"Fuel-cell System for Hand-Carried Portable Power"

By
Don Gervasio

Associate Professor Research
Wintech and Applied NanoBioScience Centers
Arizona State University

Presented to
KITECH

Wednesday, April 20, 2005
Incheon, KOREA

Outline

Brief General Introduction to Power Sources

Borohydride Fueling and the Hydrogen – Air Fuel cell

Other Research projects at ASU

1-Regenerative Borohydride Fuel Cell, RBFC (NASA)

2-Reformed Hydrogen Fuel Cell, RHFC (Boeing)

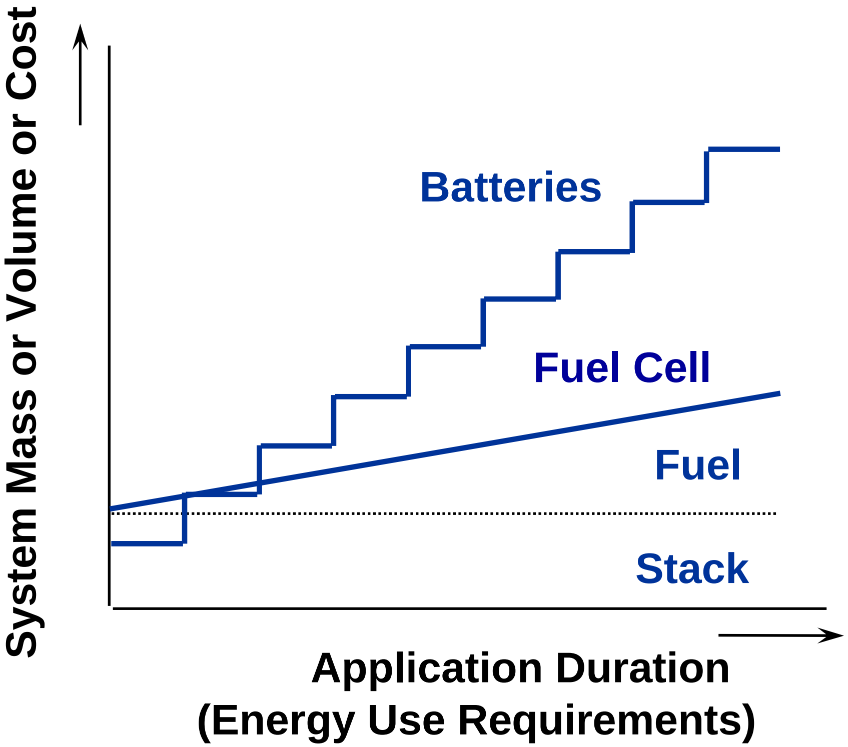
3-Proton Conducting Membranes (ARO, NASA)

4-Oxygen Reduction on Steel and Ni alloy (DoE)

5-SAM Electrocatalysts (ARO)

Introduction to Power Sources

ENERGY CONVERSION VS. ENERGY STORAGE

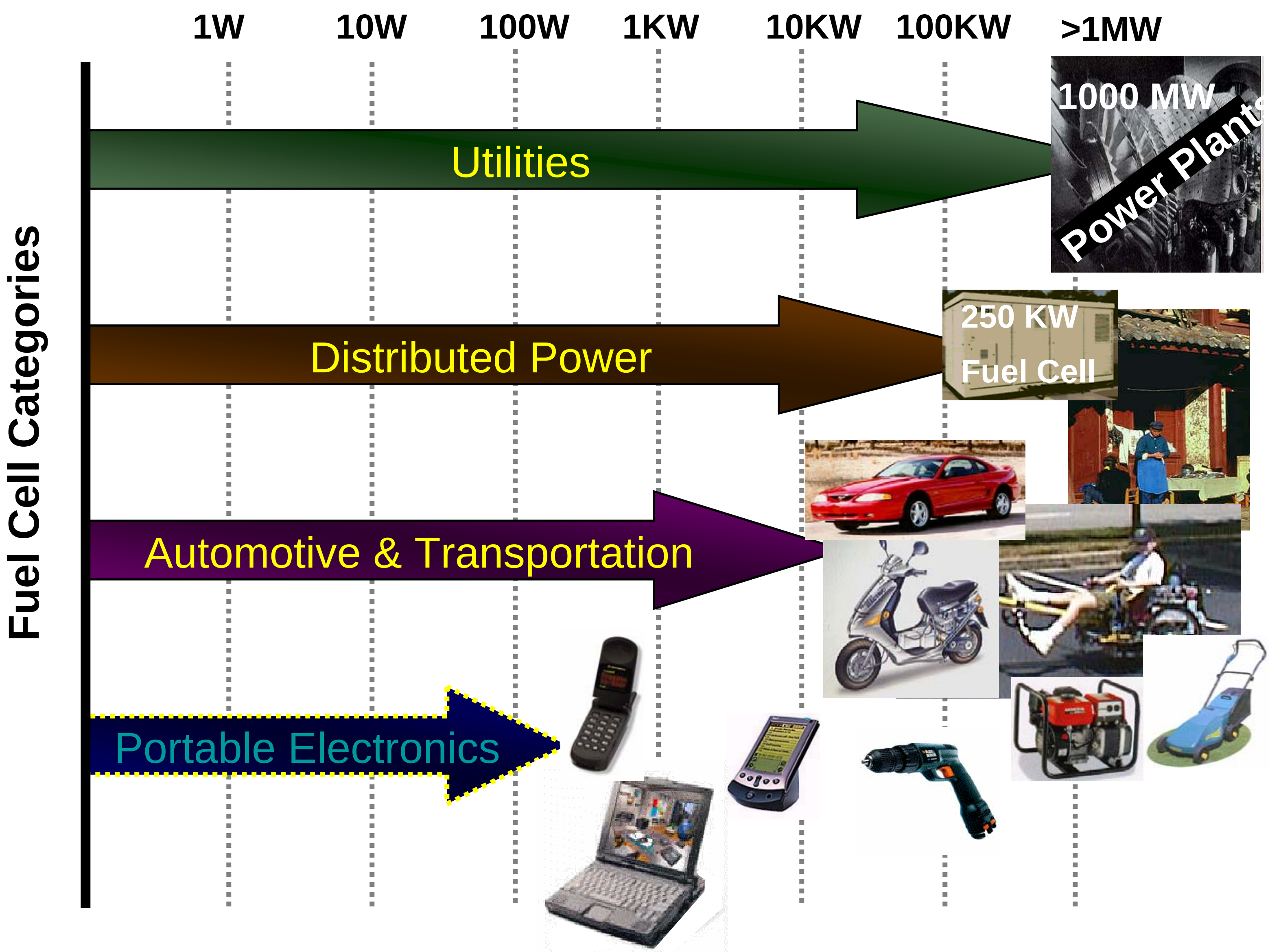


Energy Density of Selected Fuels and Batteries

Fuel:	Specific Energy (Wh/kg)
Hydrogen	33,000
Diesel Fuel	13,200
Methanol	6,200
$NaBH_4$-30%	2,500
TNT	1,400
Battery:	
Primary Battery (est. max.)	500
Rechargeable (est. max.)	200
Li/SO_2 Battery (primary)	176
Alkaline Battery (primary)	80
Nickel-Cadmium (secondary)	40

Driving Force: Substantially decreased size, weight, and cost with improved application lifetime, safety, environmental compliance and increased mobility.

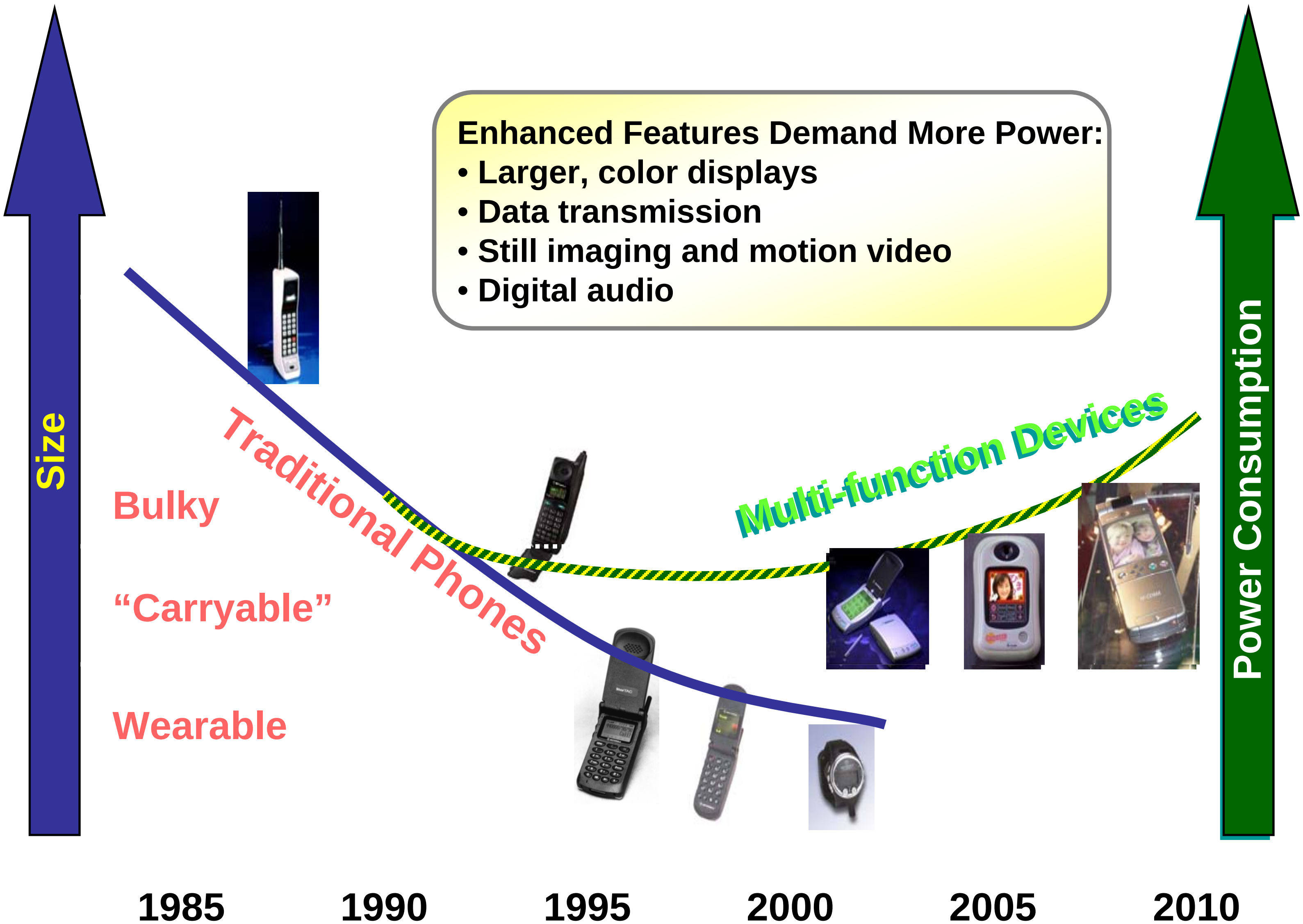
Commercial Portable Power Requirements



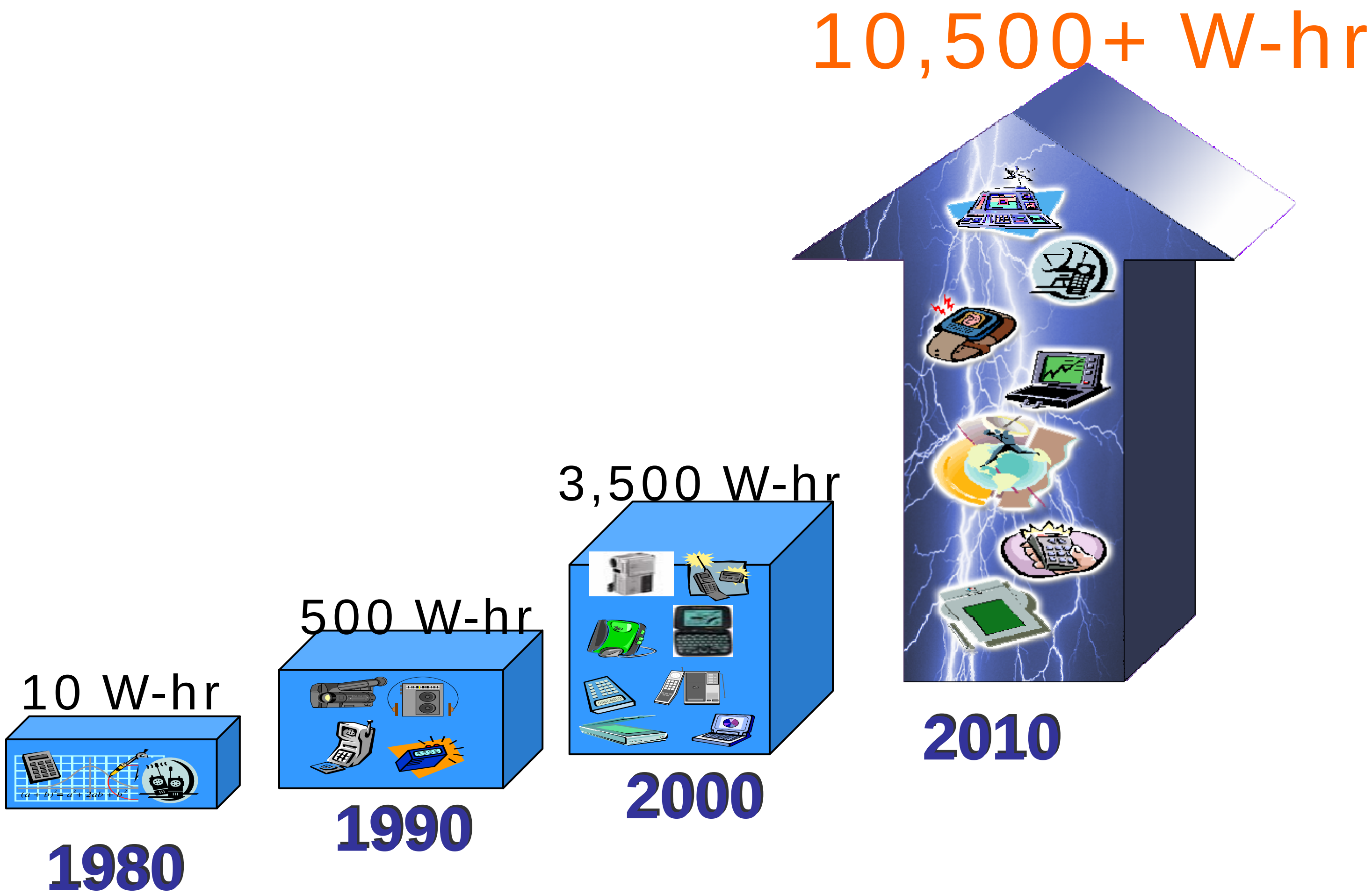
WINtech & Applied Nano Bioscience Centers at ASU

Trend in Portable Electronic Products

ASU Arizona State University



Projection of Energy on Body per Year



Categories of Fuel Cells and Applications

Solid Oxide Fuel Cell

Large Power utility, Hydrocarbon Fuel, T = 700^{o}C, Seals

RHFC HT-PEM, MC and Phos Acid

Residential Power, Impure H_2, T = 190^{o}C, Low V^{cell}

Nafion PEM

Automotive&Backup utility, pure H_2,T = RT to140^{o}C, cost

DMFC as battery replacement

Hand – Carried Portable Power, MeOH/Water, RT, stability, cost

Nafion PEM with Borohydride as battery replacement

Hand – Carried Portable Power, $NaBH_4$/water, RT,opportunity

Conclusion for Approach to Portable Power

- ***Hydrogen-Air PEM Fuel Cell***

  - Reliable

  - Maintainable

  - Affordable

- ***Hydrogen source***

  - traditional fuel problem proposed to be solved by generating hydrogen using a microfluidic reactor

  - to generate hydrogen (H_2) gas by catalytic (Ru) hydrolysis of alkaline aqueous sodium borohydride ($NaBH_4$) solution

  - to send resulting gaseous H_2 to anode and borax ($NaBO_2$) solution to waste receptacle (volume vacated by $NaBH_4$ hydrogen storage solution).

Hydrogen: the universal fuel

A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy resources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants.

