U.S. NAVAL RESEARCH LABORATORY

Hydrogen fuel cells for Unmanned Systems

***Briefing to:* DOE Hydrogen and Fuel Cell Technical Advisory Committee, Washington DC**

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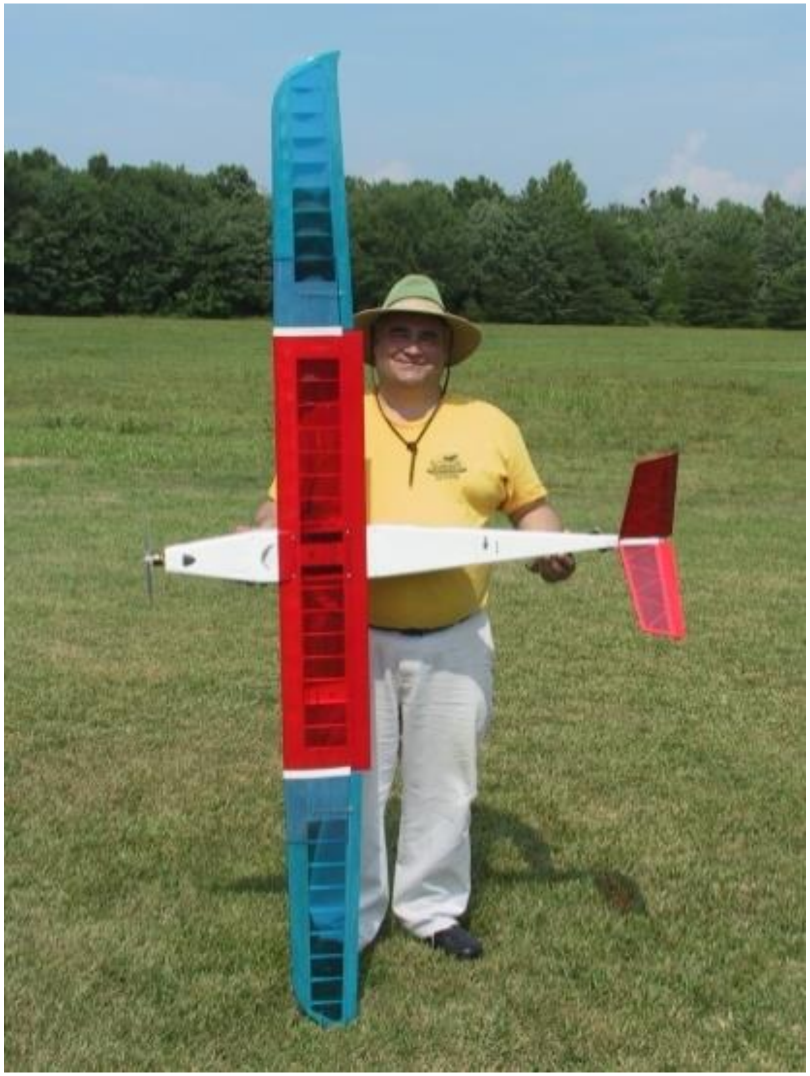
13 March 2019

Hydrogen fuel cells for UAVs

NRL has worked with hydrogen fuel cells for over 15 years.

Spider Lion! ~ 2004
100 Watt fuel cell



UAV = unmanned air vehicle
UAS = unmanned air system
UUV = unmanned undersea vehicle

Motivation for Hydrogen Fuel Cells

<u>Fuel cell advantages:</u>

- Higher energy than batteries
- Higher efficiency than engines
  - Small engines ~10-15% efficient
  - Fuel cells ~60% efficient
- Higher reliability than engines

<u>Benefit to Navy:</u>

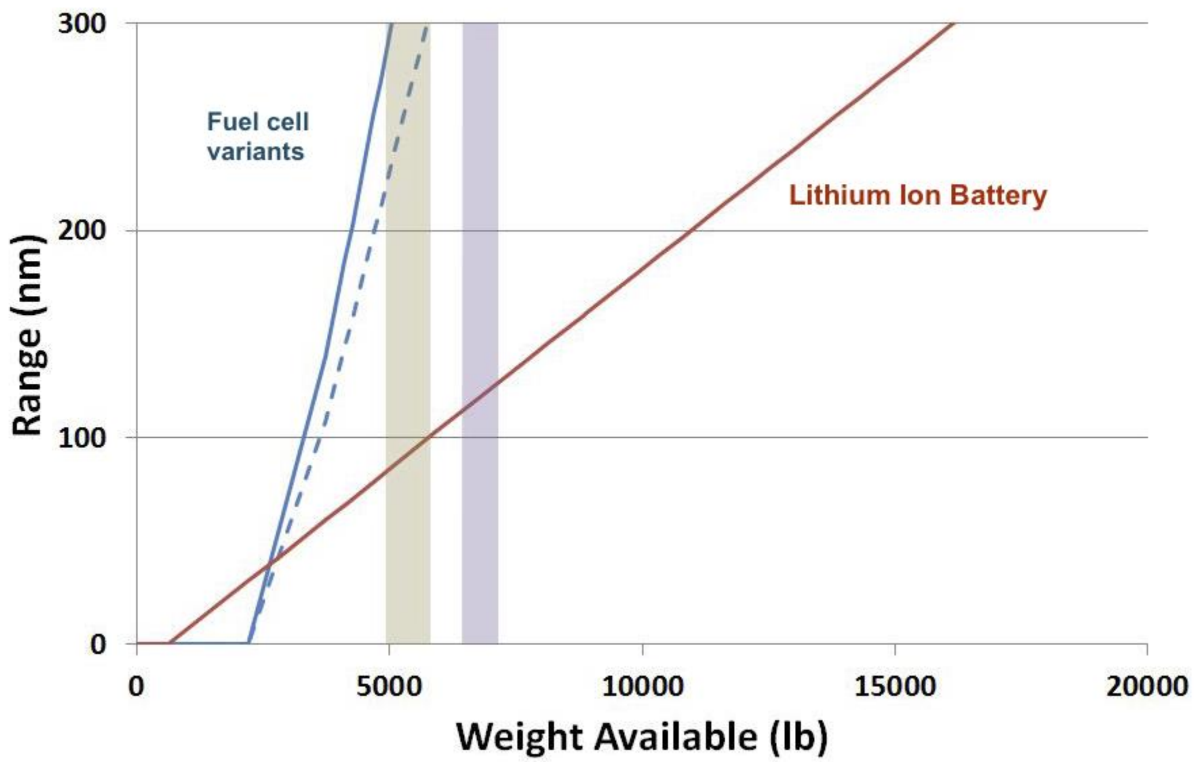
- Long endurance electric UAVs (and UUVs)
- Quiet flights at 400 ft AGL with inexpensive payload
  – Lowers cost and OPTEMPO of missions
- ***Big UAV missions with a small UAVs and UUVs***
  - Lower cost and maintenance
  - Less storage volume

