NASA Armstrong Flight Research Center

Distributed Electric Propulsion Portfolio, & Safety and Certification Considerations

Kurt V. Papathakis
kurt.papathakis@nasa.gov

Oct. 5th & 6th, 2017

Agenda

- NASA Aeronautics
- CAS Project Perspective
- Electric & Hybrid Electric Projects
  - LEAPTech
  - HEIST
  - Airvolt
  - X-57 Maxwell
  - FUELEAP
  - CAMIEM
  - LiON
- Future Distributed Electric Propulsion Considerations
- NASA Safety Approach
- Electric Propulsion Certification Considerations
- Wrap-up

kurt.papathakis@nasa.gov

NASA Aeronautics

NASA Aeronautics Vision for Aviation in the 21st Century

6 Strategic Thrusts

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Commercial Vehicles
- Transition to Low-Carbon Propulsion
- Real-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

U.S. leadership for a new era of flight

kurt.papathakis@nasa.gov

Strategic Thrusts 3 & 4

Electric Propulsion Research Themes

Strategic Thrust 3: Ultra Efficient Commercial Vehicles

2015	2025	2035
Evolutionary gains for carbon neutral growth by 2020	***Revolutionary*** improvements to fleet to achieve 2005 levels	***Transformational*** capabilities for 50% reduction of 2005 Levels

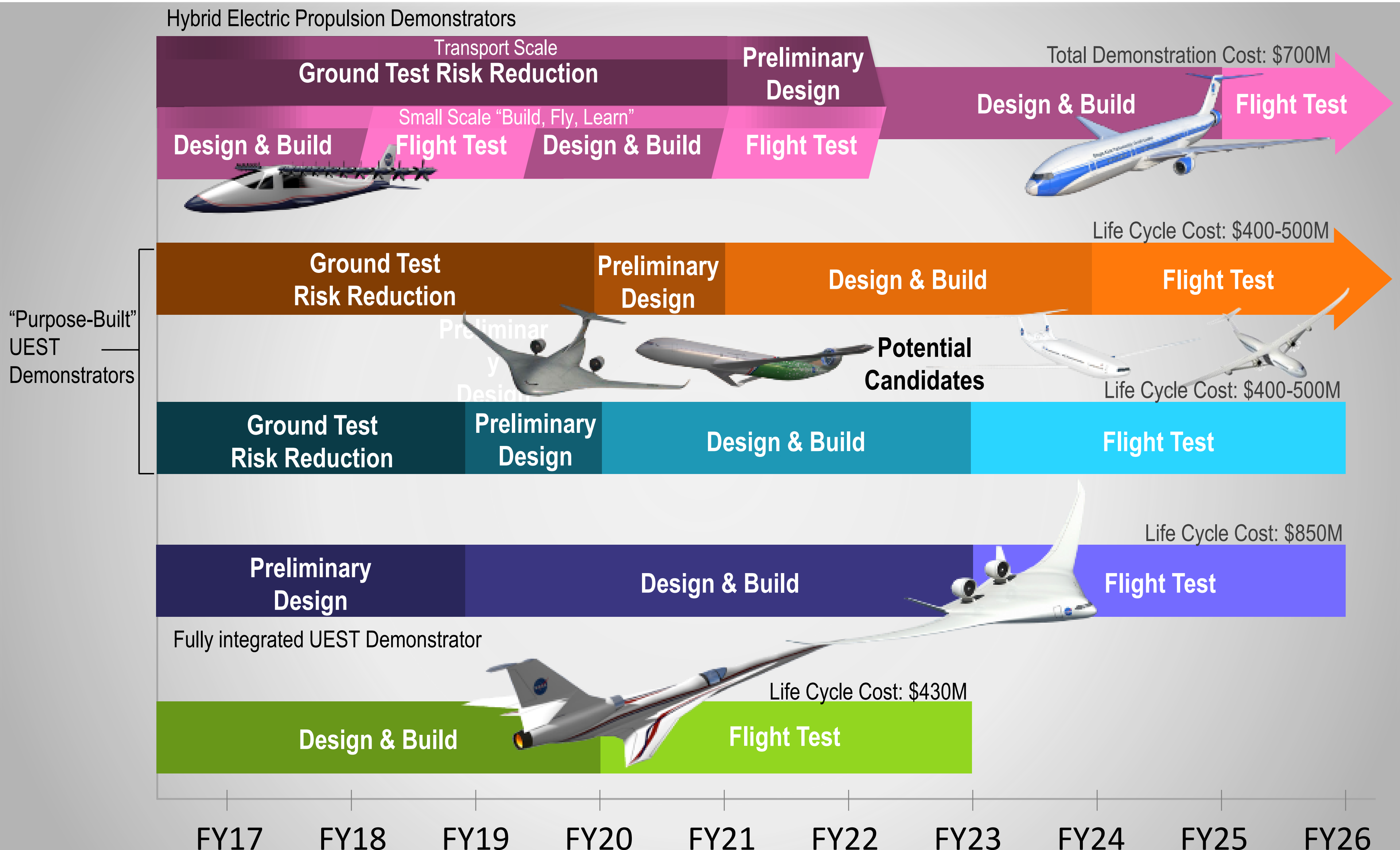
Strategic Thrust 4: Transition to Low Carbon Propulsion

2015	2025	2035
Low-carbon fuels for conventional engines	Introduction of Alternative Propulsion Systems	Alternative Propulsion Systems to Aircraft of All Sizes

- **Integrated Technology Concepts (Vehicle / Synergy)**
- **Power and Propulsion Architectures**
- **HEP Components / Enablers**
- **Modeling, Simulation, and Test Capability**

kurt.papathakis@nasa.gov

Electric & Hybrid-Electric Flight Demonstration Plan



kurt.papathakis@nasa.gov

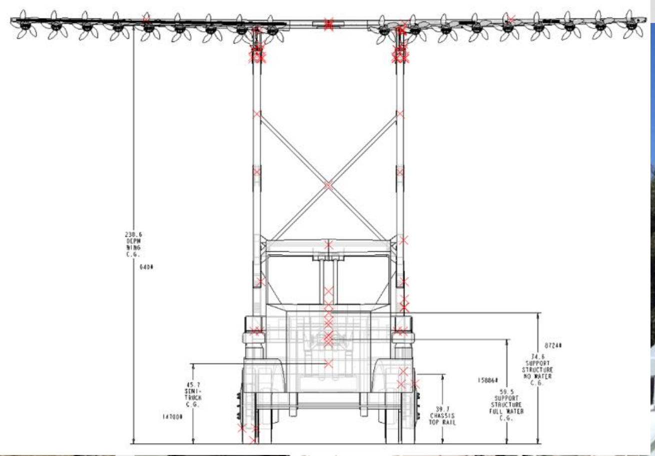
Convergent Aeronautics Solutions

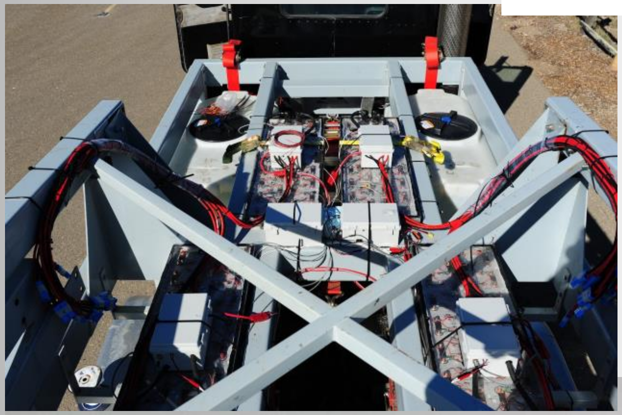
- Short project durations
- Project management – LITE
- Quickly determine technology feasibility
- Disruptive technologies
- Pulling ideas from multiple industries

