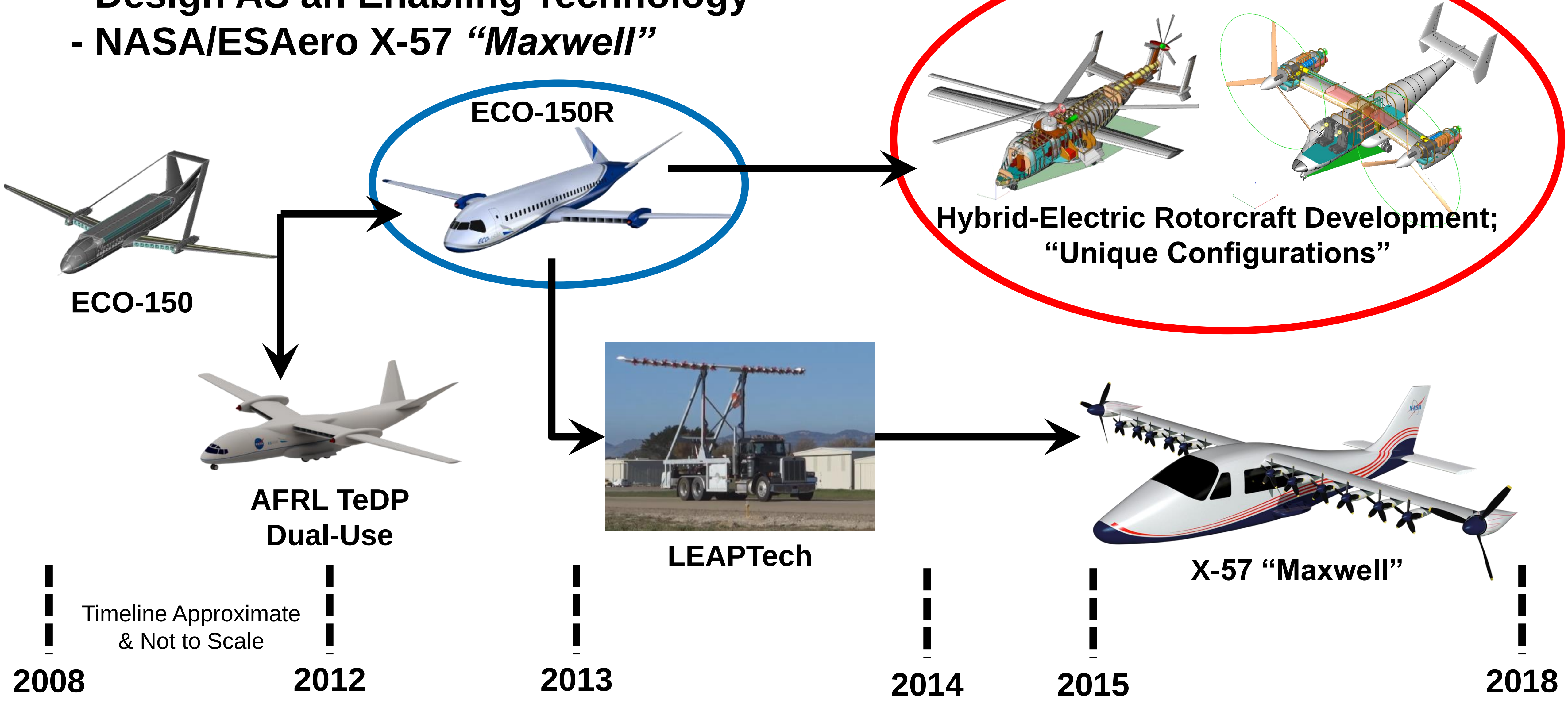

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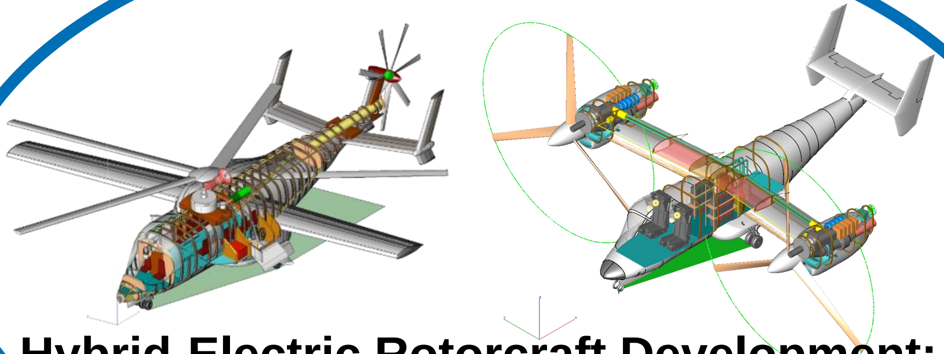

Hybrid-Electric Rotorcraft Development;
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AFRL TeDP
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X-57 "Maxwell"

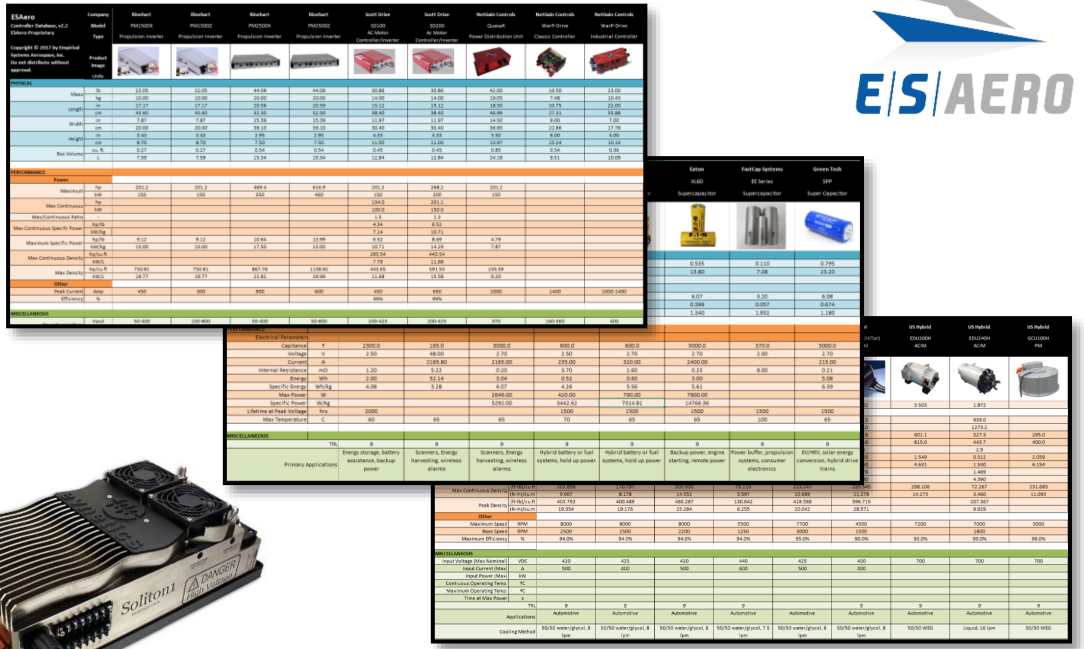
Timeline Approximate
& Not to Scale

2008 **2012** **2013** **2014** **2015** **2018**

Design as an Enabling Technology
Component Databases and Knowledge

ESAero utilizes populated databases for hybrid-electric vehicle components

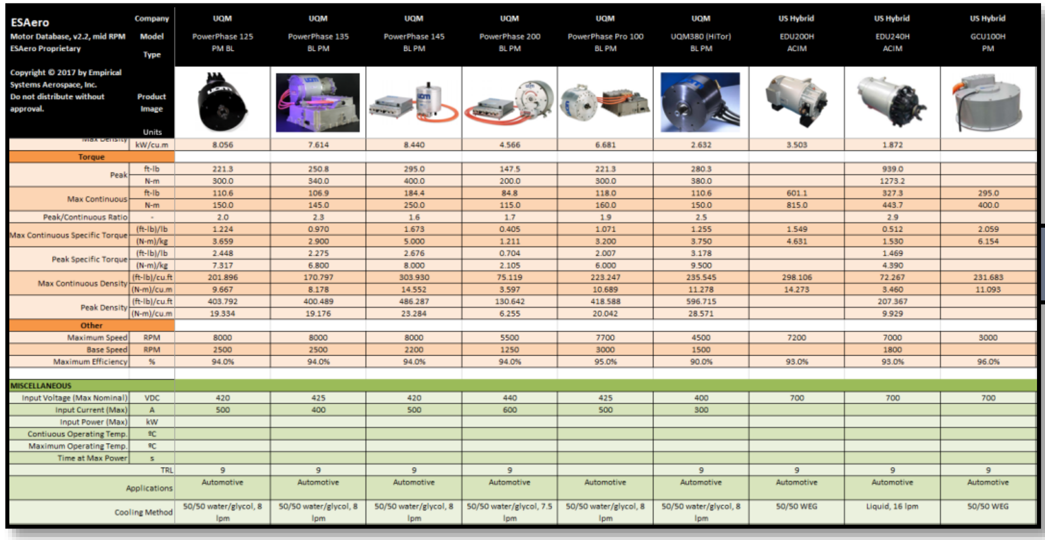
- Energy Storage (batteries, fuel cells, supercaps, flywheels)
- Electric Motors/Generators
- Engines (turbines, diesels, UAS)
- Controllers, Inverters, Rectifiers
- Power Cabling/Traction Bus



