Hydrogen Fuel Cells for Small Unmanned Air Vehicles

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Presenter:

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DOE Host:

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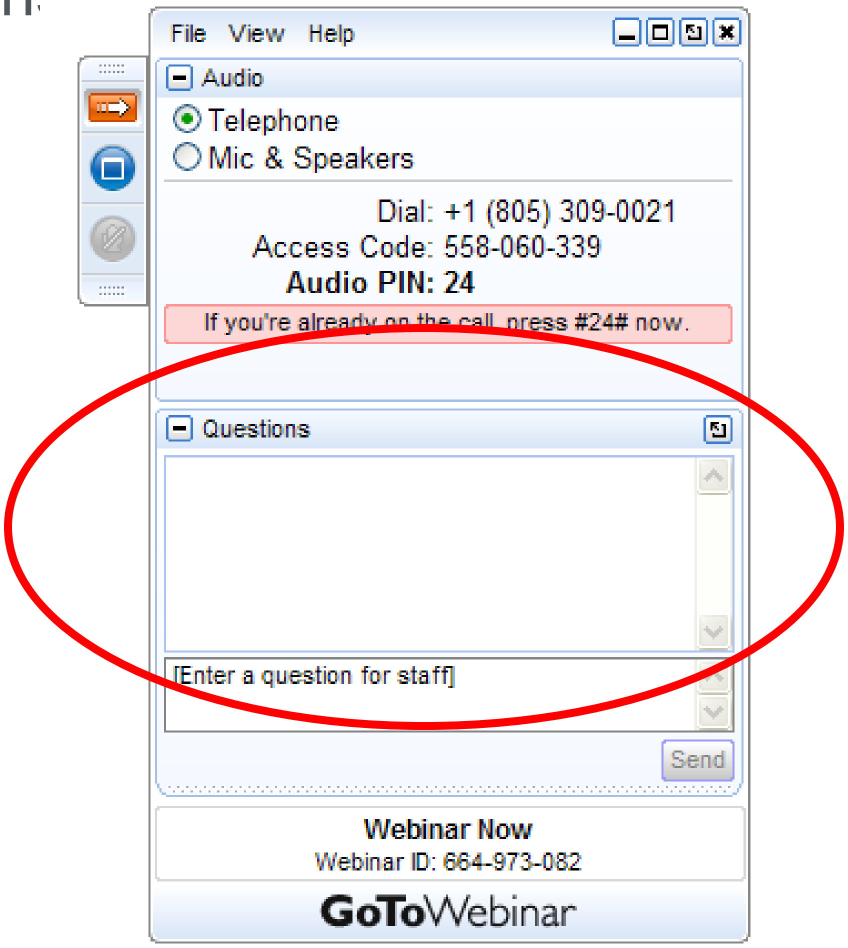
U.S. Department of Energy

Fuel Cell Technologies Office

May 26th, 2016

Question and Answer

- Please type your questions into the question box



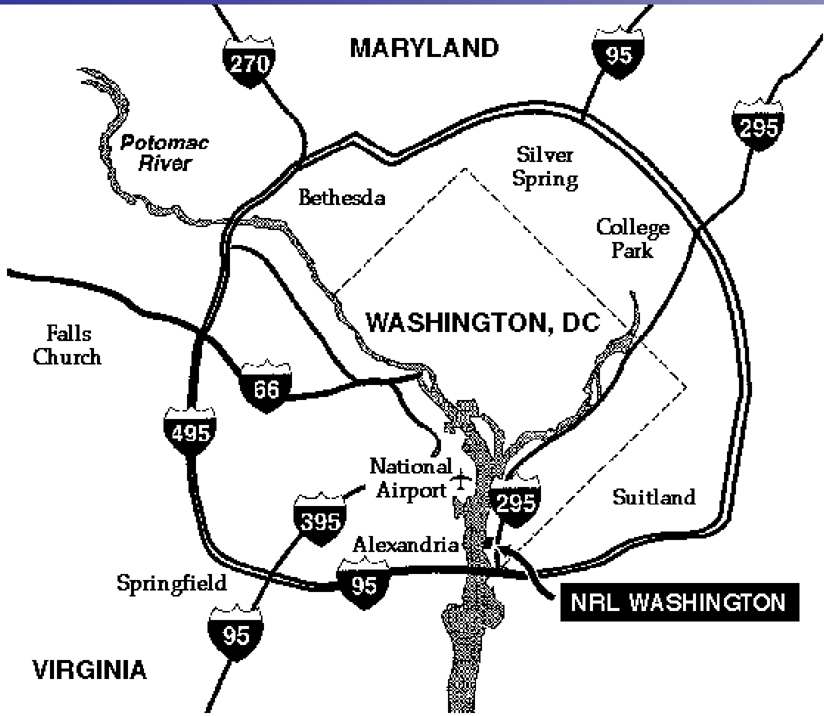
Hydrogen Fuel Cells for Small Unmanned Air Vehicles

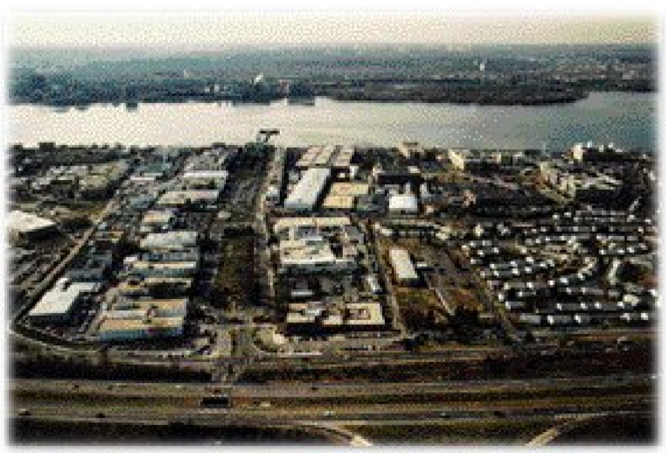
Karen Swider-Lyons
US Naval Research Laboratory
Code 6113, Alternative Energy Section, Chemistry Division

DOE webinar

26 May 2016

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

Motivation for High Power Fuel Cell Propulsion

Fuel cell advantages:

- Higher energy than batteries
- Higher efficiency than engines

  Small engines ~10% efficient

  Fuel cells ~45% efficient

Benefits for UAVs:

- 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's Dragon Eye UAV

Hydrogen Fuel

Compressed hydrogen gas only viable option for automotive industry

<u>High energy fuel</u>

–Up to 10,000 psi in development

Chevy Equinox – GM Project Driveway

ADVANTAGES

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

–No waste produced (only H_2O)

