Non-Electrical Applications within Gen IV Reactor Systems

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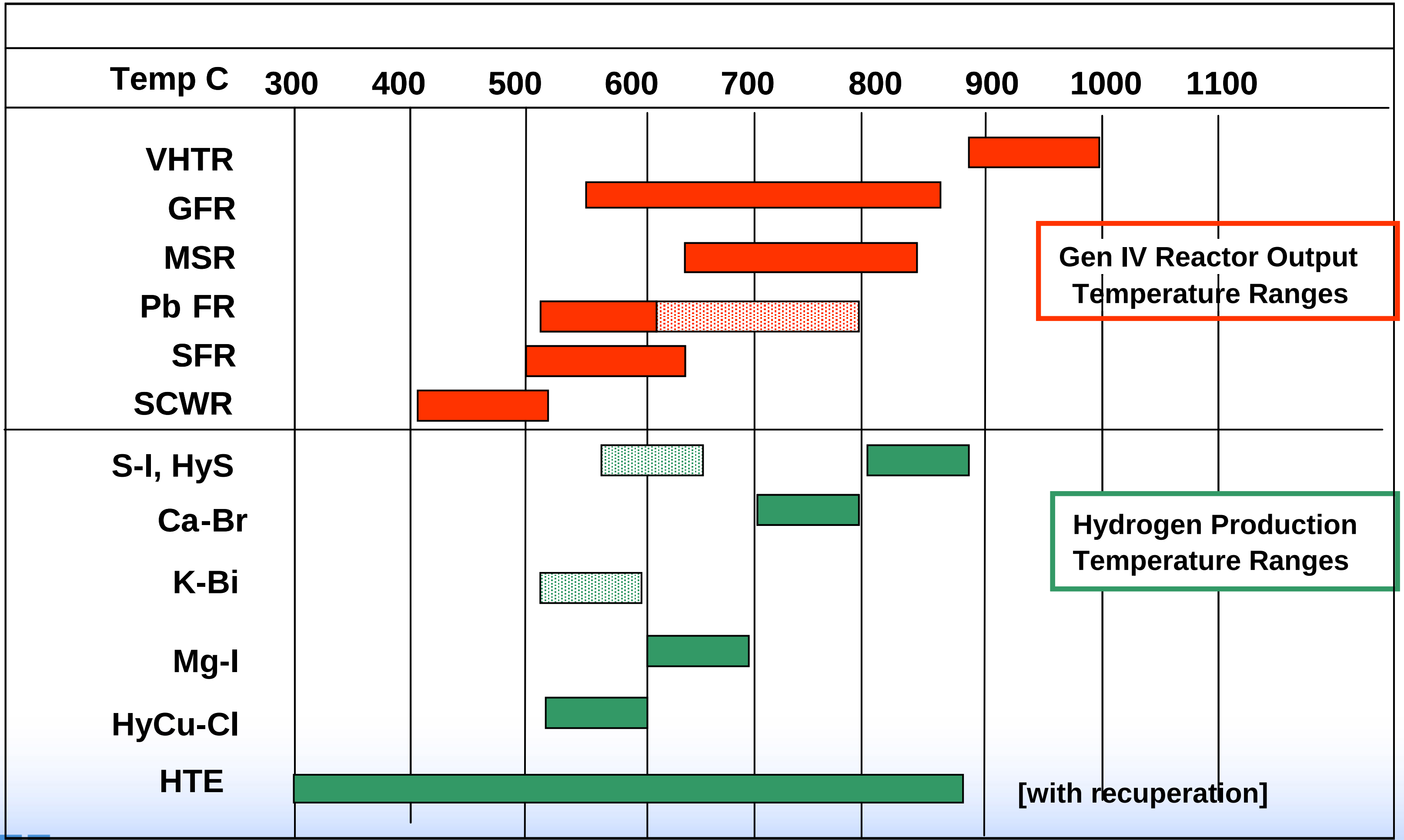
Generation IV Energy Conversion

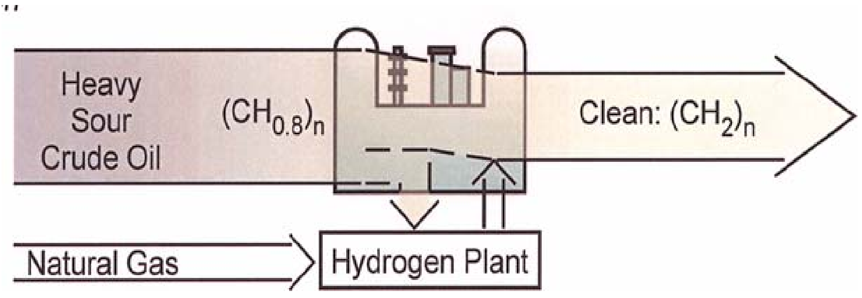
- Electrical generation - *Gen IV Energy Conversion Program*
- Hydrogen production - *Nuclear Hydrogen Initiative (NHI)*