kurt.papathakis@nasa.gov

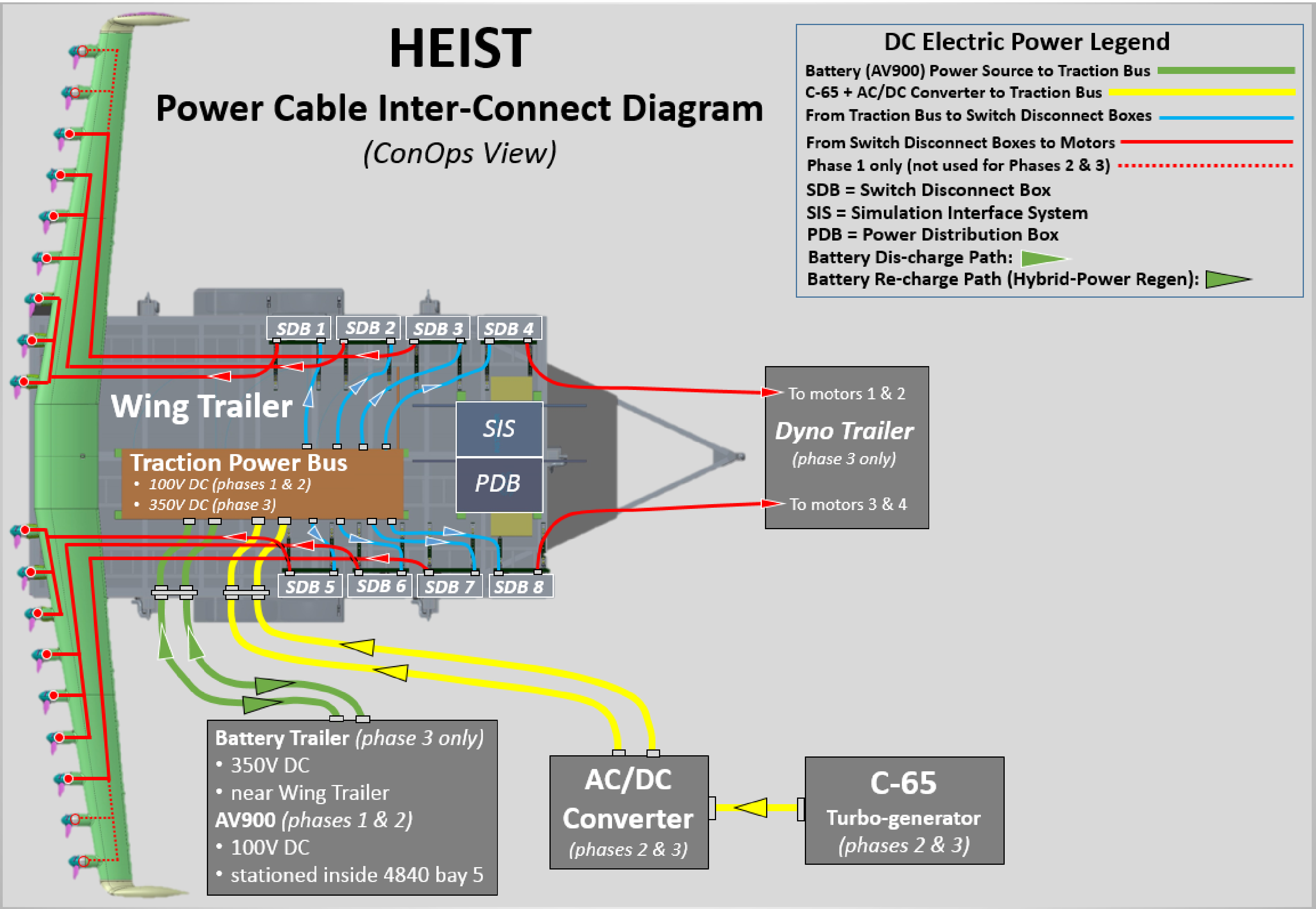
The LEAPTech Truck Experiment

1st Experiment of HEIST





Hybrid-Electric Integrated Systems Testbed (HEIST)



HEIST – Developing Distributed Electric Propulsion Control

Embedded Controllers & Distributed Intelligence

+

Power Train Command & Control Loop

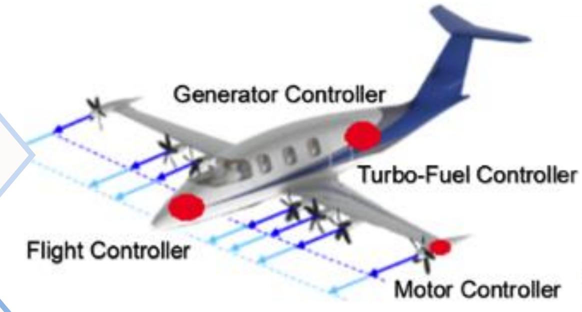
+

Aircraft / Flight Maneuver Command & Control Loop

+

Mission / Operations Command & Control Loop

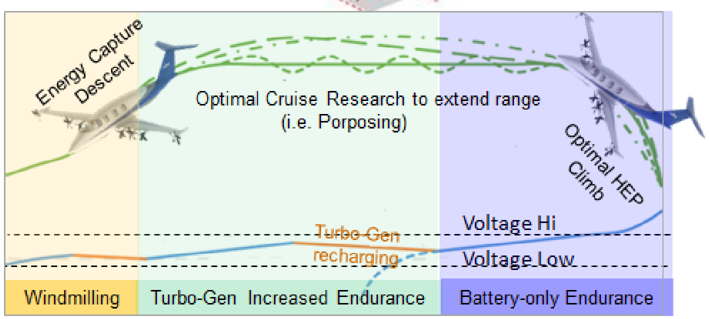
Improved efficiency for each controller (i.e. Motor, Generator, Turbine Fuel, Batteries)



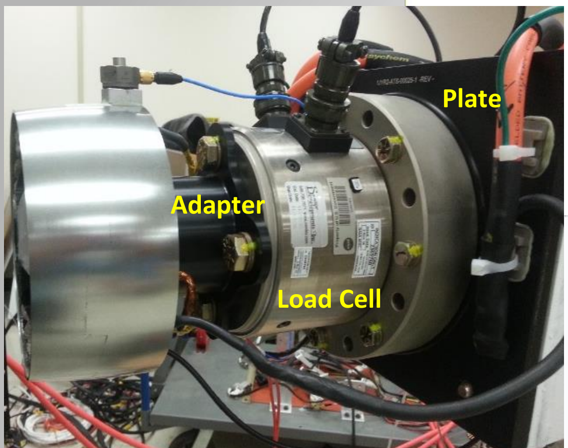
Improved Efficiency for integrated Power-Train

