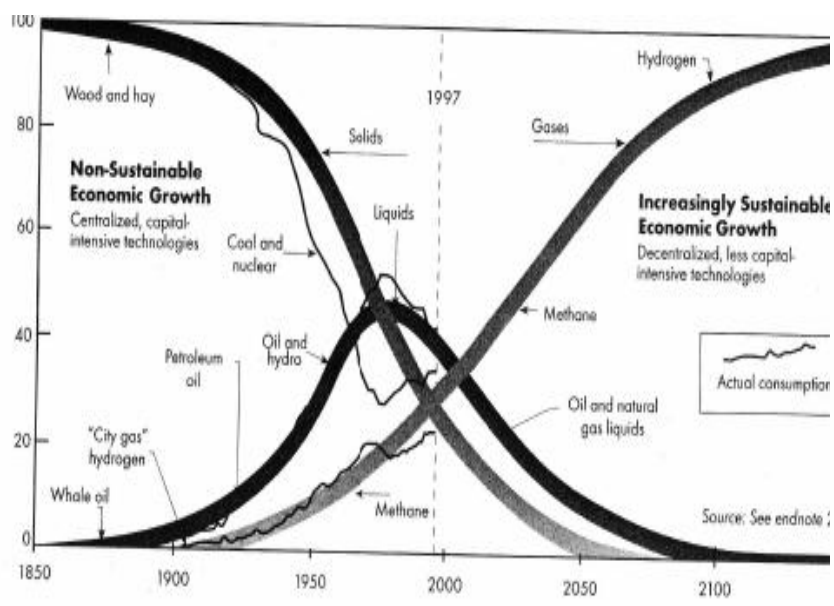
Distributed and Large Scale Hydrogen Production Methods

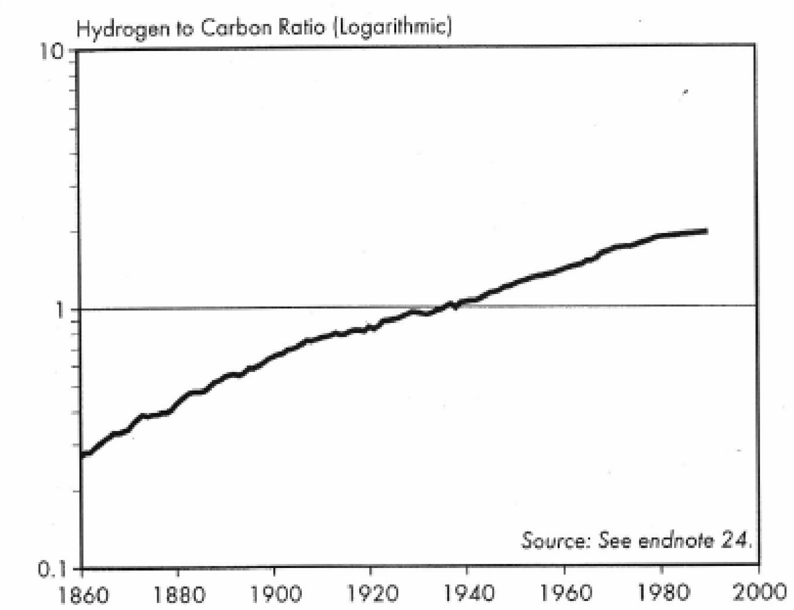
George H. Miley
University of Illinois

Outline

- ***Comments about the "Hydrogen Economy"***
- Production of Hydrogen
  - Distributed and Central Plants
  - Plasma production
    - STAR CELL
    - Jet (Torch) Production (current U of IL research)
- Hydrogen storage (comments about our Dislocation Loop research)
- *Fuel Cells (a few comments about our research)*
  - Direct Borohydride
- *Concluding comments & questions from you*

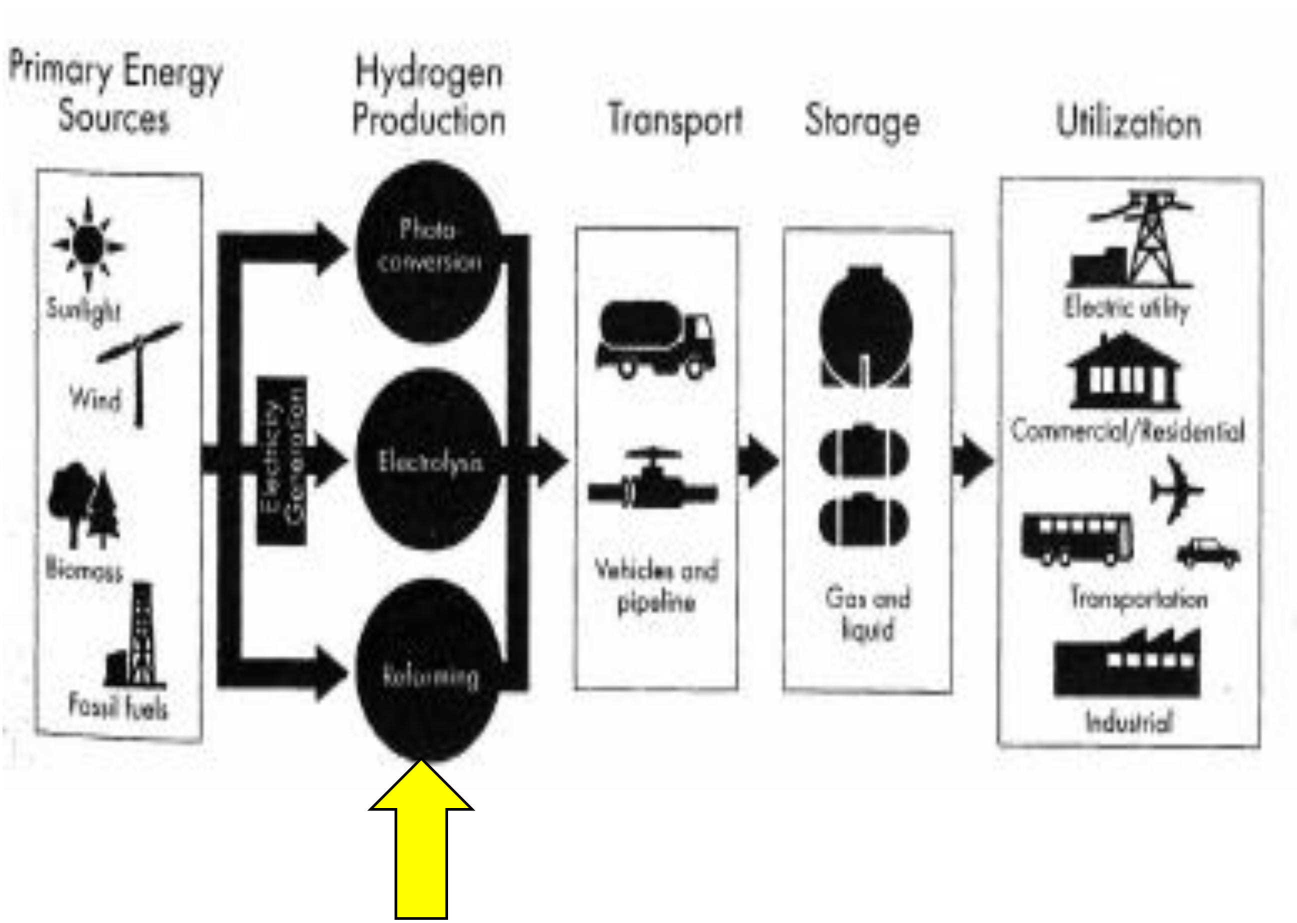
Global Energy Systems Transition, to H2 Energy Carrier 1850-2150





ResultingHydrogen-Carbon Ratio, World Energy Mix, 1860-1990

Elements of a Hydrogen Energy System



Current and projected needs – would require very significant addition of power plants for production

- contemporary hydrogen production is primarily based on fossil fuels. Produced fertilizers, in oil refineries to lighten heavy crude oils and for other industrial uses, primarily by ***steam reformation of methane***..
- In the USA the hydrogen **industry produces 11 million tons of hydrogen a year** with a thermal energy equivalent of 48! GW(t). In so doing, it consumes 5% of the US natural gas usage and releases 74! million tons of CO_2.
- **Transition to a Hydrogen Economy** will require significant expansion in the production and use of hydrogen. Use of ***hydrogen for all our transportation energy needs would require a factor of 18 more*** hydrogen than currently used. Use of hydrogen for all our non-electric energy needs would require a factor of 40 increase. At 50% efficiency, this represents **adding 4000 new 10 GWth power plants – or use of "Mosaic" discussed later (note numberber of new coal plants/week in China .**

Scaling

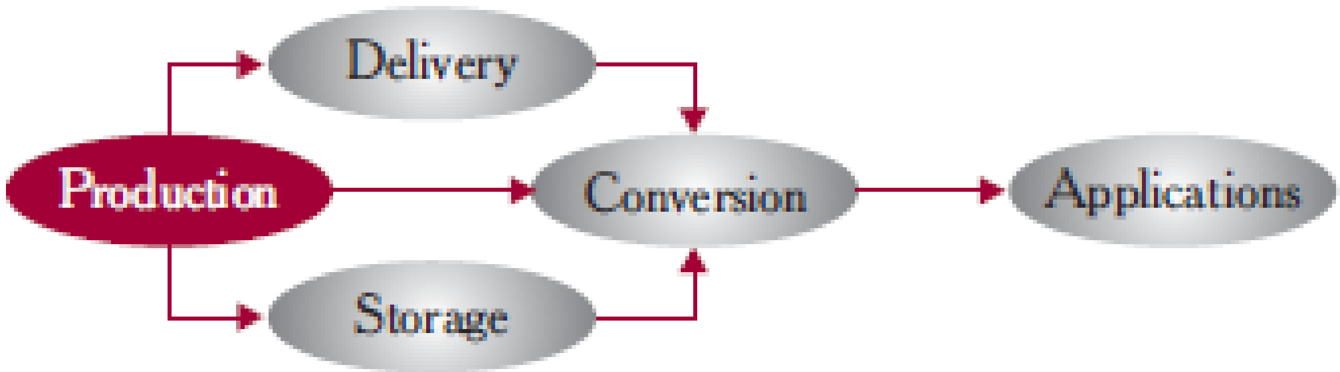
How much is 9 million tons of hydrogen per year?

Enough to fuel 20 to 30 million hydrogen fueled cars, or enough to power 5 to 8 million homes.

Outline

- Comments about the "Hydrogen Economy"
- ***Production of Hydrogen***
  - ***Distributed and Central Plants***
  - Plasma production
    - STAR CELL
    - Jet (Torch) Production (current U of IL research)
- Hydrogen storage (comments about our Dislocation Loop research)
- *Fuel Cells (a few comments about our research)*
  - Direct Borohydride
- **Concluding comments & questions from you**

H2 production – centralized or distributed – involves storage and distribution



Hydrogen can be produced in centralized facilities or at decentralized locations where it will be used onsite. From centralized facilities, it is distributed to an energy conversion device via pipeline, or stored and shipped via rail or truck. When produced onsite, hydrogen can be stored and/or fed directly into conversion devices for stationary, mobile, and portable applications.

How much hydrogen do we need?

Once applications for hydrogen as an energy carrier have become well established, the United States will require much more hydrogen than it now produces. An estimated 40 million tons of hydrogen will be required anually to fuel about 100 million fuel-cell powered cars, or to provide electricity to about 25 million homes.

Each of the following scenarios could produce 40 million tons per year of hydrogen:

Distributed Generation Production Methods

Electrolysis: 1,000,000 small neighborhood based systems could fuel some of the cars and provide some power needs.

Small reformers: 67,000 hydrogen vehicle refueling stations, which is about one third of the current gasoline stations.

Centralized Production Methods

Coal/biomass gasification plants: 140 plants each about like today's large coal fired plants.

Nuclear water splitting: 100 nuclear plants making only hydrogen

Oil and natural gas refinery: 20 plants, each the size of a small oil refinery, using oil and natural gas in multi-fuel gasifiers and reformers.

"A Production Mosaic"

Many factors will affect the choice of production methods, how they will be used, and when they might be demonstrated and commercialized. Visualizing a mosaic of future production methods provides a perspective for the Roadmap. The combination of distributed and centralized production, plus advanced methods that are not yet available, could be combined to create a future industry producing 40 million tons of hydrogen per year. Here is one scenario:

100,000 neighborhood electrolyzers	4 million tons
15,000 small reformers in refueling stations	8 million tons
30 coal/biomass gasification plants	8 million tons
10 nuclear water splitting plants	4 million tons
7 large oil and gas SMR/gasification refineries	16 million tons

Production Mosaic for 40 million tons?

This photovoltaic array at SunLine Transit Agency in Thousand Palms, California, is used with an electrolysis unit to create hydrogen for fuel cell-powered buses

H2 fueling stations today

- Today, there are two ways hydrogen fueling stations can generate hydrogen on-site: **through natural gas reforming or water electrolysis.**
- Nearly all of the hydrogen generated in the United States today is produced through steam reforming of natural gas in large industrial facilities similar to oil refineries. However, steam reforming can also be performed on a smaller scale on hydrogen fueling station sites. In the steam-reforming process, natural gas reacts with steam at high temperatures over a catalystto produce hydrogen gas.
- Electrolysis, in contrast, generates oxygen and hydrogen from water using. eectrolysis . It is a **more expensive way** to produce hydrogen, but it generates no on-site emissions and may be an attractive option in locations that have low-cost off-peak power generation. In addition, electrolysis can be powered by renewable fuels such as wind and solar power to create emissions-free, renewable hydrogen.

Solar powered electrolysis station in Thousand Palms, CA for fueling fuel cell buses

Demonstration stations are used to develop experience and standards

- **Hydrogen Fueling Station Design Standards**
- A large number of possible codes and standards can come into play for permitting design and construction of hydrogen fueling stations. Additional federal, state, and local requirements may also apply.
- Model code provisions related to general design issues include:
- Facilities
- Equipment
- Barrier walls
- Weather Protection
- The safety of employees and customers depends on proper design, location, and operation of storage and dispensing equipment and the proper installation and operation of leak detection, fire detection, and fire suppression equipment. In addition, incompatible materials or improperly installed equipment can lead to fuel contamination, which can degrade the performance of the fuel cells that power hydrogen-fueled vehicles. Model code provisions related to equipment specifications include:

U.S. DOE -Hydrogen Fueling Station Case Studies

- Although only about 60 hydrogen fueling stations have been approved for operation in the United States, many more are planned. The case studies presented here are examples of operational projects throughout the nation.

:

- Washington, District of Columbia
- Oakland, California
- White Plains, New York

Wash DC

•**<u>Step Three: Fully integrated fuel stations (which include traditional fuels and hydrogen)</u>**

•Step Four: Mini-network "lighthouse projects" (which are semi-commercial, public-private partnerships that involve multiple energy companies, governments, and fleets of 100 or more vehicles) to be developed within the next 5 years

•***Step Five: Mini-networks that connect hydrogen fueling corridors to be developed during the 2010-2020 time period.***

3355 Benning Road, NE - Washington, DC
Fuels Available: Gasoline Gaseous hydrogen (5,000 psig) Gaseous hydrogen (10,000 psig) Liquid hydrogen.
Hydrogen Delivery: Liquid hydrogen is delivered to the station by a tanker truck.
Liquid Hydrogen Storage:stored below-grade in 1,500-gallon (400-kg) double-walled, insulated, ss vessels at -420°F.
Vaporizer: Avaporizes the liquid h2 by raising its temperature from -420°F to ambient
Compressors: three-stage compressor takes taporized gas to 5,500 psig.;one-stage compressor goes to 11,000 psig.
Gaseous Hydrogen Storage: Gaseous hydrogen from the compressor is stored at 5,500 psig in 24 ASME cylinders (above grade) and at 10,000 psig in three ASME cylinders (above grade).
Dispensers: one liquid hydrogen dispenser and one gaseous hydrogen dispenser with dual hoses for dispensing at 5,000 psig and 10,000 psig (20 kg per day).