DISDAVANTAGES

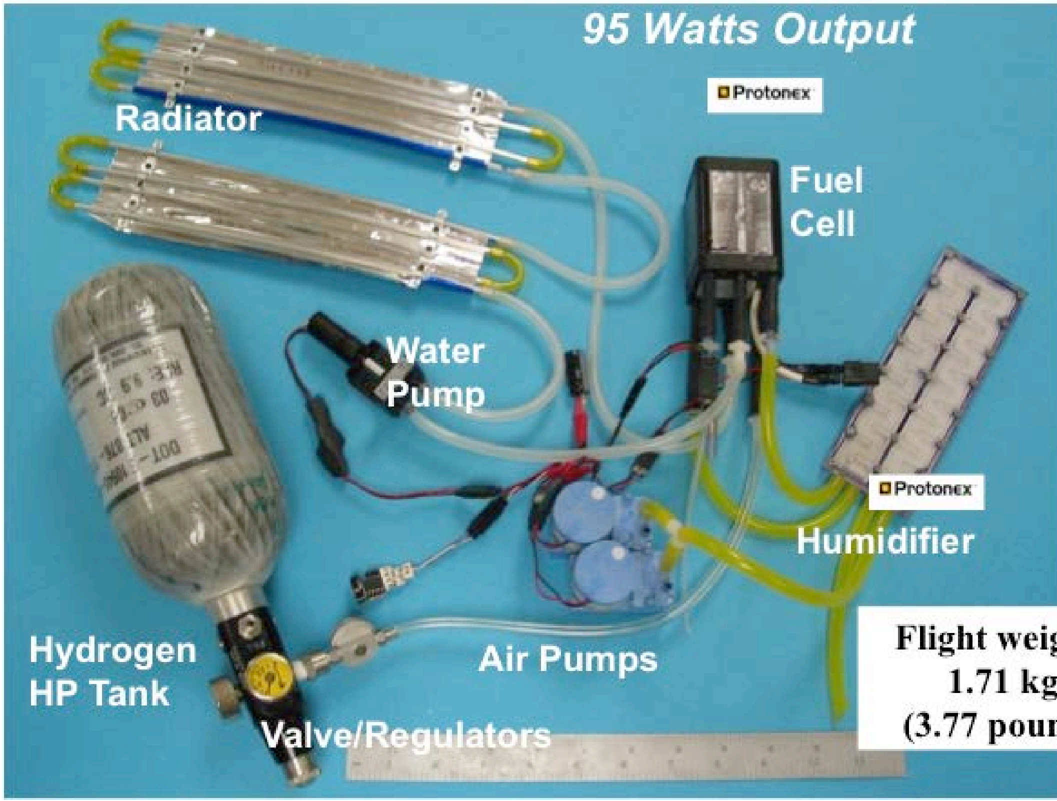
–Difficult logistics for remote land locations

–Large storage volume (but OK for UAVs)

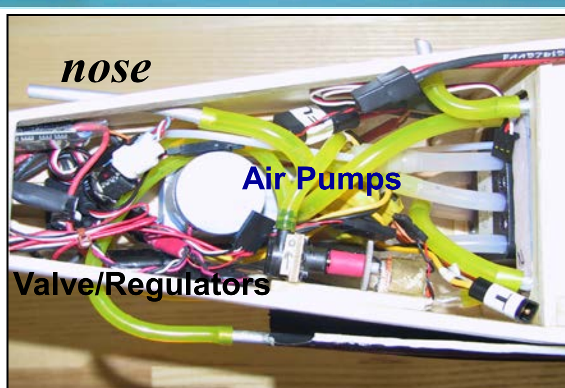
New airvehicle propulsion system - hydrogen fuel cell

NRL Chemistry and Tactical Electronic Warfare Divisions

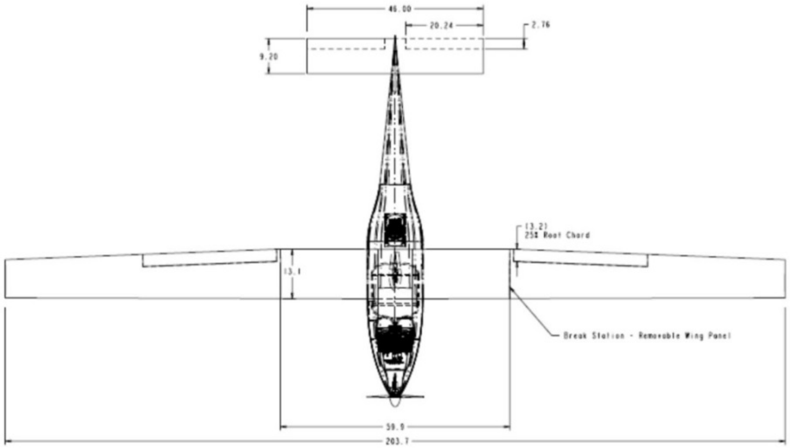
Spider-Lion: Nov 2005: 15 g H2 (2 w%) 3 Hr 19 minutes

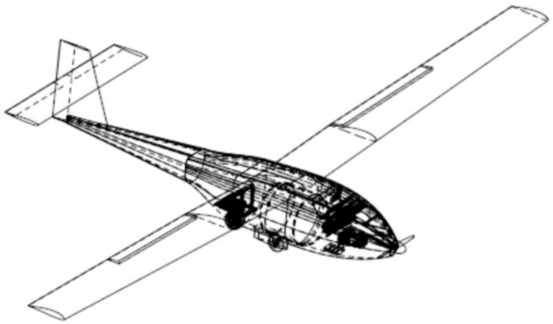


Flight weight:
1.71 kg
(3.77 pounds)



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





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

Hydrogen Fuel Cells

All Hands Television video 2009

(4 minutes and 11 s)


2016-05-26 Hydrogen Fuel Cell for Unmanned Airvehicles
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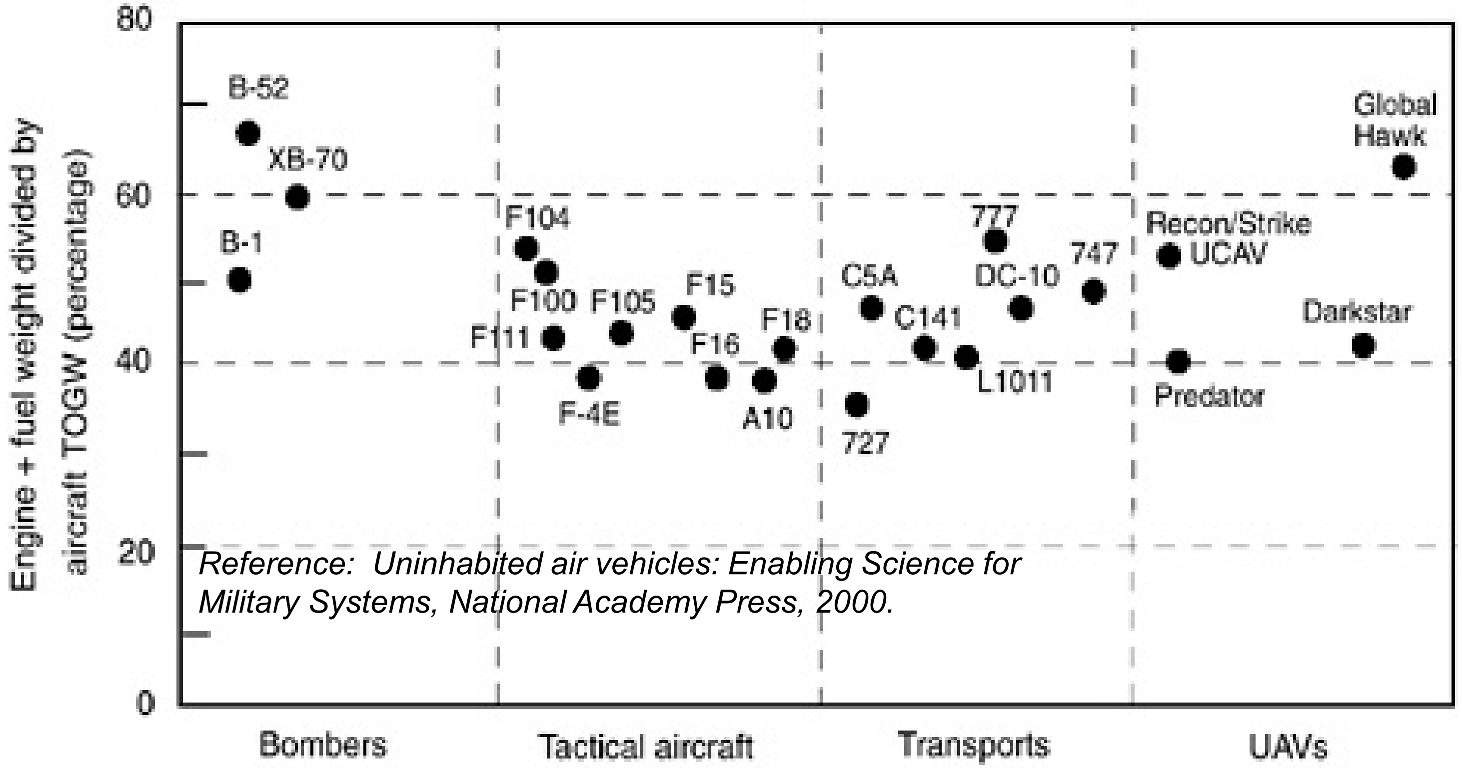
Propulsion system weight vs. gross takeoff weight



Reference: Uninhabited air vehicles: Enabling Science for Military Systems, National Academy Press, 2000.