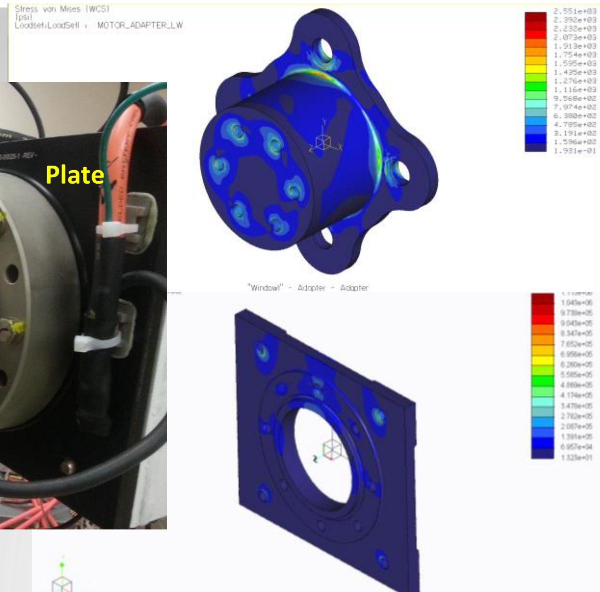
- *Electric Motors Used as Control Effectors*
- *Reduce Vertical Tail Size*
- *Failure Recovery*

- *Peak Seeking Control*
- *Optimal Flight Profile*
- *Recharge Batteries*
- *Extend Range*



Airvolt – Fully Instrumented, Single-Propulsor Test Stand



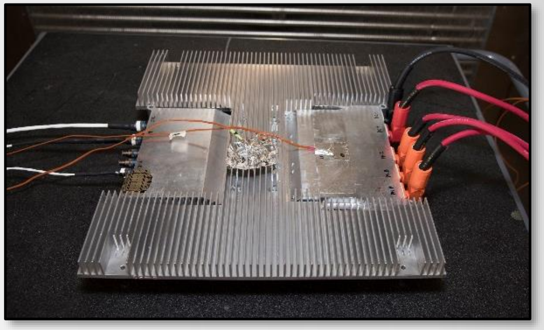


kurt.papathakis@nasa.gov

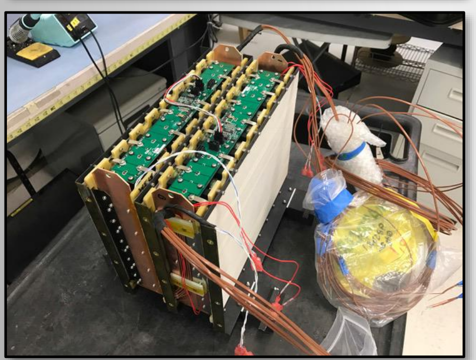
X-57 Maxwell (SCEPTOR)

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

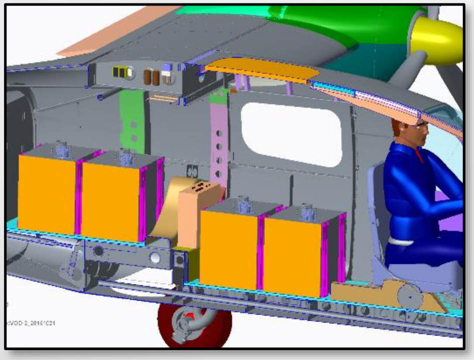
X-57 Battery Module (¼ Pack) before Short Circuit Test



Cruise Motor Inverter Environmental Testing at NASA

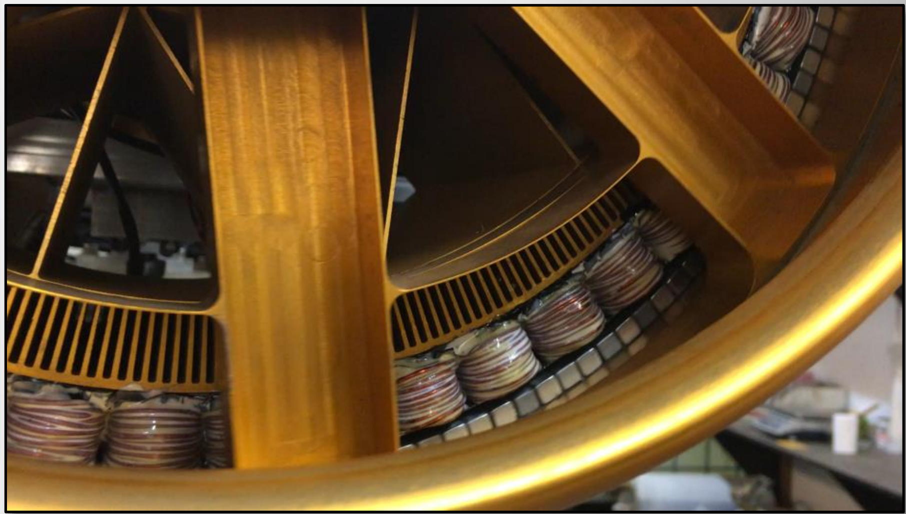


X-57 Thermal Runaway Unit (2 Trays; ½ Module)



One Battery Pack (4 Module, ½ Ship Set)

