Air Force Research Laboratory

AFRL HERITAGE | 1917–2017

100 YEARS OF U.S. AIR FORCE SCIENCE & TECHNOLOGY

UAS Hybrid Power & Propulsion

21 June 2017

Michael Rottmayer, PhD

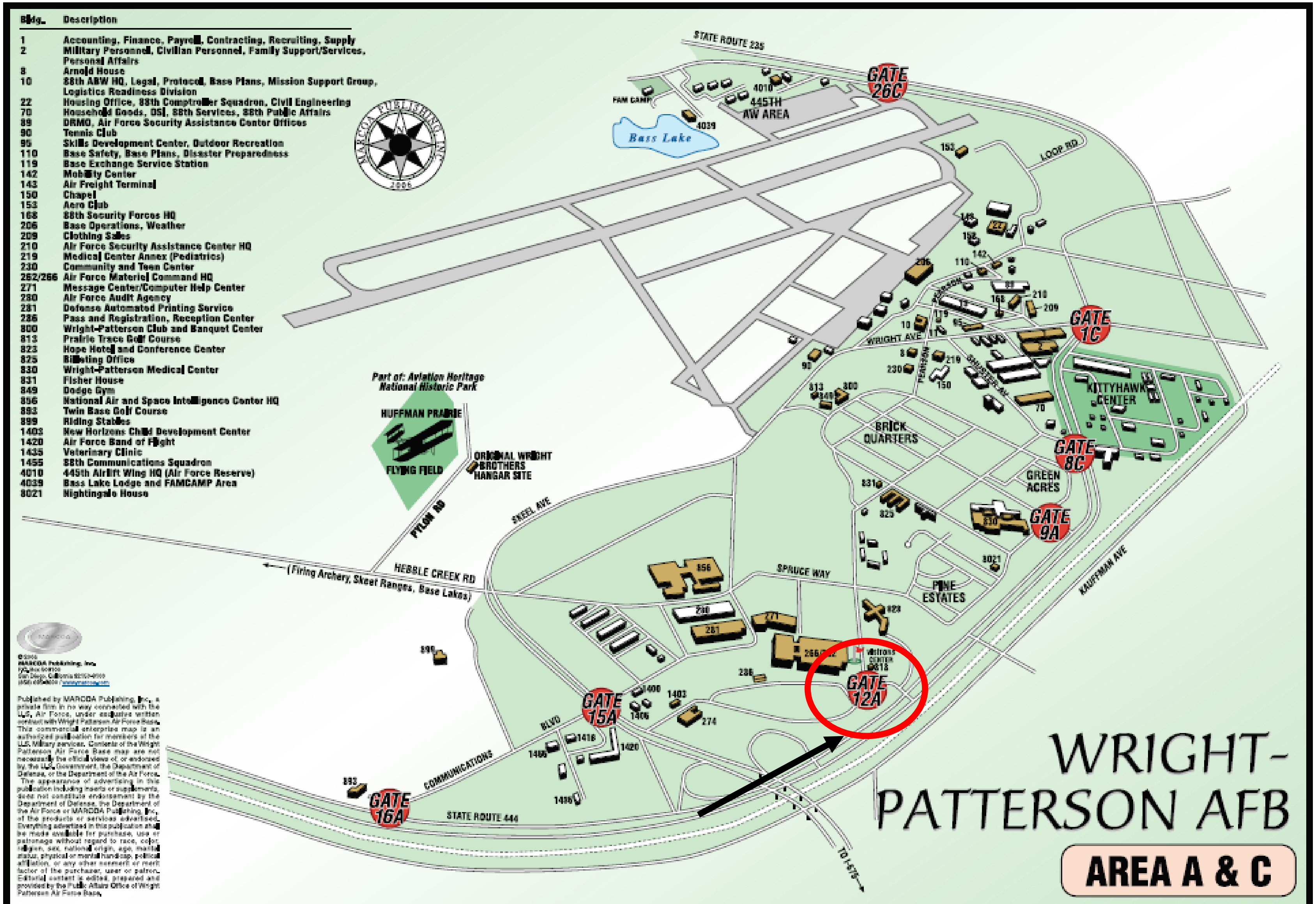
AFRL / RQQE

Power and Control Division

Aerospace Systems Directorate

Integrity ★ Service ★ Excellence

Visitor Passes



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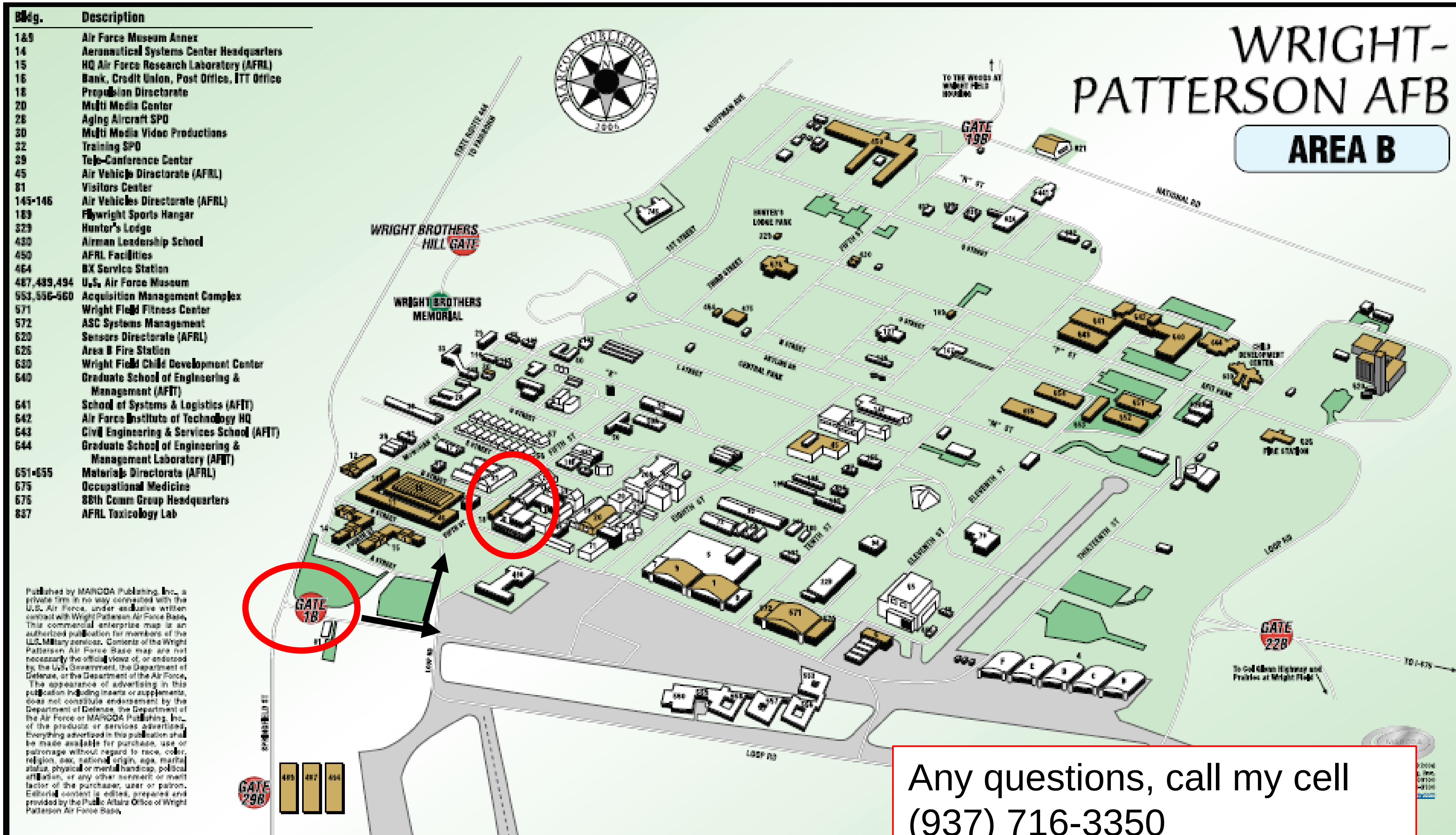
AFRL/RQ Power and Control
Meet in front lobby Building 18
Lab Tour of Building 23



Any questions, call my cell
(937) 716-3350

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AFRL Technical Directorates & Competencies

AF Office of Scientific Research
- Aerospace, Chemical & Material Sciences
- Education & Outreach
- Mathematics, Information, & life sciences
- Physics & Electronics

Aerospace Systems
- Air Vehicles
- Control, Power & Thermal Management
- High Speed Systems
- Space & Missile Propulsion
- Turbine Engines

Directed Energy
- Directed Energy & EO for Space Superiority
- High Power Electromagnetics
- Laser Systems
- Weapons Modeling and Simulation

Information
- Autonomy, C2, & Decision Support
- Connectivity & Dissemination
- Cyber Science & Technology
- Processing & Exploitation

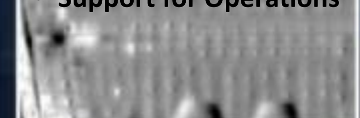
Human Performance
- Bio-effects
- Decision Making
- Human Centered ISR
- Training

Munitions
- Fuze Technology
- Munitions AGN&C
- Munitions System Effects Science
- Ordinance Sciences
- Terminal Seeker Sciences

Sensors
- Advanced Devices & Components
- Layered Sensing Exploitation
- Multi-Int Sensing (RF/EO)
- Spectrum Warfare

Space Vehicles
- Space Electronics
- Space Environmental Impacts & Mitigation
- Space OE/IR
- Space Experiments
- Platforms & Operations Technologies

