Fuel Cells for Long Endurance Unmanned Aerial Systems

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UAS Power & Control Vision & Approach

- AF Vision Statement: To Deliver Affordable and Integrated SUAS Assets with the Following Attributes:
  - **Exponential Force Multiplier**
    - Cross domain integration across mission sets
  - **Easily Integrated Asset**
    - Deployable by a variety of means, providing flexibility, reach, penetration, and integration with joint forces
  - **Cost Savings Enabler**
    - Employing low cost SUAS with increased functionality improves combat effectiveness and efficiency
- **Approach:**
  - Leverage unique expertise in hybrid power and flight control technologies to address current and future UAS requirements
  - Develop hybrid propulsion system architectures and control strategies
  - Foster critical industry / Govt partnerships to develop, demonstrate and transition technologies into next generation UAS
  - Perform integrated UAS ground/flight testing to validate technology predictions

U.S. AIR FORCE

Small Unmanned Aircraft Systems (SUAS) Flight Plan: 2015-2035

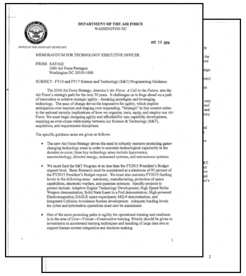
Bridging the Gap Between Tactical and Strategic

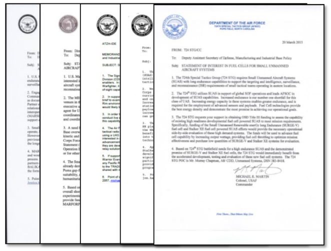
Produced by: Deputy Chief of Staff for Intelligence, Surveillance, and Reconnaissance (ISR)

Office of Primary Responsibility (OPR): AF/A2CU, Remotely Piloted Aircraft (RPA) Capabilities

UAS Power/Propulsion: Need for Long Endurance

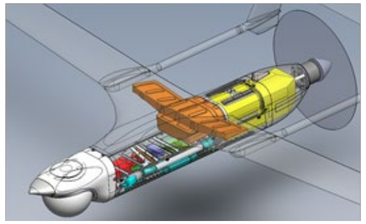
- The need for improved UAS endurance and operational reach has been echoed across USAF and DoD at all levels of leadership…
- FY16 and FY17 S&T Programming Guidance Memo, William A. LaPlante (Former Assistant Secretary of the Air Force, Acquisition)
    - “We must continue to pursue advances in affordable unmanned systems. They may **provide increased range, endurance, and persistence with reduced size, cost, and complexity**. In high intensity conflicts, they **will provide increased capability and additional capacity to supplement high-end aircraft**.”
- Small Unmanned Aircraft Systems (SUAS) Flight Plan: 2016-2036, Lt. Gen Robert P. Otto, Deputy Chief of Staff for ISR (A2)
    - “To support the expanding roles of SUAS, **propulsion systems that are fuel efficient…are needed to increase platform speed and endurance as well as support various power-hungry SUAS payloads**.”
- Multiple DoD User letters of interest demonstrating need for long endurance SUAS and support for AFRL/RQQ UAS Hybrid Power program
    - “…**Increased endurance and station time is our number one shortfall**…” – COL Michael Martin, 724th STG Commander, AFSOC
    - …The **lack of endurance is the number 1 complaint** by the operators.” – Donald Reedy, PM UAS, USSOCOM PEO-FW





AFRL/RQQ UAS Power & Control Portfolio

Tactical Off-Board Sensing (TOBS)



Description

Development of key power & control technologies to improve SUAS capabilities as a force multiplier

Focus Areas

Tactical Off-Board Sensing (TOBS)
- Air-launched UAS to provide remote sensing to manned A/C
- Integration with existing battle management system
- Increased autonomy enabling supervisory control of UAS

Quiet, Hybrid Electric Prop/Power
- Quiet power generation and thruster technologies
- Hybrid electric power systems (ICE/Batt, FC/Batt, etc.)

