NASA Armstrong Flight Research Center

Distributed Electric Propulsion Portfolio, & Safety and Certification Considerations

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Agenda

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

Sustainable

Transformative

U.S. leadership for a new era of flight

NASA Aeronautics Vision for Aviation in the 21st Century
Strategic Thrust 3: Ultra Efficient Commercial Vehicles

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

Strategic Thrust 4: Transition to Low Carbon Propulsion

2015: Low-carbon fuels for conventional engines
2025: Introduction of Alternative Propulsion Systems
2035: 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
Electric & Hybrid-Electric Flight Demonstration Plan

Hybrid Electric Propulsion Demonstrators

- Transport Scale
  - Ground Test Risk Reduction
  - Preliminary Design
  - Design & Build
  - Flight Test

- Small Scale “Build, Fly, Learn”
  - Preliminary Design
  - Design & Build
  - Flight Test

Total Demonstration Cost: $700M

Life Cycle Cost: $400-500M

Potential Candidates

- Preliminary Design
- Design & Build
- Flight Test

Life Cycle Cost: $400-500M

“Purpose-Built” UEST Demonstrators

- Ground Test Risk Reduction
- Preliminary Design
- Design & Build
- Flight Test

Life Cycle Cost: $850M

Fully integrated UEST Demonstrator

- Preliminary Design
- Design & Build
- Flight Test

Life Cycle Cost: $430M

Design & Build

- Flight Test

FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26
• Short project durations
• Project management – LITE
• Quickly determine technology feasibility
• Disruptive technologies
• Pulling ideas from multiple industries
The LEAPTech Truck Experiment

1st Experiment of HEIST
Hybrid-Electric Integrated Systems Testbed (HEIST)

HEIST
Power Cable Inter-Connect Diagram
(ConOps View)

DC Electric Power Legend
- Battery (AV900) Power Source to Traction Bus
- C-65 + AC/DC Converter to Traction Bus
- From Traction Bus to Switch Disconnect Boxes
- From Switch Disconnect Boxes to Motors
  - Phase 1 only (not used for Phases 2 & 3)
- SDB = Switch Disconnect Box
- SIS = Simulation Interface System
- PDB = Power Distribution Box
- Battery Dis-charge Path:
- Battery Re-charge Path (Hybrid-Power Regen):

Wing Trailer
Traction Power Bus
- 100V DC (phases 1 & 2)
- 350V DC (phase 3)

Battery Trailer (phase 3 only)
- 350V DC
- near Wing Trailer
AV900 (phases 1 & 2)
- 100V DC
- stationed inside 4840 bay 5

SDB 1 SDB 2 SDB 3 SDB 4
SDB 5 SDB 6 SDB 7 SDB 8

SIS PDB

Dyno Trailer
(phase 3 only)
To motors 1 & 2

AC/DC Converter
(phases 2 & 3)

C-65 Turbo-generator
(phases 2 & 3)
To motors 3 & 4
HEIST – Developing Distributed Electric Propulsion Control

- 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

Embedded Controllers & Distributed Intelligence

Power Train Command & Control Loop

Aircraft / Flight Maneuver Command & Control Loop

Mission / Operations Command & Control Loop
Airvolt – Fully Instrumented, Single-Propulsor Test Stand
Fostering Ultra-Efficient, Low-Emitting Aviation Power

Fuel cell variant of the X-57 Maxwell

Heavy fuel

- Reformer
- Fuel Cell
- Combustor
- Turbocharger
- Elec. Bus

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

NASA X-57 Mod II “Maxwell” Flight Demonstrator

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

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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)

Performance Prediction with FEM

Stator design: LaunchPoint & UTEP

NScrypt SmartPump and Direct Write Printer
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

<table>
<thead>
<tr>
<th>Thrust Area</th>
<th>SOA</th>
<th>Transformative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computation</td>
<td>Empirical “trial-and-error” method</td>
<td>Predictive computation accelerates development</td>
</tr>
<tr>
<td>New Materials</td>
<td>Commercial “off-the-shelf” materials</td>
<td>New materials components designed and fabricated</td>
</tr>
<tr>
<td>Decomposition Mechanisms</td>
<td>Electrolyte decomposition poorly understood</td>
<td>Electrolyte Design Rules</td>
</tr>
<tr>
<td>Electric Flight</td>
<td>Academic, laboratory studies</td>
<td>Electric flight systems modeling, instrumentation, test and analysis</td>
</tr>
</tbody>
</table>

**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

4. Computational Materials Screening

**Electrolyte Data Mining**

**Cathode Screening Workflow**

10 million database candidates screened for critical properties

New candidates have lower operating voltages which decrease decomposition

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How the all the projects come together…

LEAPTech → FUELEAP → X-57 Maxwell → HEIST → CAMIE

Larger-scale DEP Architectures

On-Demand Mobility

LEAPTech → Airvolt → FUELEAP → X-57 Maxwell → HEIST → CAMIE

LiON

Larger-scale DEP Architectures

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LiON

Larger-scale DEP Architectures

On-Demand Mobility

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Where do we go from here?