Materials and Manufacturing
- Functional Materials & Applications
- Manufacturing & Industrial Technology
- Structural Materials & Applications
- Support for Operations



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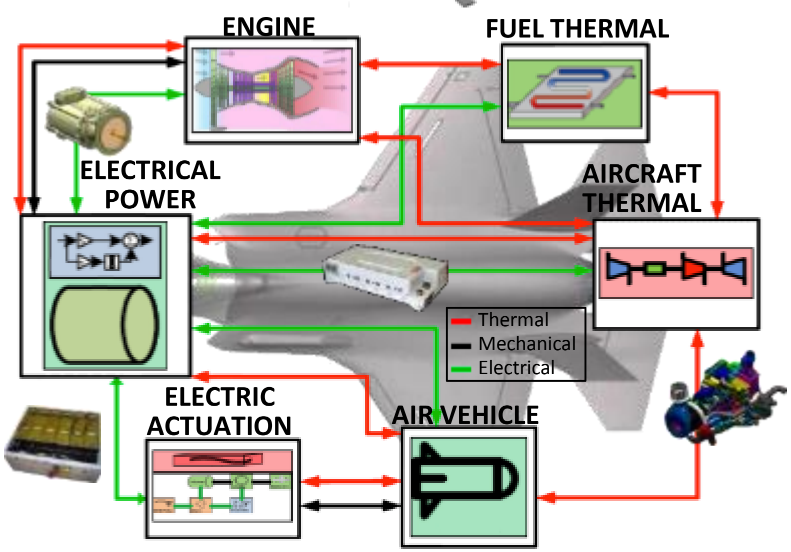
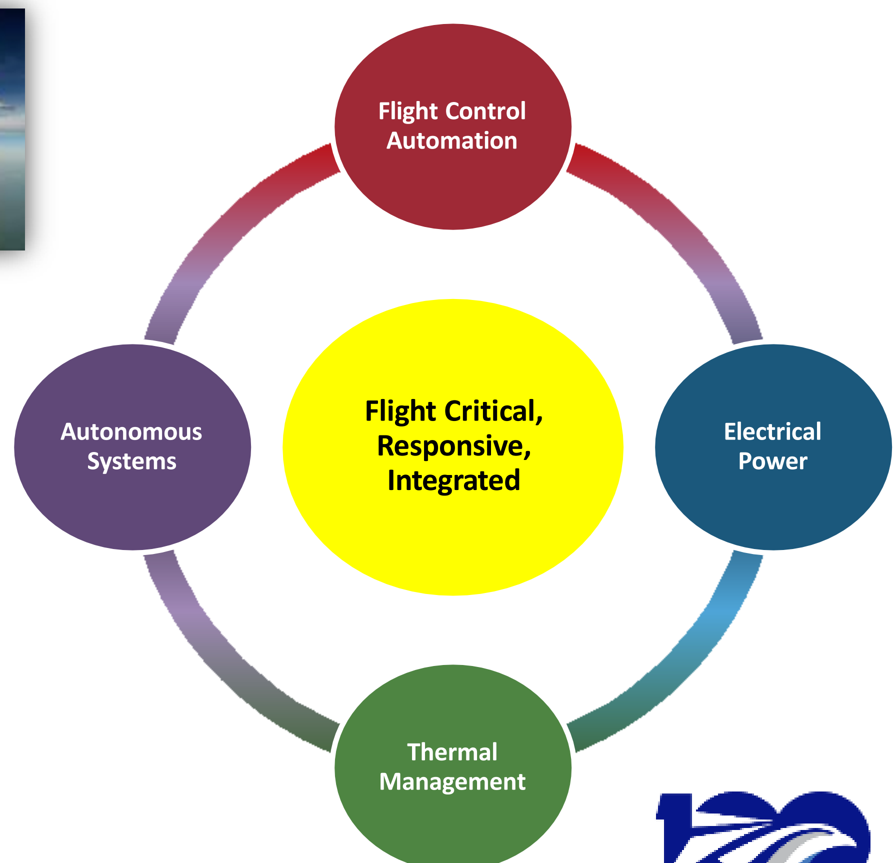
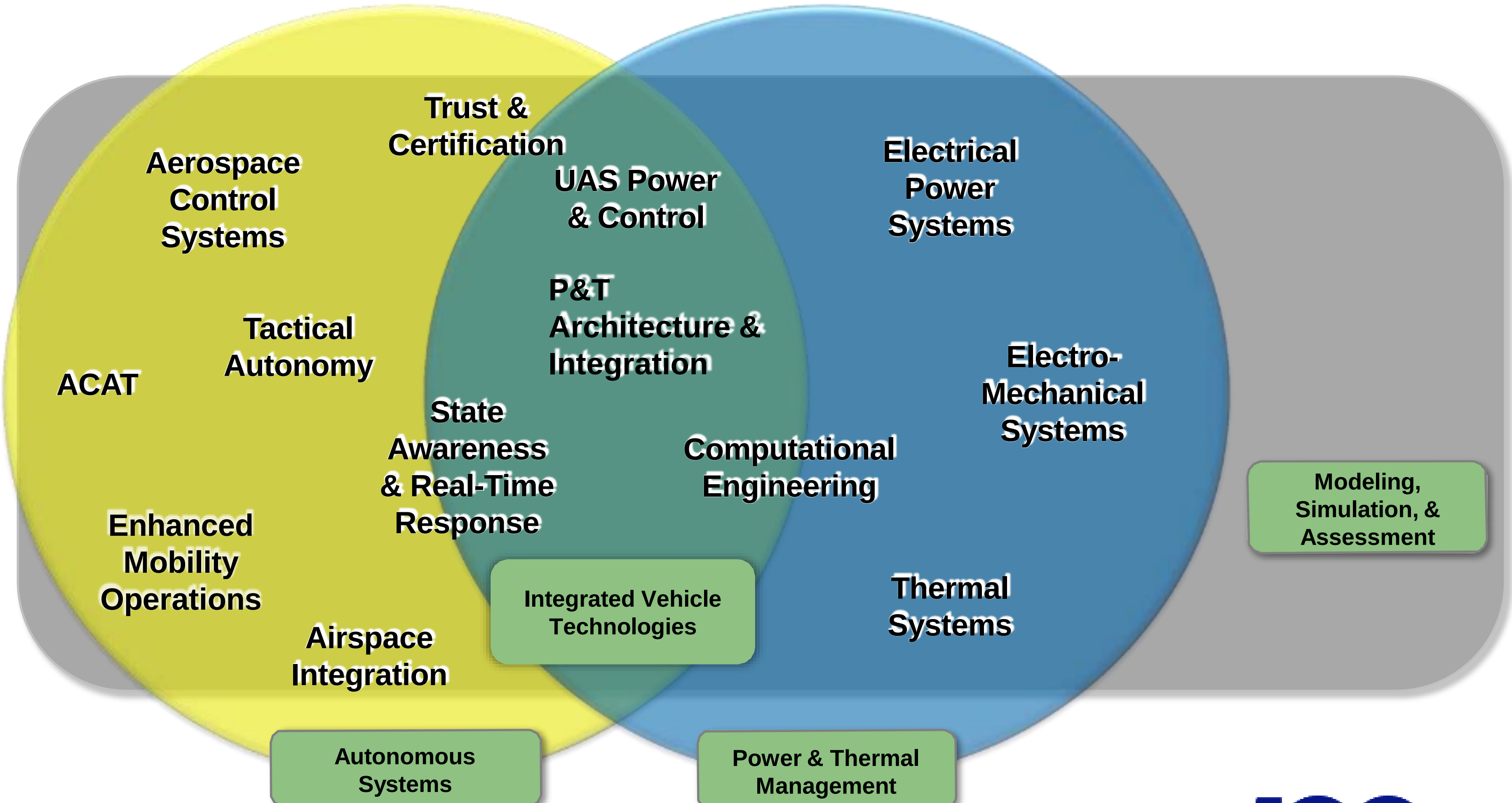
Power & Control Division Vision (AFRL/RQQ)