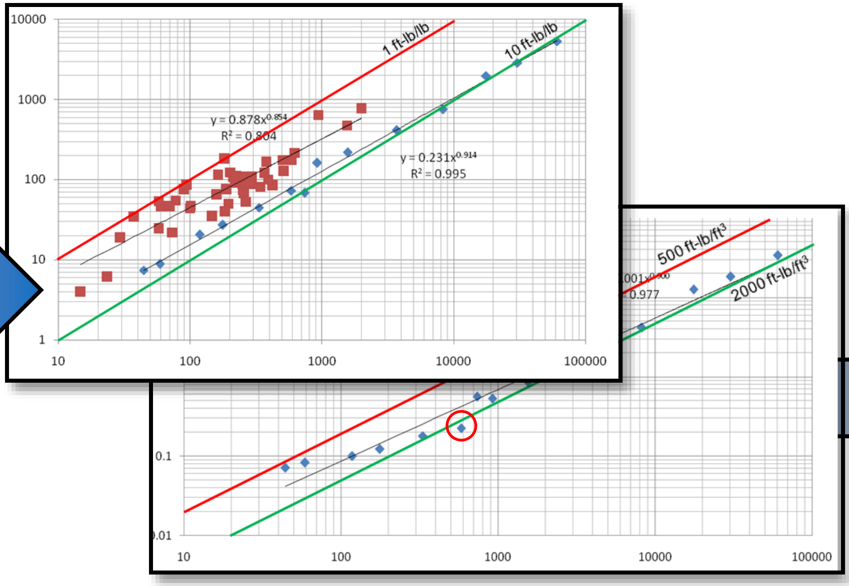
Generate empirical models

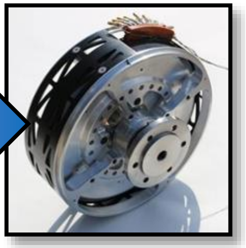
Establish technology trends

Identify suppliers



ESAero Motor Database, v2.2, mid RPM ESAero Proprietary. Copyright © 2017 by Empirical Systems Aerospace, Inc. Do not distribute without approval.	Company / Model / Type / Units	UQM PowerPhase 125 PM BL	UQM PowerPhase 135 BL PM	UQM PowerPhase 145 BL PM	UQM PowerPhase 200 BL PM	UQM PowerPhase Pro 100 BL PM	UQM UQM380 (HiTor) BL PM	US Hybrid EDU200H ACIM	US Hybrid EDU240H ACIM	US Hybrid GCU100H PM
Max Density	kW/cu.m	8.056	7.614	8.440	4.566	6.681	2.632	3.503	1.872	
Torque										
Peak	ft-lb	221.3	250.8	295.0	147.5	221.3	280.3		939.0	
	N-m	300.0	340.0	400.0	200.0	300.0	380.0		1273.2	
Max Continuous	ft-lb	110.6	106.9	184.4	84.8	118.0	110.6	601.1	327.3	295.0
	N-m	150.0	145.0	250.0	115.0	160.0	150.0	815.0	443.7	400.0
Peak/Continuous Ratio	-	2.0	2.3	1.6	1.7	1.9	2.5		2.9	
Max Continuous Specific Torque	(ft-lb)/lb	1.224	0.970	1.673	0.405	1.071	1.255	1.549	0.512	2.059
	(N-m)/kg	3.659	2.900	5.000	1.211	3.200	3.750	4.631	1.530	6.154
Peak Specific Torque	(ft-lb)/lb	2.448	2.275	2.676	0.704	2.007	3.178		1.469	
	(N-m)/kg	7.317	6.800	8.000	2.105	6.000	9.500		4.390	
Max Continuous Density	(ft-lb)/cu.ft	201.896	170.797	303.930	75.119	223.247	235.545	298.106	72.267	231.683
	(N-m)/cu.m	9.667	8.178	14.552	3.597	10.689	11.278	14.273	3.460	11.093
Peak Density	(ft-lb)/cu.ft	403.792	400.489	486.287	130.642	418.588	596.715		207.367	
	(N-m)/cu.m	19.334	19.176	23.284	6.255	20.042	28.571		9.929	
Other										
Maximum Speed	RPM	8000	8000	8000	5500	7700	4500	7200	7000	3000
Base Speed	RPM	2500	2500	2200	1250	3000	1500		1800	
Maximum Efficiency	%	94.0%	94.0%	94.0%	94.0%	95.0%	90.0%	93.0%	93.0%	96.0%
MISCELLANEOUS										
Input Voltage (Max Nominal)	VDC	420	425	420	440	425	400	700	700	700
Input Current (Max)	A	500	400	500	600	500	300			
Input Power (Max)	kW									
Contiuous Operating Temp.	ºC									
Maximum Operating Temp.	ºC									
Time at Max Power	s									
TRL		9	9	9	9		9	9	9	9
Applications		Automotive	Automotive	Automotive	Automotive	Automotive	Automotive	Automotive	Automotive	Automotive
Cooling Method		50/50 water/glycol, 8 lpm	50/50 water/glycol, 8 lpm	50/50 water/glycol, 8 lpm	50/50 water/glycol, 7.5 lpm	50/50 water/glycol, 8 lpm	50/50 water/glycol, 8 lpm	50/50 WEG	Liquid, 16 lpm	50/50 WEG





Design as an Enabling Technology
Electric/Hybrid-Electric Components Applied to VTOL

E|S|AERO

Investigated electric and hybrid-electric rotorcraft (5,000 – 30,000 lb DGW)

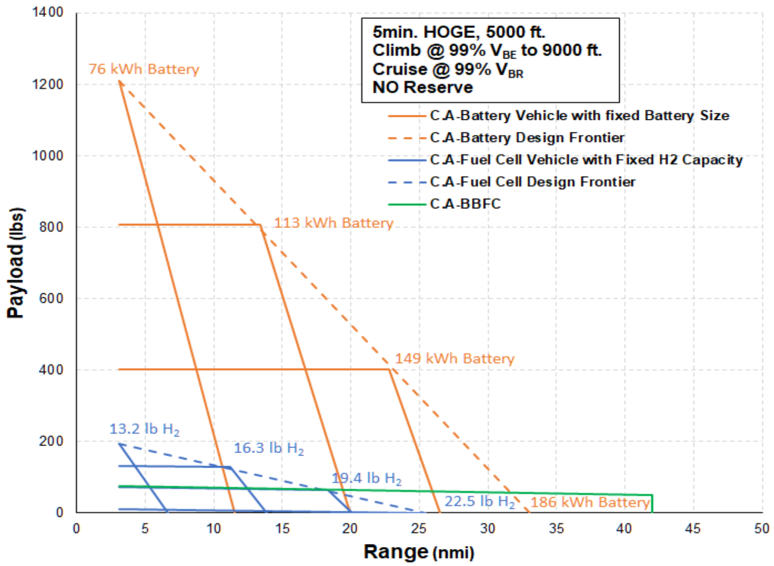
- Helicopters
- Tilt-Rotors
- Compounds

Today, heavy electric components reduce payload capability.

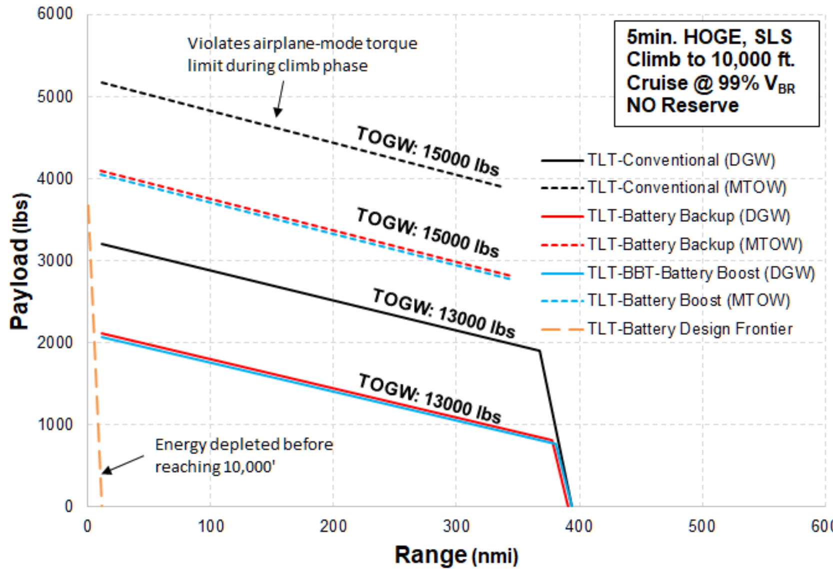
Range improvements possible with greater efficiency, improved integration (PAI) & energy management.

With +30 year technology, hybrid-electric rotorcraft can be competitive with conventional systems.

