Fuel Cell UAV Research At The Naval Research Laboratory

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Agenda

- Fuel cell capabilities and issues
- Current research efforts
- Paths to tactical fuel cell UAVs

Fuel cell Capabilities and Issues

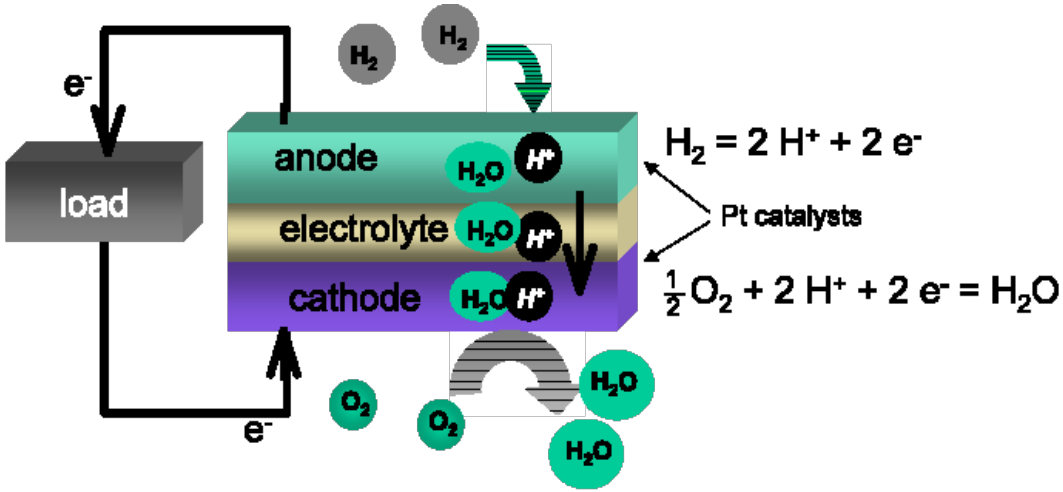
- How does it work?
- Why use a fuel cell?
- Strengths & weaknesses

Proton Exchange Membrane (PEM) Fuel Cells

Fuel conversion systems convert chemical energy to electrical energy

- Engines
  - Low efficiency at small sizes (<10%)
  - Liquid hydrocarbon fueled
- Fuel cells
  - High efficiency (~45%)
  - Hydrogen fueled
  - Operate at ~50 - 80 °C

H_2-fueled PEM fuel cells are being developed for automobiles as highly efficient alternatives to gasoline engines



Proton exchange membrane fuel cell
Perfluorosulfonic acid (Nafion™ polymer) membrane

Motivation for High Power Fuel Cell Propulsion Systems

Fuel cell advantages:

- Higher energy than batteries
- Higher efficiency than engines
  Small engines ~10% efficient
  Fuel cells ~45% efficient

Fuel cell disadvantages:

- Lower power density (W/l, W/kg)
- Large fuel tank volume
- Fuel availability

Benefit to Navy:

- Long endurance electric UAVs
- Quiet flight at lower altitude with cheaper payloads
- Lowers cost and OPTEMPO of missions
- Bigger UAV missions with a small UAV
  - Lower cost and maintenance
  - Less storage volume

Advantages of electric propulsion

- Near silent operation
- Instant starting
- Increased reliability
- Ease of power control
- Reduced thermal signature
- Reduced vibration
- No electric generator

Energy of Fuel Cells vs. Batteries for Ion Tiger system

16 kg GTOW – 6 kg (38% wt) fuel cell propulsion plant

- 6 kg fuel cell propulsion system (with 1 kg fuel and cooling)
  = Specific energy of 1300 Wh/kg
  – Demonstrated 26 hours of flight at 300 W

- Compare to high energy Lithium battery
  = Specific energy of 200 Wh/kg
  – 4.8 hours of flight at 300 W from 6 kg of battery
  – OR 30 kg needed to fly for 24 hours at 300 W

Hydrogen as a Fuel

HIGH ENERGY FUEL

- Energy/weight: ~ 4600 Wh/kg
- Up to 10,000 psi gas in development
  - 5000 psi best weight advantage for UAVs
- International path for fuel cell automobiles

ADVANTAGES

- Responds immediately to change in load
- No waste produced (only H_2O)
- Produced and monitored onboard naval platforms

DISADVANTAGES

- Difficult logistics for remote land locations
- Large storage volume vs liquid

Progression of Fuel Cell Systems

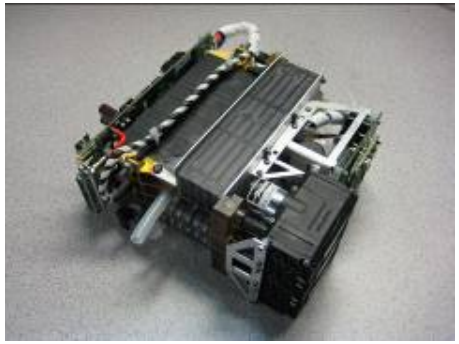
- XFC-I - 300W system, 1.0 kg

- XFC-II - 330W system
  - TRL increase

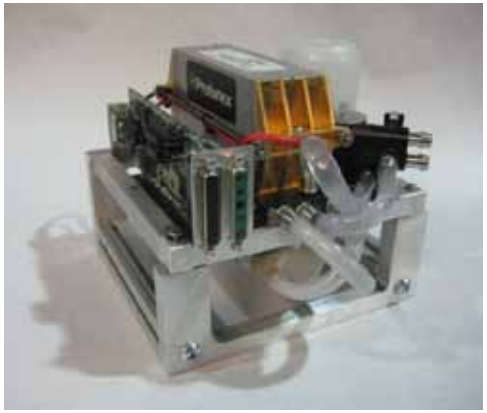
- 550 Watt System, 1.1 Kg
  - Ion Tiger/XFC
    - 4 units delivered (IT)
    - new humidifier and air blower
    - integrated control electronics
    - 99% H_2 utilization
    - Demonstrated 26-hr endurance in Nov 2009

    - TRL increase
    - Drop-in replacement for XFC-II
    - Build and test 14 systems (XFC)