Advantages of electric propulsion

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

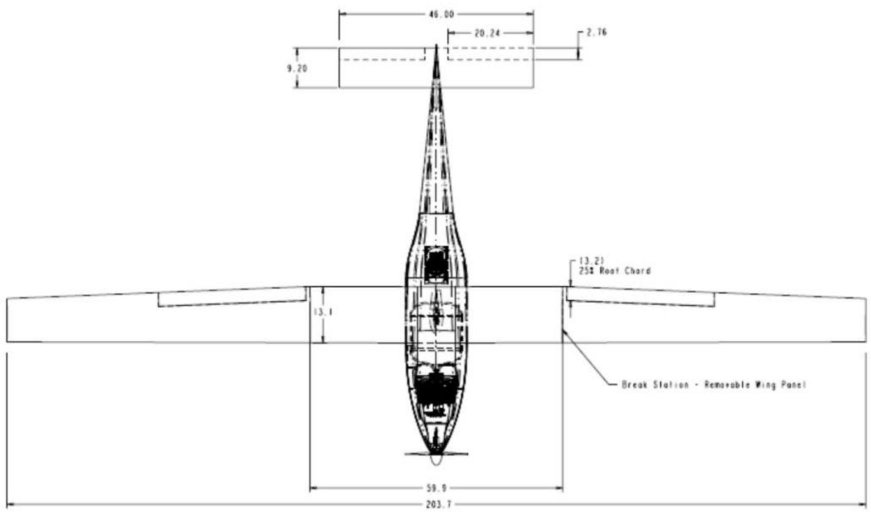
Fuel Cells Compelling for Long Endurance Vehicles

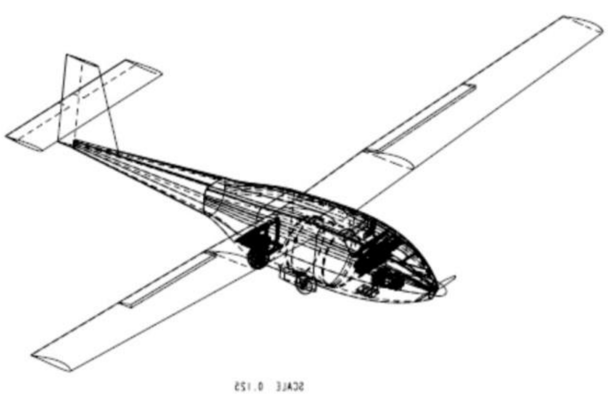
High energy of H_2 × high efficiency of fuel cell = long endurance



- ***For smaller systems and short missions – batteries always preferred***

Ion Tiger – UAV for 24 h flight with 5 lb payload (2009)

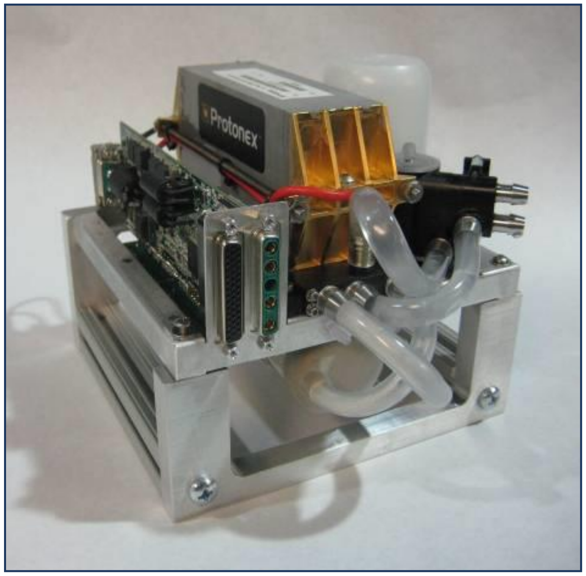




NRL built up vehicle to wrap around hydrogen tank

Swider-Lyons, et al., AIAA, 2011-6975

Protonex Technology Corporation



Ion Tiger Program Fuel Cell:

•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

Successfully flown by NRL since 2009 in Ion Tiger and XFC
Several improvements:
Electronics
Hydrogen valves

Demonstrated a flight on Boeing Insitu April 2016 – put 2 systems together

Water-cooled for high power
Uses commercial fuel cell membranes (WL Gore, 3M, etc)

Hydrogen storage progression

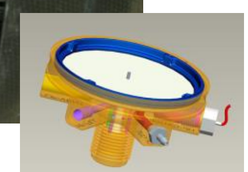
Spider Lion - 2005
COTS paintball tank & regulator
610 Wh of hydrogen in 0.93 kg
1.6 wt% hydrogen

2.8x

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

2.9x

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



- NRL teamed with Hypercomp Engineering on H_2 Storage
- Type 3 metal liner & carbon overwrap
- NRL lightweight regulator

