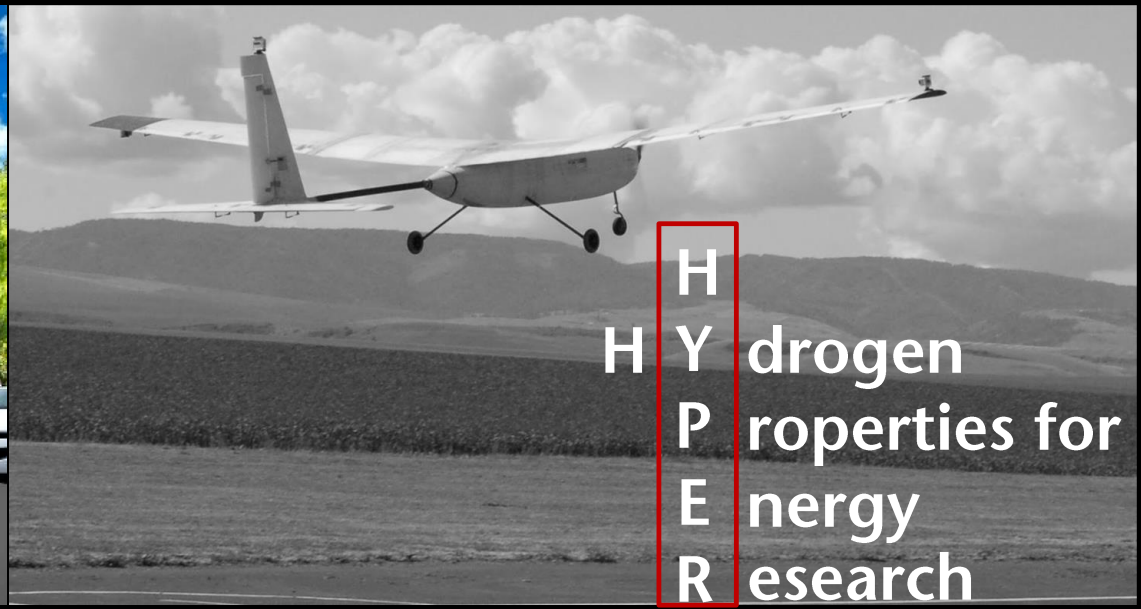
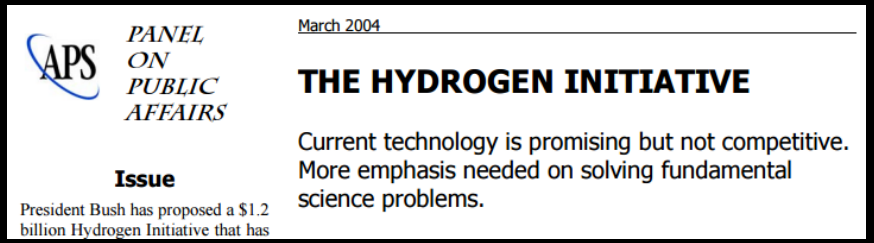
A Hydrogen Economy for Washington State and Jefferson County



Jacob Leachman, Ph.D.
Assistant Professor, co-Founder Protium Innovations LLC
School of Mechanical & Materials Engineering
jacob.leachman@wsu.edu (509)335-7711
http://hydrogen.wsu.edu

WASHINGTON STATE UNIVERSITY

Hydrogen In the News:



APS PANEL ON PUBLIC AFFAIRS

March 2004

THE HYDROGEN INITIATIVE

Current technology is promising but not competitive. More emphasis needed on solving fundamental science problems.

Issue

President Bush has proposed a $1.2 billion Hydrogen Initiative that has

SCIENTIFIC AMERICAN™

Automakers Launch Hydrogen Cars

The market is finally ready for electric vehicles, powered by fuel cells, argue Honda, Hyundai and Toyota

November 21, 2013

MIT Technology Review

Forget Hydrogen Cars, and Buy a Hybrid

By Kevin Bullis on December 12, 2014

WIRED

Elon Musk Calls Hydrogen Fuel Cell Cars 'Bullsh*t'

BY DAMON LAVRINC 10.22.13 | 5:32 PM | PERMALINK

The Path to H_2:

1) Making H_2:

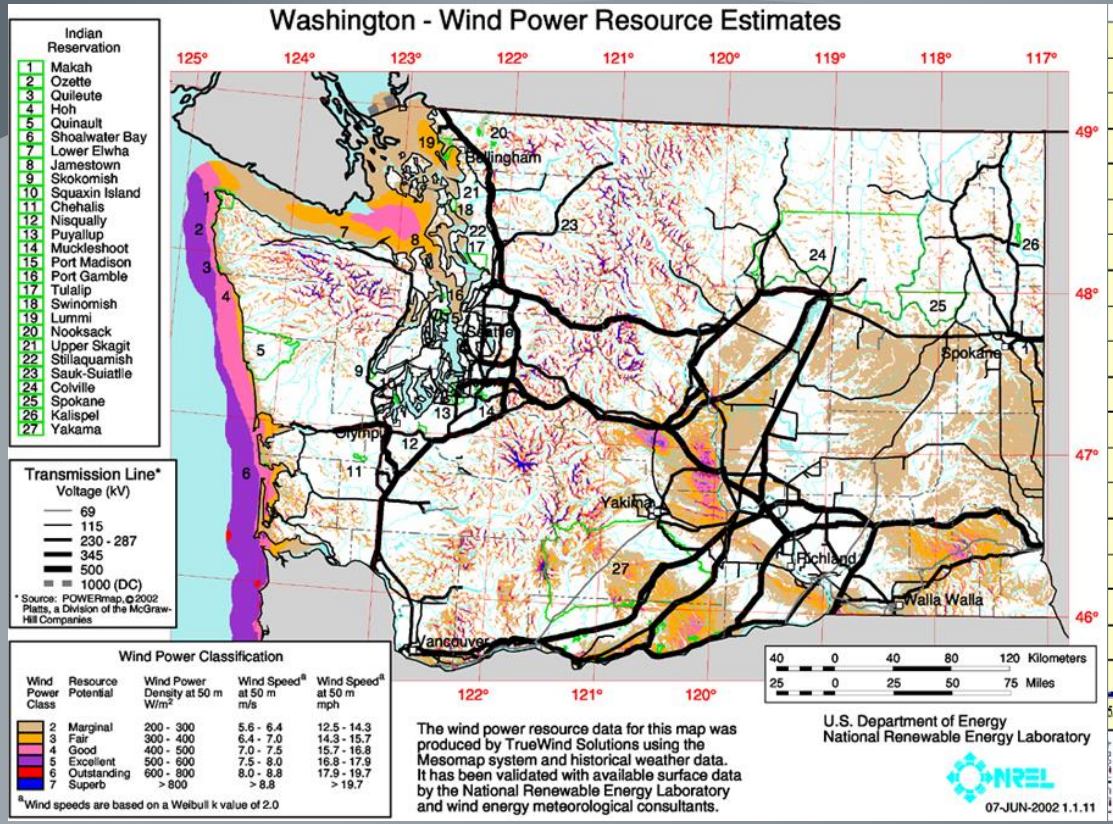
"Sure I'll take that energy off your hands… it'll cost you."