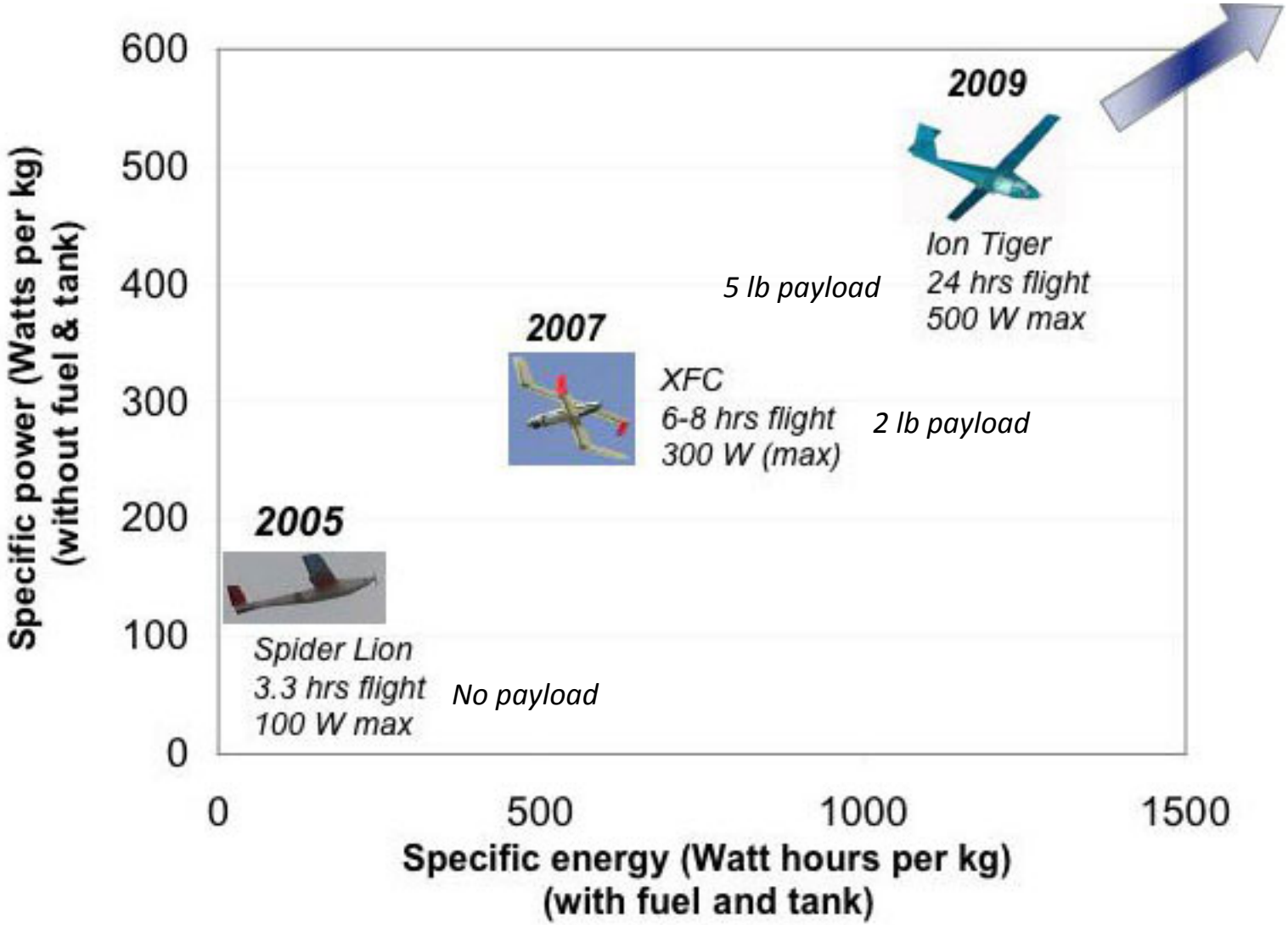
POWERED BY Protonex



- IT 2 - 1500 W System
  - 1.8kg target weight
  - Brassboard under contract



NRL Progress in Fuel Cell Propulsion Systems



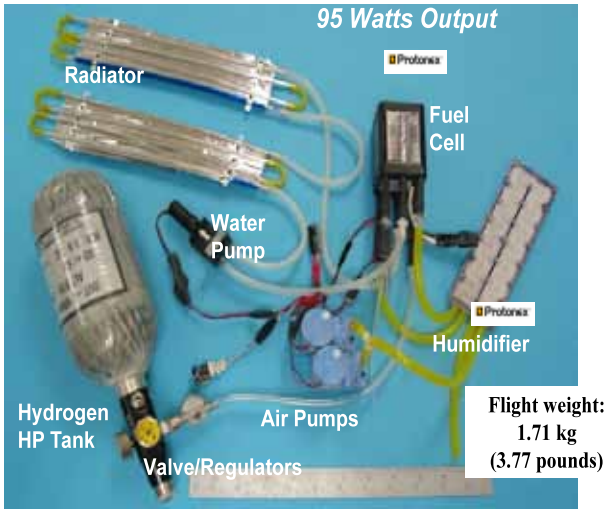
NRL Research Efforts

- Spider Lion
- XFC
- Ion Tiger

Spider Lion

- 2004-2005
- Internally Funded Proof-of-Concept
- Commercial fuel cell stack
- Paintball H_2 tank
- Balance-of-plant (BOP) - in house
- No payload (or rate-of-climb!)