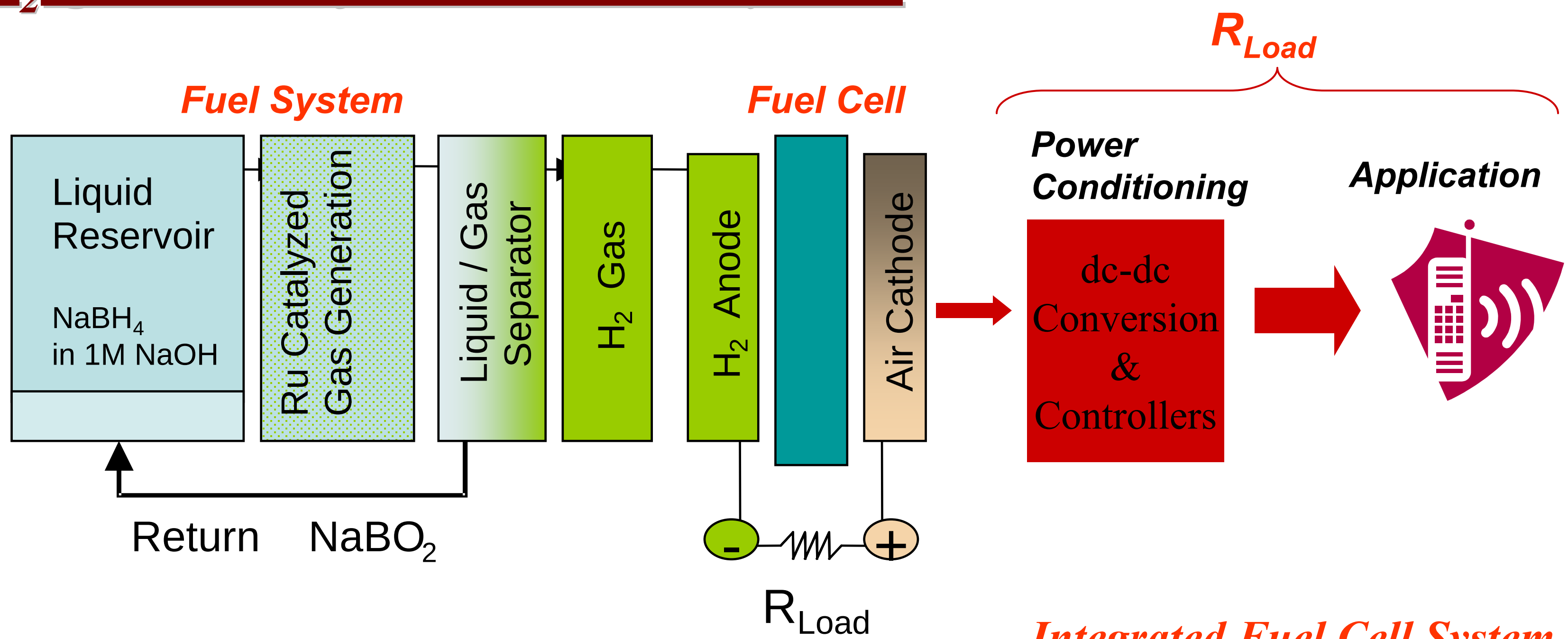
—

The National Academies Committee on Alternatives and Strategies for Future Hydrogen Production and Use

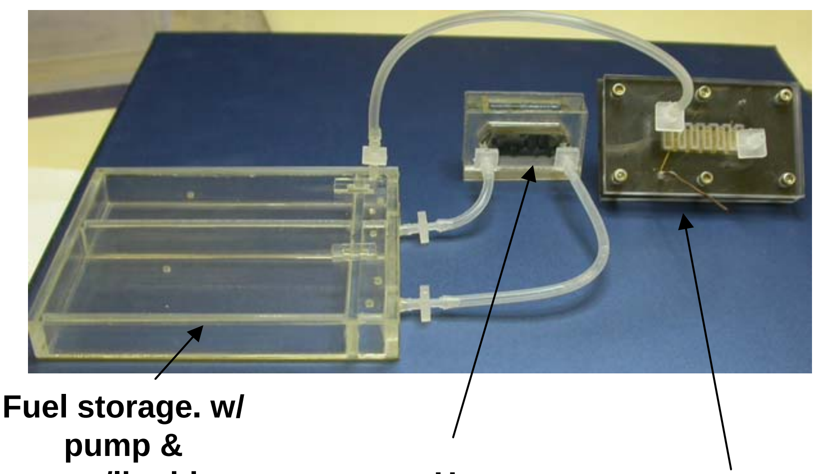
February 2004

Sodium Borohydride System Overview

Diagram of ASU Room Temperature H_2-generator fed Fuel Cell System



Integrated Fuel Cell System



- H_2 generation:
  via low-temp catalytic $NaBH_4$ hydrolysis

$$NaBH_4 + 4\,H_2O \xrightarrow{\text{Ru catalyst}} 4\,H_2 + NaB(OH)_4$$

WINtech & Applied Nano Bioscience Centers at ASU

Efficiency of Borohydride Fuel Cell System

ARIZONA STATE UNIVERSITY

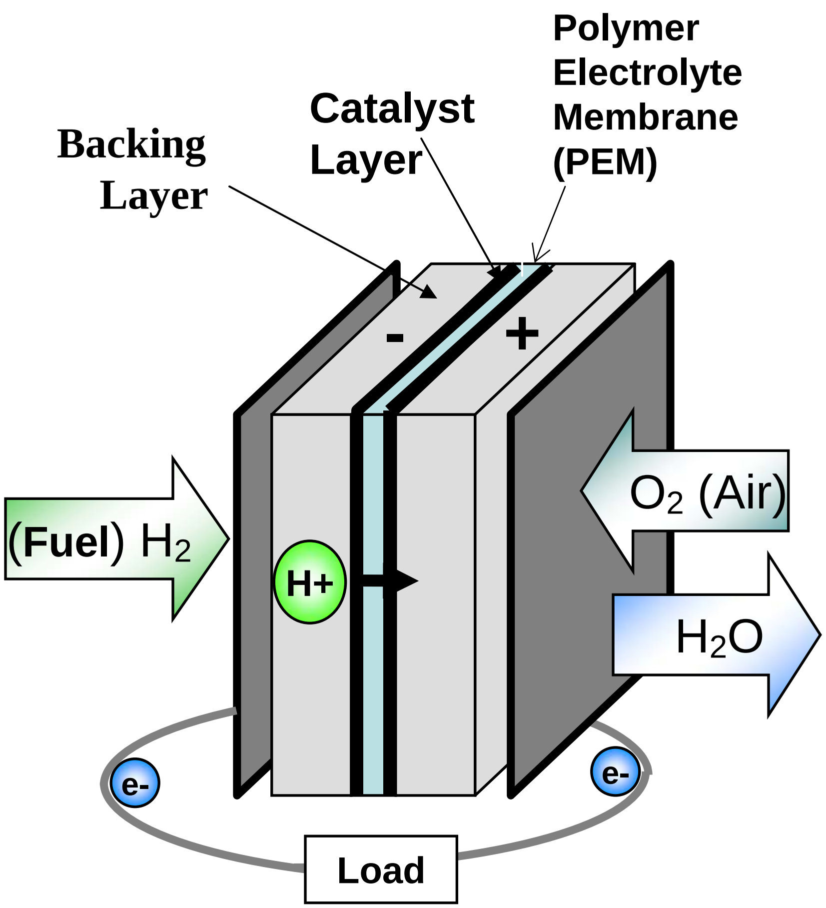
First Order Estimation of Efficency for Low Temperature Borohydride Fuel Cell System

Objective is for 1W to 10W for 9,000 hours (1year).

Efficiency Breakdown **System Component**	**GOAL** **Efficiency**		**Today** **Efficiency**	**Comments**
Fuel Input Volume	95%		95%	Fuel loss (fresh cartridg w/ 1 year half life used within a month).
Liquid Pump	99%		90%	Piezo- or echem- pump (milli-liters/minute); mW's parasitic loss.
Air Pump	95%		80%	Miniature Air pump/fan (100 sccm) 0.1 W parasitic loss.
Yield of H_2	98%		98%	At least 98% hydrolysis; depends on rate of H_2 generation
Anode polarization	98%		98%	Voltage losses. Operating potential ~ 0.04V vs NHE (ideal is zero)
Cathode Polarization	75%		70%	Operating potential ~ 0.8V vs NHE (Ideal is 1.23V); decay < 10 microV/hour
Water Return Subsystem	99%		90%	If needed, same as liquid pump
Anode/Cathode collection	95%		90%	Current collector sheet resistance < 0.2 Ohm cm^2
Membrane IR Loss	95%		90%	Proton conductivity > 0.01 S cm^{-1}
Total Elec. Loss, R-internal	95%		90%	At max power where R-load = R-internal, then iR loss is j^2 times R-internal
DC-DC Converter	90%		80%	Assumes stack voltage of 0.7 to 2.8V.
Gas/Liquid Separation	100%		100%	Passive devices
Net System Efficiency	49%		24%	25 to 45 % is reasonable
				Areal power density = 0.1 (passive air) 0.35 W/cm^2 (active) at 0.8V per cell.
NET POWER DENSITY	**100**	**W/liter**	**	Volumetric power density =100 W/l
NET ENERGY DENSITY	**1000**	**Wh/l**	**	For $NaBH_4$-30; 2500Wh/l x Efficiency = System Energy density
				System Energy density=~1250Wh/l, ignoring V(Fuel Cell)
				If 10% total volume is Fuel Cell, then System Energy Densit is ~1000Wh/l.

Fuel Cell

Fuel cell
- best alternative to batteries for man portable power



Schematic Diagram of a Conventional Fuel Cell

Fuel cells are similar to batteries but:

-Have higher energy density for
* for longer application life than a battery of same size

or

*same application life with smaller lighter fuel cell than the battery that's replaced

-Allow instant chemical recharge

Room temperature fuel cell ideal for:

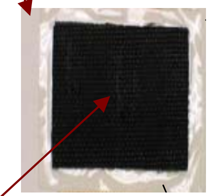
-portable applications

-close proximity to people!

Actual Fuel Cell Hardware

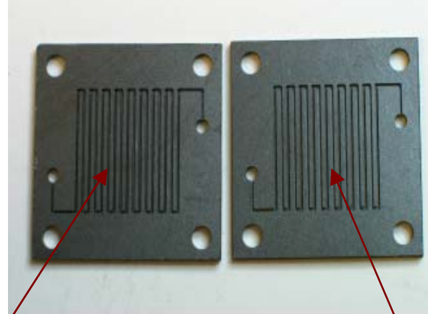
Nafion membrane

Membrane Electrode Assembly (MEA)



Electrode
(Pt on carbon cloth)

Serpentine Flow Field: 21x(0.5x0.76)
Overall Dimensions: 38 x 38 x 2 mm

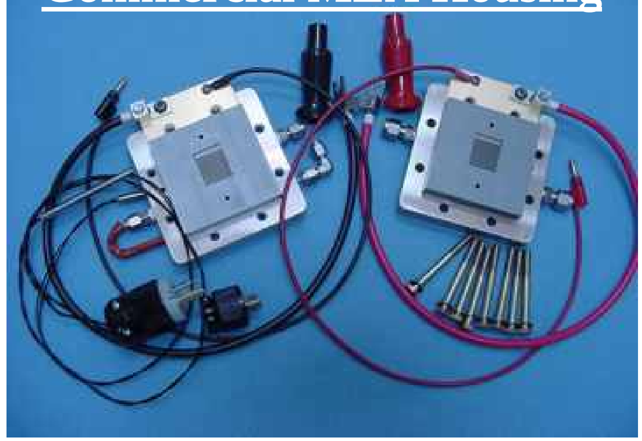


Moldable Graphite Fuel Cell Housing

- current collector
- gas flow field

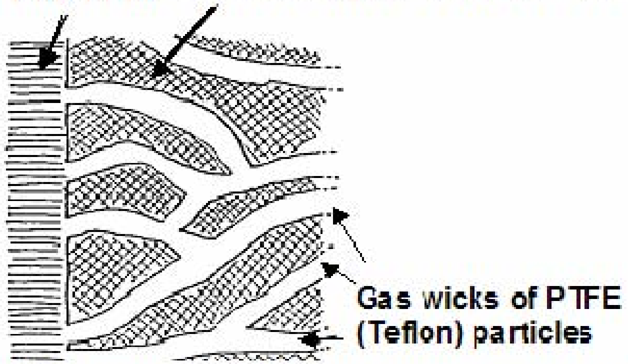
H_2 flow field
Anode current collector

O_2 flow field
Cathode current collector

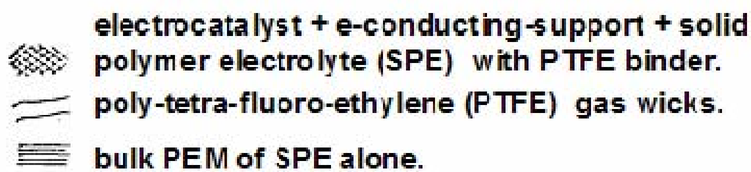


Commercial MEA Housing

Electrode / Membrane Interface in a MEA

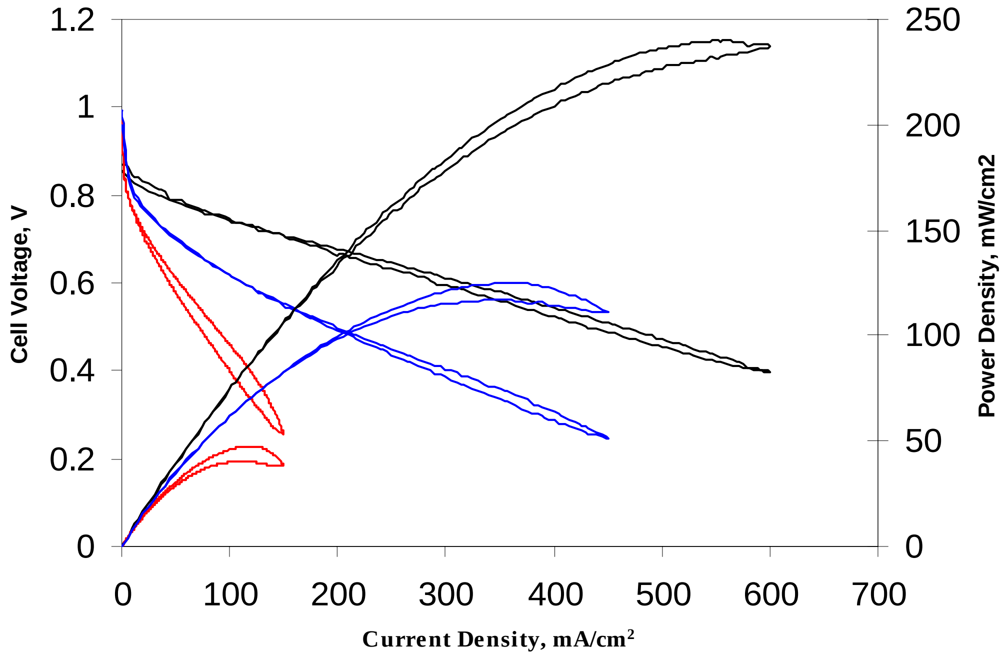


Model of semi-hydrophobic gas-fed electrode modified with solid polymer electrolyte membrane (PEM)



Interfacial region between bulk solid polymer electrolyte (SPE) membrane and the active-layer of Pt-catalyzed gas-fed porous electrode.

Effect of Electrode Preparation on MEA Performance



Polarization curves for 3 MEAs with different amounts of Nafion. O_2 / H_2 flows: ~15 : 20 sccm. T=22°C. Ambient pressure.