Two extremes in size; capacity

- Distributed Units
  - Electrolyzes etc for H2 filling stations
  - Issues = costs, safety, complexity of running
- Central production units
  - Type of power (Nuclear, renewable, etc.) /
  - Distributions must be worked out
  - Opportunity for hybrid electric-H2

Efforts to reduce cost of distributed electrolysis units Example - Possible Advanced distributed station

High-Capacity, High Pressure Electrolysis System with Renewable Power Sources

ELECTROLYZER DEVELOPMENT PROJECT PARTNERS

Avalence, Milford, CT

Design, Fabrication, and Testing

MIT, Cambridge, MA

Two Phase Fluid Design

HyperComp, Brigham City, UT

Cell Carbon Fiber Wrapping

Hydrogen Energy Center, Portland, ME

Siting and Installation Funding

MaineOxy, Auburn, ME

Revenue Operation

ELECTROLYZER DEVELOPMENT

Barriers Addressed

- Capital Cost –**Increasing the Production Capacity for a Single Module Will Take Advantage of Economies of Scale**
- System Efficiency –**Demonstrate that the Direct High Pressure Electrolysis Maintains the High System Efficiency Demonstrated in the Smaller Scale Systems**
- Renewable Power Integration –**The Pilot Plant System will Be Compatible with Wind Power Input (and PV inherently) for Performance Testing at NREL**

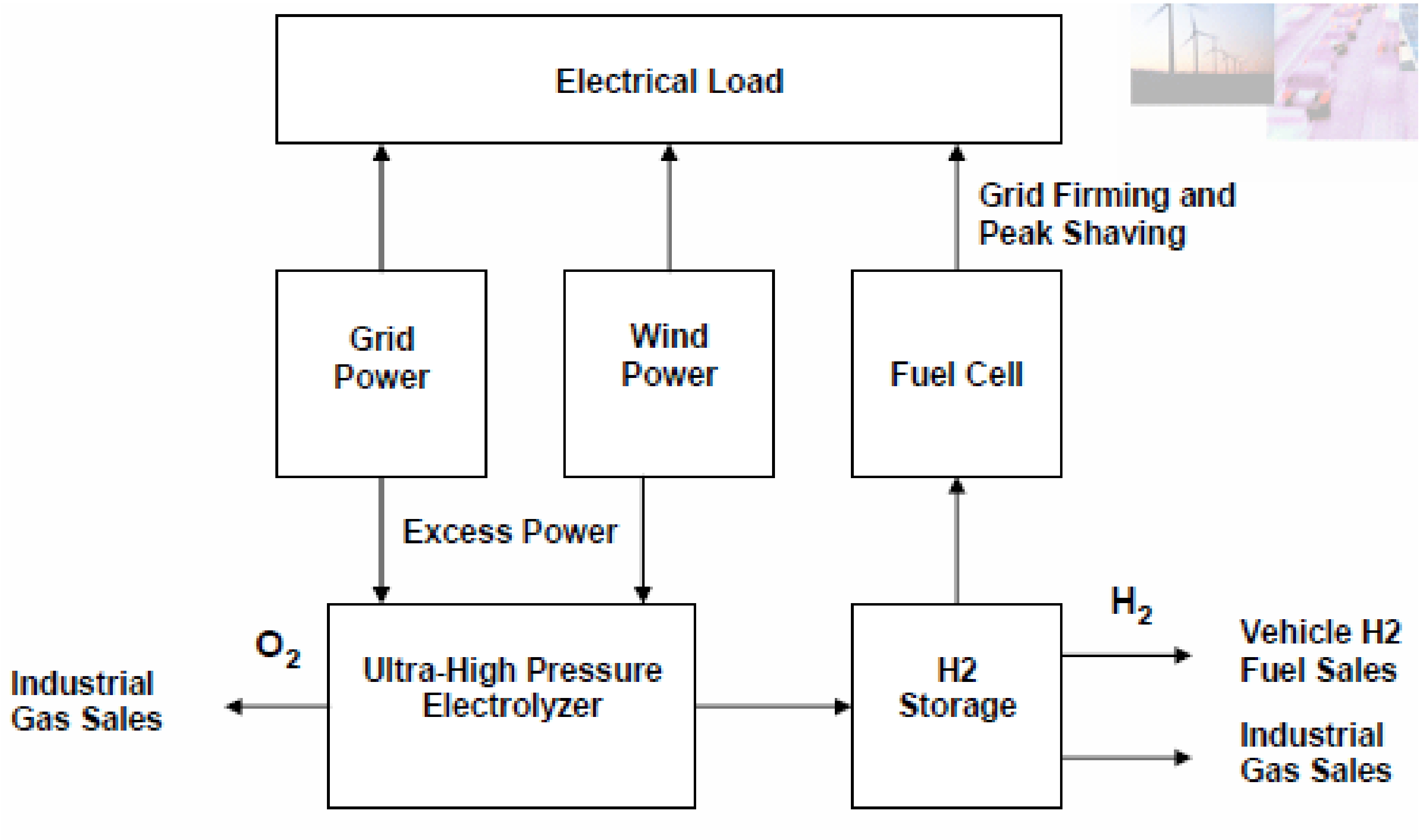
Project Design Challenges

- Gas Exit Manifolding
- Membrane to Manifold Sealing
- Fluid and Power Penetrations
- Composite Wrapping “Heavy” Cylinder
- Process Control of a Multiple, High-Capacity Cell Array

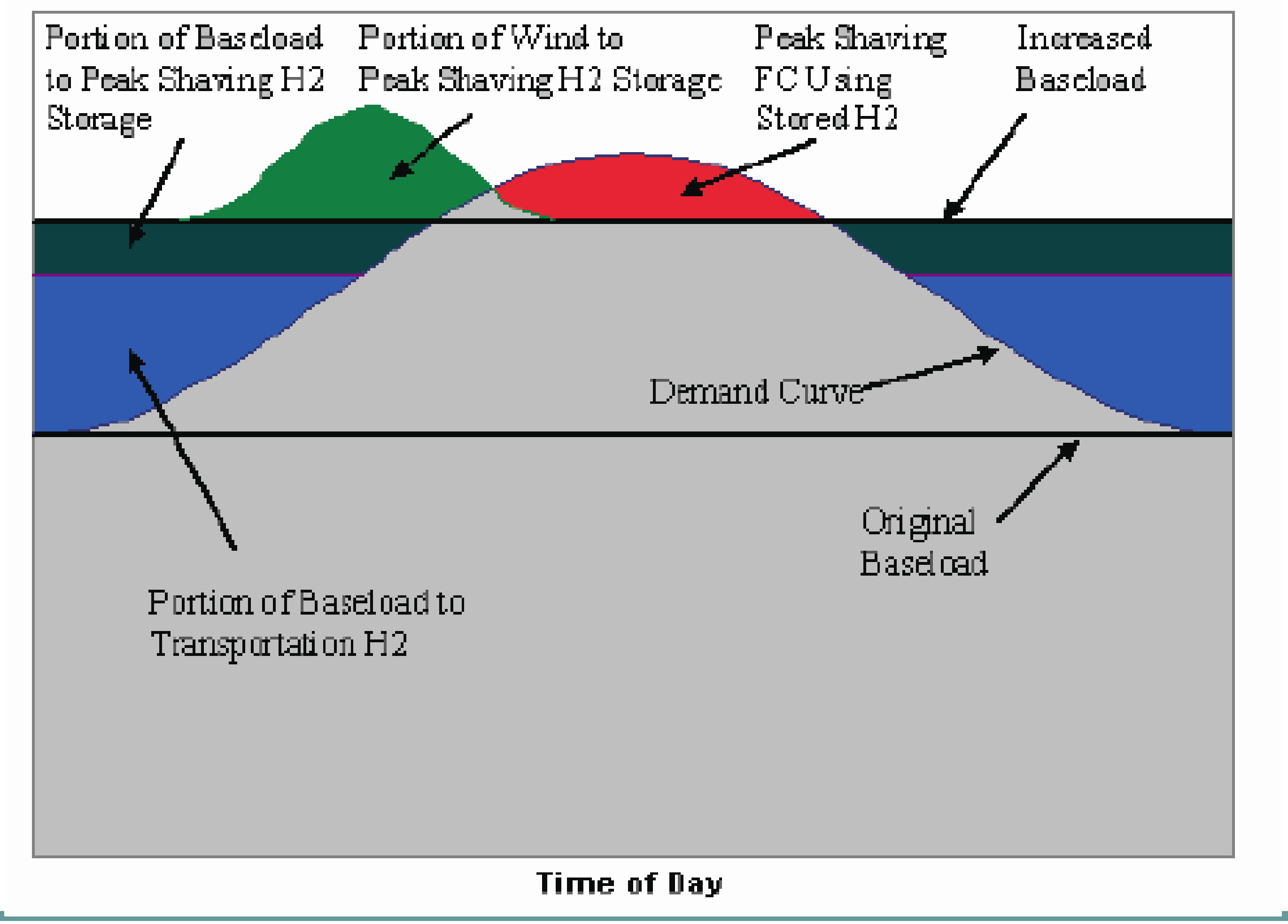
Pilot Plant Design

- 20 Cell Array
- 6500 psi Capable
- At Least 30 kg/day Production
- Compatible With Variable Voltage Wind and Solar (PV) Power
- Capable of “Harvesting” Both H_2 and O_2
- Fully Automated Process Control

The Fully Integrated System Block Diagram



Example of Fully Integrated Wind, Base Load Power And Electrolyzer Hydrogen For Peak Shaving, Baseload Firming, And Transportation Fuel Production



Hydrofiller 5000 to Produce Green Hydrogen For Transportation Fuel Sales

Hydrofiller 5000 Using Wind Power Is Superior To Retail Gasoline At $3/Gal

- *300 Kg/Day 750 kW Rating*
- *2012 Commercial Price Target: $650K*
- *Assume 35% Availability for Wind Power Yields 38,000 kg/yr*

"Green" Hydrogen Costs:

▪ 20 Yr. Depreciation	:$0.85/Kg
▪ 3%/Yr. O&M and Overhaul Average	: 0.51
▪ Wind Power Cost ($.035/kWh & 54 kWh/kg)	: 1.89
▪ Transport To User Site	: 0.50
▪ Markup	: 1.00
▪ Green H2 Retail Price	:$4.75/Kg

"Green" FC Vehicle @55 Mi/kg (@$4.75/kg) = 8¢/Mi

Polluting Gas Vehicle @30 Mi/Gal (@$3/Gal In US) = 10¢/Mi

Central Stations – 1 10 GW scale

- Reforming vs. dissociation of water
- Power (Renewable, conventional coal or FutureGen, Nuclear (fission, fusion))

H_2 Production Using Renewable Energy Sources

- Harness renewable energy to power electrolysis
- Potential sources are wind, geothermal, solar, and hydroelectric, thermochemical conversion of biomass, photolytic and fermentative micro-organism systems, and photoelectrochemical systems
- Advantage:

  -Energy is “free” and clean
- Disadvantage:

  -Technology to harness energy is expensive

Future Generation Plant/Methane Steam Reforming

- Involves utilizing a hydrocarbon such as coal or methane to produce H_2 thermochemically
- Coal → $CO + H_2$ then $CO + H_2O$ → $H_2 + CO_2$
- Advantages:

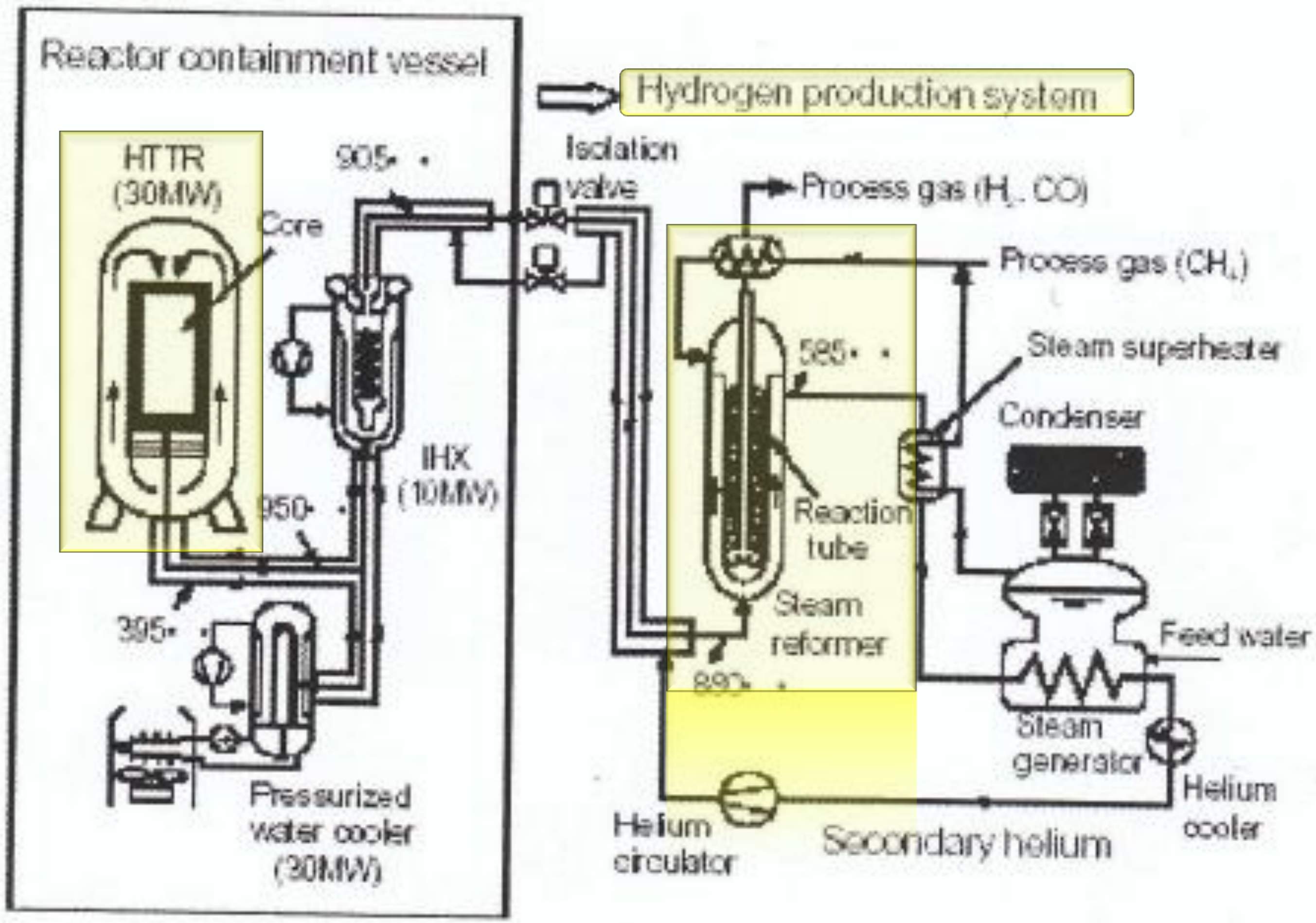
  -Costs comparable to thermochemical cycles like SI cycle