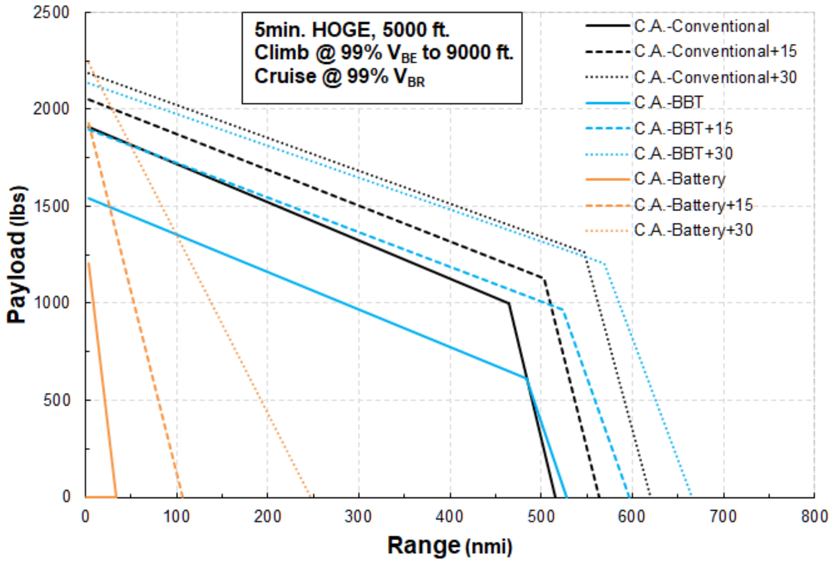
Electric and Fuel Cell Helicopters



Hybrid Propulsion Tiltrotors



Future Hybrid Helicopters

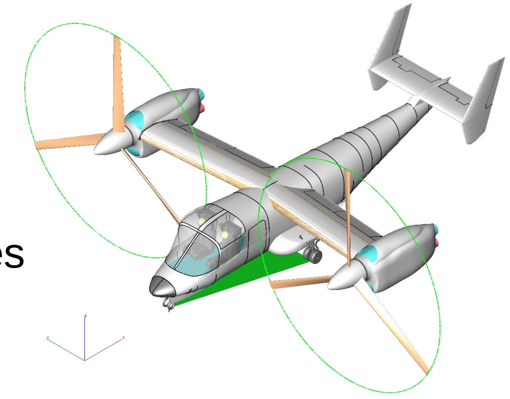


Design as an Enabling Technology

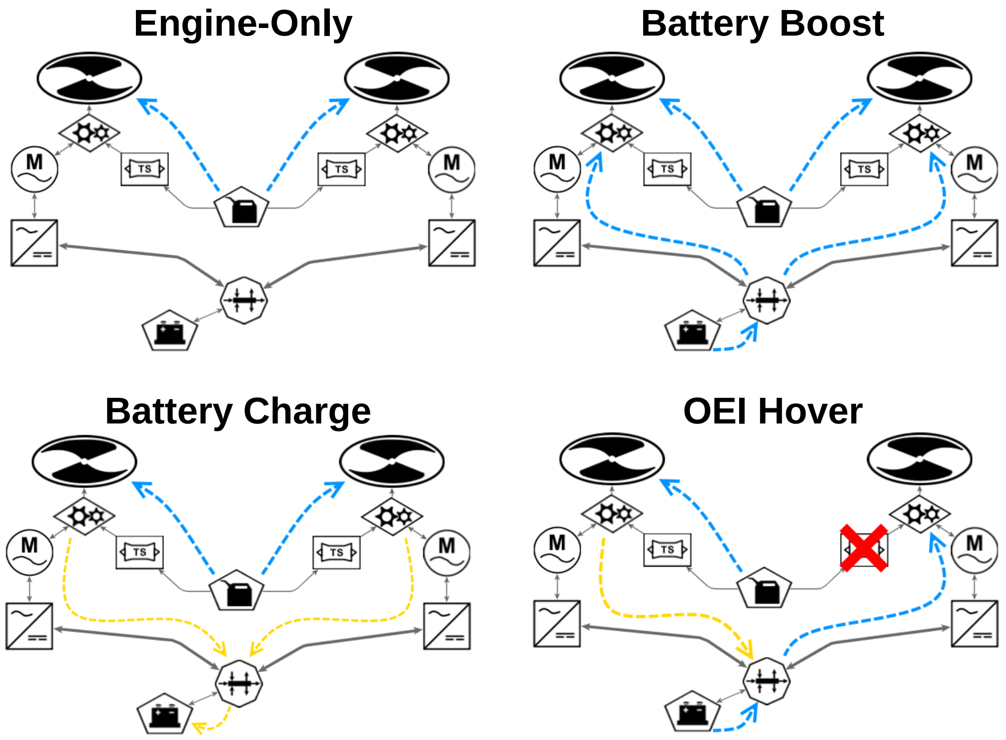
Hybrid-Electric Applied to Rotorcraft

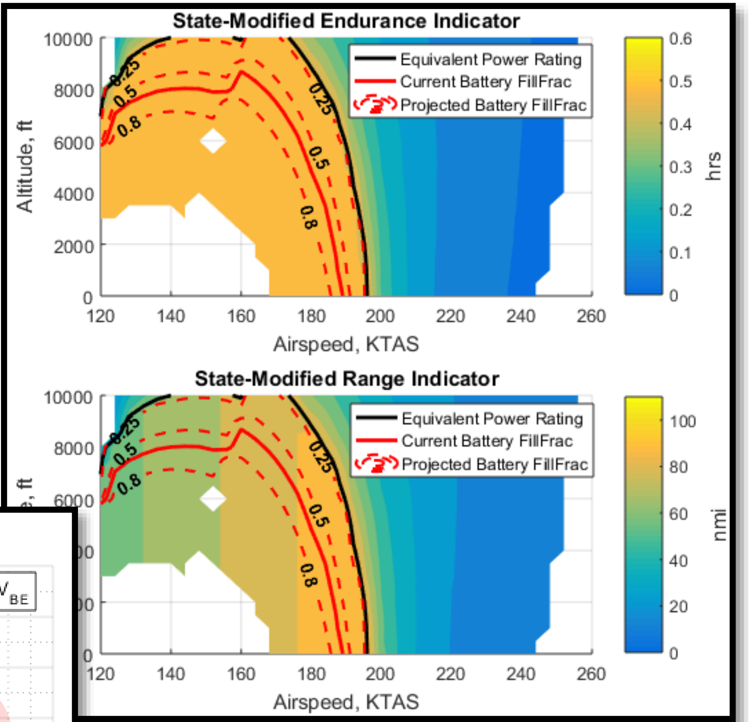
Energy Management and Mission Planning are critical to hybrid rotorcraft

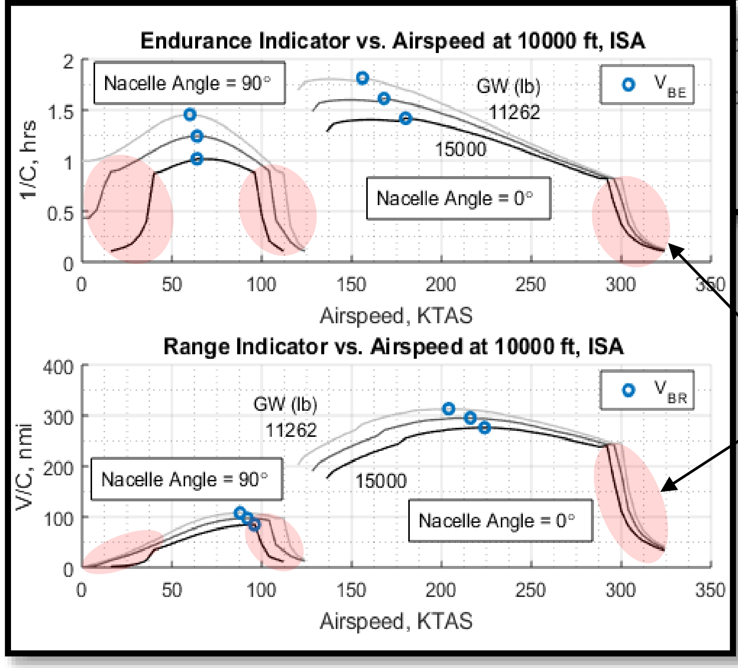
- Balance dissimilar energy sources
- Continuous vs. Peak operation
- Thermal management of electrical components
- Consideration for OEI/contingency cases
- Concrete Knowledge about Components and Failure Modes