5000 psi H_2 demonstrated

Solid fuels not practical

Ion Tiger 24-Hour Flight with Fuel Cell

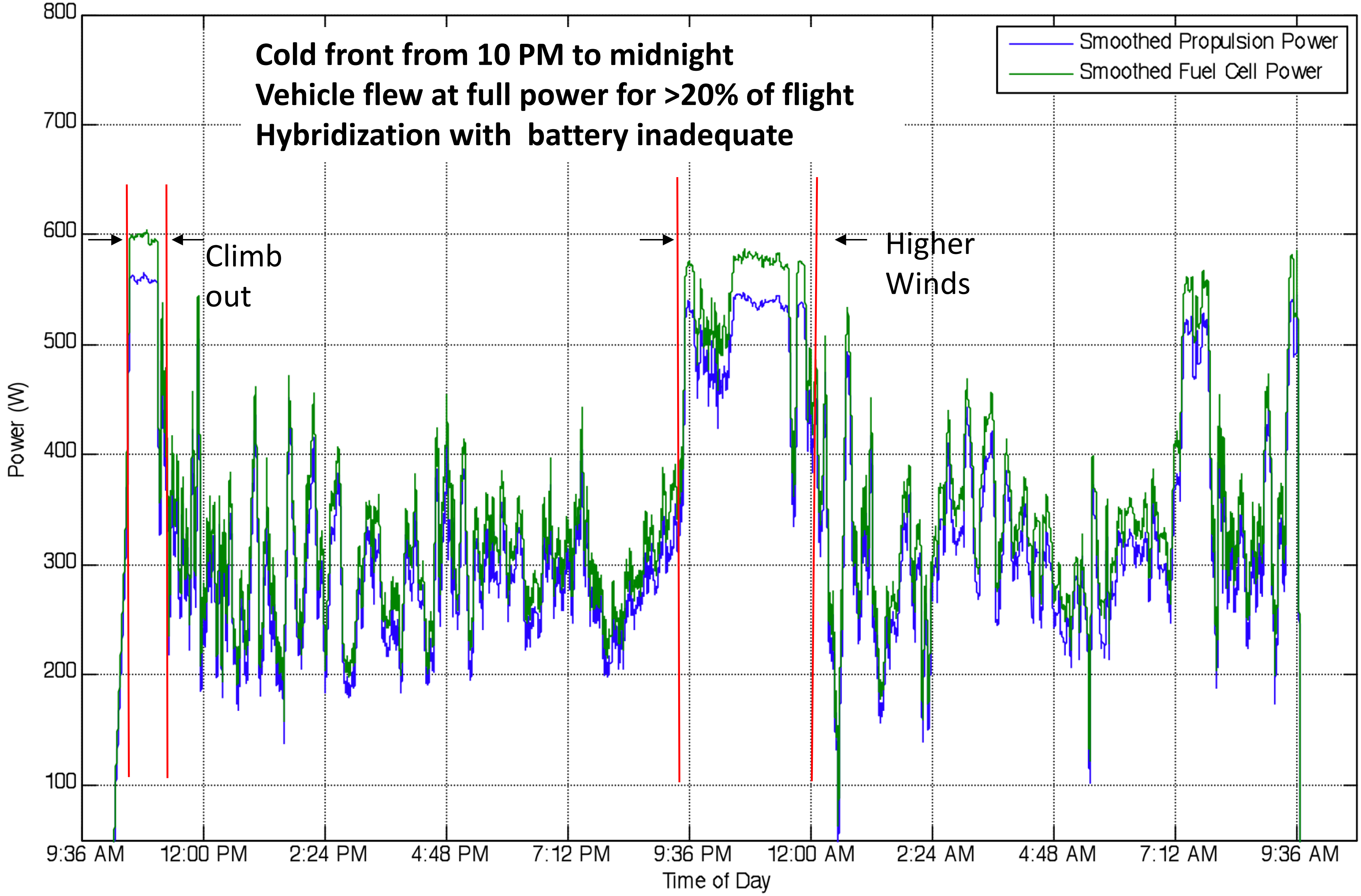
23 h flight October 2009 with 4 lb payload

26 h flight 16-17 November 2009 with 5 lb payload

Protonex 580-W fuel cell
5000 psi H_2 (500 g)

“unofficial” world records for fuel cell powered flight”

Power profile for 23 hr flight



Energy of Fuel Cells vs. Batteries

16 kg GTOW - 38 wt% fuel cell propulsion plant

- **7 kg fuel cell propulsion system (with fuel and cooling)**
  = Specific energy of 1100 Wh/kg for compressed H_2
- 26 hours of flight at 300 W

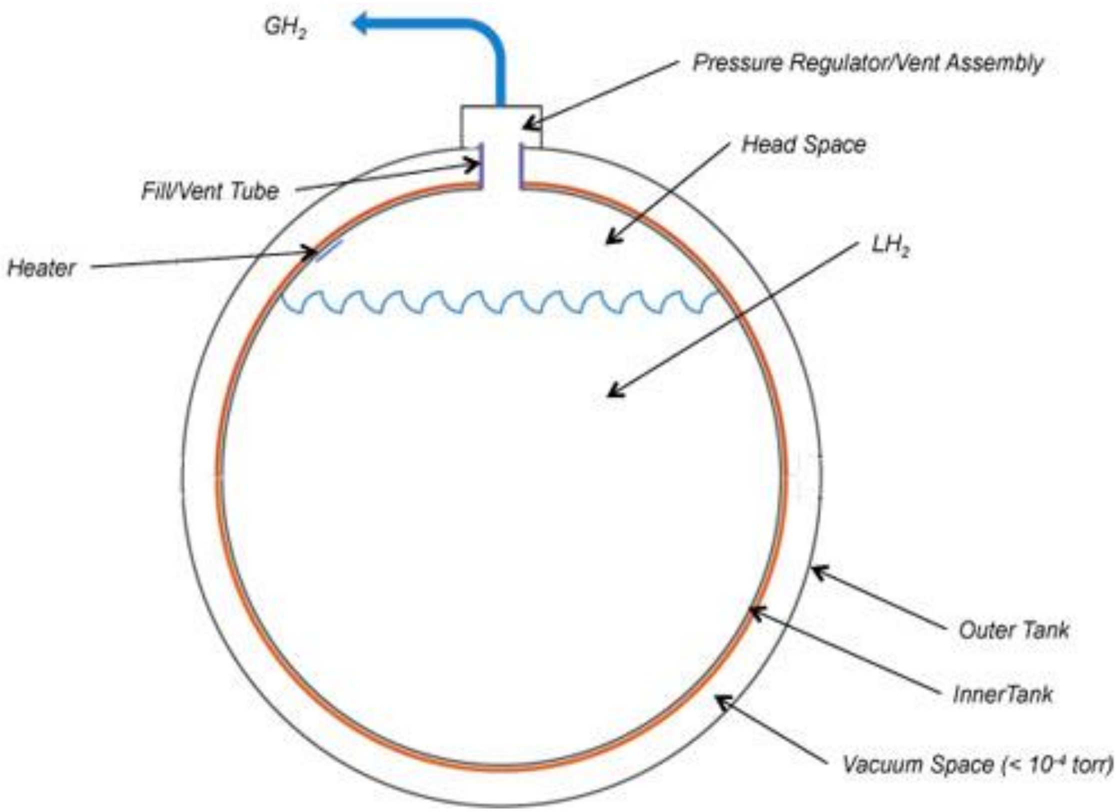
- **Compare to high energy Lithium battery**

