# Fuel Cell Propulsion for Small Unmanned Airvehicles:
# -**the "Ion Tiger"**

**Chemistry and Tactical Electronic Warfare Divisions**
**Naval Research Laboratory**
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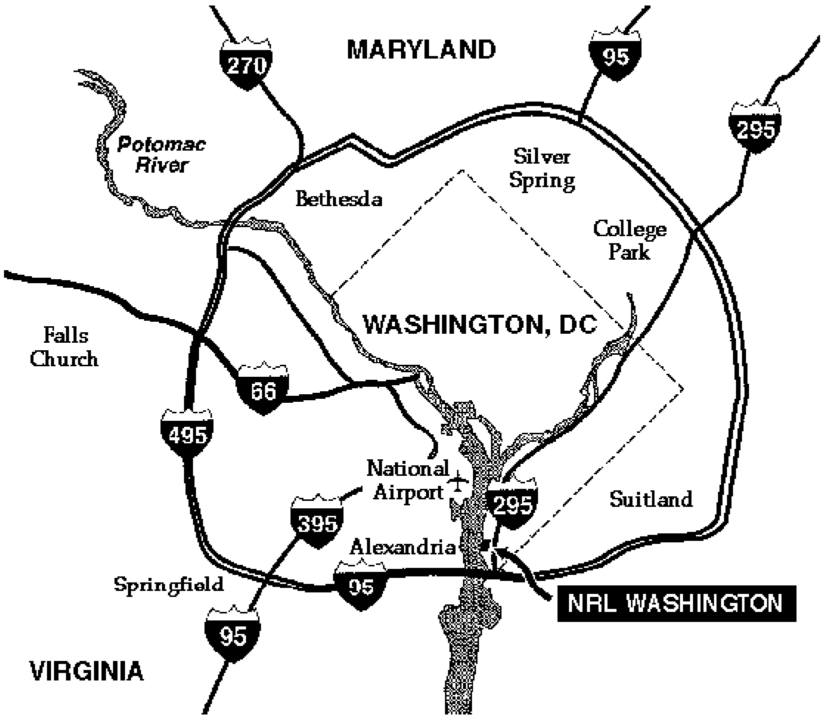
# Video story on Ion Tiger and fuel cells for the US Navy

http://www.navy.mil/swf/mmu/mmplyr.asp?id=13236

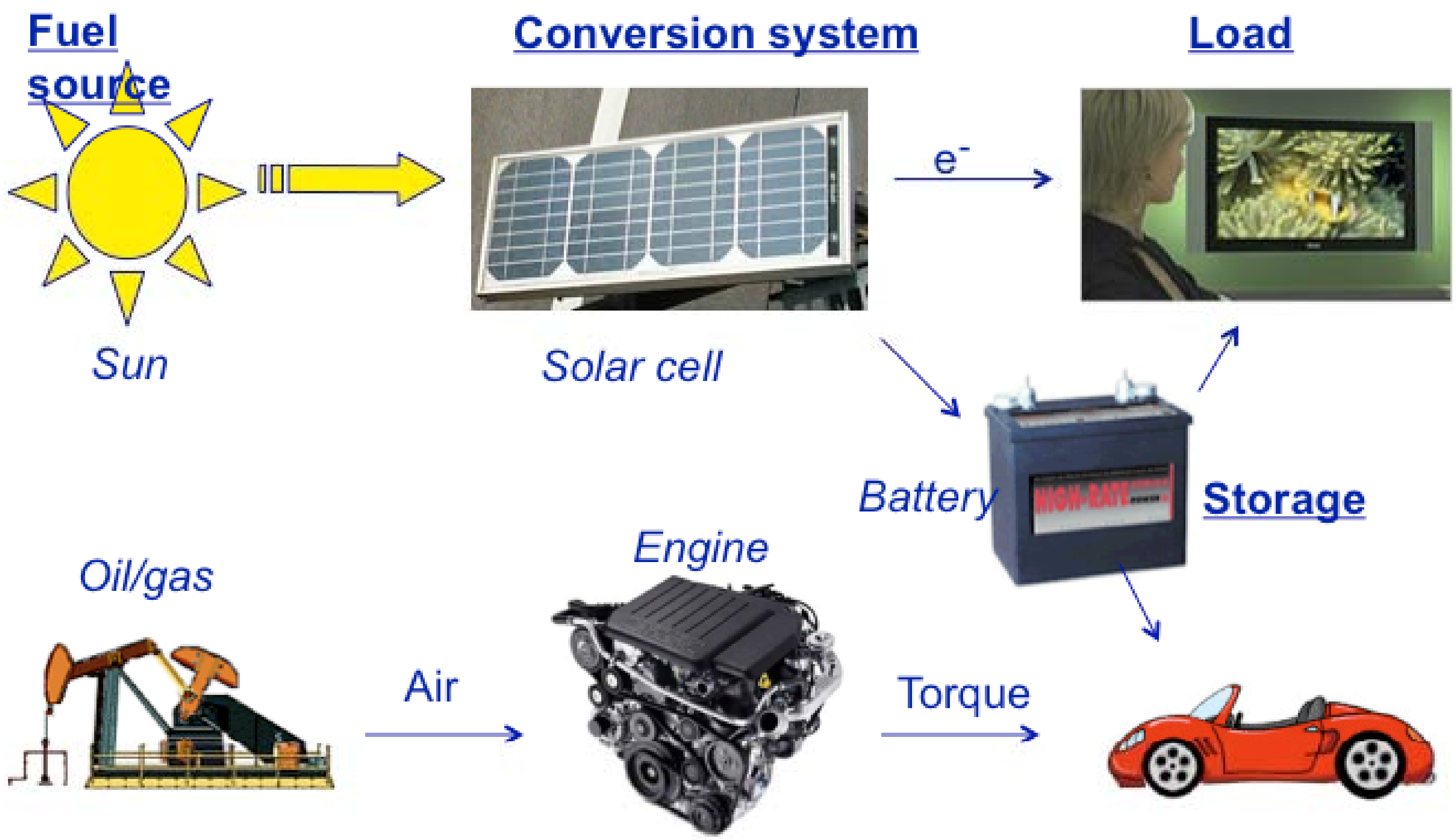
# Naval Research Laboratory (NRL)




The Navy's corporate research lab
Founded in 1923 by T. Edison

- Radar
- GPS (satellites)
- Microair vehicles
- Permanent magnets
- Enabling technologies

# Using fuel to make power and energy




Topics for improvement:

1. *Energy of fuel*
2. *Efficiency/size/weight of conversion systems*
3. *Efficiency/size/weight of storage system*
4. *Efficiency/size/weight of load*

# The US Navy is "going green"

Navy focus to be steward of the environment

Ray Mabus, Secretary of the Navy

*"Great Green Fleet" carrier strike group consisting of ships powered either by nuclear energy or biofuels with an attached air wing of fighter jets fueled entirely by biofuels.*

Task Force Energy - RADM Phillip Cullom

Task Force Climate Change

The Department of the Navy is the second largest fuel user in the DoD, consuming about 100,000 barrels a day.