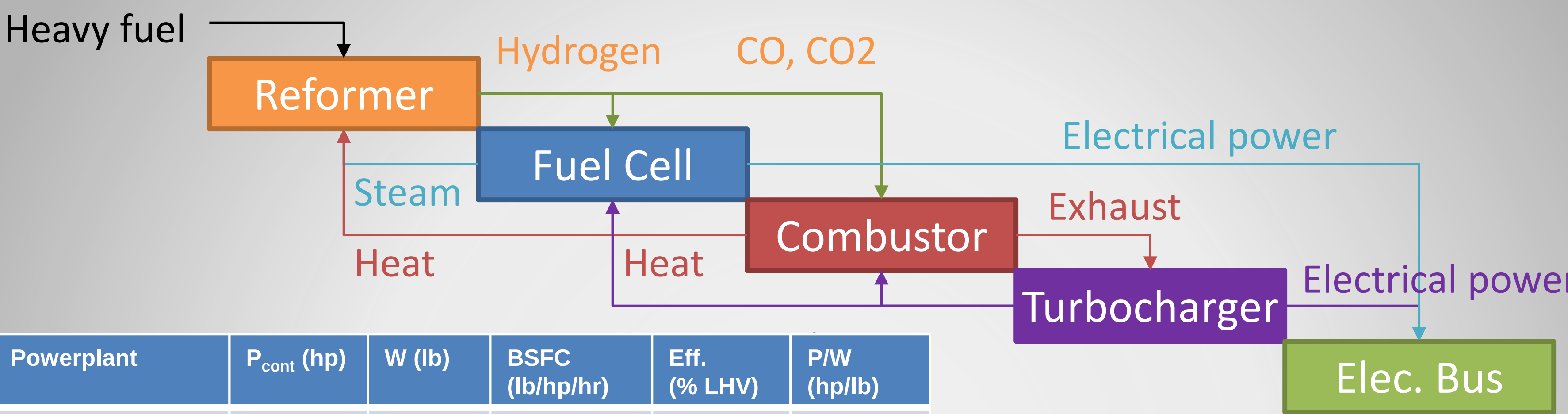
Prototype Cruise Motor



kurt.papathakis@nasa.gov

Fostering Ultra-Efficient, Low-Emitting Aviation Power

Fuel cell variant of the X-57 Maxwell



Powerplant	P_{cont} (hp)	W (lb)	BSFC (lb/hp/hr)	Eff. (% LHV)	P/W (hp/lb)
HTS900-2	891	338	0.52	26.2%	2.63
PT6A-67D	1214	515	0.53	25.9%	2.36
CT7-9B	1750	805	0.45	30.5%	2.17
IO-550N	310	450	0.49	27.9%	0.69
R912S	100	135	0.43	31.9%	0.74
DH180A4	180	315	0.40	34.6%	0.57
AE300	168	408	0.37	37.1%	0.41
SR305-230	227	455	0.36	38.1%	0.5
Siemens 260+FC	349/258	1565	0.25	55.2%	0.22
Siemens 80+FC	107/80	470	0.25	55.2%	0.23
SCEPTOR+FC	93/66	447	0.25	55.2%	0.21
SCEPTOR	93	79/504	10.46*	92.0%**	1.2/0.18

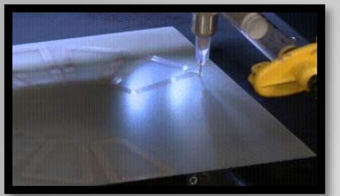
NASA X-57 Mod II "Maxwell" Flight Demonstrator

Turboshaft
Turboprop
Gasoline piston
Turbodiesel piston
Proposed fuel cell system
Pure battery-electric

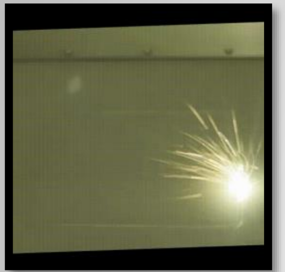
kurt.papathakis@nasa.gov

Compact Additive Manufactured Innovative Electric Motor

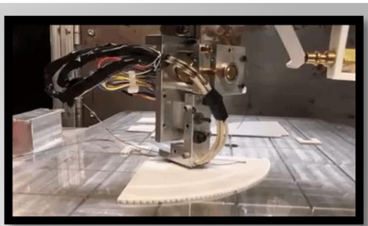
Additive Manufacturing for Electric Motors



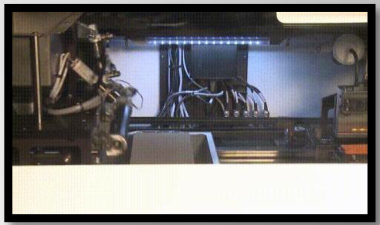
Direct Write Printing (GRC)



Selective Laser Sintering (LaRC)



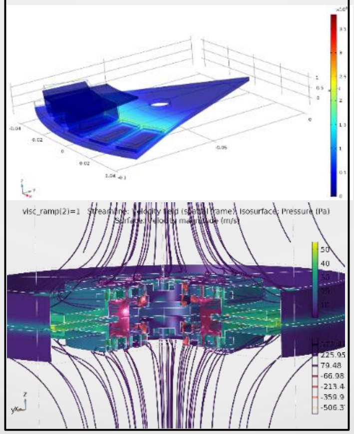
Wire Embedding (UTEP)

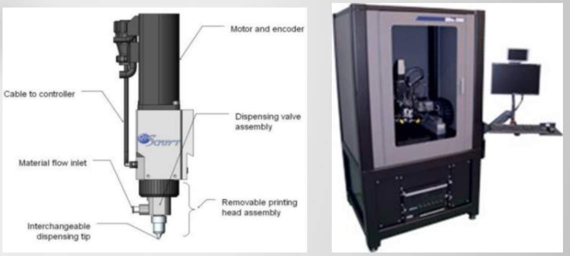


Binder Jet 3D Printing (GRC)

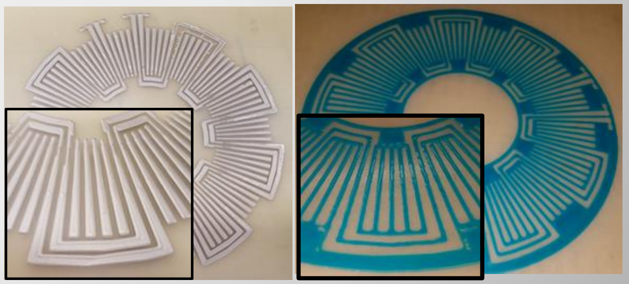
Stator design: LaunchPoint & UTEP

Performance Prediction with FEM





NScrypt SmartPump and Direct Write Printer



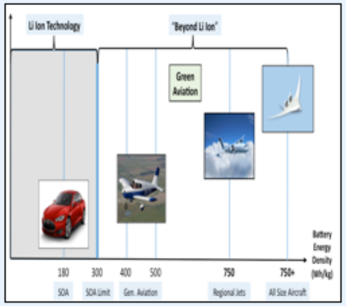
kurt.papathakis@nasa.gov

LiON: Lithium Oxygen Batteries for NASA Electric Propulsion

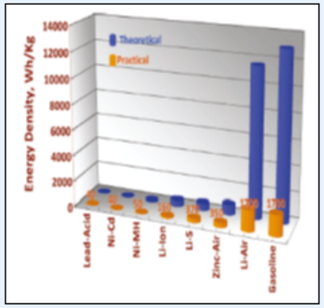
Lithium – Air feasibility for flight

1. Li-Air Batteries for Electric Aircraft

Big Question: Can we design and build a viable battery which satisfies the significant requirements of electric aircraft

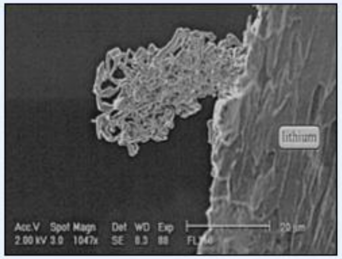


SOA Li-Ion plateaus at 300 Wh/kg. Advanced technologies required!