- 3 hrs 19 minutes endurance on 15g H_2



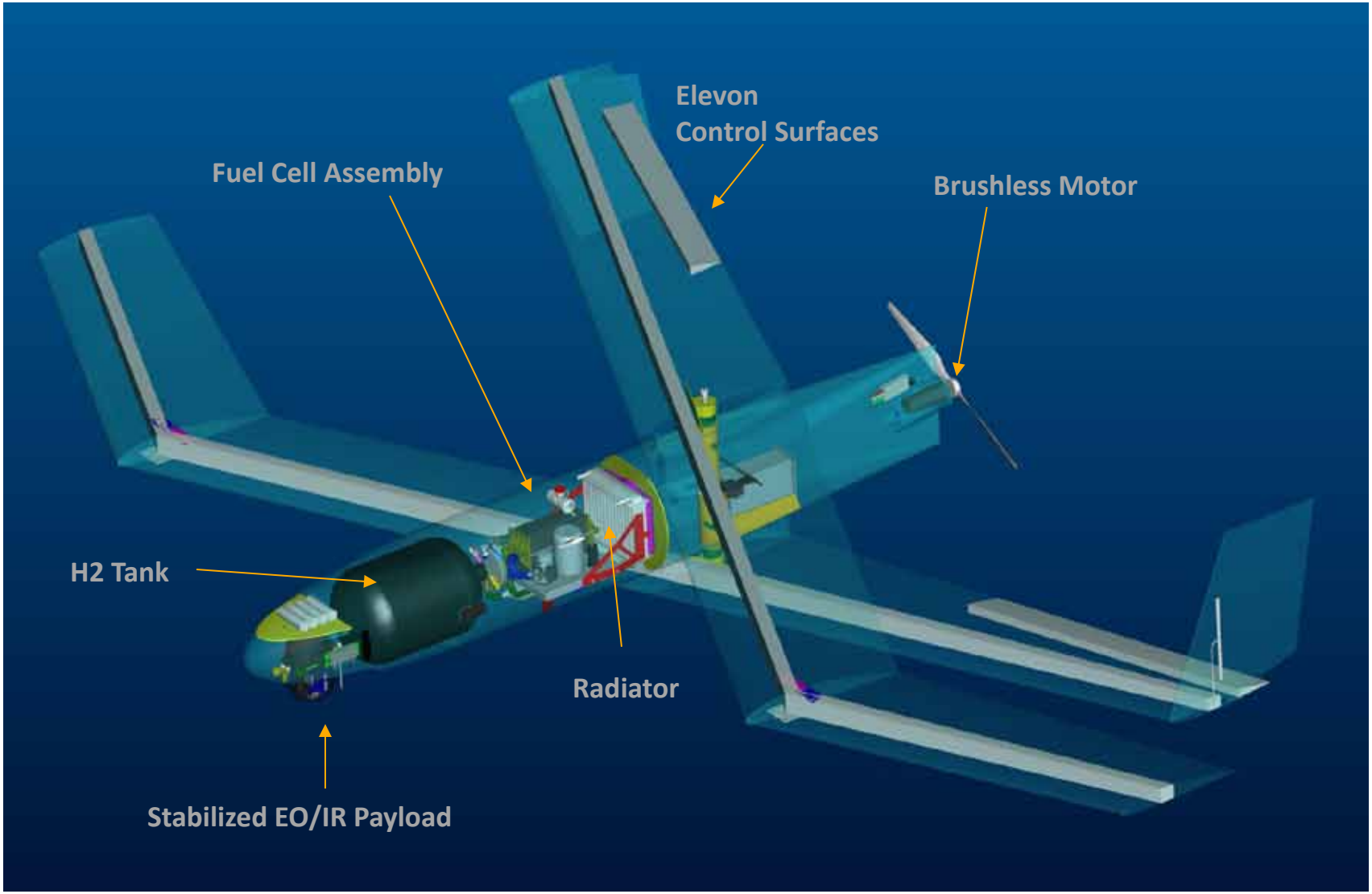
XFC
Long Endurance UAS

- 2007- Present
- Phase II Deliverables:
  - Demonstrate a vertically launched, affordably expendable, stealthy fuel cell powered long endurance Small UAS, capable of launch from land or sea
  - Demonstrate high power density modular fuel cell technology for transition to other small scale power applications
- Jointly funded by ONR, TTO, and RRTO

