The Evolution of Electric Military Aircraft

World Symposium on Electric Aircraft
Oshkosh Air Show, WI

Dr. Mark T. Maybury
Chief Scientist
United States Air Force

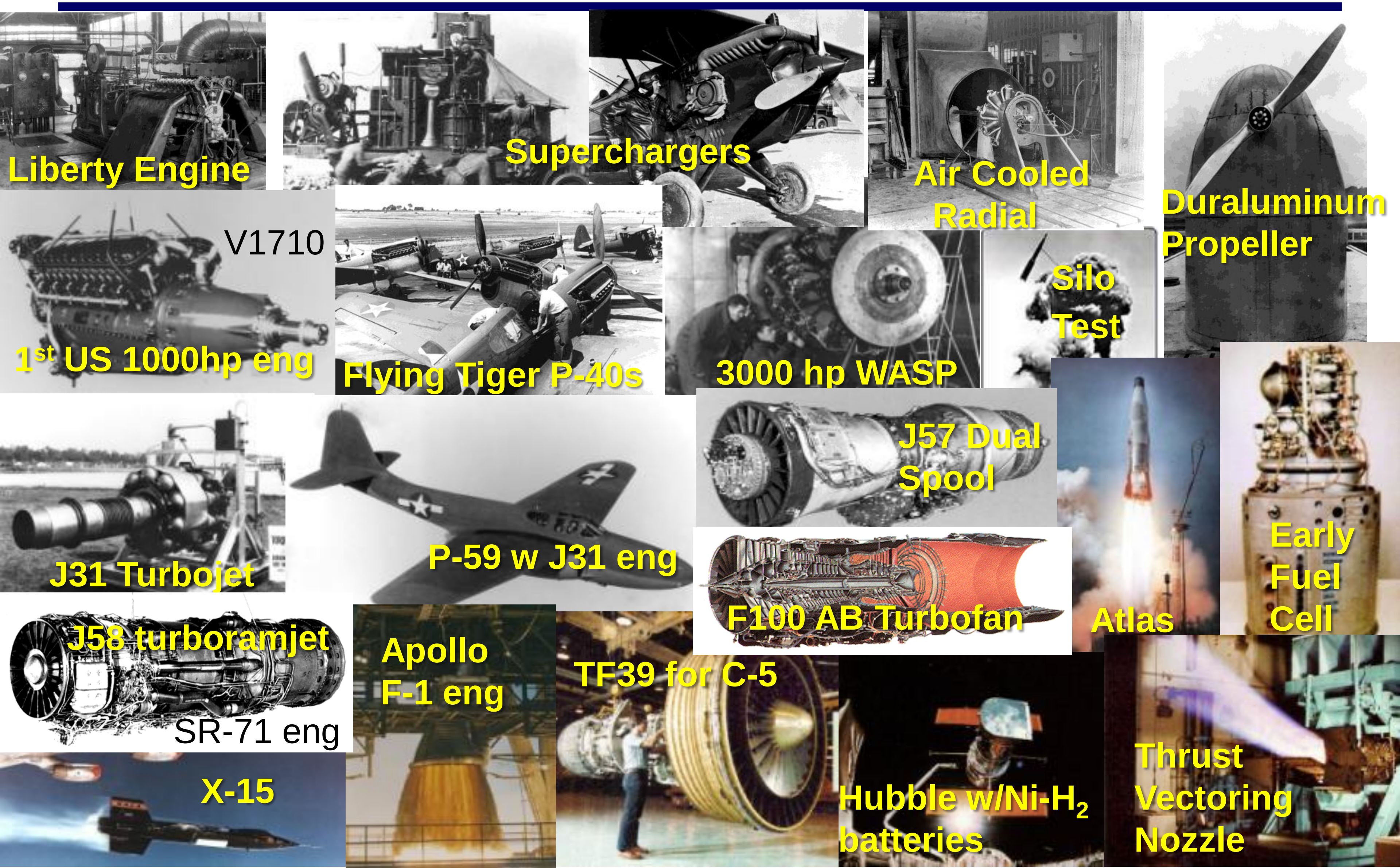
29 July 2011

Air Force Priorities

- *Continue to Strengthen the Nuclear Enterprise*
- *Partner with Joint and Coalition Team to Win Today's Fight*
- *Develop and Care for Airmen and their Families*
- *Modernize our Air and Space Inventories, Organizations & Training*
- *Recapture Acquisition Excellence*

Air Force Propulsion Heritage

U.S. AIR FORCE



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Predicting the Future

- **"Aircraft flight is impossible."** ***Lord Kelvin***
- **"The [flying] machines will eventually be fast; they will be used in sport but they should not be thought of as commercial carriers."** ***Octave Chanute, 1910***
- **"There has been a great deal said about a 3,000 mile rocket. In my opinion such a thing is impossible for many years. I think we can leave that out of our thinking."** ***Vannevar Bush, 1945***
- **"…the Gas Turbine can hardly be considered a feasible application to airplanes…"** ***Committee with Von Karman, Millikan, Kettering, 1941***

(Reported by N. Augustine)

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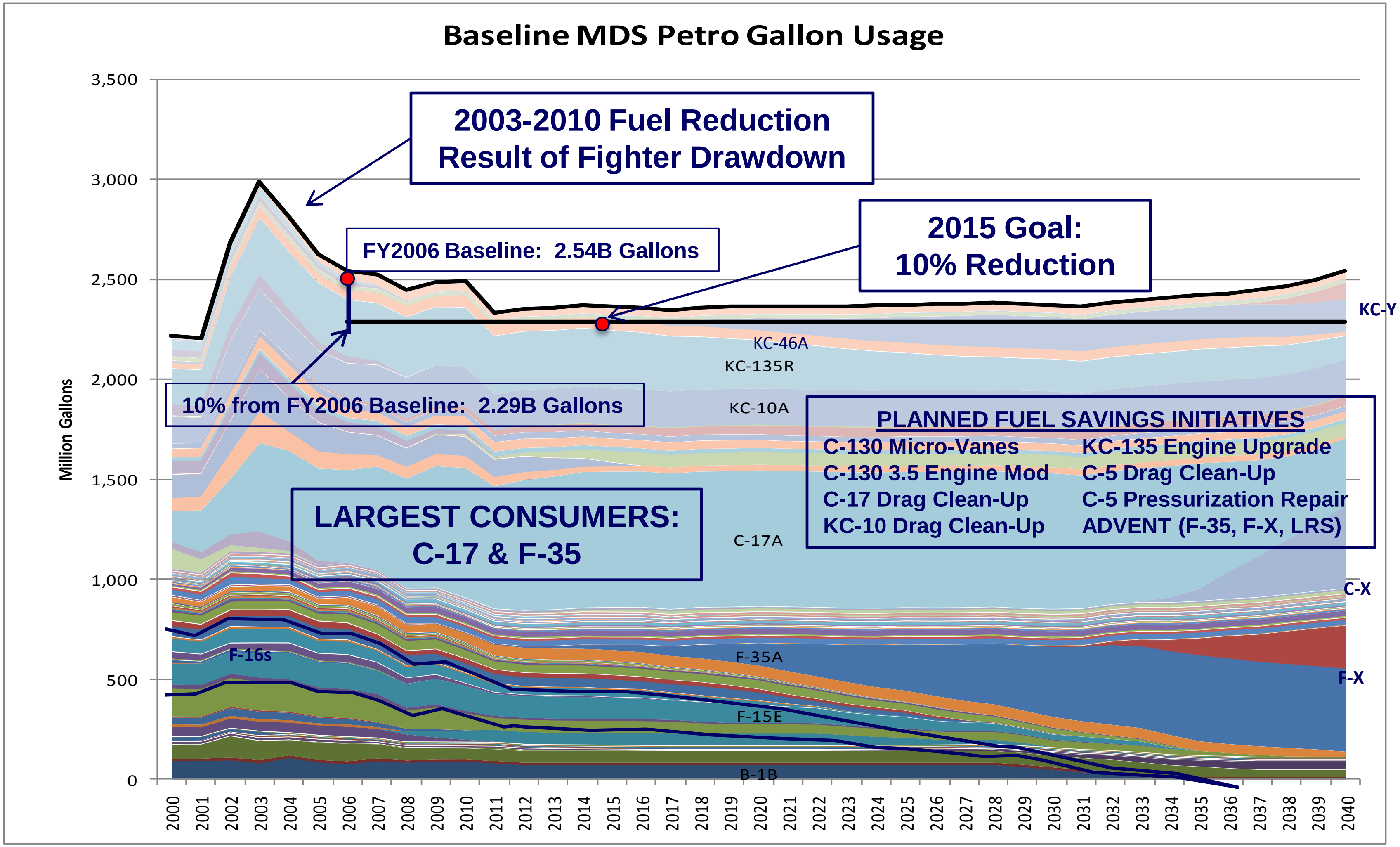
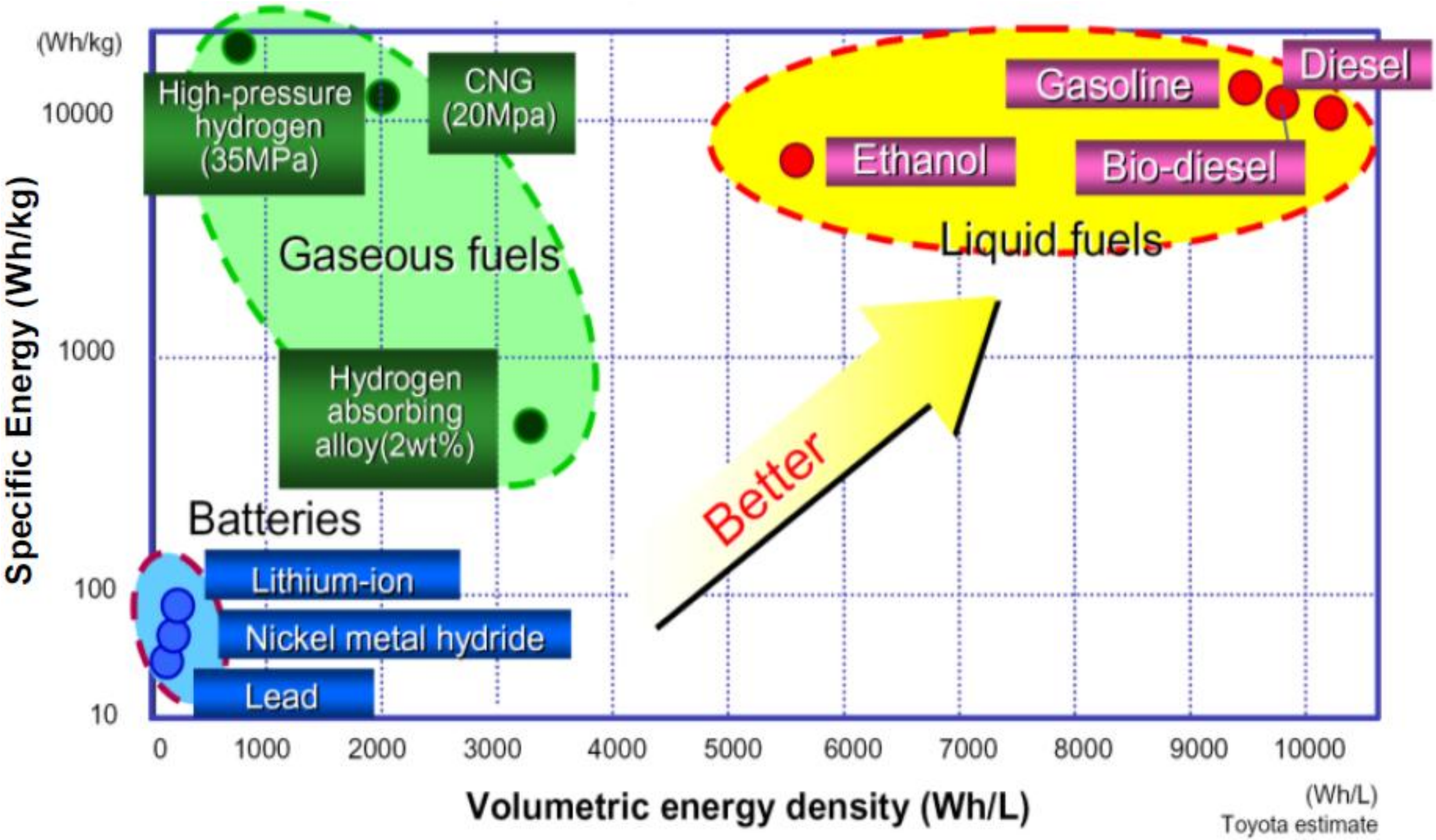
Air Fuel Consumption Growing