JP-8 Fuel Cell
- Logistically-fueled fuel cell for UAS and other power needs

Technology Goals

Group I: Advanced battery, fuel cell technologies
- >50% endurance (T), >150% endurance (O)
- Available power for >5lb payload capacity
- Enhanced capabilities for targeting and ISR data collection

Group II/III: High efficiency, Quiet JP-8 hybrid propulsion
- >50% improvement in endurance and capabilities
- Logistically-supportable, quiet operations

Group IV/V: All-electric APU for non-critical power
- 65+% efficiency, >300W/kg, JP8 Fuel

Key technologies for extended range and mission flexibility

Long Endurance UAS
Full Spectrum Propulsion Coverage for the Warfighter

2020

Group 1 SUAS Long Endurance, Off-Board Sensing

AFSOC, SOCOM

Near Term Technology Goals

- > 500 hrs MTBF
- Up to 4x Range/Endurance
- 10% Dash Capability
- 25% Payload Pwr Growth
- Reduced Acoustic Signature

2025

Logistics Fueled (JP-8) Quiet Hybrid-Electric Drive

AFSOC, SOCOM, I-ARPA , LCMC/ISR, Global Hawk

Mid Term Technology Goals

- > 2000 hrs MTBF
- Up to 2x Range/Endurance
- 50% Dash Capability
- 100% Payload Pwr Growth
- Silent Operations

2030

INPPAT Hybrid Engine

Mid Term Flight Demo

- Scalable architecture
- Distributed propulsion
- Energy optimized controls
- Smart battery mgmt

2035

Long Range/Endurance Quiet Hybrid-Electric Large Class UAS

SOCOM, ACC MQ-9, LCMC ISR/SOF RQ-4

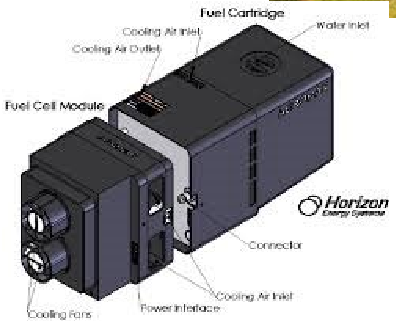
Integrated INPPAT Demo

Far Term Technology Goals

- > MTBF
- > 2x Range/Endurance
- Up to 20X Payload Power
- Reduced Acoustic/Thermal Signature
- High Performance, Low Cost

H_2 Fuel Cell Technology for SUAS Applications

Small Unmanned Air System



Polymer Electrolyte Membrane (PEM) Fuel Cell System

(Size: 7.64 x 4.13 x 6.53 inches)

Technical Approach

- Evaluate PEMFC in AFRL test facilities
- Integrate PEMFC into Desert Hawk EER/Condor SUAS
- Flight test and evaluation of PEM fuel cell systems performance on Desert Hawk EER/Condor SUAS platform

Benchtop Testing

- Efficiency testing at 20°C, 50% humidity and 200 W
- Transient Testing at 20°C, 50% humidity with profile including 200 W (loiter) 500 W (dash) 900 W (takeoff)
- Hot and Wet Testing at 49°C, 100% humidity and 200 W
- Cold and Dry Testing at -30°C, 0% humidity and 200 W
- Lifetime Testing with transient load profile for 100 hours
- Altitude testing with transient load profile at 15000 feet

Current Technology

- Currently, Small Unmanned Air Systems (SUAS) are powered by Lithium ion batteries
- Polymer electrolyte membrane fuel cells (PEMFC) by Protonex (a US company) have been developed for SUAS applications but currently reside at a TRL 5