Li-Air has the highest theoretical battery energy density

2. Li-Air Battery Challenges



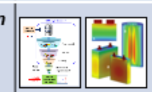
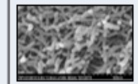
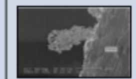
Electrolyte decomposition limits energy density and rechargeability

SOA electrolytes are flammable. Unacceptable for aircraft

Electrolytes are limiting factor for Li-Air batteries for:
- ***Practical energy densities***
- ***Rechargeability***
- ***Safety***

Feasibility Objective: design/fabricate *Li-Air electrolytes* with energy densities 400+ Wh/kg and 100+ recharges and test in an electric UAV

3. Convergent Approach

Thrust Area	SOA	Transformative	
Computation	Empirical *"trial-and-error"* method	***Predictive computation*** accelerates development	 Modeling
New Materials	Commercial *"off-the-shelf"* materials	***New materials*** components designed and fabricated	 Aerogel Structure
Decomposition Mechanisms	Electrolyte decomposition poorly understood	***Electrolyte Design Rules***	 Experimentation
Electric Flight	Academic, laboratory studies	***Electric flight*** systems modeling, instrumentation, test and analysis	 UAV Li-Air Flight

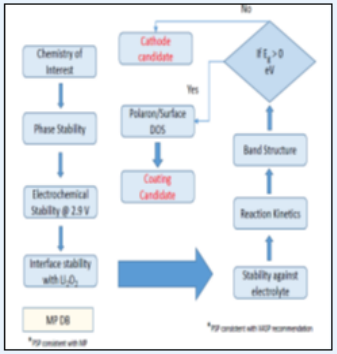
4. Computational Materials Screening

Electrolyte Data Mining

PubChem ID	Predicted improvement in charging efficiency (rel. to DME)*	Available Commercially
567509	46%	✓
44719690	50%	✓
2724291	60%	✓
69609	40%	✓
99791	58%	✓

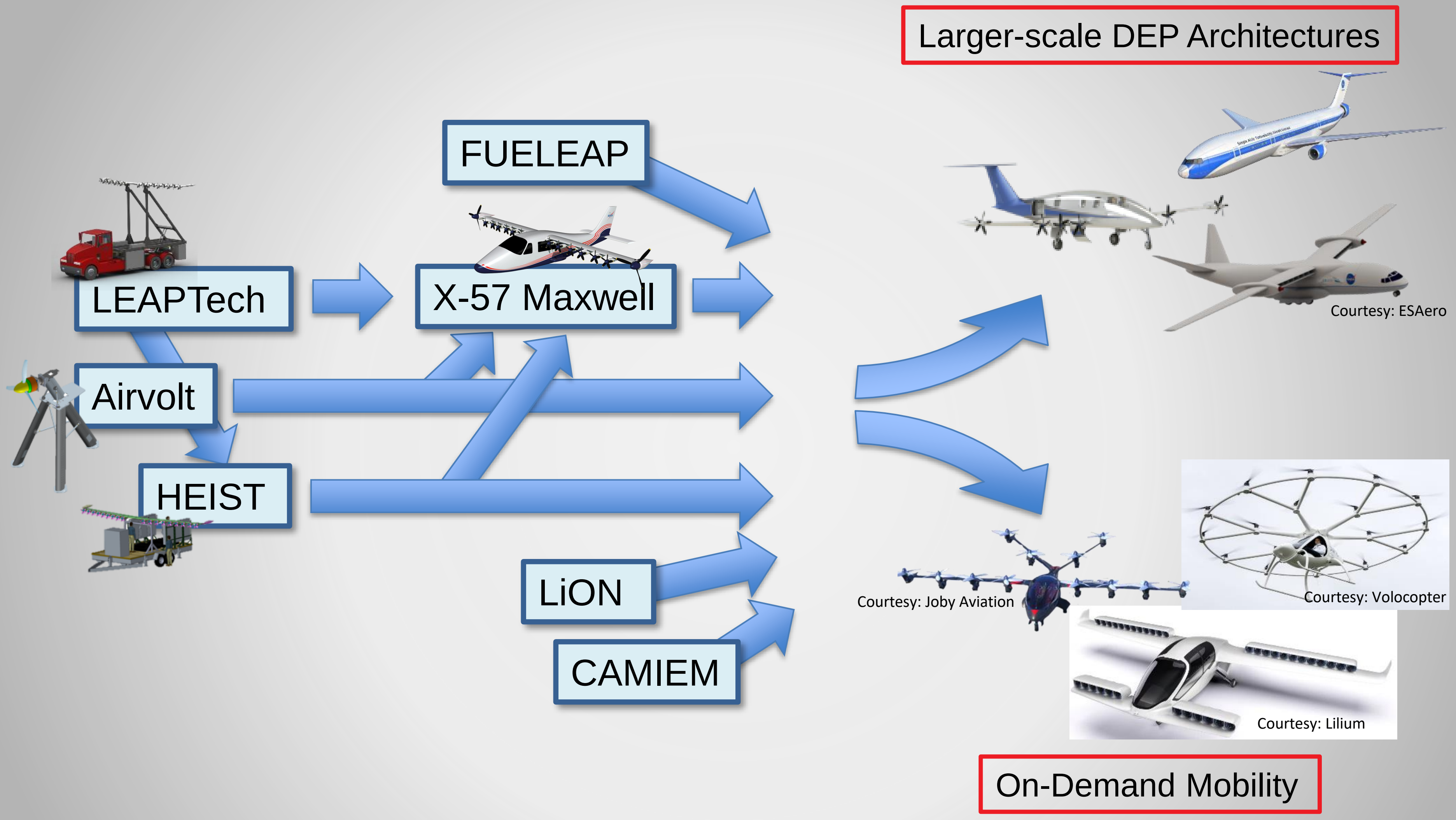
10 million database candidates screened for critical properties