Current fuel saving initiatives will not achieve 2015 10% reduction goal until 2029

Energy Density



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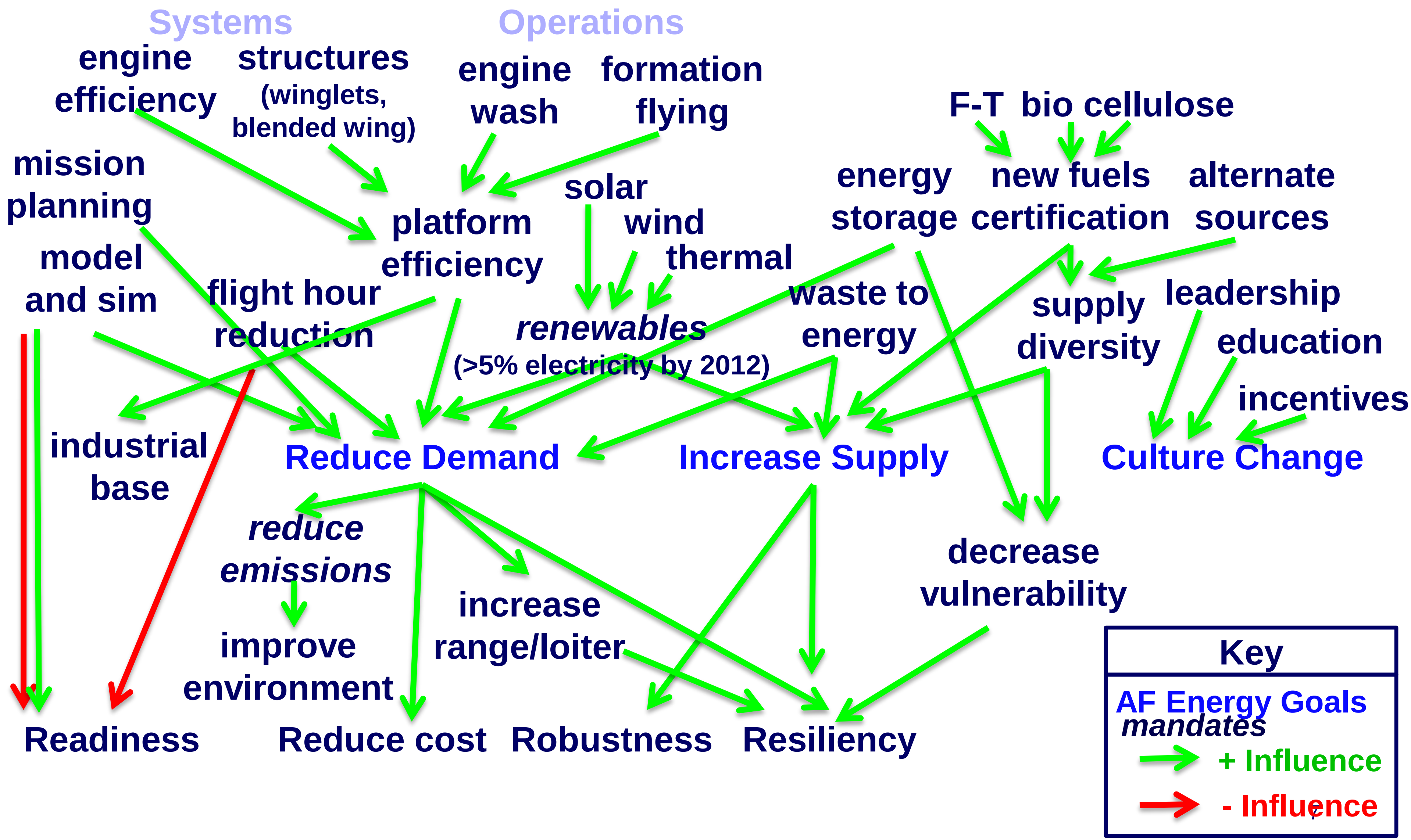
A Systems Approach to Energy Objectives and Goals



Key AF Propulsion Focus Areas

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Efficiency and Endurance

High Speed ISR/Strike

Space Lift and Power

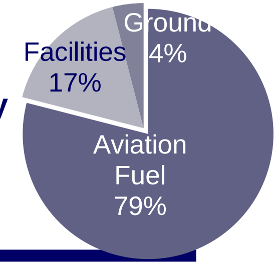
Renewable Fuels

Sustainable Power

Energy Horizons: Air Force Energy S&T Strategy

U.S. AIR FORCE

AF Energy Costs



Vision

Assured energy advantage across air, space, cyberspace and infrastructure

Objective

- **Focused S&T to accelerate revolutionary energy capabilities for Air Force missions**
- **Mid (FY16-20) and long (FY21-25) term**
- **Advance systems, operations, culture**
- **Leverage internal/external partnerships**

"For the Air Force's part, we must embrace the notion that energy efficiency is not a stand-alone priority because it binds together and enables every dimension of our mission; and the idea that energy efficiency affords us greater resiliency, which translates to greater capability and versatility."

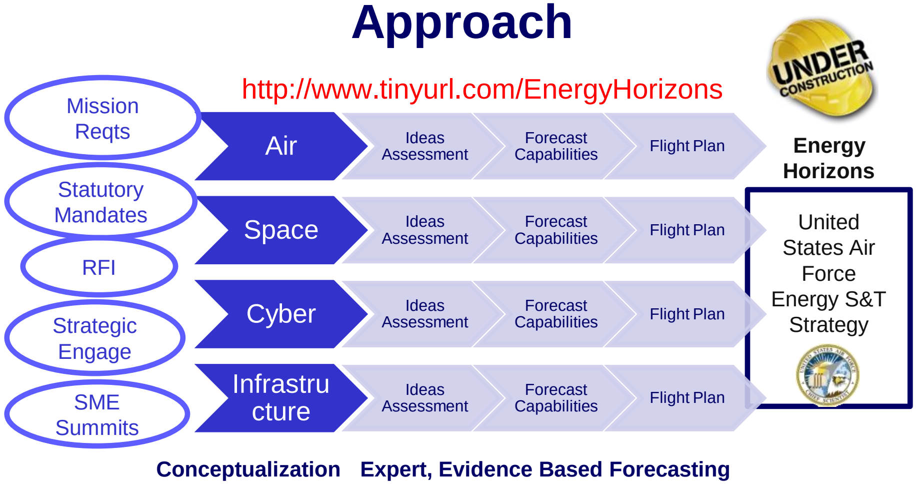
Gen. Norton Schwartz, CSAF

"Changing the culture means that all of us, from the Air Staff to Airmen at home or deployed, must learn to think of energy as part of maximizing mission effectiveness."

Ms. Erin Conaton, USecAF

Approach

http://www.tinyurl.com/EnergyHorizons



Revolutionary

Air

Space

Cyber

Infrastructure

www.tinyurl.com/EnergyHorizons

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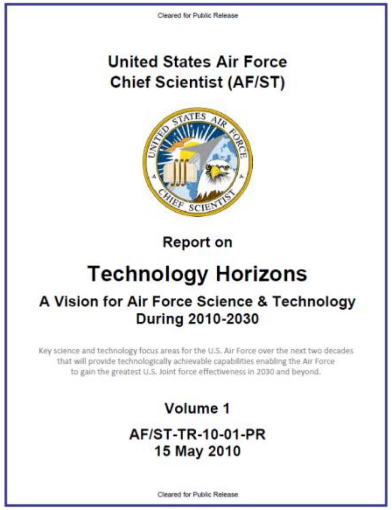
Technology Horizons


Cleared for Public Release

United States Air Force
Chief Scientist (AF/ST)

Report on

Technology Horizons

A Vision for Air Force Science & Technology
During 2010-2030

Key science and technology focus areas for the U.S. Air Force over the next two decades that will provide technologically achievable capabilities enabling the Air Force to gain the greatest U.S. Joint force effectiveness in 2030 and beyond.

Volume 1

AF/ST-TR-10-01-PR
15 May 2010

Cleared for Public Release

PCA13: High-Altitude Long-Endurance ISR Airships

PCA15: Fractionated Survivable Remote-Piloted Systems

PCA17: Energy-Efficient Partially Buoyant Cargo Airlifters

PCA18: Fuel-Efficient Hybrid Wing-Body Aircraft

PCA19: Next-Generation High-Efficiency Turbine Engines

AFRL's Propulsion Directorate

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~700 programs (MAR 10)
(OH ~350 / CA ~350)

~1,200 people (MAR 10)
(OH ~350 gov't, ~400 contr)
(CA ~200 gov't, ~250 contr)

~$331M / year (core S&T)
(FY11 PB includes FY10-FY15)
(OH ~$236M / CA ~$95M)

~$3B in facilities (MAR 10)
(OH ~$1B / CA ~$2B)

Established 1947

Edwards AFB, CA

Technologies

- Liquid Rocket Engines
- Solid Rocket Motors
- Spacecraft Propulsion

Established 1917

Wright-Patterson AFB, OH

Technologies

- Gas Turbine Engines
- Energy, Power, and Thermal Subsystems
- Alternative and synthetic fuels
- Hypersonic Propulsion

More Electric Aircraft (MEA) Historical Perspective

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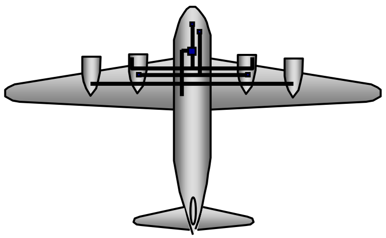
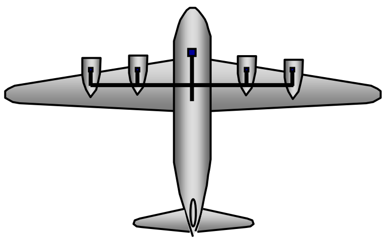
1940's | 1980's | 1990's | 2000...

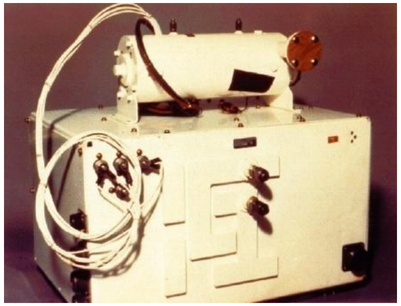
HYDRAULIC



ELECTRICAL

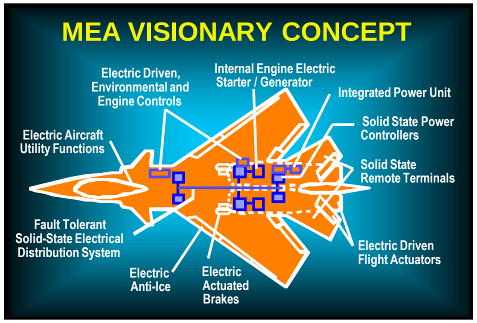


- 1943- XB-30 STUDIES COMPARED POWER-ASSISTED CONTROLS
- HYDRAULICS WON!