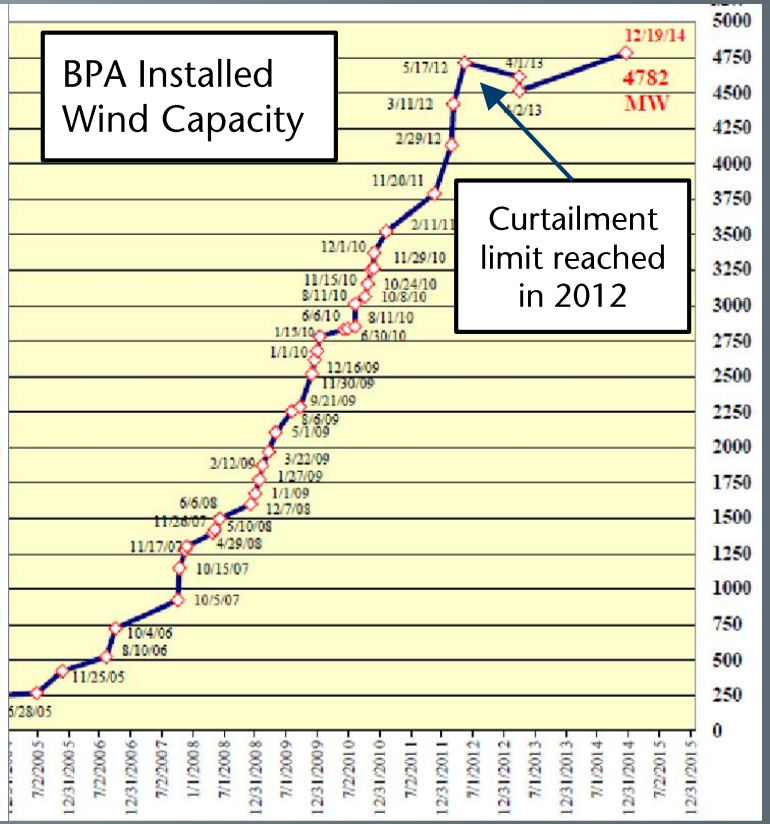
2) Storing H_2:

3) Vending H_2:

4) Using H_2:

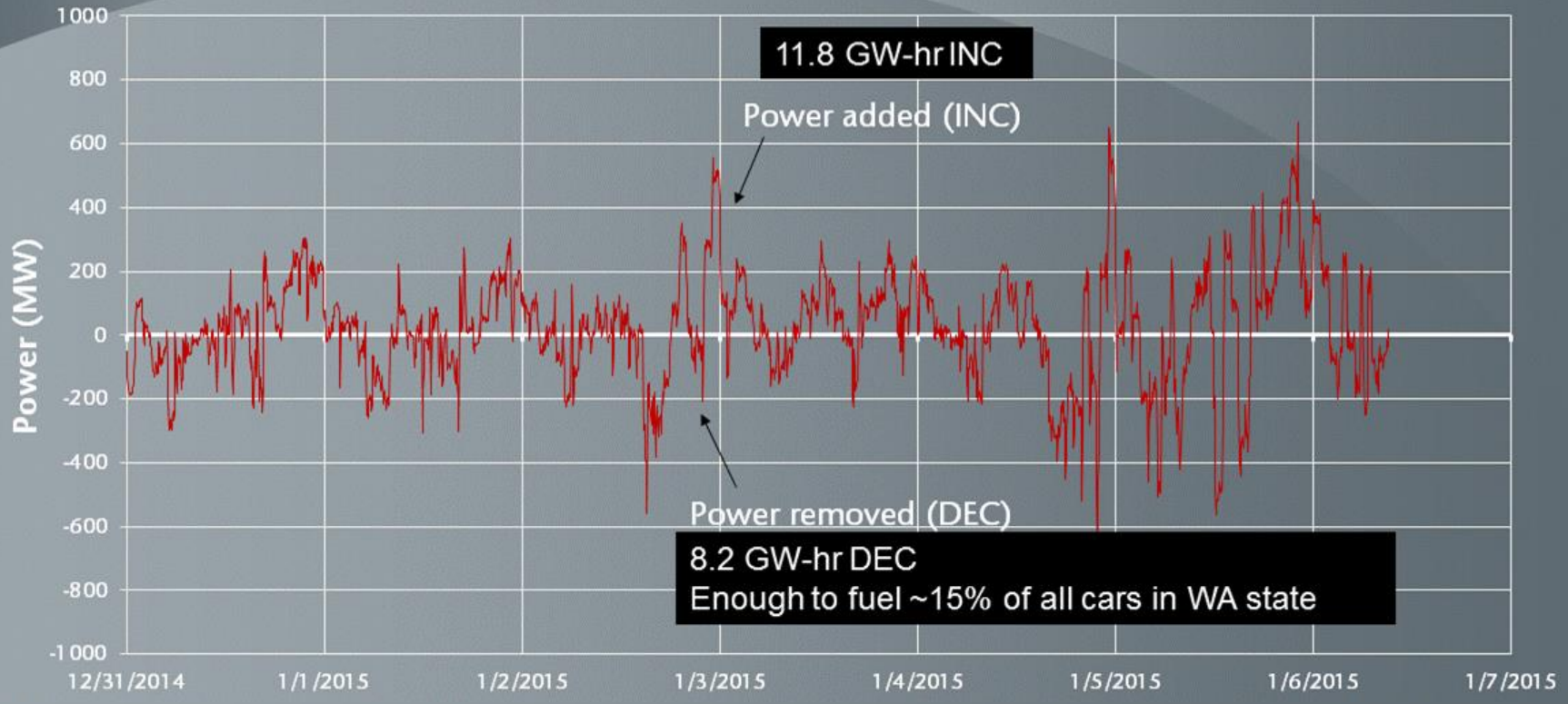
1) Making H_2: Example Electricity Grid Woes-BPA





[2]http://transmission.bpa.gov/Business/Operations/Wind/WIND_InstalledCapacity_PLOT.pdf