Impact of New Technology

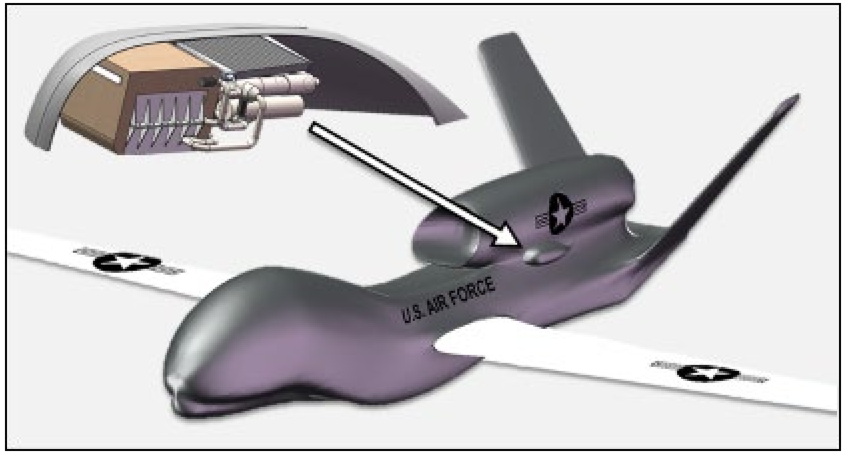
- PEMFC could increase endurance beyond the four hour objective requirement to over eight hours. Proposed COTS PEMFC are at a much lower cost and have a smaller size and weight option compared to current US options.
- Current TRL: 7 Expected TRL: 8
- Companies: EnergyOr, Intelligent Energy, HES Energy Systems

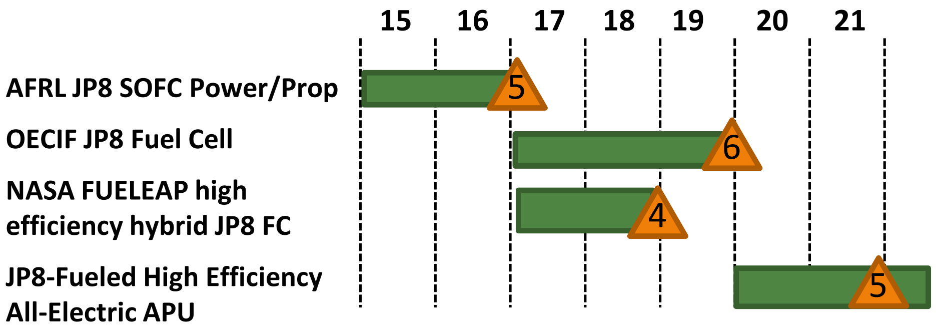
Primary Component: Direct transition to AFSOC programs identified – Tactical Off-Board Sensing (TOBS) and LM Desert Hawk EER/Condor SUAS under evaluation by AFSOC

Secondary Component: Army/Navy

Transition Strategy: TOBS is an AFSOC-sponsored Advanced Technology Demonstrator (ATD) on schedule for FY19 Operational Testing, and FY20 IOC. The Desert Hawk EER/Condor SUAS will transition to AFSOC for field trials and evaluations in FY19.

High Efficiency, Fuel Flexible (JP-8, Jet-A, Diesel) Electric APU





Description

- Develop and demonstrate a high efficiency (up to 65%), high-power-dense (up to 300 W/kg) all-electric on-board aircraft APU for high-altitude (up to 65 kft mean sea level (MSL), long-range unmanned aerial system (UAS) operations.

Technology Goals

- Develop a high efficiency, high altitude all-electric APU for on-board power to non-flight critical subsystems for long endurance missions (24+hrs)
- Increase system level power density (obj: 300 W/kg) while maintain high efficiency (>25%)
- Increasing system reliability/ruggedization
- Direct operation on JP8 fuel
- Investigate scalability, 10-100kW power levels