- 1984 - 85 HP (63 KW) ELECTRIC FUEL PUMP & CONTROLLER FOR F-16 (>5 ft^3, >100 lbs)
- ELECTRIC DRIVE STILL INFEASIBLE

- 1992 - SDI REVOLUTIONIZED POWER ELECTRONICS WEIGHT / VOLUMES
- ENABLES AIRCRAFT FLIGHT-WEIGHT ELECTRICALLY-BASED HARDWARE



- 1993 - PRESENT POWER THRUST R&D TO DEMONSTRATE A "NO HYDRAULICS" AIRCRAFT (MORE ELECTRIC, MEA)
- FEASIBILITY FLIGHT DEMO (F-16) SCHEDULED FOR EARLY FY01 FIRST FLIGHT

More Electric Aircraft (MEA)

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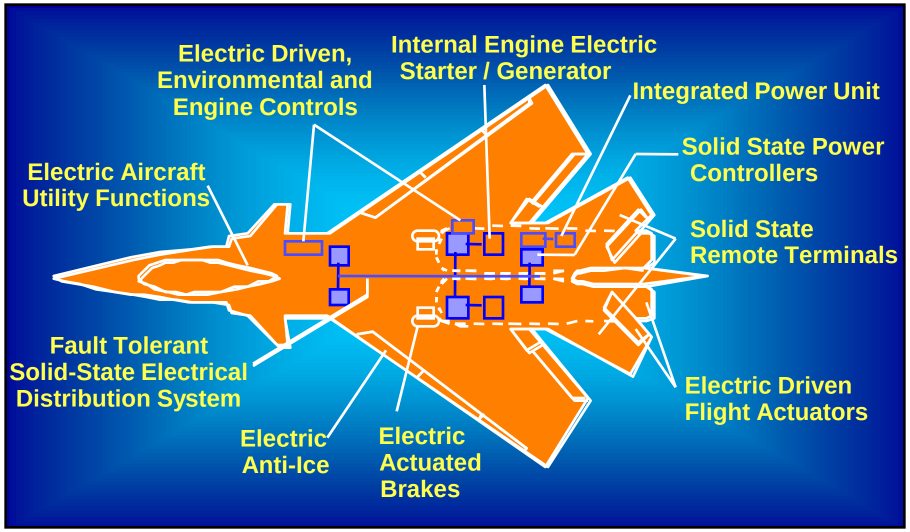
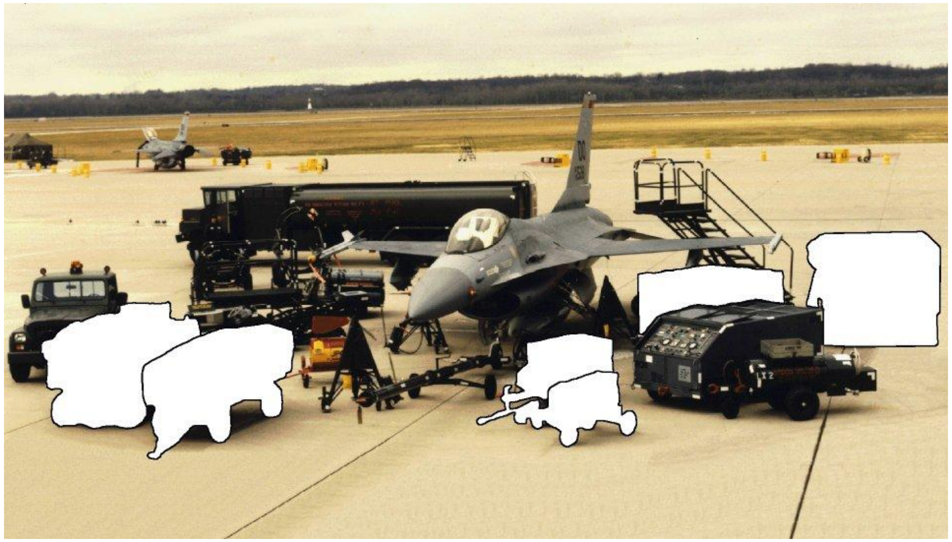
THE VISION → THE IMPACT





- ALL-ELECTRIC AIRCRAFT (NO HYDRAULICS OR BLEED AIR PNEUMATICS)
- ELIMINATION OF ACCESSORY DRIVE GEARBOX (REDUCED FRONTAL AREA)

ENABLES MISSION AVAILABLE POWER FOR LETHAL AIRBORNE DIRECTED ENERGY WEAPON

- REDUCED LCC
- DRAMATIC IMPROVEMENT IN R, M, & S
- REDUCED DEPLOYMENT FOOTPRINT AND MANPOWER
- INCREASED SORTIE GENERATION RATE

SAVINGS IN $B's WITH IMPROVED WARFIGHTING

1992 LMTAS, 1995 VITPS, & 1998 J/IST STUDIES

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MEA System-Level Payoffs

- FIGHTERS - RETROFIT (F-16, F-18, RESPECTIVELY)
  - 60, 129 ADDITIONAL AIRCRAFT (AVAILABILITY)
  - 11, 15% REDUCED MAINTENANCE MANPOWER
  - 10, 12% VULNERABILITY IMPROVEMENT
  - 7, 20% REDUCED DEPLOYMENT (C-141 LOADS OR C-17 EQUIVALENTS)

(Lockheed & Northrop MEA F-16 & F-18 Studies)

- FIGHTERS - NEW CONCEPT, INCLUDING OTHER SUBSYSTEMS INTEGRATION
  - 8 - 9% PROCUREMENT COST SAVINGS
  - 3 - 6% LCC SAVINGS
  - 20 - 30% RANGE IMPROVEMENT (120 - 170 MILES)

(Northrop/Lockheed/Boeing Vehicle Integration Technology Planning Study)

Fuel Consumption (Gal/Hr)
- C-17 - 2228
- C-141 - 2205
- F-16 - 877

(HQ AF MDS Database)

STRONG CONTRIBUTOR TO LEAN, RAPID RESPONSE AIR EXPEDITIONARY FORCE

- TRANSPORT - RETROFIT ELECTRIC ACTUATION ONLY/267 AIRCRAFT
  - 3.3 - 5.9 ADDITIONAL AIRCRAFT
  - UP TO 182 MANPOWER REDUCTION PER FLEET
  - UP TO 58% TURNAROUND TIME IMPROVEMENT

(Lockheed C-141 Electric Starlifter Study)

MEA Technologies Buy:
- Billions in LCC Savings
- 450 - 500 Additional Sorties for a...
  - 72 Aircraft Fighter Wing over a
  - 30-Day War

(Northrop MEA & F-18 Study)

MEA Transition Status Circa 2000

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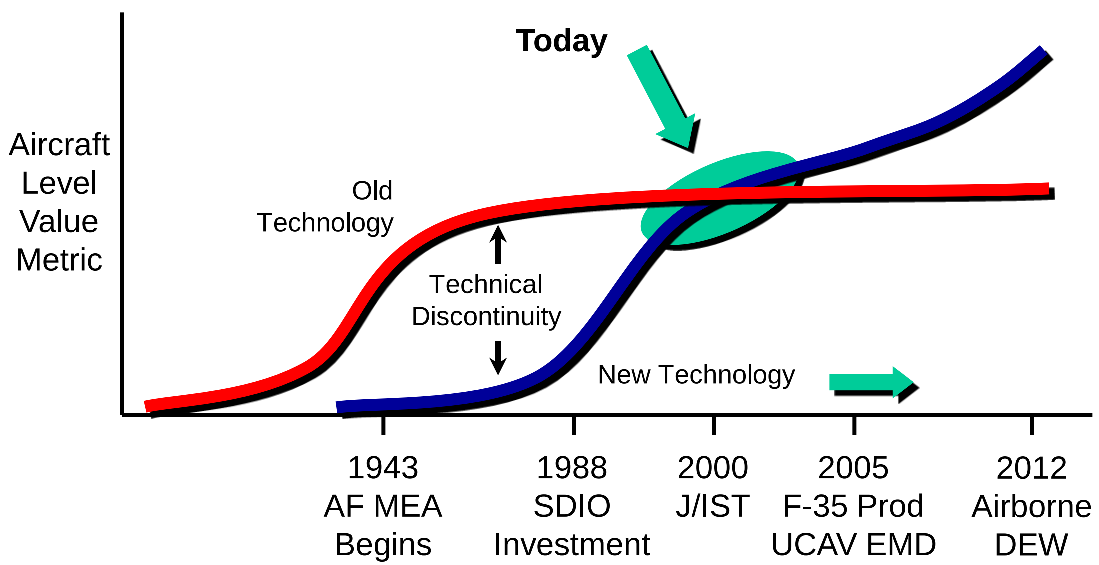
MEA transition is occurring…

- **MEA Gen I to F-35**
- **Solid state power distribution to F-22, C-130J & F-35**
  - **Baseline for all new platforms**
- **External Starter / Generator to F-35**
- **Electrical actuation to F-35 and UCAV**
- **Maintenance free battery to multiple aircraft**

Future aircraft power application…



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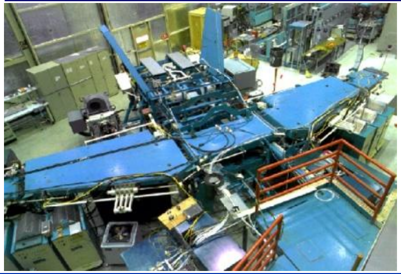
MEA Technology Demonstration for the Joint Strike Fighter