Expanding AF mission capabilities by leading the research, development, and transition of flight-critical, responsive, integrated vehicle systems





Power & Control Technology Portfolios



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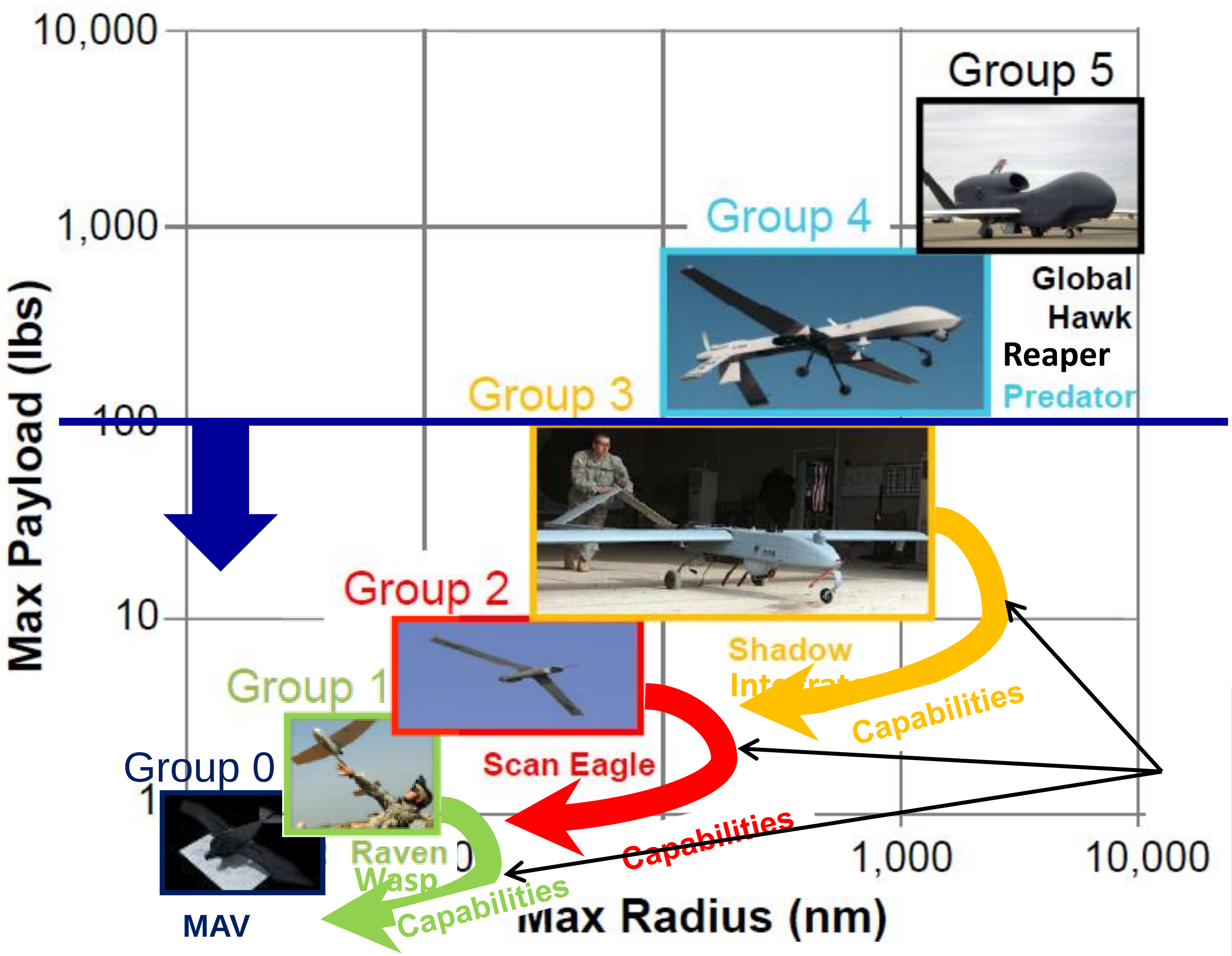
UAS Power & Control Vision & Approach

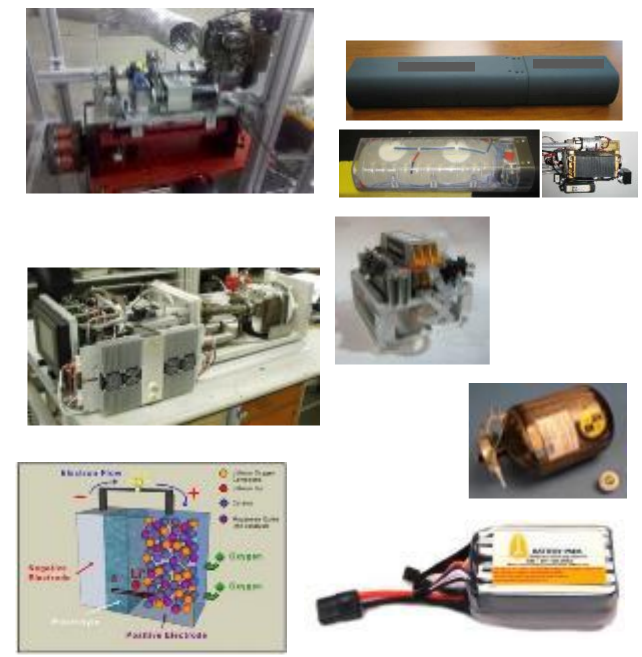
- **AF Vision Statement: To Deliver Affordable and Integrated SUAS Assets with the Following Attributes:**
  - **Exponential Force Multiplier**
    - **Cross domain integration across mission sets**
  - **Easily Integrated Asset**
    - **Deployable by a variety of means, providing flexibility, reach, 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**
  - **Explore hybrid propulsion system architectures and control strategies**
  - **Foster critical industry / Govt partnerships to develop, demonstrate and transition technologies into next generation UASs**
  - **Perform integrated UAS ground/flight testing to validate technology predictions**
  - **Coordination of R&D Across DoD / Govt Agencies, and International Partners**

SUAS Power/Propulsion

Key Challenges





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 <2021

- > 500 hrs MTBF
- Up to 2x Range/Endurance
- 10% Dash Capability
- 25% Payload Power Growth

Mid Term <2026

- > 2000 hrs MTBF
- Up to 4x Range/Endurance
- 50% Dash Capability
- 100% Payload Power Growth