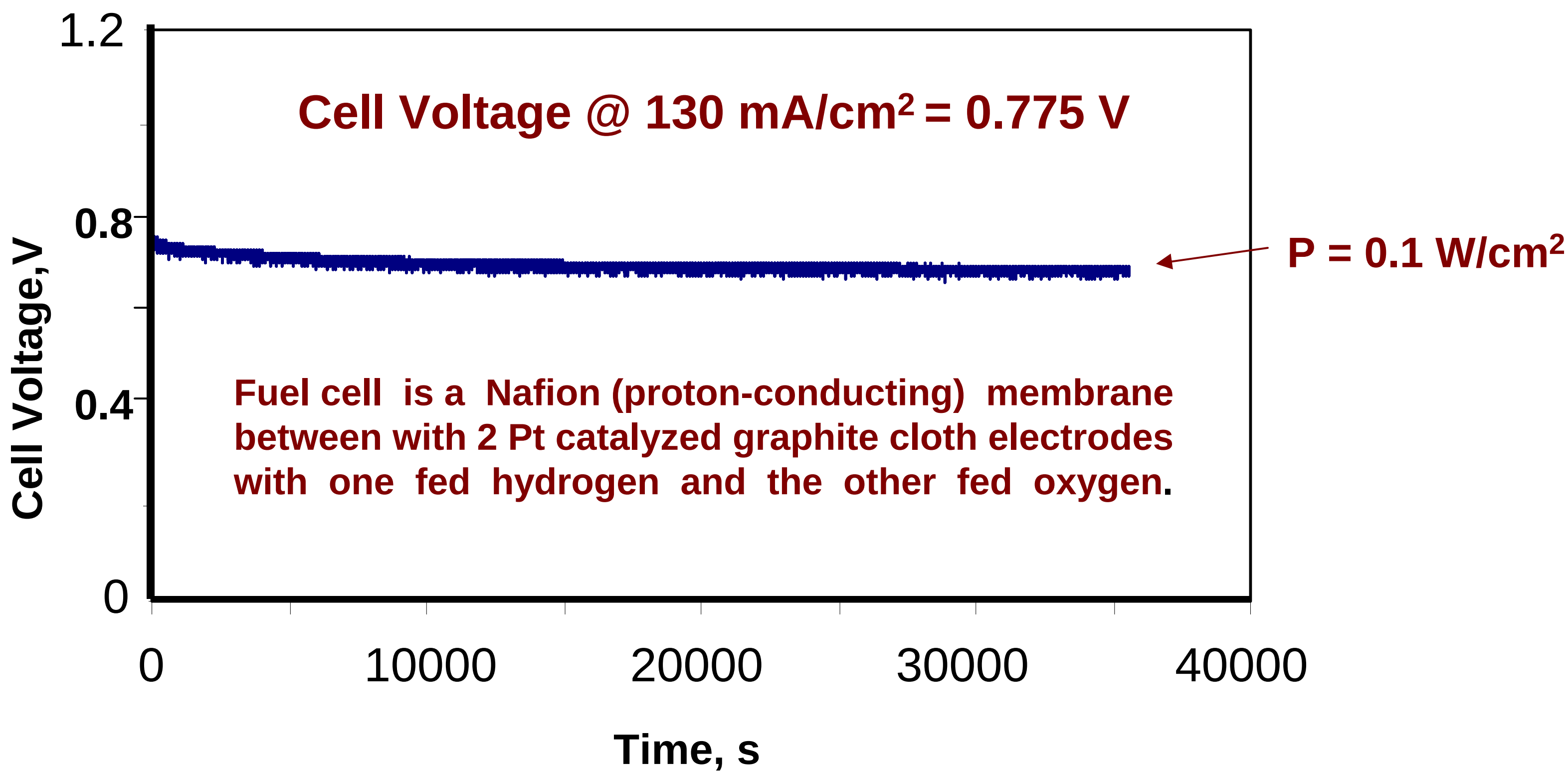
Red: **no Nafion (too little)**
Blue: **13 mg Nafion (too much)**
Black: **4.5 mg Nafion (just right)**
in 50 mg of electrode(2.3 cm²)

Conditions

Nafion117 membrane
E-TEK V2 ELAT Electrode
Pt loading=0.5mg/cm².

A^{active} =1cm².
Electrodes hot pressed on membrane for 2 minutes at 120ºC and 2800 lbs.

Steady-state Fuel Cell Operation

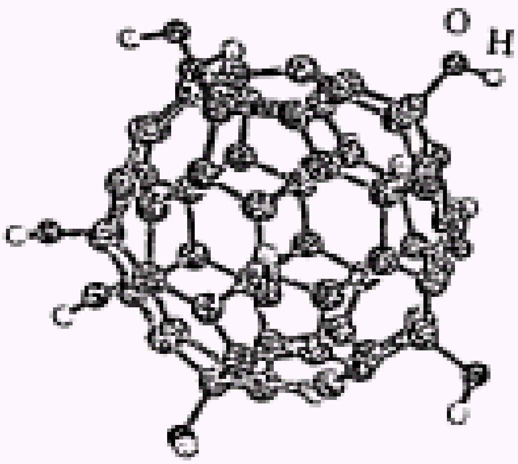


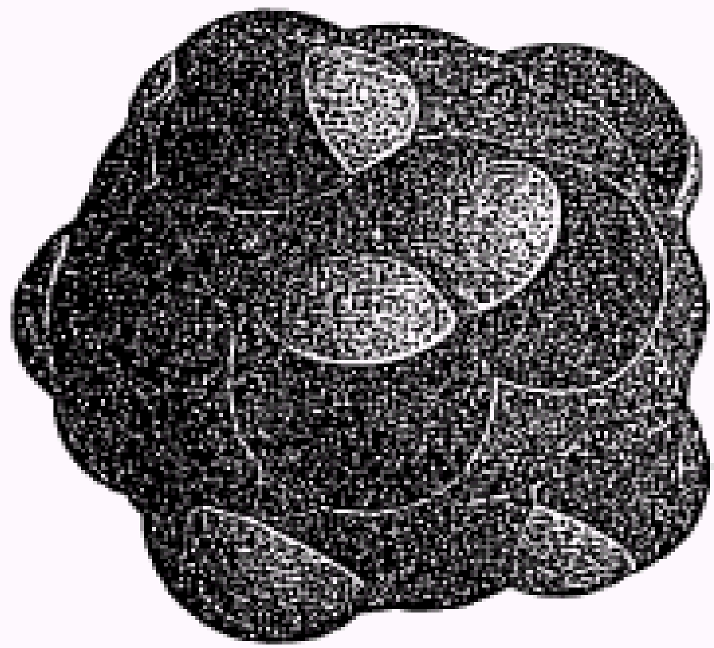
Performance of Fuel Cell fed hydrogen and oxygen in time.
Pt Loading = 0.5 mg/cm^2. 4.5 mg Nafion per 50 mg electrode.

An attractive add on:
Buckyball Proton Conducting membrane

σ_{H+} of $C60(OH)_{12} = 10^{-5}$ S cm^{-1} at ~ 25 ^{o}C

σ_{H+} of $C60(OH)_6\,(OSO_3H)_6 = 10^{-2}$ S cm^{-1}





- Simplifies fuel cell water handling since no water transferred with proton

- Allows "dead ending" of hydrogen!!

Conclusions on Fuel Cell

****Room temperature hydrogen-oxygen fuel cell provides ~ 0.1W/cm²***

****MEA consisting of Nafion 117 with E-TEK ELAT electrode is suitable for developing system***

Need a fuel !!

ARIZONA STATE UNIVERSITY

Hydrogen Generator

"A Safe, Portable Hydrogen Generator Using Aqueous Borohydride Solutions",
S.C. Amendola, S.L. Sharp-Goldman, M. Saleem Janjua, M.T. Kelly, P.J. Petillo, and M. Binder
(Millennium Cell LLC) Joint International Meeting of theECS and ISE - Honolulu, Thursday, October 21, 1999.
Battery/Energy Technology Joint General Session, Battery Division/ Energy Technology Division.

Description of fuel system

- H_2 storage in sodium borohydride ($NaBH_4$) solution,

  2200 Wh/Kg for 30wt% NaBH4, 3wt% NaOH in 67wt% H2O

- Catalytic reactor releases H_2 at ambient T and P,
- Low power pumps to move liquid fuel,
- Orientation independent

  Gas – Liquid separator membrane.

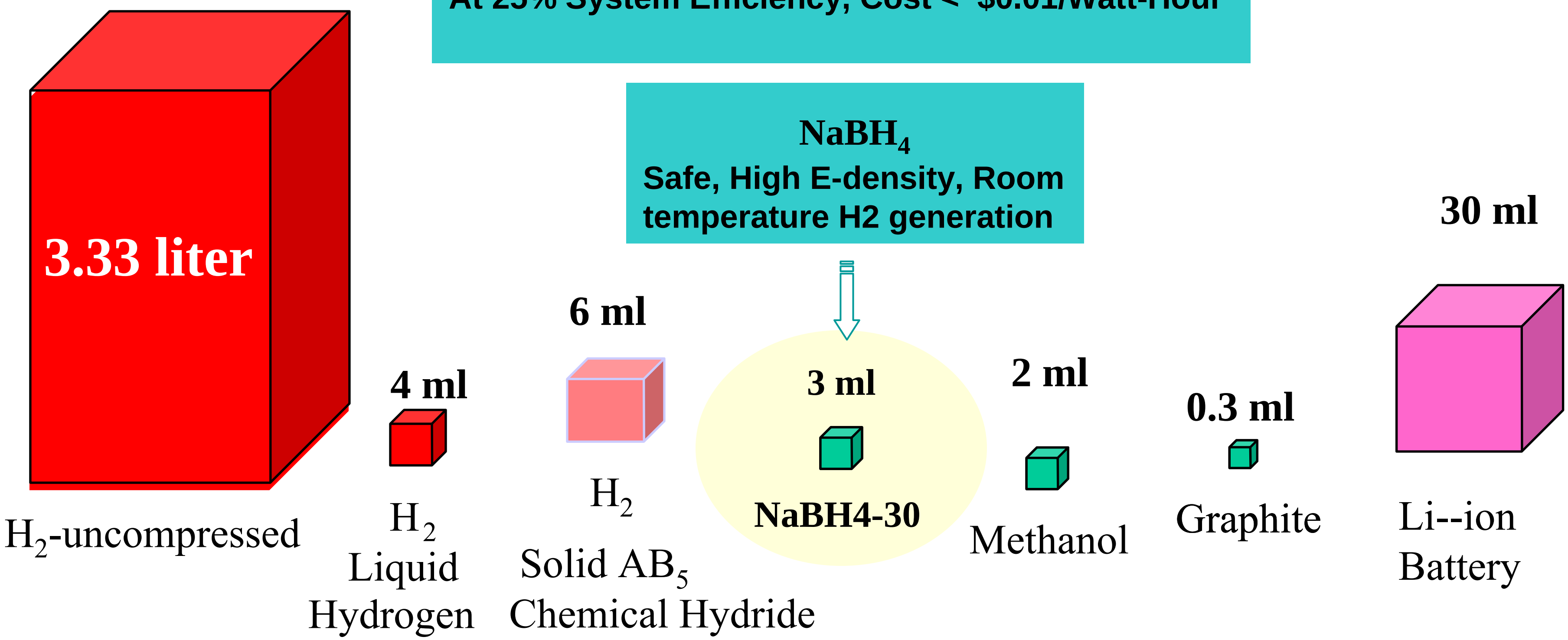
Fuels and Relative Energy Density

ARIZONA STATE UNIVERSITY

Borohydride, $NaBH_4$ … LOW COST per Watt-Hour:

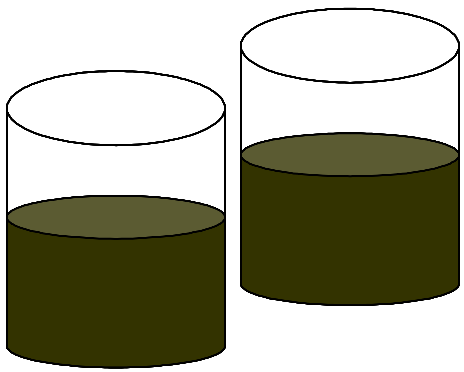
For 30% Borohydride in Water = ~ \$10/gallon
At 25% System Efficiency, Cost < \$0.01/Watt-Hour

$NaBH_4$
Safe, High E-density, Room temperature H2 generation

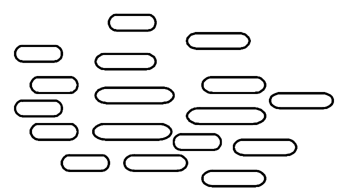


Volumes of different Fuels equivalent to ~10 Watt-hours of Electrical Energy at 100% Chemical to Electrical Conversion Efficiency.

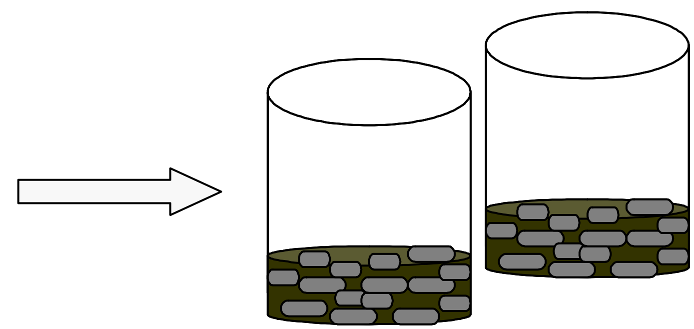
Preparation of Ru Catalyst for H_2 Generation



2wt.% and 5wt.% Ru Cl_3 solutions in DI water



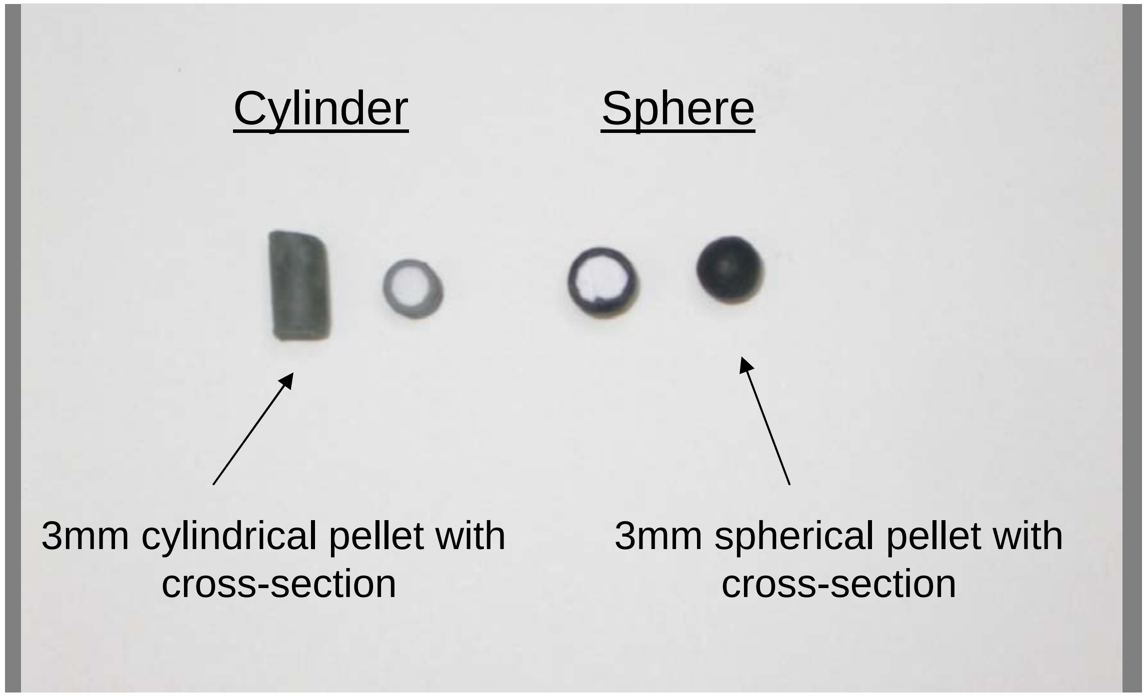
High surface area gamma alumina pellets for catalyst support



Alumina pellets soaked in the Ru Cl_3 solutions.

Solution soaked $RuCl_3$ on alumina pellets, decanted, air dried.
Samples were heated under 5% hydrogen, balance helium.
Heated at 100°C/hr to 150°C or 700°C; no dwell and 6 hour dwell.