JSF / INTEGRATED SUBSYSTEMS TECHNOLOGY (J/IST) PROGRAM

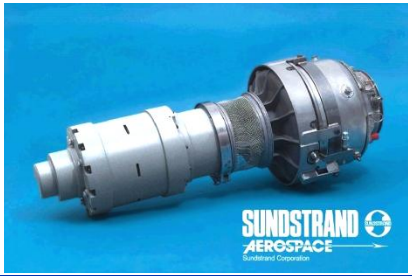


ELECTICAL POWER DISTRIBUTION SYSTEM

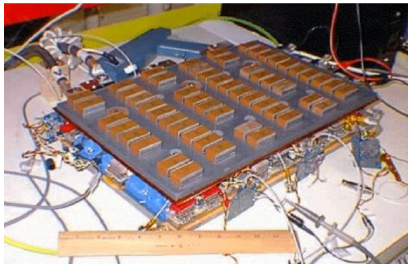
ELECTRIC ACTUATION

AFTI F-16
ELECTRIC FLIGHT DEMONSTRATION

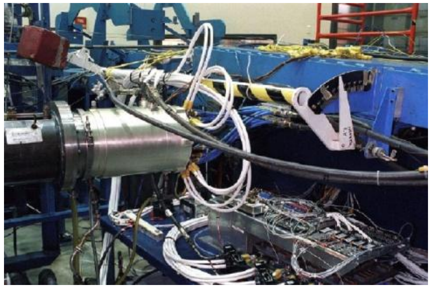
AFTI F-16 ON DISPLAY AT THE NATIONAL MUSEUM OF THE UNITED STATES AIR FORCE



INTEGRATED (AUX/EMER) POWER UNIT



MOTOR CONTROLLERS / POWER CONVERTERS



EXTERNAL STARTER / GENERATOR

ADVANCED BATTERIES

CONTACTORS & SOLID STATE POWER CONTROLLERS

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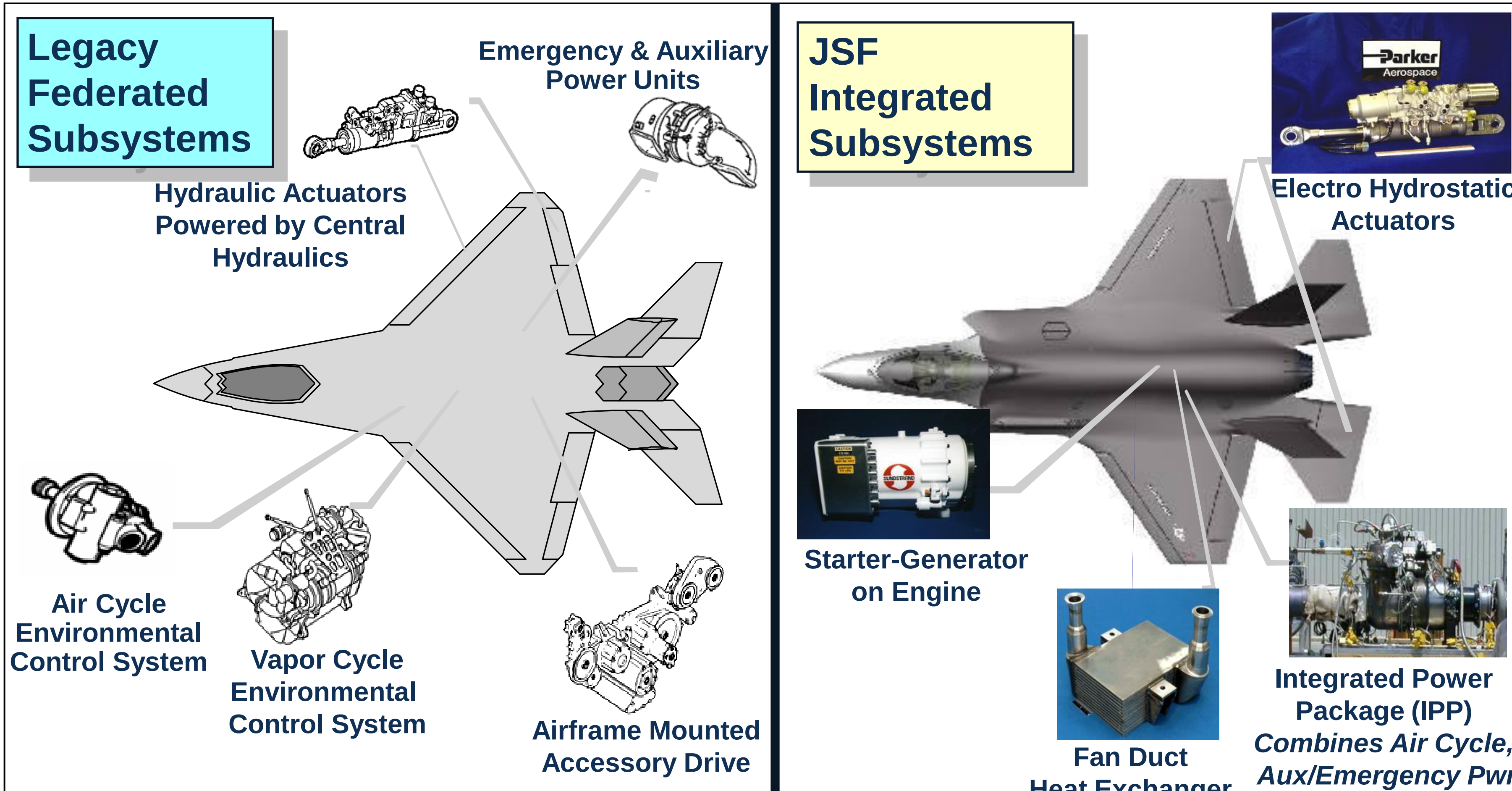
JSF Integrated Subsystems, A System Revolution



Integrated Architecture Eliminates Single Use Equipment and Reduces Aircraft Volume For Subsystems, But Adds Integration Complexity

Highly Capability Aircraft Enabled By Integrated Design

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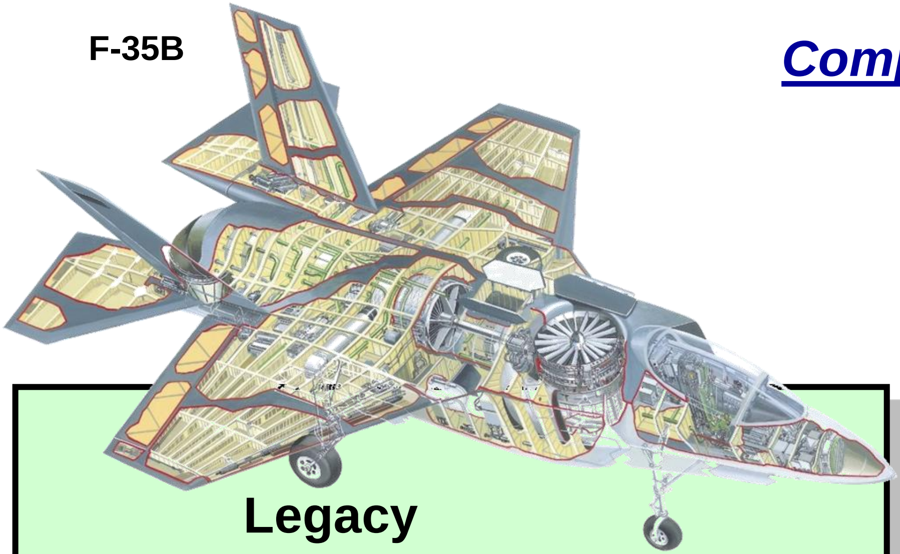

Complexity Adds To The Design Challenges

- *Harsh Thermal Environment*
- *Volume Constraints*
- *Multiple Variants Including STOVL*
- *Highly Integrated Architecture*
- *Stealthy*

Legacy

External….
- Fuel
- Weapons
- Electro-Optical Targeting System
- Countermeasures
- Electronic Countermeasures Electronics
- Tailhook

Structural Arrangement First
Systems Installation Limited and Last

F-35 Joint Strike Fighter

All Internal Plus….
- More Difficult Environment
- Supportable Low Observables
- Unprecedented Maintainability
  - Service Life
  - Remove and Replace Times
- Rapid Manufacturing
  - Lower Cost Materials

System Definition and Arrangement First
Structural Arrangement Last

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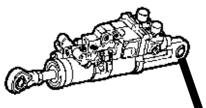
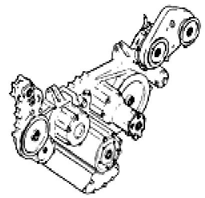
Integrated Design Has Thermal Advantages Over Legacy, But With Additional Challenges

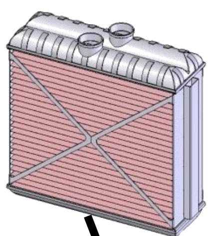
Legacy Stuff We Don’t Have



Hydraulic Flight Controls Actuators Powered by A Large Central Hydraulics
(Large Hydraulic Heat Loads)



Airframe Mounted Accessory Drive
(Lube Oil Cooled By Fuel)



Large Fuel-Air Heat Exchangers, Weight and Drag
(Primary Heat Sink for All Heat)

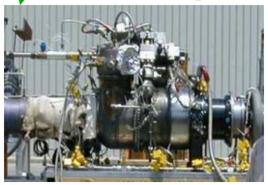
New Stuff We Do Have

JSF Firsts

Lowers Actuation Heat Generation

Electro Hydrostatic Actuators For Flight Control

Fan Duct Heat Exchanger (FDHx)

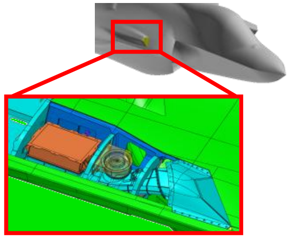


Integrated Power Package (IPP)

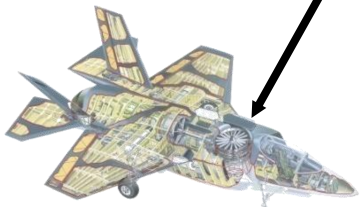
The Combination of FDHx and IPP Allows Engine Fan Air To Be Used As The Primary Heat Sink For Forced Air and Liquid Cooling

A Single, Relatively Small Fuel-Air Heat Exchanger

For Aircraft & Prop Fuel Cooled Loads - Backup for Air Cycle



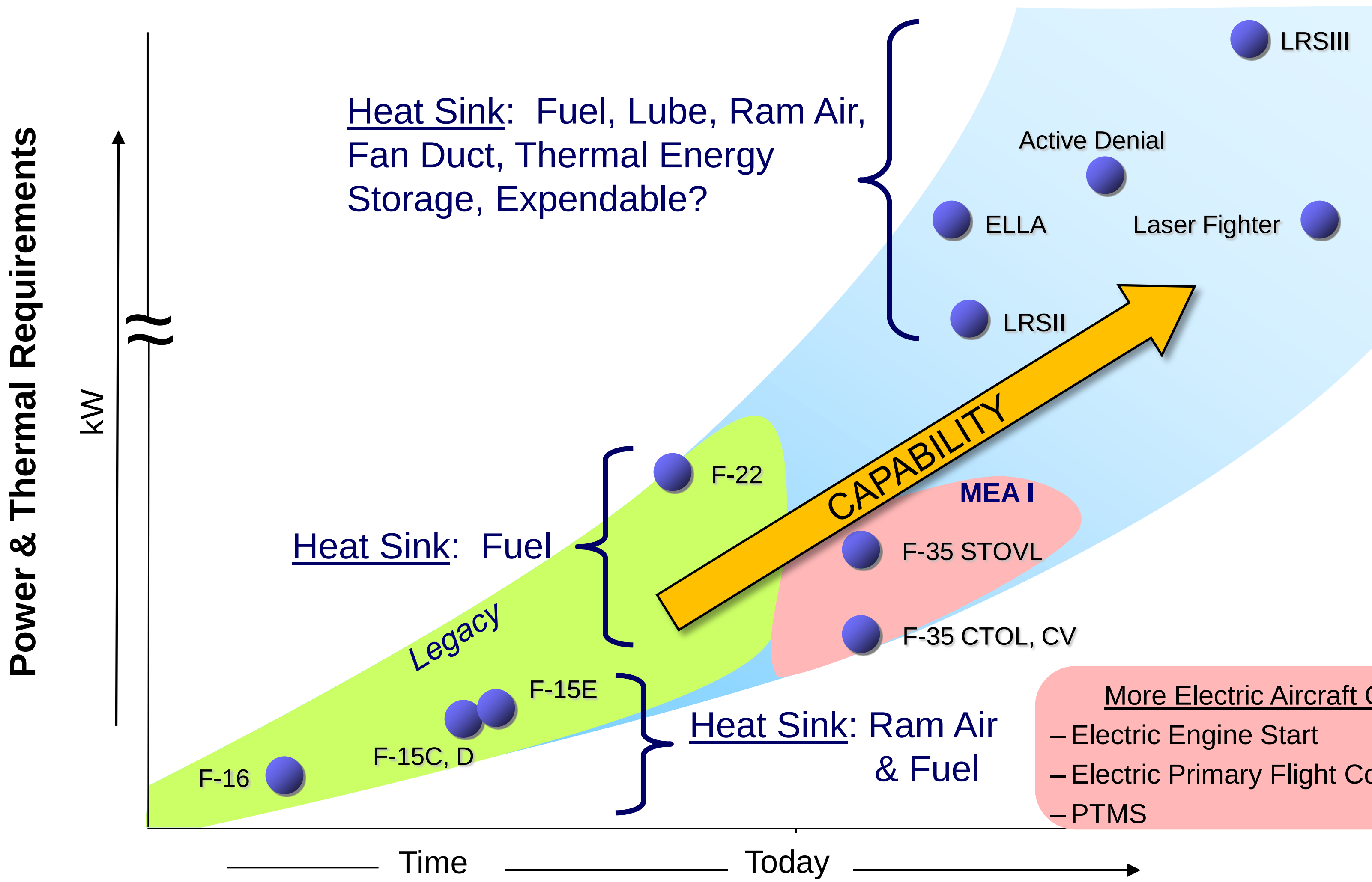
Additional STOVL Lift System Heat Loads



F-35B

Increased Capability Drives Onboard Energy Requirements

Power & Thermal Management Requirements



More Electric Aircraft Gen I

- Electric Engine Start
- Electric Primary Flight Control
- PTMS

Integrated Vehicle Energy Technology (INVENT)
What it is …

Energy Management System

Vehicle Systems / Propulsion Integration

Adaptive Power & Thermal Management System

Fuel Thermal Management System

High Performance Electric Actuation System

Robust Electrical Power System

INVENT System Integration Facility • Robust Electrical Power System

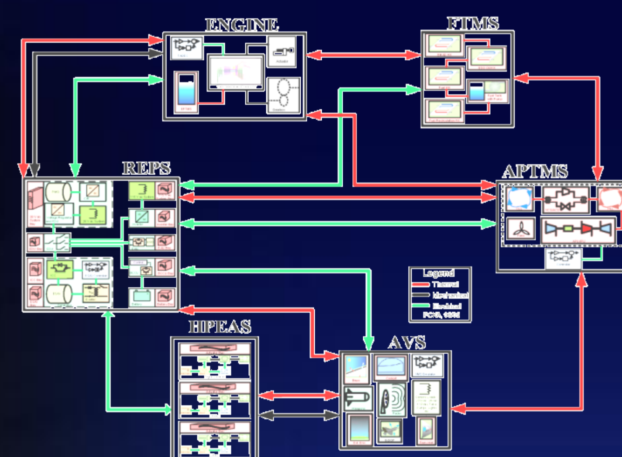
ENERGY / POWER / THERMAL

INVENT

INTEGRATED VEHICLE ENERGY TECHNOLOGY

High Performance Electric Actuation System • Adaptive Power & Thermal Management System

