Energy Storage / Integration

Integrity ★ Service ★ Excellence

Presentation to:
Northern Ohio Energy Storage and Integration Workshop

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Electrical Systems Branch
Power and Control Division
Aerospace Systems Directorate
Air Force Research Laboratory

Overview

- **AFRL Energy/Power for Air Vehicles**
  - **RQQ Power & Thermal**
    - Needs
    - Portfolios
    - In-House R&D
  - **RXA Flexible Hybrid Electronics Materials & Processing**
    - Why Direct Wright Electronics?
    - Impact of Flexible Hybrid Electronics

- **AFRL Energy Storage/Integration Research**
  - **Key Technologies**
    - Batteries
    - Fuel Cells
    - Hybrid Propulsion/Power

Overview

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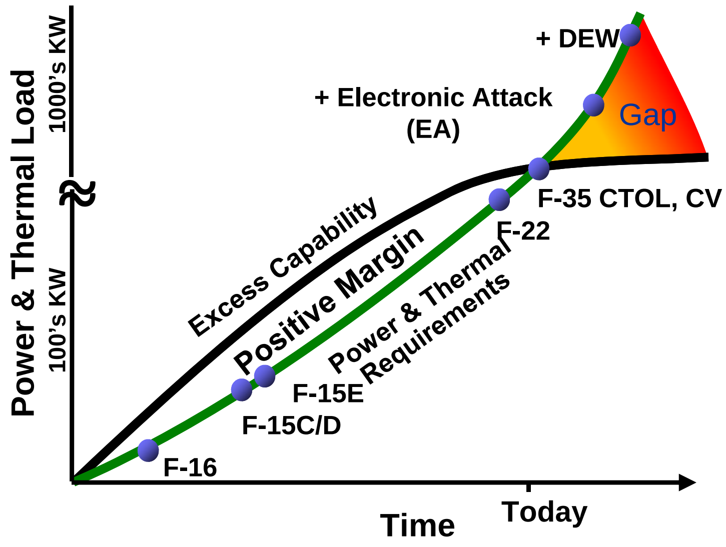
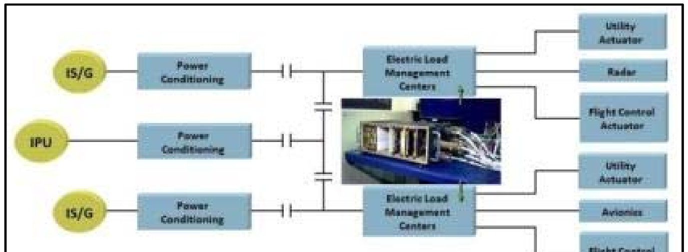
Power & Thermal Needs That Drive RQQ

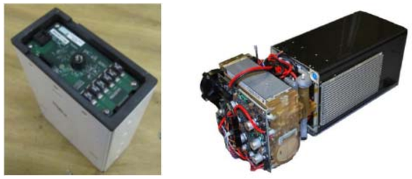
- **Aircraft Power & Thermal Management**
  - Electrical power needs continue to grow
    - Mission avionics
    - Directed Energy Weapons
  - As power needs grow so will the generation of heat which needs to be mitigated
    - More effective thermal systems
    - Higher temperature electronics
    - Less heat thru improved efficiency



AFRL/RQQ Power & Thermal Portfolios

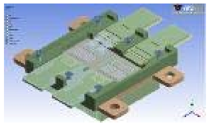


Power Management & Distribution

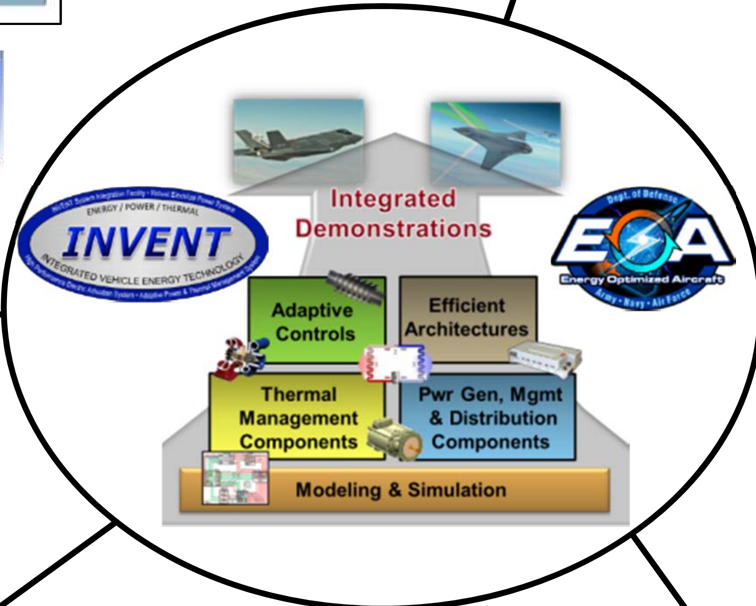


Energy Storage

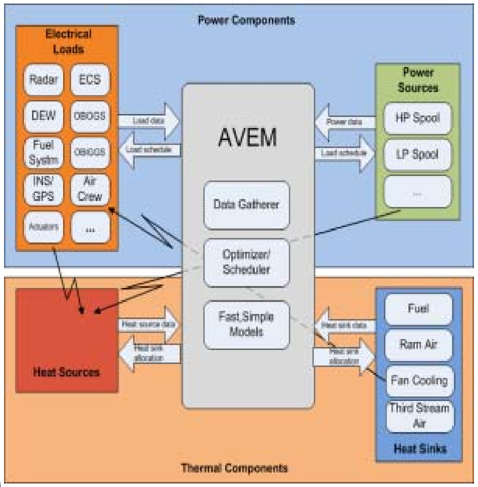
High Temp Electronics



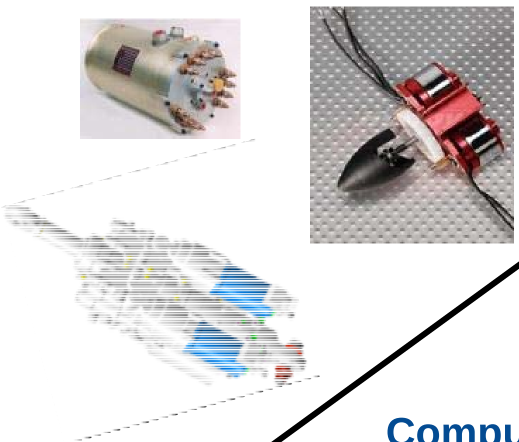
Electric Power Systems



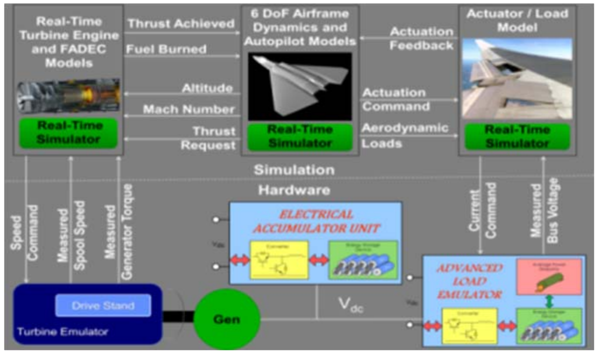
State Awareness & Real Time Response

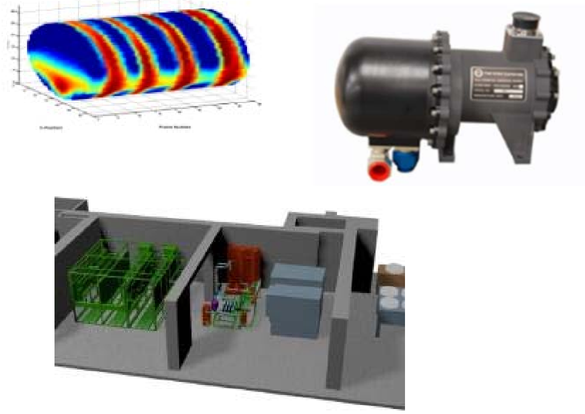


Electro-Mechanical Systems



Computational Engineering





Thermal Systems

AFRL

Power & Thermal Management In-House R&D

Advanced Power & Thermal Research Laboratory (Bldg 23)