Alumina Geometries for supporting Ruthenium Metal



- *Catalyst support features: High surface area (220m^2/g) g-alumina with total pore volume of 0.62cc/g.*
- *Improved packing of catalyst bed with spherical alumina support*

Elemental Analysis by EDAX

EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Elem	Wt %	At %	K-Ratio	Z	A	F
Al	86.02	94.44	0.7411	1.0144	0.8479	1.0016
Ru	11.28	3.30	0.0641	0.8369	0.6793	1.0000
Cl	2.70	2.26	0.0149	0.9913	0.5555	1.0000
Total	100.00	100.00				

2 wt.% Ru on alumina no dwell time

EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Elem	Wt %	At %	K-Ratio	Z	A	F
Al	85.65	94.24	0.7356	1.0148	0.8449	1.0017
Ru	11.51	3.38	0.0656	0.8373	0.6806	1.0000
Cl	2.84	2.37	0.0156	0.9917	0.5566	1.0000
Total	100.00	100.00				

2 wt.% Ru on alumina 6 hour dwell time

EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Elem	Wt %	At %	K-Ratio	Z	A	F
Al	86.30	94.29	0.7485	1.0136	0.8544	1.0016
Ru	10.53	3.07	0.0598	0.8361	0.6788	1.0000
Cl	3.17	2.63	0.0174	0.9903	0.5551	1.0000
Total	100.00	100.00				

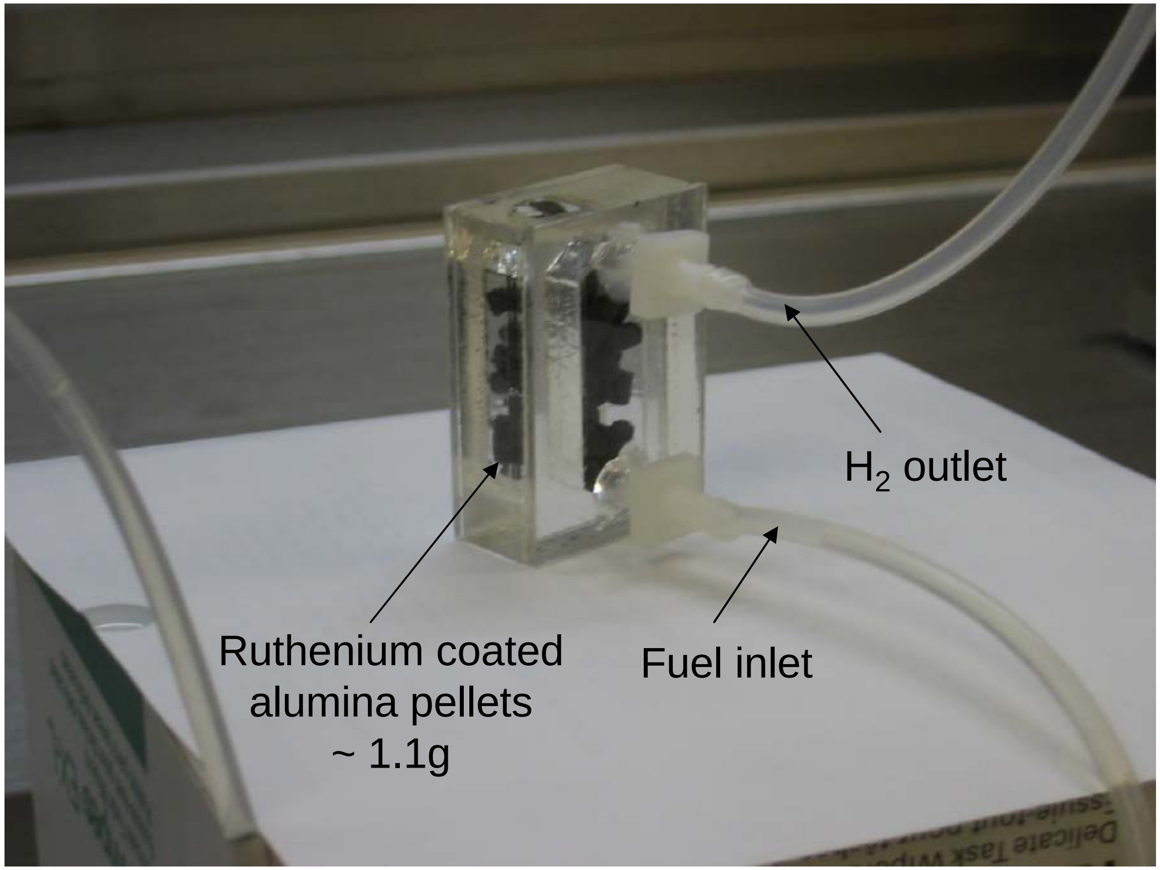
5 wt.% Ru on alumina no dwell time

EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Elem	Wt %	At %	K-Ratio	Z	A	F
Al	88.65	94.92	0.7922	1.0103	0.8833	1.0014
Ru	7.88	2.25	0.0441	0.8326	0.6715	1.0000
Cl	3.47	2.83	0.0188	0.9863	0.5494	1.0000
Total	100.00	100.00				

5 wt.% Ru on alumina 6 hour dwell time

First Generation Hydrogen Reactor

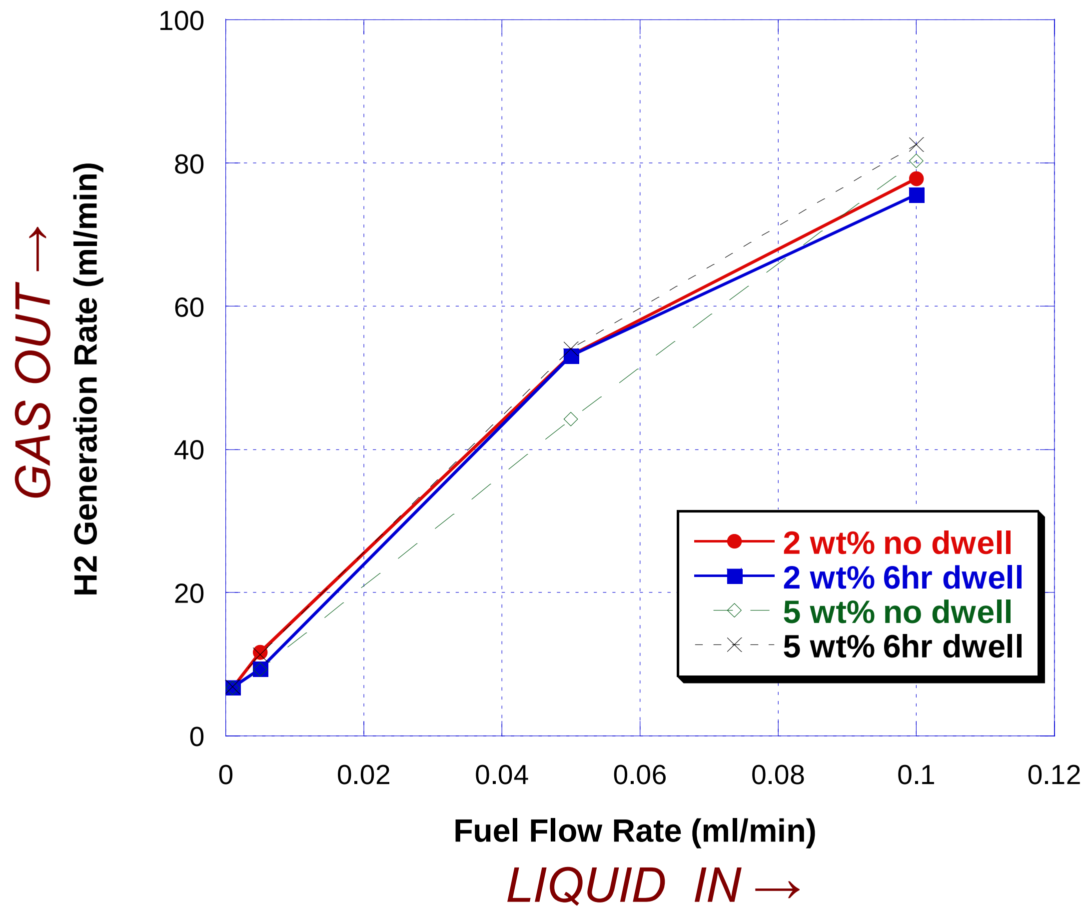


Fuel mixture composition: 30 wt% NaBH4, 4.3 wt% NaOH, 67 wt% H2O
Provides 2250 Watt-hour per liter of mixture at 100% conversion efficiency
Mass of Ru estimated at 52mg!

Catalytic Hydrogen Generation

Effect of catalyst heat treatment in forming gas

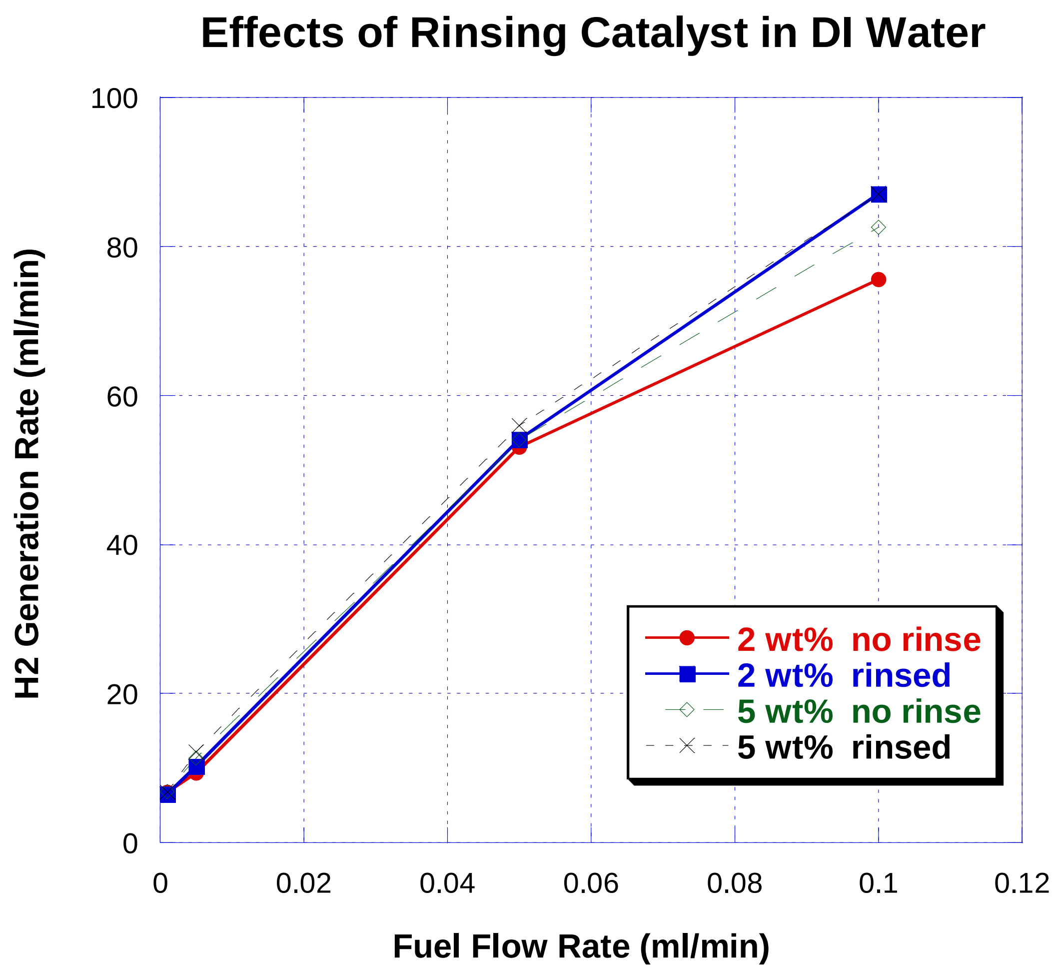
Effects of Catalyst Dwell Time in Tube Furnace



- ***Note: No GAS OUT was observed when Ru on alumina was replaced by equivalent weight of alumina only.***

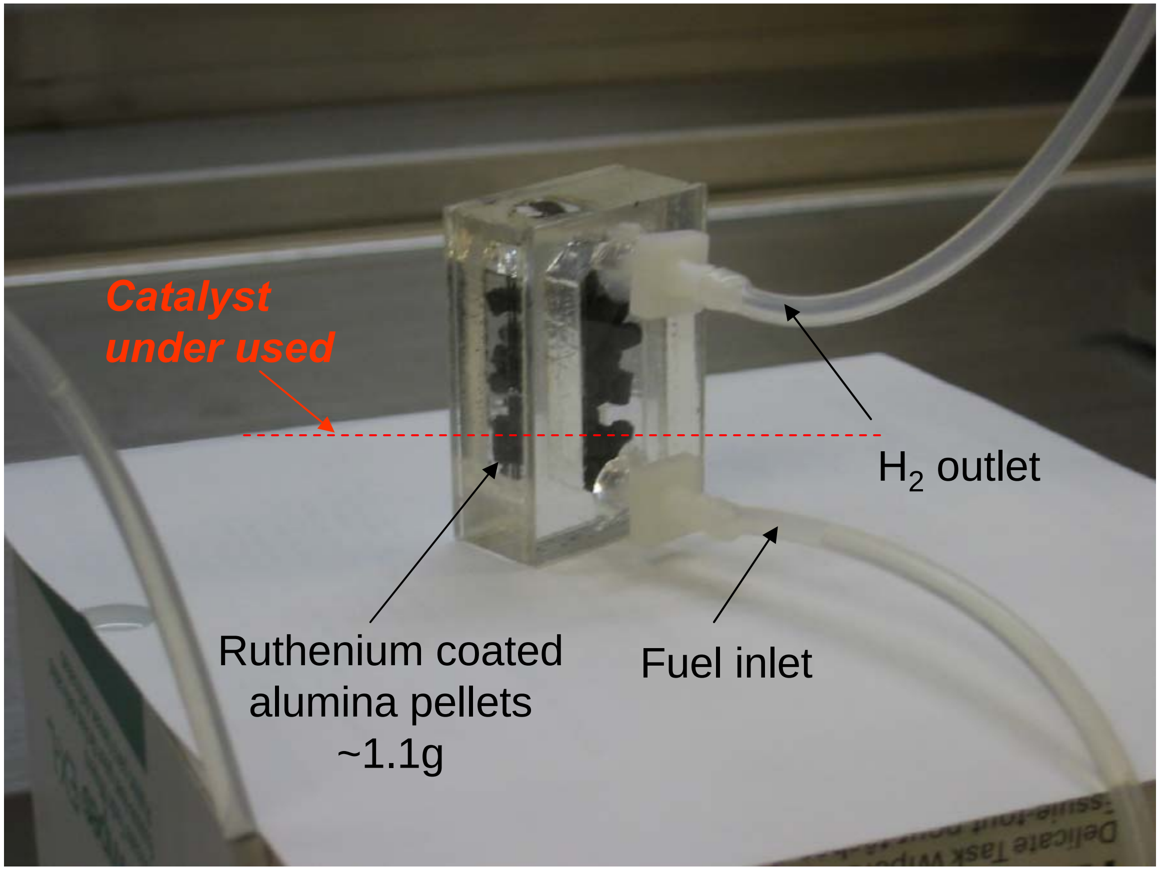
Catalytic Hydrogen Generation (cont.)

Effect of rinsing catalyst with water



** Weight % of Ru in ruthenium-on-alumina pellet is **4.6 wt%.** by EDAX and volume of colored cross-section*

Hydrogen Generating Reactor



Expected to flood chamber and generate gas and collect at top

Only utilized Catalyst on bottom

So evaluated catalyst activity to optimize Ru utilization in reactor!

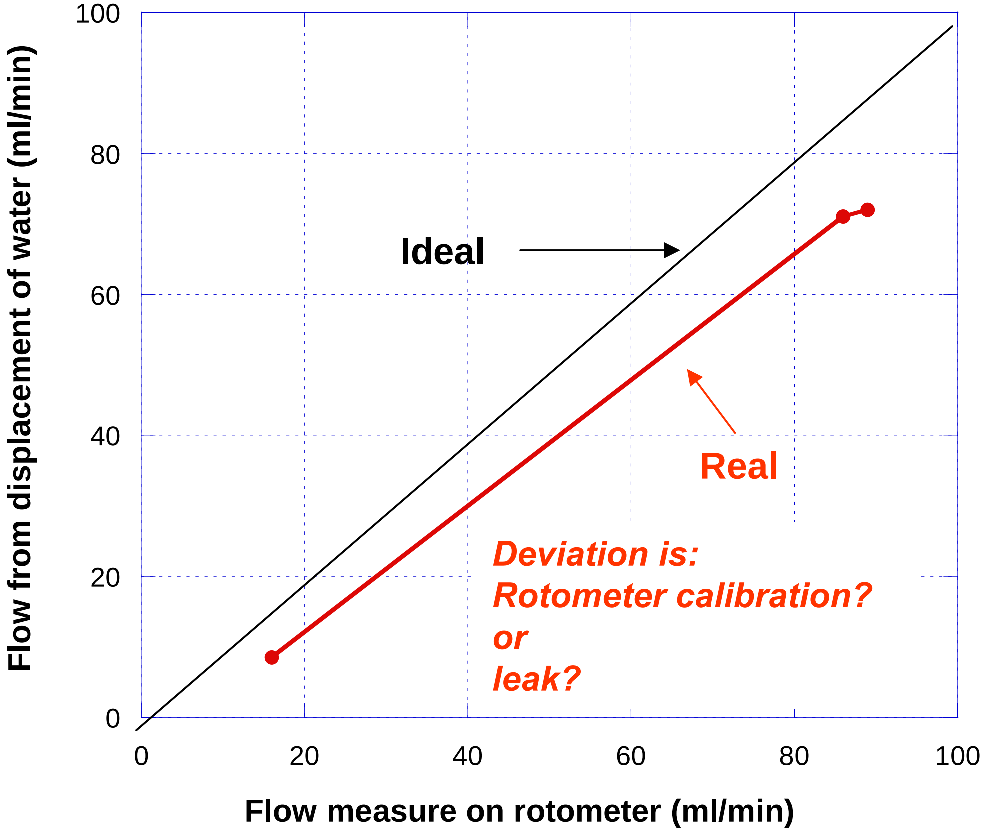
Fuel mixture composition: 30 wt% NaBH4, 4.3 wt% NaOH, 67 wt% H2O

Mass of Ru in reactor estimated at 52mg!