= 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

- **Theoretical 3x endurance increase with liquid hydrogen over compressed hydrogen**
- 7 kg fuel cell propulsion system (with fuel and cooling)
  = Specific energy of 3000 Wh/kg for liquid H_2
- 3 days of flight at 300 W

LH2 Design: nested aluminum tanks



- Vacuum between 2 aluminum spheres
- Minimize heat conduction between the 2 spheres with multilayer insulation (MLI)
- Design with appropriate boil off volume, etc.
- *Similar designs looked at for automotive and high altitude long endurance UAVs*

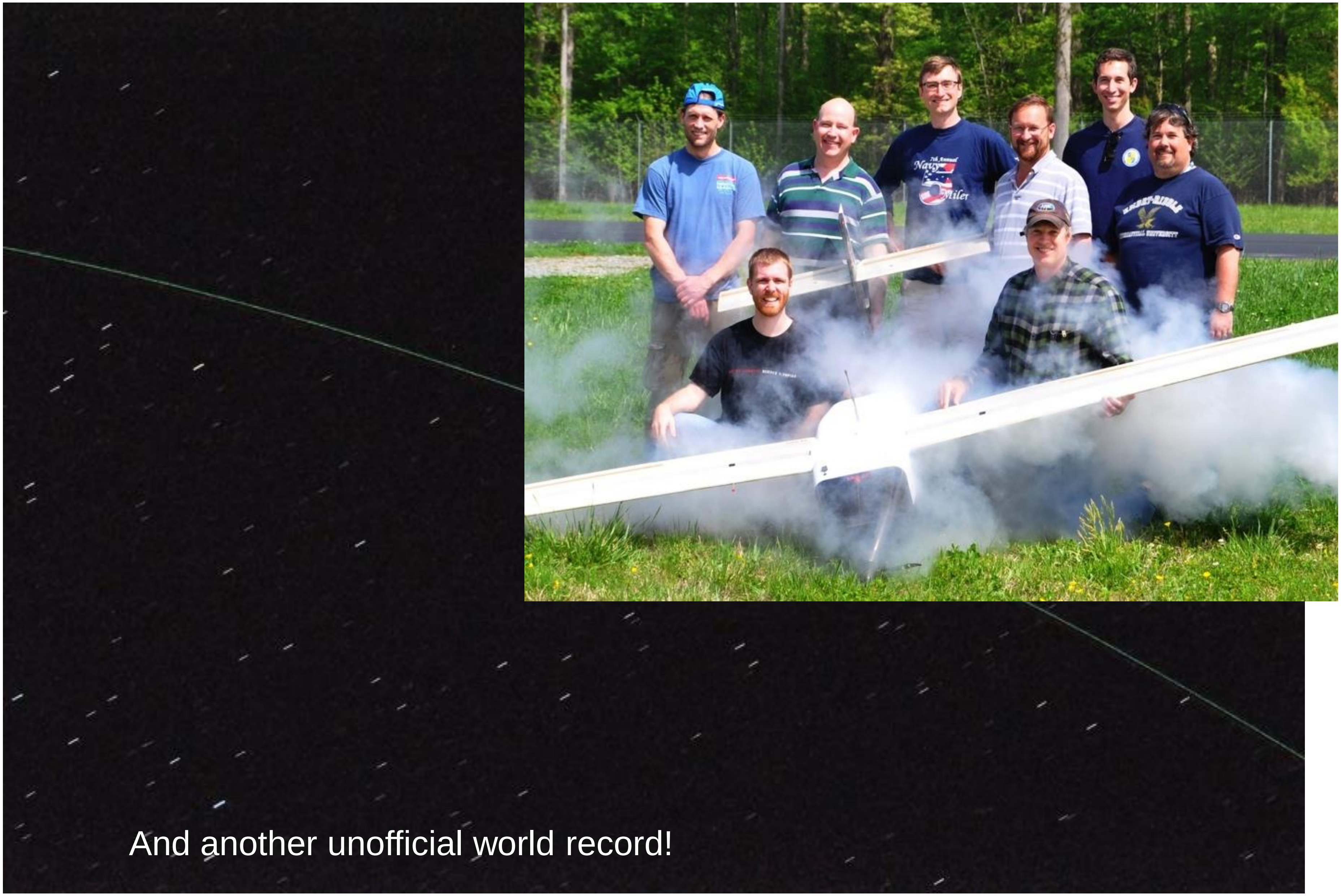
Stroman, et al., Int. J. Hydrogen Energy, vol 39 (2014)

Fueling methodology

1000 L dewar → 100 L DOT certified transfer dewar (@ NRL)
100 L transfer dewar → 22 L flight dewar (@ airfield)
Use He to inert system, then drive LH_2 into flight tank
~50% of LH_2 boils off to cool the flight tank