Power Distribution Control Schemes







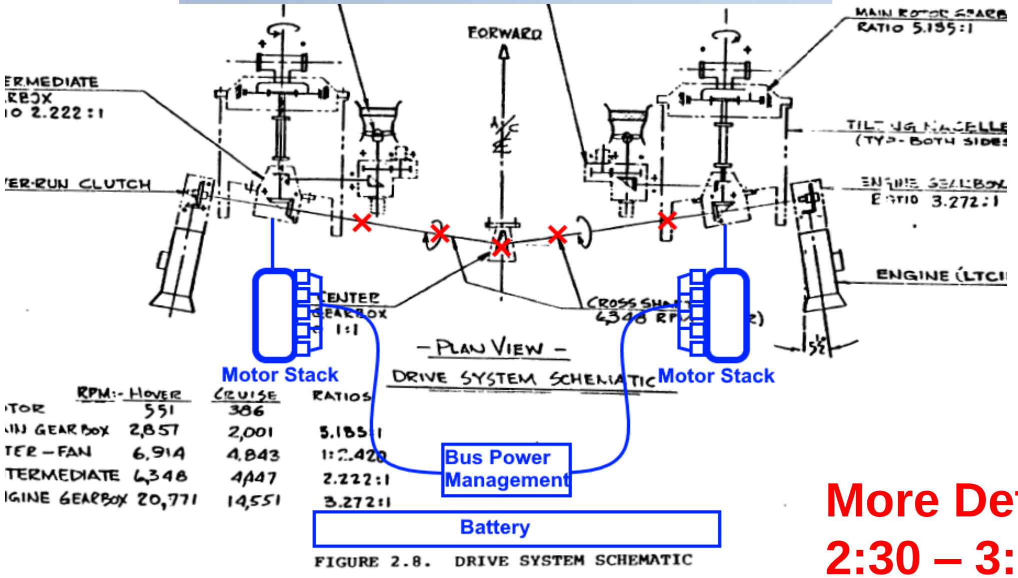
Duration limited by battery capacity

Hybrid-Electric XV-15

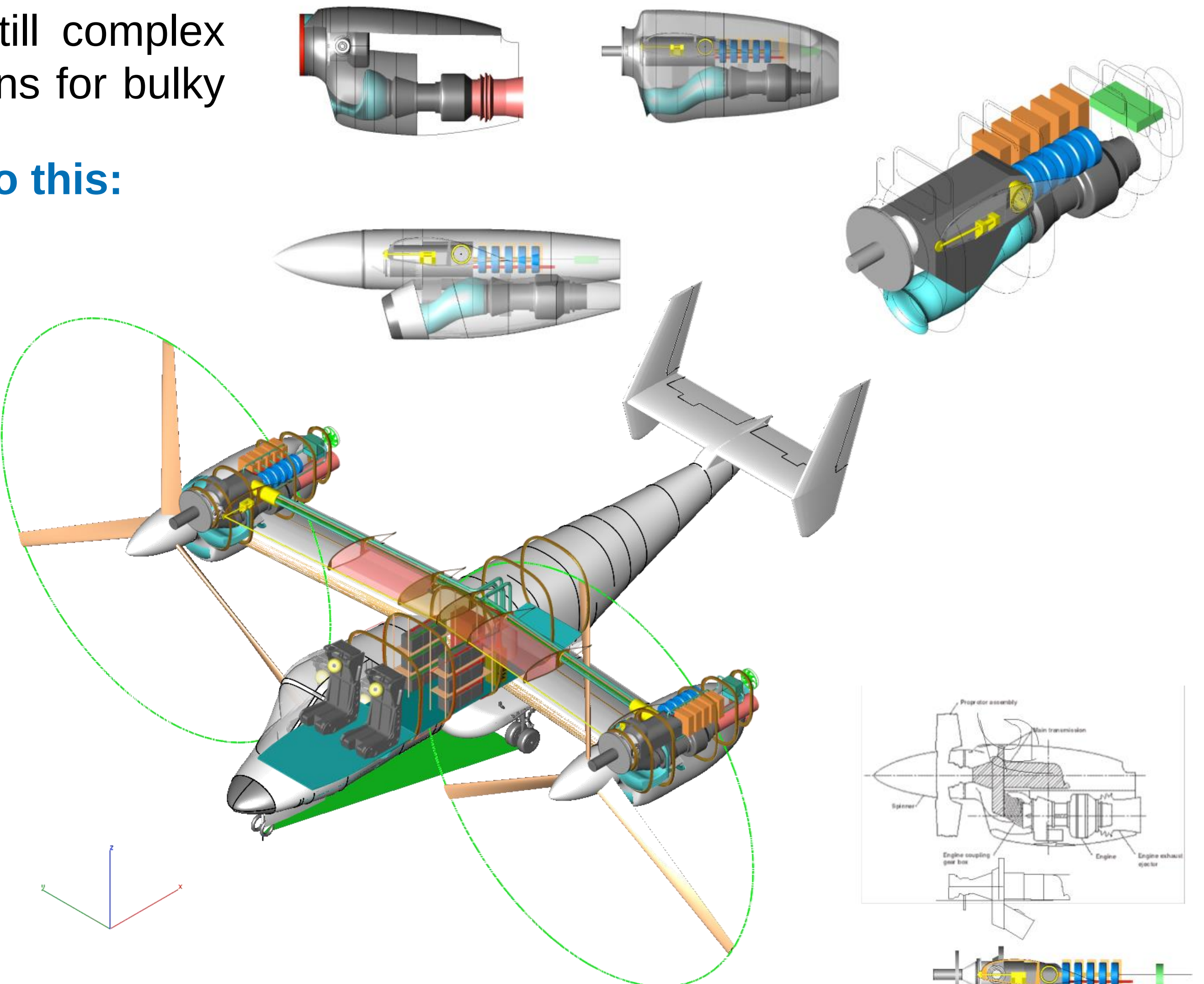
Synthesis

The Hybrid-Electric XV-15 powertrain integration is still complex compared to the XV-15’s and requires specific locations for bulky components (otherwise known as batteries!).

How do we turn this:



Into this:



More Details on FRIDAY from Reed Danis, ESAero:
2:30 – 3:30; Challenges of Hybrid-Electric VTOL Propulsion

Space Claim Challenges

Electric Propulsors integrate several components with competing SWaP sensitivities

Electric Motors:

- Larger diameter improves weight & efficiency but increases frontal area

Electric Speed Controllers:

- COTS controllers are volumetrically inefficient

Transmission:

- Major EMI challenges
- Tight bend radii
- Long cable lengths
- High voltage raises MAJOR safety concerns
  - But allows smaller gauge traction bus

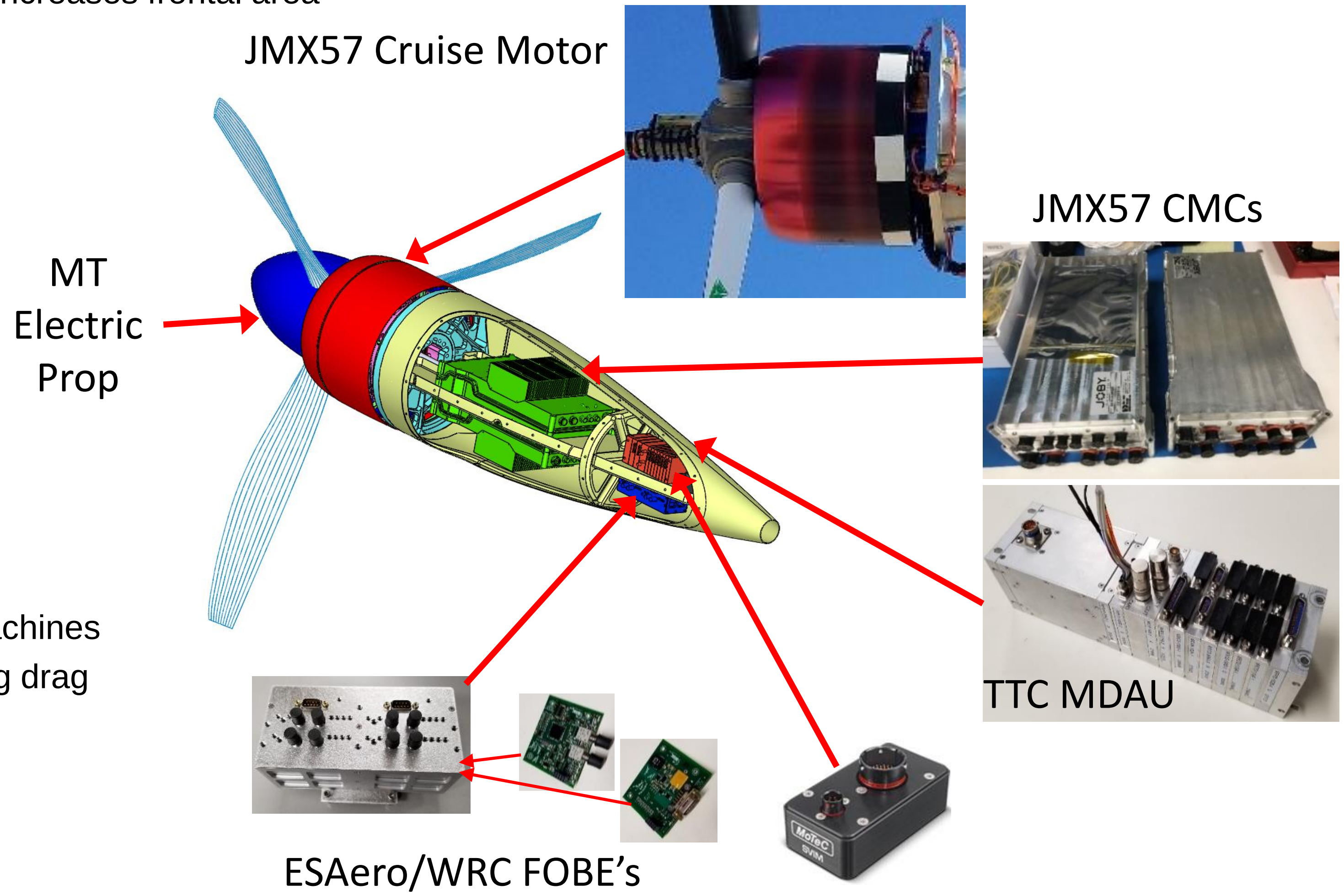
Thermal Management:

- Low quality heat from electronics
- Low natural thermal capacitance of lightweight machines
- Rejecting heat to airstream adds mass and cooling drag

Ducted Fans:

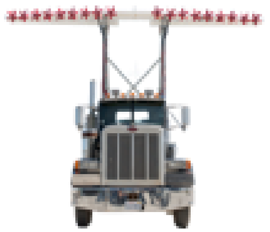
- Larger diameter improves propulsive efficiency
- Longer duct inlet improves pressure recovery
- Maintaining optimal airfoil t/c changes wing AR

X-57 Tip Nacelle Components



X-57 "Maxwell" Project Approach

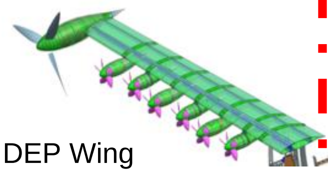
Mod 1



Ground validation of DEP high lift system "LEAPTech"

Flight testing of baseline Tecnam P2006T

Goals:
- Establish Baseline Tecnam Performance
- Pilot Familiarity



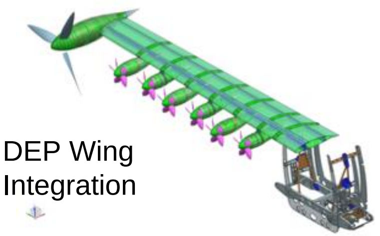
DEP Wing Development & Fab

Mod 2

Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:
- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

Mod 3



DEP Wing Integration

Flight test electric motors relocated to wingtips on DEP wing including nacelles (but no DEP motors, controllers, or folding props).

Achieves Primary Objective of High Speed Cruise Efficiency

Spiral development process
- Build – Fly – Learn

Mod 4

Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

Achieves Secondary Objectives
- DEP Acoustics Testing
- Low-Speed Control Robustness
- Certification Basis of DEP Technologies