Lifetime energy consumption costs and the "fully burdened cost of fueling and powering" all ships, planes, weapons and buildings will be a "mandatory evaluation factor"

*To fill the 450,000 gallon fuel tank on the Navy's DDG- 51 destroyer today costs $643,000*

***Concerns about cost, energy security, climate change***

# Uses of Unmanned Airvehicles (Drones)

Original military use: remote-controlled airplanes to train artillery men in anti-aircraft fighting.

Present uses -
ISR: Intelligence, Surveillance, and Reconnaissance
Communication relays
Air-to-land combat missions (Predator)
Border patrol


Emerging/Future uses:
Fire surveillance
Weather stations
Traffic
Construction
Communications relays
Food/water drops
Mail/shipping (FedEx)

Emphasis on reduced manning
Removing people from harm's way

# Power Use in UAVs

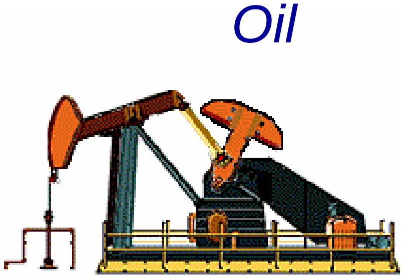
To operate a UAV, power is needed to

- Sustain level flight
- Climb and maneuver
- Fly in real/poor weather
- Power the navigator/autopilot, its flight data sensors and control surface actuators
- Operate a mission payload with its the required communications and data links

***System greatly simplified when propulsion and payloads all use electric power***

# Global Hawk – A military UAV for ISR

*Oil*



Jet fuel

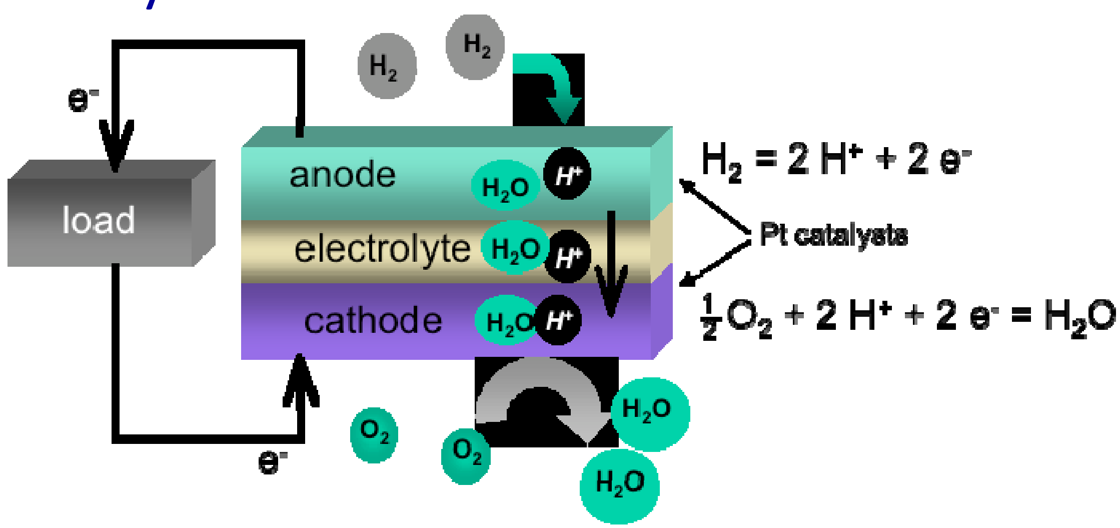
## Global Hawk - RQ-4A

high-altitude, long-endurance ISR
26,750 pounds GTOW
Jet Fuel: 15,400 pounds = **~2150 gallons**
Power Plant: Rolls Royce-North American AE 3007H turbofan
Thrust: 7,600 pounds
Speed: 391 mph
60,000 feet
Payload: 2,000 pounds
Cost: $38M

# Fuel cells vs engines

Fuel conversion systems convert chemical energy to electrical energy

- Engines
  - Run on liquid hydrocarbons
  - Efficiency limited by Carnot cycle
- Fuel cells
  - High efficiency
  - Difficult to run on liquid fuels




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

Benefit to Navy:

- Long endurance electric UAVs
- Quiet flights at 400 ft AGL with inexpensive payload
  - Lowers cost and OPTEMPO of missions
- ***Big UAV missions with a small UAV***
  - "Nano-ization" of UAVs
  - Lower cost and maintenance
  - Less storage volume

Advantages of electric propulsion

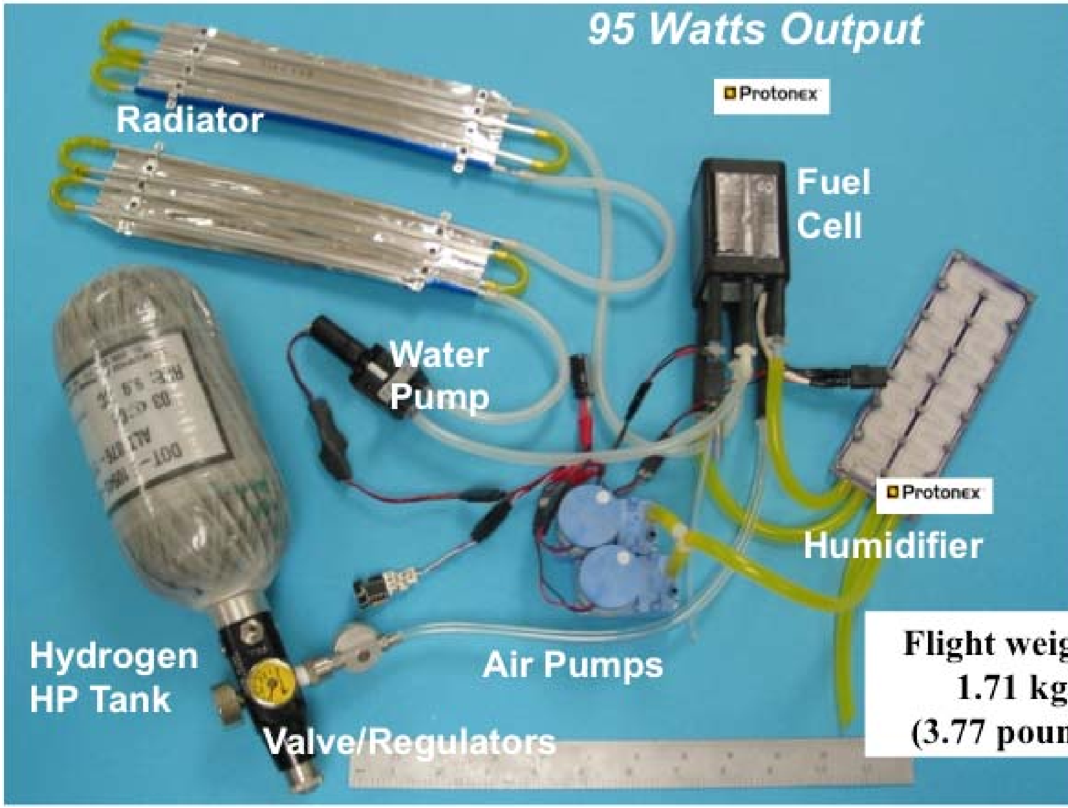
- Near silent operation
- Instant starting
- Increased reliability
- Ease of power control
- Reduced thermal signature
- Reduced vibration