<table>
<thead>
<tr>
<th>Non-cryogenic</th>
<th>100 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Seat</td>
<td>0.5 MW Total Propulsive Power</td>
</tr>
<tr>
<td></td>
<td>50-250 kW Electric Machines</td>
</tr>
<tr>
<td>19 Seat</td>
<td>2 MW Total Propulsive Power</td>
</tr>
<tr>
<td></td>
<td>.1-.1 MW Electric Machines</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Largest Electrical Machine on Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MW</td>
</tr>
<tr>
<td>3 MW</td>
</tr>
<tr>
<td>10 MW</td>
</tr>
<tr>
<td>30 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2015</th>
<th>2035</th>
</tr>
</thead>
</table>

**Superconducting**

- **Left side** – motor size, Right side – generator size for a twin turboelectric system for a fully electrified airplane

- **50 Seat Turboprop**
  - 3 MW Total Propulsive Power
  - .3-.6 MW Electric Machines

- **50 Seat Jet**
  - 12 MW Total Propulsive Power
  - .3-.6 MW Electric Machines

- **150 Seat**
  - 22 MW Total Propulsive Power
  - 1.5-.2.6 MW Electric Machines

- **150 Seat**
  - 22 MW Total Propulsive Power
  - 1-11 MW Electric Machines

- **300 Seat**
  - 60 MW Total Propulsive Power
  - 3-30 MW Electric Machines
NASA Safety Considerations for Electric Propulsion
<table>
<thead>
<tr>
<th>Project hazard summary</th>
<th>Severity/probability classification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-57 Maxwell</strong></td>
<td></td>
</tr>
<tr>
<td>HR-1 Aircraft traction battery fire</td>
<td>I D I D</td>
</tr>
<tr>
<td>HR-2 Structural failure of wing</td>
<td>I D I D</td>
</tr>
<tr>
<td>HR-3 Traction bus failure</td>
<td>I E I E</td>
</tr>
<tr>
<td>HR-5 Aircraft damage due to exposure to excessive environmental conditions during ground operations</td>
<td>N/A III D</td>
</tr>
<tr>
<td>HR-7 Wing control surface system failure</td>
<td>I D I D</td>
</tr>
<tr>
<td>HR-9 Inadequate stability control</td>
<td>I D I D</td>
</tr>
<tr>
<td>HR-11 Failure of motor mounts</td>
<td>I E I E</td>
</tr>
<tr>
<td>HR-12 Whirl flutter</td>
<td>I D I D</td>
</tr>
<tr>
<td>HR-13 Symmetric loss of cruise propeller thrust (partial/total)</td>
<td>II E II E</td>
</tr>
<tr>
<td>HR-14 Avionics bus failure</td>
<td>III E II E</td>
</tr>
<tr>
<td>HR-15 Cruise propeller performance degradation and/or separation</td>
<td>I E I E</td>
</tr>
<tr>
<td>HR-17 Battery modules separate from attach points</td>
<td>I E I E</td>
</tr>
<tr>
<td>HR-18 Abrupt asymmetric thrust</td>
<td>I D I D</td>
</tr>
<tr>
<td>HR-19 Electromagnetic interference in flight</td>
<td>N/A IV D</td>
</tr>
<tr>
<td>HR-20 Landing gear structural failure</td>
<td>II D I D</td>
</tr>
<tr>
<td>HR-21 Failure of propulsor system</td>
<td>I E I E</td>
</tr>
<tr>
<td>HR-22 Restricted and/or obstructed crew egress</td>
<td>I E N/A</td>
</tr>
<tr>
<td>HR-23 Cockpit air contamination</td>
<td>I E I E</td>
</tr>
<tr>
<td>HR-24 Inadvertent cruise motor propeller rotation</td>
<td>I E III E</td>
</tr>
<tr>
<td>HR-25 Equipment pallet separates from attach points</td>
<td>I E III E</td>
</tr>
<tr>
<td>HR-26 Personnel exposed to high voltage/current</td>
<td>I E N/A</td>
</tr>
<tr>
<td>HR-27 High lift propeller damage and/or separation</td>
<td>Analysis in work</td>
</tr>
<tr>
<td>HR-28 Classic flutter</td>
<td>I E N/A</td>
</tr>
</tbody>
</table>

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

X-57 Maxwell HR-3 traction bus failure

<table>
<thead>
<tr>
<th>Causes</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Electrical short</td>
<td>* Loss of essential avionics power</td>
</tr>
<tr>
<td>B. Wiring defect</td>
<td>* Total loss of aircraft power</td>
</tr>
<tr>
<td>C. Design error</td>
<td>* Motor failure</td>
</tr>
<tr>
<td>D. Circuit protection component failure</td>
<td>* Propeller governor failure</td>
</tr>
<tr>
<td>E. Installation error</td>
<td>* Fire</td>
</tr>
<tr>
<td>F. External/environmental abuse (thermal/mechanical)</td>
<td>* Damage or loss of aircraft</td>
</tr>
<tr>
<td>G. Grounding isolation fault</td>
<td>* Damage to ground assets</td>
</tr>
<tr>
<td>H. Inadequate grounding</td>
<td>* Injury or death to personnel</td>
</tr>
<tr>
<td>I. Operational / procedural error</td>
<td></td>
</tr>
<tr>
<td>J. Lightning strike</td>
<td></td>
</tr>
</tbody>
</table>

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)
Propeller and audio decibel-level threshold keep out zone

Manual hardware-only Emergency-Stop (E-Stop) relay network
NASA Considerations for Electric Propulsion Certification
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
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)
Motor Testing Strategy & Implementation

Total Endurance: 79 hr *

Total Vibration: >10M cycles

*hrs 24 – 79 of testing not shown