Cathode Screening Workflow



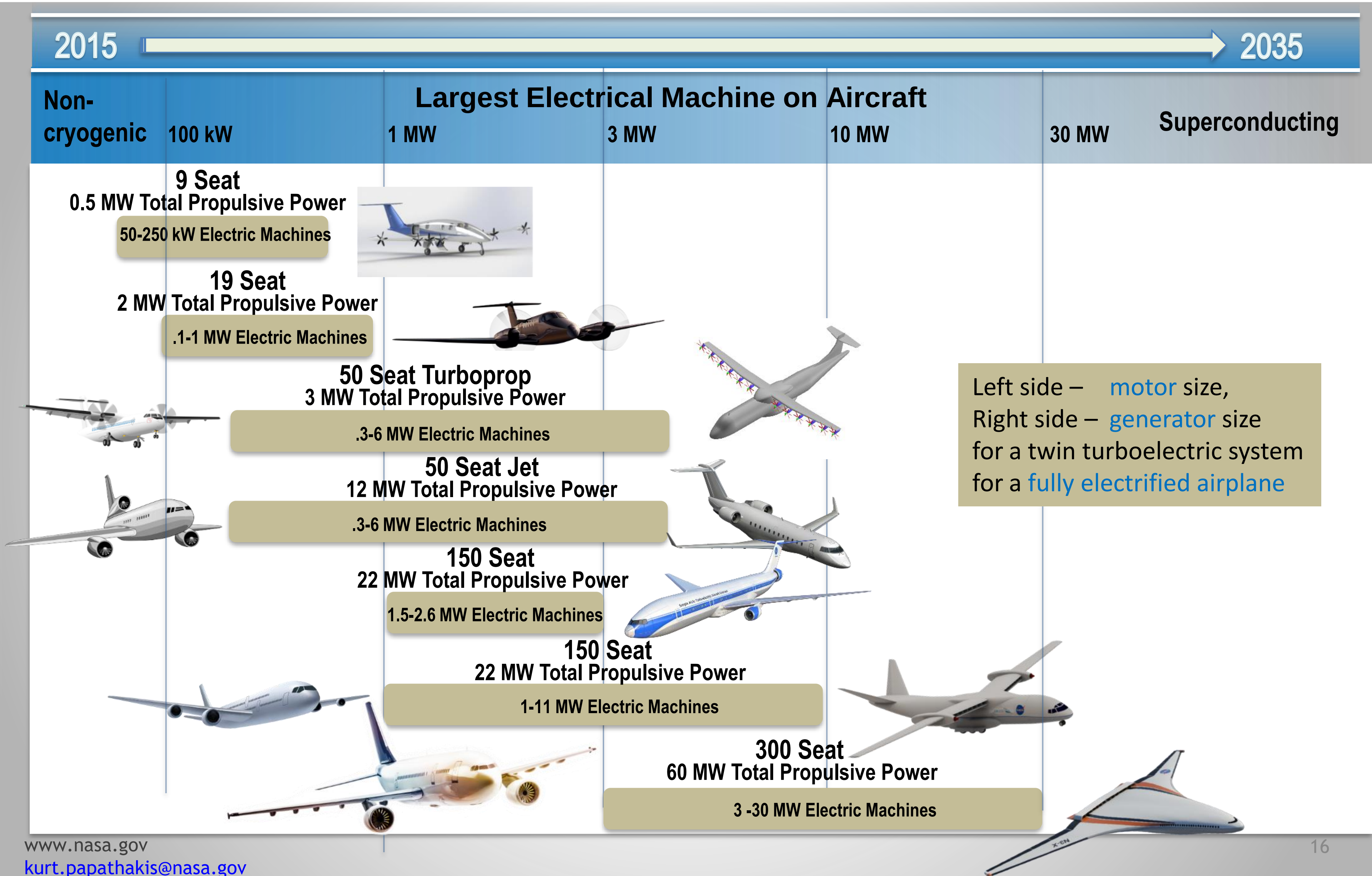
New candidates have lower operating voltages which decrease decomposition

How the all the projects come together…



kurt.papathakis@nasa.gov

Where do we go from here?



NASA Safety Considerations for Electric Propulsion

kurt.papathakis@nasa.gov

Electric & Hybrid-Electric Testbed-Specific Hazards

Project hazard summary	Severity/probability classification	
	Human	Asset
X-57 Maxwell		
HR-1 Aircraft traction battery fire	I D	I D
HR-2 Structural failure of wing	I D	I D
HR-3 Traction bus failure	I E	I E
HR-5 Aircraft damage due to exposure to excessive environmental conditions during ground operations	N/A	III D
HR-7 Wing control surface system failure	I D	I D
HR-9 Inadequate stability control	I D	I D
HR-11 Failure of motor mounts	I E	I E
HR-12 Whirl flutter	I D	I D
HR-13 Symmetric loss of cruise propeller thrust (partial/total)	II E	II E
HR-14 Avionics bus failure	III E	II E
HR-15 Cruise propeller performance degradation and/or separation	I E	I E
HR-17 Battery modules separate from attach points	I E	I E
HR-18 Abrupt asymmetric thrust	I D	I D
HR-19 Electromagnetic interference in flight	N/A	IV D
HR-20 Landing gear structural failure	II D	I D
HR-21 Failure of propulsor system	I E	I E
HR-22 Restricted and/or obstructed crew egress	I E	N/A
HR-23 Cockpit air contamination	I E	I E
HR-24 Inadvertent cruise motor propeller rotation	I E	III E
HR-25 Equipment pallet separates from attach points	I E	III E
HR-26 Personnel exposed to high voltage/current	I E	N/A
HR-27 High lift propeller damage and/or separation	Analysis in work	
HR-28 Classic flutter	I E	N/A

Project hazard summary	Severity/probability Classification	
	Human	Asset
HEIST		
HR-1 Propeller failure	I E	III C
HR-2 Traction battery fire	II E	III D
HR-3 Inadvertent system activation	I E	III E
HR-4 Electrical discharge / shock / arc flash	I E	III E
HR-5 HEIST ground asset collision	I E	II E
HR-6 JM-1 motor failure	I E	IV B
HR-7 Electrical fire	II E	III D
HR-8 Damage to HEIST assets due to environmental factors	N/A	III E
HR-9 Test article support structure failure	I E	III E
HR-10 Excessive noise exposure	II E	N/A
HR-12 Dynamometer system failure	I E	III C
HR-15 Software operation outside of intended parameters	N/A	III C
HR-16 Electromagnetic interference	N/A	IV D
HR-17 Loss of hardware communication link	N/A	IV D
Airvolt		
HR-1: Lithium polymer battery fire	II E	IV E
HR-2: Airvolt test stand structural failure	I E	III E
HR-3: Electrical fire	III D	II E
HR-4: Electrical discharge/shock	I E	III E
HR-5: Propeller / motor failure	I E	IV E
HR-6: Test personnel exposed to excessive noise during system operation	II E	N/A

Example of a Distributed Electric Propulsion Hazard

X-57 Maxwell HR-3 traction bus failure

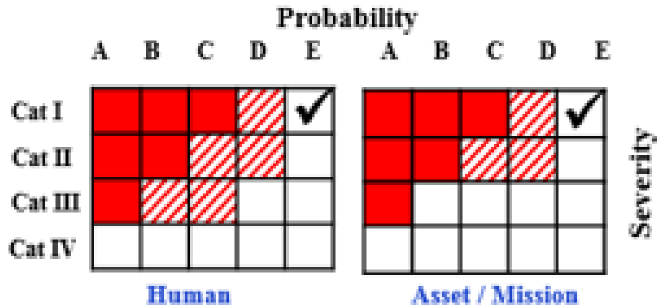
Causes

A. Electrical short
B. Wiring defect
C. Design error
D. Circuit protection component failure
E. Installation error
F. External/environmental abuse (thermal/mechanical)
G. Grounding isolation fault
H. Inadequate grounding
I. Operational / procedural error
J. Lightning strike

Effects

* Loss of essential avionics power
* Total loss of aircraft power
* Motor failure
* Propeller governor failure
* Fire
* Damage or loss of aircraft
* Damage to ground assets
* Injury or death to personnel