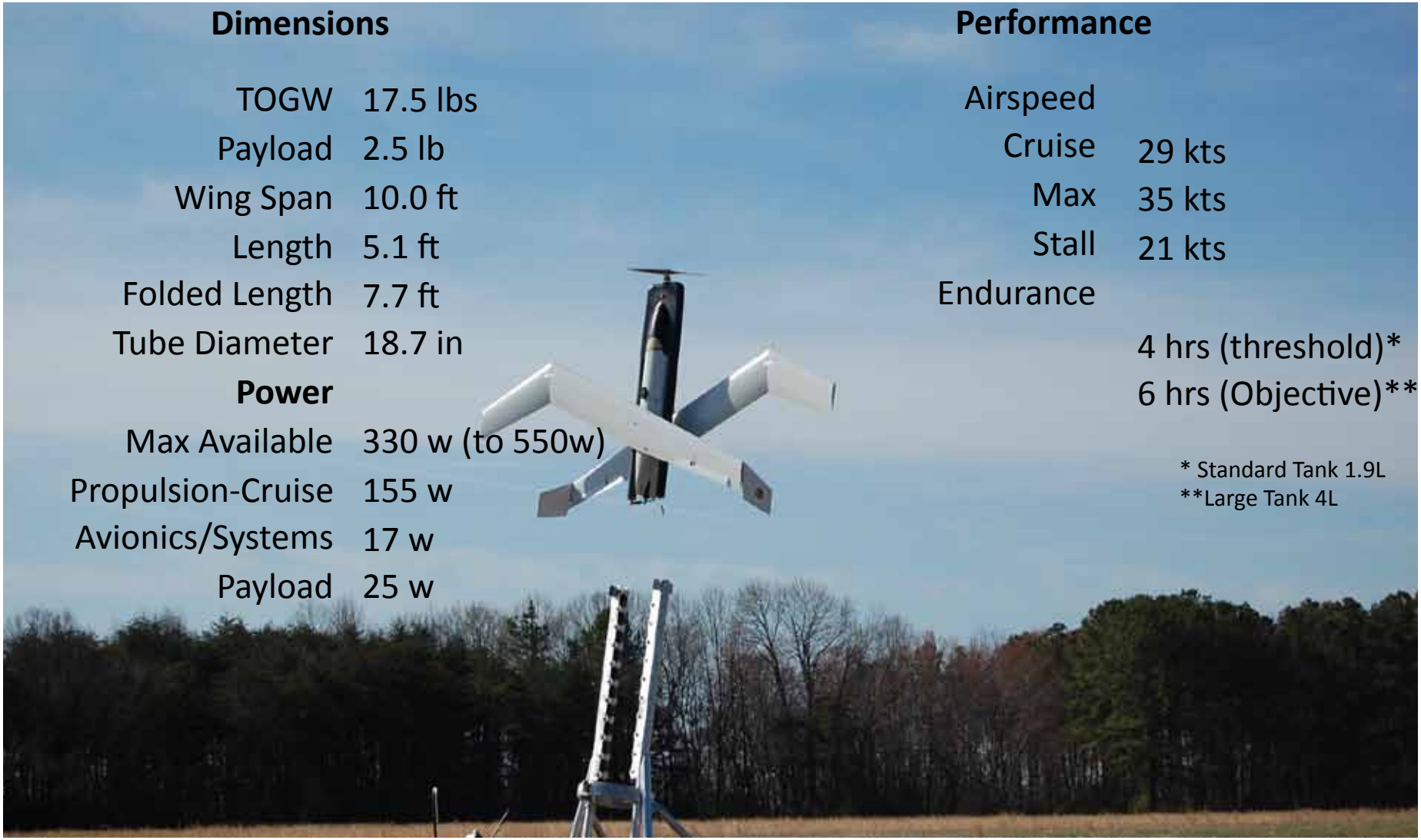
XFC
Phase 3

- 2009- Present
- Demonstrate a vertically launched, affordably expendable, stealthy fuel cell powered long endurance Small UAS, <u>launched from a submerged SSN</u>
- Submerged launch capability (and any residuals) transitioned to Industry
- Partnership with Oceaneering International, Inc (OII)

XFC General Layout



XFC Characteristics



Dimensions	
TOGW	17.5 lbs
Payload	2.5 lb
Wing Span	10.0 ft
Length	5.1 ft
Folded Length	7.7 ft
Tube Diameter	18.7 in
Power	
Max Available	330 w (to 550w)
Propulsion-Cruise	155 w
Avionics/Systems	17 w
Payload	25 w

Performance	
Airspeed	
Cruise	29 kts
Max	35 kts
Stall	21 kts
Endurance	
	4 hrs (threshold)*
	6 hrs (Objective)**

* Standard Tank 1.9L
**Large Tank 4L

Electrically-Assisted Takeoff (EATO)

- EATO consists of 2 large counter-rotating propellers, a gearbox, 2 motors and 2 LiPO batteries mounted in a jettisonable fairing
- Designed to provide 1.8 Thrust-to-weight for combined EATO-aircraft
- ~7.2 kW for 5 seconds accelerates system to ~50kts at 150 ft

XFC Accomplishments to Date

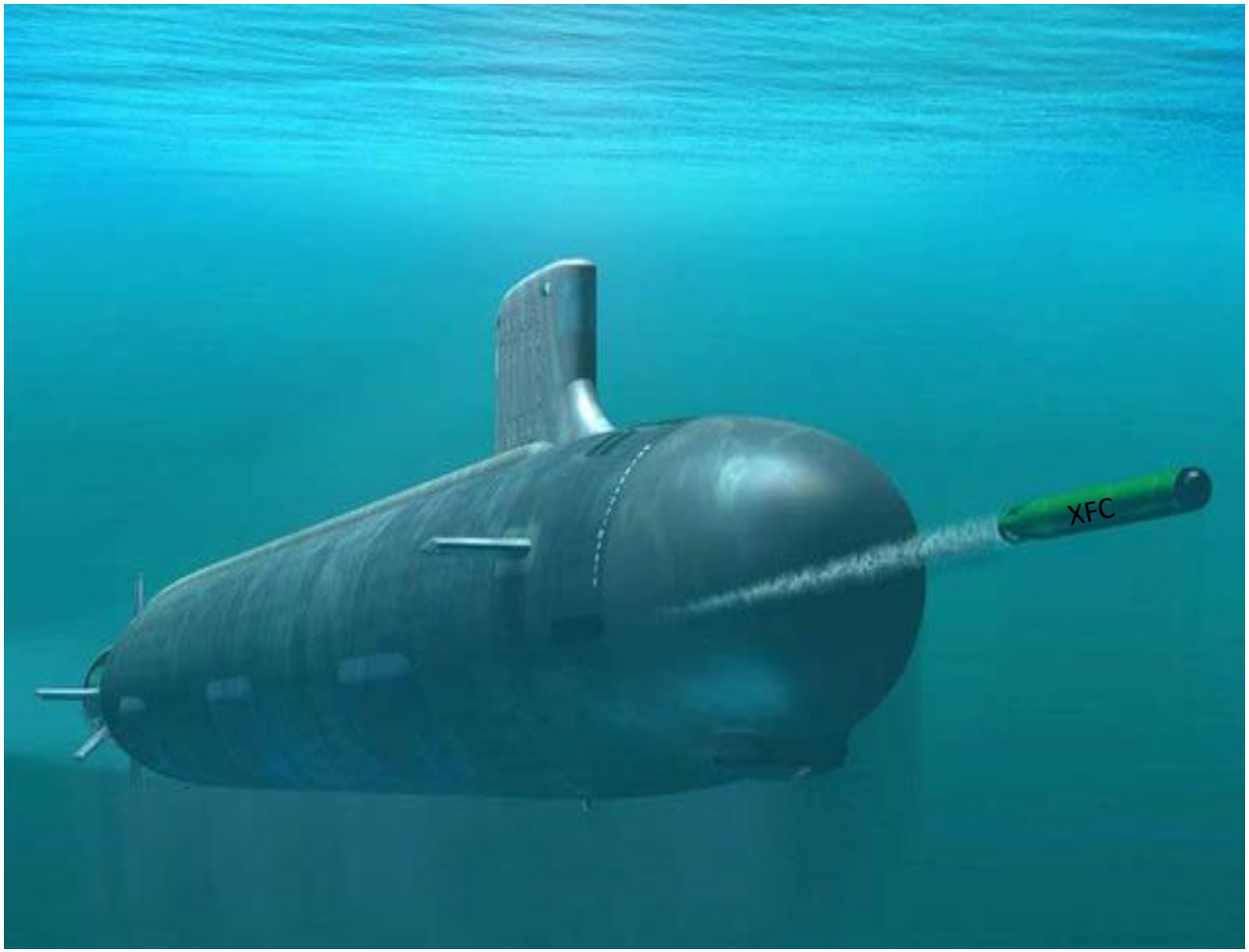
- Exceeded endurance requirements
- Demonstrated vertical launch in unfolded configuration under full autopilot control