Mod 1

Mod 2

Mod 3

Mod 4

E|S|AERO

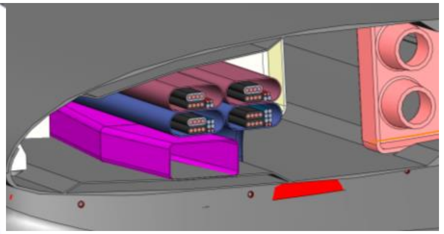
NASA

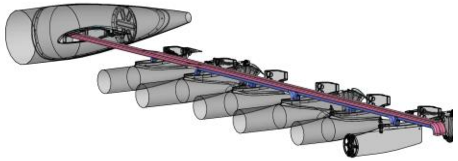
JOBY AVIATION

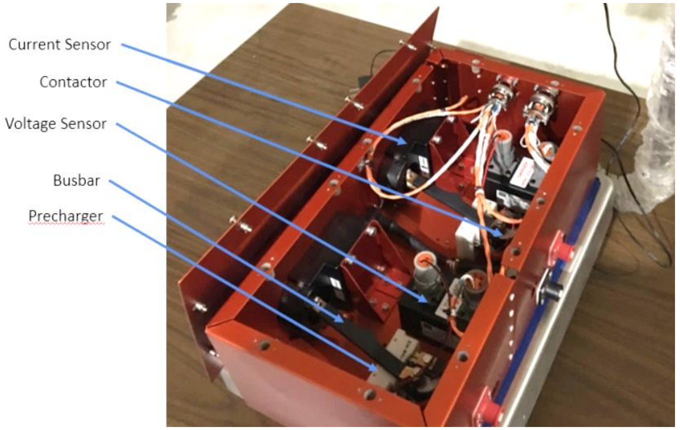
ep SYSTEMS

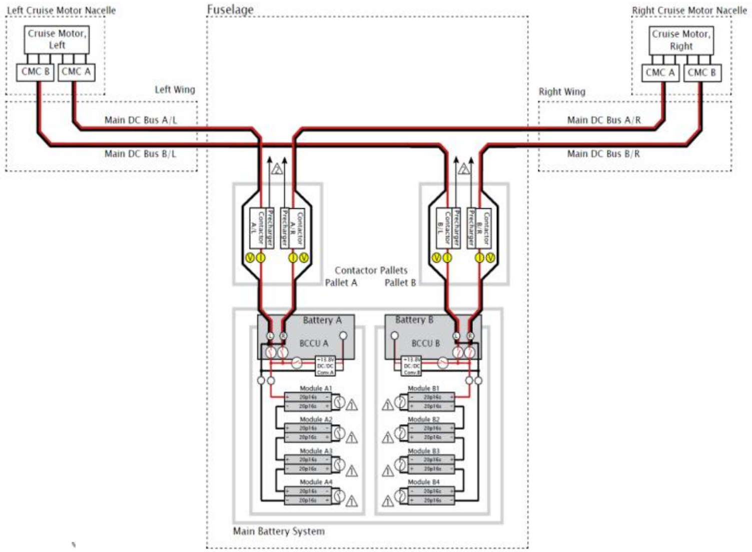
Xperimental, LLC

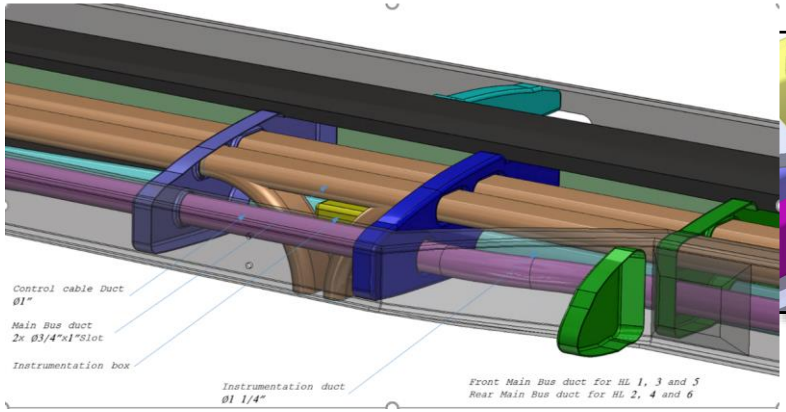
X-57 Traction Bus

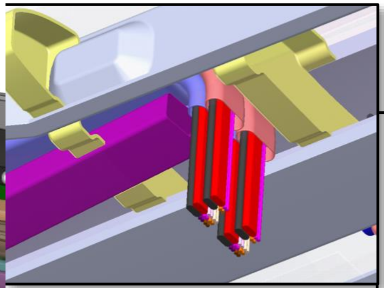


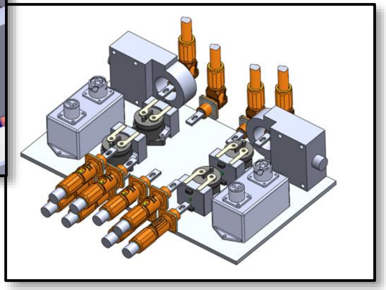








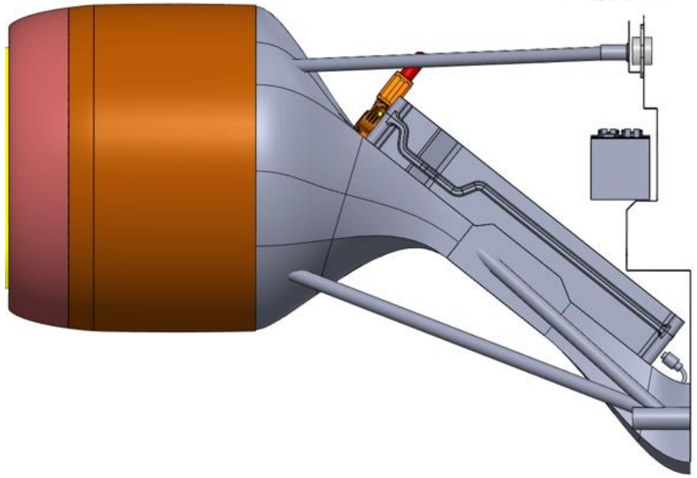


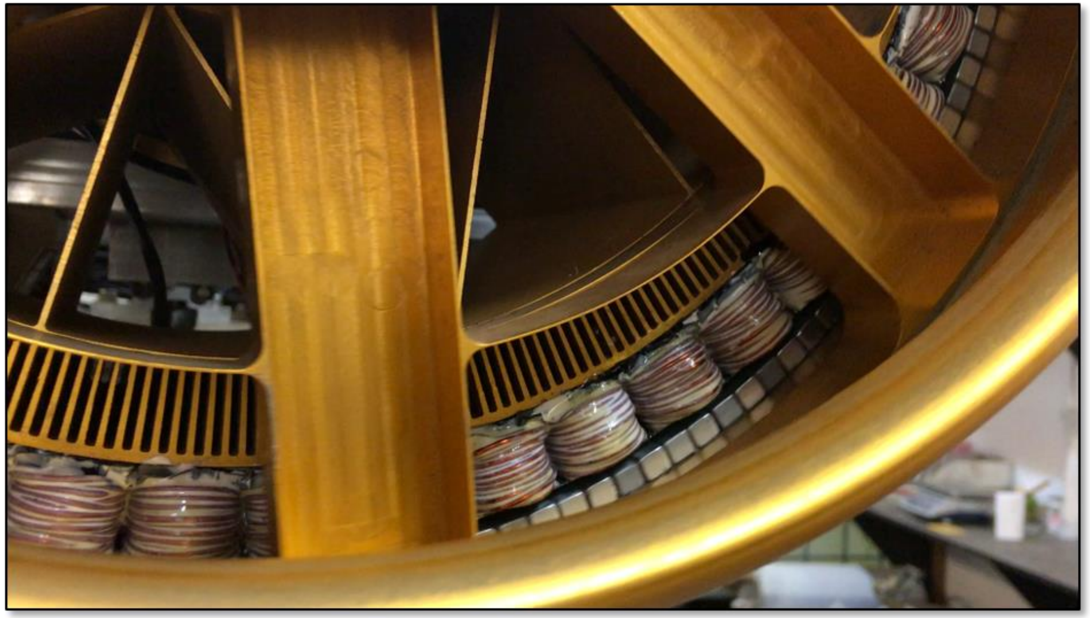


- **Redundant traction buses**. Each high-lift motor alternates buses, cruise motors pull 50% power from each bus.
- **Buses protected in separate ducts** for isolation, shielding and protection.
- **Command and Instrumentation systems routed and shielded separately** to avoid interference and common failures.
- **Redundant bus design** supports Mod IV (branches to each high lift motor).
- **Custom "flat cable" for lower inductance** and Electromagnetic Interference (EMI).
- EMI radiated emittance tests and thermal dissipation tests performed at the NEAT facility (Plum Brook Station).

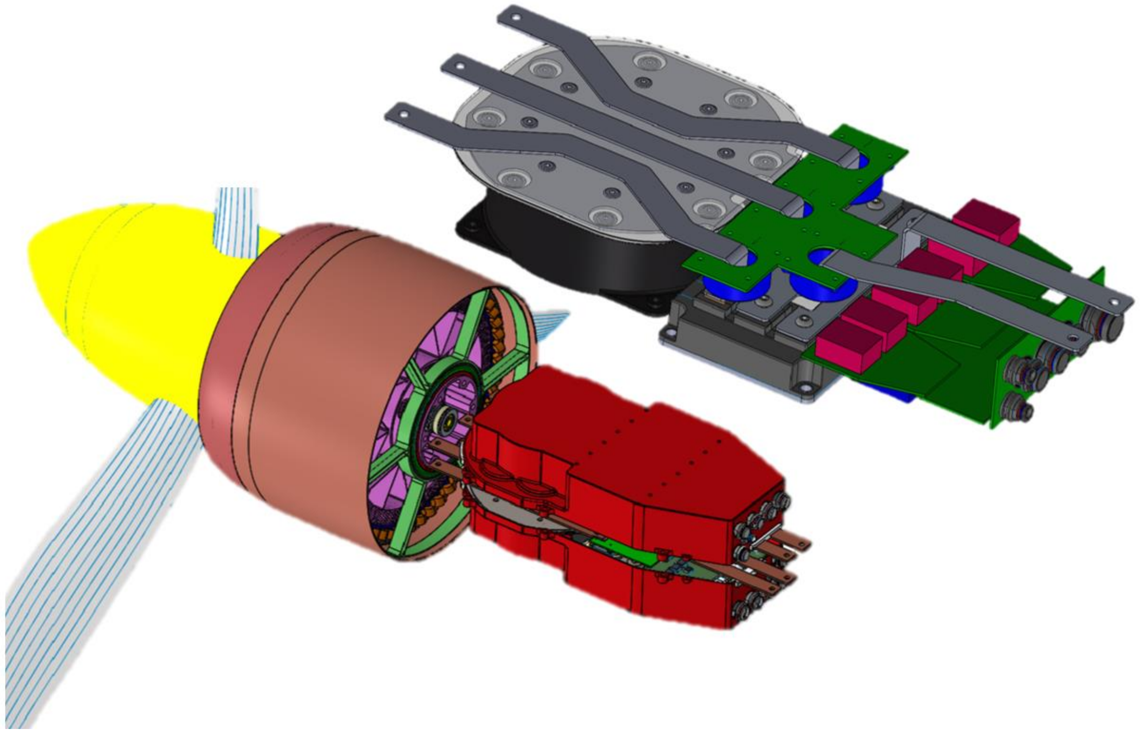
X-57 Cruise Motors

- Additional Flight motors being manufactured.
- Air cooled, direct-drive out-runner design further optimized for X-57 based on prototype performance (demonstrated large margins).
- Expected cruise operating point between 42 and 45 kW.
- Tailoring FAA engine design acceptance testing (Part 33) for NASA flight qualification.
- Initial Flight Motor Integration Underway.