***NRL – Tactical Electronic Warfare***

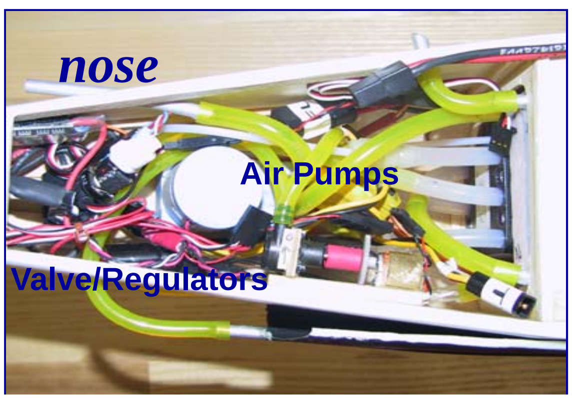
# A new airvehicle system - polymer fuel cell/hydrogen

NRL Chemistry and Tactical Electronic Warfare Divisions

**Spider-Lion: Nov 2005: 15 g $H_2$ (2 w%) 3 Hr 19 minutes**

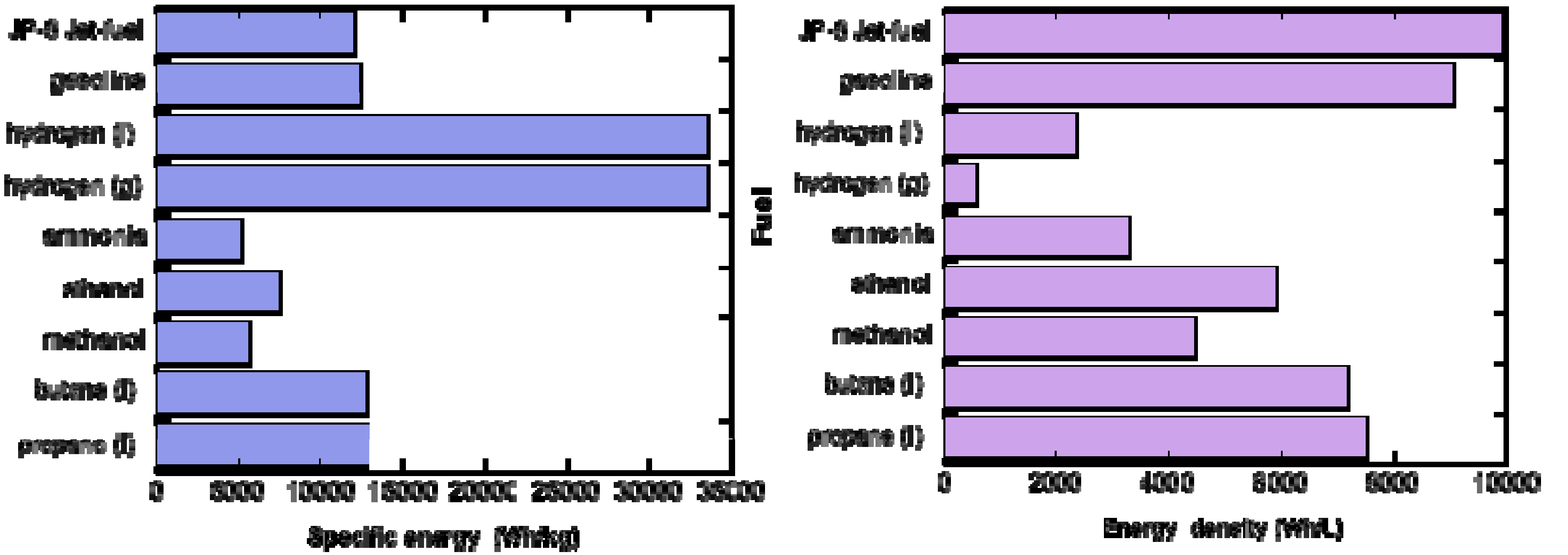



**Flight weight:**
**1.71 kg**
**(3.77 pounds)**



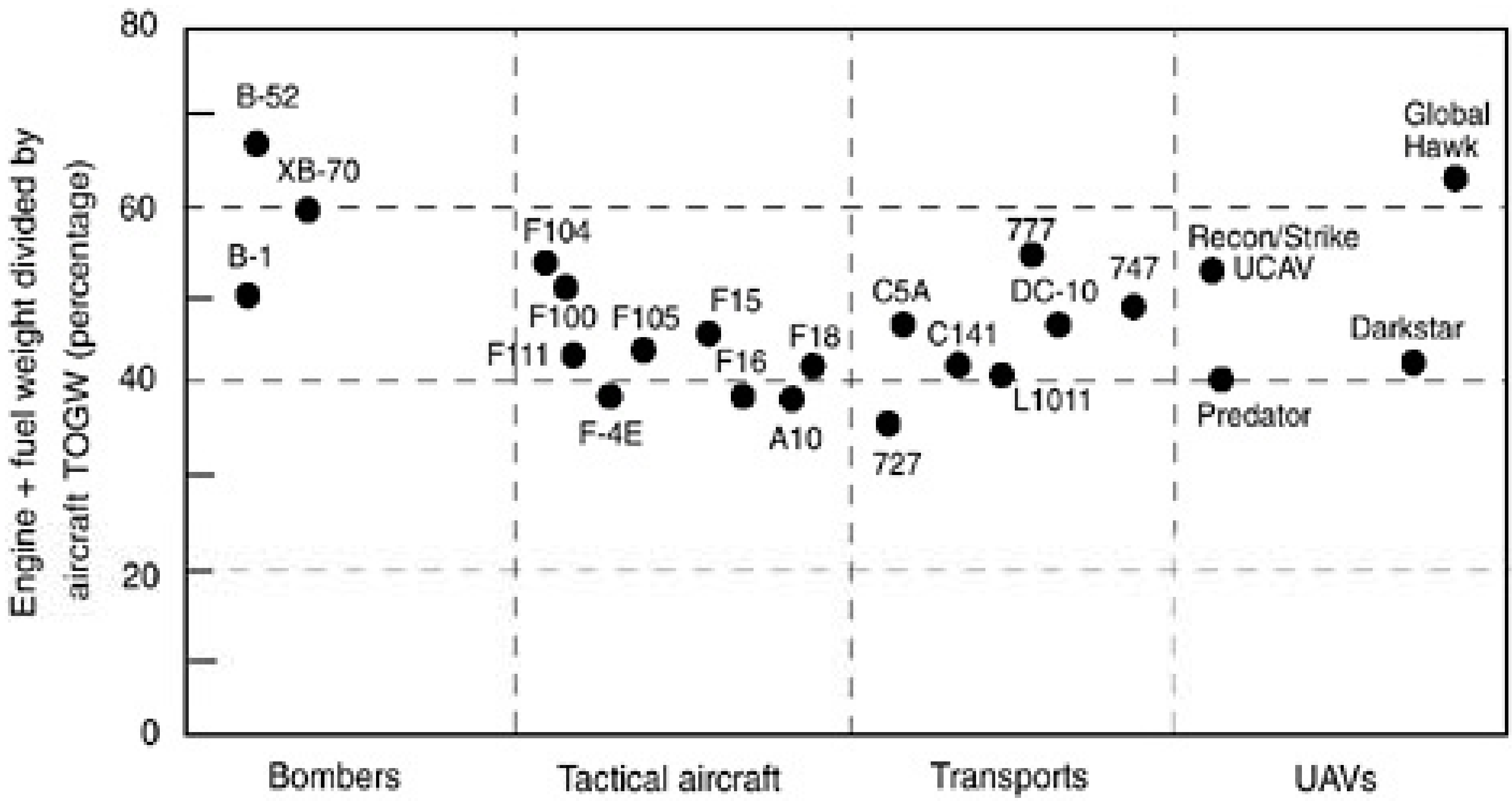

# Fuels have high energy contents

*Lower heating values (LHVs) of fuels*



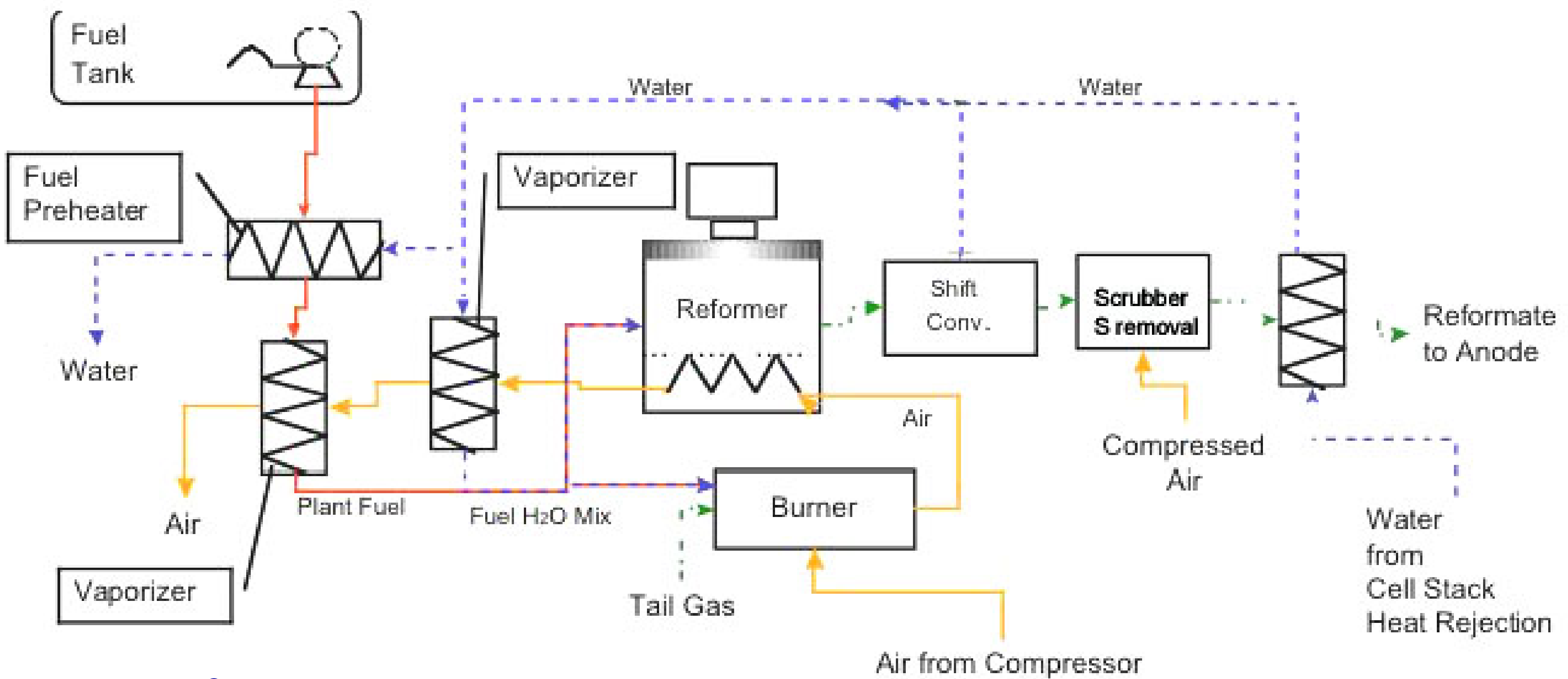

- Hydrogen gas has the *highest* specific energy but the *lowest* energy density
- Obtain higher energy density using compressed hydrogen
  - ✓ 5% hydrogen storage at 5000 PSI ~ 1670 Wh/kg
- THE MOST ATTRACTIVE: A hydrocarbon fueled vehicle
- Must consider the conversion system

# Propulsion system weight vs takeoff gross weight




- Power source and fuel are typically 35 to 65 % of vehicle weight
- For small UAVs, 38 to 40 wt% is a good target

# Hydrogen production from hydrocarbon fuels




**Steam reforming**

$H_3C\ (CH_2)_6\ CH_3 + 12\ H_2O$ (steam) + heat = $21\ H_2 + 4\ CO + 4\ CO_2$