1) Making H_2: BPA Balancing Reserves

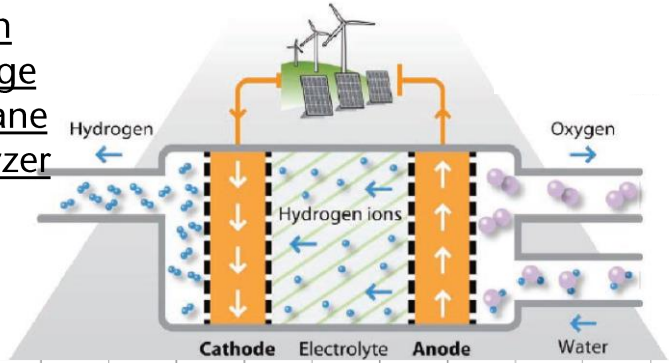


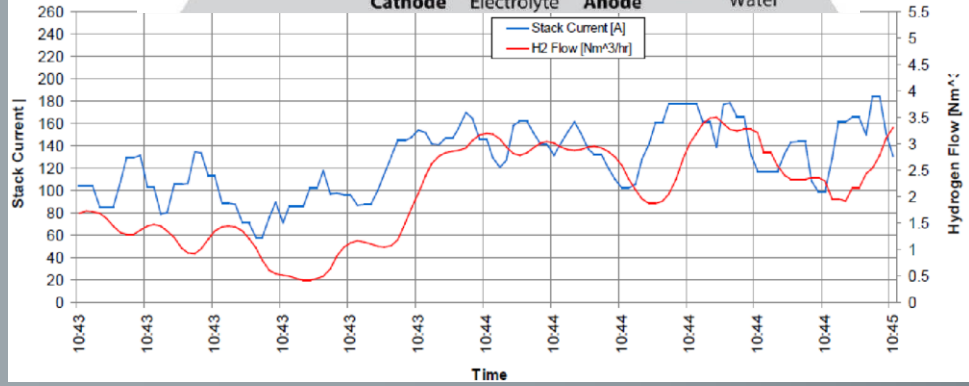
[1]http://transmission.bpa.gov/Business/Operations/Wind/reserves.aspx

1) Making H_2: NREL's Wind-to-H_2 Project

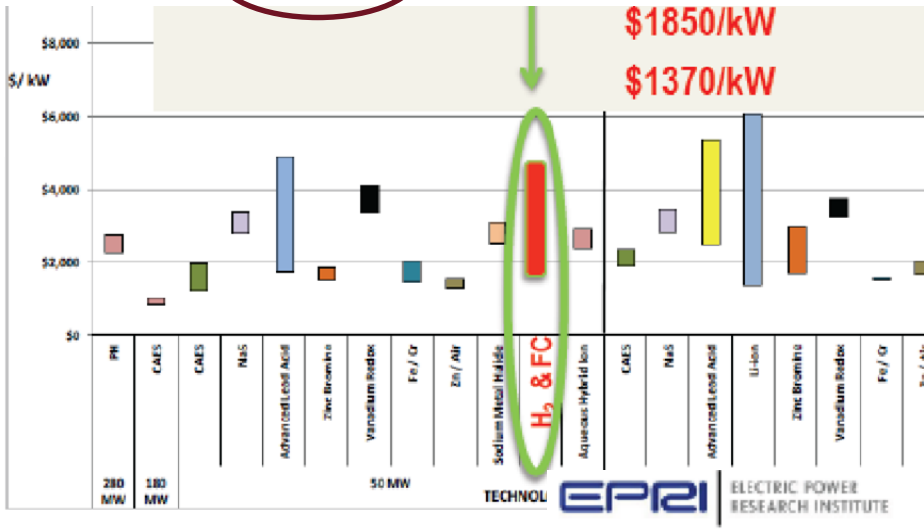
- 100 kW turbine direct coupled to 33 kW alkaline & 6 kW PEM stack

Proton Exchange Membrane Electrolyzer





Efficiency	PEM Electrolyzer		Alkaline Electrolyzer	
	LHV	HHV	LHV	HHV
Stack Efficiency				
Low Current	80% (5A)	95% (5A)	78% (30A)	92% (30A)
Rated Current	63% (5A)	75% (135A)	59% (220A)	70% (220A)



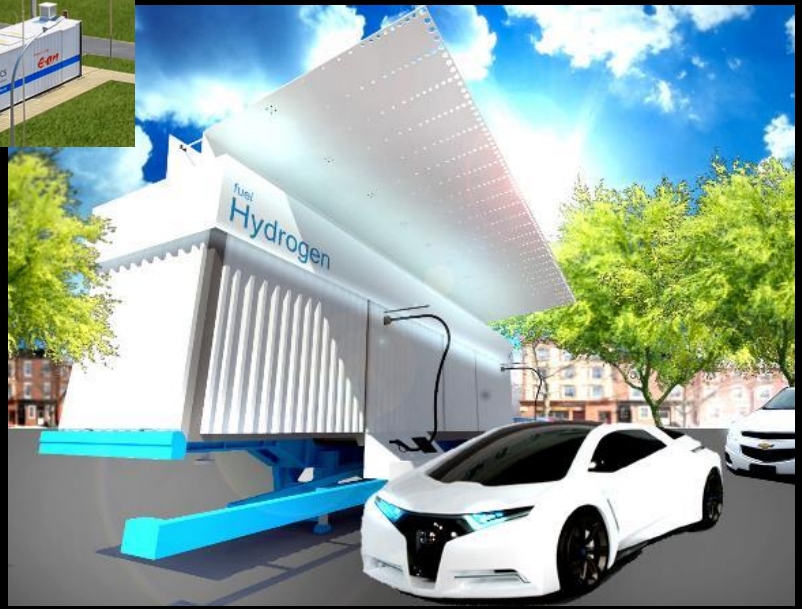
1) K. Harris, NREL to Wind hydrogen project, presentation to DOE (2009)
2) Courtesy of Monterey Gardiner/DOE FCTO (2014)

The Path to H_2:

1) Making H_2:

MW Scale Electrolysis
-$1,000/kW
-60 % efficiency
-Enables new renewables
-Oxygen byproduct uses
-Potential revenue source

2) Storing H_2:



3) Vending H_2:

4) Using H_2:

We can make hydrogen! Cool!
Now what?

2. Storing H_2: The case for liquid

- 80-90% of non-pipeline H_2 delivered via liquid tanker truck.[1]
- LH_2 will propel the early H_2 economy.[2]
- Only 8 LH_2 plants in North America
  - -Only 1 is carbon free (Niagara)
  - -Smallest is 30 tonne/day (>50 MW)
  - -Can only ramp 30%/day
- Production cost: \$5-5.60/kgLH_2
- Delivery cost: \$4-8/kgLH_2

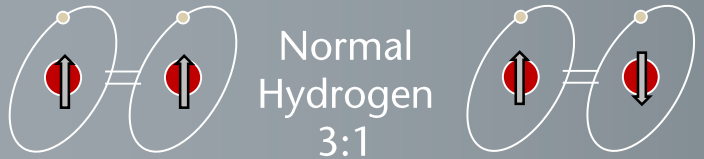
Efficient, small (<1 MW), modular H_2 liquefiers will increase renewable value and enable H_2 economy.