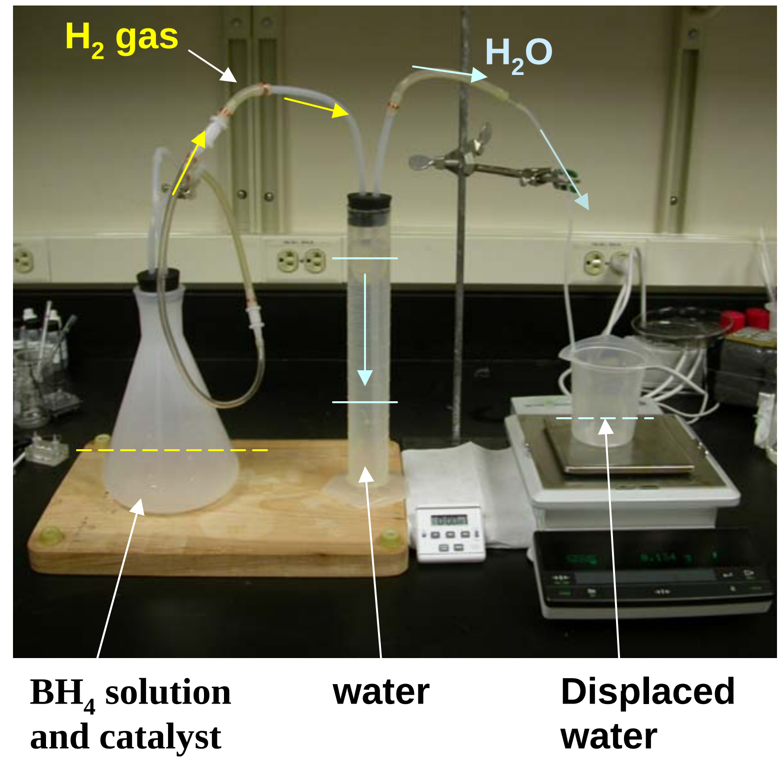
Catalyst Characterization

ARIZONA STATE UNIVERSITY

Calibration of Apparatus



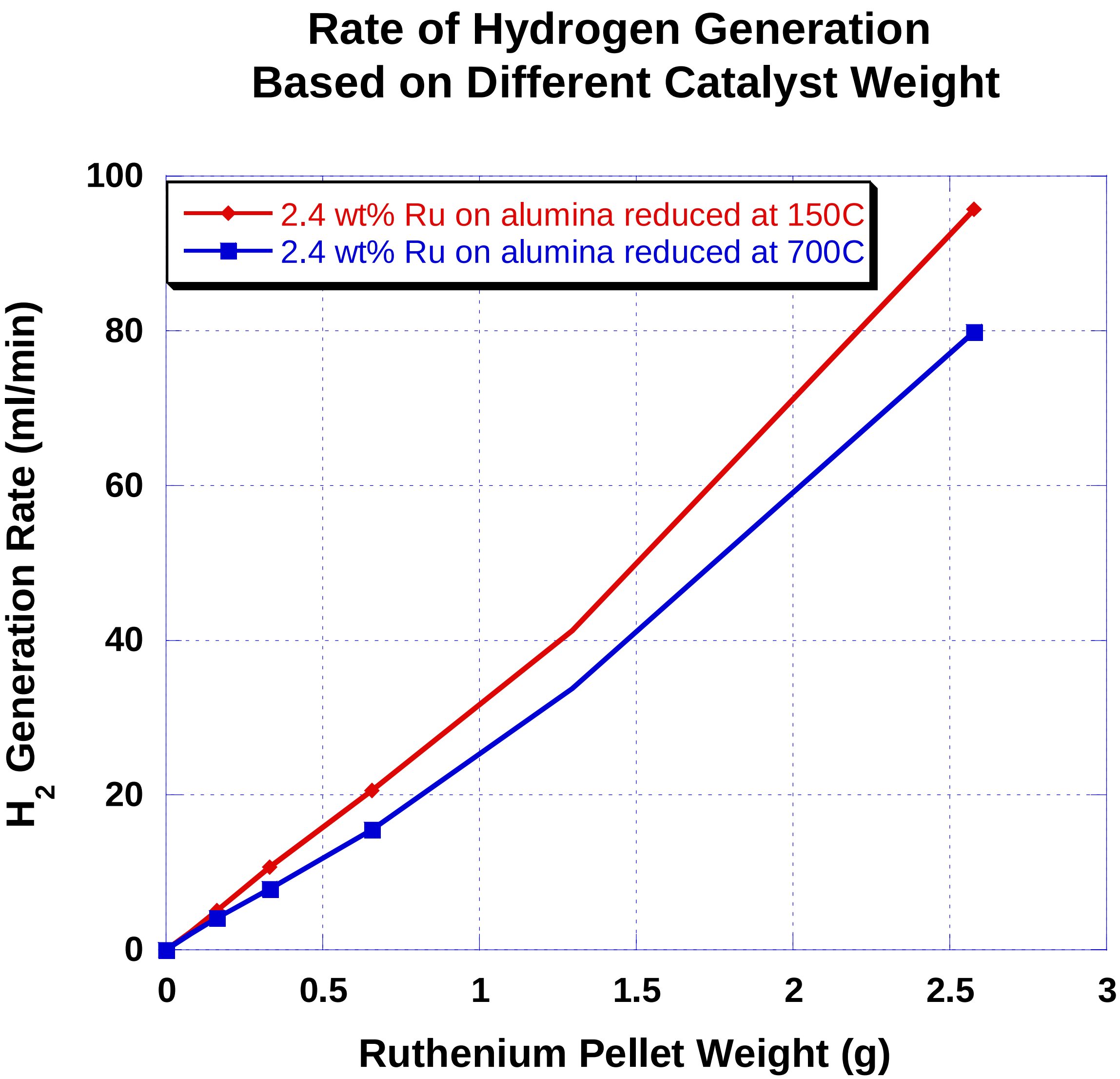
Apparatus for: H2 flow by weight of water displacement



Rate of hydrogen generation = k x *catalyst area* x [$NaBH_4$]

k = rate constant, [NaBH4] near constant. Effect of catalyst area???

Catalyst Characterization

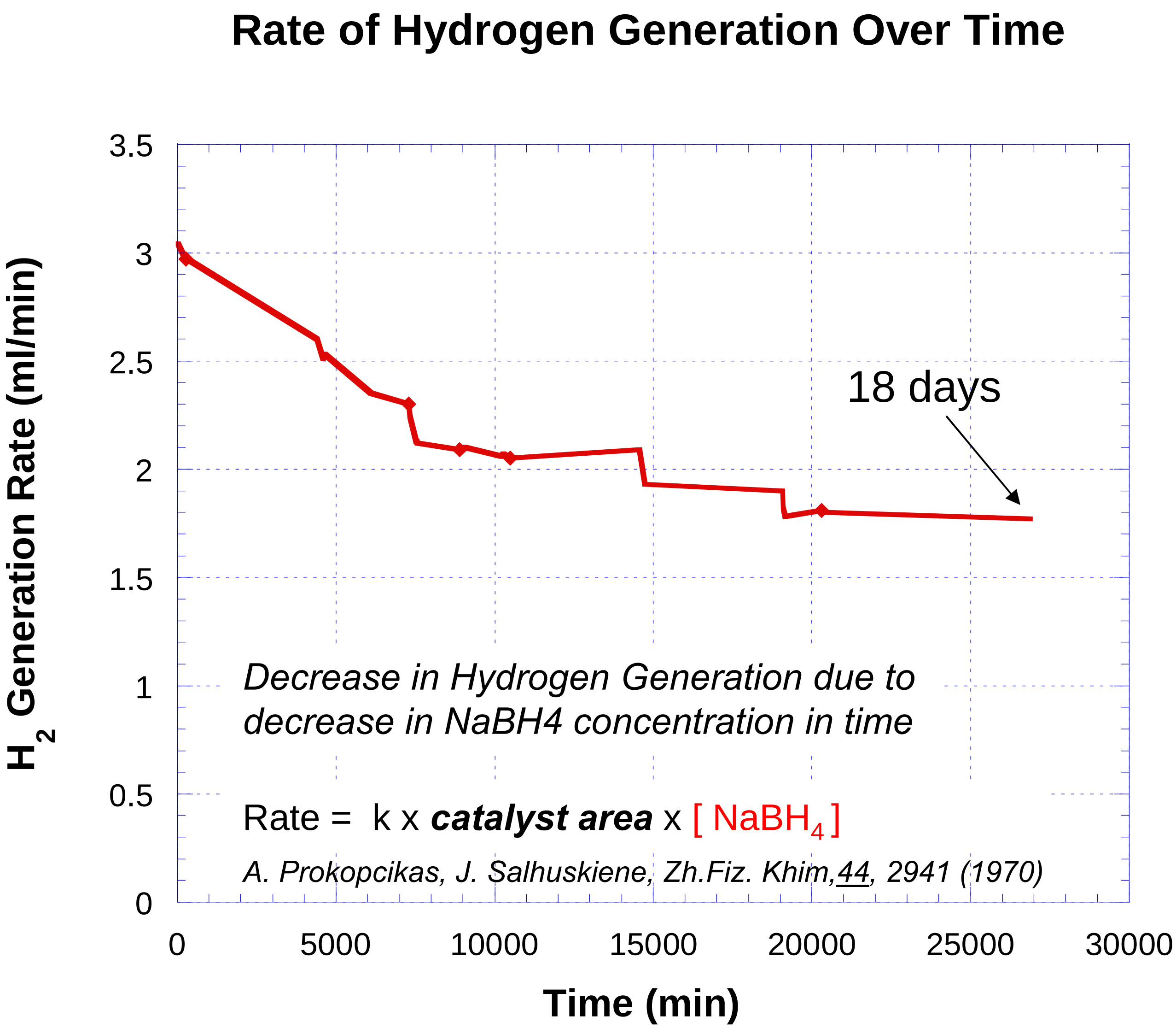


In the presence of excess constant Borohydride concentration the H_2 gas flow is proportional to the catalyst weight.

Ru weight is ~ 3% pellet.

Catalyst Characterization (con't)

no loss catalytic activity in time

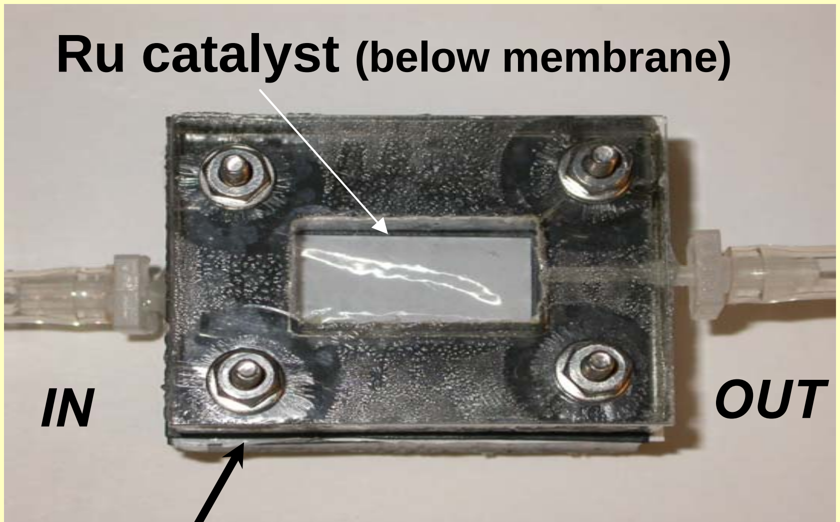


Conditions:

90 mg of 2.4 wt% Ru on alumina in excess Borohydride

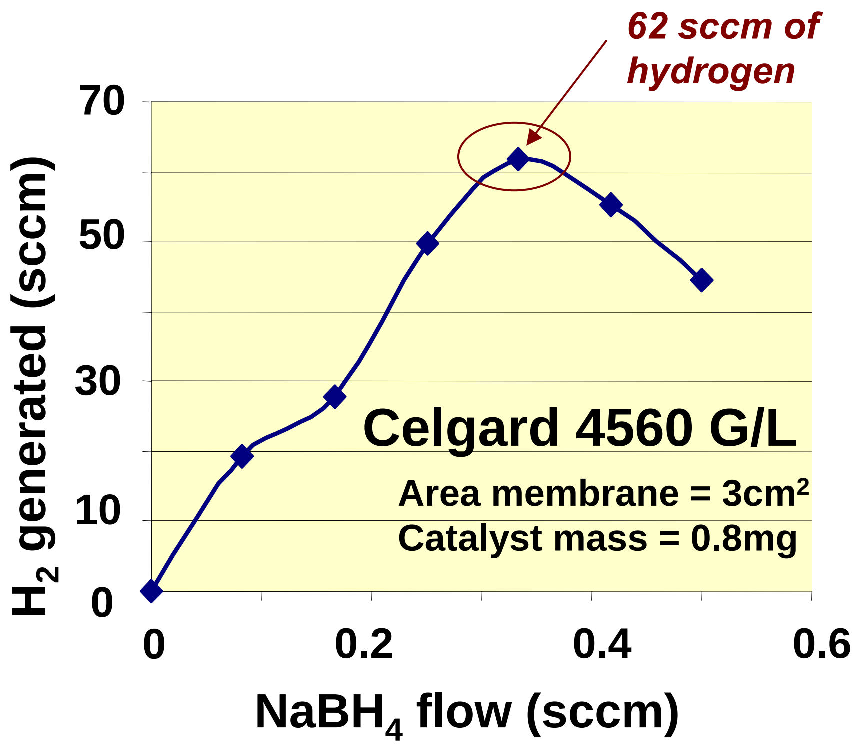
Orientation Independence

Actual
Orientation Independent
H_2 Generator



Celgard Membrane
(Gas/Liquid Separator)

H_2 Generation
through
Gas/Liquid Separating Membrane



Conclusions on Catalytic Hydrogen Generator

- ***Stable hydrogen storage solution***
  -30% $NaBH_4$ solution initially stores 2250 Wh/l
  -1/2 life of pH 14 solution is > 1 year (450 days).

- ***Active and Stable Hydrogen Generating Catalyst***
  Catalyst activity is stable for thousands of hours

- ***H_2 generation rate is proportional to catalyst area***
  Based on the cost of Ru metal and estimates of Ru used,
  Cost for Ru in H_2 generator would be < \$0.50 Watt.

- ***Celgard membrane is gas/liquid separator for gravity independence***

System Conclusions

- Fuel-cell package projected to give > 4x application life of same sized battery-pack as a result of:
  - energy dense H_2 storage (E^d > 2200 Wh/liter or kilogram)
  - compact & orientation-independent H_2 generator
  - reliable and efficient H_2 - air fed fuel cell.

- Low temperature is compatible with hand-carried portables.

- Safe: H_2 storage solution is
  - nontoxic, nonflammable
  - liquid alkaline borohydride storage cartridge leaks slowly
  - pressurized tank of H_2 is hazardous & lost nearly instantly.

- Fuel cell system is cost competitive with batteries at < $10/Watt.