Organo sulfur converted to $H_2S$

**Water-gas shift reaction**

$CO + H_2O$ (steam) $H_2 + CO_2$ (leaves 0.25-0.5% CO)

Difficult to make lightweight & compact

# Hydrogen Fuel

Compressed hydrogen gas

High energy fuel

- –Up to 10,000 psi in development
  - –5000 psi best weight advantage for UAVs
  - –Hydrogen embrittlement over 6500 psi
- –International path for fuel cell automobiles


*ADVANTAGES*

–Responds immediately to change in load – ***can be throttled***

–No waste produced (only $H_2O$)

–Produced and monitored onboard naval platforms

*DISDAVANTAGES*

–Difficult logistics for remote land locations

–Large storage volume (but OK for UAVs)

# 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**

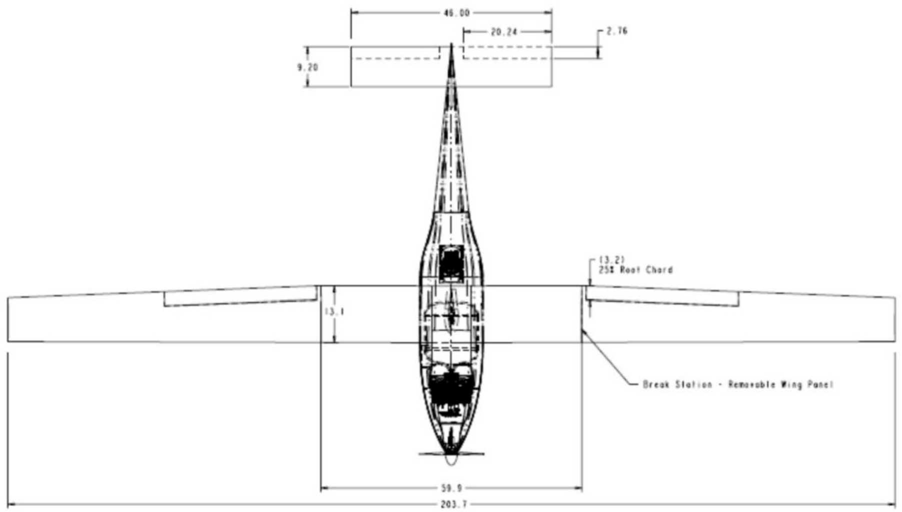
**Dimensions**

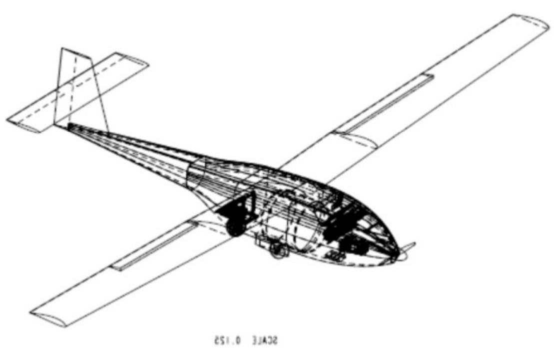
| | |
|---|---|
| • Wing Area | 16.9 $ft^2$ |
| • Span | 17.0 ft |
| • Aspect Ratio | 17 |
| • Length | 7.9 ft |
| • L/D | 17 |

| | |
|---|---|
| • **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.