1) Technology Transition Corporation (TTC), H2 & Fuel Cells Market Report (2010)
2) Elgowainy, A., Tecnoeconomic Analysis of H2 Transmission & Distribution, DOE Workshop (2014)

2. Storing H_2: The Physics

In 1932, Werner Heisenberg won the Nobel Prize:

"for the creation of quantum mechanics, the application of which has, *inter alia*, led to the discovery of the allotropic forms of hydrogen."[1]



Normal Hydrogen 3:1

Orthohydrogen

$$\psi_{tot}(antisym) = \psi_{vib}(sym)\,\psi_{rot}(antisym)\,\psi_{spin}(sym)$$

$$\psi_{rot} = 1,3,5\ldots$$

Parahydrogen

$$\psi_{tot}(antisym) = \psi_{vib}(sym)\,\psi_{rot}(sym)\,\psi_{spin}(antisym),$$

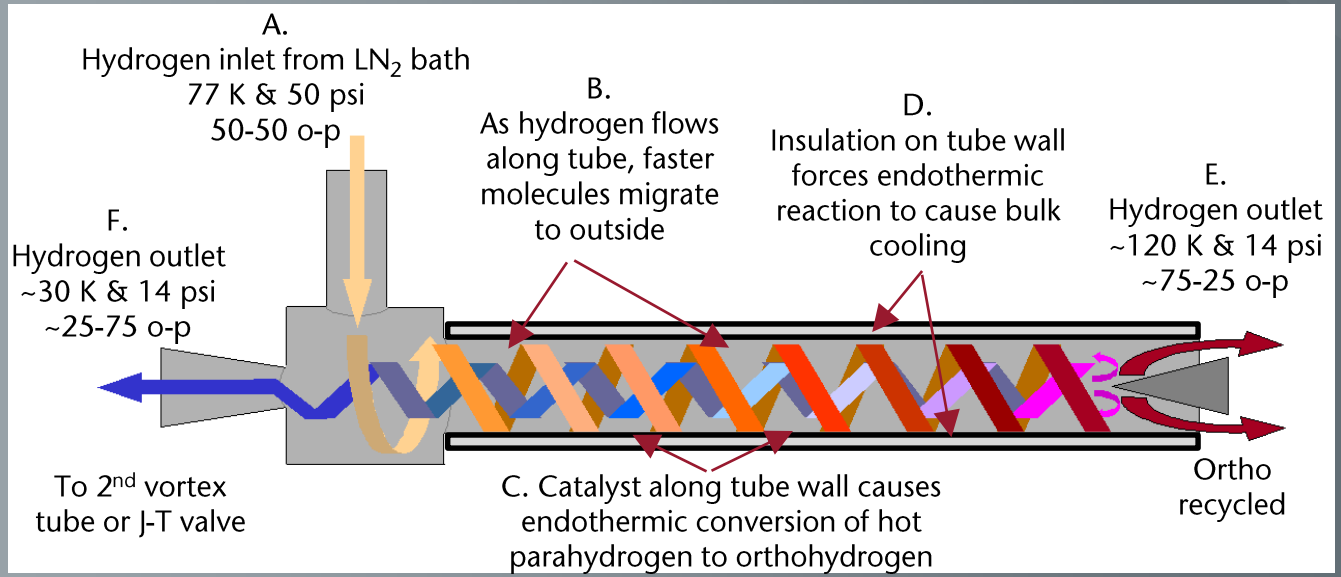
$$\psi_{rot} = 0,2,4\ldots$$

- 1st liquefied by James Dewar in 1898
- Liquefies @ 21 K (-421°F)
- Most energy intensive fluid to liquify
- Latent heat 420 kJ/kg to boil
- Ortho-para conversion yields 700 kJ/kg
- Most entropic phase change of any cryogenic material

[1]Nobelprize.org accessed 2010

2. Storing H_2: Kinetic para-ortho manipulation via vortex tube

- Vortex tubes separate faster (higher T) from slower due to flow geometry
- Enables para-ortho conversion to drive bulk cooling



The Path to H_2:

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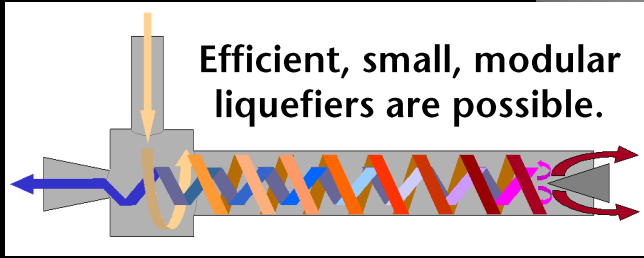


Vortex Liquefaction
-15-30% efficient
-20-30x higher value
-0.7 % loss per day

4) Using H_2:

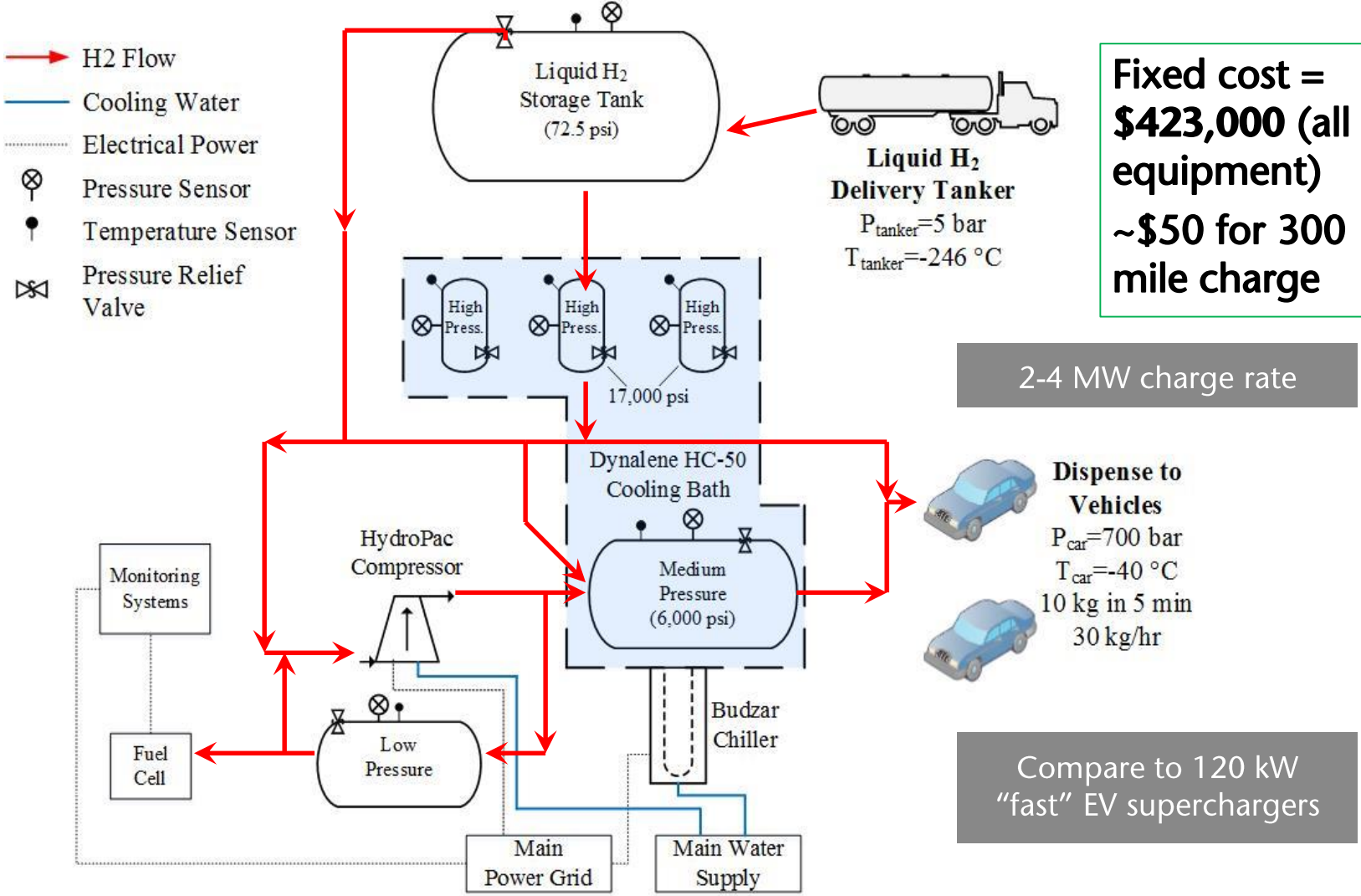
3) Vending H_2:

Portable Power to the People!

DEVELOPMENT OF DESIGN FOR A DROP-IN HYDROGEN FUELING STATION TO SUPPORT THE EARLY MARKET BUILD-OUT OF HYDROGEN INFRASTRUCTURE

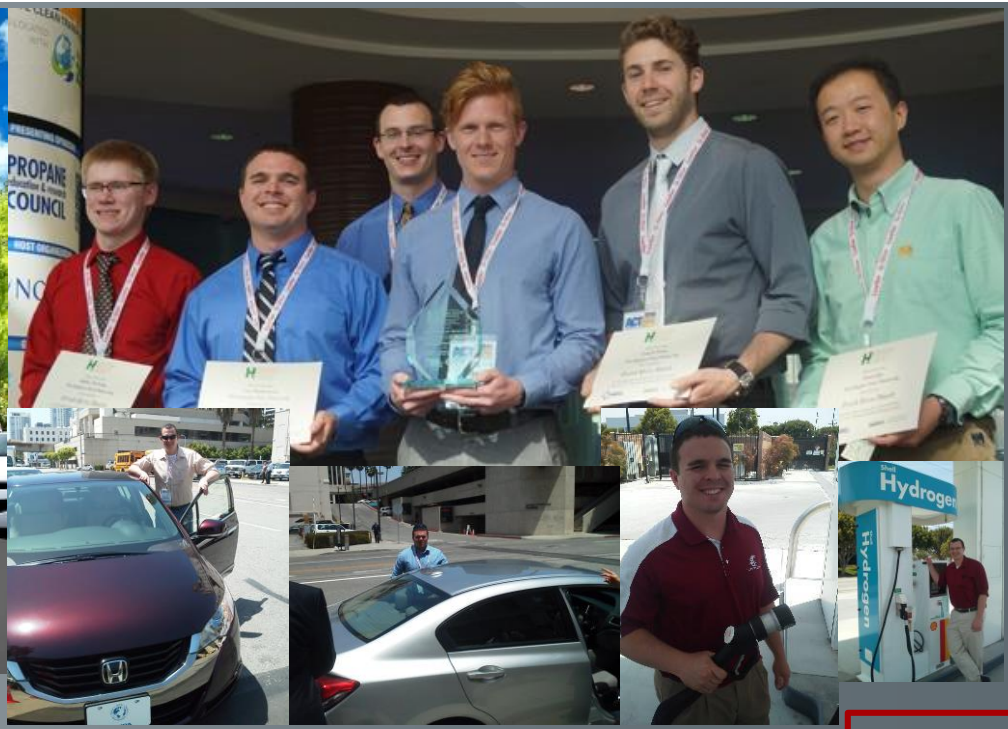
Key Rules and Guidelines:

- Low cost – current H_2 stations are $2- 4 million each
- Hydrogen delivered for $7/kg
- Fuel 2 vehicles simultaneously, 25 vehicles per day
- 5 minute fill time for 700 bar, 5 kg fuel tank
- Transportable
- Low maintenance
- Operated and monitored remotely
- Hydrogen storage should withstand 48 hr shutdown


H2 Flow
Cooling Water
Electrical Power
Pressure Sensor
Temperature Sensor
Pressure Relief Valve
Liquid H2 Storage Tank (72.5 psi)
Liquid H2 Delivery Tanker
Ptanker=5 bar
Ttanker=-246 °C
High Press.
High Press.
High Press.
17,000 psi
Dynalene HC-50 Cooling Bath
HydroPac Compressor
Medium Pressure (6,000 psi)
Low Pressure
Budzar Chiller
Monitoring Systems
Fuel Cell
Main Power Grid
Main Water Supply
Dispense to Vehicles
Pcar=700 bar
Tcar=-40 °C
10 kg in 5 min
30 kg/hr
Fixed cost = $423,000 (all equipment)
~$50 for 300 mile charge
2-4 MW charge rate
Compare to 120 kW "fast" EV superchargers

Washington State University Wins 2014 Hydrogen Student Design Contest

May 12, 2014 - 12:00pm



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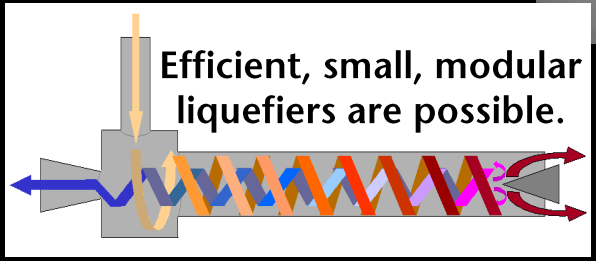

Vortex Liquefaction
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Fueling station:
-Portable/storable
-2-4 MW charge
-Shareable

4) Using H_2:

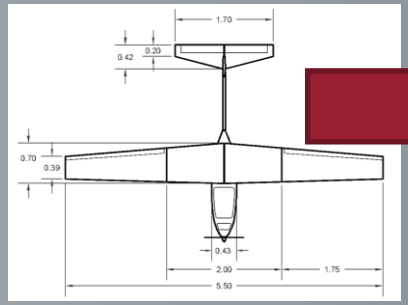
Rockets, Robots, & Racecars!