Future Research on Room Temp System

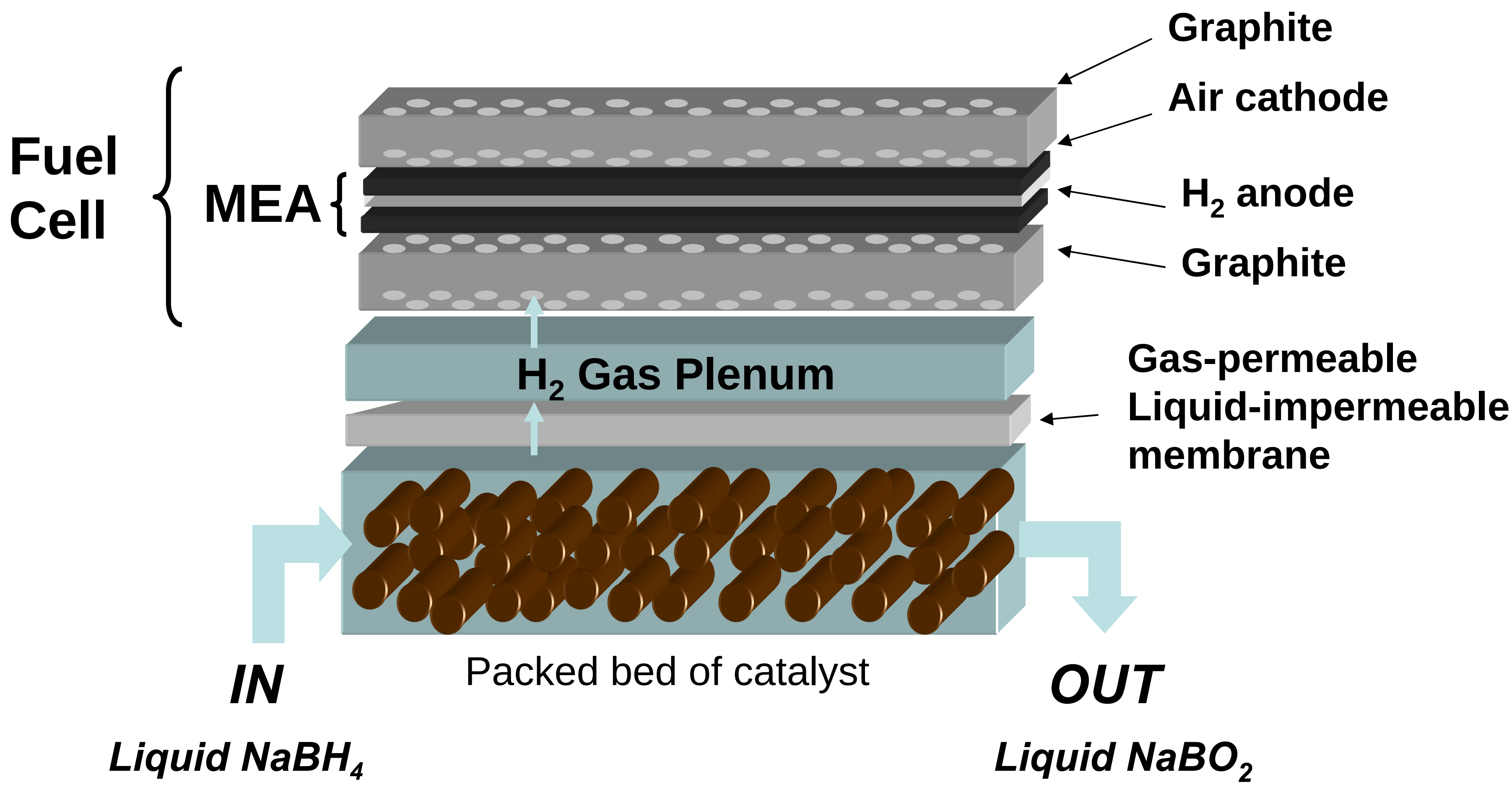
Refine H_2 generating reactor features:
* Ruthenium-coated titanium metal support*
* New gas-liquid separating membranes*
* effect of storage solution pH and additives*

Integrate H_2 generator to Low-power piezo liquids pump &fuel cell

Integrate power and control electronics

Model system features using FEMLab software

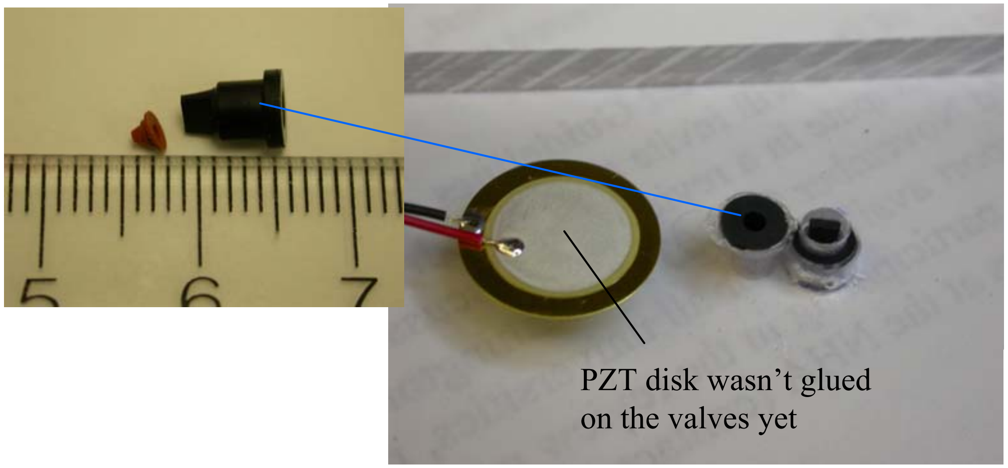
Schematic Diagram of H_2 Generator with Fuel Cell

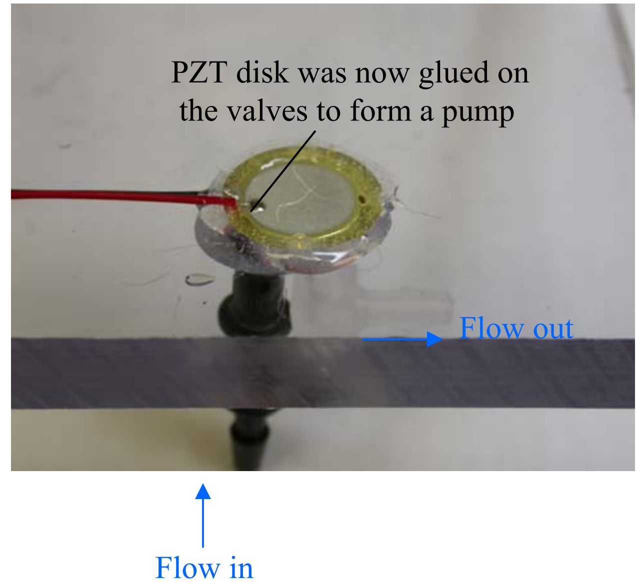


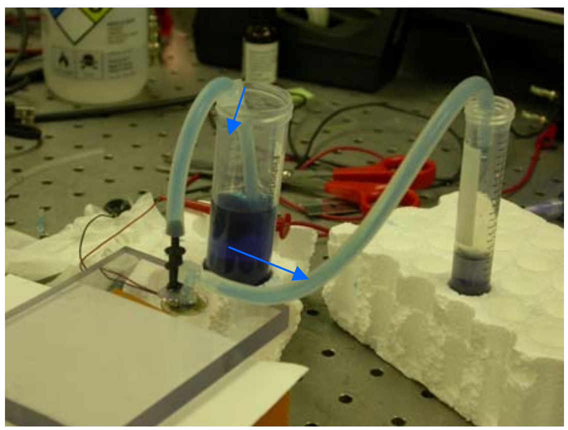
Arizona State University

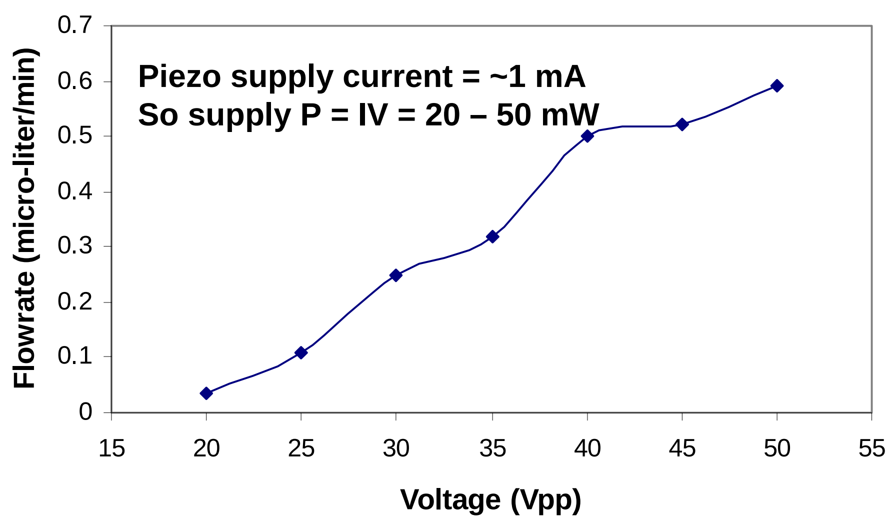
Liquid Pump Characterization

Piezo-Pump with 15 mm diameter PZT









<u>PumpCharacteristics</u>

–Low cost (~ $0.2/pump)

–Scalable; depending on frequency and voltage

–Low power (10 mW to supply a 1Watt fuel cell.

–easy to integrate to the controllers.

WINtech & Applied Nano Bioscience Centers at ASU

ARIZONA STATE UNIVERSITY

Acknowledgements

Connection One NSF-Industrial Center

&

Center for Applied NanoBioscience

&

KITECH

for Support of this Work

Other Research projects at ASU

1-Regenerative Borohydride FuelCell, RBFC
(NASA)

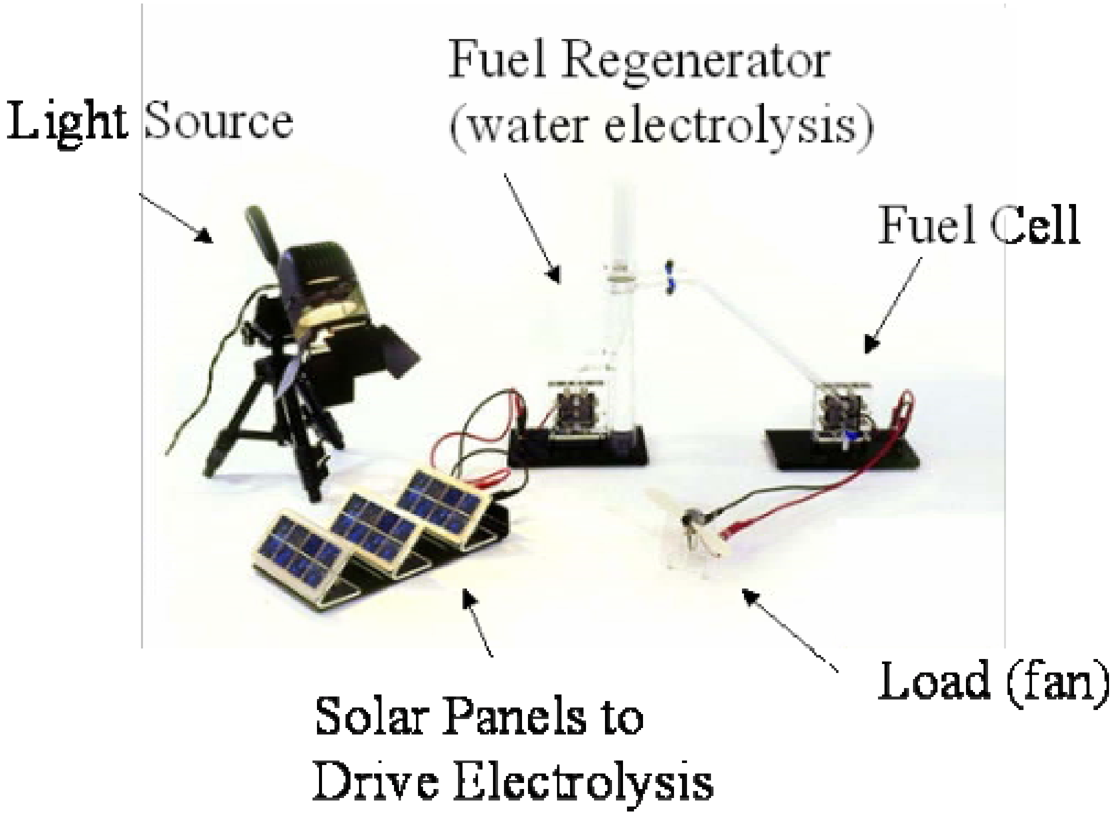
2-Reformed Hydrogen Fuel Cell, RHFC
(Boeing Aircraft Corp.)

3-Proton Conducting Membranes
(ARO, NASA)

4-Oxygen Reduction on Steel and Ni alloy
(US Dept of Energy, DoE)

5-SAM Electrocatalysts
(US Army Research Office, ARO)

1-Solar Regenerated Borohydride FuelCell



Educational Regenerative Fuel Cell System

Conservative Approach

- *Solar to Electric converter*
- *Water Electrolyzer*
    - *H_2, O_2 regeneration*
- *PEM FuelCell*

Problem

- *gas storage!*

1-Solar Regenerated Borohydride FuelCell

$$8\,e^- + 8\,H^+ + NaB(OH)_4 \longrightarrow NaBH_4 + 4\,H_2O$$

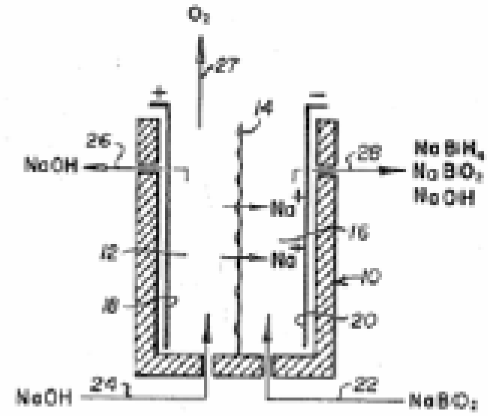


FIG. 1

Solar panel generates electrical power to drive Electrochemical reactor to electrolytically generate:
- Fuel (sodium borohydride H_2 storage solution)
- Oxidant (Peroxide O_2 storage solution).

Advantage

Liquid Fuel&Oxidant Storage
-Fuel, H_2 in Borohydride solution
-Oxidant, O_2 in Peroxide Solution

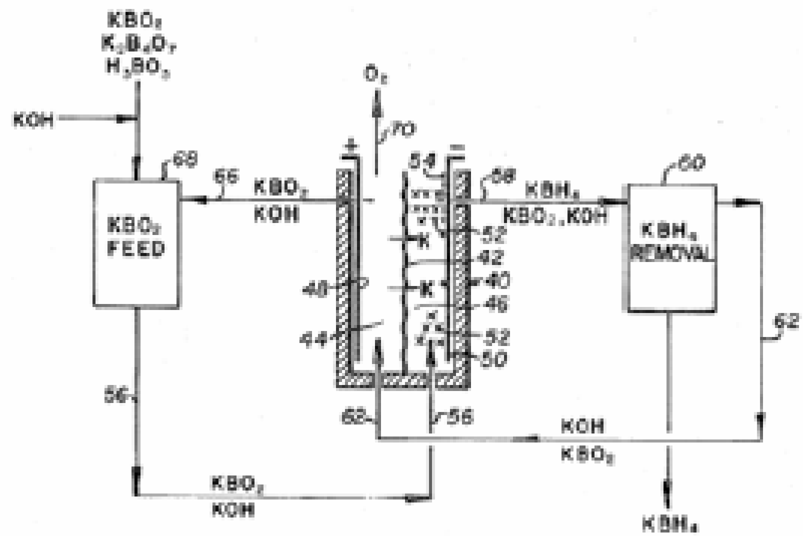


FIG. 2

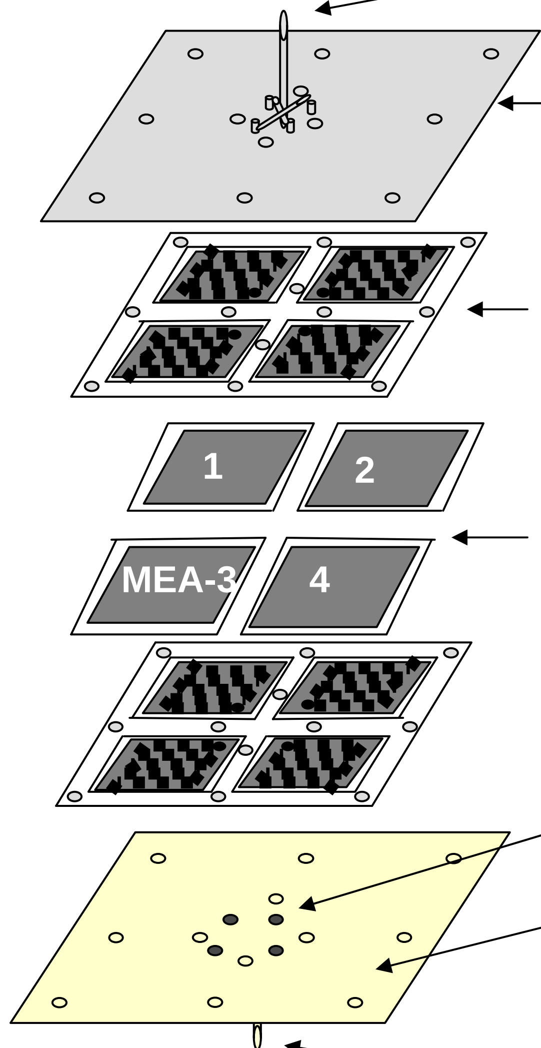
Electrolytic Process for the Production of Alkali metal Borohydrides, UP Patent 3,734,842, H.B.Cooper May 22 (1973.