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

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

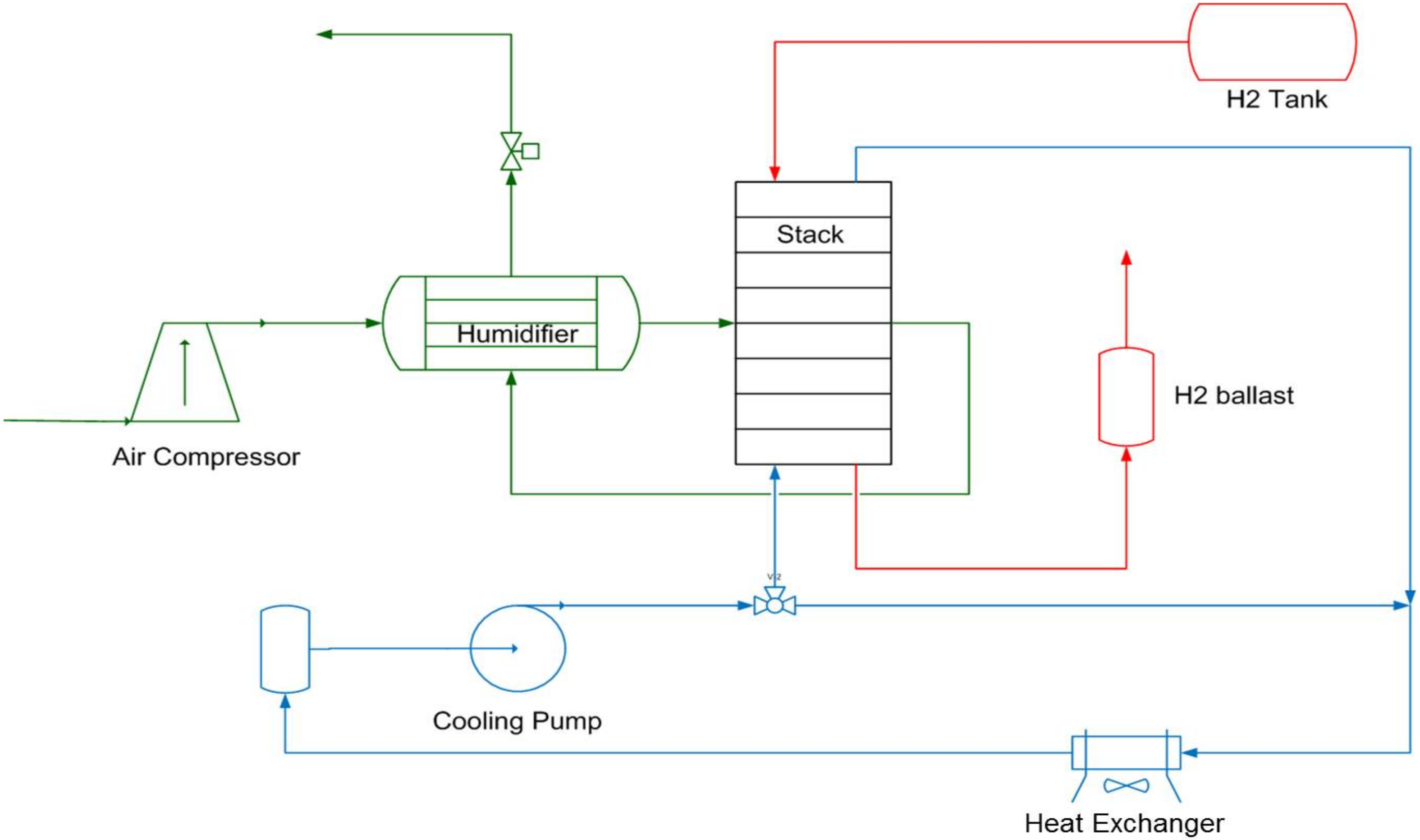
- Wing Area 16.9 ft^2
- Span 17.0 ft
- Aspect Ratio 17
- Length 7.9 ft
- L/D 17

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

Key design point – WEIGHT!!!

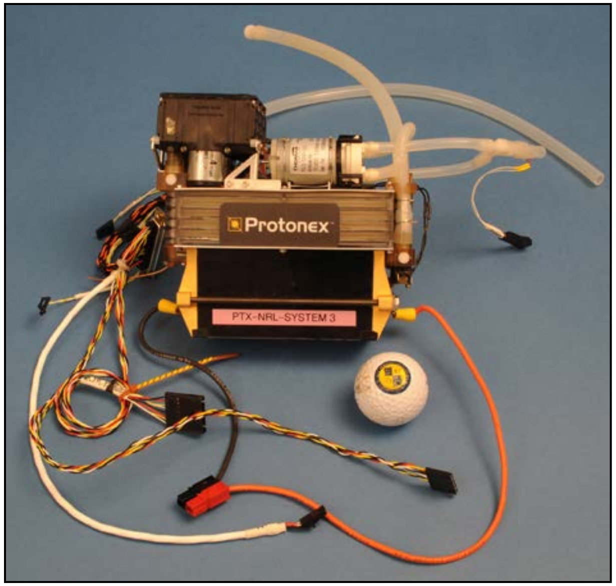
Attempts to identify a COTS airframe capable of carrying the fuel tank were unsuccessful, necessitating a custom airframe design.

Schematic of Fuel Cell System

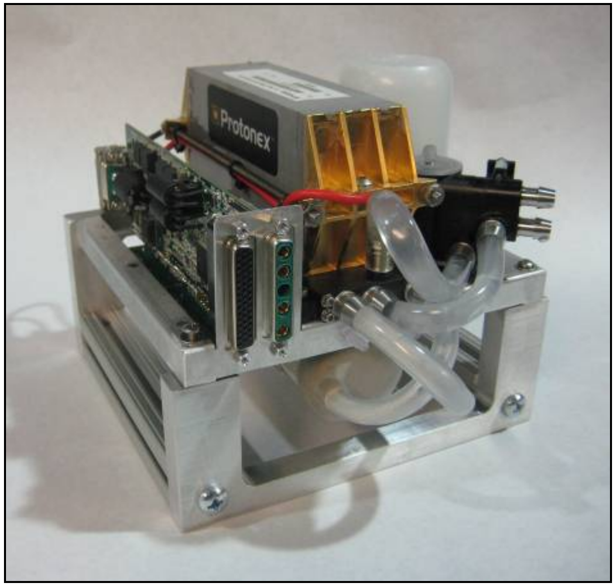


The sizing of the system is determined largely by the interrelated properties of the stack, compressor and heat exchanger.