TO DO:

- Demonstrate folded launch

- Flight demonstration
  - *Tube launch w/EATO*
  - *Autonomous flight*
  - *Mission payload*
  - *Full endurance*

Phase III
Submerged Launch Capability



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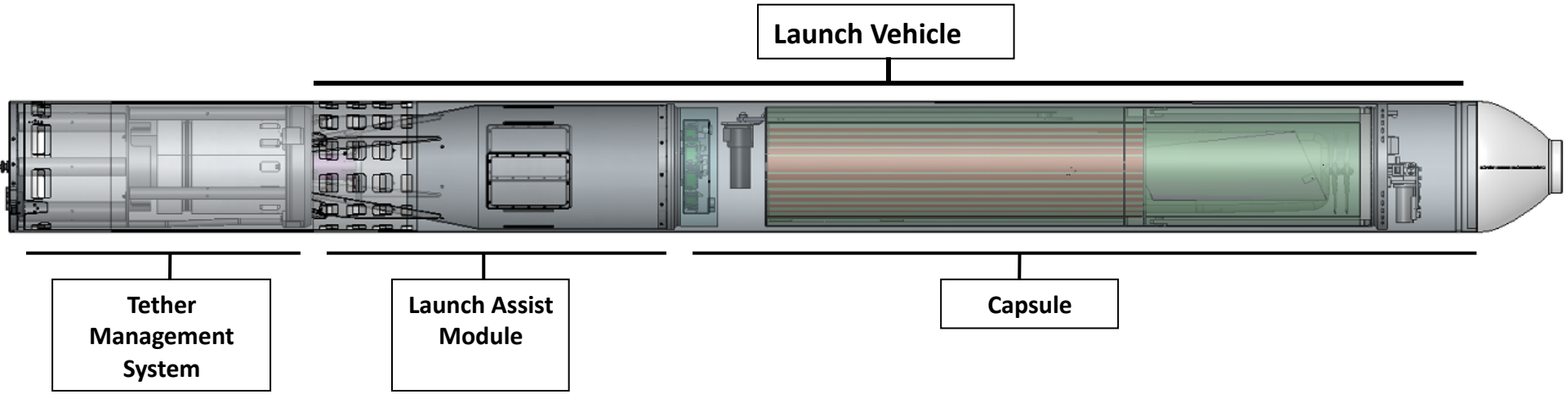
XFC CONOPS

General Terminology



Launch Vehicle – The assembly consisting of the Capsule and Launch Assist Module that exits the submarine

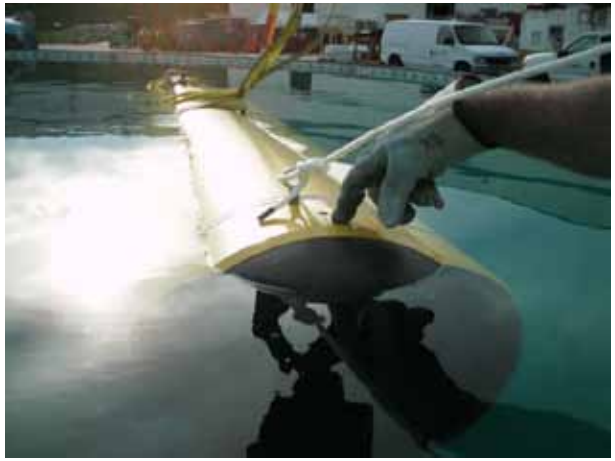
Capsule – The 1-atmosphere pressure vessel containing the XFC and other critical flight related equipment

Launch Assist Module – A remotely controlled system attached to the Capsule and tethered to the Tether Management System via a fiber optic tether

Tether Management System – The system used for managing and paying out the fiber optic tether from the submarine

Topside Control Unit – A user interface and control station that allows the operator to communicate with and control the Launch Vehicle from the submarine (not pictured)

Mass Mockup



XFC Launch Vehicle Summary

- Mass Mockup
  - Critical Design Review (25AUG09)
  - Manufacturing complete
  - Assembly complete
  - In house pool testing following assembly complete
  - NUWC Newport testing (SLSTF/Bay Shape) (04DEC09)

- Prototype
  - Preliminary Design Review (30OCT09)
  - Detailed Design Review (12FEB10)
  - Critical Design Review (12MAR10)