INVENTOR.
HAL B H. COOPER

WINtech & Applied Nano Bioscience Centers at ASU

2-RHFC: 10-Watt Planar Stack

Boeing Aircraft & NuElement
Tacoma, WA



H_2 (reformate) in

Stainless-steel Housing
(bolt-on construction)

4 Graphite Current-collectors
Each with Flow field
Each in Teflon insert

4 Membrane Electrode Assemblies

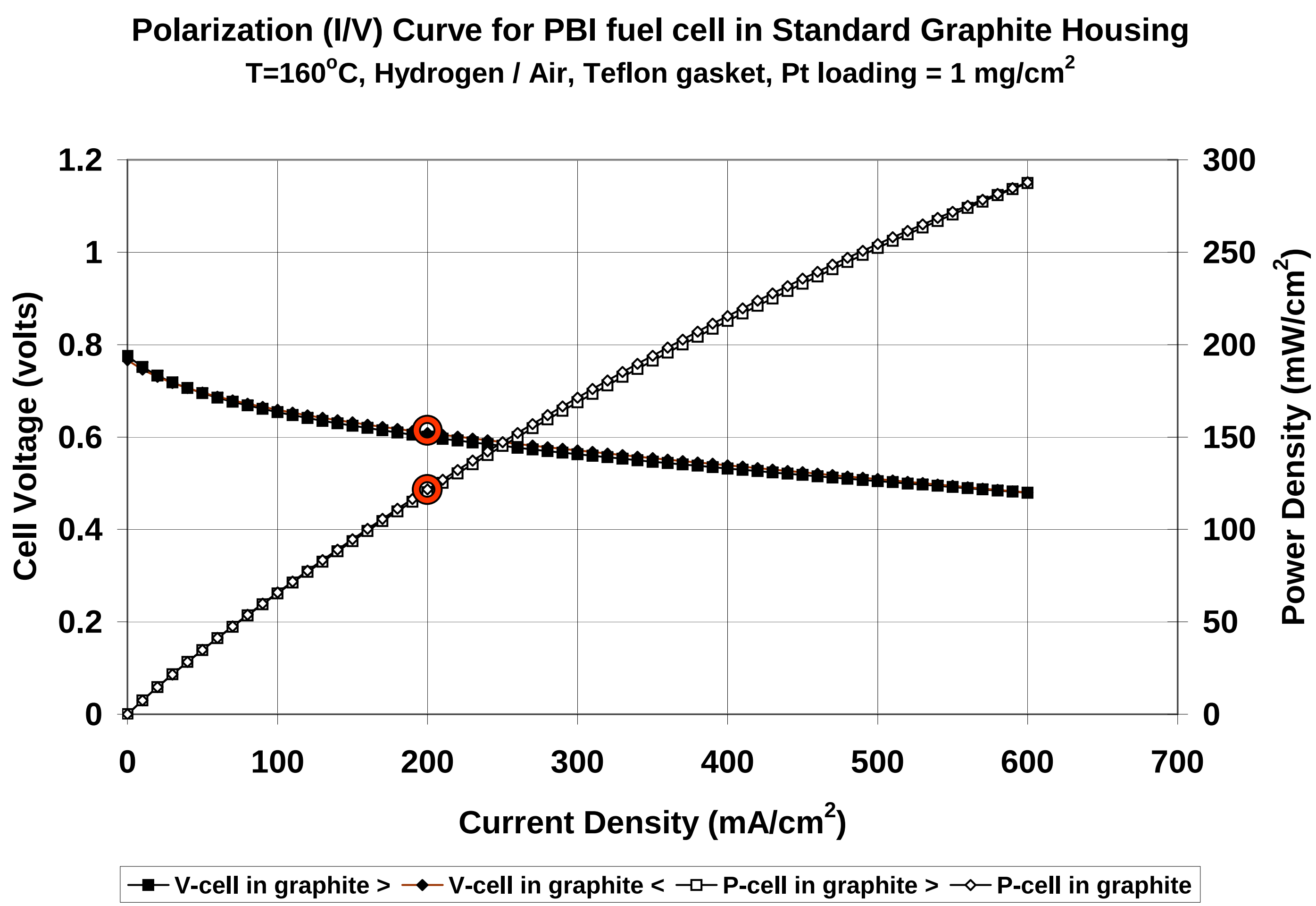
O-ring gas seals

Reinforced Teflon Sheet Insulation
(on inside) of Steel Housing Plate

Air in

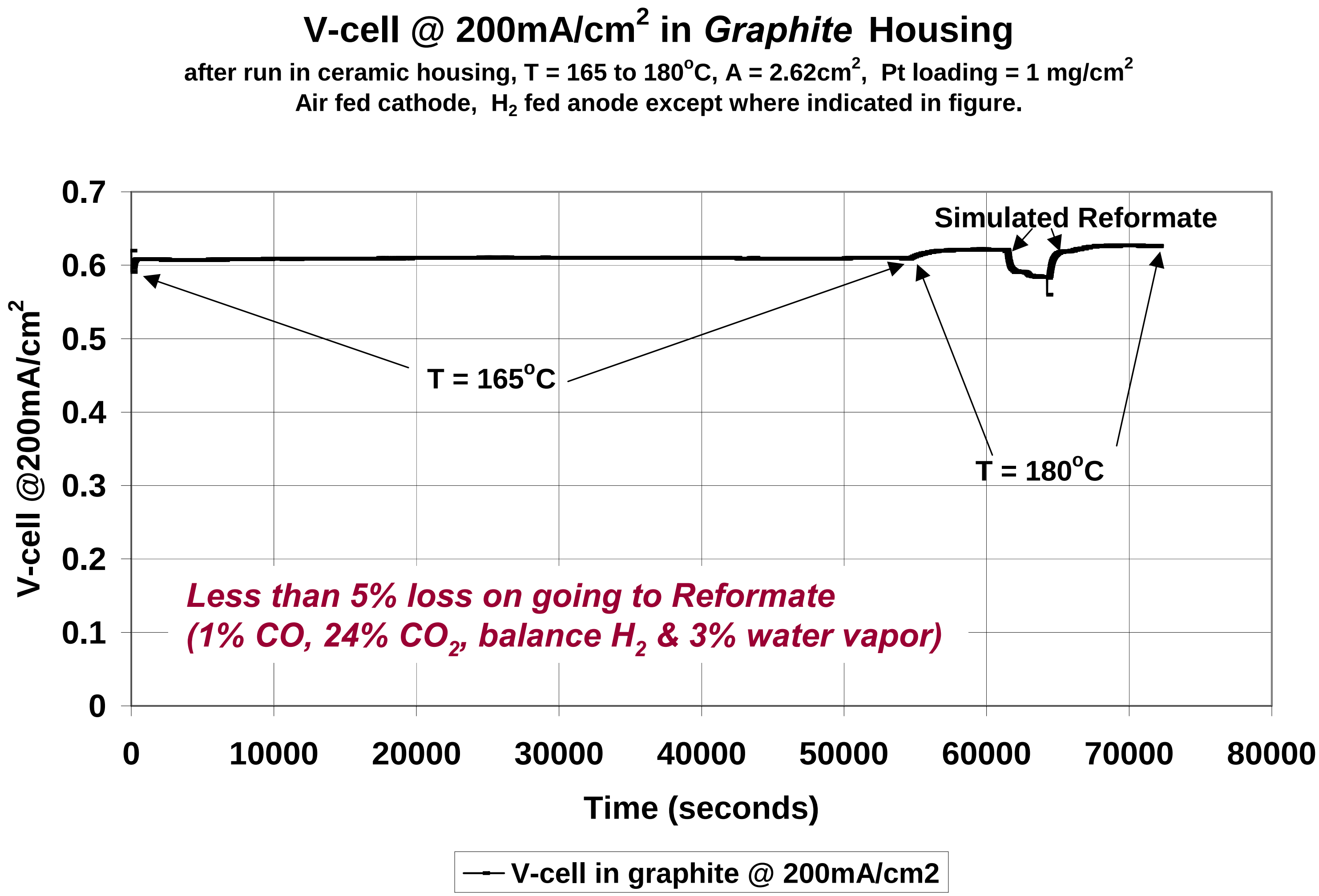
2-Performance of Reformed Hydrogen Fuel Cell

ARIZONA STATE UNIVERSITY



- ***Power per stack = <u>0.6 V x 200 mA/cm</u>^{2} x 25cm^2 per cell x 4 cells = 12 Watt***

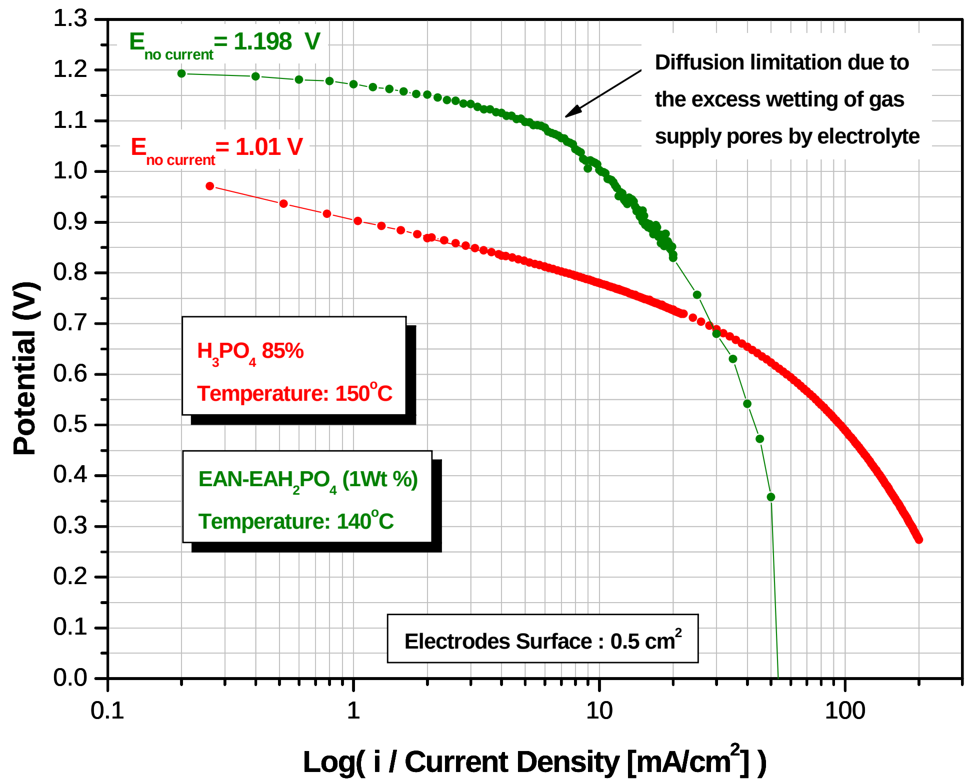
2-Relative Performance of Graphite-housed PBI-MEA Fed pure H_2 versus simulated reformate



Power per stack = <u>0.6 V x 200 mA/cm²</u> x 25cm² per cell x 4 cells = 12 Watt

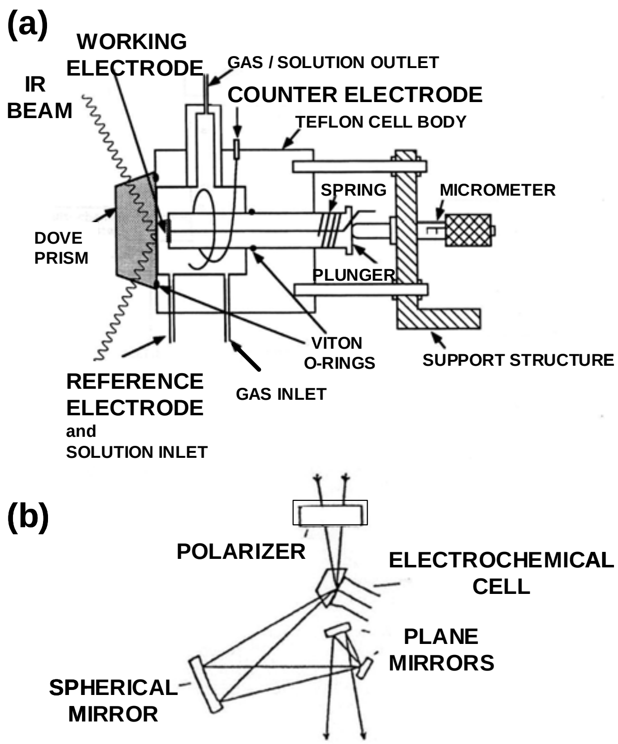
3-Proton Conducting Membranes

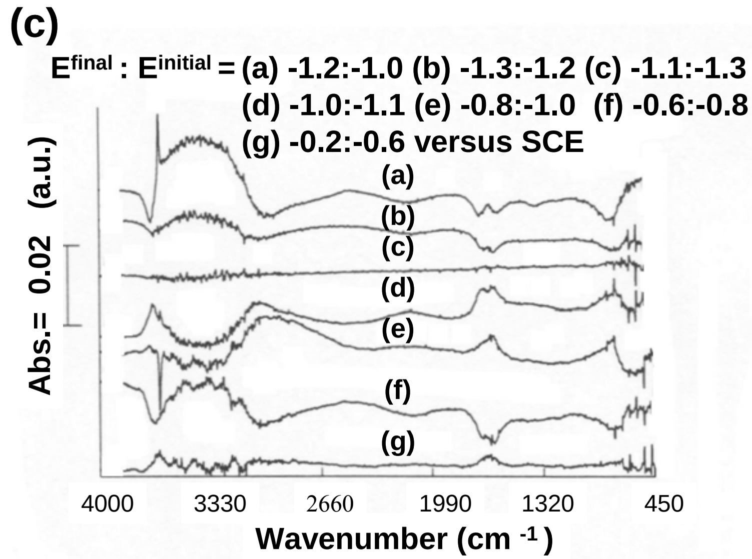
with Prof. C. Austen Angell, ASU Chem. Dept.



Polarization curves on Pt-catalyzed gas-fed electrodes in EAN-EA-H_2PO_4 and 85% H_3PO_4. Flow H_2 = 40sccm, O_2 = 30sccm, E-TEK electrode area = 0.5cm². Pt loading = 0.5 mg/cm².