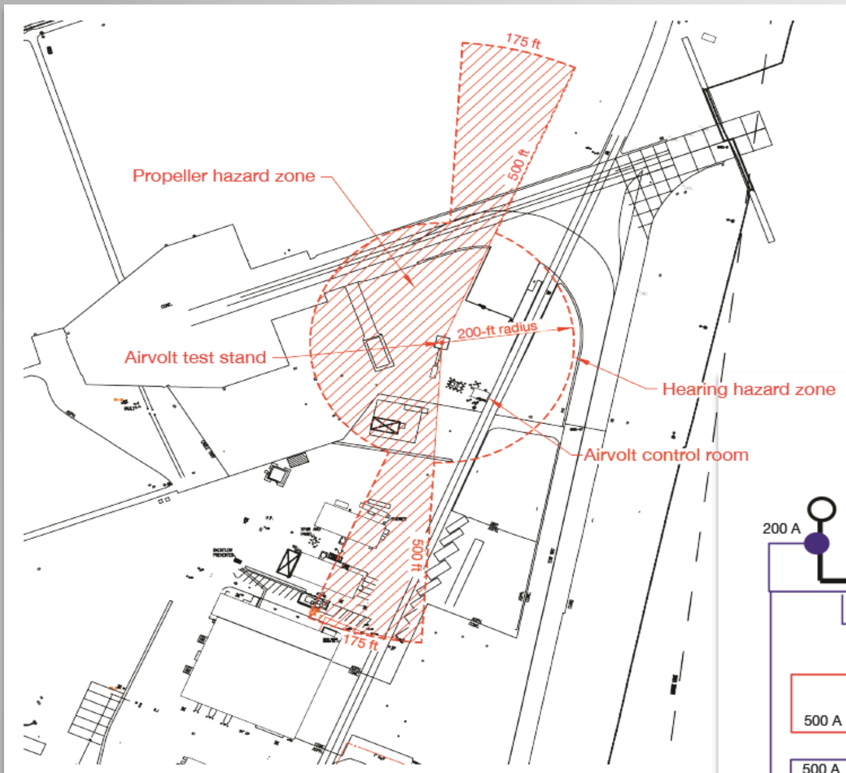
AFRC hazard action matrices



Mitigations

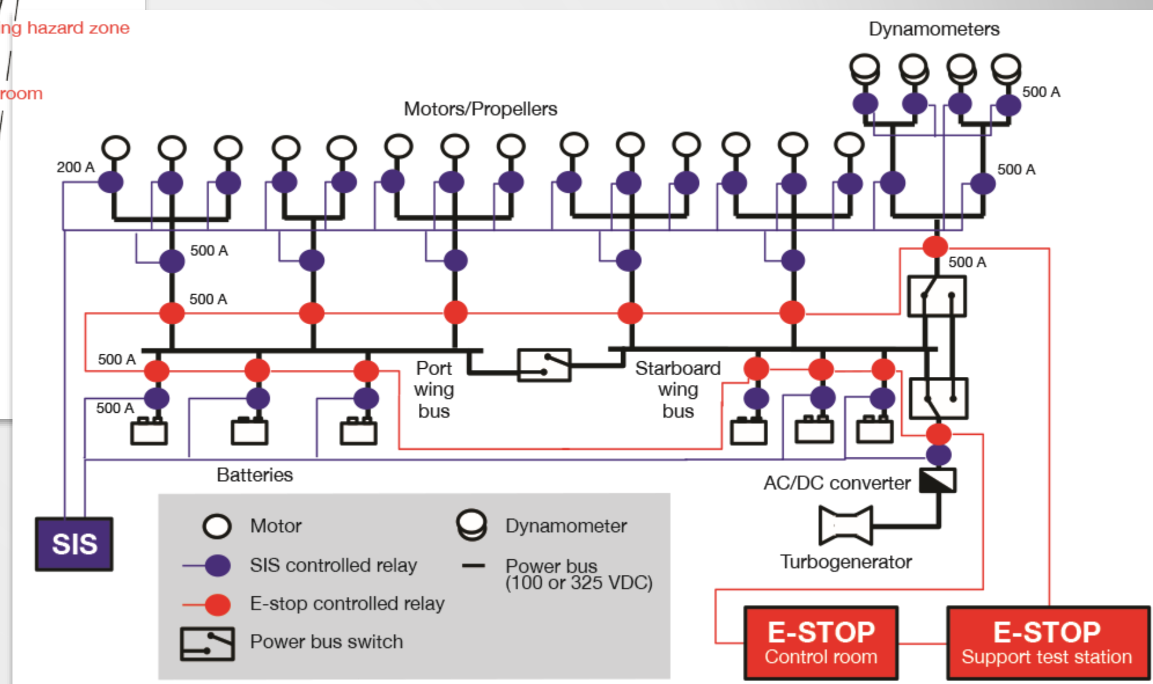
1 Design avionics bus for single fault tolerance (A,B,C,D,E)
2 Ground test (CST) (A,B,C,D,E,F,G,I)
3 Grounding checks (G,H)
4 Design with margin (de-rate power system) (C,D,F)
5 Quality control process (B,E,I)
6 Peer review of design (C)
7 VFR operations only (J)
8 Perform visual inspection of system components (A,B,D,E,F)
9 Adhere to X-57 operational placards and procedures (E,F,H,I,J)

Distributed Electric Propulsion Hazard Mitigation Examples



Propeller and audio decibel-level threshold keep out zone

Manual hardware-only Emergency-Stop (E-Stop) relay network



kurt.papathakis@nasa.gov

NASA Considerations for Electric Propulsion Certification

kurt.papathakis@nasa.gov

FAR Part 33 – Aircraft Engines applicability

- Document:
  - *ANLYS-CEPT-005 Airvolt – FAR Part 33 Aircraft Engine applicability*
- Related documents:
  - FAR Part 23 – Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
  - FAR Part 33 – Airworthiness Standards: Aircraft Engines
  - NEMA MG 1-2014 Motors and Generators
  - CEPT-SPEC-001 Motor and Controller Specifications

FAR Part 33.7 – Engine rating and operating limitations
FAR Part 33.19 – Durability
FAR Part 33.27 – Turbine, compressor, fan, and turbosupercharger rotors
FAR Part 33.28(f) – Engine control system
FAR Part 33.43 – Vibration test (reciprocating aircraft engines)
FAR Part 33.49 – Endurance Test (reciprocating aircraft engines)
FAR Part 33.83 – Vibration Test (turbine engines)
FAR Part 33. 87 – Endurance Test (turbine engines)
FAR Part 33.95 – Engine-propeller system test