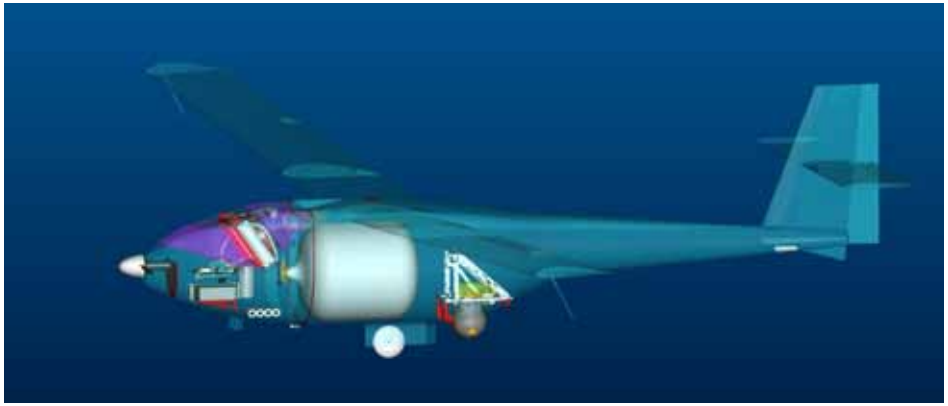
C2 Integration

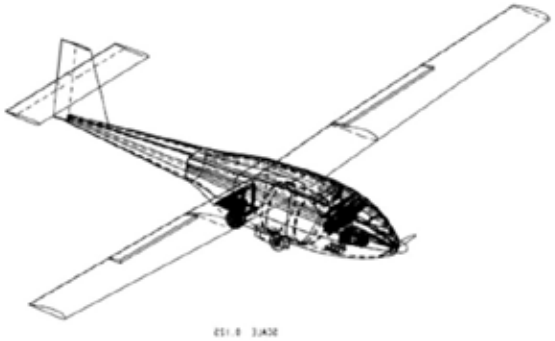
- All portions of testing completed successfully
  - C2 connection & signal strength (even with mast down)
  - Autotrack algorithm (UAV position to BYG-1)
  - Total integration took ~20 minutes

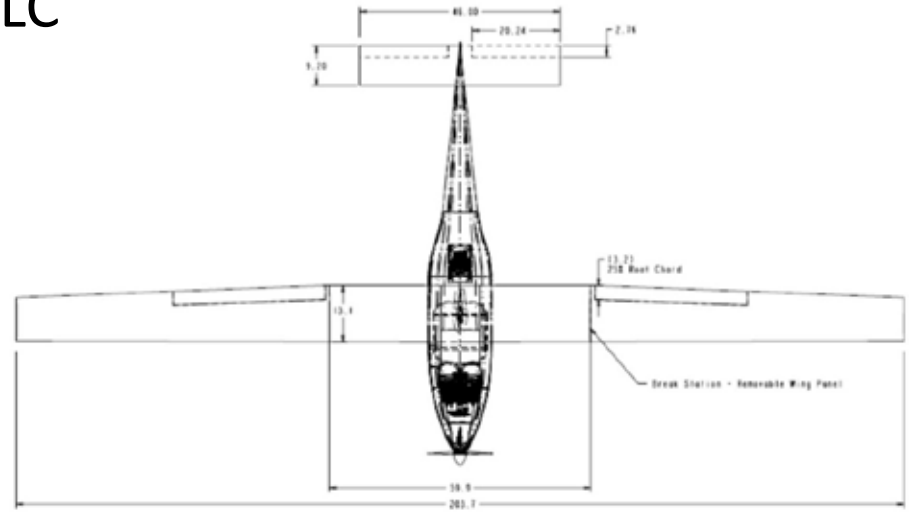
- Discussions with NUWC under way to integrate with BYG-1
  - C2 and video on host systems
  - May eliminate carry-on GCS equipment (need to ID connectivity to torpedo tube)

Ion Tiger

- 2008-2010
- Requirement:
  - Fuel Cell propulsion
  - 24 hour endurance
  - 5 lb payload
- Funded by ONR
- Collaboration with Protonex LLC and University of Hawaii







Ion Tiger Design Sizing

- **TOGW** **35.5 lbs**
  - *Fuel Cell* *2.2 lb*
  - *Fuel Tank* *8.0 lb*
    - *Fuel* *1.1 lb*
  - *Regulator* *0.4 lb*
  - *Cooling System* *1.5 lb*
  - *Propulsion System* *0.9 lb*
  - *Avionics* *1.0 lb*
  - *Airframe** *15.5 lb*
  - *Payload* *5.0 lb*

*** With NRL supplied internal mounts, wiring, etc**

Dimensions

- Wing Area 16.9 ft^2
- Span 17.0 ft
- Aspect Ratio 17
- Length 7.9 ft
- L/D 17

- **Cruise Power** **267w**
  - *Propulsion* *200 w*
  - *Avionics* *20 w*
  - *Flight Controls* *20 w*
  - *Payload* *20 w*
  - *Conversion Losses* *7 w*

Attempts to identify a COTS airframe capable of carrying the fuel tank were unsuccessful, necessitating a custom airframe design.
Designed & integrated at NRL, vehicle fabricated at Arcturus UAV.

Summary

Ion Tiger program has been successful.

- Completed 26+ hour flight with 5lb payload

Demonstrated:

- High performance fuel cell
- Throttleable operation from 5-100% power
- Improved radiators/thermal strategy
- Lightweight hydrogen storage

Other enabling technologies:

- Thermal model
- Improved fuel cell components
- Fuel cell system model
- Method for recovery of poisoned fuel cells

To Hybridize or not?

- Both Ion Tiger and XFC systems are non-hybridized
  - No battery power to propulsion
  - FC power direct to motor

- The IT endurance flights had long periods of full power operation

- *Maximum power of fuel cell is maximum power of system*

- HIL studies show a *decrease* in endurance of hybridized system vs nonhybrid
  - Additional component weight decreased fuel load
  - Load leveling didn't improve system efficiency

- Conclusion: Hybridize if you can't get a powerful enough fuel cell

Ongoing Research Areas

- Further FC Development
- LH2 Experimentation
- Hydrogen Logistics
- FC Poisoning & Recovery
- Tactical FC Aircraft Concepts

Further Fuel Cell Development

- Increase in fuel cell power from 550W to 1.5 kW
  - Protonex Technology Corp under contract
  - brassboard system delivered 8/2010
- Flightweight versions projected to weigh ~1.5kg
- Areas for Improvement:
  - Better performance at altitude
  - TRL
  - Shelf life

Liquid Hydrogen Demonstration

- ~3x more dense than gaseous H_2 at 5000psi
- Trades heavy PV/light fuel for lighter tank, insulation, and denser fuel
- Current effort: Demonstrate 3-day flight with Ion Tiger aircraft
  - Work is ongoing
  - flight demo expected 1Q11

Hydrogen Logistics

Hydrogen is not a logistic fuel, why make it one?