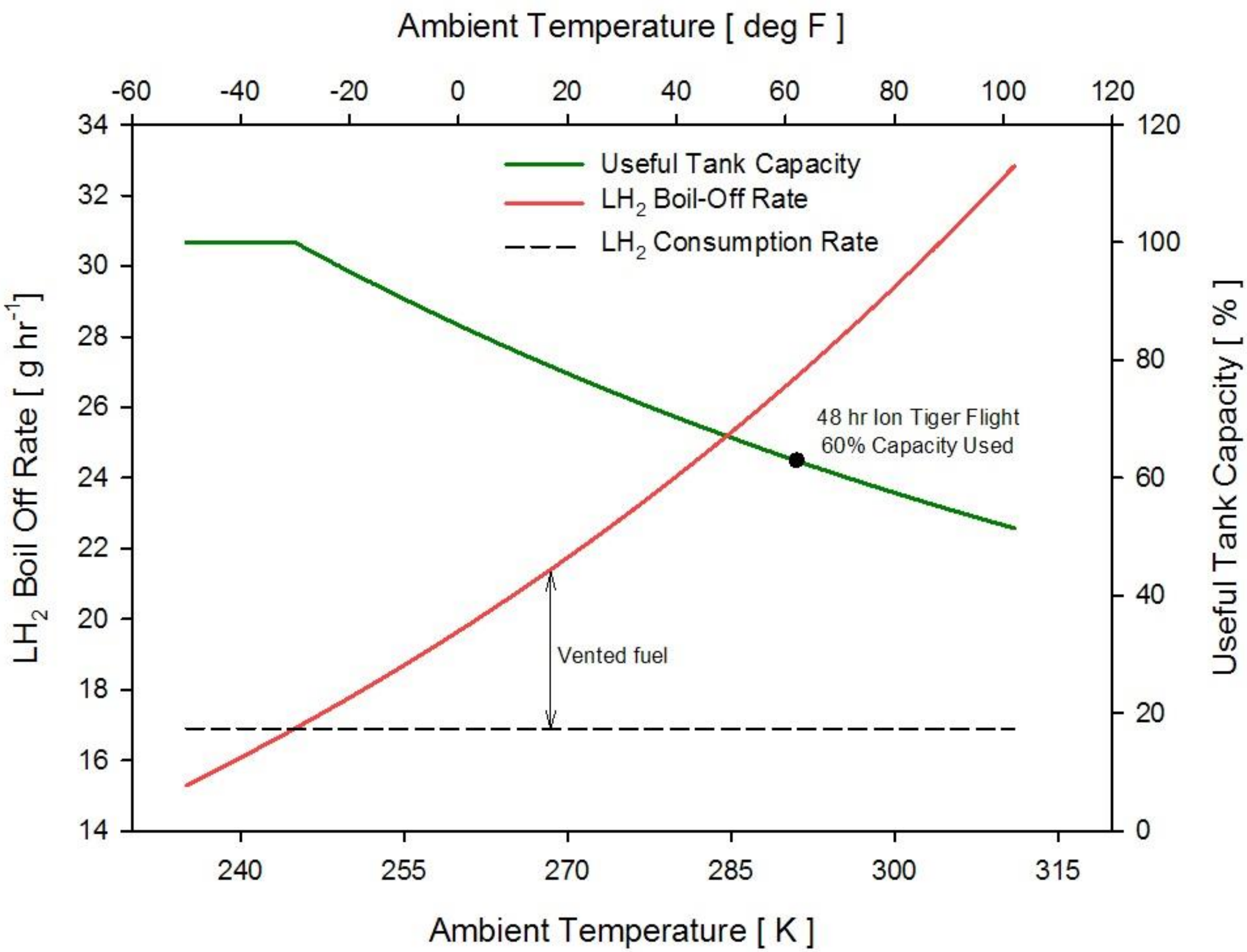
- Safety:
  - Ground everything
  - Nomex suit, etc.

48-h flight 16-18 April 2013



And another unofficial world record!

Significant LH_2 loss due to heat leak



Stefan- Boltzmann Radiative heat transfer

$$Q = \sigma\,(T_1^4 - T_2^4)$$

$T_1 = 20$ K

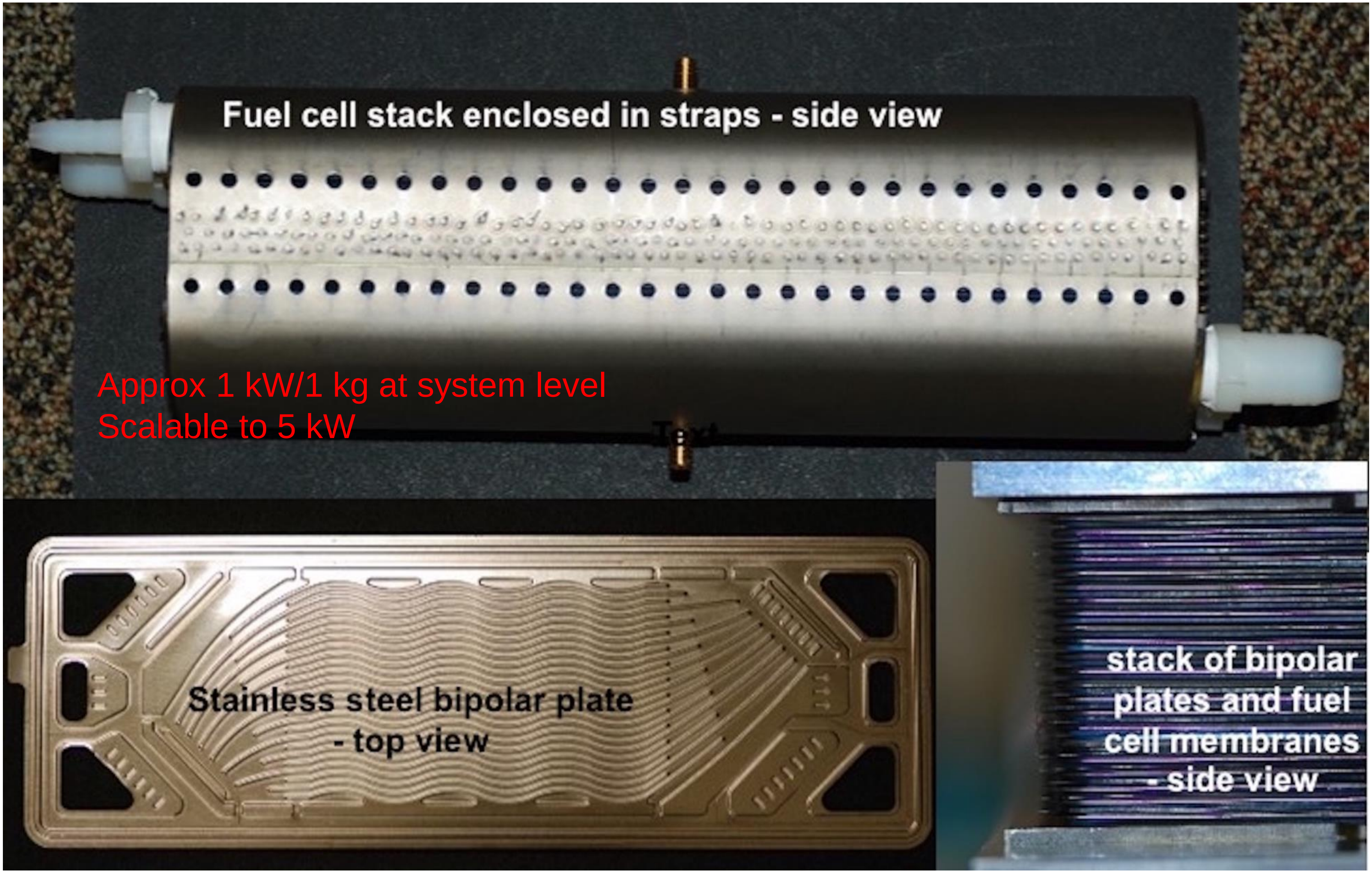
T_2 = ambient

Options: decrease LH_2 boil off through increased insulation (increased volume & weight)

Fly at very cold temperatures.