  -Uses coal, a plentiful fossil fuel, in a near clean process
- Disadvantages:

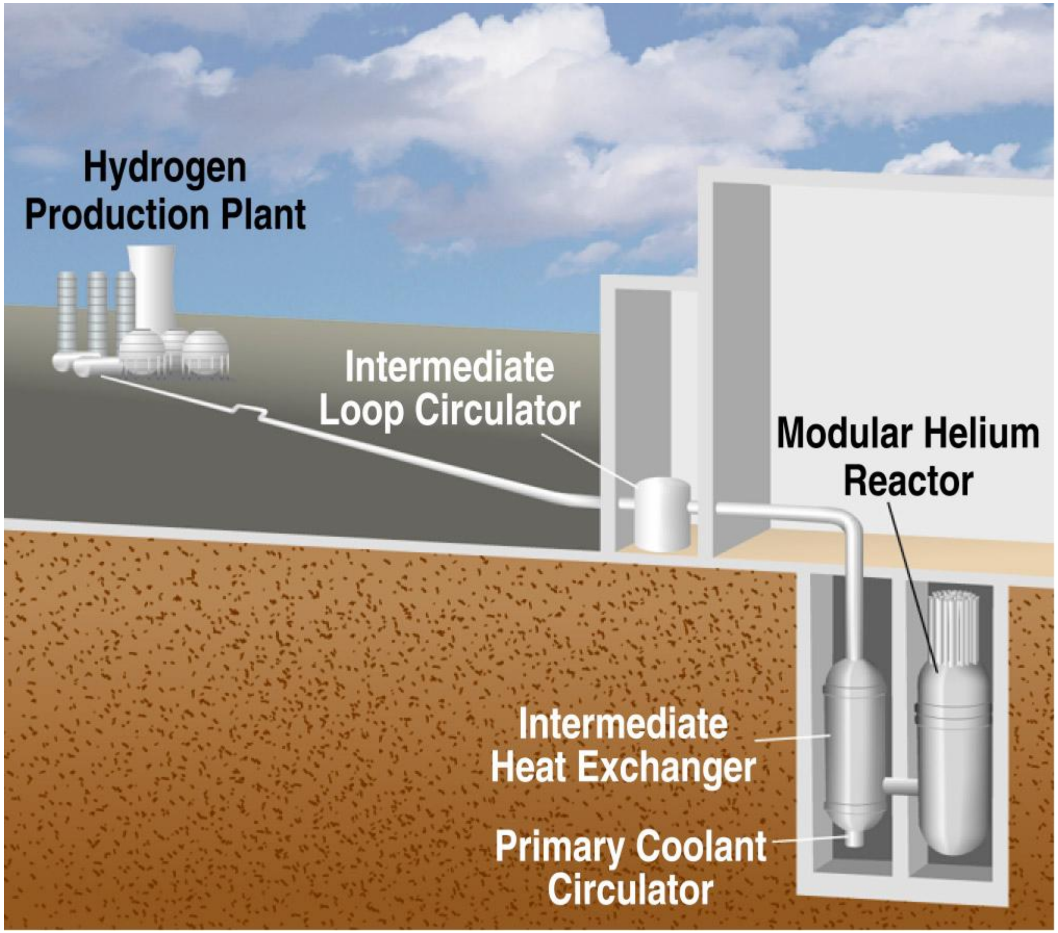
  -Expensive to start up and future of carbon sequestering unknown

  -Funding and political issues associated with plant startup

Central Plant Example --Schematic Flow Diagram of HTTR *Fission Reactor) Hydrogen Production System



Demo plant planned at INEEL



Use of heat vs electricity increases overall efficiency = High Temp Electrolysis (HTE)

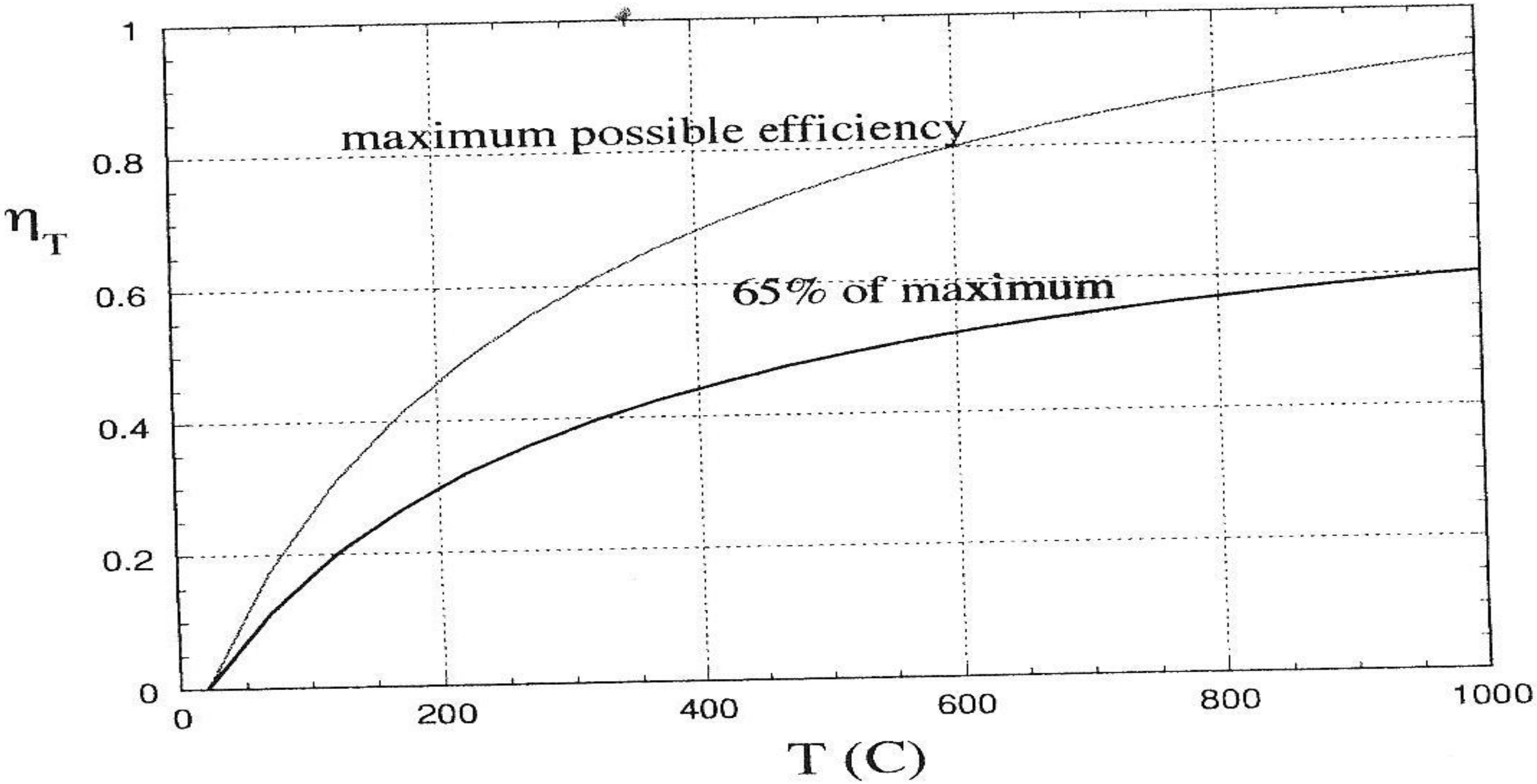


Fig. 4. Theoretical thermal water-splitting efficiencies.

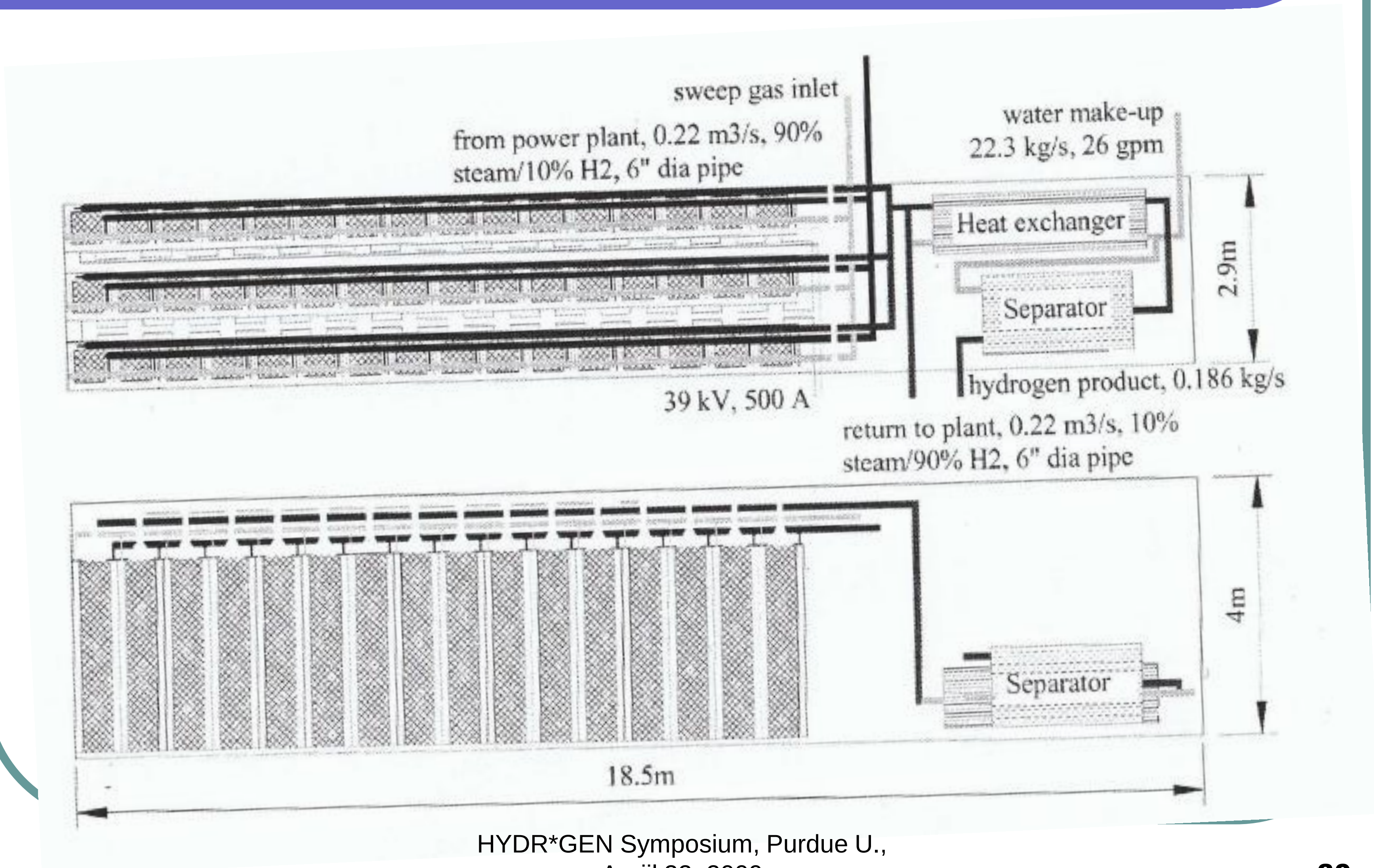
High Temperature Electrolysis (HTE)

- Uses HTGR for thermal energy to drive power cycle and heat steam for electrolysis
- Advantage:

  - 36-38% efficient without consumption of fossil fuels or corrosive materials
- Disadvantage:

  - Efficiency limited by heat cycle and temperature

Modular Hydrogen Plant Using High Temp Electrolysis (THE)



Thermochemical Production of H_2

- Many different cycles of chemical reactions already discovered to produce H_2
- Cycles can be coupled with a Modular Helium Reactor for heat supply for efficiency near 50%
- Some cycles better than others depending on their characteristics (i.e. # of reactions and elements involved, etc.)
- 3 major cycles: Sulfur-Iodide, UT-3, and Westinghouse

Thermochemical Production of H_2

- Advantages

  - All chemicals are fully recycled except for H2O

  - H2O is inexhaustible resource

  -Essentially greenhouse gas emission free

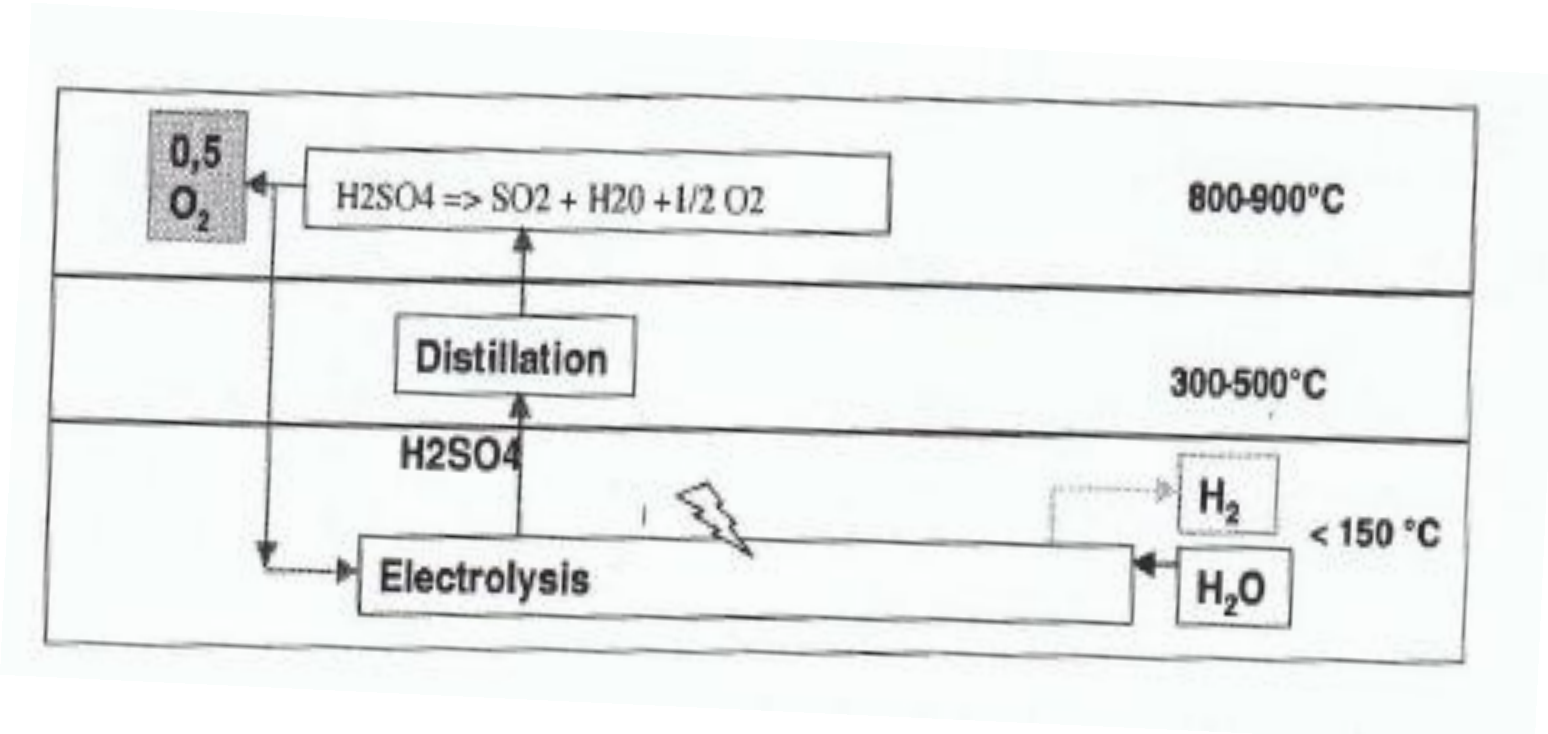
  -High efficiency since not restricted by Carnot cycle