Modeling & Simulation with Hardware-in-the-Loop



Adaptive Smart Aircraft Power Systems

Model Based Design

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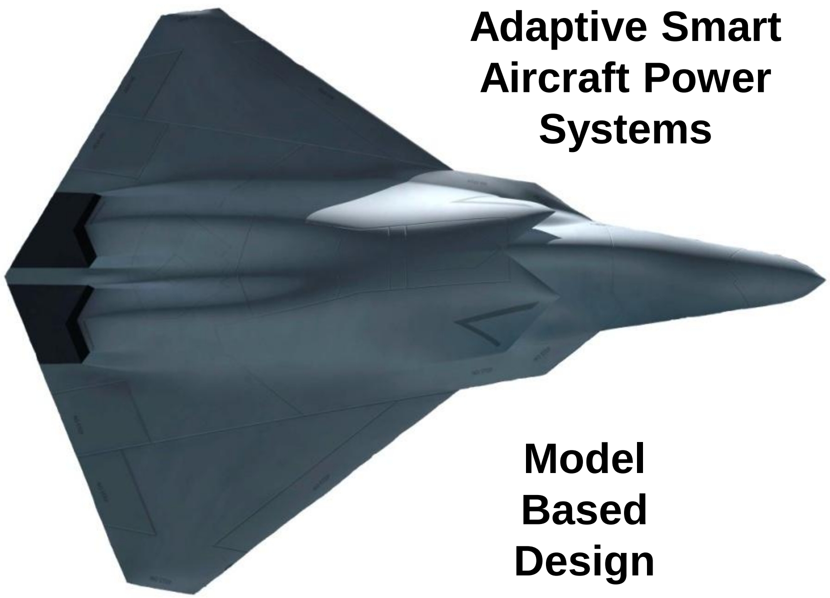
Integrated Vehicle Energy Technology (INVENT)
What it does for the Warfighter

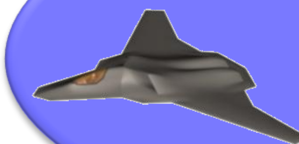
INVENT System Integration Facility • Robust Electrical Power System
ENERGY / POWER / THERMAL
INVENT
INTEGRATED VEHICLE ENERGY TECHNOLOGY
High Performance Electric Actuation System • Adaptive Power & Thermal Management System



Adaptive Smart Aircraft Power Systems

Model Based Design

Performance



- Range Improvement
- No Flight Envelope Restrictions

Energy

- Reduce Demand
- Change Culture

Acquisition

- Reduce time & cost
- Fly it before you build it!
- Change Culture

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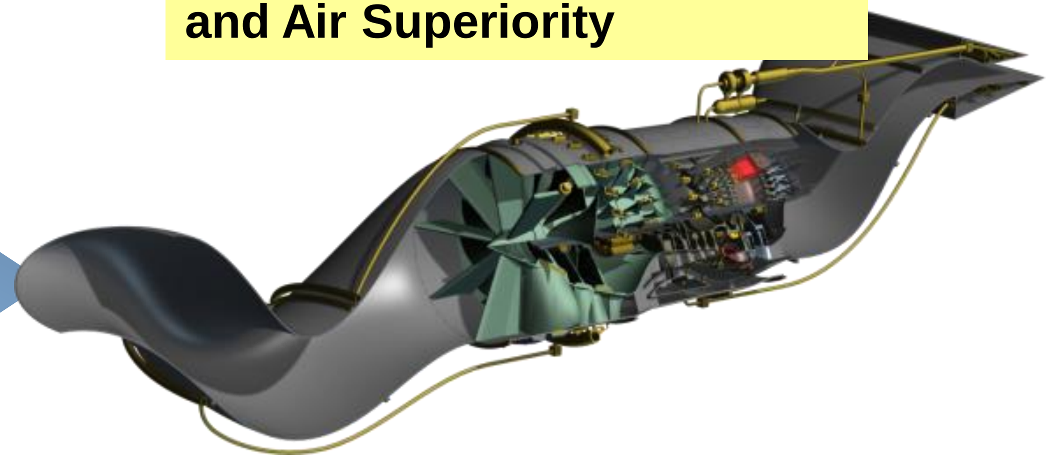
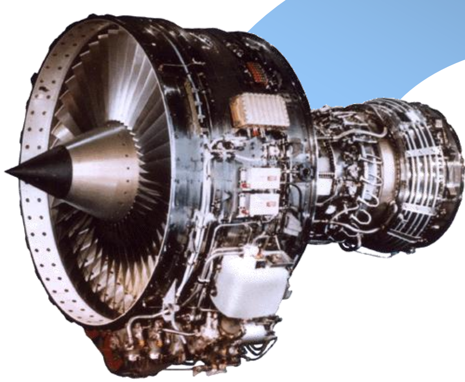
ADaptive Versatile Engine Technologies (ADVENT)

High Performance...

The Needed Capability:
Global Precision Attack / ISR
and Air Superiority





- **Energy saving by optimizing engine cycle up to 30%**
- **Rolls Royce North America and General Electric**
- **Engine demonstrations in 2013**

Fuel Efficiency...

Combines the capabilities of long range, high efficiency flight and high speed dash as well as supporting AF energy usage reductions

Vehicle / Engine Integration Focus

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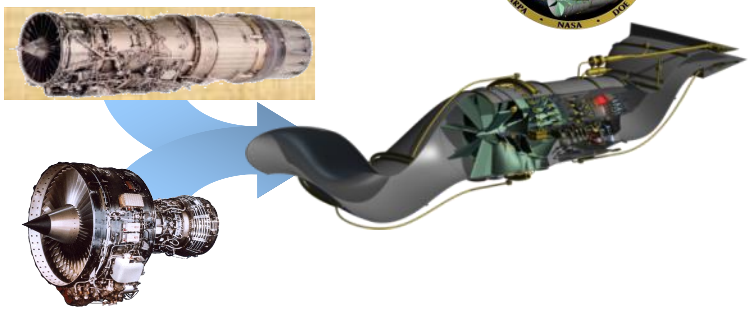
Adaptive Versatile Engine Technology (ADVENT)

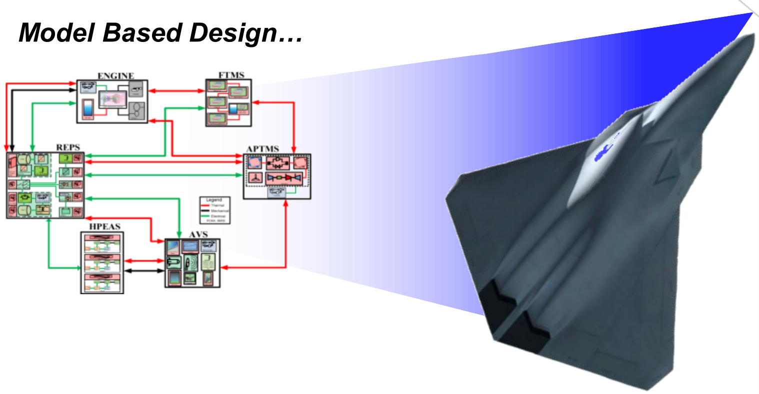
High Performance...



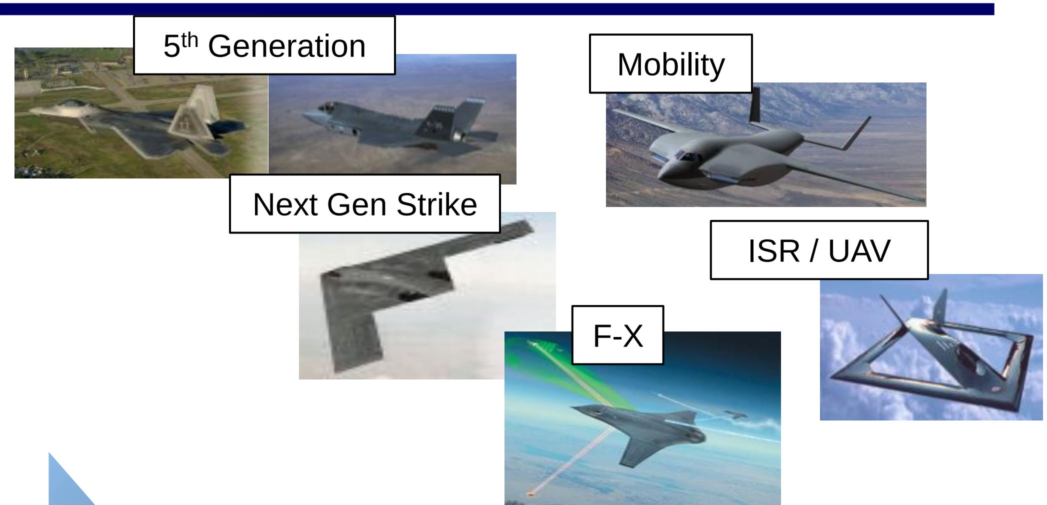
Fuel Efficiency...

Integrated Vehicle Energy Technology (INVENT)

Model Based Design…



Adaptive Smart Aircraft Power Systems…



Integrated Program Benefits:

- Improved Range/Endurance Goal
  - 30% Advanced Engine Cycles
  - 10% Aero Improvements
  - 10% On-Demand Integrated Systems
- No Thermal Management System (TMS) restrictions
- 5X P&T Capacity (MW Class DEW)