NRL does not recommended LH2.

New: NRL’s 1.5 to 3 KW fuel cells Stamped metal bipolar plates

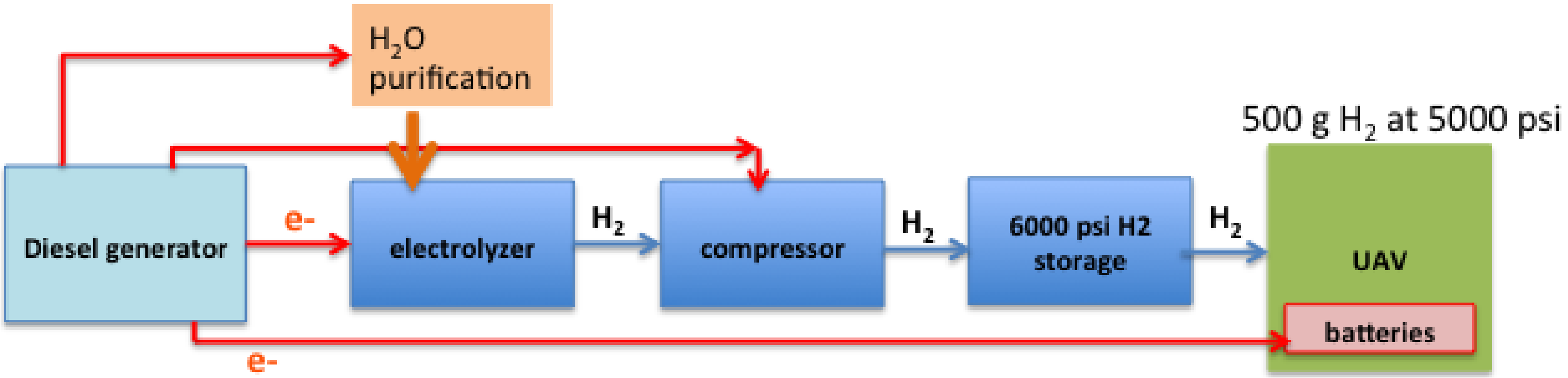


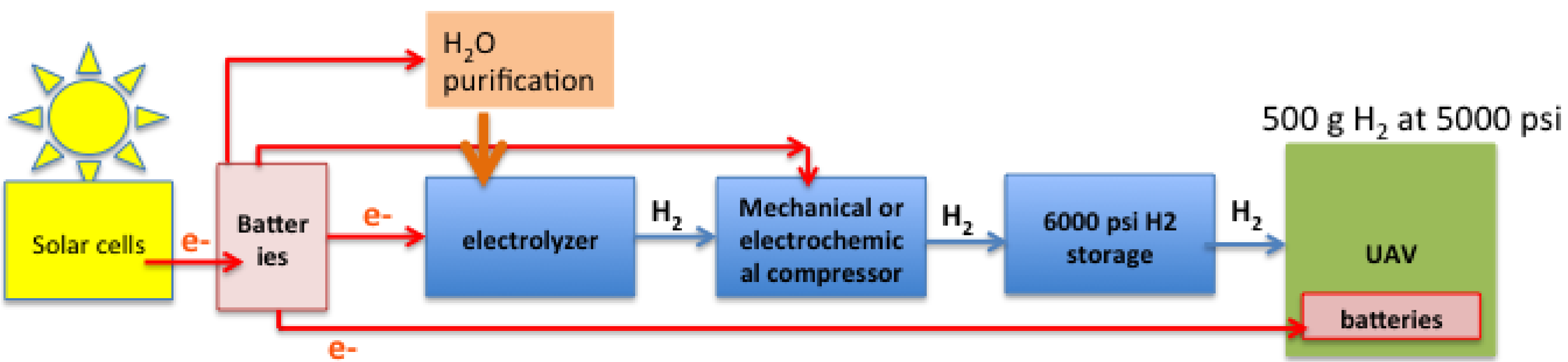
Leverage “automotive” technology for stamped bipolar plates

In field hydrogen fueling

Present method is to refuel from commercial bottles of 6000 psi H2. Takes about 2 minutes

Look at different technologies for in field fueling





Millennium Reign Scalable Hydrogen Fueling Appliance

Specification	Value
Max Pressure	410 bar (6,000 psig)
Production rate	2 kg/day

Advantages of mech. compression and alkaline electrolysis

- Relatively inexpensive– both mech. compression and electrolysis
- Mature technology
- Efficient???

Conclusions:

- System is robust – worked “right out of the box”
- System was designed for cost and simplicity
- Mechanical compressor requires overhaul every 300h

HyET Electrochemical Compression

HyET Hydrogen
Efficient purification & compression

Specification	Value
Max Pressure	410 bar (6,000 psig)
Production rate	2 kg/day

Advantages of e-chem compression

- Silent operation
- Purification
- No moving parts
- Longer lifetime???