- Disadvantages

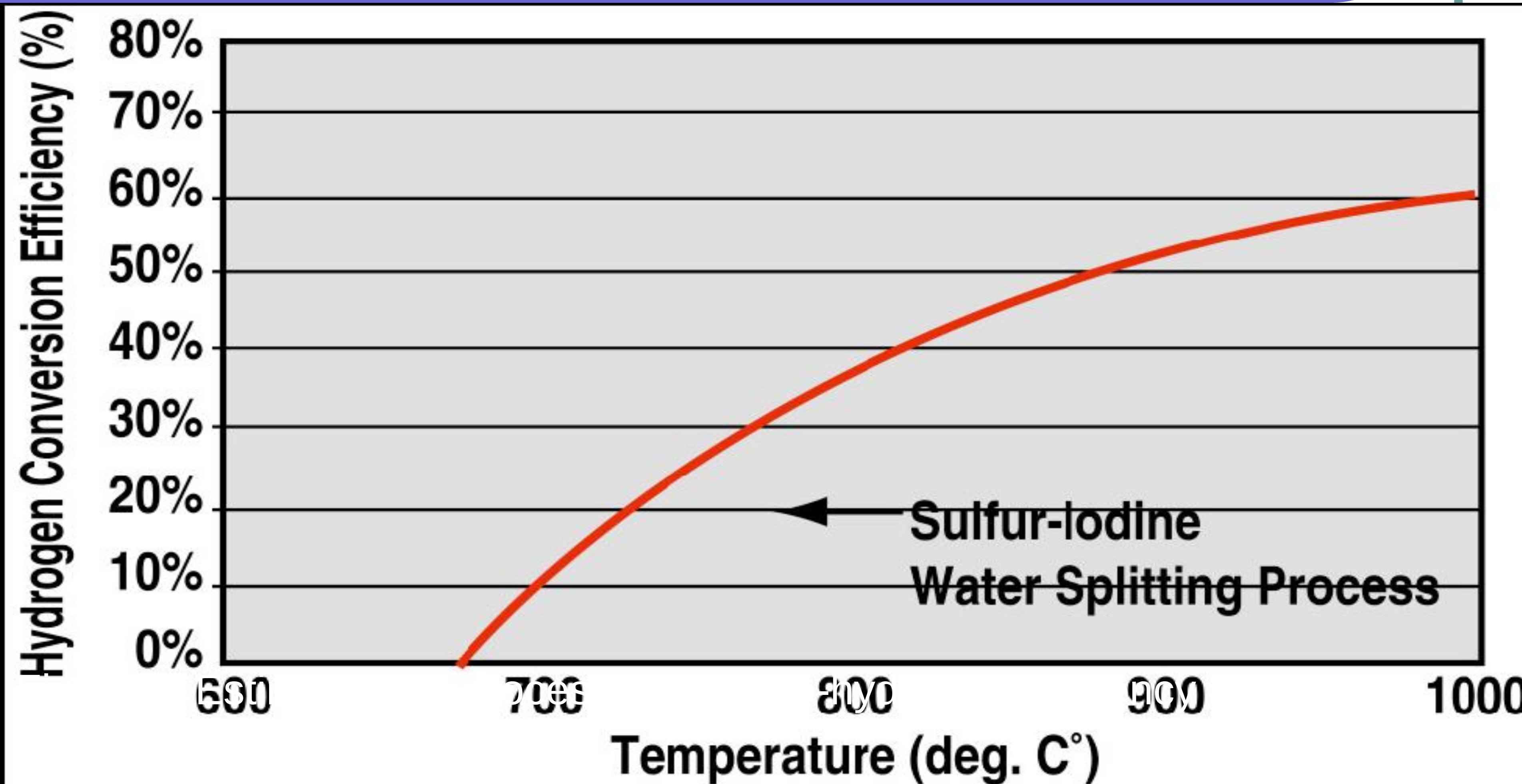
  -Require materials that can withstand high temperature and pressure and corrosive chemical

  -Most have not been tried on a large scale to determine feasibility

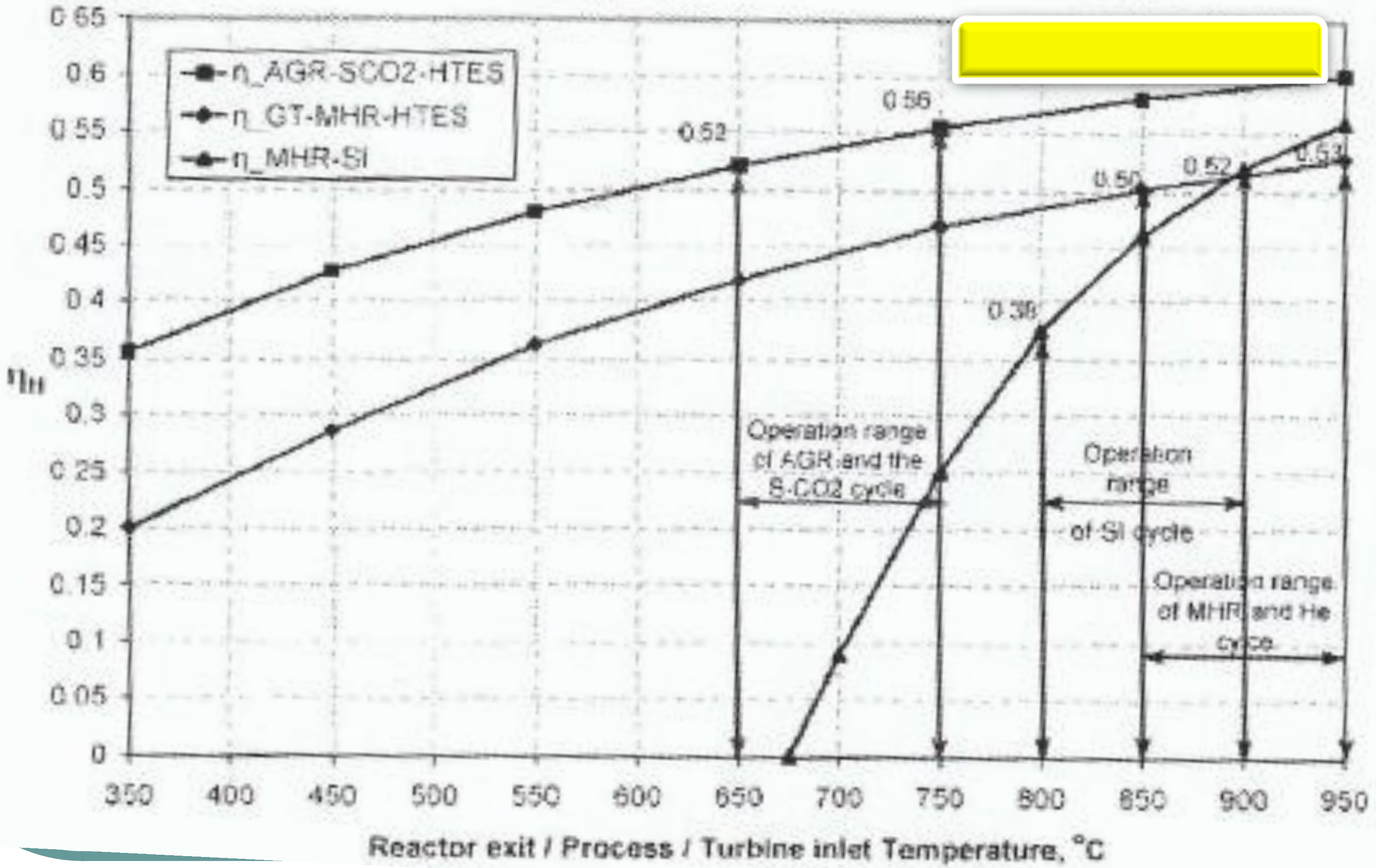
Hybrid S Cycle - Chemical



SI Cycle offer high efficiency at hi T



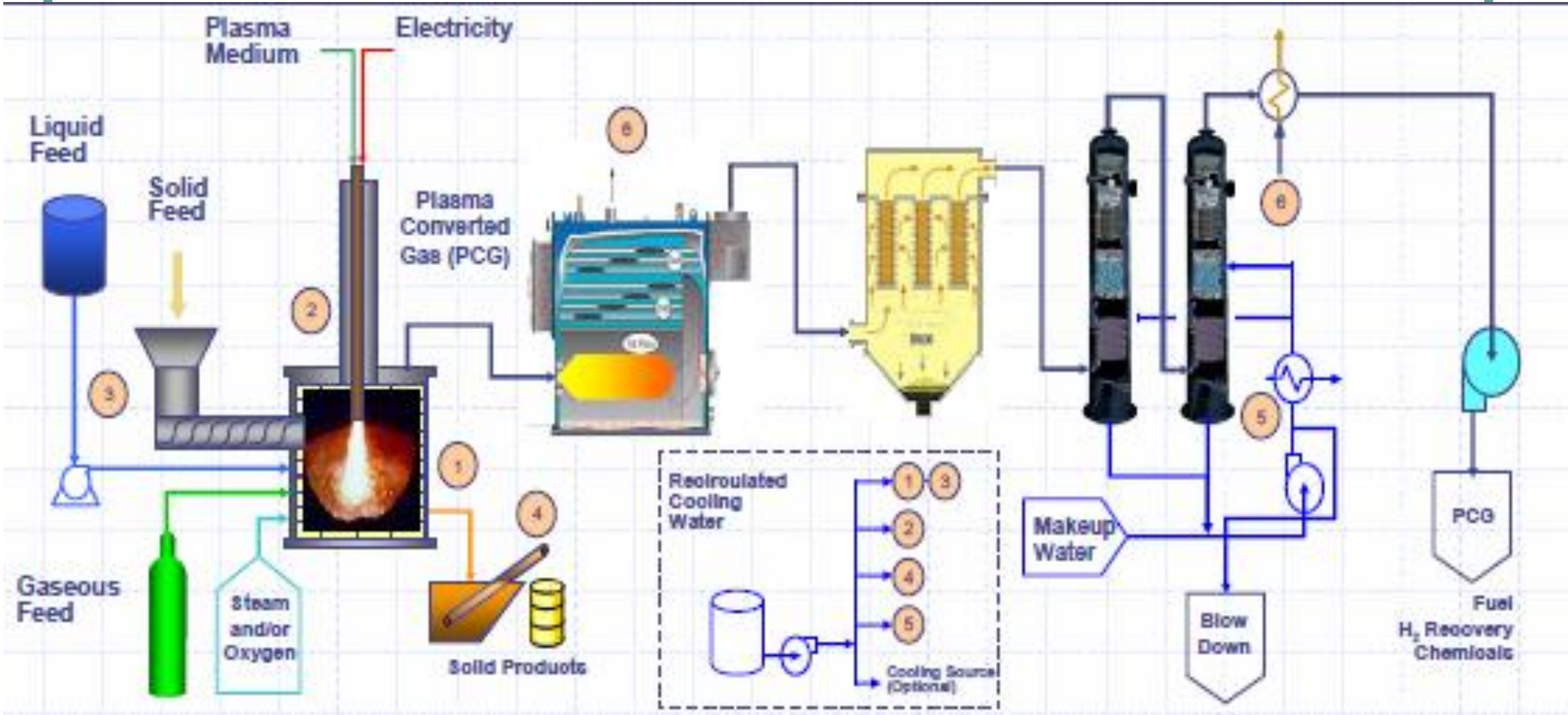
Comparison of Thermal-to-Hydrogen Efficiencies of HTE and SI Thermochemical Processes



Outline

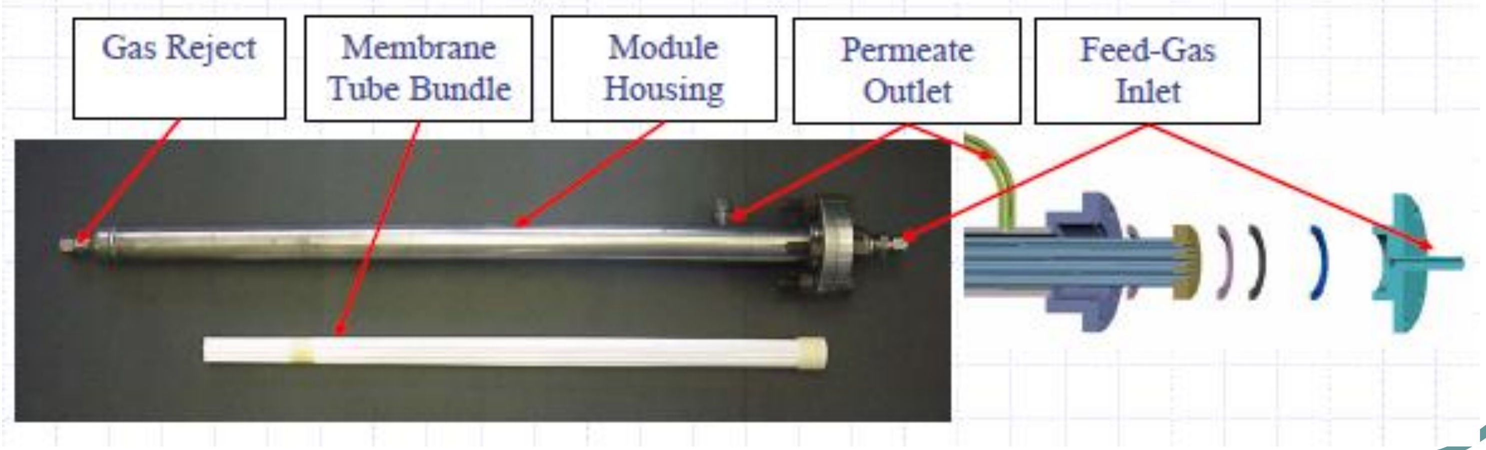
- Comments about the "Hydrogen Economy"
- Production of Hydrogen
  - Distributed and Central Plants
  - **Plasma production**
    - **STAR CELL**
    - Jet (Torch) Production (current U of IL research)
- Hydrogen storage (comments about our Dislocation Loop research)
- *Fuel Cells (a few comments about our research)*
  - Direct Borohydride
- *Concluding comments & questions from you*

StarCell - PLASMA CONVERTERSYSTEM

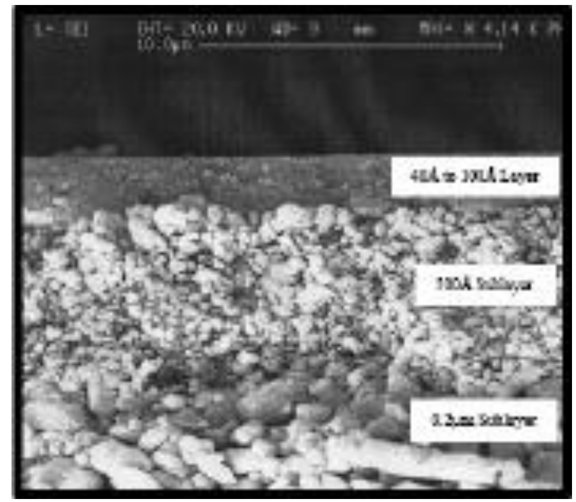


StarCell: How It Works

- StarCell Modules are stainless steel housings with Carbon Molecular Sieve tube bundles inside.
- Mixed gas enters through the inlet port and hydrogen permeates through the membrane.
- Hydrogen exits through one exit port and the reject gas exits through another.