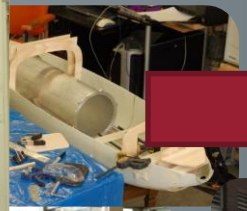
3) Vending H_2:

4. Using H_2: Liquid Hydrogen Fueled UAS

- Funded $20,000 on June 30th 2012
- Mission From Dean: Be the first university team to design, build, and fly an LH_2 fueled UAV.

4. Using H_2: Design - Build - Test





WASHINGTON STATE UNIVERSITY


WASHINGTON STATE
UNIVERSITY
WORLD CLASS. FACE TO FACE.

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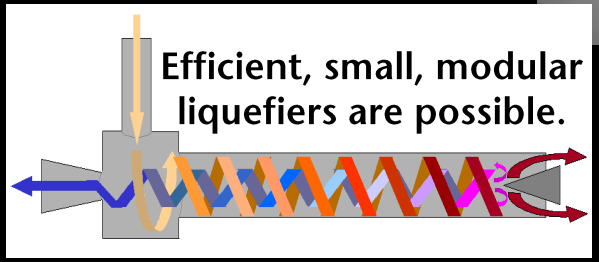

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The 2014-2016 H-Prize Competition

H2 Refuel

U.S. Department of Energy

About the H-Prize

H2 Refuel is the 2014-2016 H-Prize competition. It challenges America's innovators to deploy an on-site hydrogen generation system, using electricity or natural gas, to fuel hydrogen vehicles, that can be used in homes, community centers, retail sites or similar locations. The best entry, based on technical and cost criteria, will win $1 million.

The H-Prize was established by the 2007 Energy Independence and Security Act to be a series of competitions to encourage and reward innovations and advances in hydrogen energy technologies.

The H-Prize is administered by the Hydrogen Education Foundation, and sponsored by the Department of Energy's Fuel Cell Technologies Office.

Read the federal register notice about the H-Prize >>

HYDROGEN PROPERTIES FOR ENERGY RESEARCH (HYPER) LAB

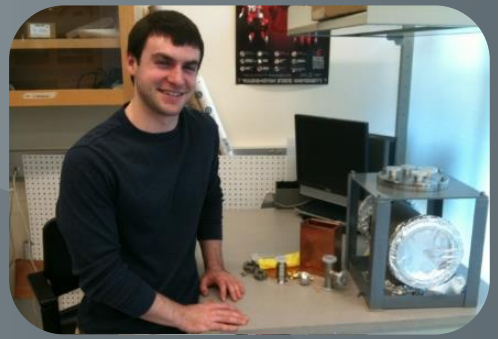
How you can help

There are many ways to show your support:

1. **Pledge a donation**. Washington State University is a public, non-profit institution that is limited from crowd funding due to state law. Your donation will be used for travel to conferences and competitions to spread the word, hourly student pay to build the talent pipeline, and initial testing of new ideas to enable new hydrogen technologies. Gifts to WSU are easy. If you are interested, contact Don Shearer at this info:
   Don Shearer, Director of Development
   Voiland College of Engineering and Architecture
   Washington State University
   PO Box 642714
   Pullman, WA 99164-2714
   Office: (509) 335-4733; Cell: (509) 432-6906

2. **Be a part of our team**. Send a short statement of interest to jacob.leachman@wsu.edu

3. **Keep listening!** Add the HYPER lab feed to your feedly or other readers by pasting this link: http://hydrogen.wsu.edu/feed. Or signup for our e-mail newsletter:



Thank you!