- 44 Laboratories, 54,000 square feet total lab space.
- Redundant chilled (1.5 MW) and tower (500 kW) water cooling systems.
- 5 MW of connected electrical power - 480 VAC, 208 VAC
- Reconfigurable lab spaces

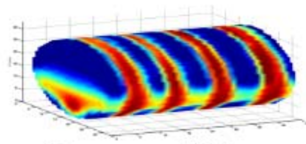
Power Generation, Storage, and Distribution

Power Semiconductors
- Silicon Carbide
- Nanoscale Thin Films
- Atomic Layer Deposition

Wide Temp Dielectrics & Capacitors
Magnetics
Hi Temp Superconductivity

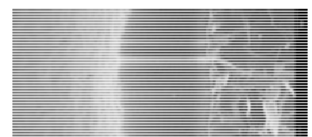
Batteries
- Solid State
- High Energy Hybrids

Thermal Transport, Storage, and Conversion



Characterization of Evaporating Fluids
- High Rate Heat Exchange

Electric Actuation TM



Carbon Nanotubes for Thermal Conductivity

Thermoelectric Power Generation

Modeling, Simulation, Analysis, and Test

Model Based Design

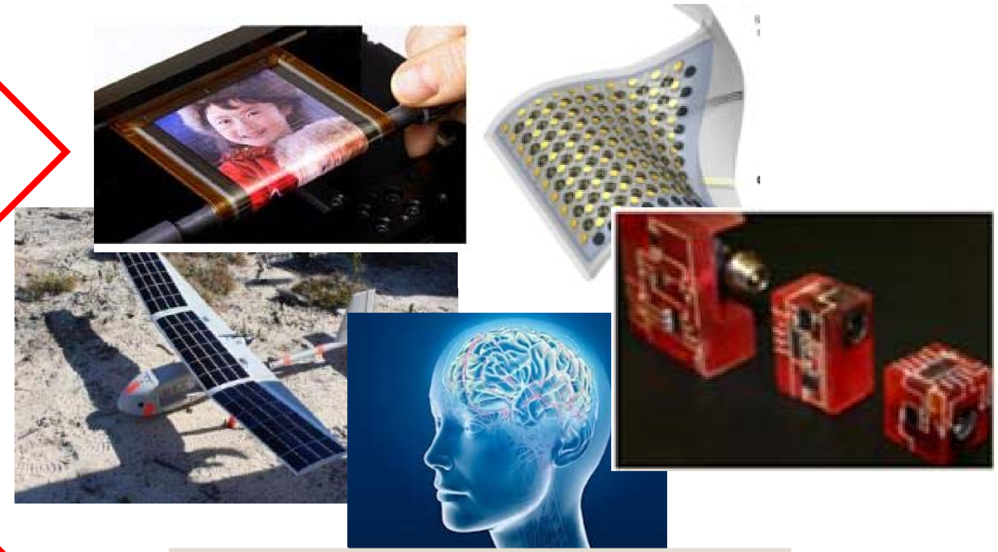
Hardware-in-the-Loop Simulations

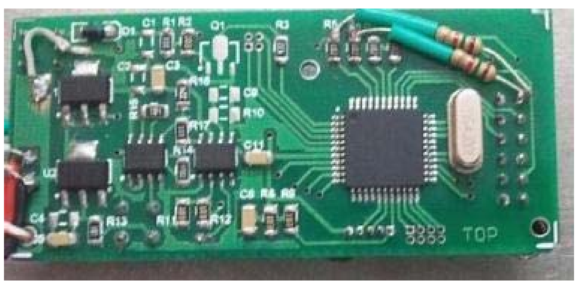
Model Verification & Validation

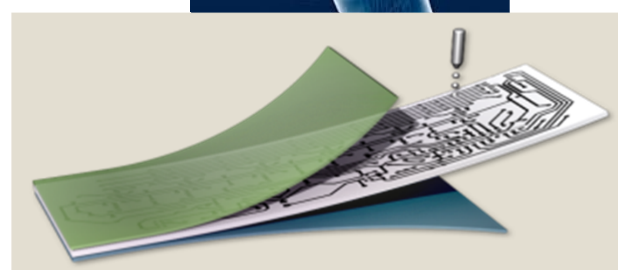
Why Direct Write Electronics?

Rigid and 2-D

Compliant and 3-D







Discrete Components

- Robust
- Mfg Processes & Flow
- Scalability & Modularity
- Failure & Lifetime
- Repair
- Performance

Integrated Constituents

- Survivable
- Integrated Mfg & Design
- Digital to Device
- Design to Life
- Application Determined Perf.

How could Flexible Hybrid Electronics Impact the AF?

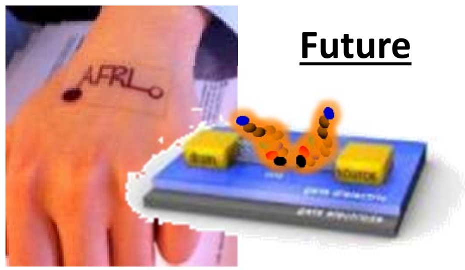
Human System and Cognition

Human Performance limits capability in MANY Military Missions
….and New Technologies are Needed to Sense, Assess and Augment the “Man-in-the-Loop”

- **Information Overload**
- **Missed Intelligence**
- **Threat/Danger Missed**

Today

Future



Embedded Electronics for ISR and EW

Information and tracking in contested environments (A2/AD) is foundational to decision making and force projection

- **Communication (conformal apertures)**
- **Distributed electronics for feedback and structural health monitoring**
- **Reconfigurable Electronics**

Integrated Power for Autonomous Ops

Energy limits operational capabilities and mission impact for large time and distances scenarios

Issues:
- **Cost & Weight**
- **Scale-up**
- **Durability**

Integrated Power harvesting, storage, and management

Expected 1.5X – 3X increase in flight endurance.