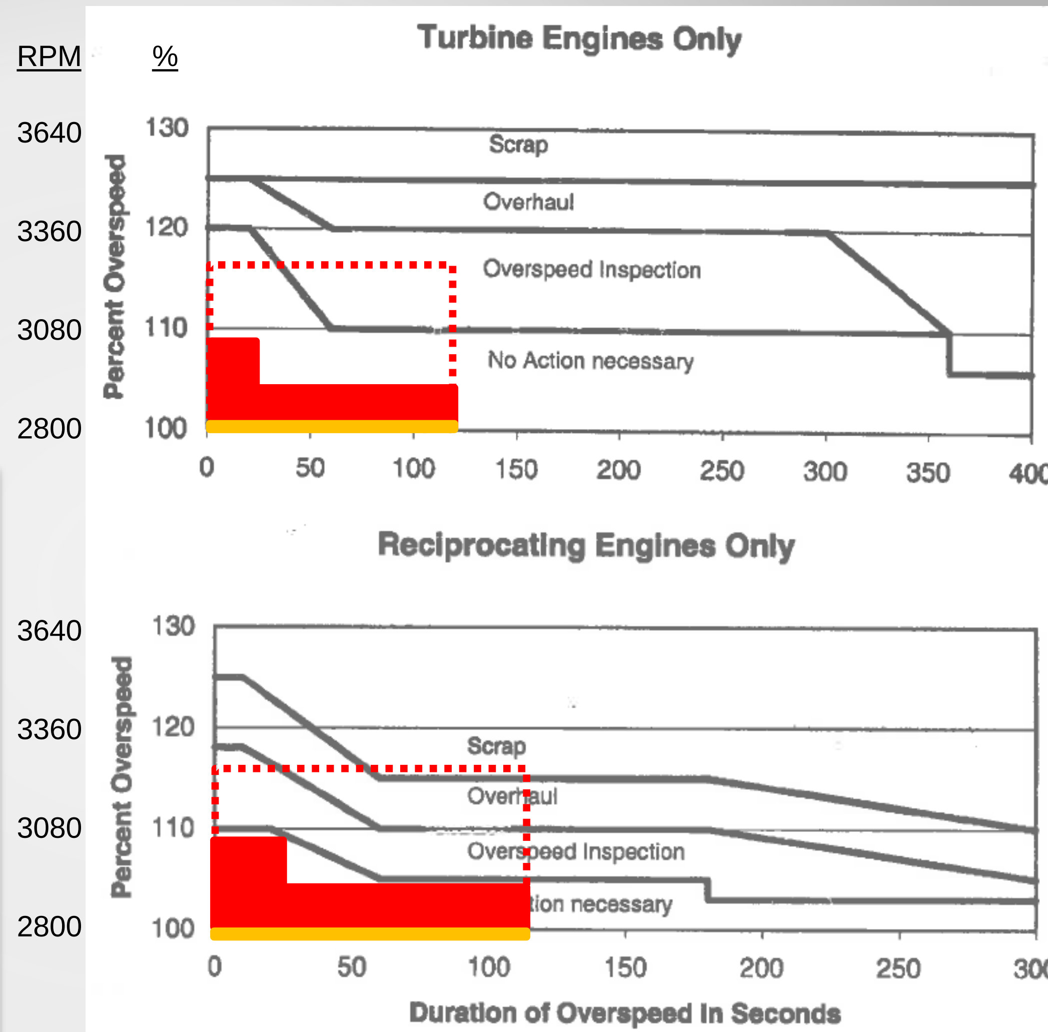
kurt.papathakis@nasa.gov

Propeller / Motor Overspeed

RPM	Comment
3240	– 120% Max Rated Speed *(FAR Part 33.27)*
2800	– 100% Rated Speed *(MT-7 Propeller)*
2700	– 100% Max Rated Speed *(JMX57 Motor)*

FAR Part 33.27

- Seeks **15 min** at **120%** maximum operating speed
- **15 min** would lead to the propeller being '**Scrapped**'
- We estimated at in an emergency condition, X57 team would need **2 min** to get the plane ready for unpowered landing
- However, the propeller **may not** be able to handle at 120% for 2 min
- 25 sec – 113% (of rated motor speed)
- 95 sec – 108% (of rated motor speed)

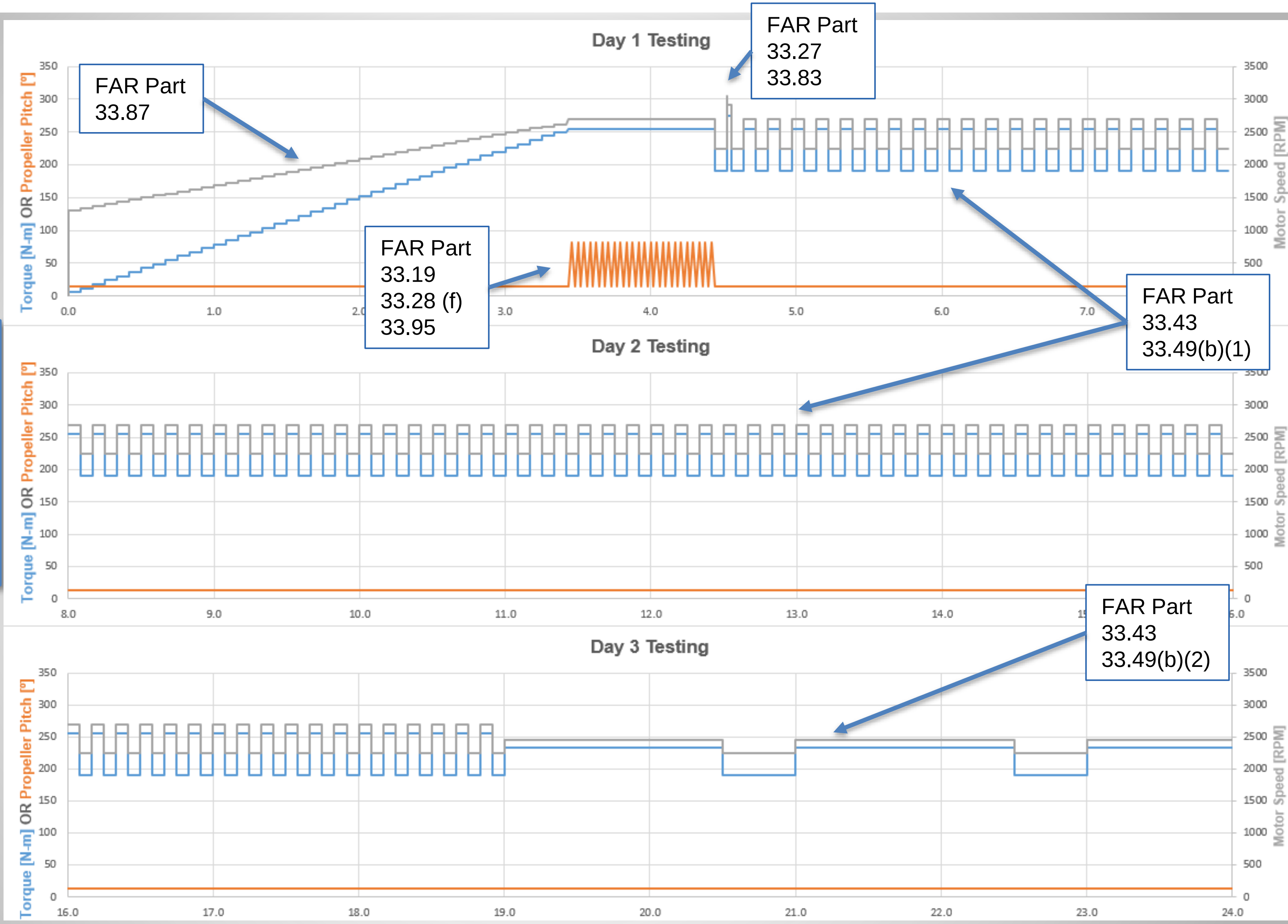


kurt.papathakis@nasa.gov

Motor Testing Strategy & Implementation

Total Endurance: 79 hr *

Total Vibration: >10M cycles



*hrs 24 – 79 of testing not shown

Backup Slides

kurt.papathakis@nasa.gov