Maximum capability may be realized via integration of combined technologies

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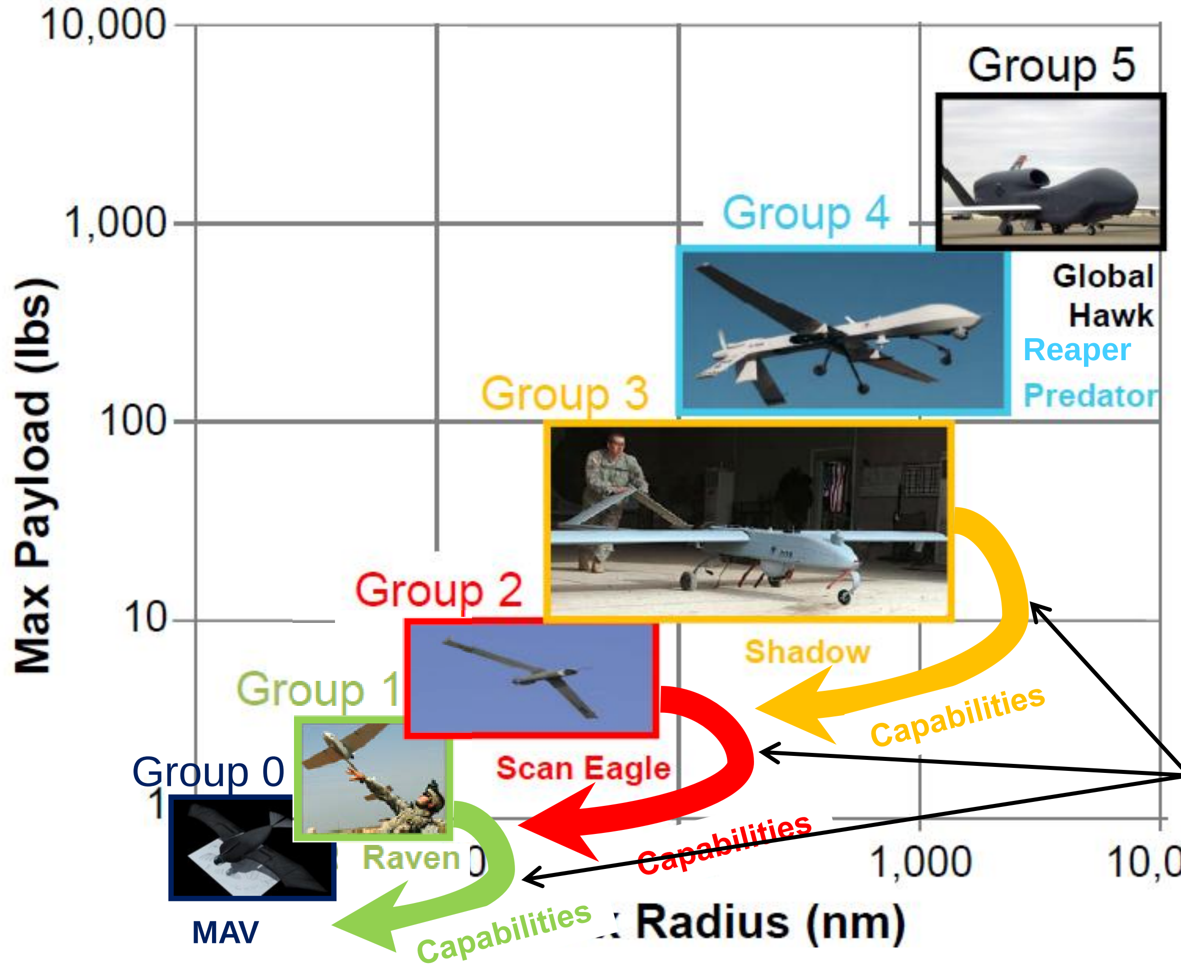
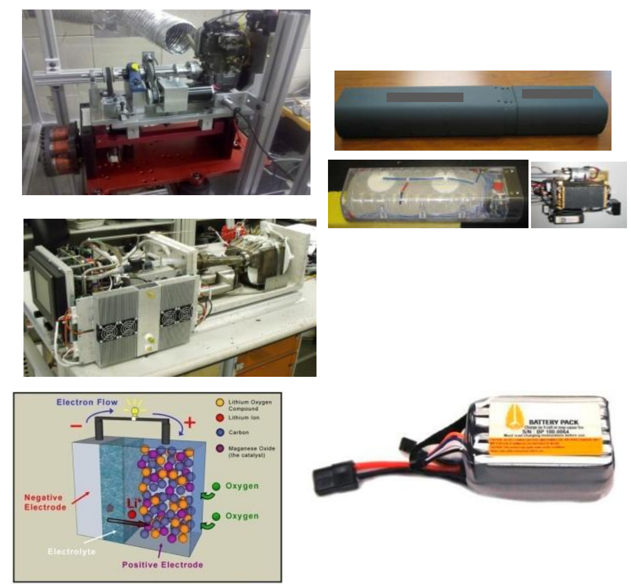
RPA Energy Efforts

Bring larger platform capabilities into smaller platforms for lower operational costs





Enhanced Power/Propulsion Systems
- Increased Endurance
- Excess Payload Power
- Quite Operation
- Increased System Reliability

RPA Capabilities Enable Fuel Savings

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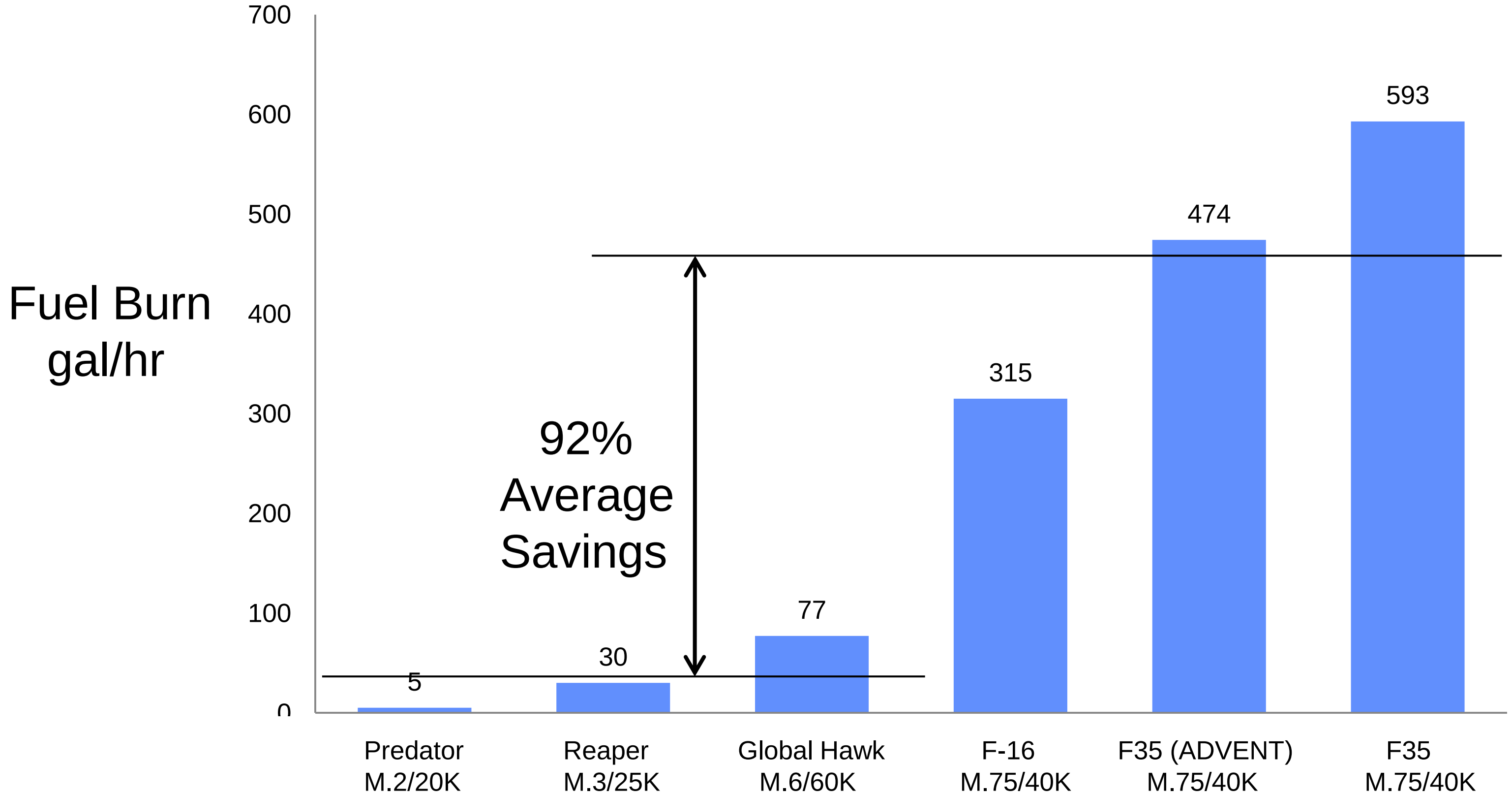
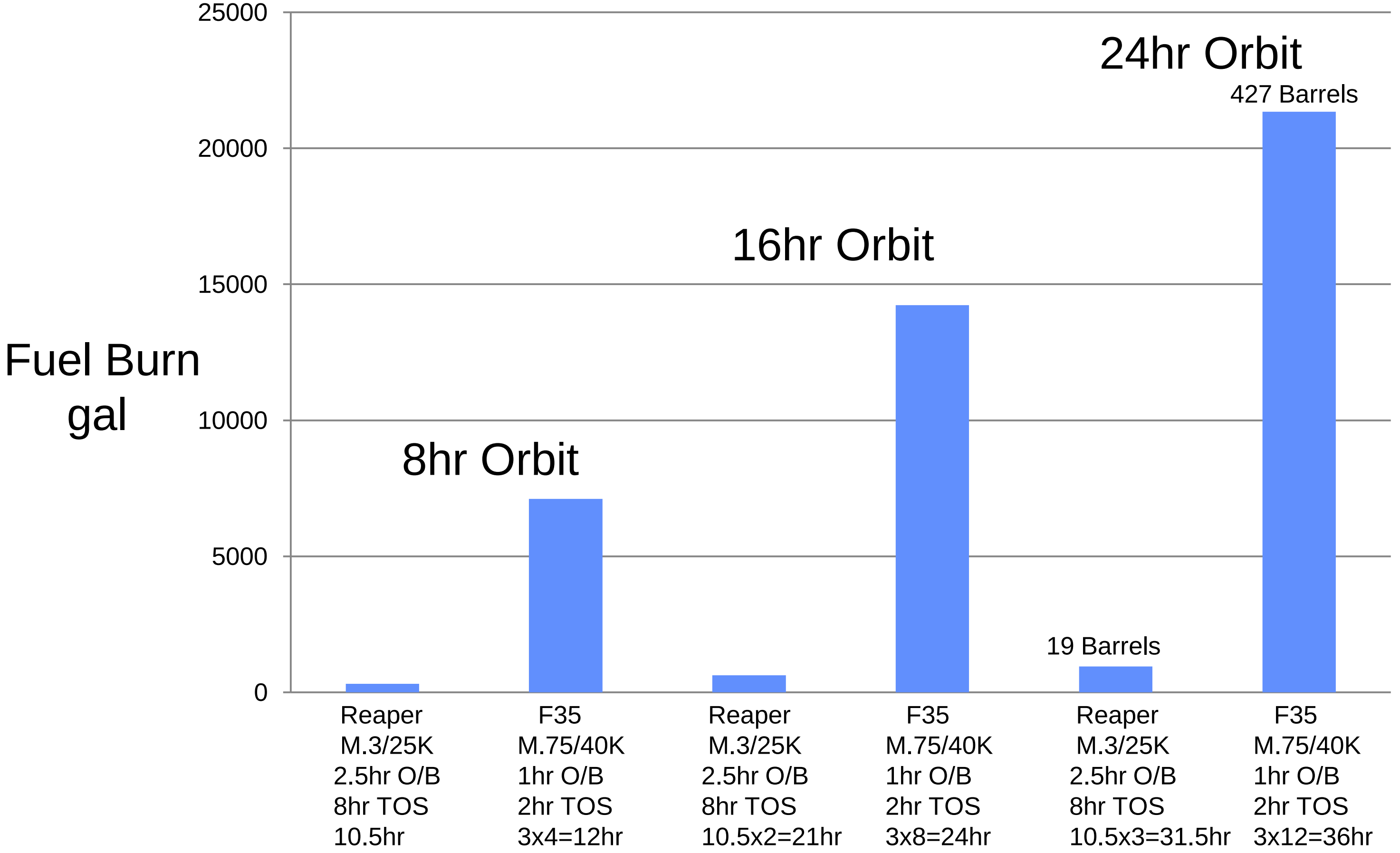
" While increasing RPA fleet…we're going to somehow decrease our fuel consumption. It's counterintuitive." Dr. Maybury AF Chief Scientist – InsideDefense interview 14Apr11



RPAs Burn A Magnitude Less Fuel

RPA vs Fighter Orbit Fuel Burn



24 hr Orbit: 19 vs 427 Barrels

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Energy Usage to Support

• Fuel Distribution/Air Refueling	RPA < Fighter/Attack/Bomber
• Initial Deployment Footprint	RPA < Fighter/Attack/Bomber
• Sustained Maintenance	RPA < Fighter/Attack/Bomber
• Personnel	RPA < Fighter/Attack/Bomber
• Overall Air Mobility Requirements	RPA < Fighter/Attack/Bomber

***Postulate*: As RPA Capabilities/Missions Increase;**
AF Fuel/Logistics/Air Mobility Requirements Decrease

Silent Operations

- **Noise**
  - **Domestic: Quality of life (noise abatement)**
  - **Overseas: Quality of survival (stealth)**
- **2010 National Aerospace R&D Plan**
  - **EPNdB = Effective perceived noise (level) in decibels**
  - **Near Term (<5 years): reduce noise of main rotor gearbox (–15 dB)**
  - **Mid Term (5-10 years): reduce noise of main rotor gearbox (–20 dB)**
- **Quiet Aircraft Technology program (NASA, FAA)**
- **Silent Aircraft Initiative (MIT, Cambridge University)**