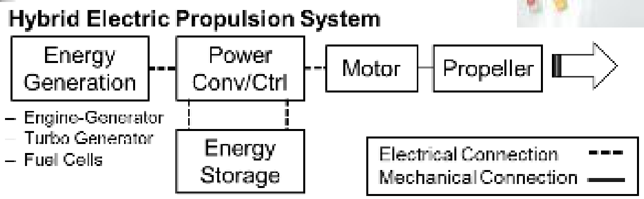
Development Status

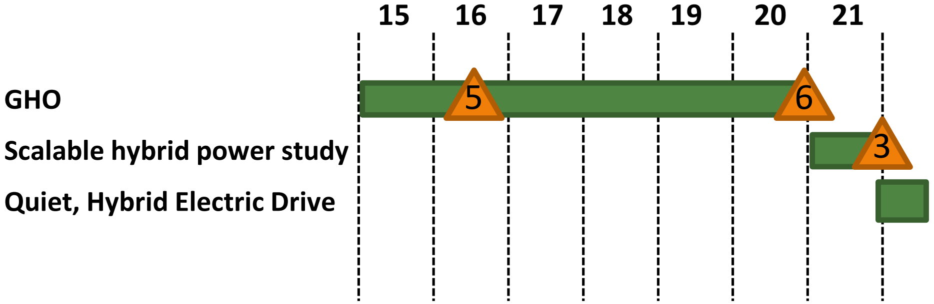
- Technology Status
  - Conceptual APU design complete in partnership with RQ-4 OEM
  - Demonstrated feasibility through M&S scaled bench tests
  - Leverage high power dense SOFC SBIR, partnership with Army OECIF JP8 fuel cell development & NASA FUELEAP investments
  - Breadboard JP8 power system development in progress
- Transition Status/Relevance
  - High transition potential with interest expressed from RQ-4 Global Hawk SPO, UAS OEM Primes for use as a high efficiency APU and hybrid electric propulsion system

SOFC APU System Key Metrics

- SOFC Stack Power Density: 350-500 watts/kilogram
- Overall System Power Density: 150-300 watts/kilogram
- Stack Efficiencies up to 65% LHV of JP-8
- System Efficiencies greater than 30% LHV of JP-8
- Start up time; less than 30 minutes
- Sulfur Tolerance: 50 ppm in reformate, 3000 ppm in JP-8 before reforming
- Thermal Cycle Life: 50 cycles (near-term); 150 of cycles (long-term)
- Cycle Time: 20 to 30 hours
- Lifetime: 1000 hours (near-term); 5000 hours (long-term)

Hybrid UAS Power Systems





Description

- Develop next generation hybrid electric power and propulsion solutions for extended endurance/range, reduced acoustic signatures, and modular/scalable to different SUASs