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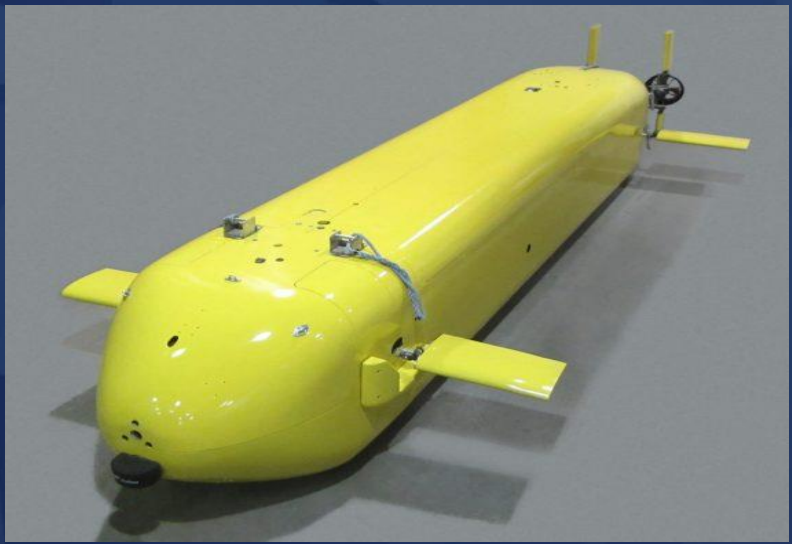
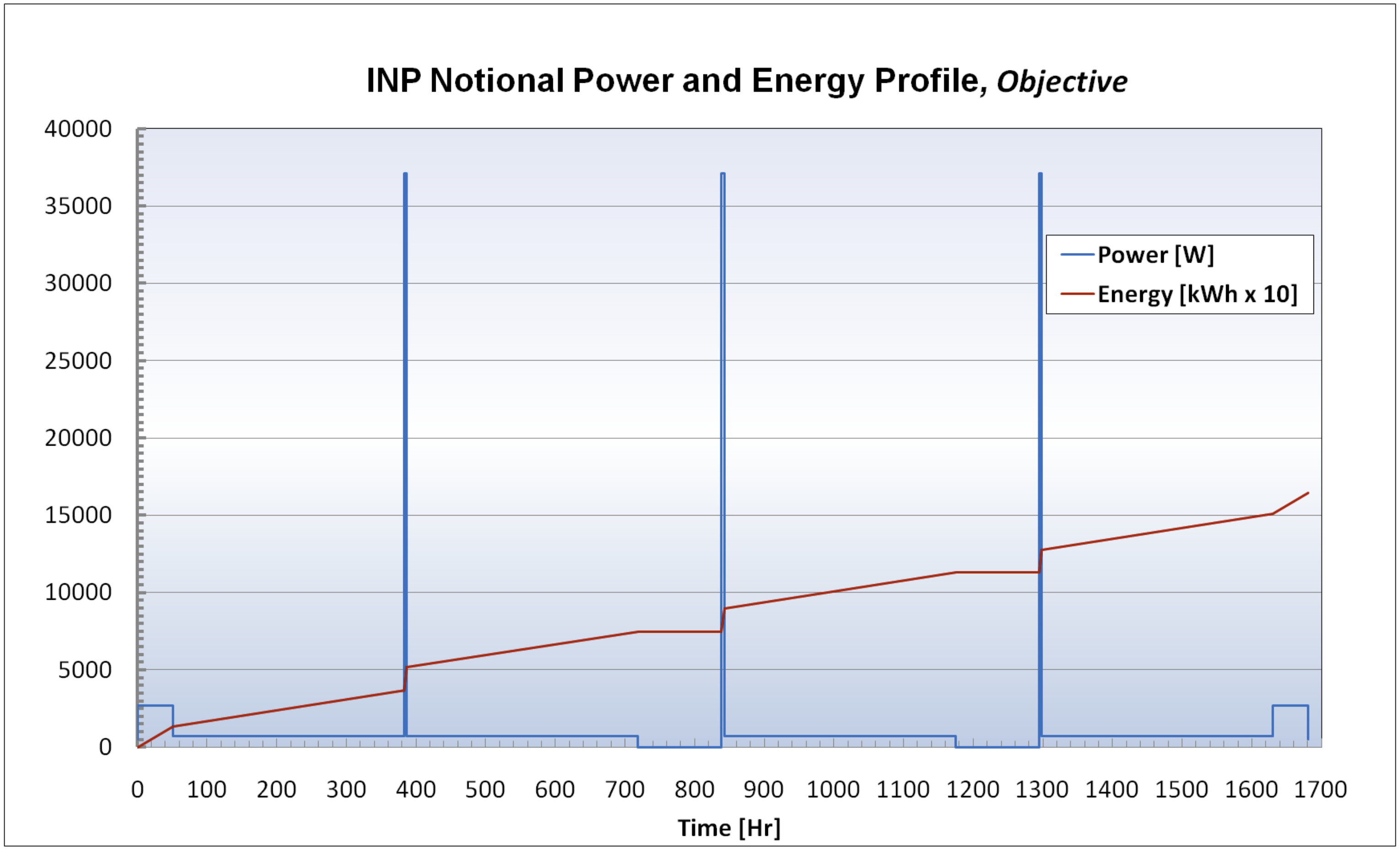
Hydrogen fuel cells for unmanned undersea vehicle propulsion



PRIME 2016/230th ECS Meeting, October 2-7, 2016, Honolulu, Hawaii

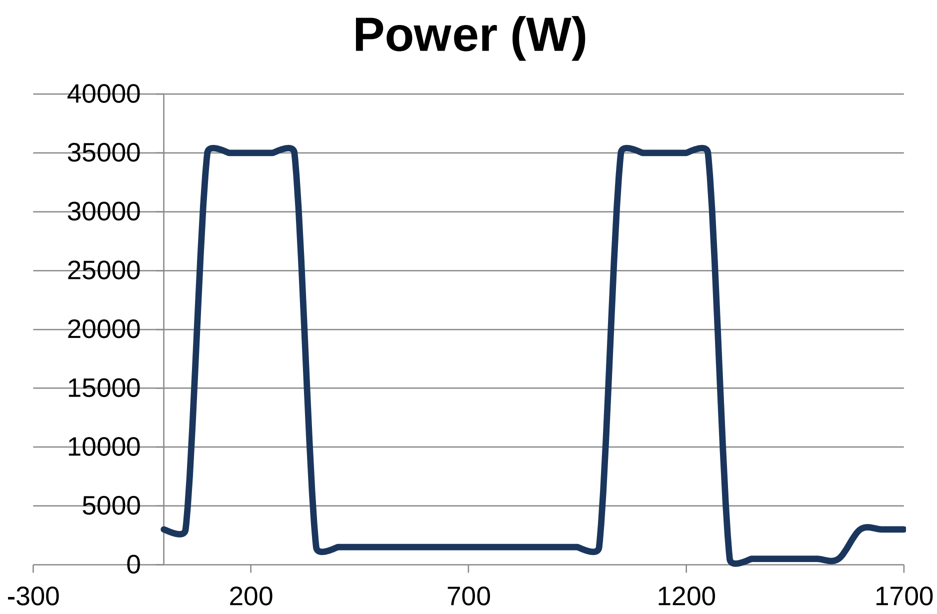
What is the best power system for a UUV?