Survivable Electronics

Precision effects with smaller, low profile munitions pressing requirement for current and future platform effectiveness

- **Robust electronics in extreme environments (shock, vibration, thermal)**

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    - Batteries
    - Fuel Cells
    - Hybrid Propulsion/Power

Key Technologies

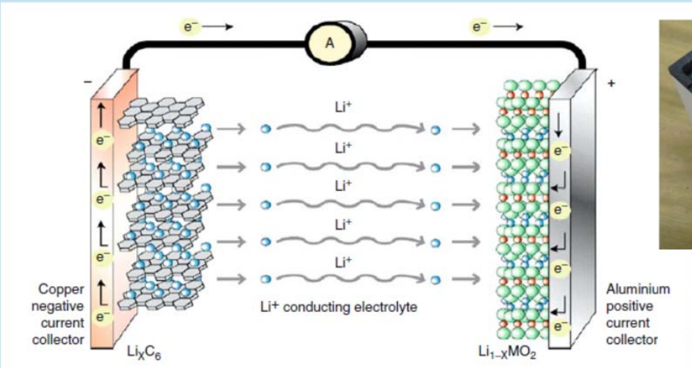
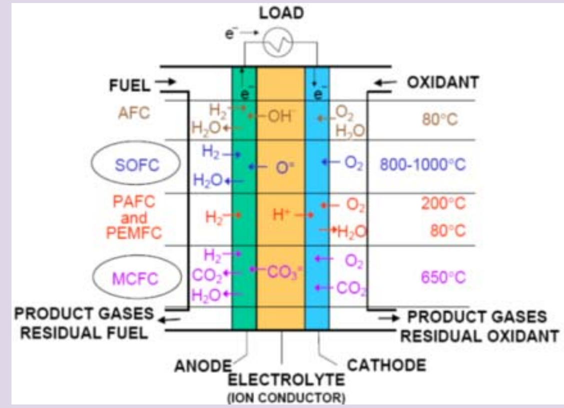


Fig. 10.6 Schematic representation of Li-ion cell operating mechanism

Batteries



Fuel Cells

Hybrid Power & Propulsion

Key Technologies

- **Batteries**
- **Fuel Cells**
- **Hybrid Propulsion & Power**

Key Technologies

- **Batteries**
  - **Focus on Energy Storage for Aircraft / Directed Energy Weapons DEW**
    - **Key challenges include maintaining battery safety at high performance operating conditions**
- **Fuel Cells**
- **Hybrid Propulsion & Power**

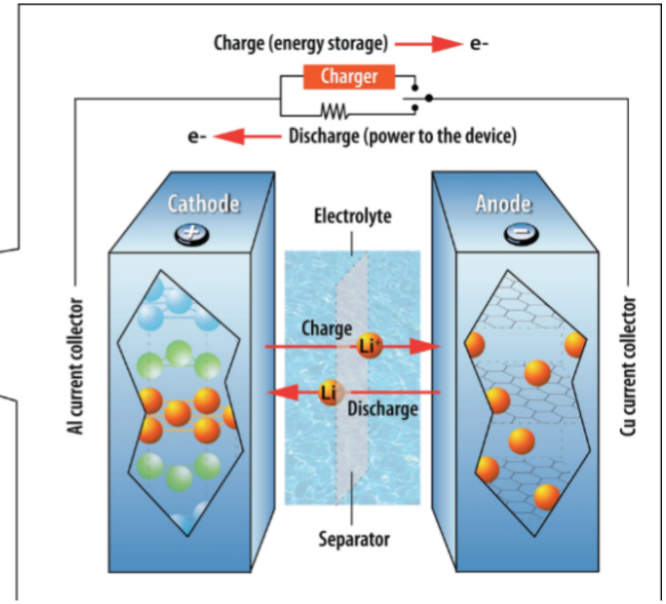
High Performance Lithium-ion Battery Safety


Lithium-ion battery fires on board the Boeing 787 Dreamliner



Fires caused by Lithium-ion batteries

High Performance,
Safe Lithium-ion Battery Challenge



Discharge: power to the device
Charge: energy storage

Objective:

Develop safe, high performance lithium-ion battery for aerospace applications

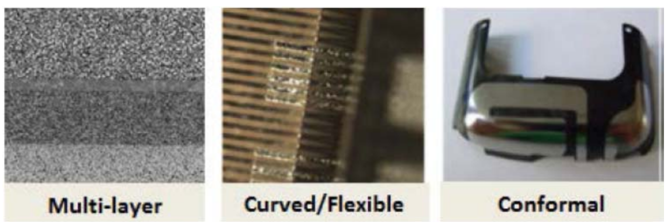
- Operating temperatures (-40 to 75°C), Storage temperatures (-55 to 85°C)
- Non-flammable electrolyte, stable electrodes, stable separator
- Cell failure propagation mitigation (no thermal runaway)
- Abuse tolerant (overcharged/overdischarged)
- High charge rate /discharge rate (>20 C-rate)
- Energy density (>250Wh/kg)
- Power density (>7.5kW/kg)
- Low life-cycle costs

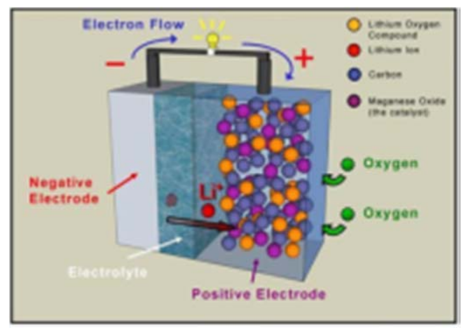
250 Wh/kg Pack => 325 Wh/kg Cells
(assuming 1.3x packing factor)

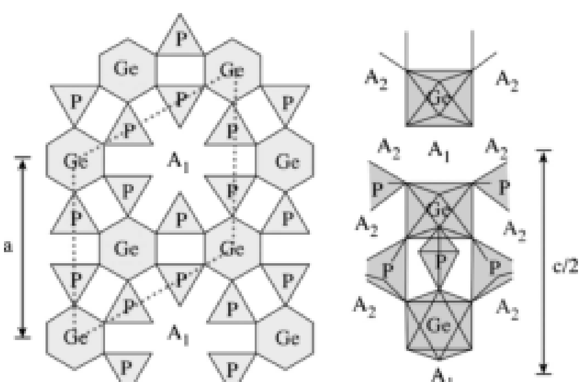
AFRL

RQQ Electrochemical Systems Development and Characterization

- **In-House R&D Program Product Areas**
  - Solid-State, Safe Li-Ion Cell
  - Advanced Fabrication
  - Structural Cell Design







LAGP Crystal Structure

Safe
- Non-flammable in military environment

Lightweight
- Improved Energy Efficiency

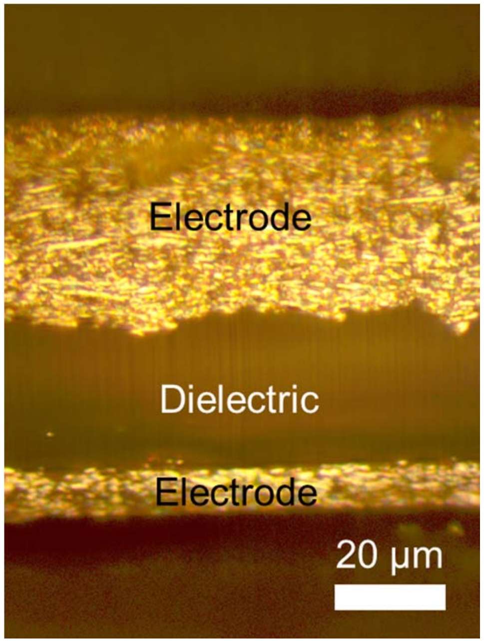
Multifunctional
- Save system mass & volume