Progression of Flight-Weight Fuel Cell Systems



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



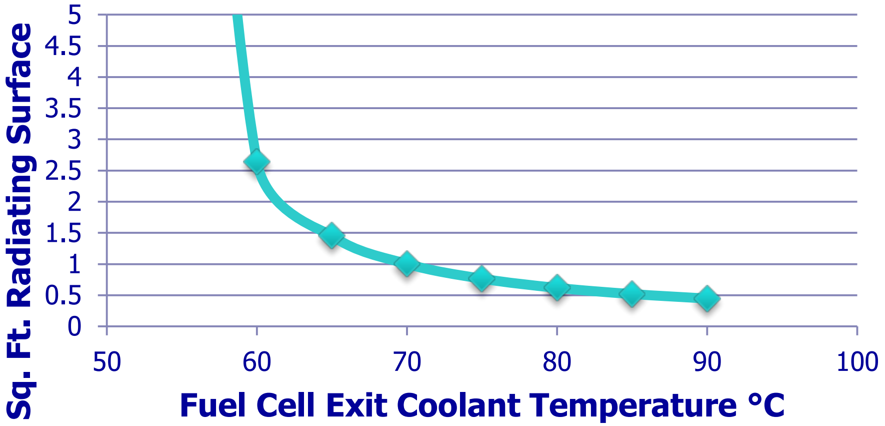
Ion Tiger Program Product:
- ***1 kg and 550 W net***

New components/features
- **new humidifier design**
- **new air blower**
- **higher power stack**
- **integrated control electronics**
- **99% H_2 utilization**

POWERED BY
Protonex

Ion Tiger Radiator Cooling System 120 ° F/49 ° C ambient operation

At start of program, fuel cell could not operate above 60 °C
Requires 7x larger radiator vs fuel cell that operates at 80 °C



$$dQ/_{dt} = h\,A[T(t)_{HEX} - T_{ambient}]$$

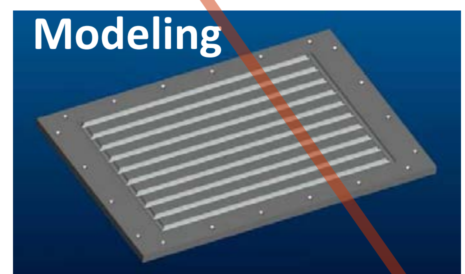
$$A = \frac{dQ/_{dt}}{h\,\Delta\,T(t)_{HEX-ambient}}$$

Improvement for Ion Tiger: Incorporate new fuel cell membranes with higher temperature capability – operation at higher temperatures even better!

Ion Tiger Radiator Cooling System

New radiator enables Ion Tiger operation in 120°F environment

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



Operation in warmer environments

Enabled by technical solutions:

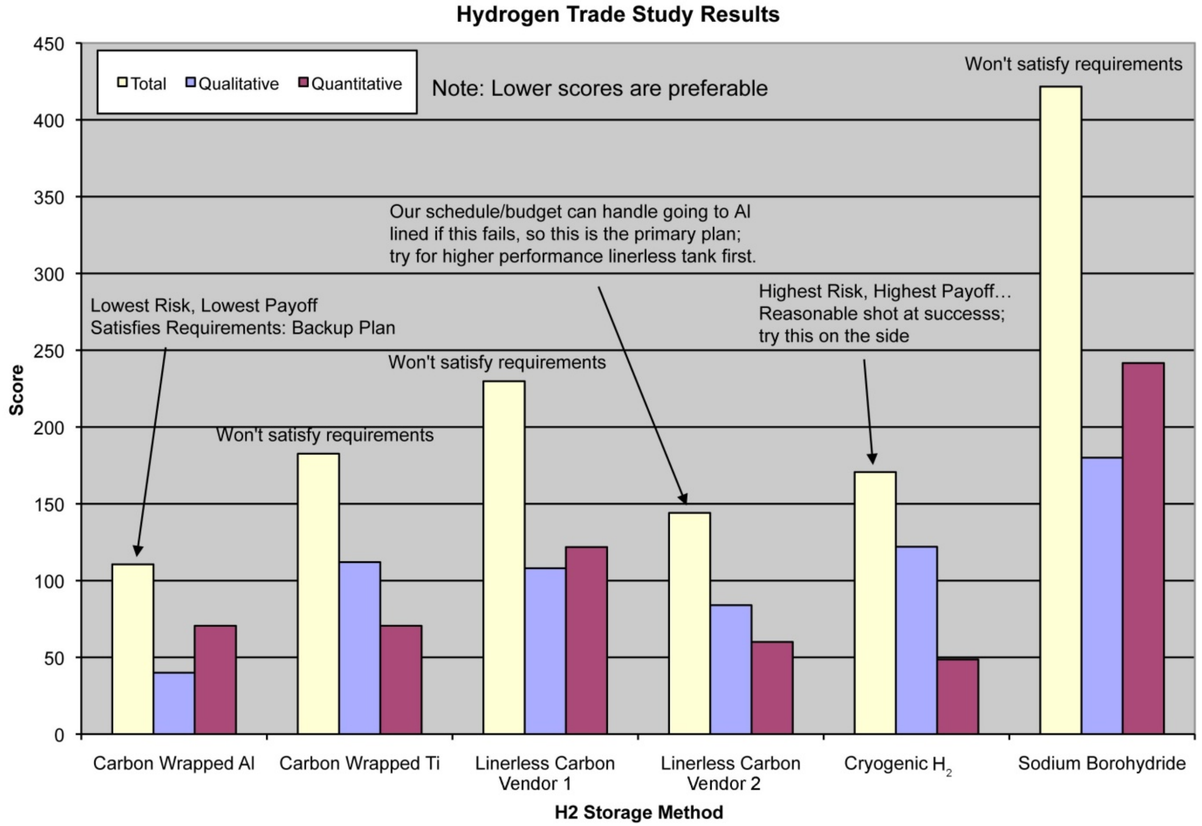
- Lightweight radiator with improved heat transfer
- Higher fuel cell temperature with robust humidifier design and stack membranes

Solutions came from:

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

NRL H_2 Storage Trade Study

- H_2 storage trade study for UAVs in Ion Tiger Program
- Major Conclusions
  - 5000 psi GH_2 could support 1 day flight; lowest technical risk
  - LH_2 could support up to 3 day flight; much higher technical risk
  - Assumed existing Ion Tiger airframe; larger aircraft → longer flight endurance



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**
<u>Lower safety factor allowed for aerospace</u>

Ion Tiger Hydrogen fuel cell UAV

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

26 h 1 min flight
16-17 November 2009 with
5 lb payload
5000 psi H_2 (500 g)

48 h flight April 2013 with
liquid hydrogen

"unofficial" world records
for fuel cell powered flight"