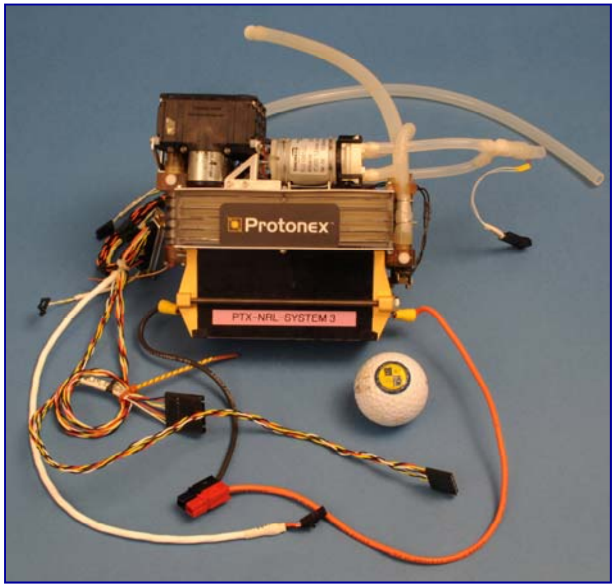
# Ion Tiger Airframe

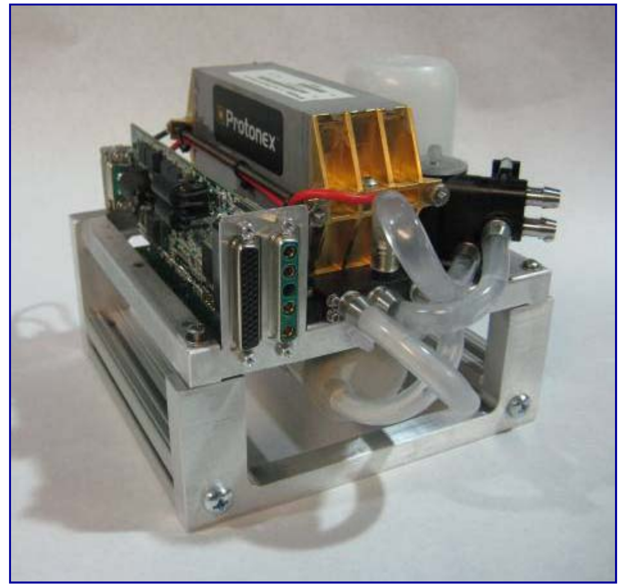


Designed at NRL by Greg Page/Rich Foch

# Progression of Fuel Cell Systems




Fuel cell at beginning of program (Fall 2007):
*1 kg and 300 W net*

POWERED BY Protonex

**Ion Tiger Program Product:**

- ***1 kg and 550 W net***

***New components/features***

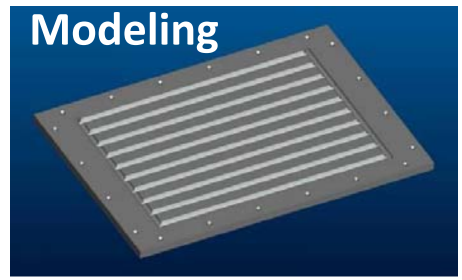
- new humidifier design
- new air blower
- higher power stack
- integrated control electronics
- 99% $H_2$ utilization

# Ion Tiger Radiator Cooling System

**New radiator enables Ion Tiger operation in 120°F environment**

✓ **Developed analytical tools for future designs/improvements**

**Spider Lion Radiator**


**Operation in warmer environments**


**Enabled by technical solutions:**

- Lightweight radiator with improved heat transfer
- Higher fuel cell temperature with robust humidifier design and stack membranes

**Solutions came from:**

- Thermal modeling of fuel cell and radiator
- Wind tunnel testing of radiator designs
- Improved radiator fabrication expertise

# NRL Hydrogen Fuel Tank Development

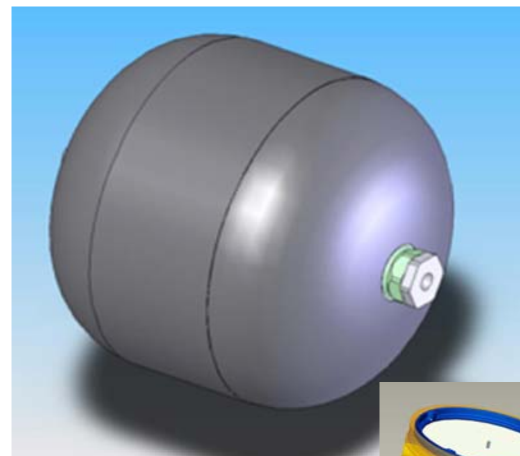
Spider Lion - 2005
COTS paintball tank & regulator
610 Wh of hydrogen in 0.93 kg
1.6 wt% hydrogen

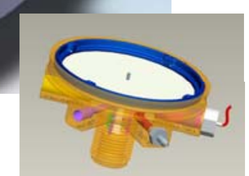

2.8x

- 2007
Modified COTS tank & custom regulator
1800 Wh hydrogen in 1 kg
4.5 wt% Hydrogen

2.9x

**Ion Tiger - 2009**
Custom tank & regulator
500 g hydrogen in 3.8 kg
13% hydrogen storage





## Exploit new technologies

- **Linerless tanks**
- **New composite wraps**
- **High strength, lightweight materials (Carbon nanotubes)**
- **Liquid (slush) $H_2$**

# Carbon Overwrapped Aluminum $H_2$ Tanks

New technologies demonstrated:
* Metal spinning for custom tanks sizes
* Demonstrated new resins with 10% more strength