Structurally Robust
- Carry / conform to mechanical load

Efficient
- Provide energy storage

Characterization of Printed Capacitors

AFRL/RXAS



Cross-section of PMMA cap

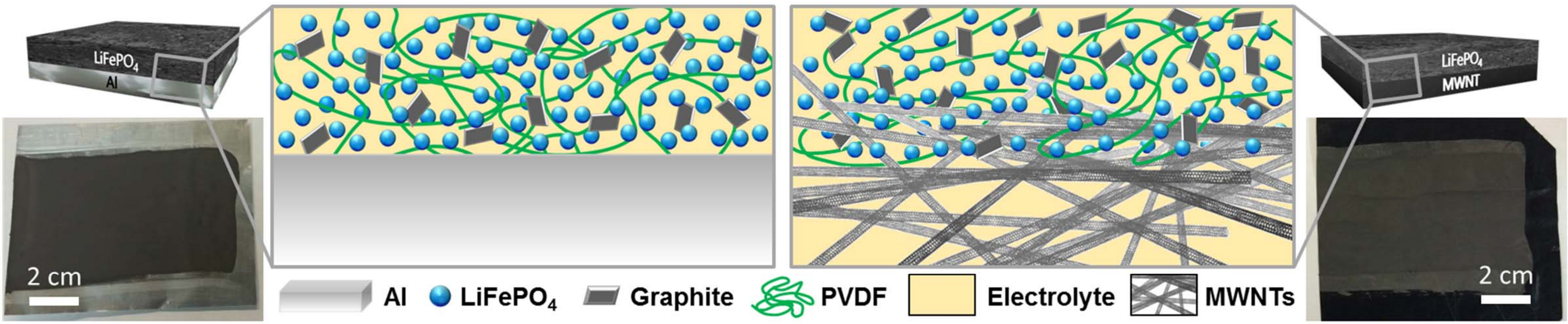
	Capacitance (nF)	Breakdown Voltage (V)	Dielectric Thickness (µm)*	Closest Approach (µm)*
Target/layer[+]	***1.0***	***3,000***		
UltraFlex	0.5	100	20	0.4
PMMA	0.2	1,000	20	2
PMMA	0.35	500	10	1

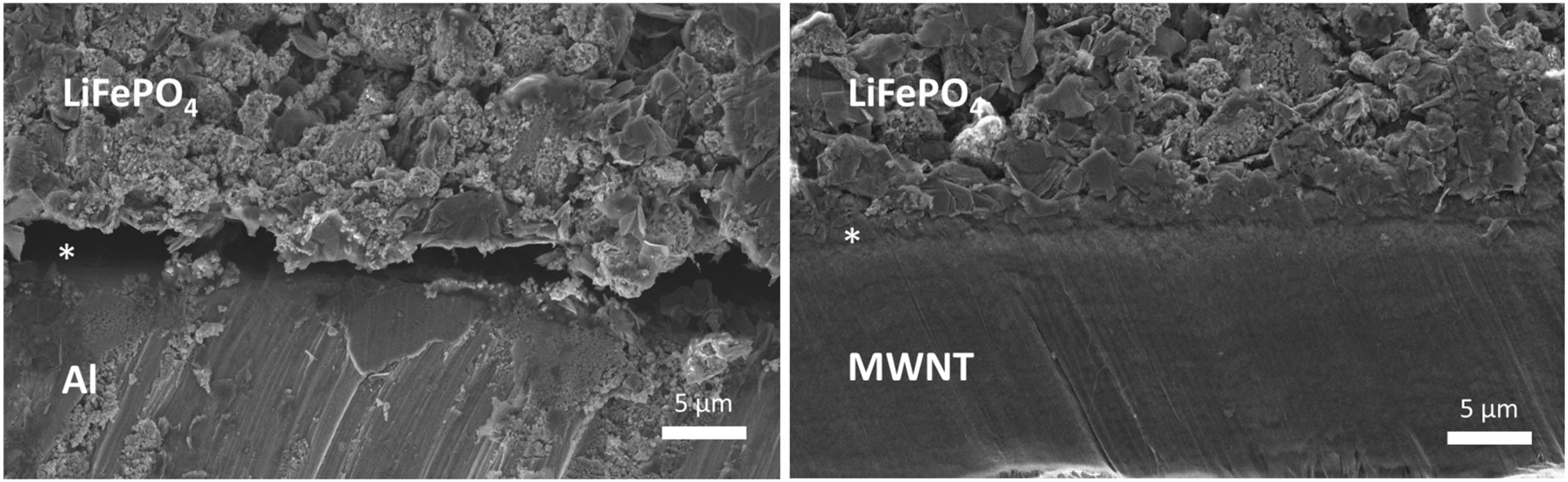
[+]Assuming 100 layers
*rough estimate based on dielectric properties

- **Multiple working PMMA capacitors were printed**
- **Capacitance and relative permittivity were used to estimate dielectric thickness**
- **Cross section was also used to estimate dielectric thickness**
- **Breakdown voltage and breakdown strength was used to estimate distance of closest approach**