from: ***Large Displacement Unmanned Undersea Vehicle Innovative Naval Prototype Industry Day, March 10, 2011.***

Short bursts of 37 kW with 1.5 kW base load
Looks ideal for hybrid small fuel cell (~ 5kW) + batteries

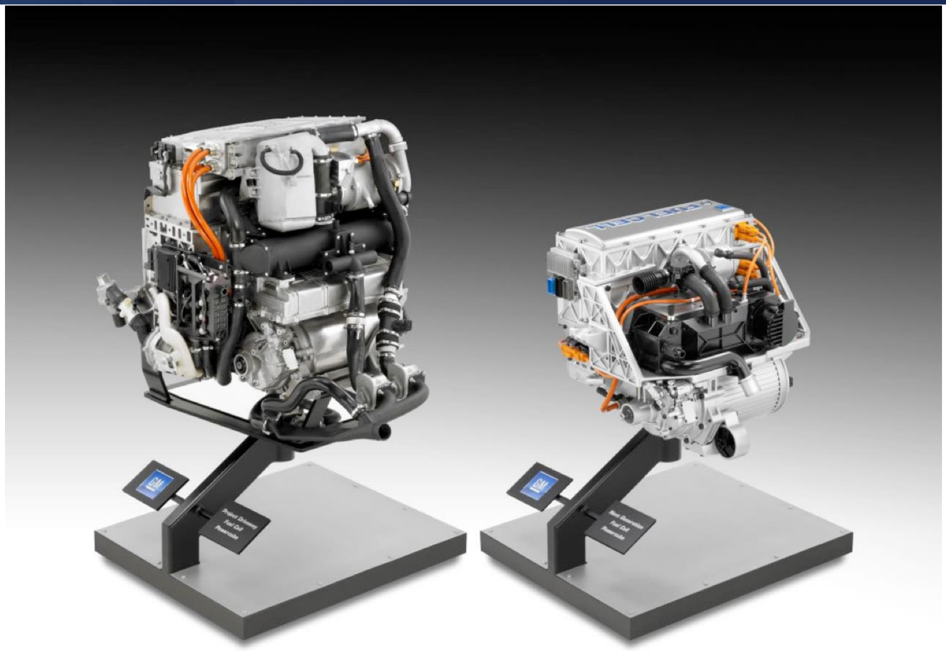
But what if…



If future missions determine that high power is needed for longer periods…

Small fuel cell with battery not an option.

Automotive fuel cells commercially available



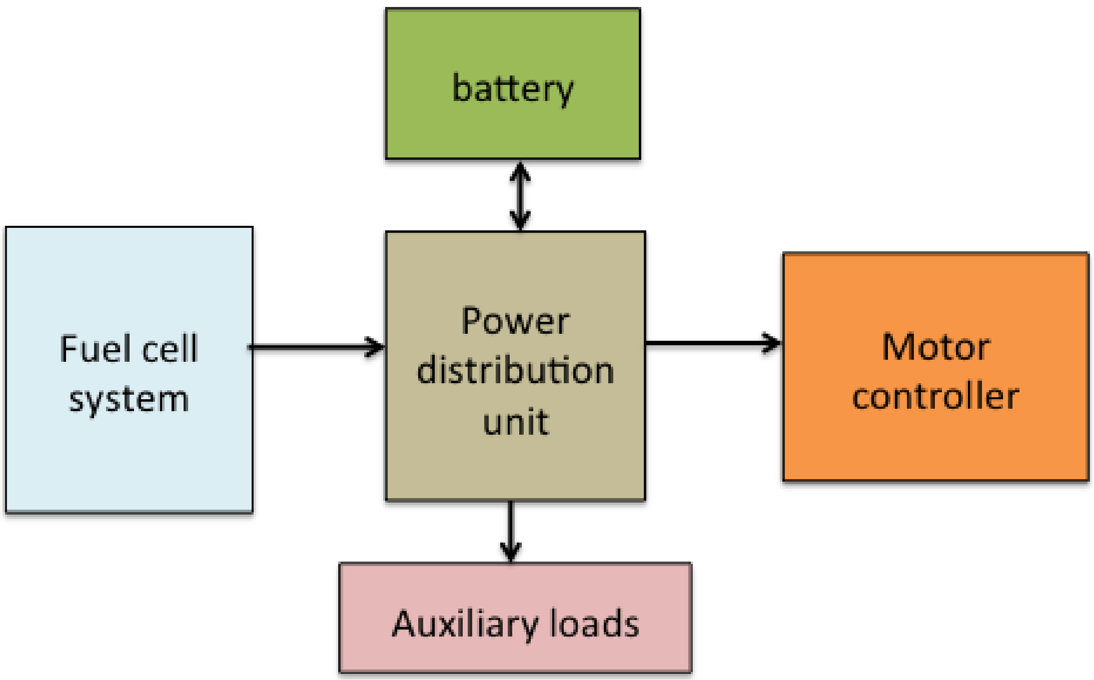
GM Project Driveway Fuel Cell Powercube   GM Next Generation Fuel Cell Powercube

- **Automotive fuel cells nominally 93 kW**
- **NRL-ONR program based around General Motors fuel cell system**
- **GM has demonstrated over 3 million road miles on “4.5” system used in Chevy Equinox/Project Driveway**
- **GM moving to smaller system with Honda**

Fuel cell power train

Much work needed on power distribution

- Safety
- Power arbitration of battery and motor with fuel cell
  - *Fuel cell must be ready to respond to changes in load*



Status of NRL-GM-ONR program (2016)

- **Air independent brass board system developed**
  - 500 h (3 week) operation of fuel cell in hybrid mode
  - Additional 1000 h under water operation
  - Full demonstration of system in Hydranox vehicle
    - Prototype for fuel cell power train
    - end-to-end demonstration of all of the controls for the full power hybrid power train in a fully submerged vehicle while operating the motor/propeller and control surfaces.

- **Parallel effort on fueling structure with H2 and O2.**
  - System under test at NASA White Sands, NM

Acknowledgements

UAV work: Michele Anderson and Richard Carlin, ONR Code 33
UUV work: Dan Deitz and Jon Erickson, ONR Code 32