4-Corrosion…Surface FTIR of Steel

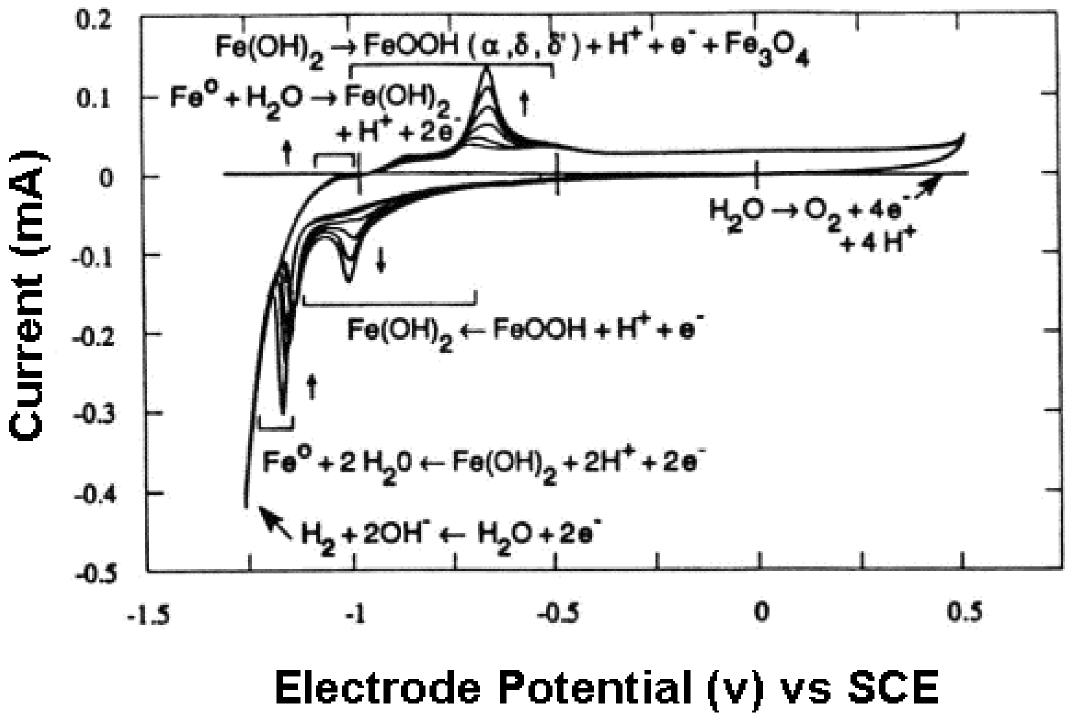




Surface infrared spectra of steel in 1 M KOH
Upon changing potential from initial to final.

Electrochemical Fourier Transform Infrared (Echem-FTIR) reflectance surface spectroscopy method: (a) Electrochemical Infrared Reflectance Cell, (b) Reflectance Absorption Optics, (c) Infrared difference spectra for carbon steel in 1M KOH.

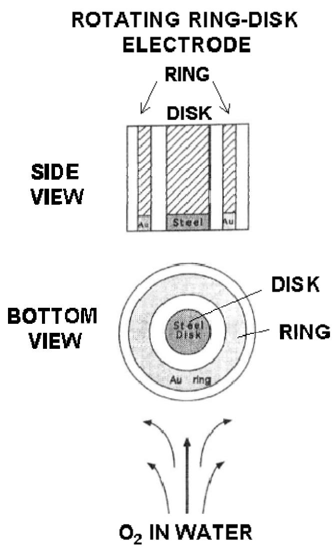
4-Surface Voltammetry of Steel

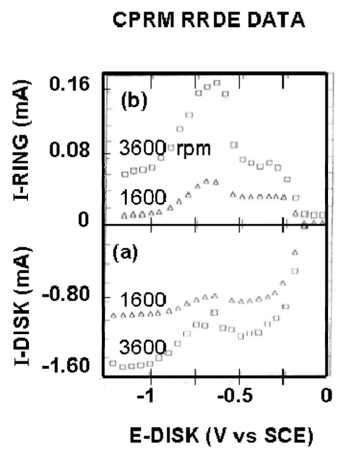


Cyclic voltammogram for an ASTM A516 steel disk (A=0.3 cm2) in aqueous anaerobic 1M KOH solution (pH=14). Room temperature. Scan rate = 10 mV/sec.

Voltammetry peak assignments made from in situ FTIR experiments

4- Oxygen Reduction on Steel and Ni alloy





CPRM for O_2 in 1 M KOH with
(a) O_2 reduction on steel disk
(b) H_2O_2 oxidation on Au ring

Linear regression of the ring and disk data Yields plots of $i_{dl}/(i_{dl}-i)$ versus $\omega^{-1/2}$ which yield slopes, S_2, and intercepts, I_2.

Regression of the i_D/i_R versus $\omega^{-1/2}$ plots yields slopes, S_1, and intercepts, I_1.

These S and I values can be used in the following expressions

$$k_1 = S_2 Z_1 (I_1 N - 1) / (I_1 N + 1)$$
$$k_2 = 2 S_2 Z_1 / (I_1 N + 1)$$
$$k_3 = Z_2 S_1 N / (I_1 N + 1)$$

Schematic of rotating ring disk electrode (left)

O_2 reduction current (right, bottom) on a steel disk

Peroxide (H_2O_2) oxidation current (right, top) on the Au Ring.

Result of Rotating Ring Disk Electrode (RRDE) Study

rate constants for oxygen reduction

Rates constants for O_2 reduction at different potentials

Rate Constant (cm/s)	Potential versus SCE (volts) 0.85	0.45
k_1 (anodic)	360×10^{-5}	59×10^{-5}
k_2 (anodic)	[a]960×10^{-5}	[b]230×10^{-5}
k_3 (anodic)	[a]950×10^{-5}	65×10^{-5}

[a]Hydroxide (water) dominant product of O_2 reduction
[b]Peroxide product of O_2 reduction

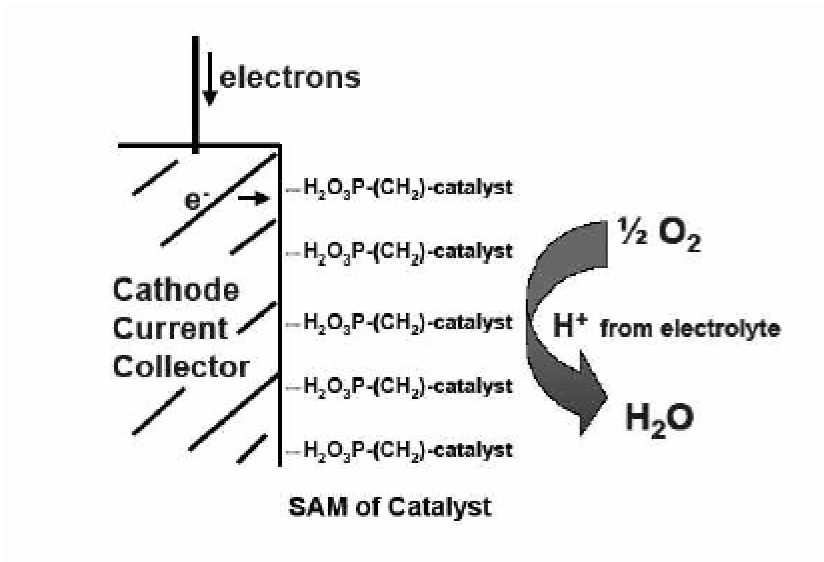
Oxygen Reduction Mechanism

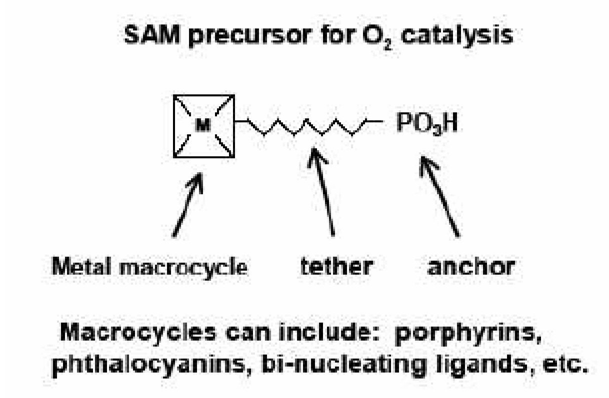
$$O_2 \xrightarrow{+4e^-,\ k_1} H_2O$$

$$O_2 + 2e^- + H^+ \xrightarrow{k_2} H_2O_2 + 2e^- + H^+ \xrightarrow{k_3} H_2O$$

$$H_2O_2 \xrightarrow{k_4} \text{Solution peroxide}$$

5-Self Assembled Monolayer (SAM) of Electrocatalysts





Schematic diagram of SAM of catalyst on an inert metal surface

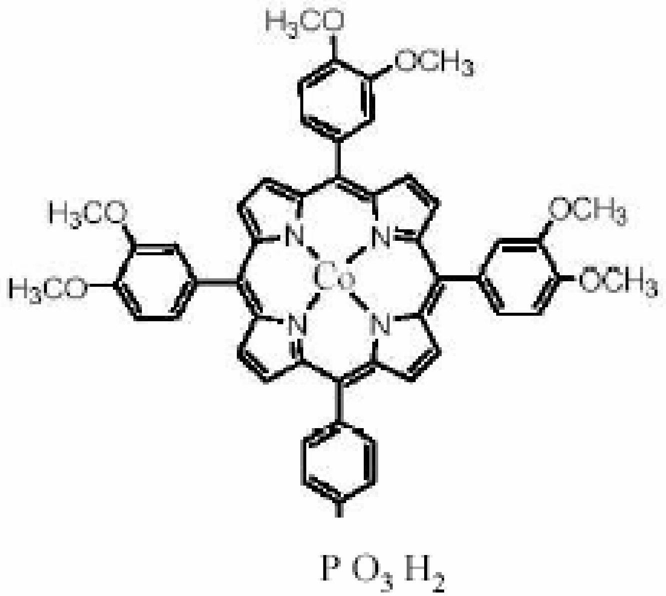
Schematic diagram of the precursor to SAM

5-Precursors to Electroactive SAMs

Model of Surface Catalyst

6-FHP

6-ferrocenylhexyl phosphonic acid

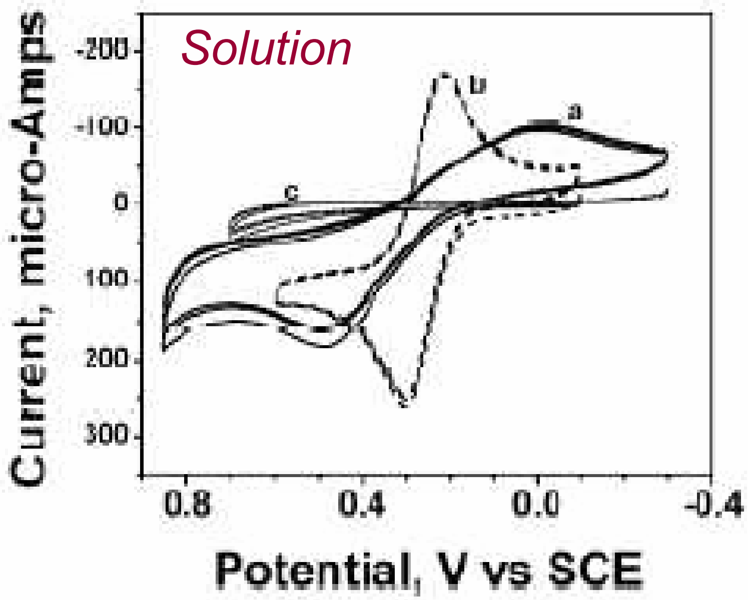


Catalytic SAM Precusor

Co-P

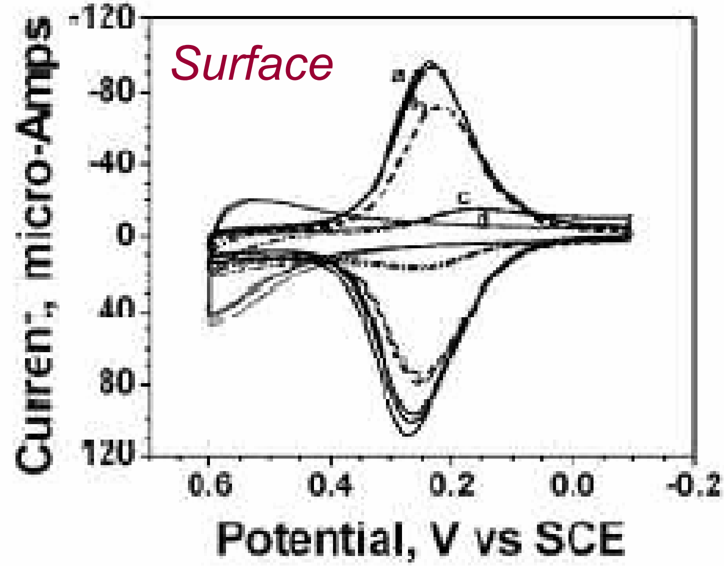
Co(II)
5-(4dihydroxyphosphorylphenyl)
10,15,20 tris(3,4dimethoxyphenyl)
porphyrin

5-Voltammetry of Ni with Electroactive Solution vs Surface Species



(I)

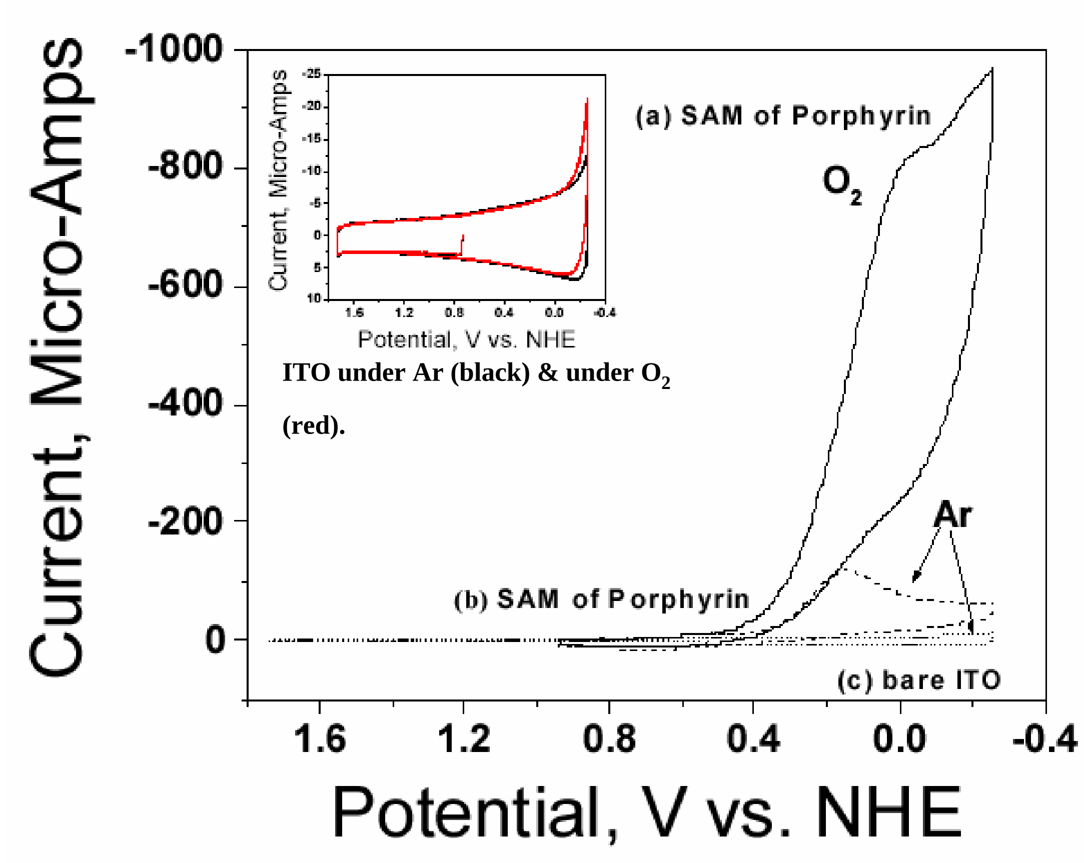
Voltammograms of Ni and Pt in 0.1 molar NaClO4 in 50% MeCN and 50% water under Argon.
(a) Ni with 0.5 mM ferrocene present;
(b) Pt with 0.5 mM ferrocene present;
(c) Ni with no ferrocene in solution.
Scan rate: 100 mV/s; area of all electrodes: 2 cm2.



(II)

Voltammograms of a Ni electrode in 0.1 M NaClO4 in 50% MeCN and 50% water under Argon.
(a) the first scan with 6-FHP on the Ni from 0.5 mM FHP solution in 7:3 CHCl3: CH3OH;
(b) after continuous scanning 10 minutes;
(c) after stored in electrolyte for 24.5 hours and retested;
(d) bare Ni electrode.
Scan rate: 100 mV/s; Area of Ni: 2 cm2.

5-O_2 Reduction Catalyzed by SAM of Co-P on ITO



Voltammograms of ITO in 0.01 M triflic acid (a) with a SAM of Co-P under O_2, (b) with a SAM of Coporphyrin under Ar and (c) bare ITO under Ar. Scan rate 100 mV/sec. Electrode area = 2.7 cm^2.

Prospects for Future Research

* Further size reduction of Borohydride system using MEMS

* Nanoporous supports with SAM of electrocatalysts

* Biofuel cells & Biosensors

* Develop new non-Pt Electrocatalysts (e.g., for H_2 oxidation)

* Model Fuel Cells
with FEM-lab

Arizona State University - BioDesign Institute

ASU Arizona State University AZ Biodesign Institute View from campus

GouldEvans LORD·AECK·SARGENT

Arizona State University – Flexible Display Center