M&P Ceramic Membranes



- *Temperatures > 400°C*
- *Steam sterilizable to > 125°C*
- *Burst pressure > 500 psi*
- *pH resistant*
- *Excellent radiation resistance*
- *Unaffected by solvents, oxidants, etc.*
- *Rugged, reliable, long life > 5 years*

Table 1. Characteristics of M&P's Ceramic Ultrafilters and Microfilters

Characteristic	Ultrafilters	Microfilters
Active layer:	γ- or α-alumina	α-alumina
Pore Size:	40Å to 0.2μm	0.5 to 3μm

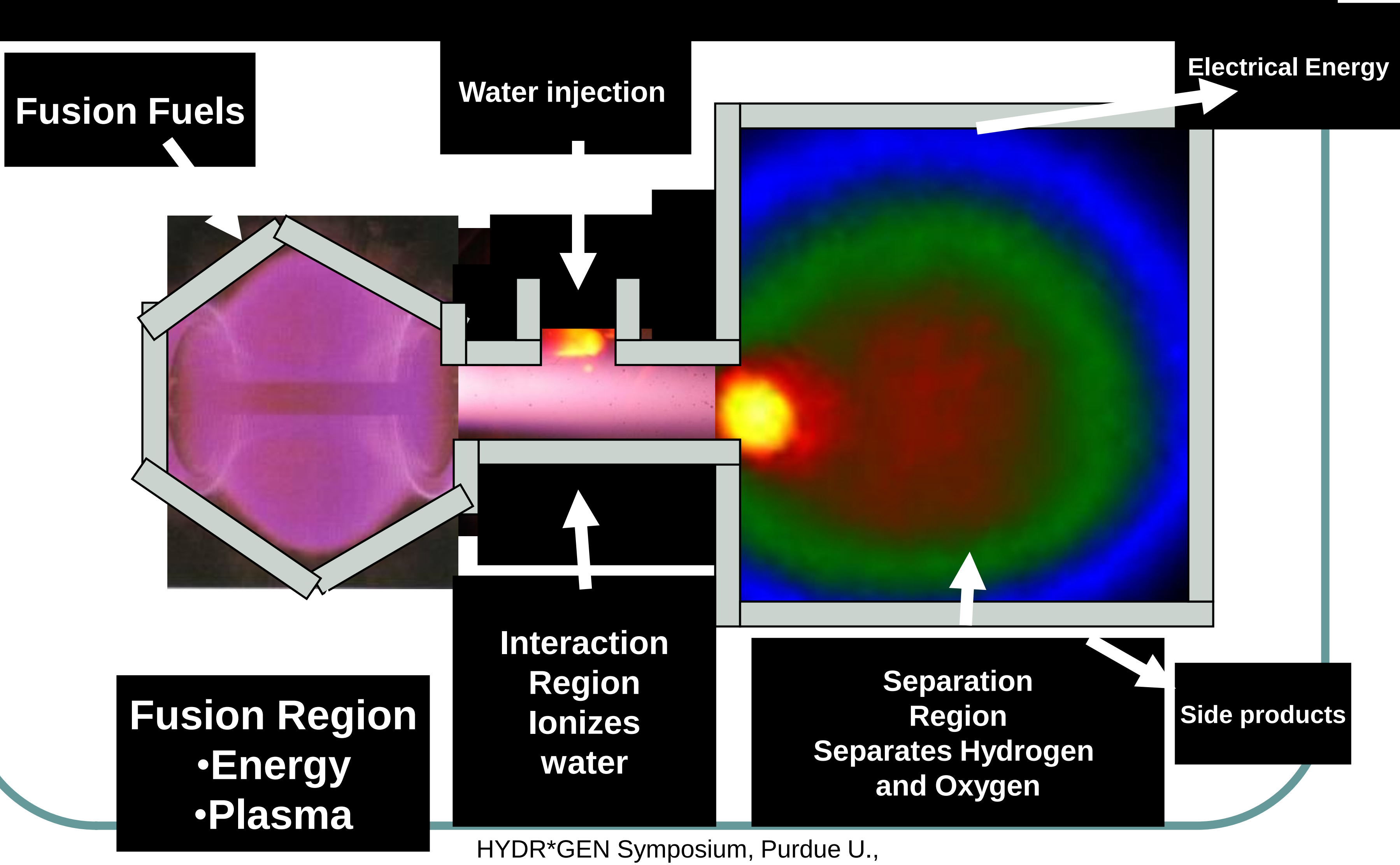
StarCell Test Discussion

- Hydrogen rich gas has been produced from waste material and purified on a commercial scale.
- H_2 Recovery rates of > 80%
- 2 Stage purification from 50% to 96%
- Low gas temperature had a significant impact on membrane performance.
- Membranes performed equally well on PCG and bottled (baseline) gases.
- Testing validated laboratory results on membrane performance.
- Membrane poisoning was minimal on 2 / 3 membranes after >2 months of gas exposure.

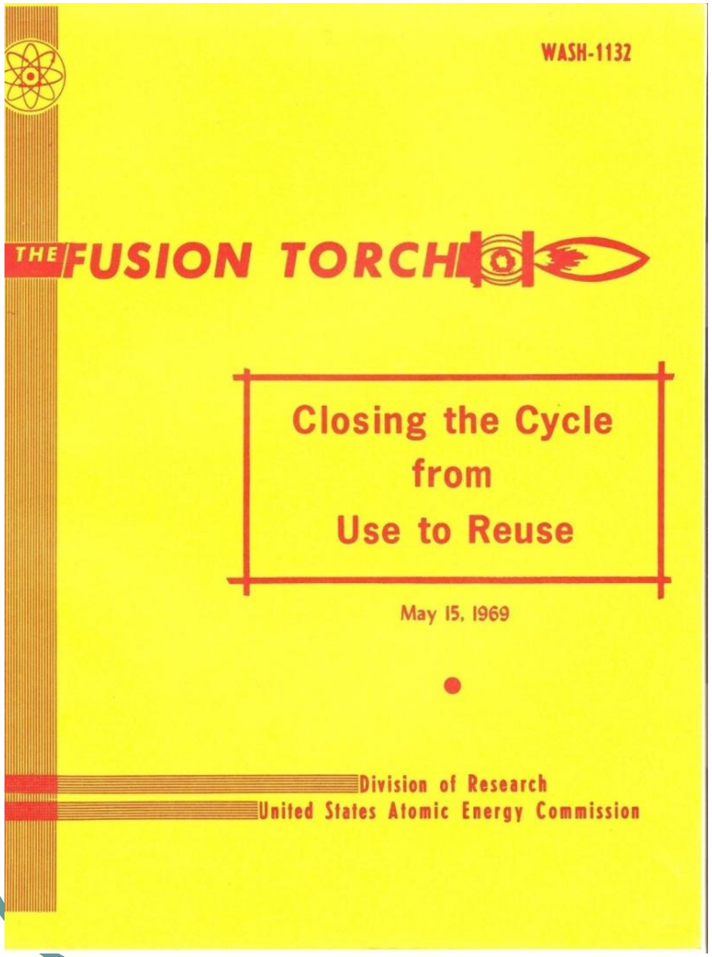
Outline

- Comments about the “Hydrogen Economy”
- Production of Hydrogen
  - Distributed and Central Plants
  - **<u>Plasma production</u>**
    - STAR CELL
    - **<u>Jet (Torch) Production (current U of IL research)</u>**
- Hydrogen storage (comments about our Dislocation Loop research)
- *Fuel Cells (a few comments about our research)*
  - Direct Borohydride
- *Concluding comments & questions from you*

Conceptual H2 Fusion Torch Schematic

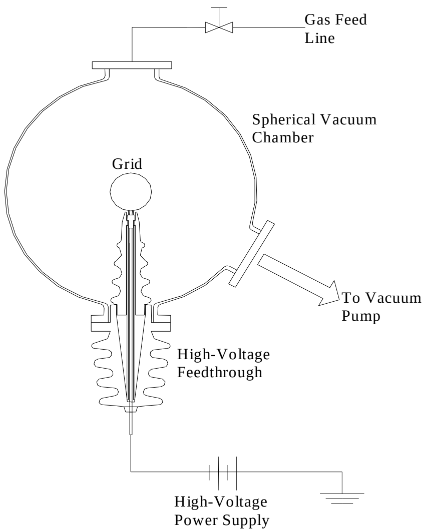


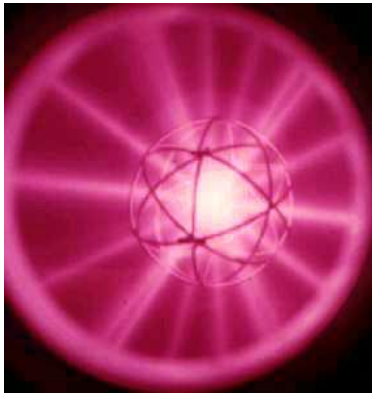
The Hydrogen Fusion Torch is a variation of the Materials Recycle Fusion Torch invented in 1968 [B. J. Eastlund and W. C. Gough, "The Fusion Torch –Closing the Cycle from Use to Reuse" WASH 1132, Division of Research, USAEC, Washington DC, May 15, 1969.]



- **Endorsed by USAEC and Nobel Laureate Glenn Seaborg**
- **DOE fusion development efforts currently focused electrical product. But material recycling, and hydrogen production such as discussed here, open up a whole new horizon for fusion applications.**
- **Fusion development is often viewed as long term, but use of the IEC concept discussed here offers simpler ,small devices that can be rapidly developed.**

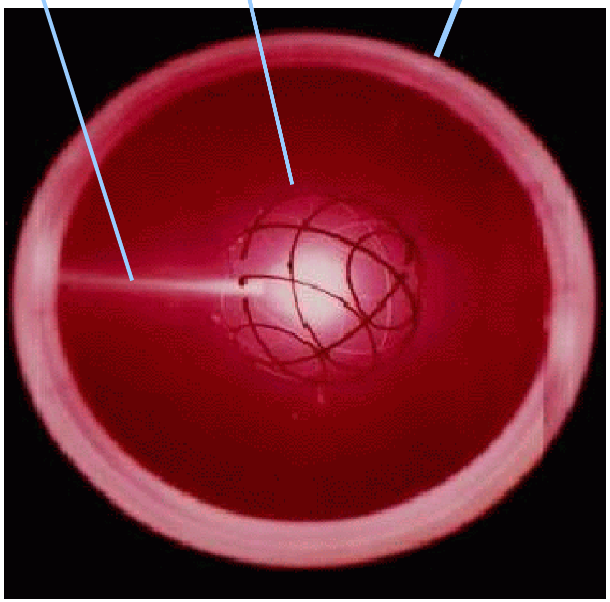
U of Illinois Research on plasma processing --Near term – electrically driven IEC plasma jet Is basis for plasma production of H2



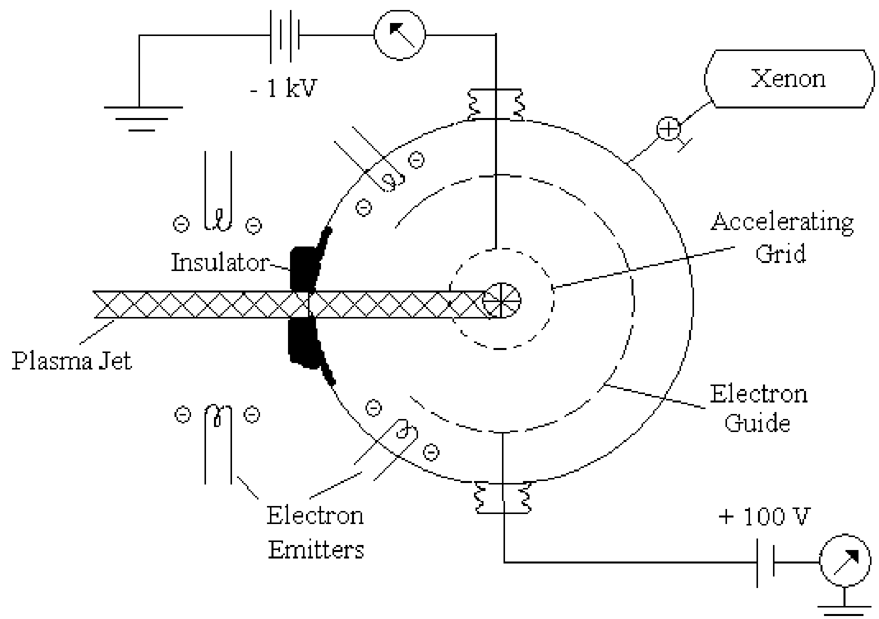


Basic concept of gridded IEC with “ion formed” potential well . U of Illinois devices uses grids designed to form the “STAR” mode (right) to direct ion beams through grid openings – avoiding grid erosion. Grids will be removes in future ion injection device.

"Jet Mode" operation of the IEC for torch uses an enlarged grid opening to extract jet for processing.



Jet Mode IEC

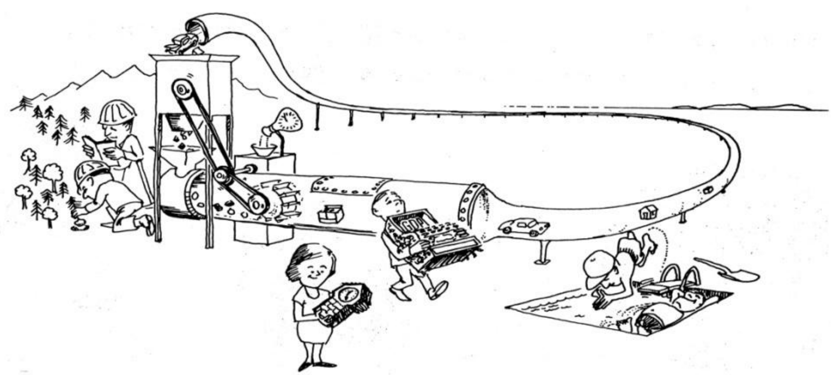


Spherical IEC Space Thruster

Estimated Performance: T = 34 mN, Isp = 3000 s, Accelerating Potential: 600 V
Input Power ~750-800 W, P_{jet} = 500 W, η_t ~ 62-68%