<u>Compressed hydrogen</u>

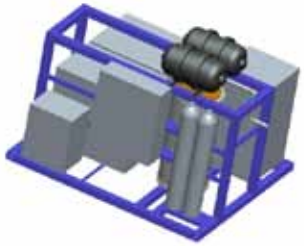
Commercial system available to electrolyze water

System components:

- Electricity (hotel power or diesel generator)
- Electrolyzer
- Compressor

No need to store large amounts of hydrogen – fuel and fly

Small enough to be part of the system or airfield equipment
doesn't answer off-field ops



Sierra Lobo No-Vent t[m] LH Prototype
<u>10kg of LH2/day</u>
97.5 x 114 x 86.3 inches
Requires: 1 gal/hr water
40kW elec. Power
1.2 kg H_2/day needed for tactical Ion Tiger (1.5 kW system/700 W av)

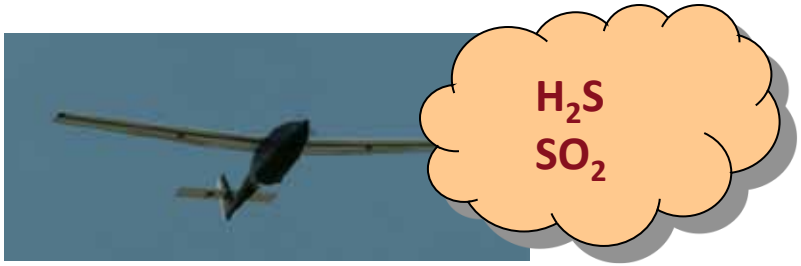
<u>Cryogenic hydrogen (Liquid hydrogen – LH2)</u>

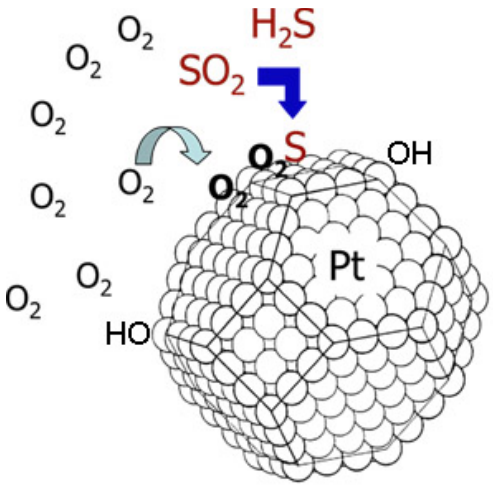
Portable systems available from and in development by:

- Sierra Lobo
- Linde

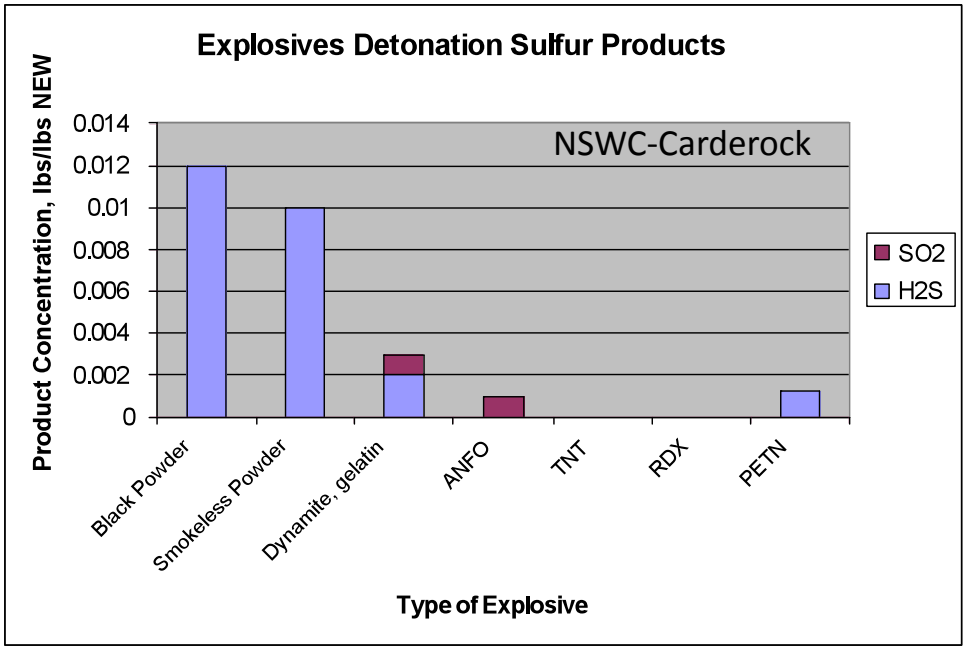
Fuel cell Poisoning and Recovery

- Motivation: Develop methods to regain power *during operation and maintenance* if catalysts are poisoned.
  - Sulfur in air can poison cathode catalysts
  - Electrode performance can be regained under certain cycling conditions