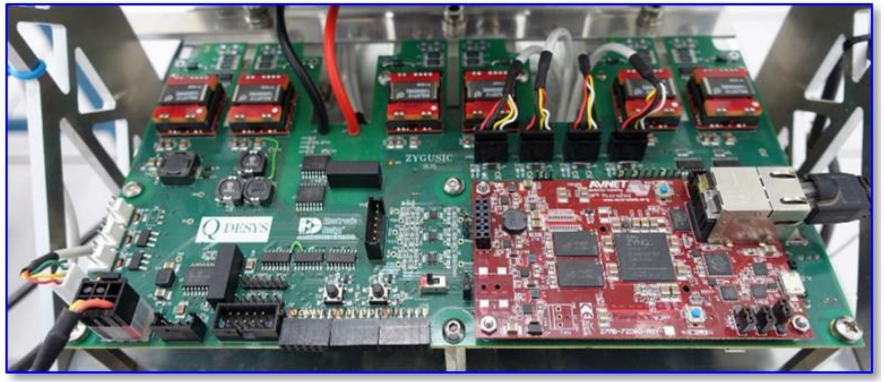


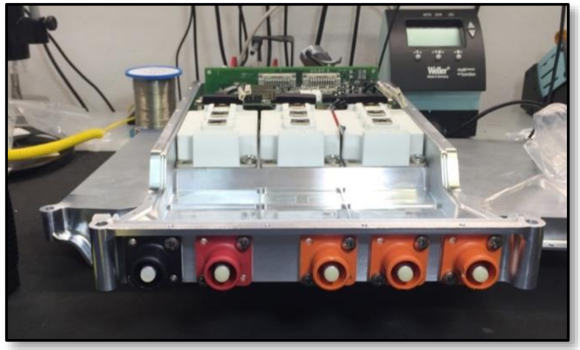


X-57 Cruise Inverters



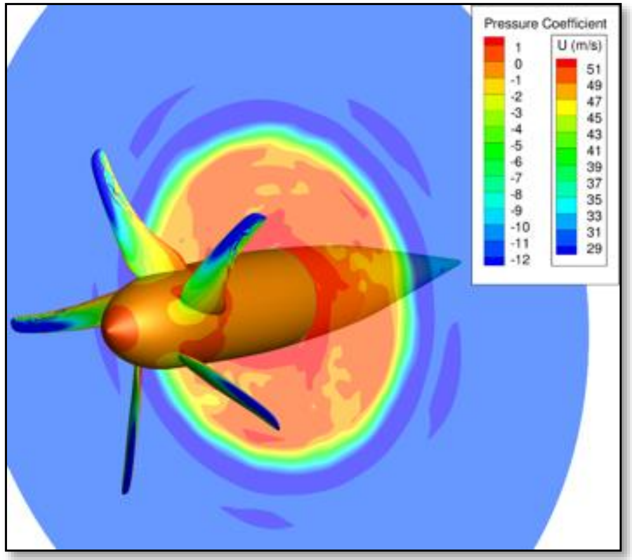
- **Qdesys Motor Control** implemented on Xilinx Zynq FPGA+ARM
- **Redundant architecture**: each power train contributes half of the torque
- **Aluminum enclosure** (EMI shielding) Aerospace connectors for I/O.
- Prototype Running at **200%** of rated power
- **Software initial release validated.**
- **Environmental screening** (shake and bake) of prototype unit completed.

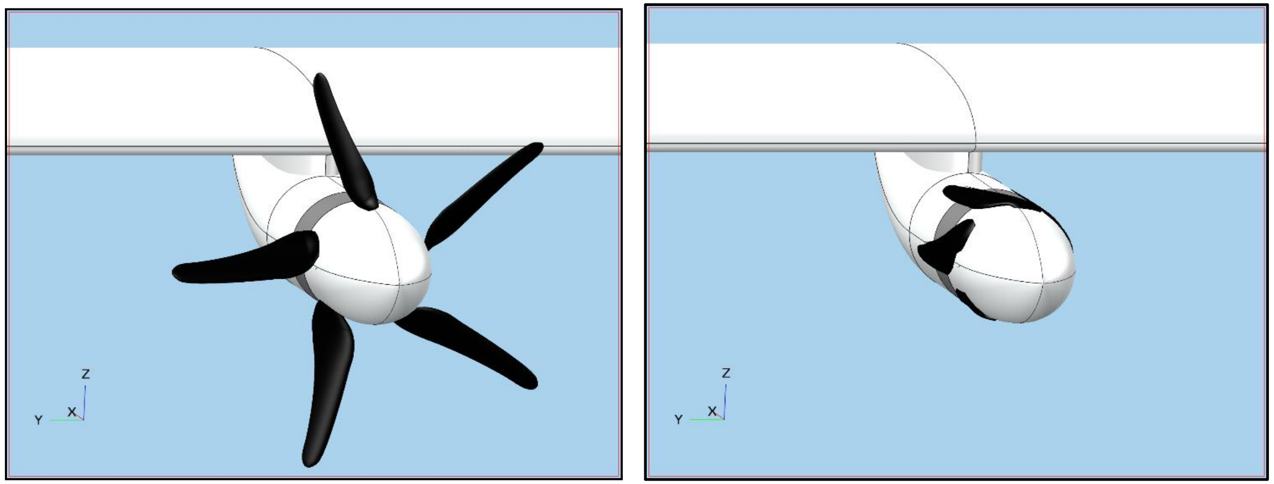




X-57 High Lift/Distributed Electric Propulsion System

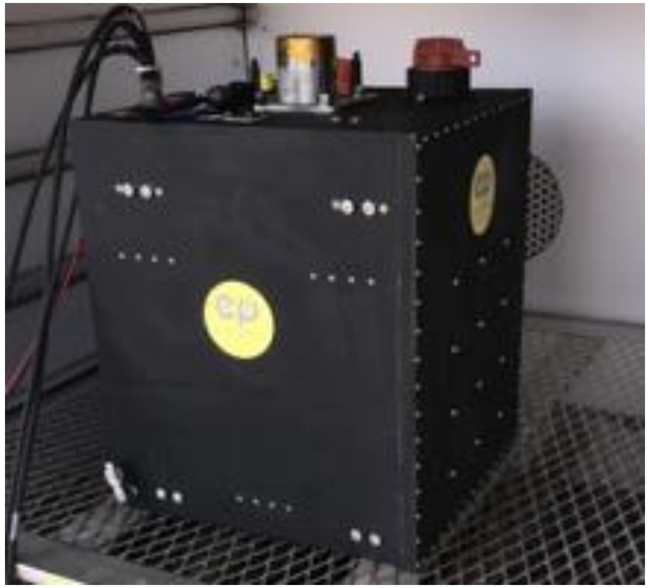
- High Lift System implemented during MOD IV.
- Mod III dummy nacelles must model OML to account for drag penalty.
- X-57 team developed initial blade geometry for uniform axial velocity increase and folds nearly flush with high-lift nacelles in cruise.
- CFD indicates wing and propeller design will meet or exceed requirements for stall speed.
- DFx about to start at ESAero



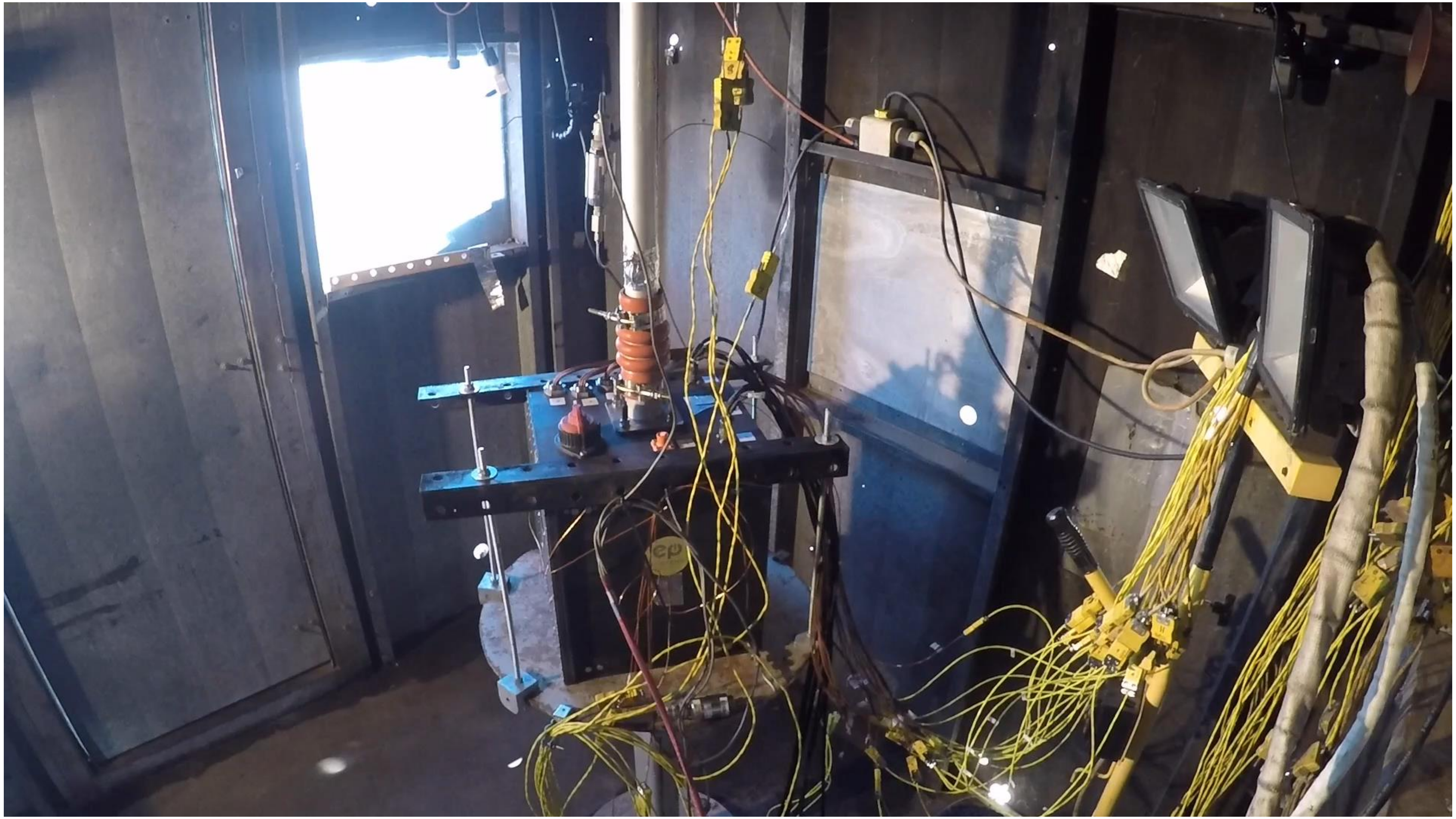


X-57 Flight Batteries (Original Approach)

- Major Lessons Learned for Aviation Battery Development.
- Use of lighter more energetic cells can pose greater safety risks.
- Cooling of cells while minimizing cell-to-cell propagation risks.
- Containment of gases and particulates drive closed designs and increased weight.
- Lighter weight Thermal Management & Containment is possible.
- eVTOL target of 30% Packaging overhead is achievable and to be demonstrated on X57.