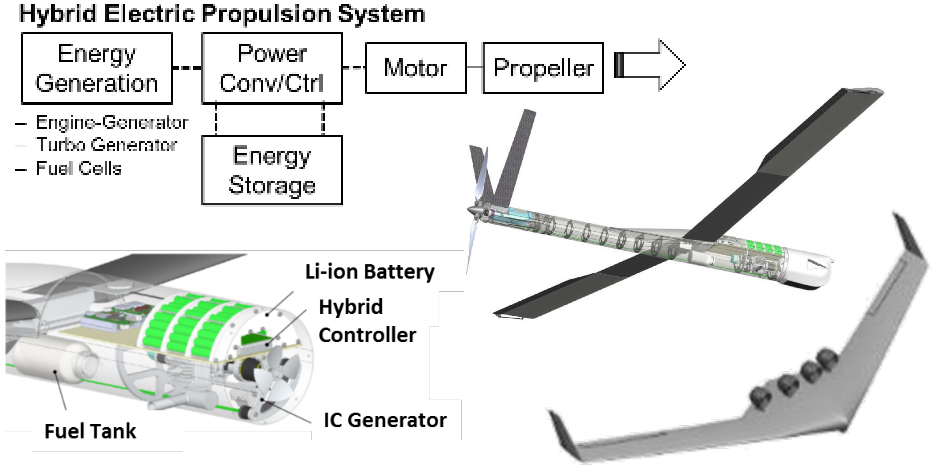
Technology Goals

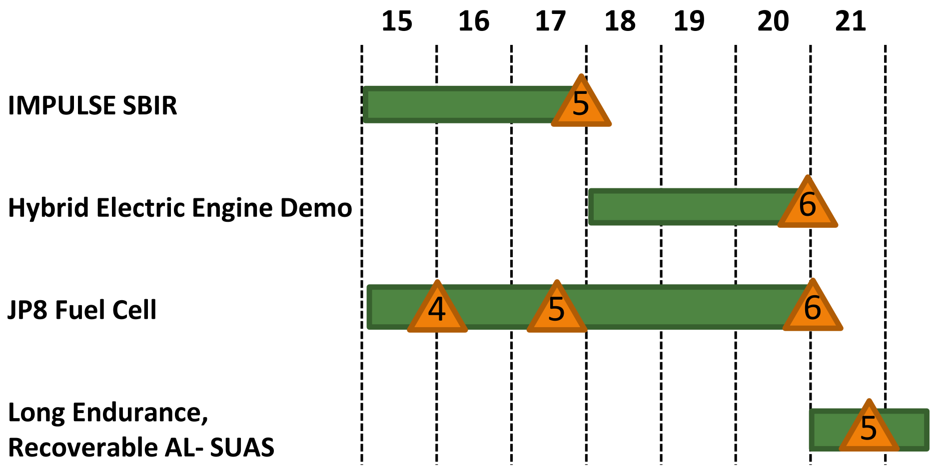
- Compact, smart power management for efficient system operation and modularity
- Safe electrical monitoring and protection
- Development of quiet propulsion and power generation technologies with a focus on scalability and reliability

Development Status

- Technology Status / Approach
  - FY17 Flight Demo (Battery), FY19 Flight Demo (Turbogen)
  - FY20: Downselection of optimal hybrid technology with focus on Scalability, acoustics, increased reliability, & high efficiency
  - Integrate smart power controls for modular architecture
  - Develop and demonstrate modular, quiet hybrid electric technology. Integration and flight demonstration in SUAS(s)

Hybrid UAS Power Systems





Description

- Develop next generation hybrid electric power and propulsion solutions for extended endurance/range (15+ hrs), reduced acoustic signatures, and modular/scalable to different Group 2/3 SUASs

Technology Goals

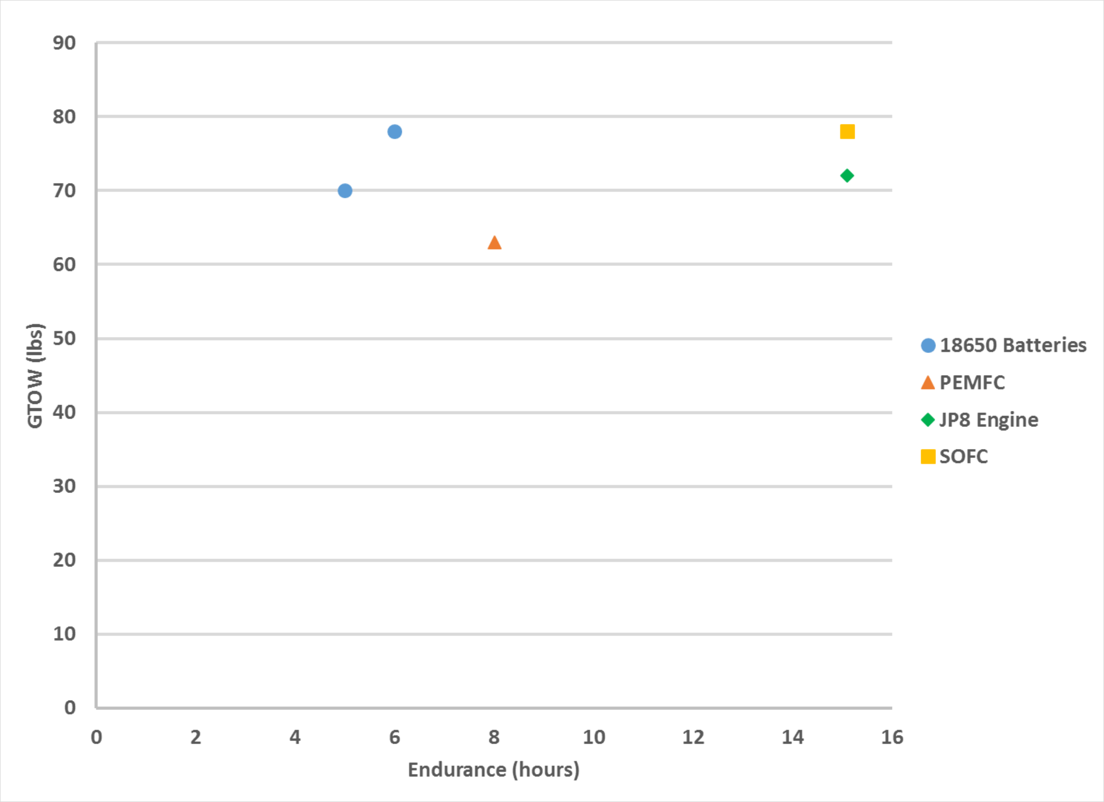
- Maturation and demonstration of Group 2/3 SUAS prototypes
- Development of high efficiency hybrid electric power system
- Development of quiet propulsion and power generation technologies with a focus on scalability and reliability

