A Roadmap to Our Sustainable Aviation Future:

Challenges and Opportunities of Aircraft Electrification

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PM, Electrified Powertrain Flight Demonstration Project
NASA ARMD Integrated Aviation Systems Program

Michigan Initiative for Sustainable Aviation (MISA)
September 19-20, 2023
Subsonic Transport Market - Global competition expanding

- $78B positive trade balance; $1.8T total U.S. economic activity
- 10.9M direct/indirect jobs
- 21.3B tons of freight transported by U.S. airlines in 2019
Subsonic Transport faces growing environmental pressure

Airplane & Engine Level

<table>
<thead>
<tr>
<th>CO₂ standard</th>
<th>Airplane-level</th>
<th>CAEP/10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New for 2020</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nvPM standards</td>
<td>Engine-level</td>
<td>CAEP/10 (/11 in 2023)</td>
</tr>
</tbody>
</table>

Noise regulation
- Airplane-level
- Chapter 14/Stage 5

Existing periodic updates
- LTO NOx regulation
- Engine-level
- CAEP/8

Flight shaming, new standards, noise-limited capacity

IATA ATAG Goal for Net-Zero Carbon by 2050

FAA Population Impacted by 65 (& 55) dB

ICAO CAEP exploring the feasibility of a “long-term aspirational goal” for carbon
### 2030-2035 Entry-Into-Service Targets for EAP: Thin haul, regional and next generation Sustainable Aviation markets

<table>
<thead>
<tr>
<th>Market</th>
<th>Regional Air Mobility</th>
<th>Regional Turboprops &amp; Turbofans</th>
<th>Single Aisle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passengers</td>
<td>1-19</td>
<td>20-150</td>
<td>150-more</td>
</tr>
<tr>
<td>Speed</td>
<td>$\approx$150-250 mph</td>
<td>$\approx$300-400 mph</td>
<td>$\approx$500-700 mph</td>
</tr>
<tr>
<td>Range</td>
<td>$\approx$100-500 miles</td>
<td>500-1500 miles</td>
<td>1500-3500 miles</td>
</tr>
<tr>
<td>Power</td>
<td>$\approx$1MW</td>
<td>1 to 5 MW</td>
<td>3 to 30MW</td>
</tr>
<tr>
<td>Heat</td>
<td>$\approx$200 kW waste heat</td>
<td>200kw to 1MW waste heat</td>
<td>600kW to 6MW waste heat</td>
</tr>
</tbody>
</table>
Some questions need to be answered before electric aircraft flights are widespread:
- Has the **technology** improved enough?
  - Battery technology, thermal management, …
- How much **storage** is needed for reserves?
- How would the **diversion** due to bad weather be handled?
- How can an electric aircraft be **certified**?
  - Safety (fire)
- Would **NAS operations** be affected by electric aircraft?
  - Takeoff, climb, cruise performance
  - Turnaround time
- How much **infrastructure** change would be required?
For EAP aircraft to become real, three roadmaps are needed:

- Technology (and utilities)
- Regulatory
- Infrastructure

WHAT ARE THE BARRIERS THAT MUST BE TACKLED FOR EACH ROADMAP?
<table>
<thead>
<tr>
<th>Barrier Risk</th>
<th>Risk Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Voltage Operation at Altitude</td>
<td>Given that arcing, partial discharge and corona of high power/voltage transmission cables can occur at cruise altitudes or due to life effects, there is the possibility that the demonstrator could have <strong>power system failures, resulting in potential loss of aircraft.</strong></td>
</tr>
<tr>
<td>Thermal Management</td>
<td>Given that the amount of electrical power required for the demonstration is unprecedented in flight and generates <strong>significant low quality/low grade heat</strong>, there is a possibility that there will be <strong>unforeseen challenges in designing a low parasitic power thermal management system.</strong></td>
</tr>
<tr>
<td>Battery System Performance Shortfall</td>
<td>Given that the battery pack requirement exceeds current state of the art technology, there is a possibility that the <strong>battery system design does not meet performance requirements,</strong> resulting in a <strong>higher battery weight and decrease Vision Vehicle performance.</strong></td>
</tr>
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## MW-Class Powertrain Barrier Integration Risks

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<th>Barrier Risk</th>
<th>Risk Statement</th>
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<tr>
<td><strong>Propulsion System Integration</strong></td>
<td>Given that this electrified aircraft propulsion system is novel, there is a possibility that there are unforeseen conflicts in the turbomachinery integration with electric machines, resulting in, but not limited to, reduced operability and larger system weight that decreases overall Vision Vehicle performance.</td>
</tr>
<tr>
<td><strong>Powertrain System Integration</strong></td>
<td>Given that this powertrain system is novel, there is a possibility that there it will not meet stability, EMI compatibility, or performance requirements which will require a redesign, resulting in an increase in cost and delay in schedule for Vision Vehicle development.</td>
</tr>
<tr>
<td><strong>Aircraft System Integration</strong></td>
<td>Given that MW EAP has never been deployed on an aircraft before, there is a possibility that there are unforeseen conflicts integrating EAP system into the aircraft, resulting in an increase in cost and a delay in schedule and an inefficient aircraft.</td>
</tr>
</tbody>
</table>
Evolution of All-Electric Aircraft with Advances in Battery Technology