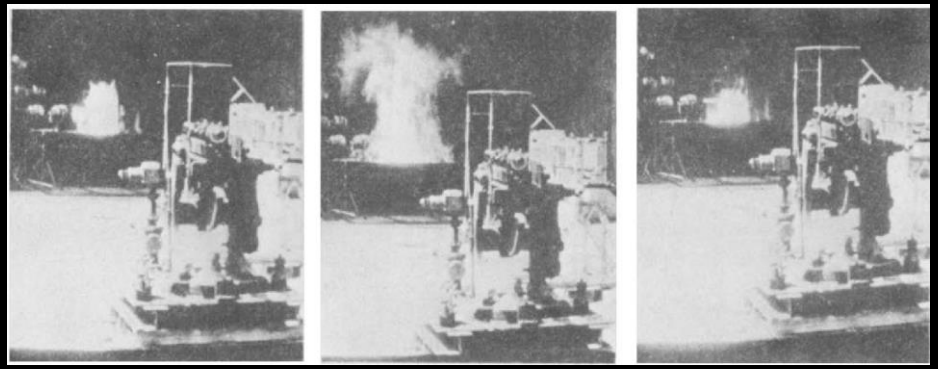
http://hydrogen.wsu.edu

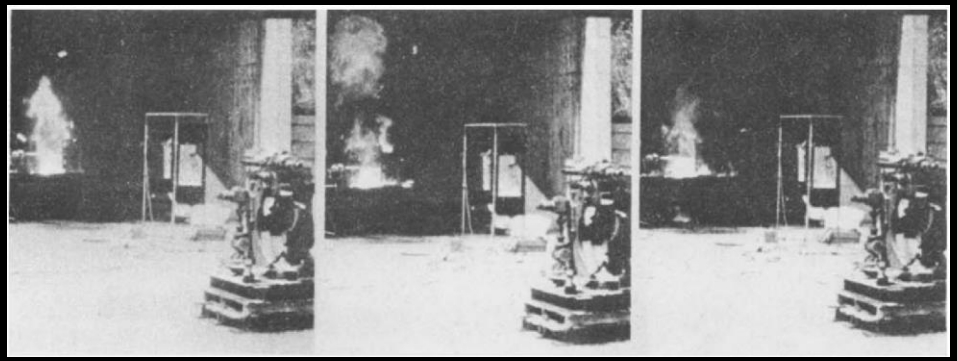
JOINT CENTER FOR AEROSPACE TECHNOLOGY INNOVATION

ESIC
Energy Systems Innovation Center

Hydrogen Safety: DOE H2 vs gas car

Hydrogen Safety: AFRL lightning & incendiary tests



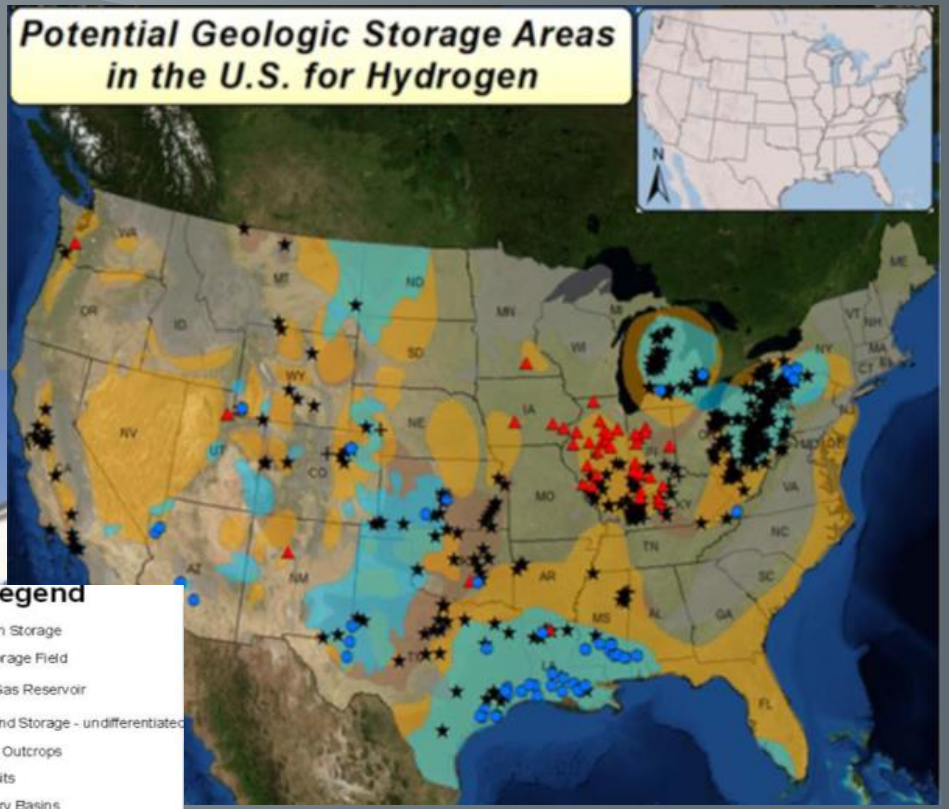


Hydrogen Safety: Hindenburg vs. Graf Zeppelins

http://heshydrogen.com/the-hindenburg-myth/

2. Storing H_2: Geological & Gaseous

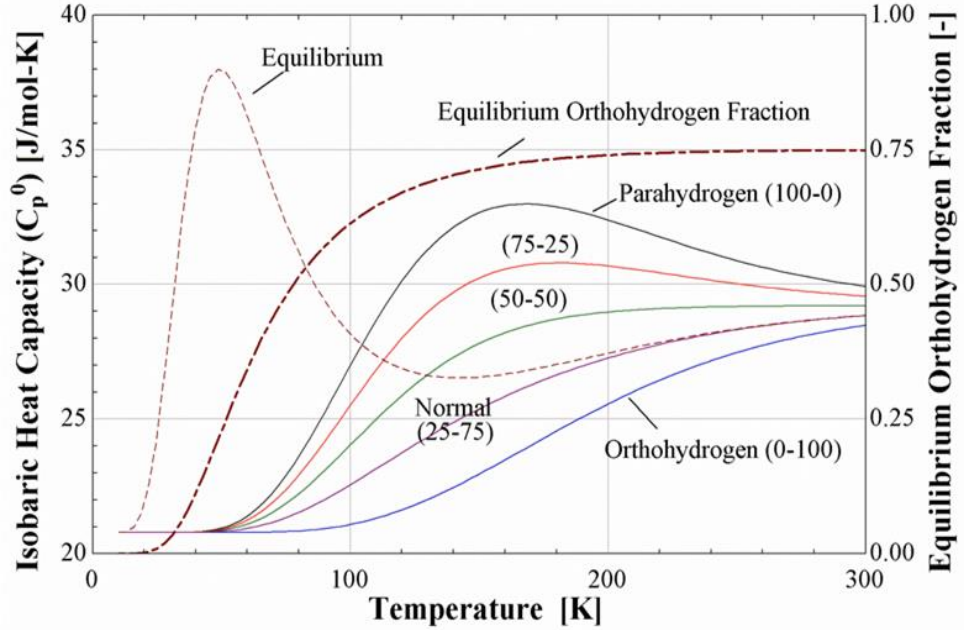
- Gaseous at 700 bar (10,000 psi) and 295 K is 39.7 g/L
- $700/kg above ground vs. $7/kg below ground

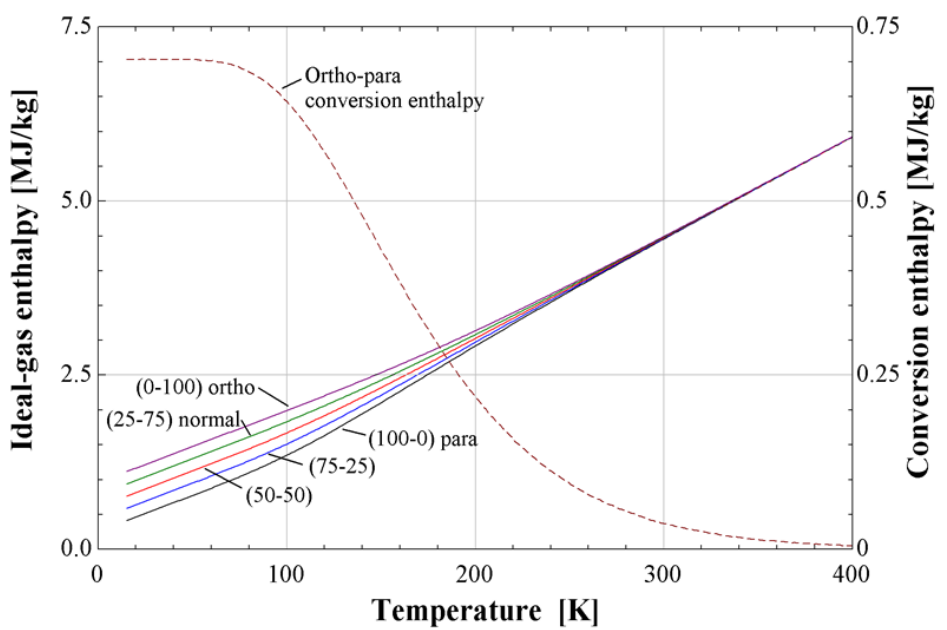


1) Lord et al. Sandia Report SAND2011-6221

2. Storing H_2: Ortho-para effects on properties

- Heat of ortho-para conversion must be removed for liquefaction.
- AirProducts uses 6 catalytic conversion beds.[1]