22-liter tank made by metal spinning

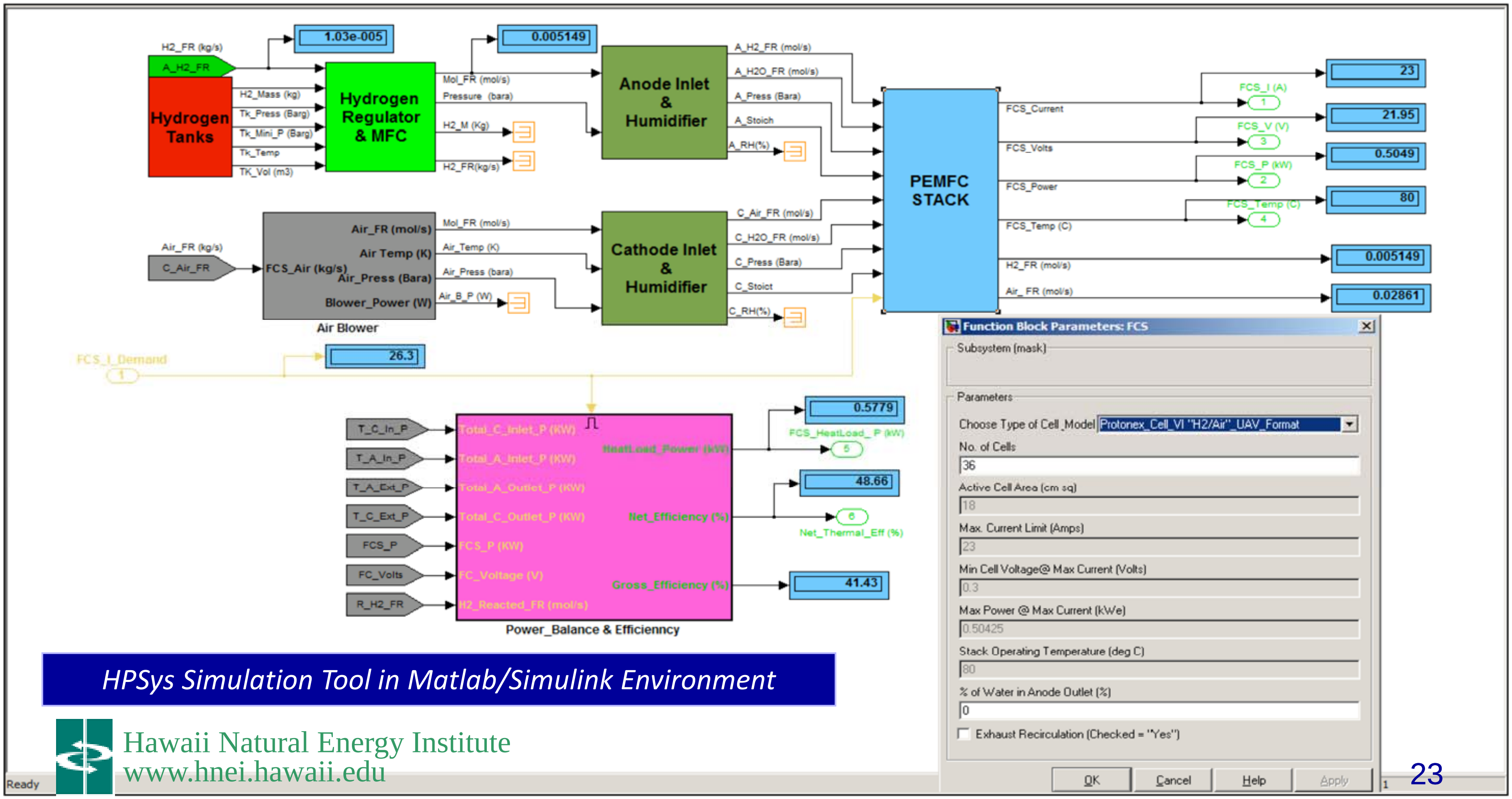
Carbon Overwrapped Pressure Vessel

Integrated into the Ion Tiger

500 g hydrogen storage in 22-L tank weighing 3.6 kg (8 lbs)
including 0.15 kg regulator = **13% $H_2$ storage**

# Hybrid Power System Simulator

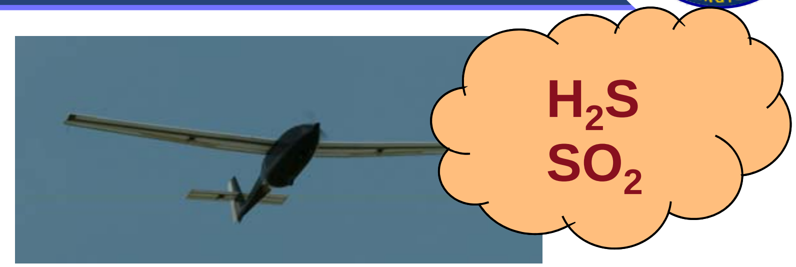
- Simulator developed to model system performance and determine best conditions for system optimization
- Hawaii will train NRL how to use tool for future development efforts