Today's Open Economy

Tomorrows Closed Materials'
Economy with Hydrogen Energy



Hydrogen Fusion Torch to enable the hydrogen economy

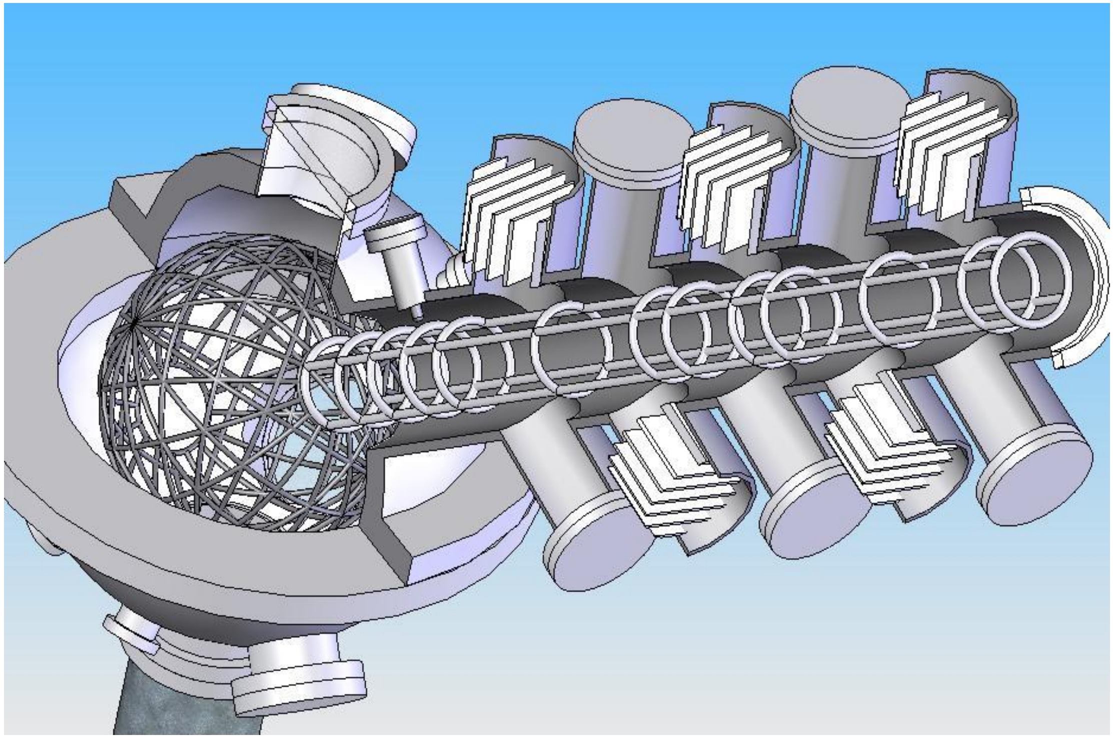
- **The hydrogen plasma torch is a natural extension of the original fusion torch concept as applied to hydrogen production from water.**

- **This approach improves efficiency of production by using a plasma for complete dissociation plus electrostatic separation and excess energy recovery**

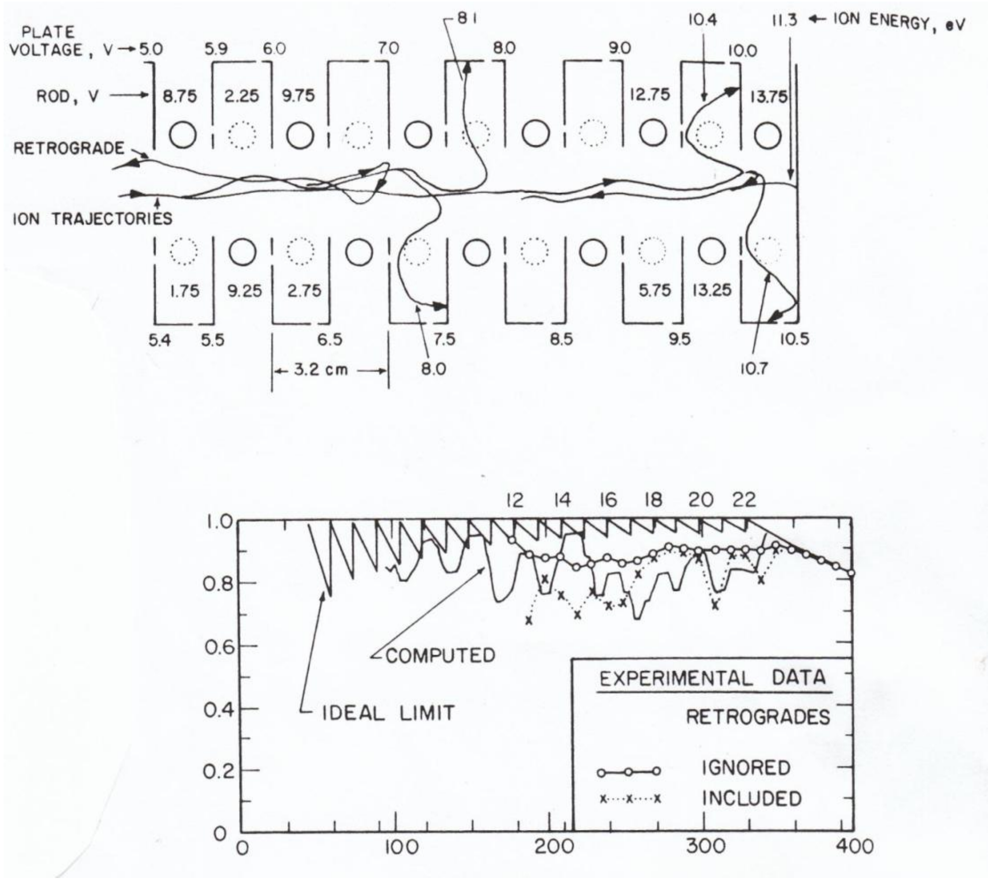
- **Thus, the plant is a dual electrical – hydrogen generator. Side products are helium and oxygen.**

Lab demonstration of electrically driven torch

2-kW experimental unit to demonstrate the electrically driven IEC H2 plasma torch. An air plasma is used. Water is injected into the jet plasma near the chamber exit, followed by the electrostatic separation-energy recovery structure . Products are N2, O2, H2 and electricity



Electrostatic separation of ions from jet plasma also enables energy recovery. LLNL experiments demonstrate high efficiency for separation – energy recovery



Plasma Torch splitting efficiency

- Assuming 90% efficiency for ionization of h20 = 1853.8 / 0.9 = **2059.8 kJ/mol needed**
- **With 95% efficient recovery total energy released when bonds are formed = (485.6 + 862.4) * 0.95 = 1280.6 kJ/mol**
- Thus the efficiency is: 1280.6 kJ/mol / 2059.8 kJ/mol = **62.2%.**
- Higher than thermal processes

P-B11 Fusion Torch to enable the hydrogen economy

•Replace electrically driven IEC with fusion power IEC unit to enable economic large-scale production.

•A natural extension of the original fusion torch concept for materials recycle as applied to hydrogen production from water.

•Improves efficiency of production by using a plasma for complete dissociation plus electrostatic separation and excess energy recovery

•Dual electrical – hydrogen generator. Side products are helium and oxygen.

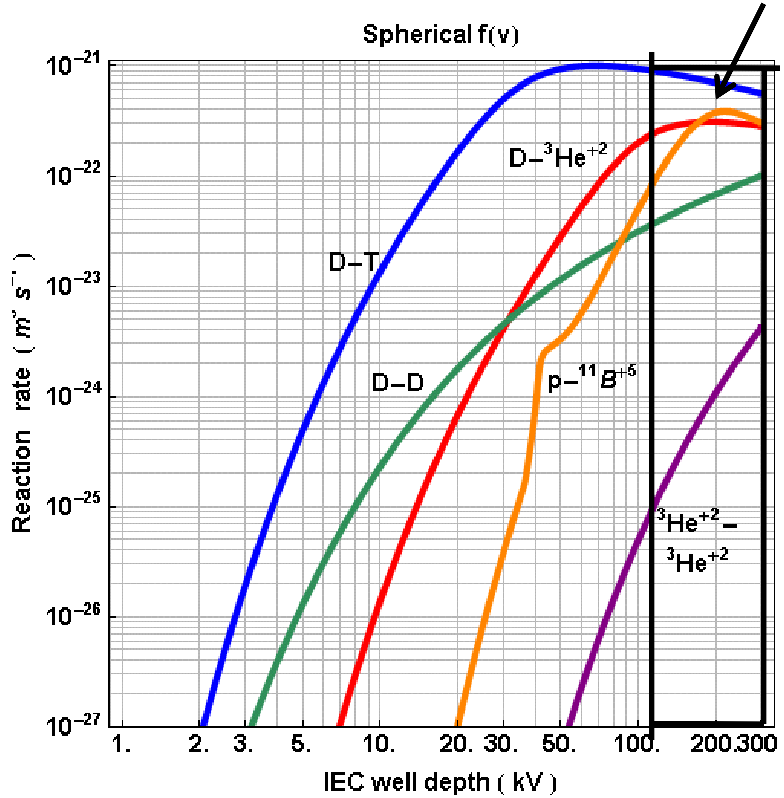
Why IEC for p-B11?

- Non-Maxwellian – ions in potential well at ~ 80% of applied voltage – for p-B11 requires about 150 kV (already achieved)
- Allows jet plasma reaction product exhaust (divertor) for processing section and direct energy conversion channel.
- Simple construction and small high power density units.
- Electrically driven version allows early market penetration (also waste processing market = syngas production from garbage and food wastes) while still developing fusion technology for p-B11

IEC Can Match Fusion Cross Sections Requirements

<σv>(E) vs kV

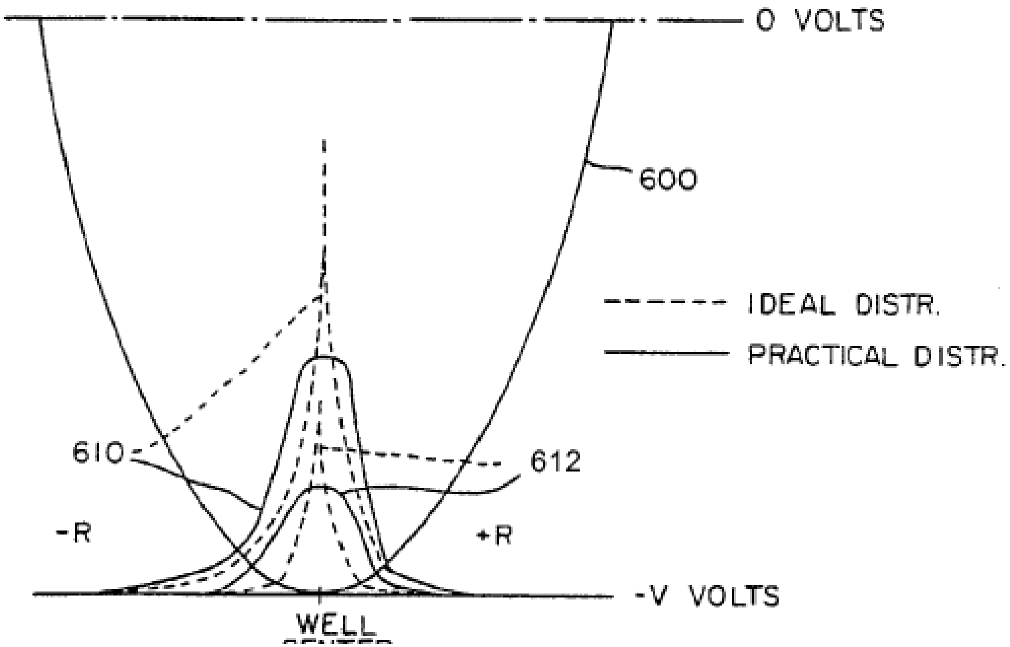
Region of Interest = 150-250 kV



Cross Sections from John Santarius, Fusion Technology Institute, University of Wisconsin

IEC Ion Physics – the key is a deep potential well to trap ions

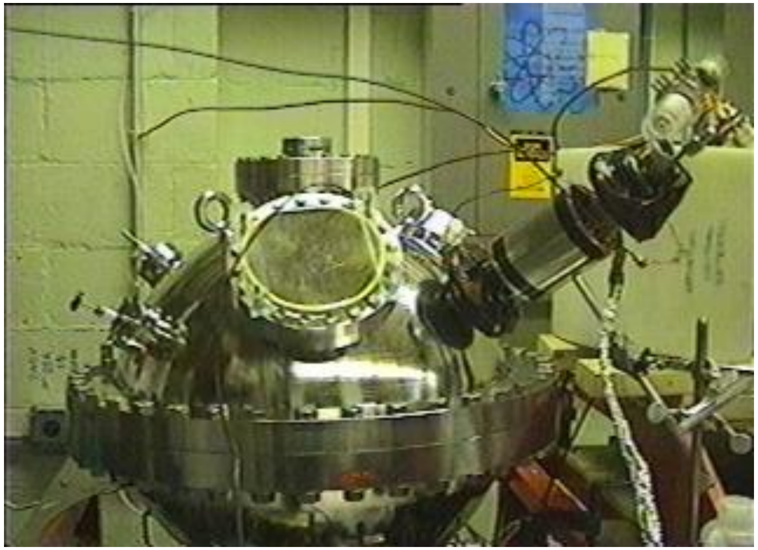
FIG. 7A

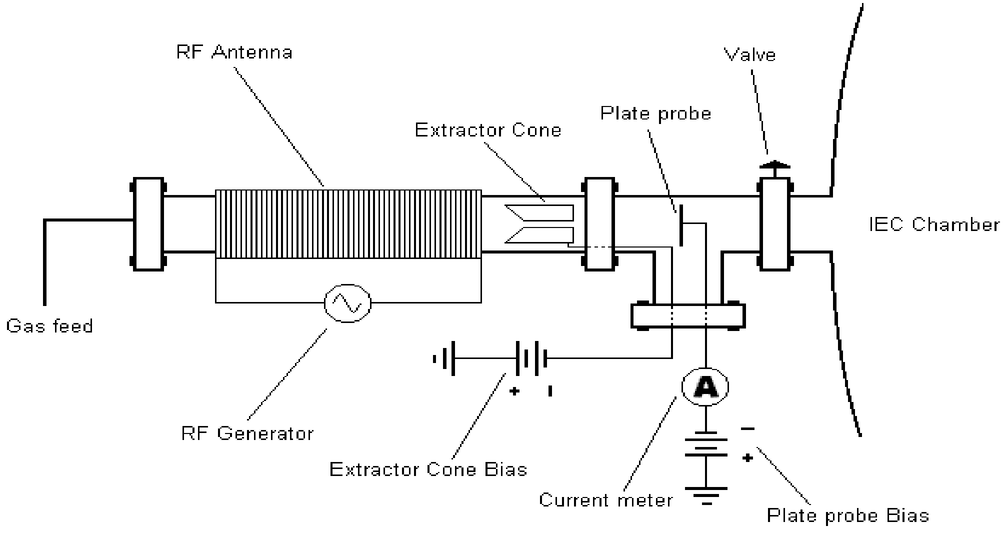


1. Ions form deep potential well ($\Phi \sim E_{injection}$)
2. Electrons confined by the electrostatic potential
3. Ion distribution is strongly non-thermal
4. Ions coming to edge of well fall into the interior
5. Ion density strongly peaks at r=0
6. Ion convergence allows attractive reactor

Diagram from US patent application 11/527,906, “Method and Apparatus for Controlling Charged Particles”, R.W. Bussard, (2006).

