Hydrogen Fuel Cells for Small Unmanned Air Vehicles

Presenter:
Karen Swider-Lyons : US Naval Research Laboratory

DOE Host:
Pete Devlin : Market Transformation Manager, FCTO

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• Please type your question 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
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
High energy fuel
  – Up to 10,000 psi in development

**ADVANTAGES**
– Responds immediately to change in load – *can be throttled*
– No waste produced (only H$_2$O)

**DISADVANTAGES**
– 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)
• 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 ft²
• 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.
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% H₂ utilization
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

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

\[ \frac{dQ}{dt} = hA[T(t)_{\text{HEX}} - T_{\text{ambient}}] \]

\[ A = \frac{dQ/dt}{h \Delta T(t)_{\text{HEX-ambient}}} \]
Ion Tiger Radiator Cooling System

New radiator enables Ion Tiger operation in 120°F environment

✓ Developed analytical tools for future designs/improvements

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 \( \text{H}_2 \) Storage Trade Study

- \( \text{H}_2 \) storage trade study for UAVs in Ion Tiger Program
- **Major Conclusions**
  - 5000 psi \( \text{GH}_2 \) 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 H₂ Tanks

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

500 g hydrogen storage in 22-L tank weighing 3.6 kg (8 lbs)
including 0.15 kg regulator = 13% H₂ storage

Lower safety factor allowed for aerospace
Ion Tiger Hydrogen fuel cell UAV

26 h 1 min flight
16-17 November 2009 with
5 lb payload
5000 psi H₂ (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\textsubscript{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

- Cold front from 10 PM to midnight
- Vehicle flew at full power for >20% of flight
- Hybridization with battery inadequate

Climb out

Higher Winds
“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

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

Managing heat leak vs ambient temperature

Options: decrease LH₂ boil off through increased insulation (volume & weight)
Fly at very cold temperatures.

\[ Q = \sigma (T_1^4 - T_2^4) \]

\( T_1 = 20 \text{ K} \)
\( T_2 = \text{ambient} \)

Stefan- Boltzmann
Radiative heat transfer
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

3-D Printing in Hydrogen Fuel Cells for Unmanned Systems

March 2014 ~ 400 W NRL-made stack flown on Ion Tiger
Titanium Bipolar plates by 3D Laser Sintering

Unconstrained gaskets

Assembly guides and gasket orientation

Freudenberg 0.8 mm

Textured gaskets and BPP w/ gasket constraints

1st short stack to pass leak tests

Leak test fixture

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

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

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<th>Improved fuel cells</th>
<th>Aerodynamics</th>
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<td>More efficient/effective catalysts</td>
<td>Low drag vehicles</td>
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<tr>
<td>Improved hydrogen/oxygen diffusion</td>
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<td>Higher performance polymer electrolyte membranes</td>
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**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 H₂ 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.
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 H₂ generator
2.5 kg 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

Thank you!

*Michele Anderson and Richard Carlin, ONR Code 33*

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LH2 fueling system on loan from General Motors

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Question and Answer

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Presenter(s):
• Karen Swider-Lyons : US Naval Research Laboratory

DOE Host:
• Pete Devlin : Market Transformation Manager, DOE Fuel Cell Technologies Office
  – Peter.Devlin@ee.doe.gov

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