Development Status

- **Technology Status / Approach**
  - >50% improvement in endurance and capabilities
  - Logistically-supportable, quiet operations
  - Conceptual SUAS and series hybrid engine design complete, development under IMPULSE SBIR & Hybrid-Electric SUAS Demo
  - FY17 Flight Demo (Battery), FY19 Flight Demo (Turbogen)
  - FY19: Hybrid HF engine air-launch flight test
  - JP8 fuel cell validated, full system dev & flight testing by FY20

Hybrid UAS Power Systems

- Comparison of heavy fuel IC generator vs SOFC for hybrid applications
  - SOFC at 150 W/kg and 25% efficiency
  - HF Engine at 1000 W/kg and 10% efficiency
- Batteries alone cannot provide the energy density needed to reach the 15 hour endurance goal
- HF engine provide a near term solution due to the quick start up times, lower cost and higher TRL level that SOFC
- SOFC and HF generators provide approximately the same endurance for a Group 2/3 SUAS platform
- SOFC systems are desired to provide quiet operations



AFRL UAS Hybrid Electric Propulsion Approach

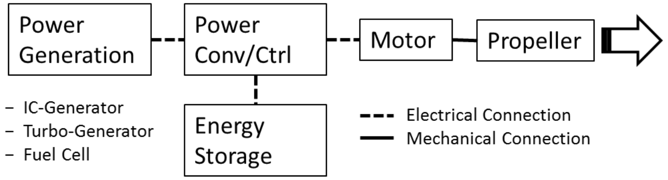
- Series hybrid power system enables new and enhanced operational capabilities
  - **High energy** component (i.e. Fuel Cell, Generator) to provide a steady state power and recharge the high power density component
  - **High power** component (Battery) to provide peak power requirements
    - Peak power needed for UAS take offs, altitude changes and high speed dashes
  - No change in operational performance – dash speed, climb rate, altitude, etc.
  - Example based on hybrid electric power system @ 25% efficiency, 250 W/kg power density