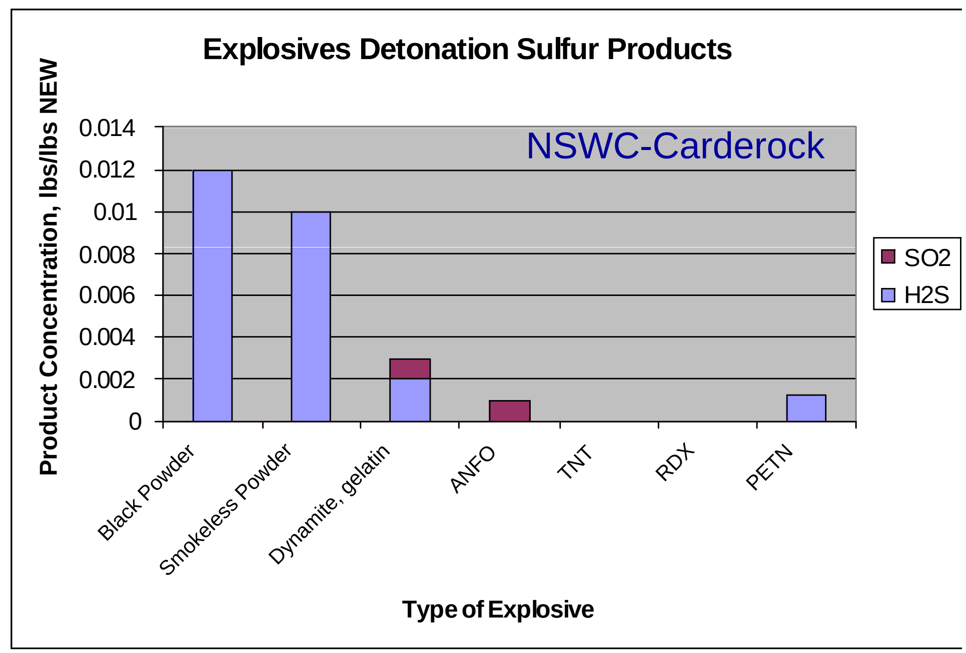


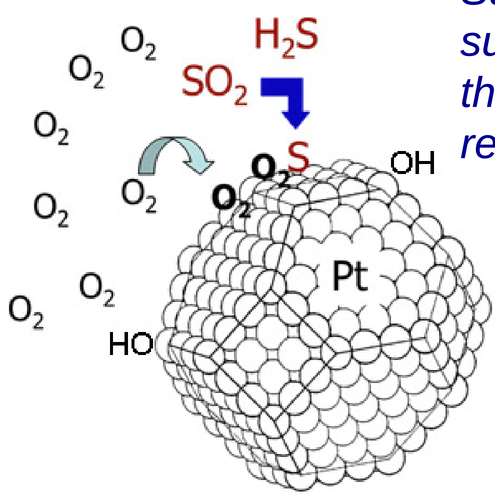

*HPSys Simulation Tool in Matlab/Simulink Environment*

# Fuel cell survivability in naval environments

- 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

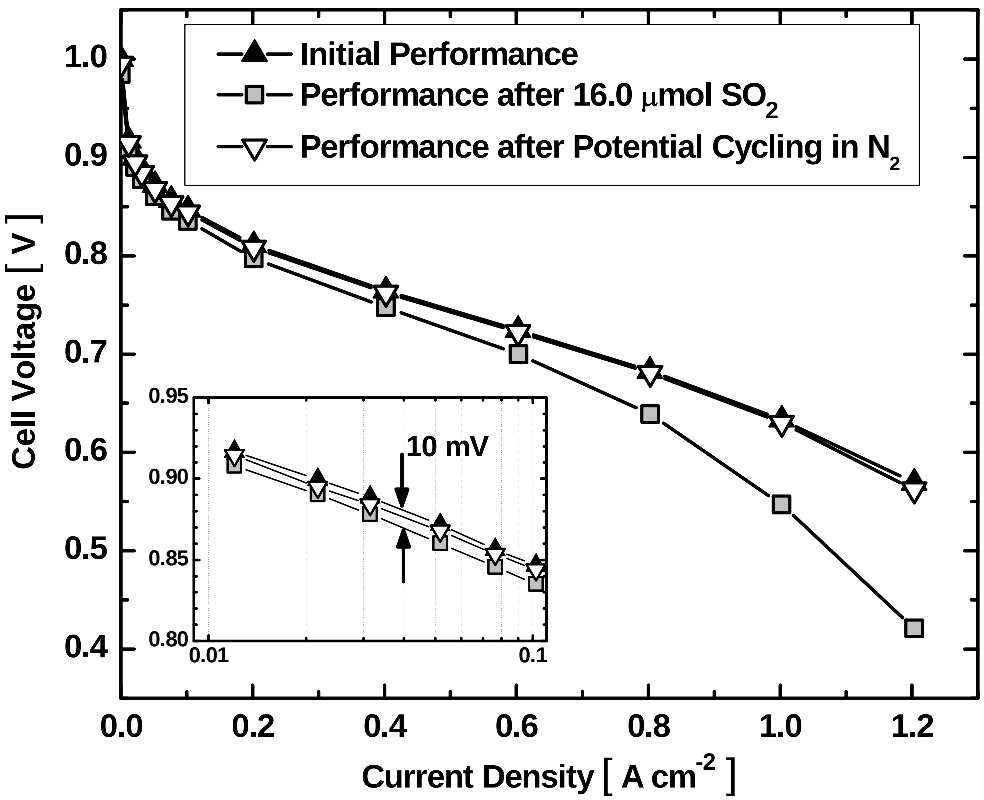



*Sulfur blocks surface of Pt so that $O_2$ cannot react*

# New method developed to recover sulfur-poisoned fuel cell



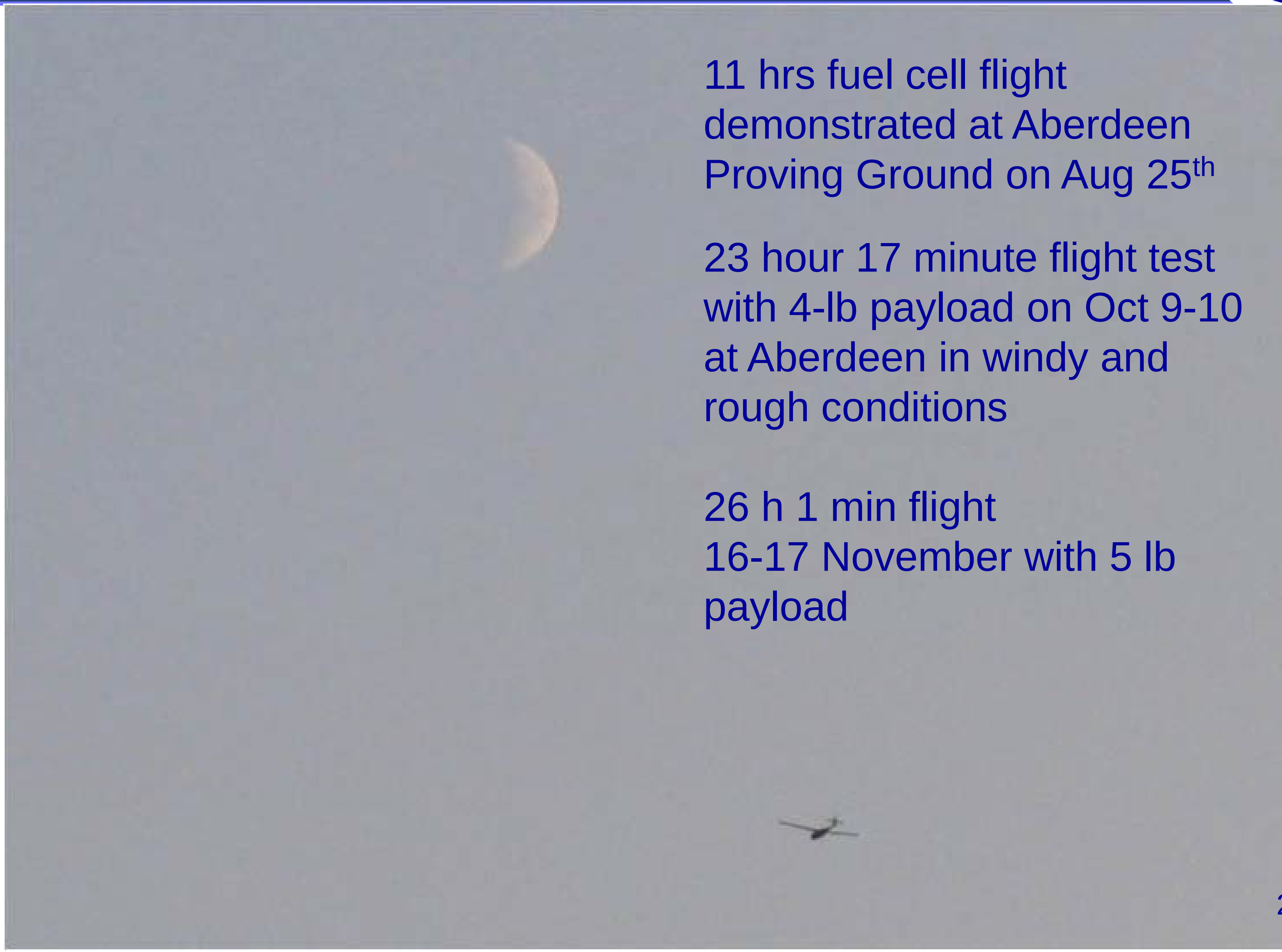

New method demonstrated to recover fuel cell performance in less than one minute

- ✓ *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***

# Flight testing

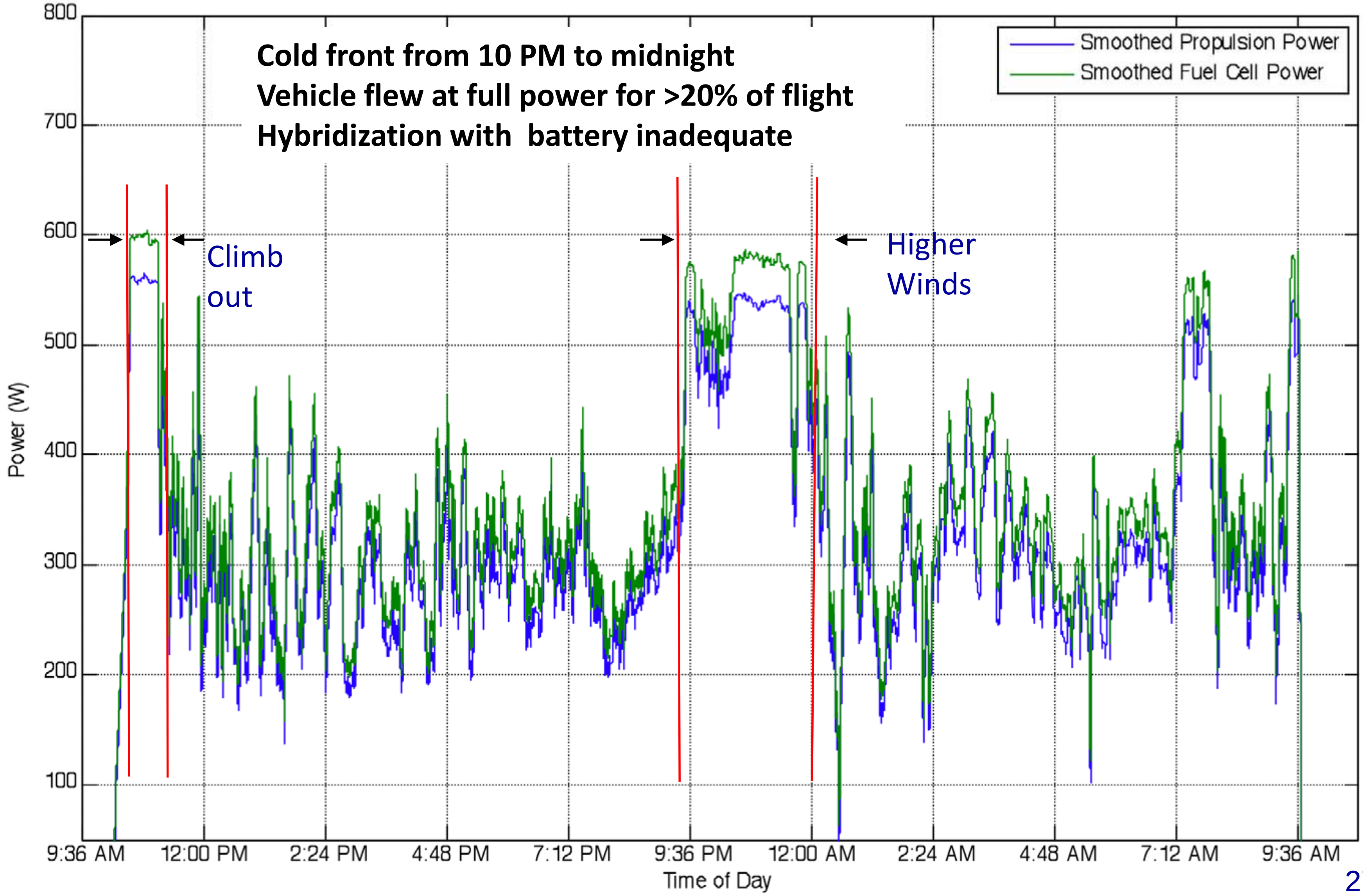


11 hrs fuel cell flight demonstrated at Aberdeen Proving Ground on Aug 25th

23 hour 17 minute flight test with 4-lb payload on Oct 9-10 at Aberdeen in windy and rough conditions

26 h 1 min flight
16-17 November with 5 lb payload

# Power profile for 23 hr flight



# System level considerations

"Hybridization" will not work for naval platforms

- The 11- and 23- hour flights had periods when fuel cell used at full power for long periods of time
  - *Maximum power of fuel cell is maximum power of system*
- May be an opportunity for load leveling if we can get small high power batteries

# Energy of Fuel Cells vs. Batteries for Ion Tiger system

16 kg GTOW - 38 wt% fuel cell propulsion plant

- 6 kg fuel cell propulsion system (with fuel and cooling)
  = Specific energy of 1300 Wh/kg
  - 24 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 logistics/safety

**<u>Compressed hydrogen</u>**

Commercial system available to make hydrogen from water (electrolysis)

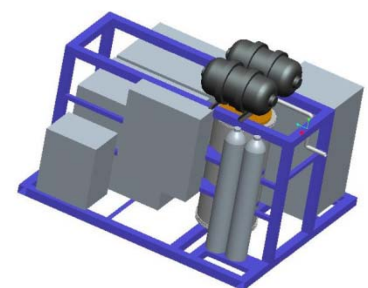
System components:

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

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

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

Portable systems available from and in development by: Sierra Lobo, Aeroviroment, Linde



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
0.5 kg $H_2$/day needed for Ion Tiger
1.2 kg $H_2$/day needed for Ion Tiger-T

*Fits in back of pickup truck*
*Produces enough H2 to have 15 UAVS in the air at all time*