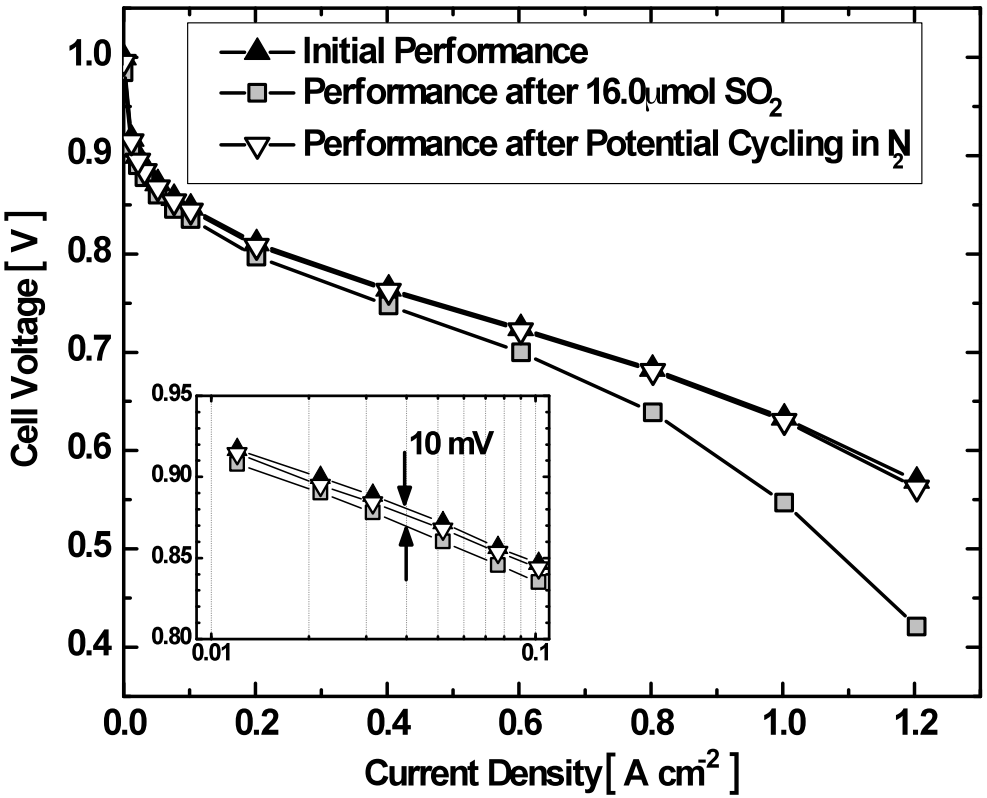




Sulfur blocks surface of Pt so that O_2 cannot react



New method developed to recover sulfur-poisoned fuel cell



New method demonstrated to recover fuel cell performance in less than one minute

- ✓ *Cycle electrode to high potential (1.1 V) to oxidize sulfur to sulfate*
- ✓ *Desorb the sulfate at low potentials (<0.2 V)*

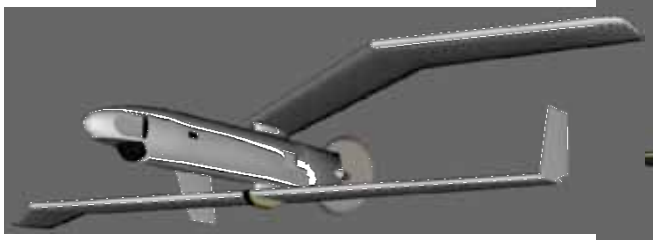
The result of several years of research ….

Fuel cell performance can be recovered during flight if the fuel cell is contaminated

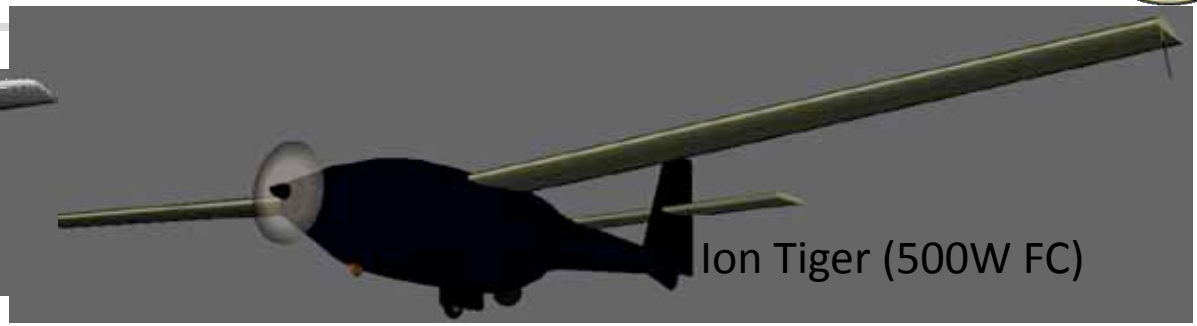
Hawaii Natural Energy Institute
www.hnei.hawaii.edu

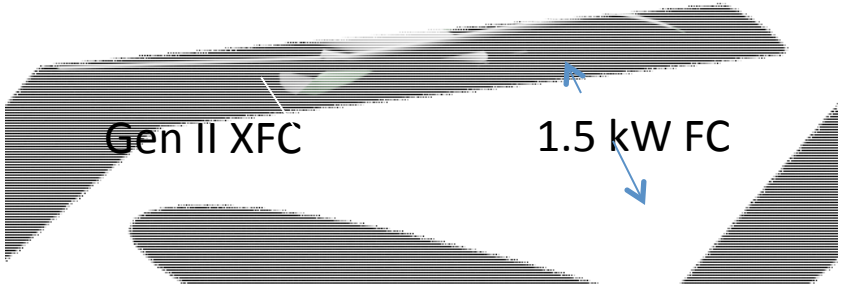
For FY-10: Chloride (Sea spray) Poisoning

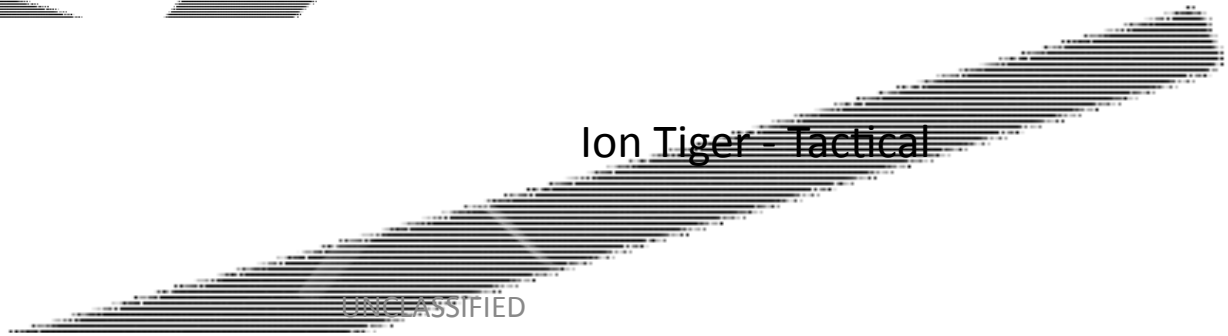
Tactical Fuel Cell Aircraft Concepts



XFC (300/500W FC)







Questions?