Flexible & *Foldable* Batteries
Metal Foil vs. MWNT Current Collector

AFRL/RXAS

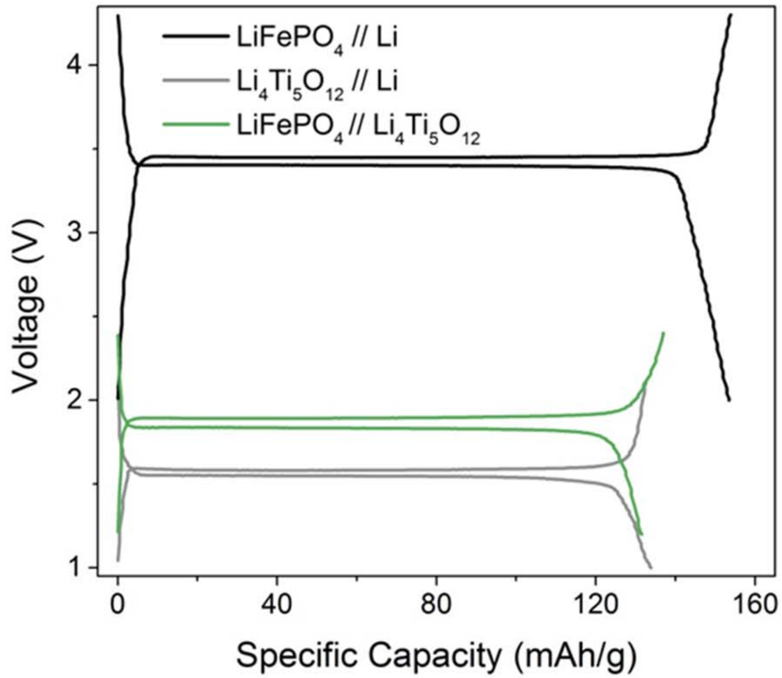


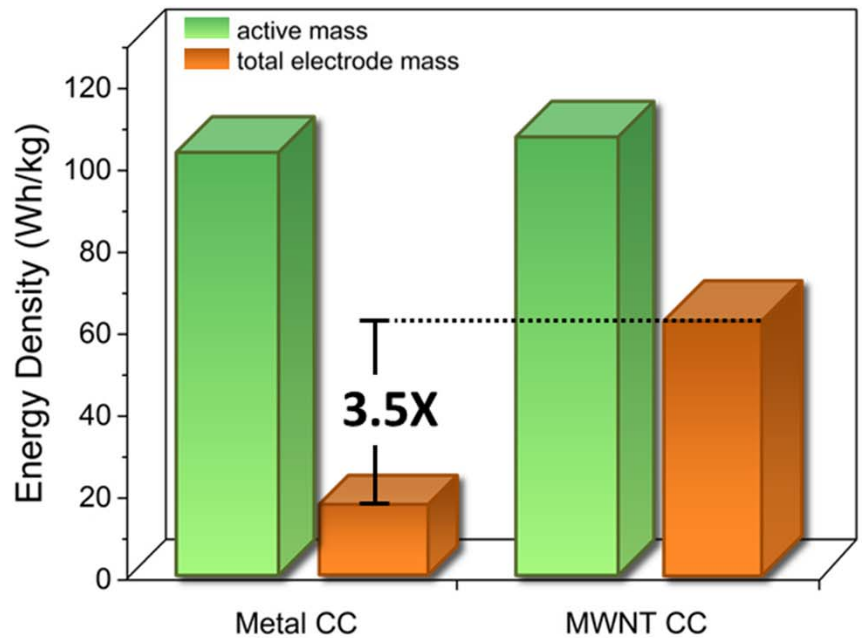


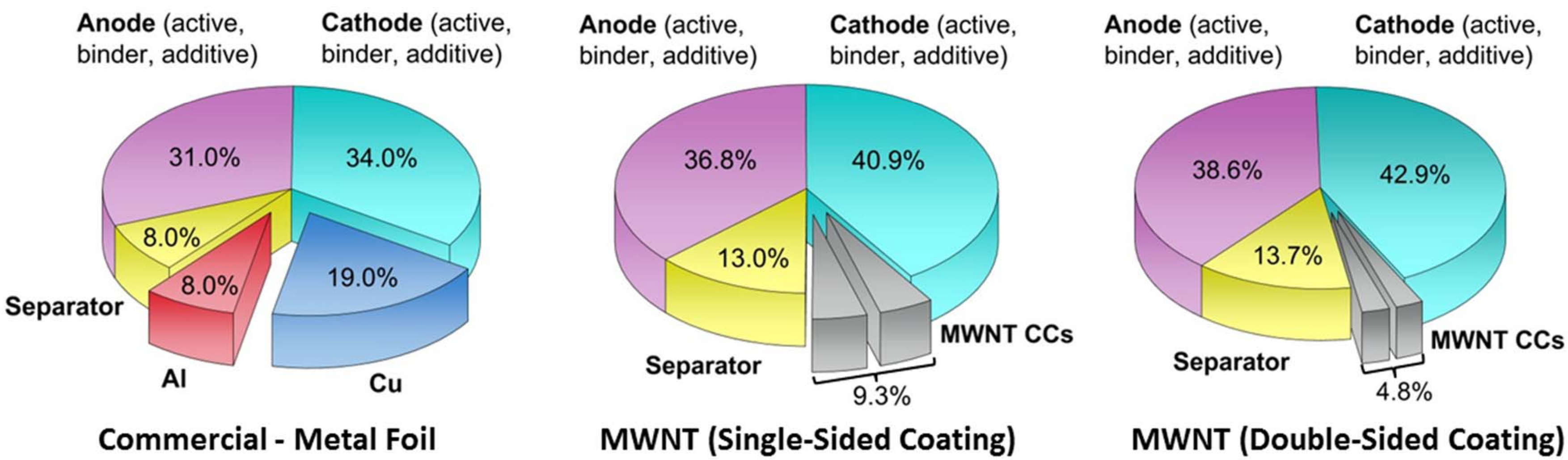
MWNT CC offers *enhanced adhesion* & better electrolyte wetting