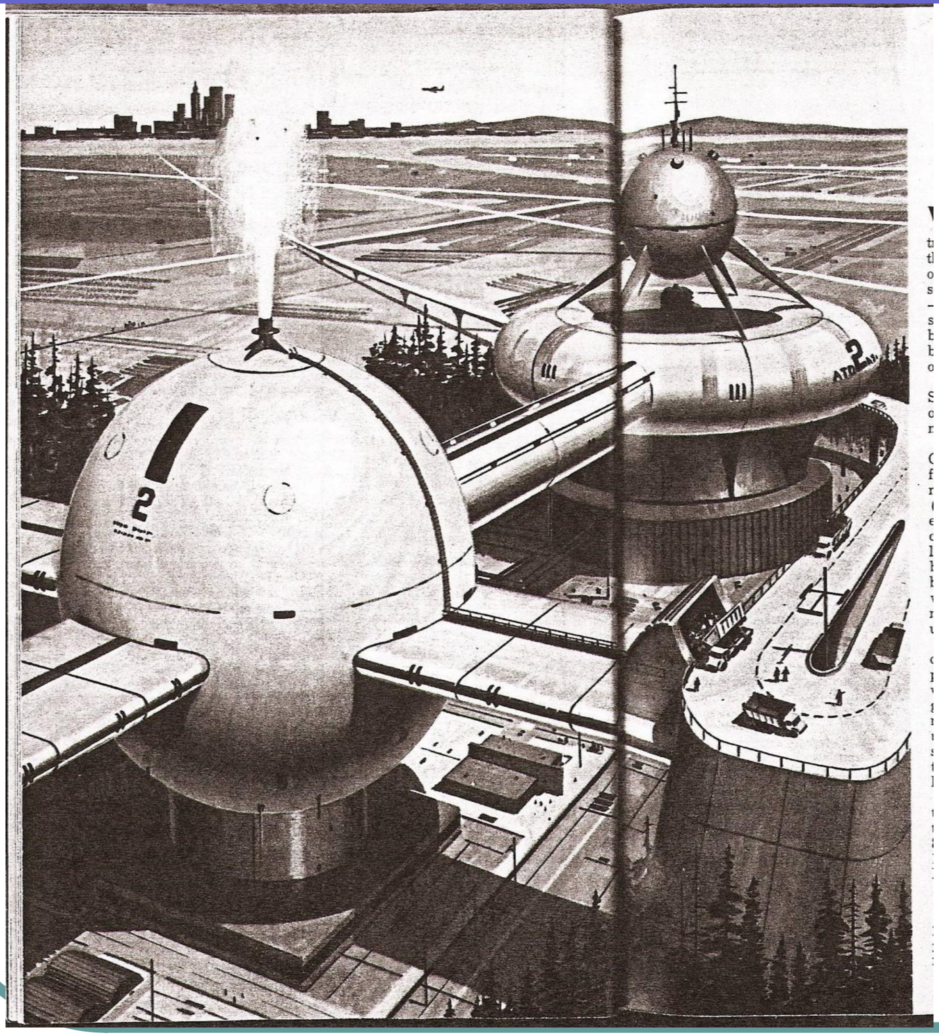
Ion- injected IEC provides way to increase potential well depth and volume





Present single gun device - sketch of injector gun is shown att he right

Vision --The IEC p-B^{11} H_2 Fusion Torch Industrial Process of the Future



Boron and Hydrogen Fuel

- **Energy**
- **Plasma**

Plasma Processing Separates Water into Elements

Energy conversion provides Electricity and portable Fuels

Demonstrate p-B11 IEC is the key for development

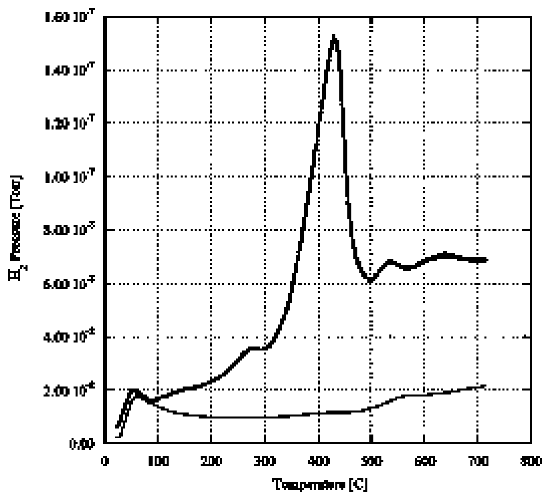
Outline

- Comments about the "Hydrogen Economy"
- Production of Hydrogen
  - Distributed and Central Plants
  - Plasma production
    - STAR CELL
    - Jet (Torch) Production (current U of IL research)
- ***Hydrogen storage (comments about our Dislocation Loop research)***
- *Fuel Cells (a few comments about our research)*
  - Direct Borohydride
- Concluding comments & questions from you

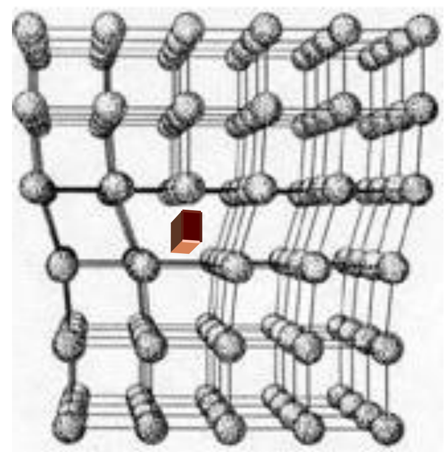
H2 Storage

- Key System Component – both at production plant, filling station and in mobile applications (e.g. automotive)
- Various approaches
  - High pressure tanks
  - Cryogenic liquid
  - Hydrides
  - Other research: e.g. carbon nano-tubes

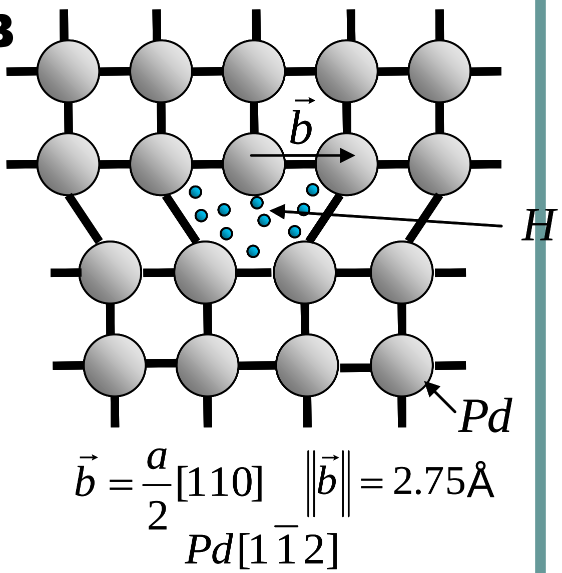
Our Dislocation-Loop-Cluster Studies (Current research –new concept)



A



B



Thermal Desorption demonstrates loop absorption

Cluster regions can have hydrogen densities approaching 10^{24}/cc. SQUID magnetic measurements: H/D loaded Pd/PdO has type-II superconductor performance.

Our Dislocation-Loop-Cluster Studies (Current research –new concept)

Manufactured by repeated electro absorption – desorption plua low temperature annealing – stress induced progressively produces more dislocation void regions which act as traps to form Bose-Einstein cluster state of H

Thermal Desorption demonstrates loop absorption

Cluster regions can have hydrogen densities approaching 10^{24}/cc.
SQUID magnetic measurements: H/D loaded Pd/PdO has type-II superconductor performance.

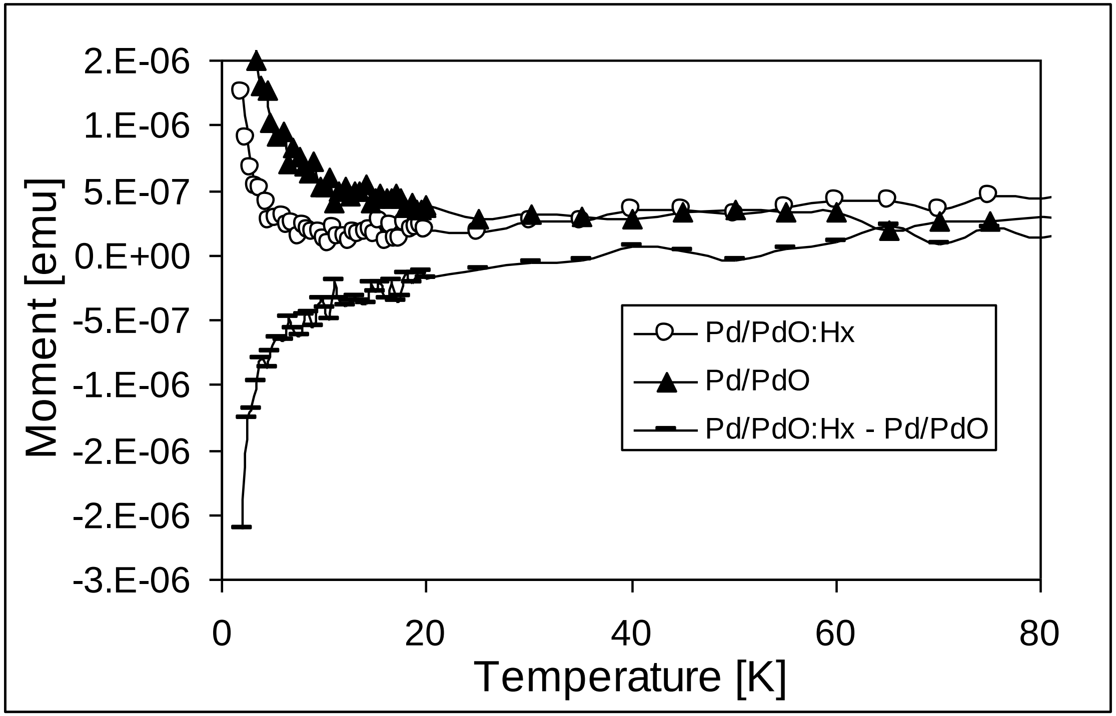
Cluster Parameters

- Extrapolating the results of thermal desorption measurements for various residual hydrogen concentrations, it is possible to estimate a radius R_H of residual hydrogen distribution with respect to dislocation cores. When $<x>=H/Pd = 6x10^{-4}$.
- The binding energy of hydrogen within the Pd estimated. Using Garlic-Gibson kinetics for the kinetic parameters of second-order thermal activation processes in the thermal desorption analysis (TDA). The activation energy of desorption (effective binding energy of hydrogen atoms within the lattice) is ~ 0.65 ± 0.10 eV.

  Consistent with the result of Kirchheim for hydrogen trapping at dislocation core sites in cycled Pd.

  Indicate all residual hydrogen is bound solely inside the deepest core sites, or say, inside the dislocation loops, with minimal radius RH = 2.75 Å, close to the Burgers vector b [101]=2.75 Å.
- Depending on average residual concentration <x> and dislocation density N_d, the effective loading ratio inside the loops in a Pd f.c.c. lattice is determined by the simple formula: $x_{eff} = \sqrt{2}<x>/N_d<x>/b^2$. Accordingly to this formula at Nd ~ (1.0-2.0)x1011 cm-2 and <x> ~ (4-6) $x10^{-4}$ x_{eff} would be in the range of $1.0<x_{eff}<3.0$, suggesting superstoichiometric hydride formation in the deep dislocation cores.

Experimental Magnetic Moment Measurements show superconducting state



The magnetic moment of H_{2}- cycled PdHx(fg) samples in the temperature range of $2 \leq T < 50$ K is significantly lower than M(T) for the original Pd/PdO.

Summary- clusters lead to localized SC – verifying extremely high density state in loop

- These results show that an anomalous diamagnetic response in these electrodes occurs at temperatures below 30 K. This is attributed to the appearance of superconductivity in Pd hydride phase inside the deep dislocation cores .
- This interpretation is also consistent with the temperature and field dependencies of corresponding magnetization curves.
- Both the shape and field behavior of the magnetization curves have the characteristics of a non-linear, irreversible magnetization function of a type-II superconductor.

New Nano-Structured

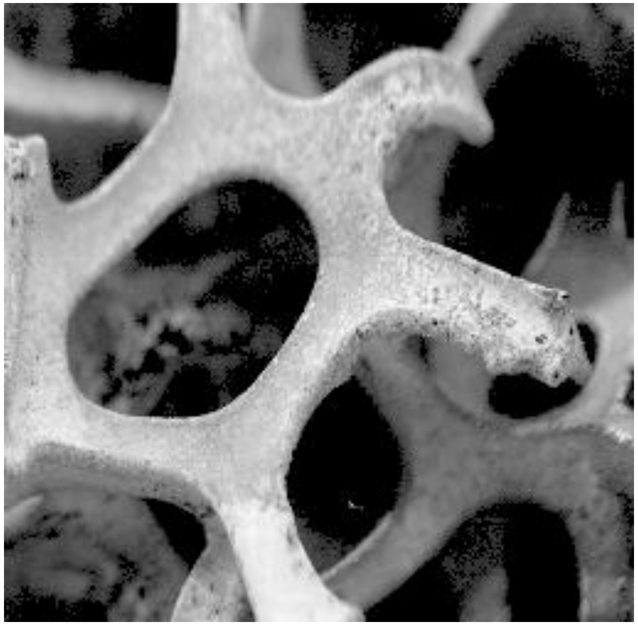
- Objective – mimic dislocation loop structure obtained from cycling, but –
- Increase the density (#/cc) of loops

Nano-Structure Film Electrodes

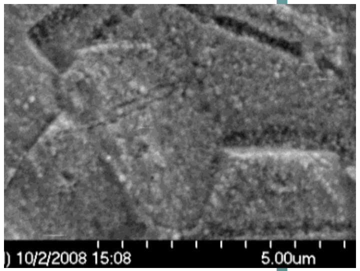
- Recently a new type of electrode, the NSF electrode, is being developed to create cluster formation in nanostructures . The concept is to mimic the dislocation loops , but have a larger volumetric concentration than in the cycled electrode.
  - Palladium is deposited on a nickel substrate using an electroless deposition technique originally developed by R.N. Rhonda of the International Nickel Plating Company.
  - Auger spectroscopy confirmed the deposited palladium on Ni microstructure completely and thinly. Roughly 0.05g of palladium is deposited on each 25cm^2 electrode at a thickness of roughly 50 nm.
  - The structures provided with the nano thin layer coatings are thought to provide the conditions needed for cluster formation. More needs to be studied to understand the true promise of this new electrode design.