# Going green with flight

**Global Hawk**
**~700 gallons or 2272 kg or**
**or 2.5 tons of jet fuel per day**

**Ion Tiger**
**500 g of hydrogen per day**

**For a 20% efficient $H_2$ generator**
**2.5 kg of hydrocarbon fuel per day**
**~900x more efficient**

# Summary and Outlook

Ion Tiger program has been successful.

Completed 26+ hour flight with a 5 lb payload

Success owed to:

High performance fuel cell

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

Next plans:

Higher power fuel cell for improved tactical capability

Liquid hydrogen for up to 3 day missions

The improvements:

1. *Efficiency/size/weight of conversion system (fuel cell)*
2. *Efficiency/size/weight of storage system ($H_2$ tank)*
3. *Efficiency/size/weight of load (UAV with low drag & and signature)*
4. *Energy of fuel*

# Research topics

**Improved fuel cells**
More efficient/effective catalysts
Improved hydrogen/oxygen diffusion
Higher performance polymer electrolyte membranes

**Hydrogen storage**
Higher strength carbons (overwrap)
New material for hydrogen storage

**Hydrogen production**
Biological/electrochemical/solar
From oil/gas

**High efficiency motors**
Permanent magnets

**Lightweight materials**
Light airframe

**Aerodynamics**
Low drag vehicles

**Thermal management**
High efficiency radiators

**System level modeling**
Simulink, etc.

**Improved batteries**
For backup/load leveling

**Lighter payloads/avionics**
Improved electronics
Camera optics
Communication systems

**Autonomy**
Artificial intelligence

# Some final comments and thoughts

**The Wright Brothers first flight was made successful by their development of a new 12-HP aluminum engine**
***First time that aluminum was used for engines***

**They went out of business because they were aeronautical engineers and did not have the ability to improve engine technology**

**New propulsion systems are critical to transportation – 50 years from now will we be flying in clean, quiet commercial passenger planes?**

# The people who made this happen (NRL Code 5712)

23-hour flight at Aberdeen Proving Ground


*Not shown: Greg Page and Rick Foch*, airframe designers
Rick Stroman, Fuel cell systems; Mike Baur, Ground station/Flight controls

# Thank you!

Revolutionary Research . . . Relevant Results