Full-Cell Electrochemical Performance

AFRL/RXAS

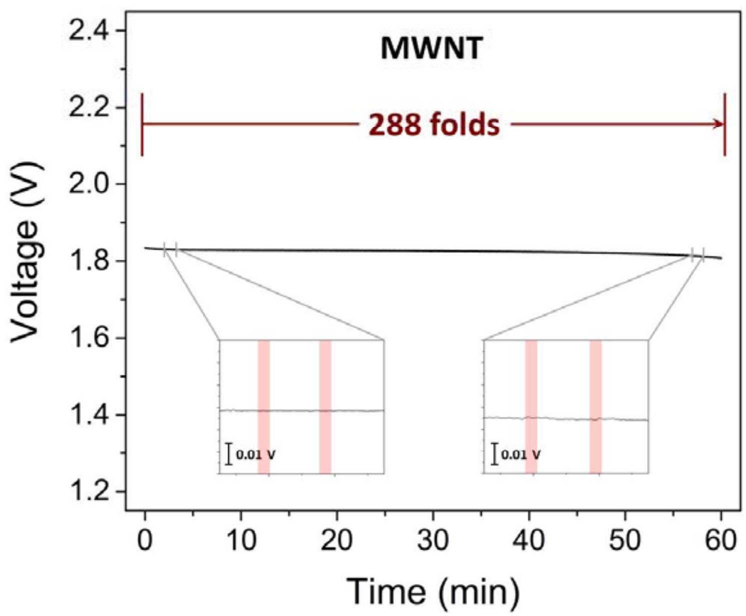


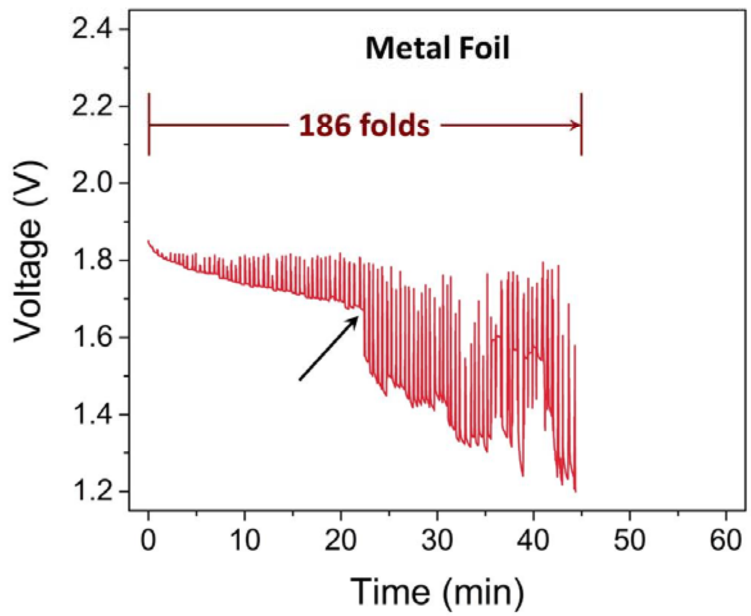


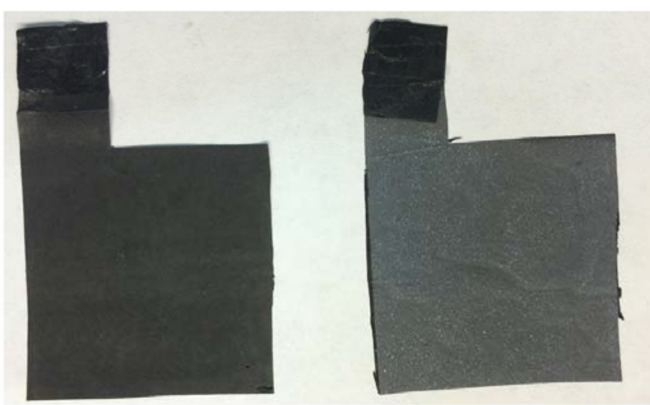


Fold/Crease Testing

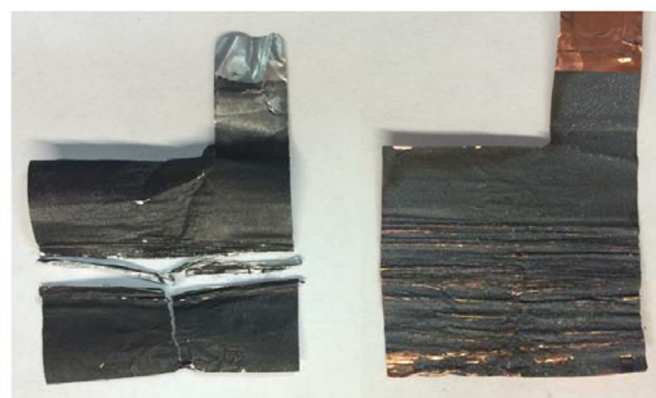
AFRL/RXAS







LiFePO$_4$/MWNT Li$_4$Ti$_5$O$_{12}$/MWNT



LiFePO$_4$/Al Li$_4$Ti$_5$O$_{12}$/Cu

Key Technologies

- **Batteries**
- **Fuel Cells**
  - **Focus on Power Systems for Unmanned Aerial Vehicles**
    - **Key challenges include increasing power density and operation of logistically available fuels (jet fuel, diesel)**
- **Hybrid Propulsion & Power**

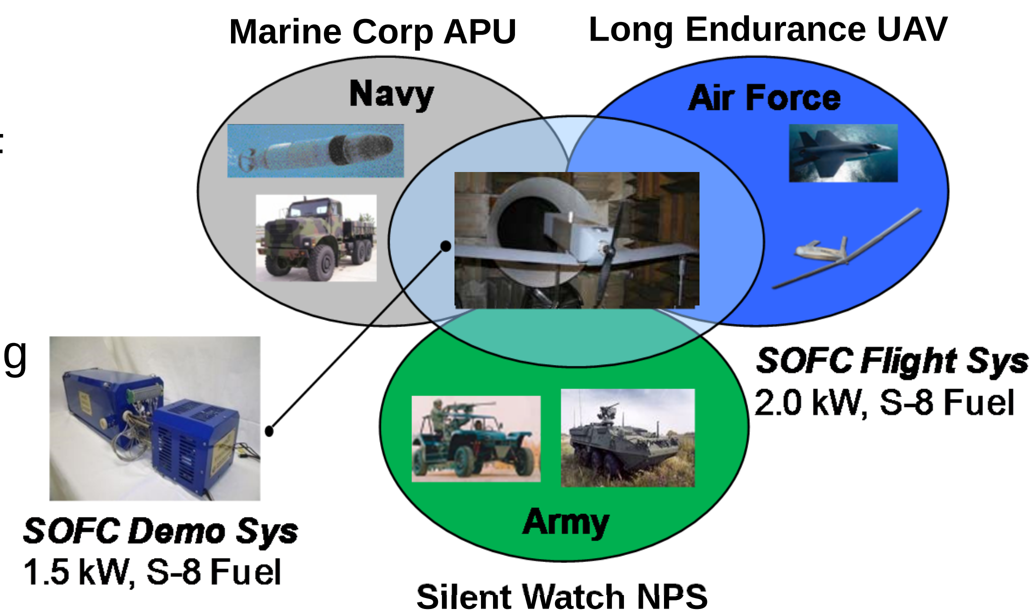
Logistically Fueled Solid Oxide Fuel Cells

Objective
– Develop/demonstrate a quiet, light-weight, power system utilizing JP-8 logistic fuel for AF UAV and Army Silent Watch applications

Key Benefits
– Highly efficient power system solutions for long endurance mission requirements
– Solid oxide fuel cells (SOFC) have demonstrated the potential for fuel-flexible operation

Risks/Challenges
– Achieving >30% power system efficiency while operating on logistic fuels for extended mission durations (> 50 hrs)
– Integration of the fuel cell system into a power-dense package (> 150 W/kg)

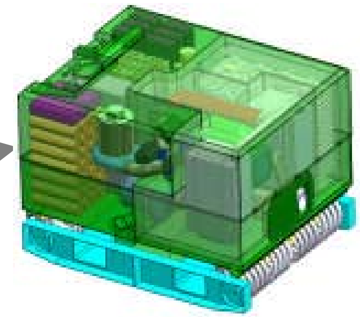
Benefits to the Warfighter
– Fulfill defense-essential need for efficient, long-endurance power systems utilizing JP-8 fuel



AFRL

SOFC System Development

Marine Corp APU
12 kW (JP-8)
>25 W/kg; >30%



Navy (ONR)

Army (TARDEC)

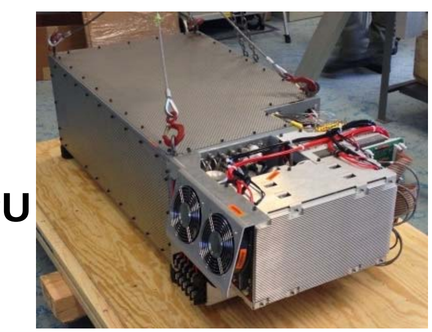
Air Force (AFRL)

2005	2008	2009	2010
2 kW (Diesel) ~10 W/kg <20% (DoE)	1 kW (S-8) 20 W/kg 26% TRL-3	1 kW (S-8) 40 W/kg 26% TRL-4	1.6 kW (S-8) 90 W/kg 24% TRL-5

Singapore (DSTA)

Vehicle APU
1.2 kW (ULSD)
<40 W/kg; 17%

Silent Watch APU
7 kW (JP-8)
>25 W/kg; >35%

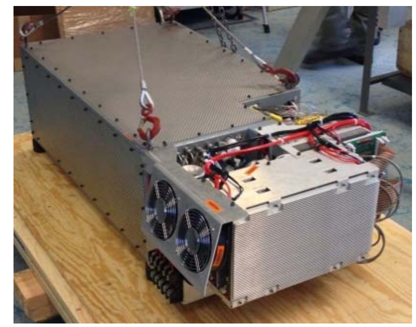


OSD SBIR: Power Dense SOFC

OBJECTIVES & PAYOFFS:

- **Develop high power density Solid Oxide Fuel Cell (SOFC) stacks (> 500 W/kg)**
- **Potential for high thermal eff. (30 – 45%) / 1000's hrs operational life**
  - IC Engine Baseline (< 10 hp): < 20%, 100's hrs
- **Power density main barrier to adoption of SOFC-based power systems**
  - Current SOFC power system ~100 W/kg (IC engine ~1000 W/kg)
  - Stack 30-40% of total SOFC power system weight (@ 200-300 W/kg stack)
  - Increased stack power density (500 – 1000 W/kg) = 2x – 4x increase in system level power density (100 W/kg to 200-400 W/kg)
- **Enable SOFC systems to meet and/or exceed IC engine performance**
  - 200 W/kg @ 30% comparable endurance to 1000W/kg @ 20%