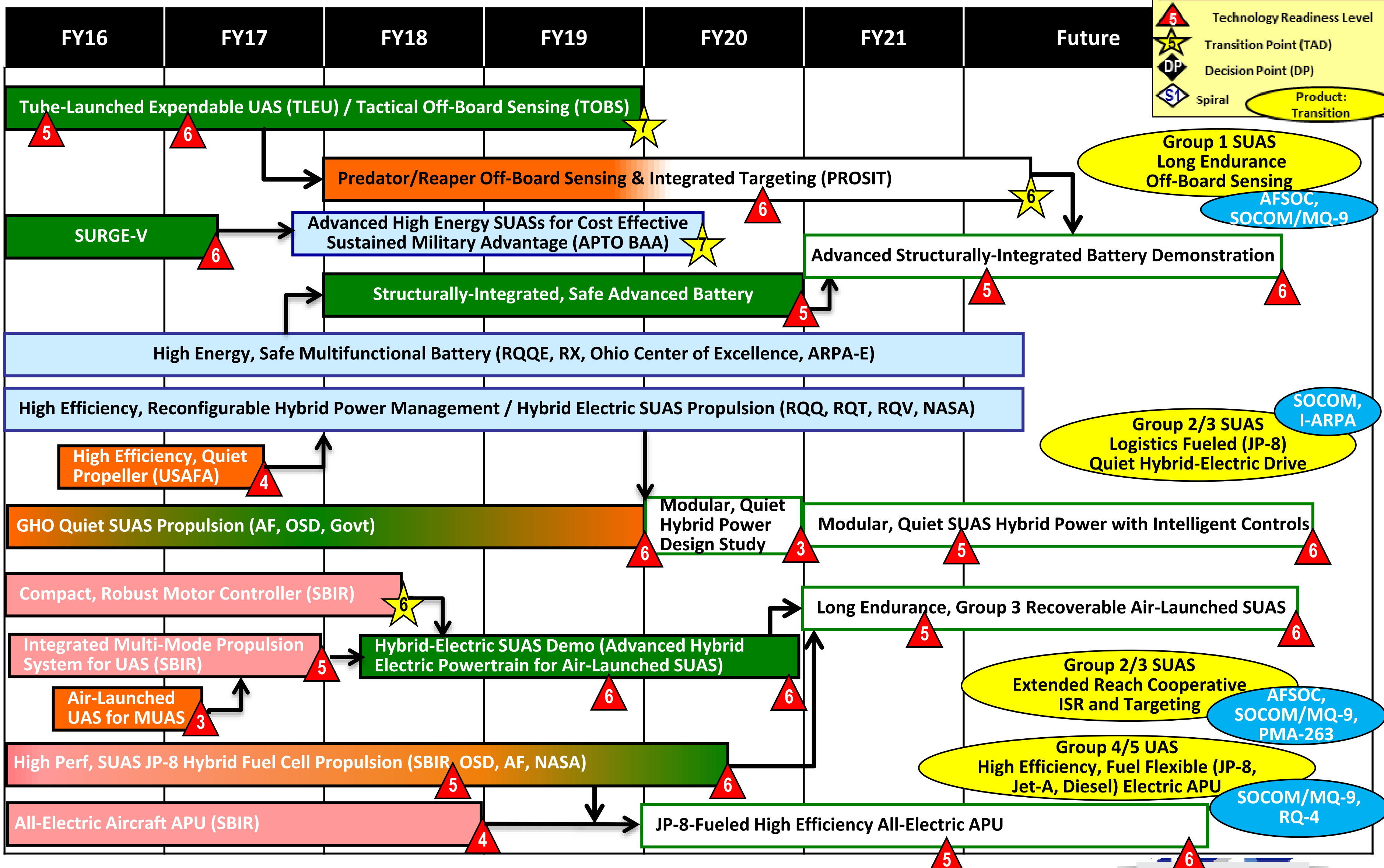
Logistic Fueled STUAS
Hand-Launched SUAS
Air-Dropped TLEU

(Group 1 – Group 3 Propulsion)

Recoverable Air-Dropped UAS
Large Class UAS APU

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

UAS Power & Control
Strategic Roadmap



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

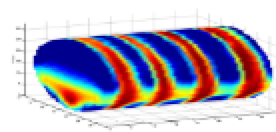
Power Generation, Storage, and Distribution

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

Wide Temp Dielectrics & Capacitors
Magnetics
Hi Temp Superconductivity

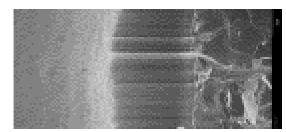
Batteries
- Solid State
- High Energy Hybrids