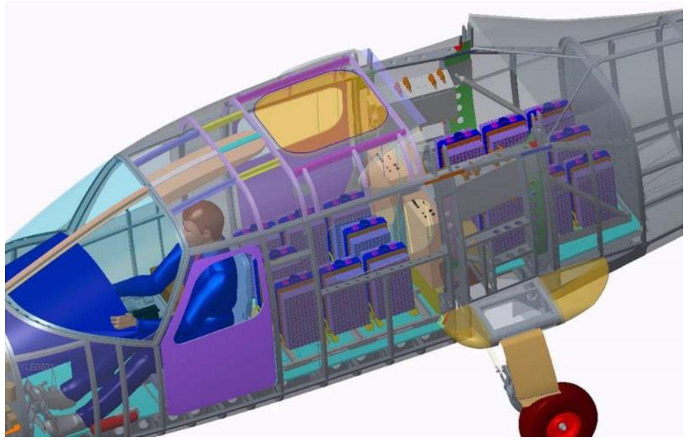


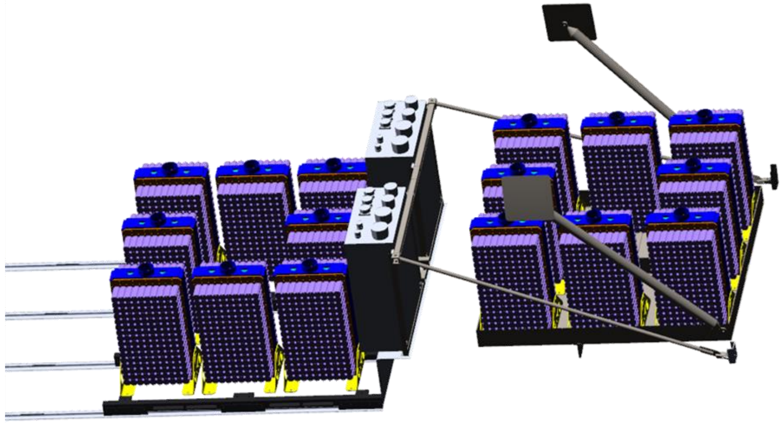
X-57 Flight Battery Destructive Testing

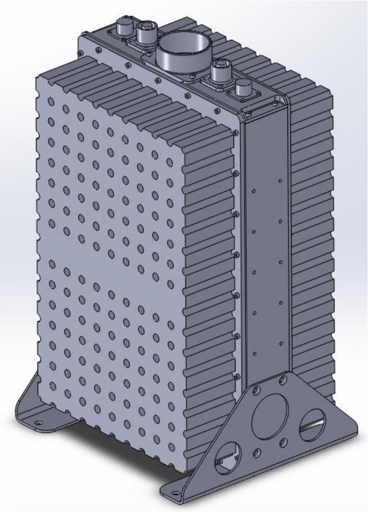


X-57 Flight Batteries (New Approach)

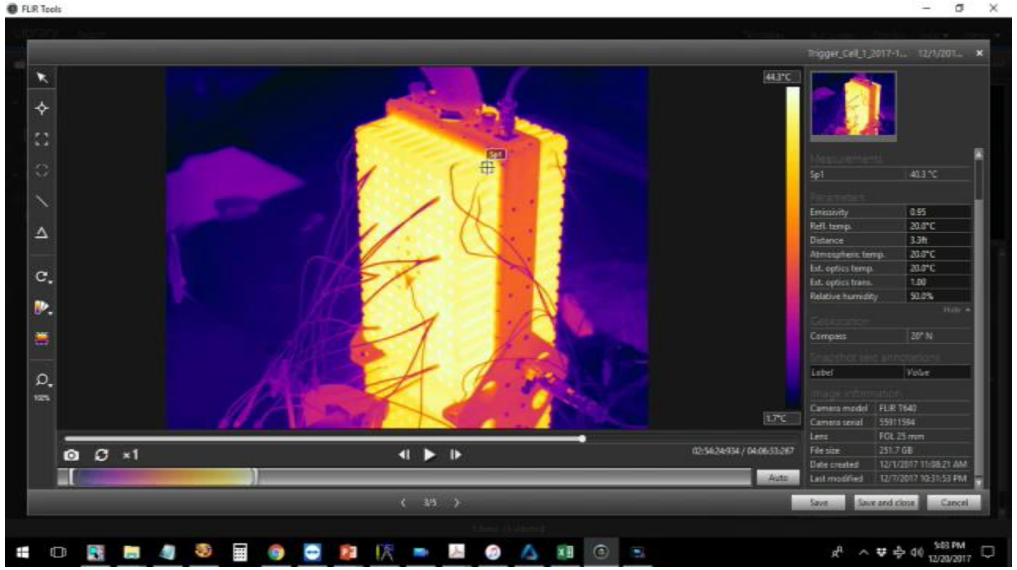
- EPS Led, ESAero and NASA Supported Design.
- Organized into 16 battery modules per aircraft, split into two packs, each with 8 battery modules and a control module.
- Cooling analysis drove module spacing.
- Nickel Cobalt Aluminum 18650 cells selected; Cells arranged in 20p16s modules.
- Each pack is 20p128s; 47 kWh useful capacity, 461 VDC nominal (416 to 525 across SOC range), peak discharge of 132 kW.
- Will comply with flight environment, including 18 g crash loads, -5 to +45 °C operating environment.