UAV Propulsion
1.6 kW (S-8), >90 W/kg, 24%



Silent Watch APU
7 kW (JP-8), >25 W/kg; >35%

TECHNICAL CHALLENGES:

- **Scaling up from high power density, button cell performance**
  - Interconnect resistance, interfacial gradients, fuel utilization
- **Operation on logistic fuel reformate**
  - Diluted H_2 content, CO utilization
  - Sulfur impurities in fuel

APPROACH / MILESTONES:

- **Phase I:** Demonstrate high power density (> 1W/cm^2), large area (50 – 150 cm^2) cells
- **Phase II:** Demonstrate high power density (> 500 W/kg), SOFC stack (500W – 3kW)
- All demonstrations on simulated logistic fuel reformate (desulfurized)

AF SBIR: Secondary Power System for Large Class UAS

OBJECTIVES & PAYOFFS:

- Develop / demonstrate an all-electric onboard aircraft APU for high altitude, long range UAS operations
  - High efficiency (25+%)
  - High power dense (150W/kg)
  - High altitude (up to 65kft MSL)
  - JP-8 fuel compatible
- Provides on-board electric power to non-flight critical subsystems for long endurance missions (24+hrs)

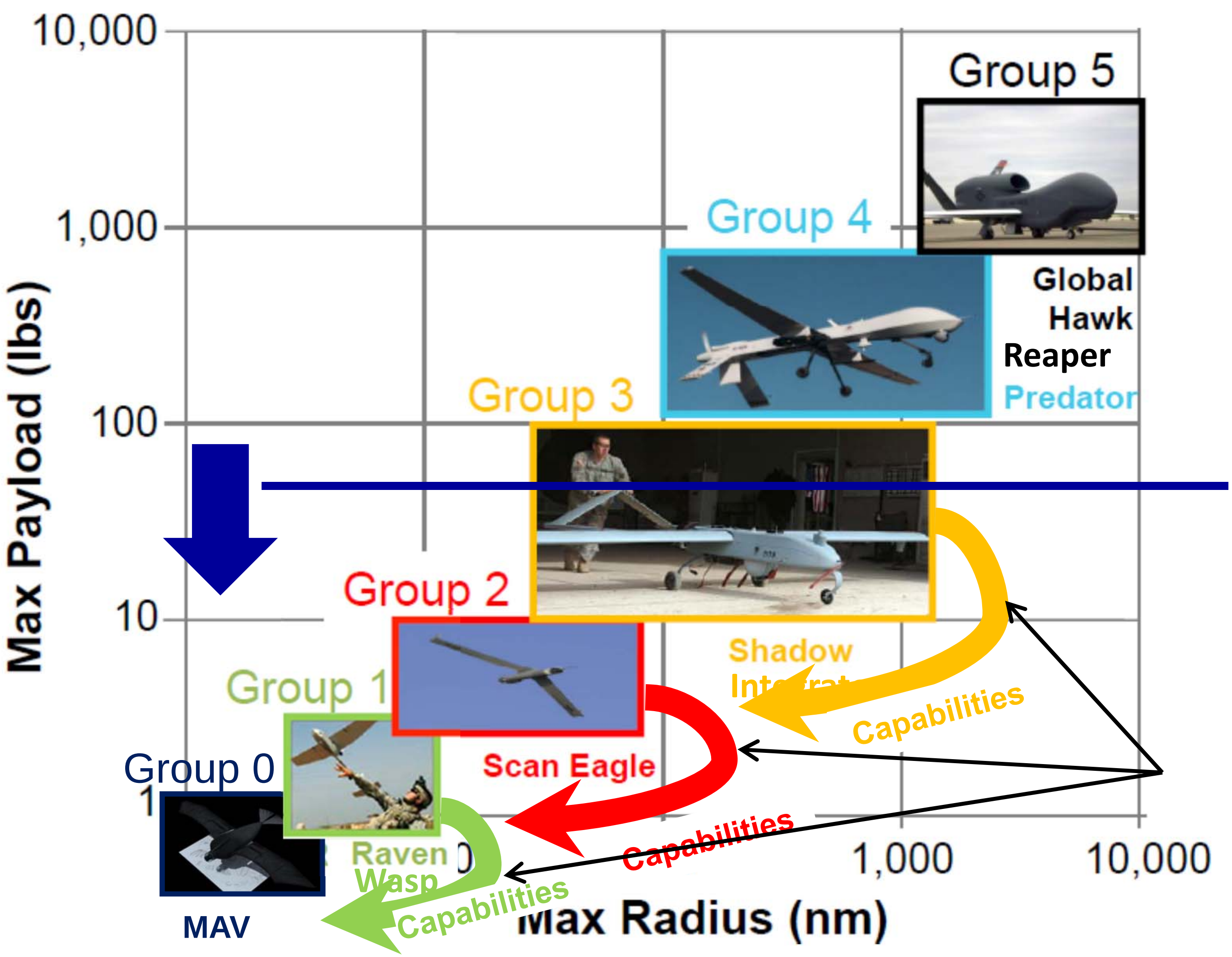
APPROACH / MILESTONES:

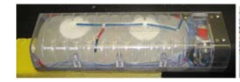
- <u>Phase I</u>: Design advanced all-electric APU concept capable of supporting on-board UAS operations. Demonstrate feasibility through M&S scaled bench tests
- <u>Phase II</u>: Develop advanced power system operating on JP-8 fuels. Demo reliable and efficient operations over the 24hr mission duration (threshold) in a simulated operational environment (objective)

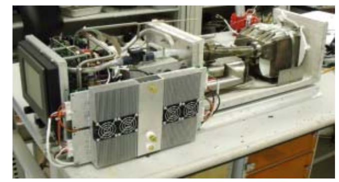
Key Technologies

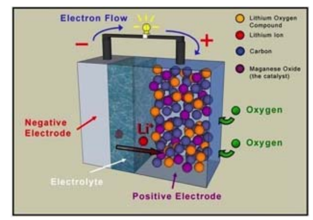
- **Batteries**
- **Fuel Cells**
- **Hybrid Propulsion & Power**
  - **Focus on Power Systems for Unmanned Aerial Vehicles**
    - **Key challenges include increasing propulsion system efficiency and reliability**

SUAS Power/Propulsion









Enhanced Hybrid Electric Power/Propulsion Systems

- Increased Endurance
- Excess Payload Power
- Quiet Operation
- Increased System Reliability

Small UAV / RPA Systems

SUAS Power/Propulsion

Goals

Near Term - 2016

- > 500 hrs MTBF
- 2x Range/Endurance
- 10% Hybrid Duty Cycle*
- 25% Payload Power Growth

Mid Term – 2023

- > 2000 hrs MTBF
- 4x Range/Endurance
- 50% Hybrid Duty Cycle*
- 100% Payload Power Growth



Logistic Fueled STUAS
Hand-Launched SUAS

(Group 1 – Group 3 Propulsion)

Air-Dropped TLEU
Large Class UAS APU

(Group 1 – Group 3 Propulsion)
(Group 4 / Group 5 Secondary Power)