Energy of Fuel Cells vs. Batteries for Ion Tiger system

16 kg GTOW - 38 wt% fuel cell propulsion plant

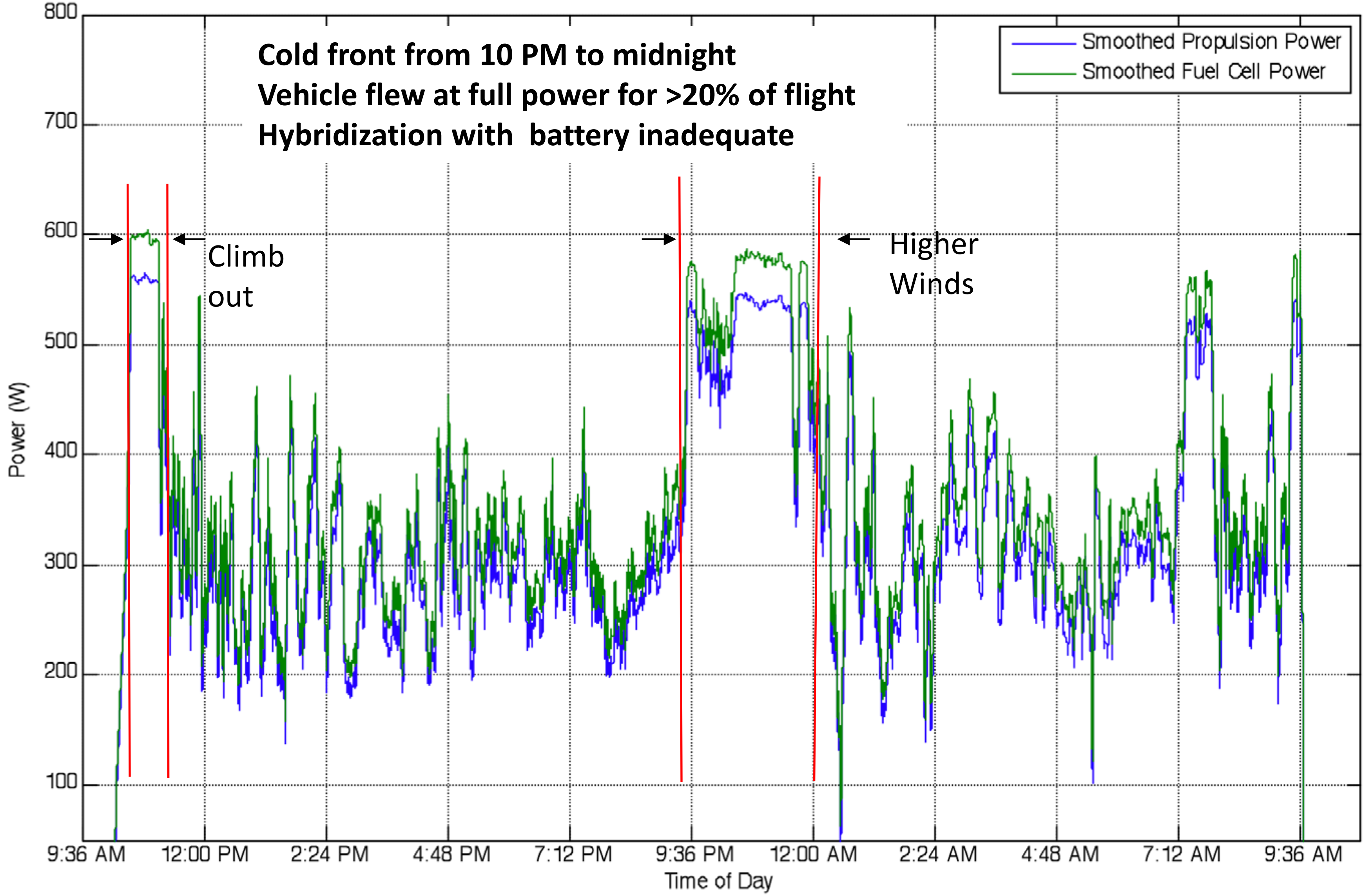
- 7 kg fuel cell propulsion system (with fuel and cooling)

  = 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

Power profile for 23 hr flight

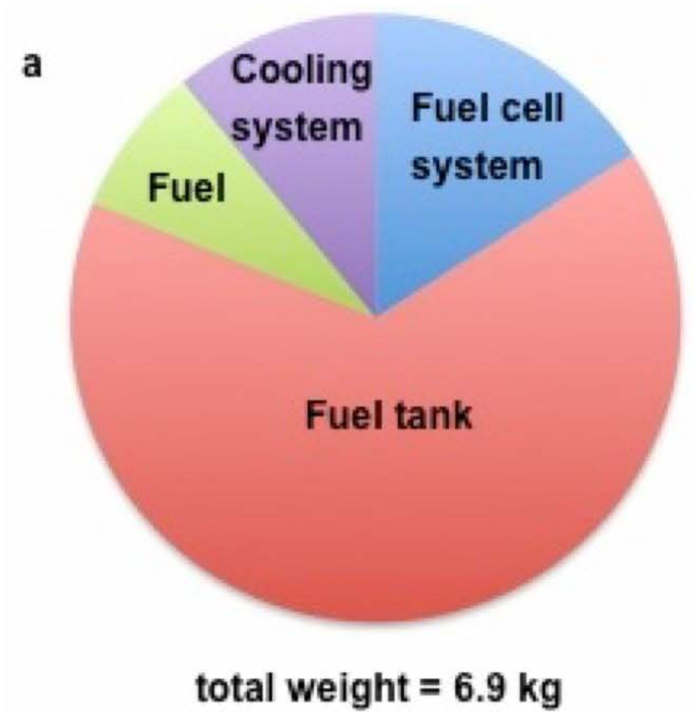


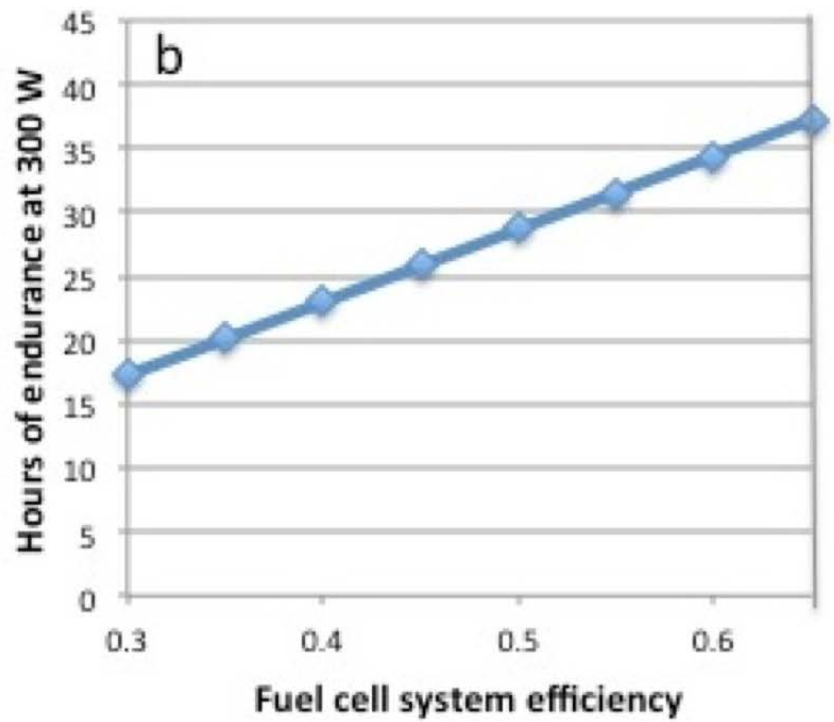
System level considerations

"Hybridization" not appealing 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 have to fly into head wind for sustained periods of time*
- May be an opportunity for load leveling if we can get small high power batteries