FAA: Continuous Low Emissions, Energy and Noise (CLEEN) Program
NASA: Environmentally Responsible Aviation (ERA) Project

Advanced RPA Propulsion Acoustic Signature Tuning

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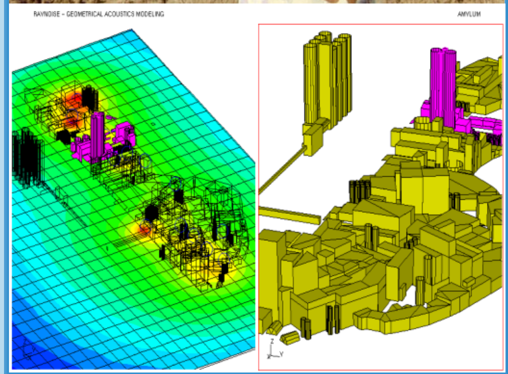
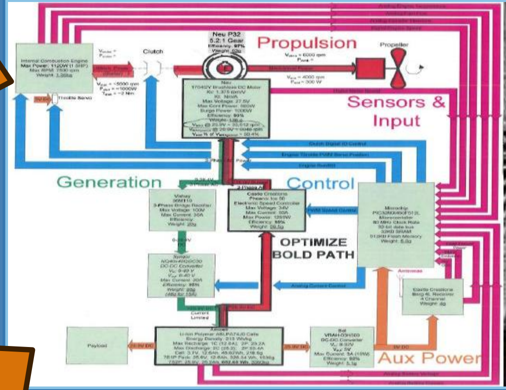
SOCOM / USArmy

Mission requirements, planning and capability evaluation



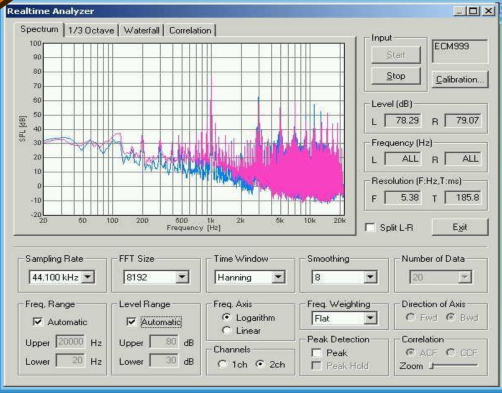
AFRL/ RHCP & RZPG

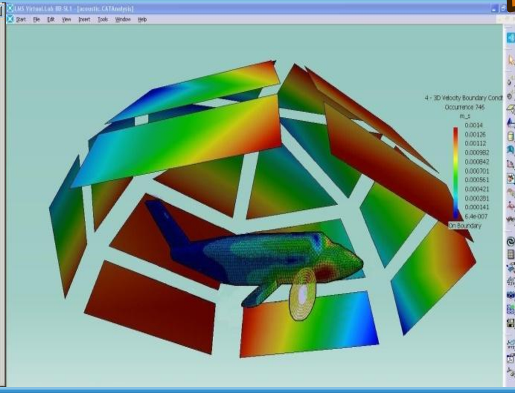
System hardware performance & acoustic



AFRL/ RHCB & RZPG

Software assesses probability of ground





Hybrid / Electric
UAV Propulsion & Power Systems

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Technology Options

Nutating ICE (AFRL/RZTP & ARL/VTD)

- 7.2 HP @ 5000 RPM
- 5.2 Lbs.
- Fuel Type: JP8 and DF2
- Smooth torque production
- Exhaust released closer to atmospheric pressure
- Expecting to run late-June or early-July 2011

Advanced ICE Technology (NWUAV)

- Muffler provides:
  - lower fuel consumption
  - higher power
  - lower noise
- Currently being staged for deployment on the Scan Eagle and Integrator UAV's

Solid Oxide Fuel Cell (AFRL/RZPS)

- Providing prime power and propulsion for RPAs (50 – 150 lbs)
- Advantageous over ICE for >33 hrs endurance
- Insitu Integrator initial flight demonstration on S-8 planned for Fall 2011

Hybrid Electric (AFIT & AFRL/RZPG)

- Combines advancements in ICE and electric technologies for propulsion/power
- Can more easily tune acoustic characteristics
- 1.25hp plant
- AFIT flight test of HE RPA scheduled for fall of 2011

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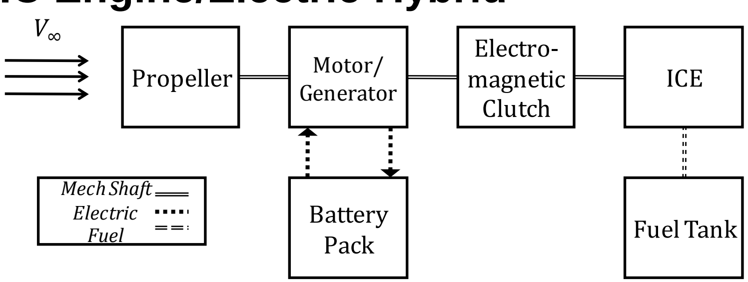
Energy Storage Capabilities

- **Electrochemical**
  - – **Small Platforms**
    - **Typically Hand-Launched**
  - – **Low Signatures**
    - **Acoustic**
    - **Thermal**
  - – **Limited Endurance (< 10 hrs)**
  - – **Limited Payload (< 4 lbs)**
- **Hydrocarbon Fuels**
  - – **Larger Platforms**
    - **Greater Logistics**
      - – **Fuel, Launch/Recovery**
  - – **Large Signatures**
    - **Acoustic, Thermal**
  - – **Long Endurance/Range**
  - – **Large Payload**

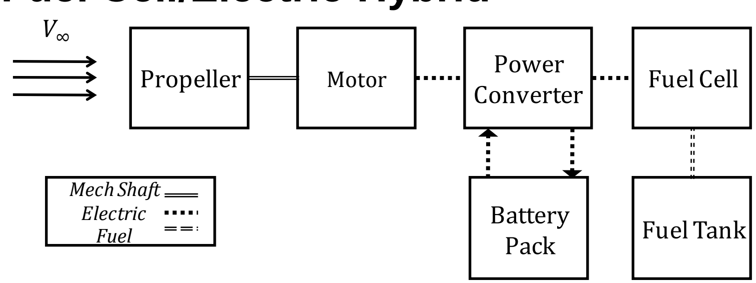
Hybrid-Electric Power System

- **Two or more power sources acting together or independently**
  - **Coupled through Electric Motor or Power Management**
- **Combines the advantages of both electric and fuel-powered systems**
  - **Long Range**
  - **Long/Quiet Endurance**
  - **Efficiency**

IC Engine/Electric Hybrid

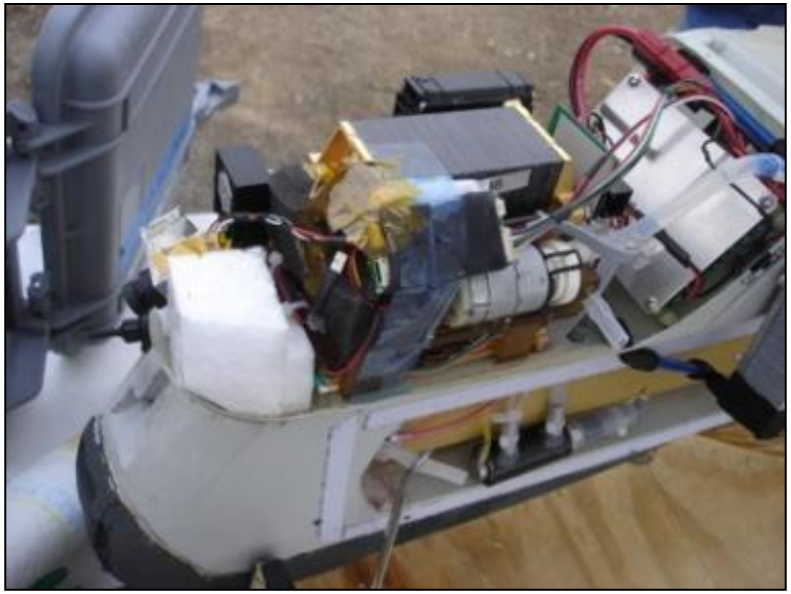


Fuel Cell/Electric Hybrid



RPA Hybrid Electric Propulsion Demonstration

Propulsion Directorate developed hybrid battery-fuel cell system which extended flight duration to 9 hours 5 minutes (from 2.5 hours)



<u>Operational PUMA Characteristics and Performance</u>

Wingspan: 8.5 feet
Weight: 14.2 pounds
Speed: 25-50 km/hr
Endurance: Rechargeable batteries - 2.5 hr
Propulsion: Electric
Average Power: 150 W
Cruise Power: 100 W Peak Power: 500 W

Batteries & Liquid Hydrocarbon Fuel Cells to Power Small RPAs

- Small RPAs need suitable power source for propulsion and on-board systems
- Desired endurance times (> 8 hrs) cause battery weight to exceed lift capacity; IC engine fuel efficiencies are too low
- Fuel cells give lightweight power system but must operate on logistical LHC fuel
- JP kerosene fuels ideal, liquid propane is usable; need on-board fuel processor
- Solid-oxide fuel cells are best to date; current record held by U. Michigan team > 9 hrs aloft with propane in small RPA



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Energy Harvesting and Storage

The Sciences

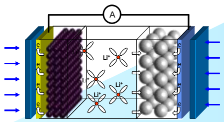
Basic research for integration of advanced materials and micro-systems into future Air Force systems requiring multi-functionality

- Energy conversion
- Energy storage
- Others

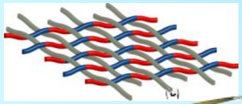
State-of-the-Art

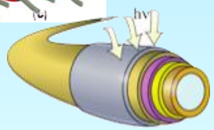
Full dependence on fossil/synthetic fuels with high carbon footprint for power and energy

Current S&T Effort

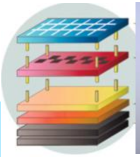


"Stretchable" thin-film Li ion batteries





Multifunctional textiles for solar/thermal energy harvest/storage



"Hybrid" energy harvester

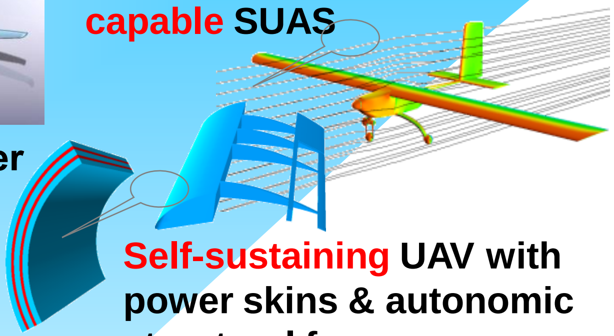
Solar powered UAV

Dye-sensitized solar cell films integrated onto quasi-wing structure

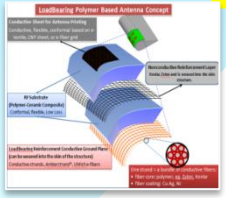
Next Step

Lightweight hybrid-powered sensor platforms

Advanced highly capable SUAS



Self-sustaining UAV with power skins & autonomic structural frames



Potential Impacts

- Autonomic structural frames of microvascular composites for self-healing and self-cooling functions
- Structural integration of energy harvest/storage capabilities – Self-sustaining UAV and hybrid-powered aircraft