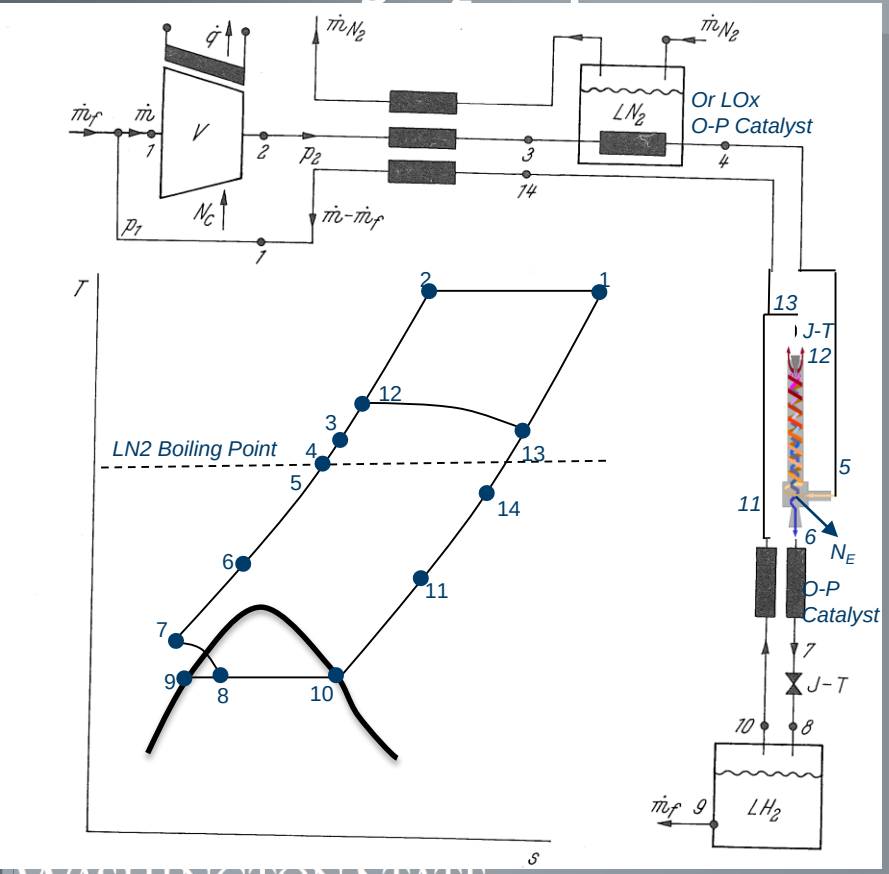


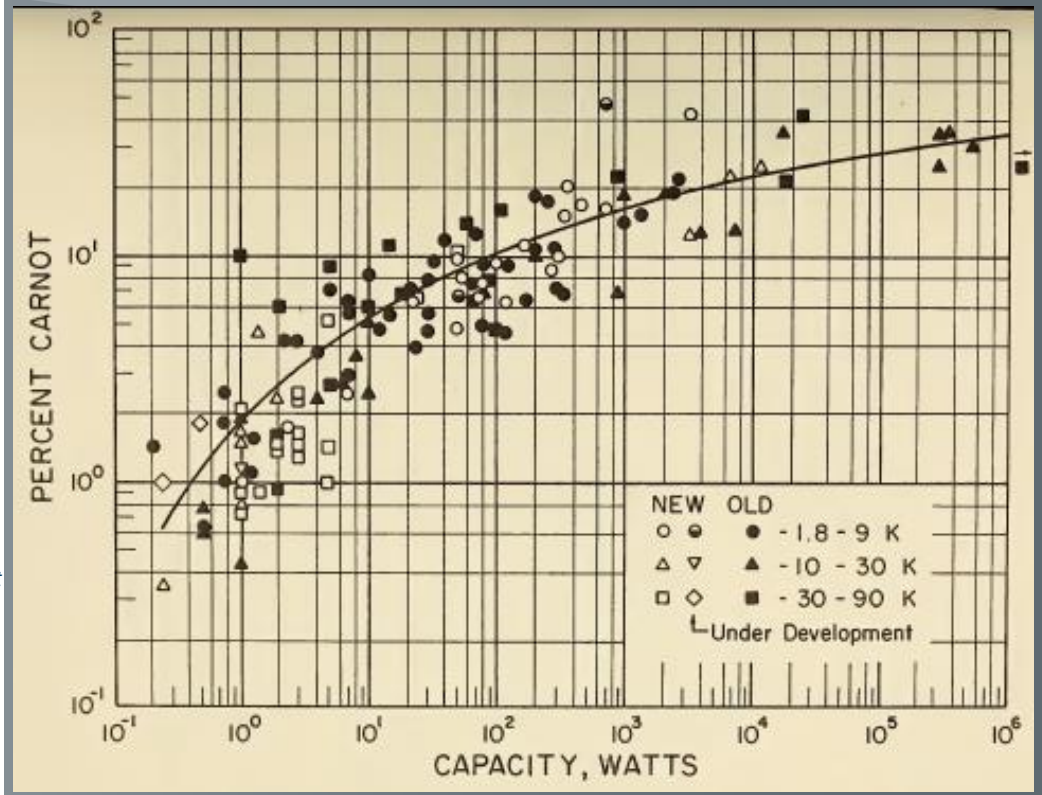
1) G.E. Kinard, "The Commercial Use of Liquid Hydrogen," ICEC17 (1998)

2. Storing H_2: Vortex concept testing progress

- Early findings anticipated for May 2015
- Direct comparison of catalyzed vortex tube
- Measured ortho-para composition at outlet

2. Storing H_2: Liquefaction Efficiency





[1] Strobridge, T.R., "Cryogenic Refrigerators – An Updated Survey," NBS Technical Report 655 (1974).

2. Storing H_2: Liquefaction Efficiency

Gas	Normal Boiling Point (K)	Volume reduction to liquefy (-)	Carnot COP (-)	Exergy to liquefy (kW-hr/kg)			
				Cooling	Condensing	Ortho-Para	Total
Methane	111.67	636.1	0.6	0.0769	0.2417	--	0.3186
Nitrogen	77.36	696.4	0.35	0.0547	0.1611	--	0.2158
Hydrogen	**20.27**	**851.0**	**0.07**	**1.5894**	**1.6777**	**0.6529**	**3.92**
Helium	4.22	756.2	0.01	1.9169	0.4133	--	2.3302