**Hybrid duty cycle refers to percentage of overall aircraft mission that the rechargeable energy storage is utilized. This can be for peak power conditions (such as dash) or electric-only operation.*

Hybrid-Electric SUAS

Hybrid Electric Research Collaboration (HERC)

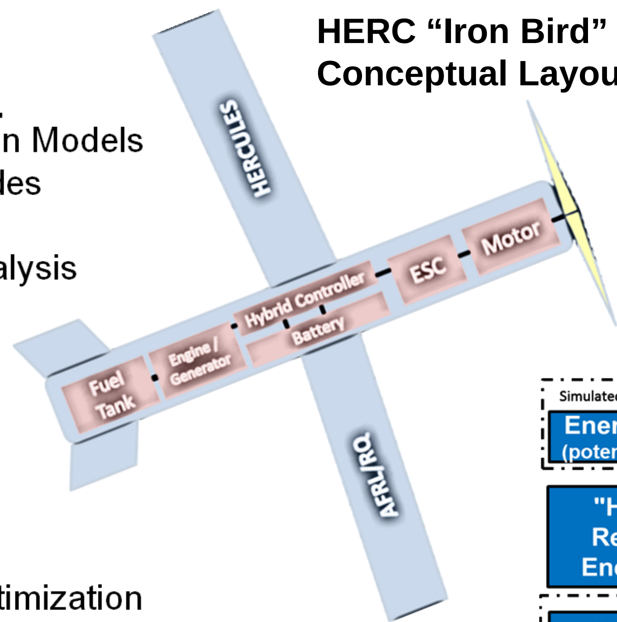
Objective: To address next generation AF Weapon System power and propulsion needs through hybrid electric solutions for Class 2 / Class 3 SUAS

Approach: Leverage current expertise and test capabilities across the Aerospace Systems Directorate (RQQE / RQQM / RQT)

Modeling & Simulation

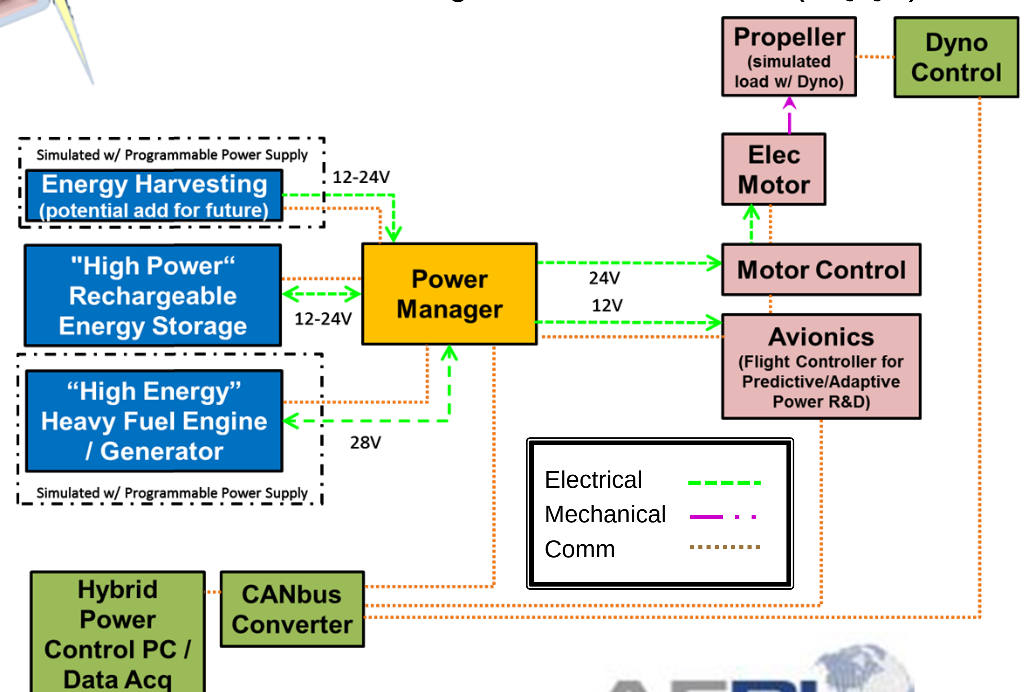
- Propulsion System Optimization Models
- Propulsion/Power System Trades
- Tip-to-Tail System Models
- Aerodynamic Performance Analysis

HERC "Iron Bird" Conceptual Layout



Hybrid Propulsion System Development

- Heavy Fuel Engines (RQT)
- Efficient/Quiet Propellers (RQQM)
- Electric Motors (RQQM)
- Fuel Cells/Batteries (RQQE)
- Power Management & Distribution (RQQE)



Key Challenges

- **Integration**
  - Power Management
  - Mechanical Coupling
  - Efficient System Design/Optimization
- **Transient (non-steady state) operation**
  - Controls
  - Transitions between operating points
- **Validation / Analysis of hybrid power system approaches**

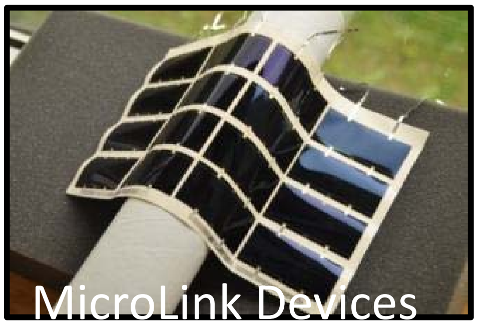
Solar-Powered Raven Program Overview
Successful Demo of Solar Raven

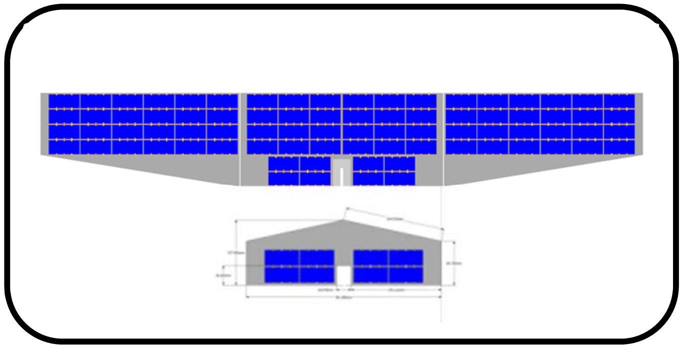
AFRL/RXAS

Problem – Currently deployed UAS systems (e.g., Raven) have very limited flight endurance (e.g., flight time < 1 hour for Raven) and range due to battery propulsion system.

Goal – Develop advanced materials and manufacturing technologies for lightweight energy harvesting devices (solar cells) and integrate into a small UAS platforms for extended flight endurance.

Inverted metamorphic, epitaxial lift-off, GaAs-based solar cell array





Prototype Raven vehicles with integrated solar power and power electronics have been tested by AFSOC and other SOF users.

Payoff – Impact to mission flight endurance – up to a 3X increase in daytime flight time. SOF users & AFSOC providing both in-kind and direct co-funding to increase TRL for tech transition.

Accomplishments – Demonstrated first high efficiency (nominal 30% for cells), lightweight, flexible solar cell array. In Raven flight test, demonstrated 90% increase in power and 60% increase in flight endurance. Demo'd 75% increase in endurance for solar Puma.

- **For further information, please contact …**

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