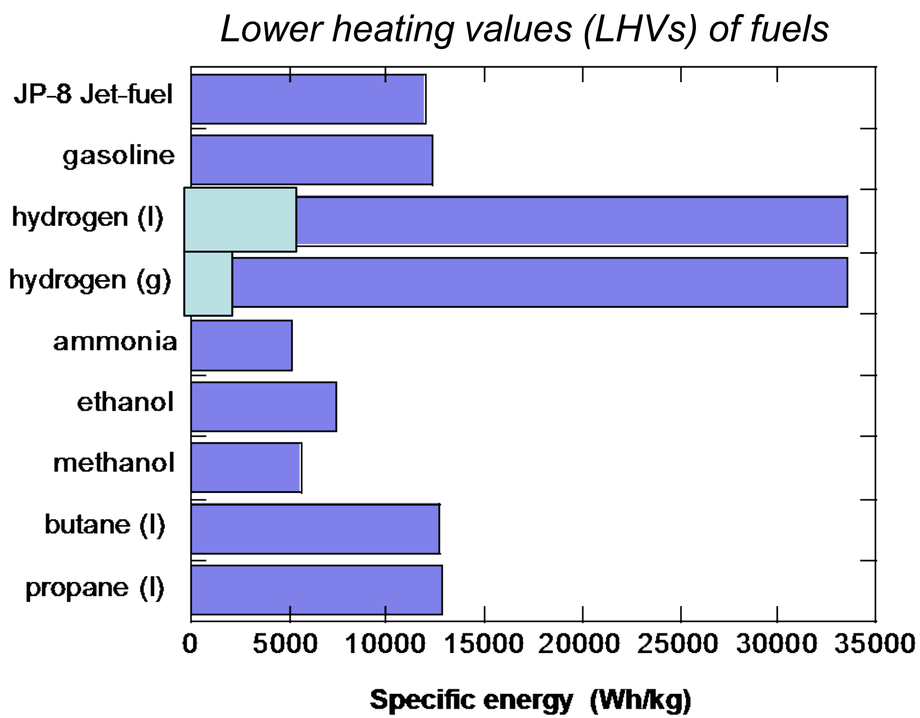
Role of efficient electrocatalysts





"Hydrogen Fuel Cells for Small Unmanned Air Vehicles," K. Swider-Lyons, R. O. Stroman, B. D. Gould, J. A. Rodgers, J. Mackrell, M. Schuette, G. Page, ECS Trans. 2014 64(3): 963-972; doi:10.1149/06403.0963ecst

Gaseous v liquid hydrogen

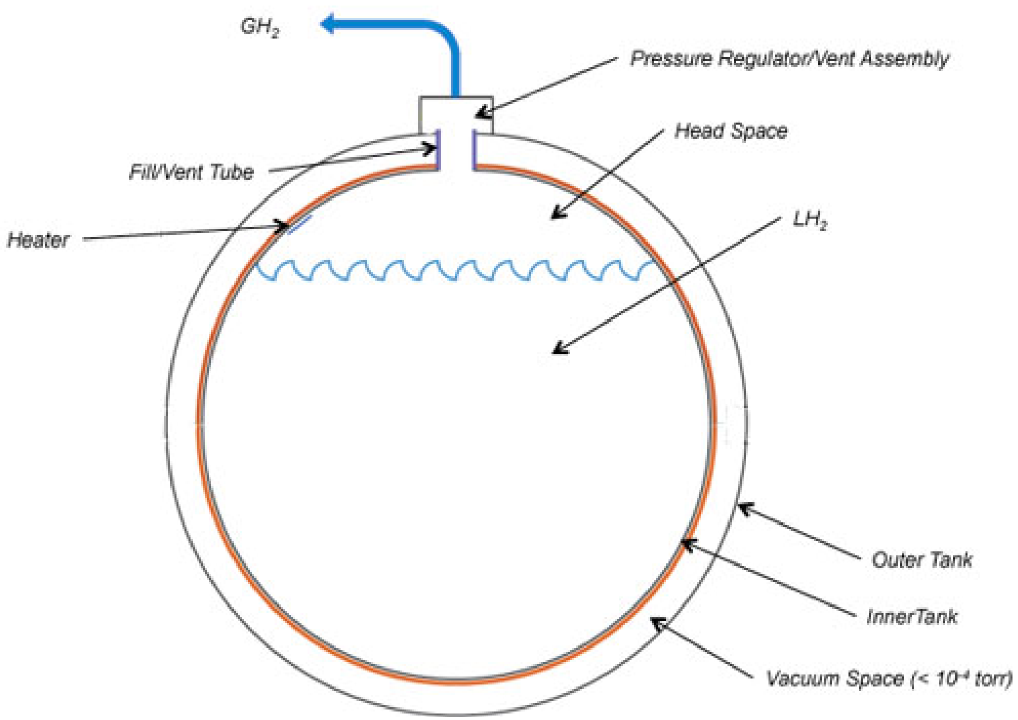


- Liquid hydrogen is 3x denser than gaseous H2 at 5000 psi
- No need for "heavy" high pressure storage tank
  - GH2 = 50 psi
- Path to 3 day flights of Ion Tiger and 3000 Wh/kg system

48-h flight 16-18 April 2013

And another unofficial world record!

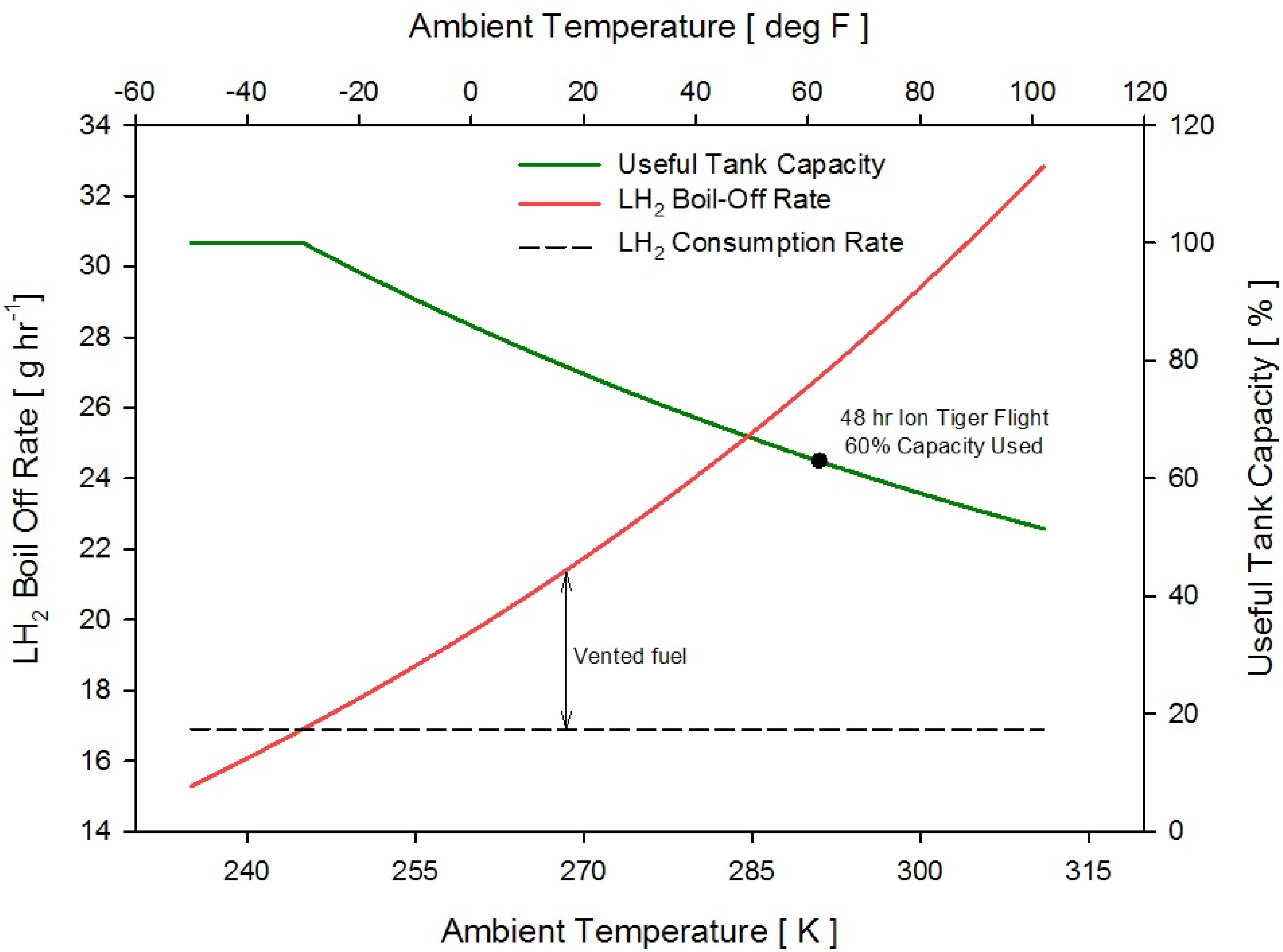
LH2 Design: nested aluminum tanks



- 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)

Managing heat leak vs ambient temperature



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 (volume & weight)
Fly at very cold temperatures.