Boeing/Insitu RQ-21A Blackjack

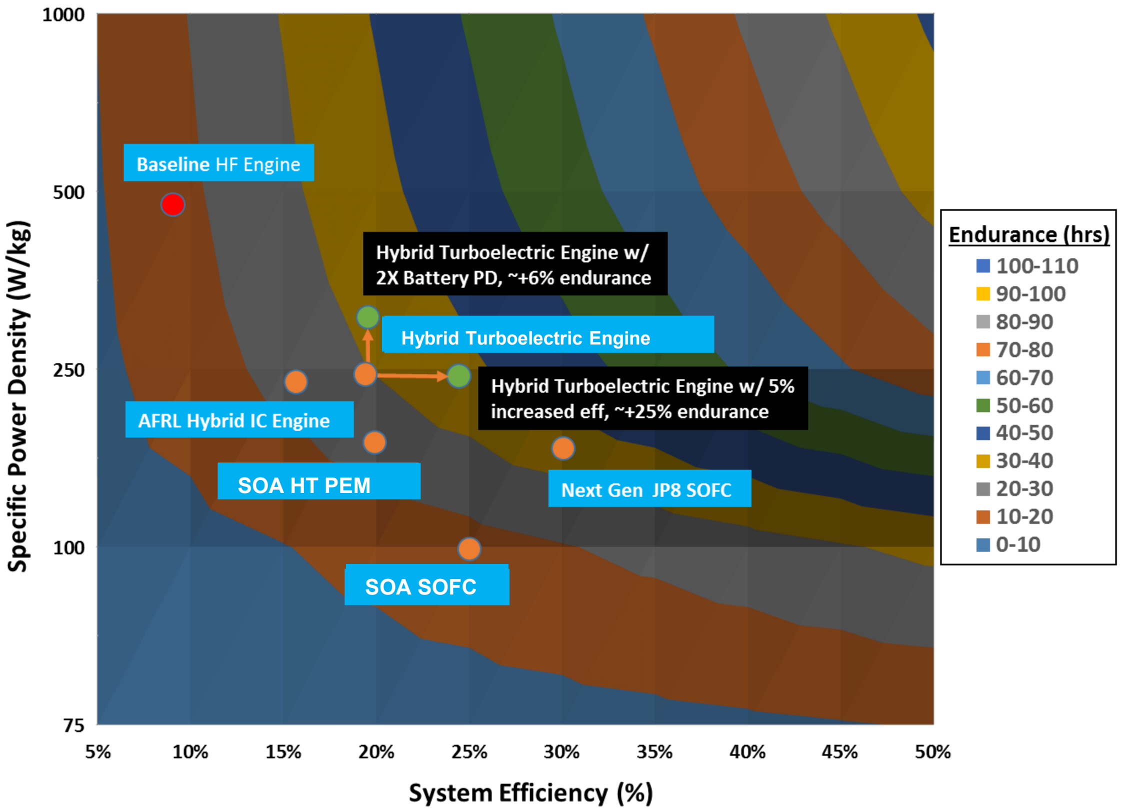
Parameters	Baseline RQ-21 SUAS with HF engine	Hybrid Electric Propelled SUAS
Max Endurance	16 hrs	35+ hrs
Max Range	1000 mi	2200+ mi

Assumptions:
- RQ-21 Blackjack UAS endurance based on constant cruise power
- Same power/propulsion + fuel weight
- Technologies scale linearly to ~2kW

Series Hybrid Electric Propulsion System



Endurance Curves, Future RQ-21 SUAS



Status of AFRL H_2 Fuel Cell UAS Products

- **Group 1 (< 20 lbs GTOW) SUAS Product**
  - Extended endurance for tactical off board sensing
    - FY19: Benchtop testing of PEMFC from EnergyOr, HES Energy Systems and Intelligent Energy under relevant conditions
    - FY20: Integration, flight test and evaluation of PEMFC performance on Condor platform
- **Group 2/3 (21 to <1320lbs GTOW) SUAS Products:**
  - Extended Reach Cooperative ISR and Targeting
    - Long endurance (15+hr) Group 3 recoverable air-launched SUAS with integrated flight controls
    - FY18: Hybrid engine flight test, FY20: Hybrid HF engine air-launch flight
    - FY19: JP8 hybrid fuel cell full system developed & bench tested
- **Group 4/5 (>1320lbs GTOW) UAS Product:**
  - High Efficiency, Fuel Flexible (JP8, Jet-A, Diesel) Electric APU
    - Develop and demonstrate a high efficiency (up to 65%), high-power-dense (up to 300 W/kg) all-electric on-board aircraft APU for high-altitude (up to 65 kft mean sea level (MSL)
    - FY18: Design / risk-reduction testing on JP-8 fuel cell / turbogen hybrid
    - Long term vision: Long Range/Endurance Quiet Hybrid-Electric For Large Class (Group IV/V) UAS

Military Applications for Fuel Cell Systems

Application	Current Technology	Advantages of SOFC
Soldier Power (0.1-1 kW)	Li-Ion Rechargeable Batteries	Increase mission durations by having power source to charge batteries
UAVs (0.1-10 kW)	**Batteries and Combustion Engines**	**Increase mission durations and allow for larger payloads**
Power Generators (2–5 kW)	Large Diesel generators	Noise reduction and fuel cost reduction
Auxiliary Power Unit (1-20 kW)	**Internal Combustion Engines**	**Enhance mission capabilities and reduce fuel cost**
Silent Mobility (2-20 kW)	Internal Combustion Engine	Increased range and provide exportable power