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

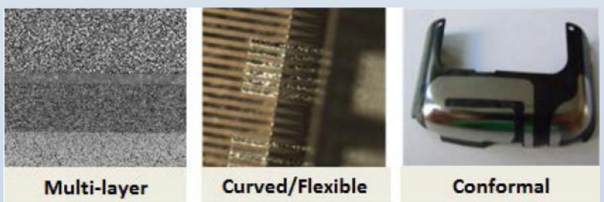
Electrochemistry
In-House Research

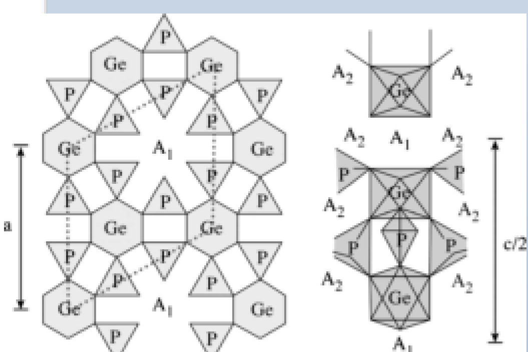
Advanced Energy Storage/Energy Conversion Development

- **Solid-State Lithium-Ion Battery**
- **High Performance Lithium-Oxygen Battery**
- **High Energy/High Power Hybrid Battery**
- **Battery Characterization and Analysis for Aircraft, DEW, and SUAV Applications**

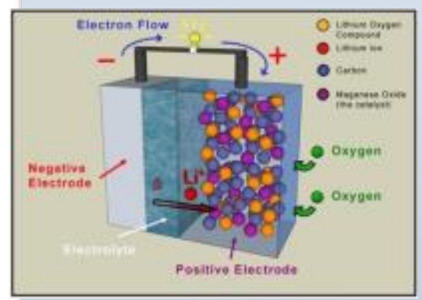
RQQ Electrochemical Systems Development and Characterization

- **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

High Capacity Cathode Materials Functionalized with Carbon for Lithium-Ion Batteries

Dr. Joseph Fellner and Dr. Lawrence Scanlon --- (16RQCOR301)

High Capacity Cathode Materials Functionalized with Carbon for Lithium-Ion Batteries

STATUS QUO

Primary lithium batteries

• Lithium CFx batteries • Energy densities of 300-500 Whr/kg • Very high rates of heat generation when discharged at moderate to high rates • CFx discharge theoretical capacity of 865 mAh/g

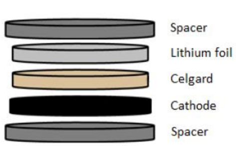
Secondary lithium-ion batteries

• Flammable electrolytes • Some cathode active materials produce oxygen when heated • Cathode capacities of 150-200 mAh/g • Use of Ni/Co oxides can result in high cost

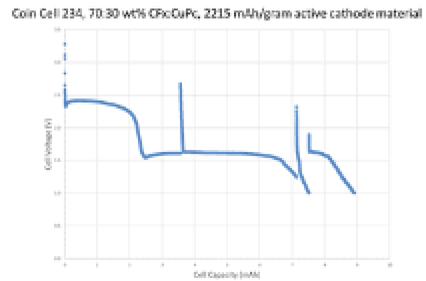
NEW INSIGHTS

Organic Cathode Active Materials

• Very high primary discharge capacities of Cu phthalocyanine, >2200 mAh/g when integrated with CFx • Use of DFT can be used to help determine suitable organic materials for further use and development • Limitations in rechargeability of phthalocyanines - new organic-based rechargeable active materials to be developed

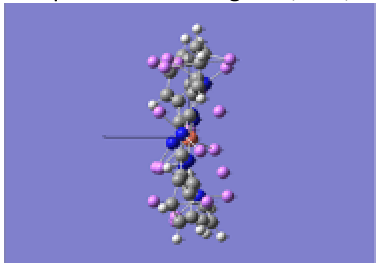


MAIN ACHIEVEMENTS:



Combination of CFx and Copper Phthalocyanine (Pc) results in hybrid batteries with extremely high discharge capacities

• Design, fabrication, and testing of Li-based batteries • Demonstration of extremely high discharge capacities by use of a hybrid cathode chemistry • Ab-initio determination of cathode active material structure, capacity, and voltage • Determination of fundamental material parameters using XRD, BET, SEM, etc.



Lithium addition to Pc results in deformation of the structure but also enables more lithium addition

HOW IT WORKS:

• CFx and nano-sized CuPc used as cathode active material • Discharge of CFx produces nascent nano-sized carbon greatly enhancing electrical conductivity • Two-voltage plateau cell with greatly enhanced capacity is the result

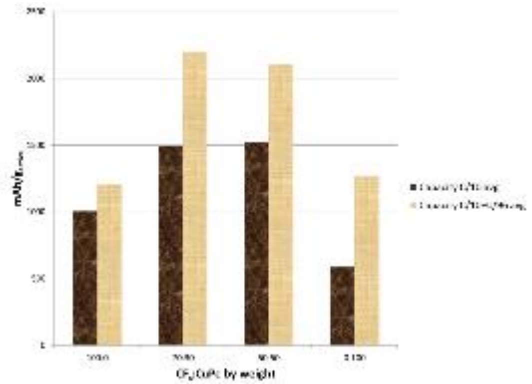
ASSUMPTIONS AND LIMITATIONS:

• DFT models are based at 0K • Hybrid cathode can only be discharged to achieve these high rates • DME electrolyte used is flammable

QUANTITATIVE IMPACT

Current Impact

• 2-fold increase in primary battery discharge capacity with reduction in heat generation and state-of-charge indicator



Discharge capacity of CFx-CuPc primary battery as a function of compostion

END-OF-PHASE GOAL

Planned Impact

• Utilize the hybrid battery concept to enhance rechargeable organic cathode active materials • Hybrid primary battery concept to be used in future weapon systems • DFT-modeling used for future modeling of battery materials

Research Goals

• Completion of the hybrid battery concept into a solid-state cell • Discovery of new organic-based rechargeable cathode active materials • Discovery of new relationships of voltage and capacity for organic-based active materials

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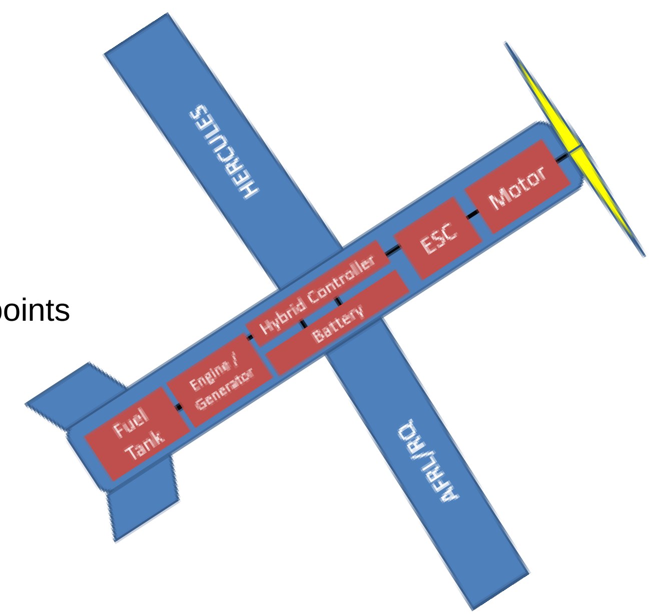
Hybrid Electric Research Collaboration on Unmanned Long Endurance Systems (HERCULES)
- AFRL Internal R&D -

Objective: To address key integration & hybrid controls issues for improved operational efficiency / reliability of hybrid electric UAS propulsion architectures

Approach:
- Develop a hybrid electric UAS propulsion test bed for collaborative research across AFRL, other Govt agencies, Industry, and Academia
- Research and explore novel energy optimized power management and control approaches for next generation series hybrid electric UASs

Key Challenges
- **Integration**
  - Power Management
  - Mechanical Coupling
  - Efficient System Design/ Energy Optimization
- **Transient (non-steady state) operation**
  - Efficient power controls / electrical protection
  - Fast transitions between operating points
- **Validation / analysis of hybrid power system approaches**

HERCULES "Copper Bird" Concept



Modeling & Simulation
- Propulsion System Optimization Models (RQQ, RQT)
- Propulsion/Power System Trades (RQQ, RQT)
- Tip-to-Tail System Models (RQV)
- Aerodynamic Performance Analysis (RQV)

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

Wrap-Up

- **Development of key power & control technologies to improve SUAS capabilities as a force multiplier**
- **Numerous collaborative efforts across Govt, Industry and Academia underway supporting all product areas**
- **Group 1 SUAS Long Endurance, Off-Board Sensing**
  - **Development of advanced long endurance SUAS technology providing remote sensing for off-board OPS**
  - **Addressing SOCOM / AFSOC requirements for stand-off and under weather off-board sensing**
  - **Near term transitions: TOBS and SURGE-V**
- **Logistics Fueled (JP-8) Quiet Hybrid-Electric Drive**
  - **Development of next gen hybrid electric power & propulsion solutions for extended endurance/range, reduced acoustic signatures, and modular/scalable to different SUASs**
  - **Addressing SOCOM and other Customer needs and requirements for long endurance, quiet operations**
- **Extended Reach Cooperative ISR and Targeting**
  - **Design/develop long endurance Group 3 recoverable air-launched SUAS with integrated flight controls enabling supervisory management of UAS and cooperative control of unmanned teams**
  - **Addressing SOCOM / AFSOC needs and requirements for extending MQ-9 operational reach and signature reduction**
- **High Efficiency, Fuel Flexible (JP-8, Jet-A, Diesel) Electric APU**
  - **Develop and demonstrate a high efficiency all-electric on-board aircraft APU for high-altitude, long-range unmanned aerial system (UAS) operations**
  - **Addressing needs and requirements for more on-board electrical power to support adv payloads and other subsystems**

Questions