Ways to “enhance” your flight test

- Choose a nice day for flight test
  - Cool in morning, sun in afternoon with little wind
    - Catch thermals
    - Reduce requirement for radiator
  - For LH2 – choose cold day
    - Decreases H2 boil off and reduces size of radiator
- Don’t carry a payload
  - Reallocate 5 to 7% of vehicle payload weight to fuel or fuel cell

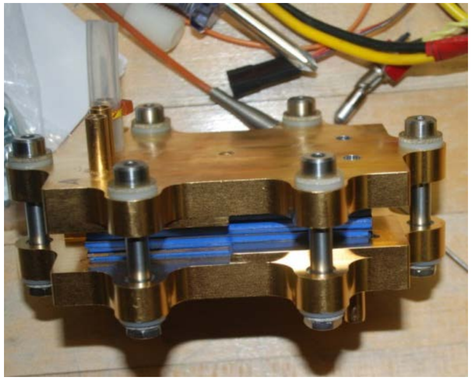
In house development of fuel cells

The NRL crew after the successful flight of a 3-D printed fuel cell aboard the Ion Tiger UAV. Left to right: Dan Edwards, Drew Rodgers, Ben Gould, Steve Carruthers, Mike Schuette, and Karen Swider-Lyons. Not shown: Chris Bovais.

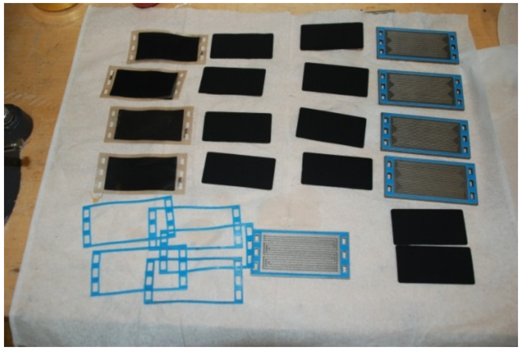
March 2014 ~ 400 W NRL-made stack flown on Ion Tiger

Titanium Bipolar plates by 3D Laser Sintering

Unconstrained gaskets

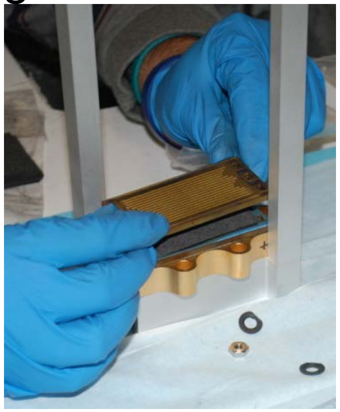


Textured gaskets and BPP w/ gasket constraints



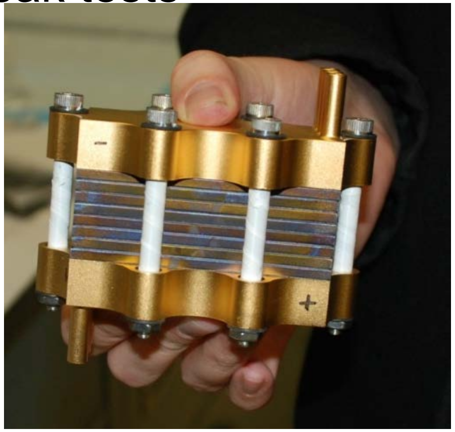
Leak test fixture

Assembly guides and gasket orientation

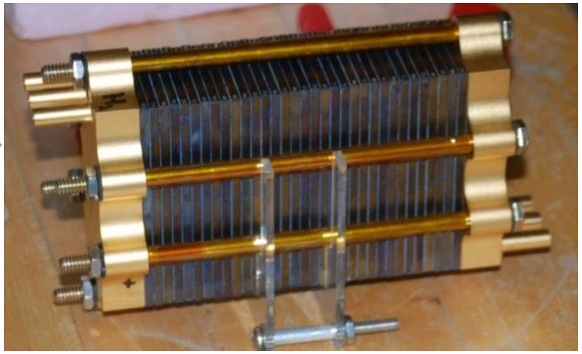


Freudenberg 0.8 mm

1st short stack to pass leak tests



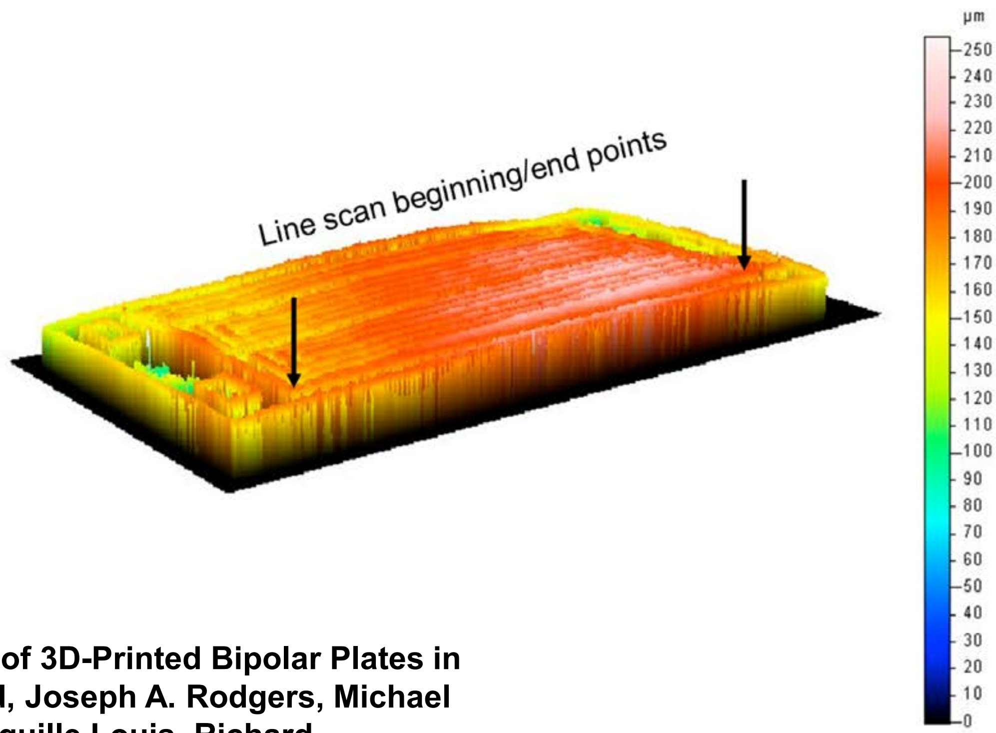
32-cell “full” stack



- Learned to how to seal a stack and how to assemble
- Full stack was showing high cell-to-cell variability and 80% power