Summary

- Fuel cells are critical for long endurance and range for various UAS platforms
- Fuel cells are key for hybrid electric propulsion to provide quiet operations
- SOFC provide more on-board electric power to support advanced payloads and other subsystems for Group 4/5 UAS Platforms

- Long term vision: Long Range/Endurance Quiet Hybrid-Electric For Large Class (Group IV/V) UAS
- The limiting factors with SOFC are the low power density and the long start up times

Questions?

Hybrid Electric UAS Design Considerations

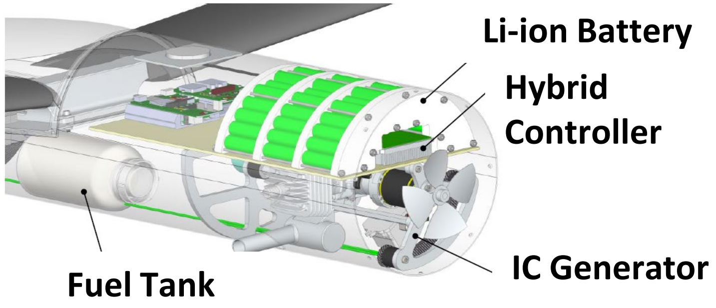
- **Needs to be treated from a “system-level” perspective**
  - **Power system cannot limit platform ability to meet operational metrics**
  - Transparent impact to user (similar to battery- or engine-based system)
  - Power system requirements (size, duty cycle) will be tied to specific platform / mission type
- **Application may have an impact on UAS design**
  - **Ground-launched UAS weight-limited** and require fast startup (<10 minutes)
  - **Air-launched UAS volume-limited** w/ folding wings and require high altitude remote cold start
  - APU systems efficiency is key driver
- **A number of technical and operational challenges exist**

Technical Challenges
- Increased persistence >15 hrs, Obj. 50hrs
- Increased dash speed >90 knots, Obj. >150knots
- Increased payload capacity >10 lbs, Obj. 40lbs
- Excess power for payloads >500 W (payload/platform dependant)
- Acoustic signature
- Ruggedized system (MIL-STD 810G)

Operational Challenges
- **Operational Conditions**
  - High G-loads during launch/recovery
  - Fuel availability/Hazmat (consistent with existing)
  - System signature (thermal; visual; acoustic)
  - Small operational footprint
- **Environmental Conditions**
  - High winds (> 25 knots); Wide temp range (-40 to +49°C); High altitudes (>15k ft MSL)
  - Dirty operational environments (dust, sand)
  - Varied weather conditions
  - Potential for maritime operation

Hybrid UAS Power System
Technology Challenges & Opportunities

- Ideal hybrid power system component characteristics (vs. current off-the-shelf):
  - **Hybrid Li-ion battery**
    - Specific energy >300 Wh/kg (230 Wh/kg)
    - Specific power >2500 W/kg (1150 W/kg)
    - Fast charge up to 3C rate (1C charge)
    - Stable over a wide ambient temperature range:
      - -40°C to +60°C operation (-20°C to +49°C)
    - Cycle life: >500 cycles @ 80% capacity (350 cycles)
  - **High energy power generation (i.e. generator, fuel cell, etc.)**
    - Operating efficiency >30% (10% efficiency) (25% efficiency)
    - Specific power (dry) >800 W/kg (1200 W/kg) (150 W/kg)
    - Operating life >1000hrs (100hr MTBO) (1000 hrs)
  - **Lightweight hybrid power management**
    - Specific power >5000 W/kg (3000 W/kg)
    - Operating life >1000hrs (<500hrs)
    - Tolerance to harsh environment: mechanical shock/vibration, high temperature, etc. (Limited)



Need for close integration of propulsion, power, and thermal
Better component doesn't always mean a better system