Nano-Structure Electrodes

Ni felt



Ni Foam



Zoom-in view Showing Pd nanostructures on the Ni Foam

Cluster type electrodes have four major applications

Hydrogen Storage

LENR fusion power cells

ICF hot fusion targets

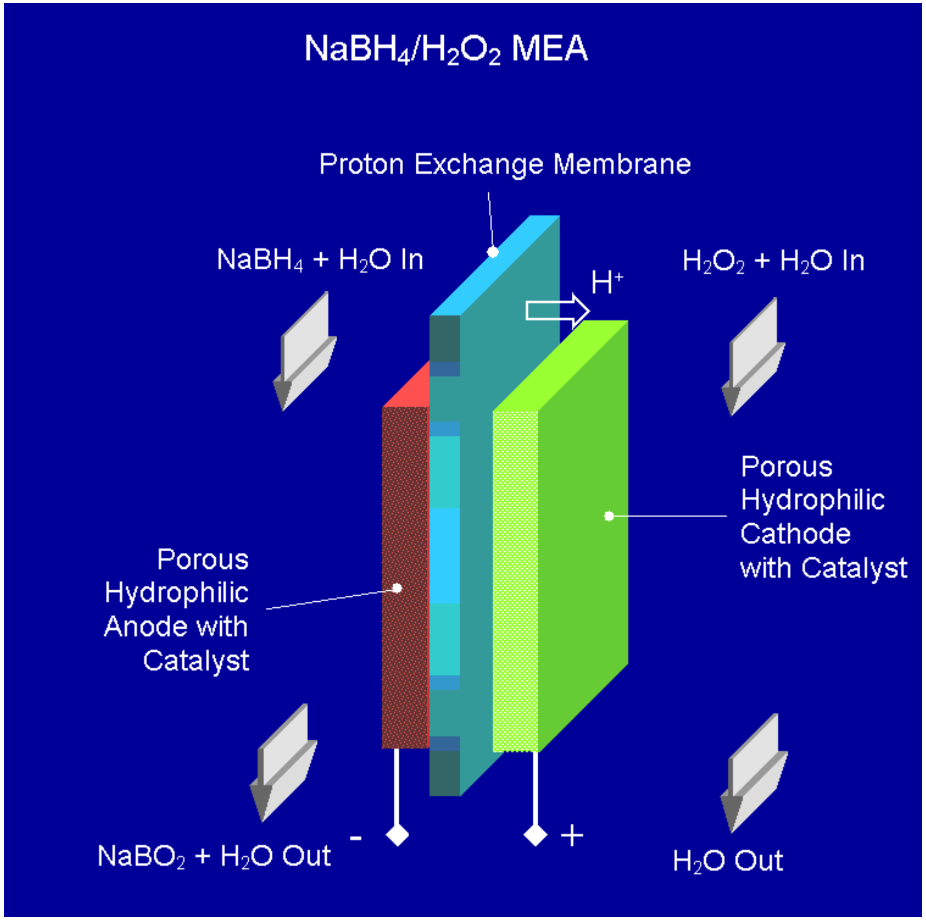
Superconducting wires

Outline

- Comments about the "Hydrogen Economy"
- Production of Hydrogen
  - Distributed and Central Plants
  - Plasma production
    - STAR CELL
    - Jet (Torch) Production (current U of IL research)
- *Hydrogen storage (comments about our Dislocation Loop research)*
- ***<u>Fuel Cells (a few comments about our research)</u>***
  - **<u>Direct Borohydride</u>**
- Concluding comments & questions from you

Comments about -- $NaBH_4/H_2O_2$ and $NaBH_4$/Air Fuel Cells

$NaBH_4/H_2O_2$ FC Schematic



All liquid $NaBH_4$ / H_2O_2 Fuel Cell Reactions

- Anode Reaction:

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 8H^+ + 8e^- \quad (-0.45\ V)$$

- Cathode Reaction (assuming H^+ charge carrier; alternately OH^- is used in some designs):

$$4H_2O_2 + 8H^+ + 8e^- \rightarrow 8H_2O \quad (1.78\ V)$$

- Overall Reaction:

$$NaBH_4 + 2H_2O + 4H_2O_2 \rightarrow NaBO_2 + 8H_2O \quad (2.23\ V)$$

The only waste products are water and sodium metaborate, which can be recycled to produce new sodium borohydride either at a central plant (currently feasible) or in the fuel cell itself (currently under development).

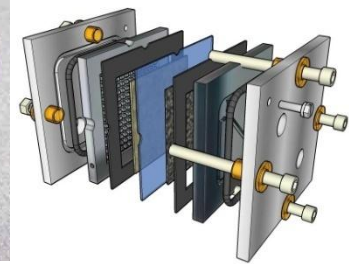
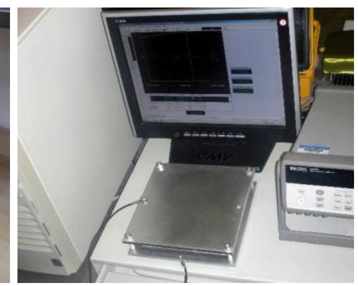
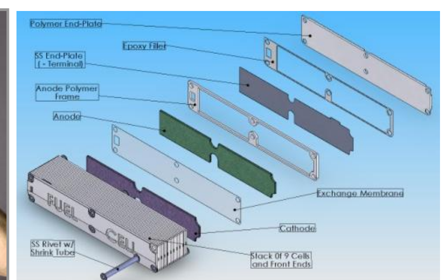
The $NaBH_4$ / O_2 (Air) Fuel Cell Has Similar Reactions

- The anode and overall reactions are the same
- Cathode reaction:

$$O_2 + 4H^+ + 4e^- + \rightarrow 2H_2O$$

Slight efficiency loss due to higher overpotential on the air side

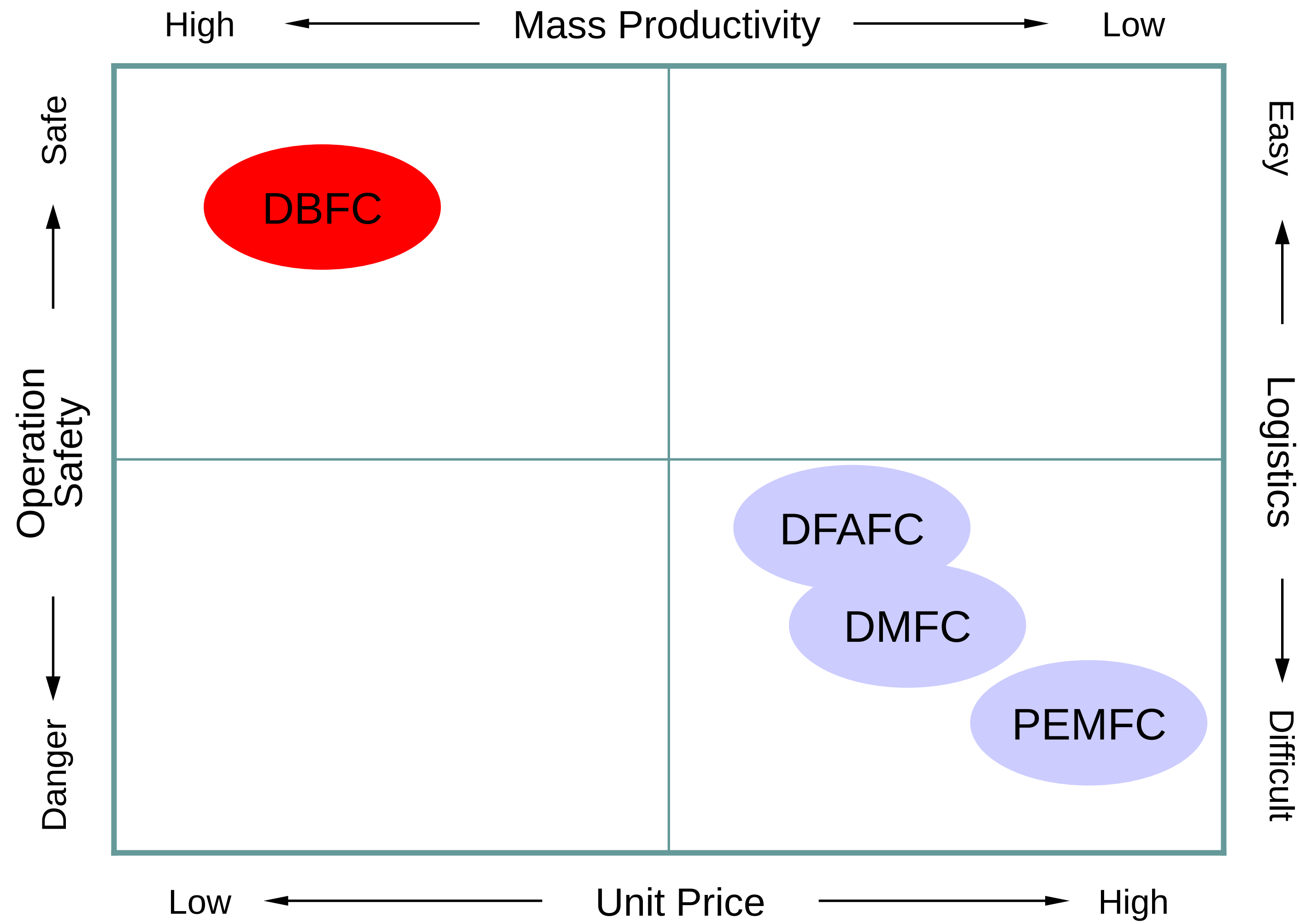
R&D Background in DBFCs at UIUC

Agencies	Achievements	Images
DARPA	**2003.10 ~ 2007.12** World's 1st $NaBH_4/H_2O_2$ DBFC	 
NASA	**2004.11 ~ 2006.6** World's 1st 1 kW DBFC World's 1st Rechargeable DBFC	 
Sandia National Laboratories	**2006.11 ~ 2009.3** World's 1st Gelled Fuel DBFC	 

5 Years of Cumulated Experience

Competition

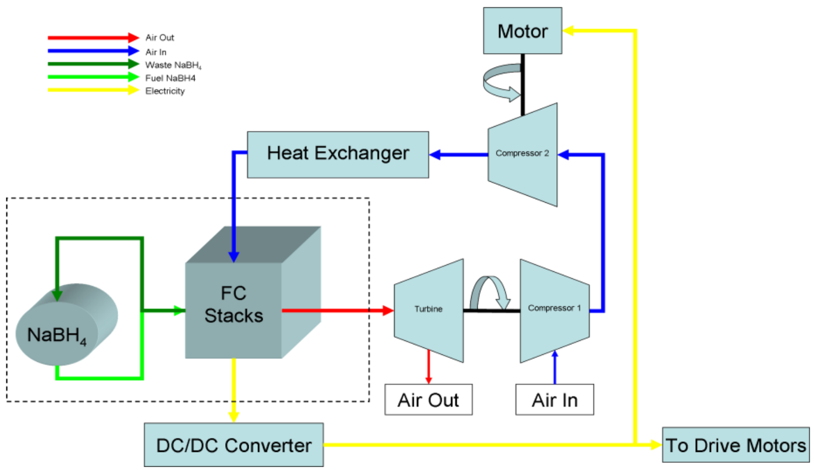
Competitive Advantages of DBFC vs other Fuel Cells



Direct $NaBH_4$/Air Fuel Cells for Automobiles Approach DOE 2015 Targets

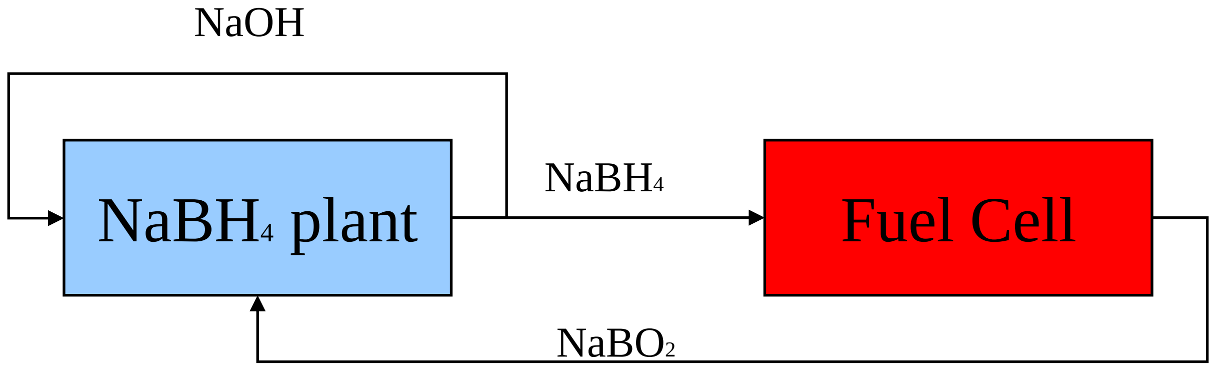
- Power density of 2200 W/L
- Specific power of 2000 W/kg
- 75% fuel cell efficiency
- System cost: $20/kW$_e$
- Durability, transient response time, cold startup time, and temperature survivability conditions can currently all be met, unlike gaseous H_2 systems.

Parameter	Value
Mass of liquid fuel	100 kg
Size of liquid fuel tank	20 gal
Parasitic Mass	20 kg
Total Fuel System Mass	120 kg
Energy Density of Fuel System	2.2 kWh/kg
Vehicle Power Consumption	20 kW
Vehicle Speed	75 mph
Vehicle Range	500 mi



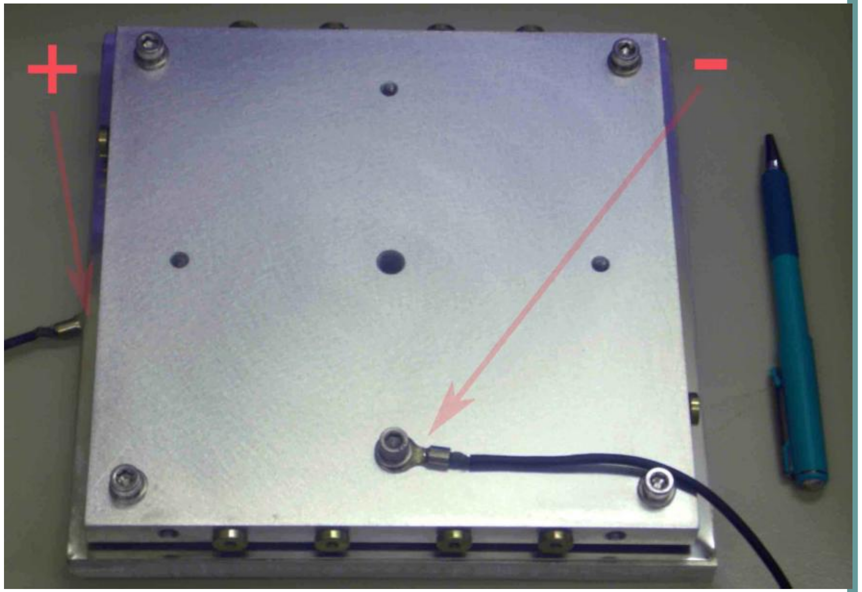
Fuel cost = key issue - Progress in $NaBH_4$ Production and Recycling Will Lower Costs

- $NaBH_4$ currently costs $50-$60 per kg, yielding an TOTAL energy cost of $0.66 per kW-hr
- Much of the cost of $NaBH_4$ is in electrolyzing Na+ from NaCl
- Millennium Cell (Eatontown, NJ) is working on a process to reduce the cost of $NaBH_4$ by extracting Na+ from the NaOH that is produced during $NaBH_4$ production and recycling the $NaBO_2$ product of the fuel cell
- NPL is working on an electrolytic process
- Under laboratory conditions, $NaBH_4$ has been produced for ~ $0.07 per kilogram, which in a $NaBH_4/H_2O_2$ fuel cell, would yield an energy cost under $0.3 per kW-hr, comparable to the cost of gasoline



STID Unitized Regenerative Cell – for use with wind or solar power stations

- The STID design uses novel catalysts and a new chemical pathway to achieve regeneration
- Currently, the only unitized hydrogen based liquid regenerative cell in development.
- Roundtrip efficiencies of 75% with cycle life of >10000 have been demonstrated.
- A complete $NaBH_4$ regenerative fuel cell system would mitigate the need to consider borohydride fuel economics



Current state-of-the-art 16-W regenerative test cell.

STID Performance Characteristics

	Energy Density	Power Density (Peak)	Power Density (Nominal)	Cycle Life
Prototype	110 W-hr/kg	400 W/kg	110 W/kg	>10000
In 5 Months	200 W-hr/kg	800 W/kg	220 W/kg	>10000

- Because the cell uses a permeable membrane, it will self discharge after a certain amount of time (~15 hrs)
- Because of this discharge/recharge cycle, the cell is ideal for periodic applications such as satellite power and load leveling

Outline

- Comments about the "Hydrogen Economy"
- Production of Hydrogen
  - Distributed and Central Plants
  - Plasma production
    - STAR CELL
    - Jet (Torch) Production (current U of IL research)
- Hydrogen storage (comments about our Dislocation Loop research)
- *Fuel Cells (a few comments about our research)*
  - Direct Borohydride
- **<u>Concluding comments & questions from you</u>**

Concluding remarks

- The hydrogen economy is a noble goal
- There are road blocks to be overcome
- To get there we need to take small steps forward
- Some steps undertaken by my research group (hydrogen torch and borohydride fuel cell) are hopefully examples
- Contributions by many research teams world wide are moving us ahead towards this goal

Thank you !

George H. Miley
ghmiley@uiuc.edu