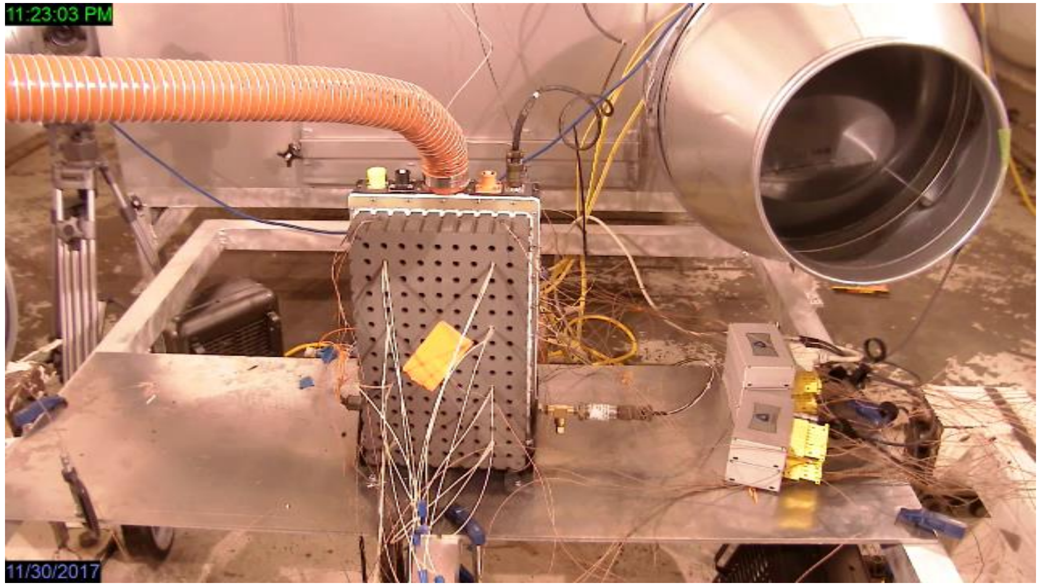






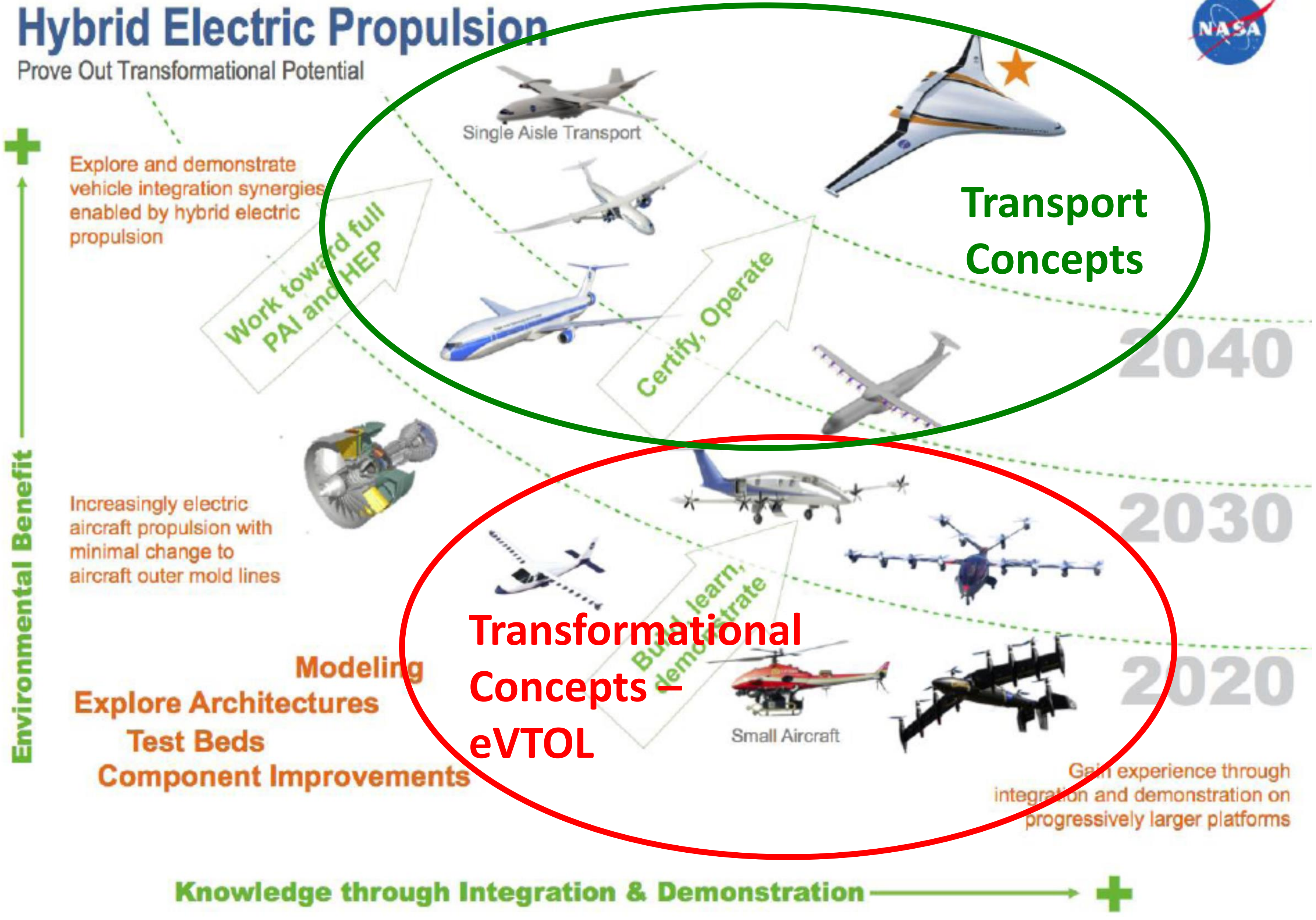
X-57 Successful Destructive Battery Test





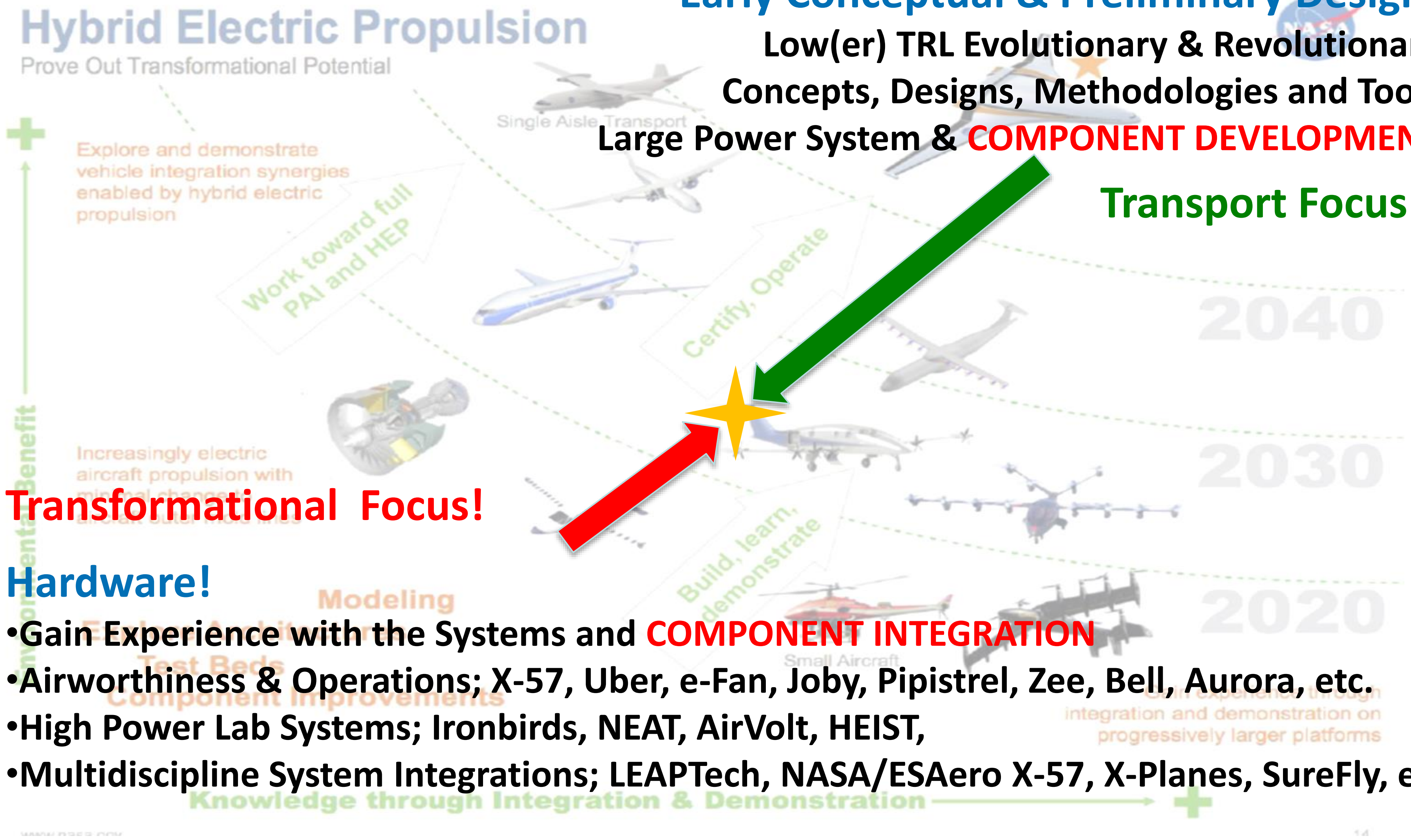
https://www.nasa.gov/centers/armstrong/feature/X-57_battery_major_milestone.html

ePropulsion Growth Potential



How will AEP Become Reality Across Vehicle Classes

Two-Tiered Approach



Early Conceptual & Preliminary Design!

Low(er) TRL Evolutionary & Revolutionary Concepts, Designs, Methodologies and Tools
Large Power System & COMPONENT DEVELOPMENT

Transport Focus!

Transformational Focus!

Hardware!

- Gain Experience with the Systems and COMPONENT INTEGRATION
- Airworthiness & Operations; X-57, Uber, e-Fan, Joby, Pipistrel, Zee, Bell, Aurora, etc.
- High Power Lab Systems; Ironbirds, NEAT, AirVolt, HEIST,
- Multidiscipline System Integrations; LEAPTech, NASA/ESAero X-57, X-Planes, SureFly, etc.

AIAA/IEEE EATS Symposium – Call for Papers

The aerospace industry has set ambitious goals for the next three generations of commercial transport aircraft to accommodate rapid growth in emerging markets and ensure sustainability of air travel. One approach being explored to meet these targets is non-traditional aircraft propulsion using electric, turboelectric or hybrid-electric powertrains. Recent workshops by the IEEE and AIAA have identified the need to bring together electrical engineers and aerospace experts as the industry looks to more electric propulsion technologies for future aircraft. The event will be co-sponsored by the IEEE (led by the Transportation Electrification Community), AIAA (led by the Aircraft Electric Propulsion and Power Working Group), and the University of Illinois at Urbana-Champaign (Grainger Center for Electric Machinery and Electromechanics, College of Engineering). This two-day symposium will focus on electric aircraft technology across three programmatic tracks: (1) electric-power enabled aircraft configurations and system requirements, (2) enabling technologies for electric aircraft propulsion, and (3) electric aircraft system integration and controls. Papers are solicited in specific areas of relevancy including, but not limited to, the following:

Track 1: Aircraft Configurations & Systems Requirements

- System feasibility studies
- Electric-enabled innovative aircraft design and propulsion concepts
- Electrical powertrain performance requirements
- Safety, critical failure modes, certification
- Lifecycle energy, operational cost, and emission analysis

Track 2: Enabling Technologies

- Machines and drives integration for optimum performance
- Conventional, cryogenic, and superconducting
- Fault tolerant power systems and components
- Energy storage devices and systems
- Electric machine and turbofan engine integration
- New material solutions or applications
- Novel thermal management solutions
- Verification and testing

Track 3: System Integration and Controls

- Electric powertrain architectures
- Fault isolation and reconfigurable systems
- Energy management systems
- Integrated electro-thermal systems
- System modeling tools
- Monitoring and diagnostics

AIAA/IEEE ELECTRIC AIRCRAFT TECHNOLOGIES SYMPOSIUM

CALL FOR PAPERS

12-13 JULY 2018 | DUKE ENERGY CONVENTION CENTER, CINCINNATI, OH

The aerospace industry has set ambitious goals for the next three generations of commercial transport aircraft to accommodate rapid growth in emerging markets and ensure the future sustainability of air travel. One approach being explored to meet these targets is non-traditional aircraft propulsion using electric, turboelectric, or hybrid-electric powertrains.

Recent workshops by the IEEE and AIAA have identified the need to bring together electrical engineers and aerospace experts as the industry looks to more electric propulsion technologies for future aircraft. For 2018, the AIAA Aircraft Electric Propulsion and Power Working Group, the IEEE Transportation Electrification Community, and the College of Engineering of the University of Illinois at Urbana-Champaign are collaborating to organize a new two-day symposium to address these issues. The event occurs on 12-13 July following the AIAA Propulsion & Energy Forum.

The symposium will focus on electric aircraft technology across three programmatic tracks: (1) electric-power enabled aircraft configurations and system requirements, (2) enabling technologies for electric aircraft propulsion, and (3) electric aircraft system integration and controls. Abstracts are solicited in specific areas of relevancy including, but not limited to, the following:

TRACK 1
Aircraft Configurations & Systems Requirements
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If you are interested in submitting an abstract or making a technical presentation please go to aiaa.org/EATS or contact the Technical Co-chairs for the symposium by 15 February:

- Phil Ansell ansell1@illinois.edu
- Andy Gibson andrew.gibson@esaero.com

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For complete Symposium details visit: aiaa.org/EATS

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