- Pack specific energy
  - Have improved > 250% since the 90s
  - Advanced chemistries needed to reach higher values
  - Pack factors need reduction from 32% to 10-20%

- Single-aisle, 737 class
  - 1000 Wh/kg

- Regional
  - 500 Wh/kg
  - 400 Wh/kg
  - 50 – 70 PAX

- 20 PAX commuter
  - 200 – 250 miles
  - 300 – 350 Wh/kg

- Current, 170-200 Wh/kg
Beyond Li-Ion

- **Today Li-ion**: Maximum cell ~300 Wh/kg
- **Near term**: Maximum cell ~500 Wh/kg?
- **Li Metal-High voltage cathode**: 755 Wh/kg
- **Li-S**: 2600 Wh/kg
- **Far Term**: Maximum cell ~900 – 1000 Wh/kg?
- **Li-air**: 3500 Wh/kg?
Evolution of Hydrogen Electric Aircraft with Advanced Technology

- Fuel cells and turbofans are two paths for integrating hydrogen solutions
- Hydrogen offers very low emissions and relatively high efficiency

**19 PAX commuter**
- < 400 miles
- < 1 MW, SOA Specific power

**50-80 PAX commuter**
- 100 miles
- 200 - 250 miles
- 4-6 MW, 2 kW/kg (60% improvement)

**112-150 PAX**
*Hybrid* Regional and Single Aisles

**Single-aisle 180 PAX, 737 class**
- 40 MW, > 4 kW/kg (3-4x improvement)

**Challenges:**
- Energy storage
- Volume
- fuel cell specific power / thermal, durability
- H2 as an energy source
H2 Key Barrier Risks

- Fuel Cell Energy Density
- LH2 Storage Technologies
- LH2 Crashworthiness
- Transfer, Disconnects, Purging & Venting
- Electrical Design Considerations
- Grounding and Bonding
- Embrittlement and Material Compatibility
- Managing Boil Off
- Integrated Thermal Management
- Insulation – Tanks, Plumbing, Fittings, etc.
- Fire and Safety
- Plumbing, Valves & Sealing
• The ability to realize a commercially viable product overcoming **non-technical barriers**

  – Operability/System-of-systems infrastructure
    • *Is this aircraft concept consistent with the air transportation infrastructure and operational environment?*

  – Stakeholder acceptability
    • *Will the world accept this aircraft?*

  – Economics
    • *Can creating the aircraft concept and bringing it into cost-effective service attract infrastructure investment and an end-user base?*
• Key Gaps: Electric Engines (Part 33); Powerplant & Energy Storage (Part 23, 25, 27)
• Means of Compliance to address key gaps: Test Methodologies
  • TRL advancement through Flight Demonstrations
EAP operability, acceptability and investment

NGOs/Associations Commitments:

• Air Transport Action Group (ATAG) - Fly Net Zero and Waypoint 2050
  – Supported by International Federation of Air Line Pilots' Associations (IFALPA)
  – Supported by Civil Air Navigation Services Organization (CANSO)
• International Air Transport Association (IATA) - Fly Net Zero
• International Coordinating Council of Aerospace Industries Associations (ICCAIA)
• International Business Aviation Council (IBAC)
• Airports Council International (ACI)
• Internation Energy Agency – Aviation Tracking Report
• Royal Aeronautical Society - Publicly reaffirmed commitment to RAE 2050 NetZero campaign
• Royal Academy of Engineers - National Engineering Policy Centre (NEPC)
• ASME, ASCE, AIChE, SAE, AIAA, IEEE, ASTM, EuroCAE...

Source: ICAO LTAG Tech SG/ 2023
The Challenge AND the Opportunity for MISA

Goal: Develop simultaneously three roadmaps that address Sustainable Aviation from the perspective of:

- **Technologies, Aircraft integration, Operability, Reliability and Maintenance Roadmap**
  - Electrification Architectures:
    - All Electric
    - Hybrid Electric
      - Electric Machines plus Gas Turbine Engines
      - Hybrid Propulsion Systems: SAF, Battery... Hydrogen, Ammonia ...

- **Infrastructure/Logistics Value Chain Roadmap**
  - For Energy Sources/Recharging/Storage
  - For Operations and Maintenance

- **Regulatory and Standards Engagement Roadmap**
  - Local
  - State
  - Federal
  - International

Potential Demonstration Pilots?