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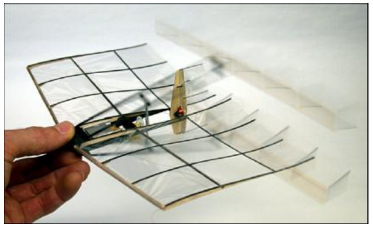
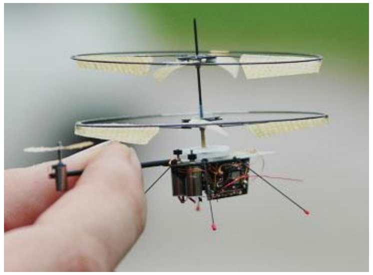
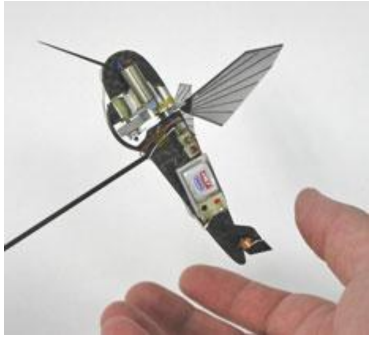
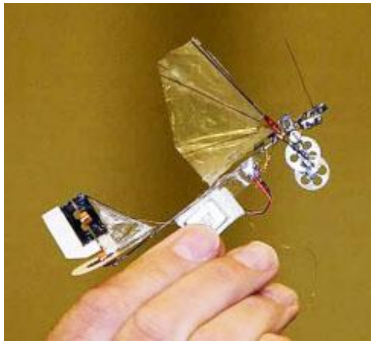
MAVs: New Aerodynamic Regimes and Microelectromechanical Components

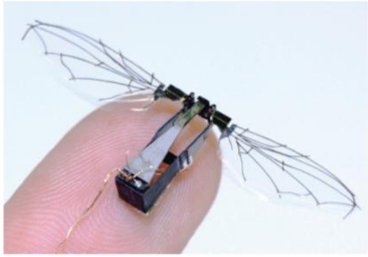
- Micro Air Vehicles open up new opportunities for close-in sensing in urban areas
- Low-speed, high-maneuverability, and hovering
- Size and speed regime creates low-Re aerodynamic effects; fixed-wing RPAs become impractical as size decreases
- Rotary-wing and biomimetic flapping-wing configurations are best at this size
- Requires lightweight flexible structures and unsteady aero-structural coupling

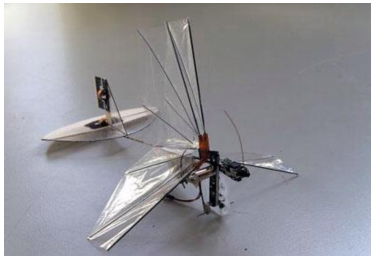


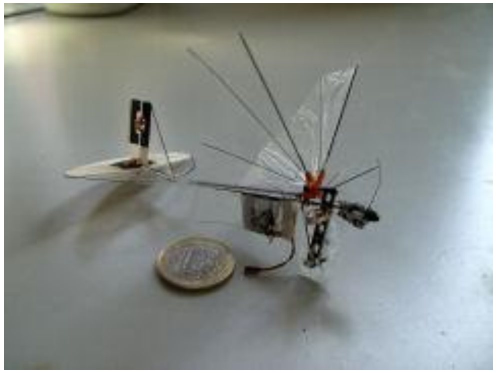


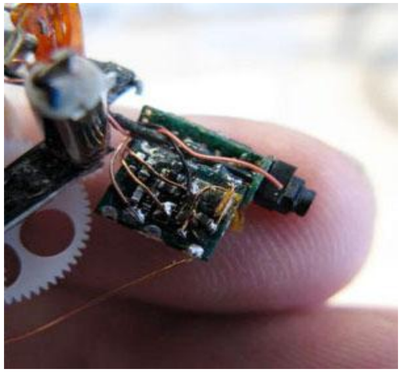












High Efficiency Photovoltaics

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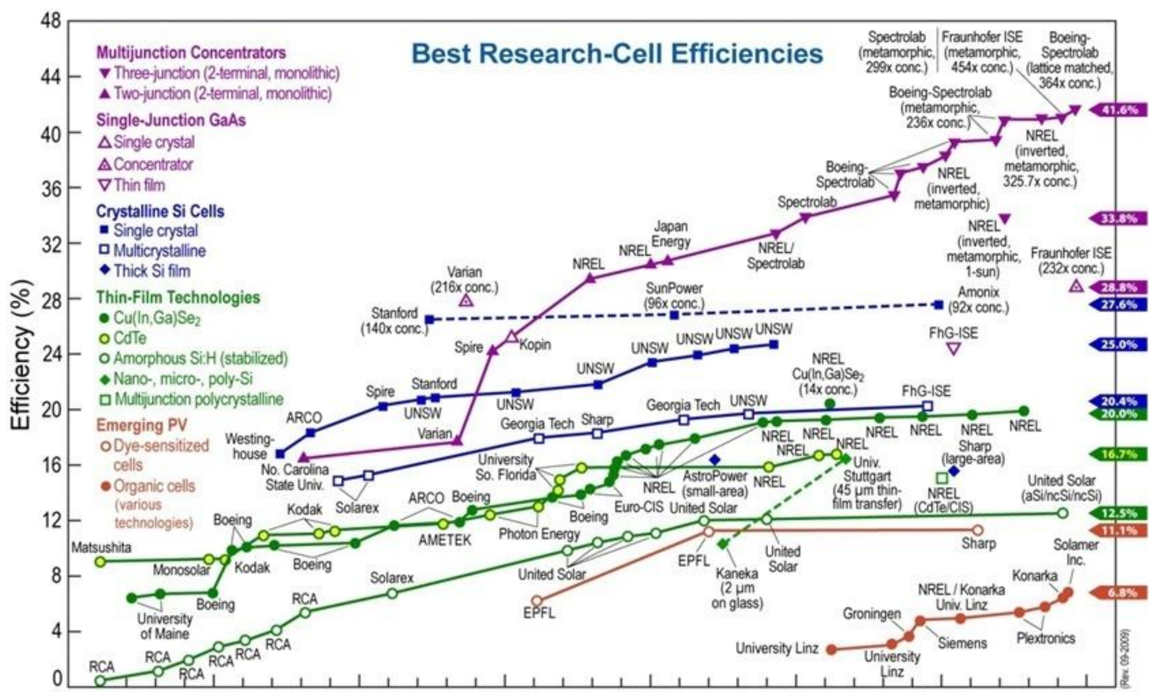
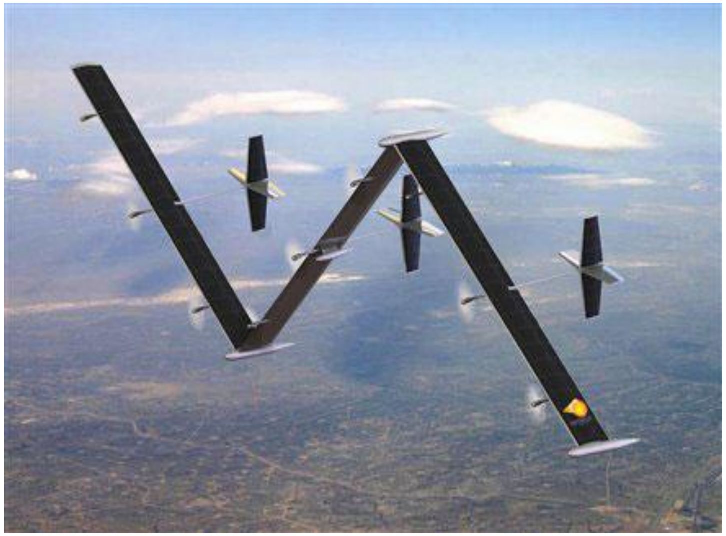
- Benefits: sustainable, clean, public opinion
- Challenges: cost, storage, distro, O&M, land, materials
- PV efficiency world record: 43.5+%
- Cost: 16-10c/kW; fossil fuels 6c/kW

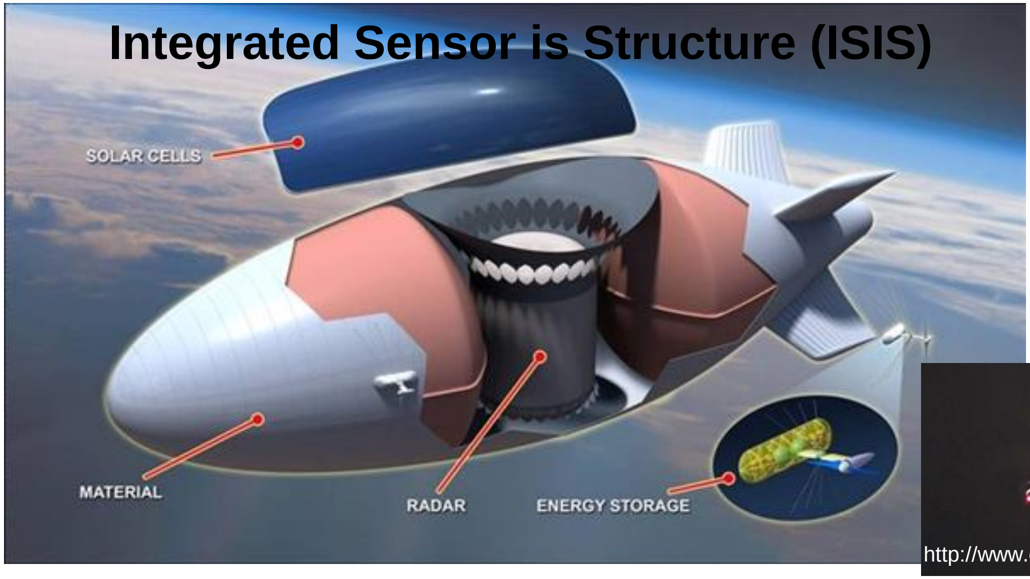


Ultra-Long Endurance Remotely Piloted Aircraft

- New unmanned aircraft systems (VULTURE) and airships (ISIS) can remain aloft for years
- Delicate lightweight structures can survive low-altitude winds if launch can be chosen
- Enabled by solar cells powering lightweight batteries or regenerative fuel cell systems
- Large airships containing football field size radars give extreme resolution/persistence



Integrated Sensor is Structure (ISIS)



http://www.economist.com/node/17951584

Spacecraft Electric Propulsion

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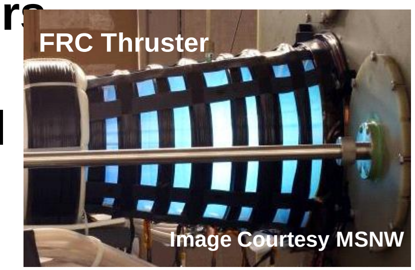
New RZ/AFOSR Academic Collaboration ($1M/year)

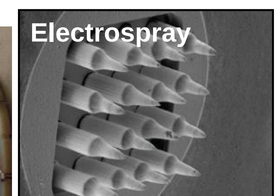
Spacecraft propulsion required for:

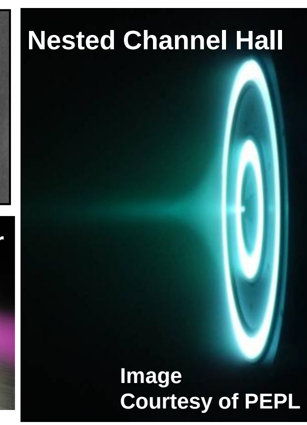
- Orbital maintenance
- Orbit transfer
- Repositioning for offensive and defensive counter-space and space situational awareness

Several approaches optimize mission benefits

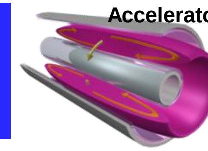
- Electric propulsion
  - Hall, Ion, FRC, electrospray thrusters
- Multi-mode propulsion
  - Combination of advanced chemical and electric propulsion systems

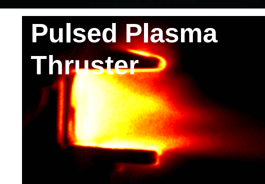






Annular Pulsed Inductive Accelerator





PennState · Colorado State University · UCLA · MSNW · Michigan Tech · Massachusetts Institute of Technology · University of Michigan · University of Washington

Propulsion Directorate leads R&D in spacecraft propulsion and established electric propulsion "Center of Excellence"

Concluding Remarks

- **We remain at the very early stages of electric propulsion evolution**
- **"More Electric" Aircraft following similar automotive hybrid/electric trends**
- **Developments over next decade in energy generation, harvesting, and efficient employment will enable key technologies and missions:**
  - **Advanced platforms and sensors**
  - **Operations in non-permissive areas**
  - **Extended range/persistence**
  - **Acoustic stealth**
  - **Hybrid propulsion systems**
- **Creative approaches and technology advances will be needed to exploit the full potential that electrical propulsion**