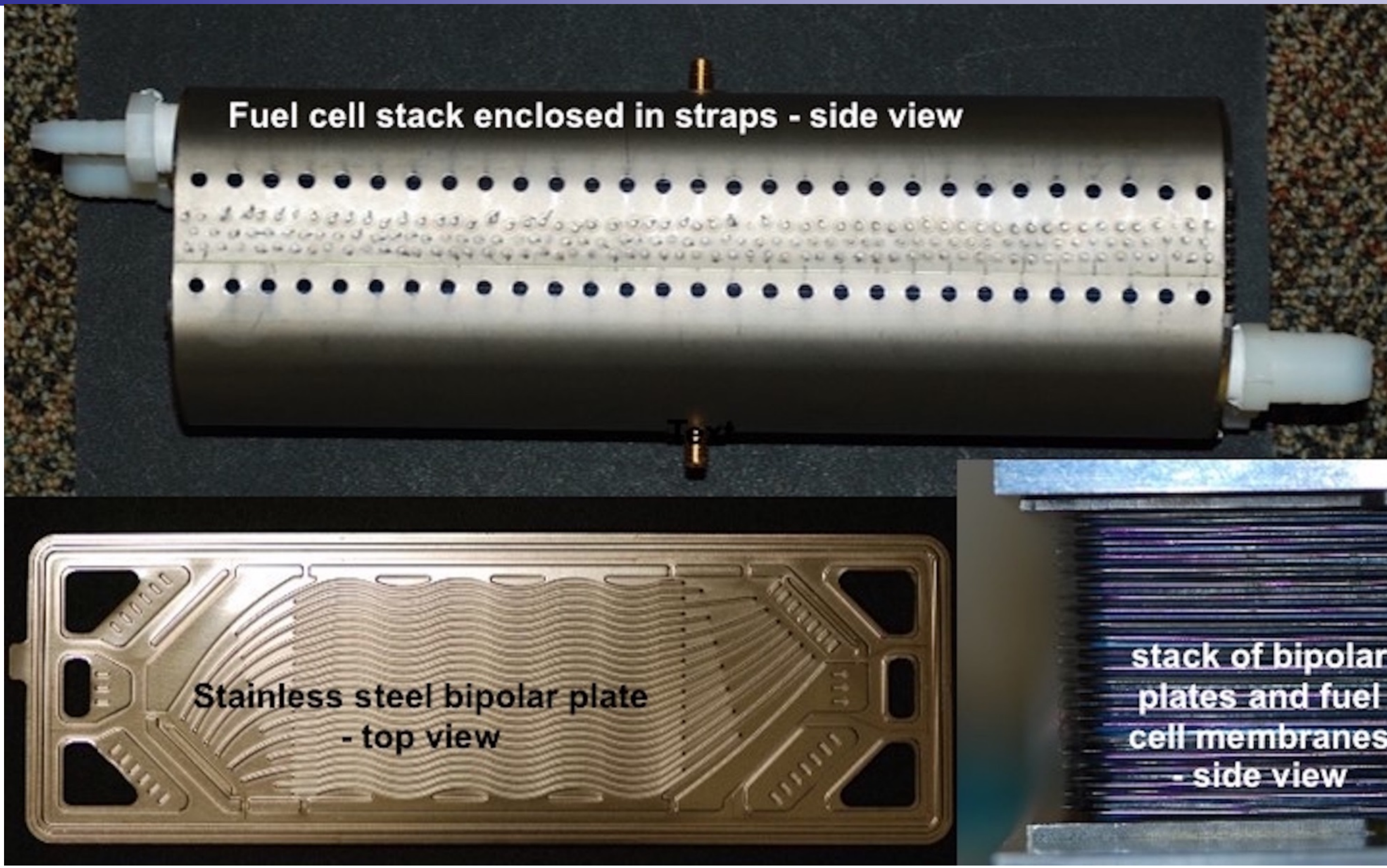
Issues with 3D printed plates

- Insufficient flatness for sealing
- Heavy



Performance and Limitations of 3D-Printed Bipolar Plates in Fuel Cells, Benjamin D. Gould, Joseph A. Rodgers, Michael Schuette, Keith Bethune, Shaquille Louis, Richard Rocheleau, and Karen Swider-Lyons *ECS Journal of Solid State Science and Technology*, **4** (4) P3063-P3068 (2015).

New: NRL's 1.5 to 3 KW fuel cells



Leverage "automotive" technology for stamped bipolar plates

Other vendors of fuel cells for UAVs

- EnergyOR
- Horizon
- UTC
- AMI/Ultra electronics - SOFC

Research toward high performance fuel cell UAVs

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

Are fuel cells for UAVs economically viable?

Cost of Li-ion battery in Raven: $1000
How much can a fuel cell system cost (including H_2 tank)?

$5000? $10,000?
$2000 profit per fuel cell
100 UAVs = $200,000 profit?

Need to sell large volumes of systems, and develop a cost model where long endurance provides economic benefit over battery.

Going green with flight

Global Hawk
~700 gallons or 2272 kg or
or <u>2.5 tons</u> of jet fuel per day

Ion Tiger
500 g of hydrogen per day

For a 20% efficient H_2 generator
<u>2.5 kg</u> of hydrocarbon fuel per day
~900x more efficient

How many small UAVs can be used to replace one large UAV?
Missions: military (intelligence surveillance)/ commercial: communications, etc

Some parting thoughts

- The fuel cells are here
- UAVs are here.
- We need lower cost fuel cells and low-cost, practical H_2 fueling to make these ubiquitous

Some References

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- K. Swider-Lyons, R. Stroman, B.D. Gould, J. Rodgers, J. Mackrell, M. Schuette, G. Page, “Hydrogen fuel cells for small unmanned air vehicles,” ECS Trans. 2014 volume 64, issue 3, 963-972.
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Thank you!

Michele Anderson and Richard Carlin, ONR Code 33

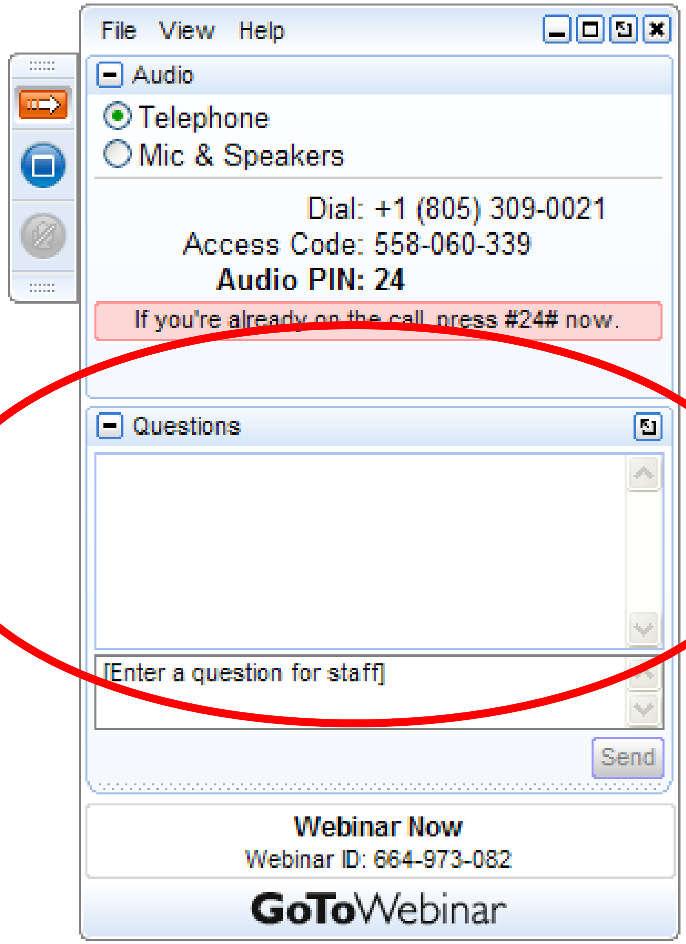
NRL's Ion Tiger team:
Benjamin Gould, Richard Stroman, Drew Rodgers, Joe Mackrell,
Mike Schuette, Greg Page, Alvin Cross, Steve Carruthers, Dan Edwards

Doug Wheeler
LH2 fueling system on loan from General Motors

Special thanks to: Keith Bethune, University of Hawaii

Question and Answer

- Please type your questions into the question box



Thank You

Presenter(s):

•Karen Swider-Lyons : US Naval Research Laboratory

DOE Host:

•Pete Devlin : Market Transformation Manager, DOE Fuel Cell Technologies Office

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