Present US Hydrogen Consumption

- Petroleum refining
  - Sulfur removal
  - Opening of Benzene rings
  - Breaking of long-chain hydrocarbons
  - trends will continue in the future, e.g. Athabasca oil sands
- Anhydrous Ammonia Production for fertilizer
- Chemical Industry
- 2005 US consumption: 13 million tons H_2/yr
  - 95% produced by steam reforming of natural gas (8 % of US natural gas use)
    Releases 80 million tons CO_2/yr

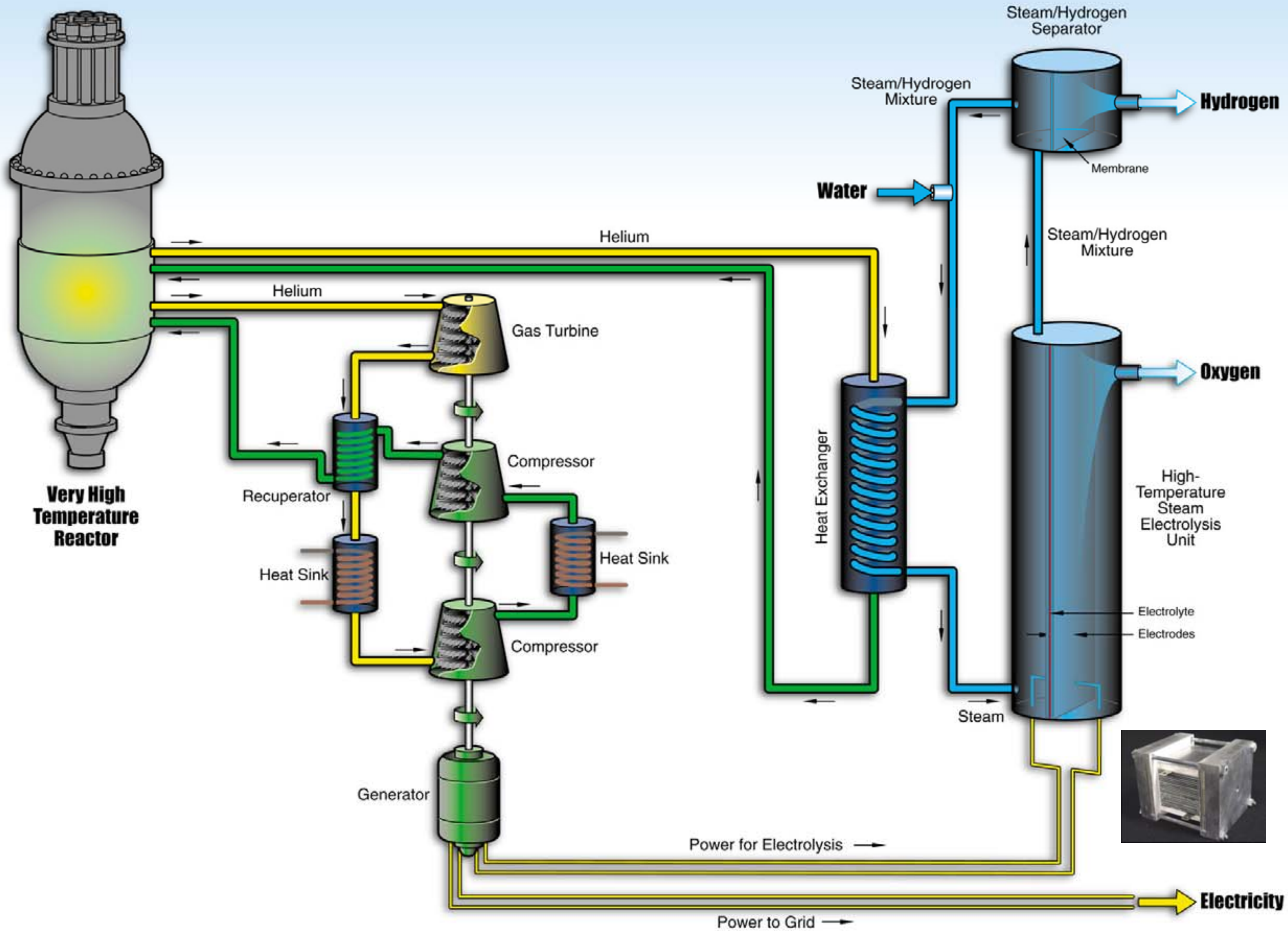
Liquid fuels production is rapidly becoming the major market for hydrogen

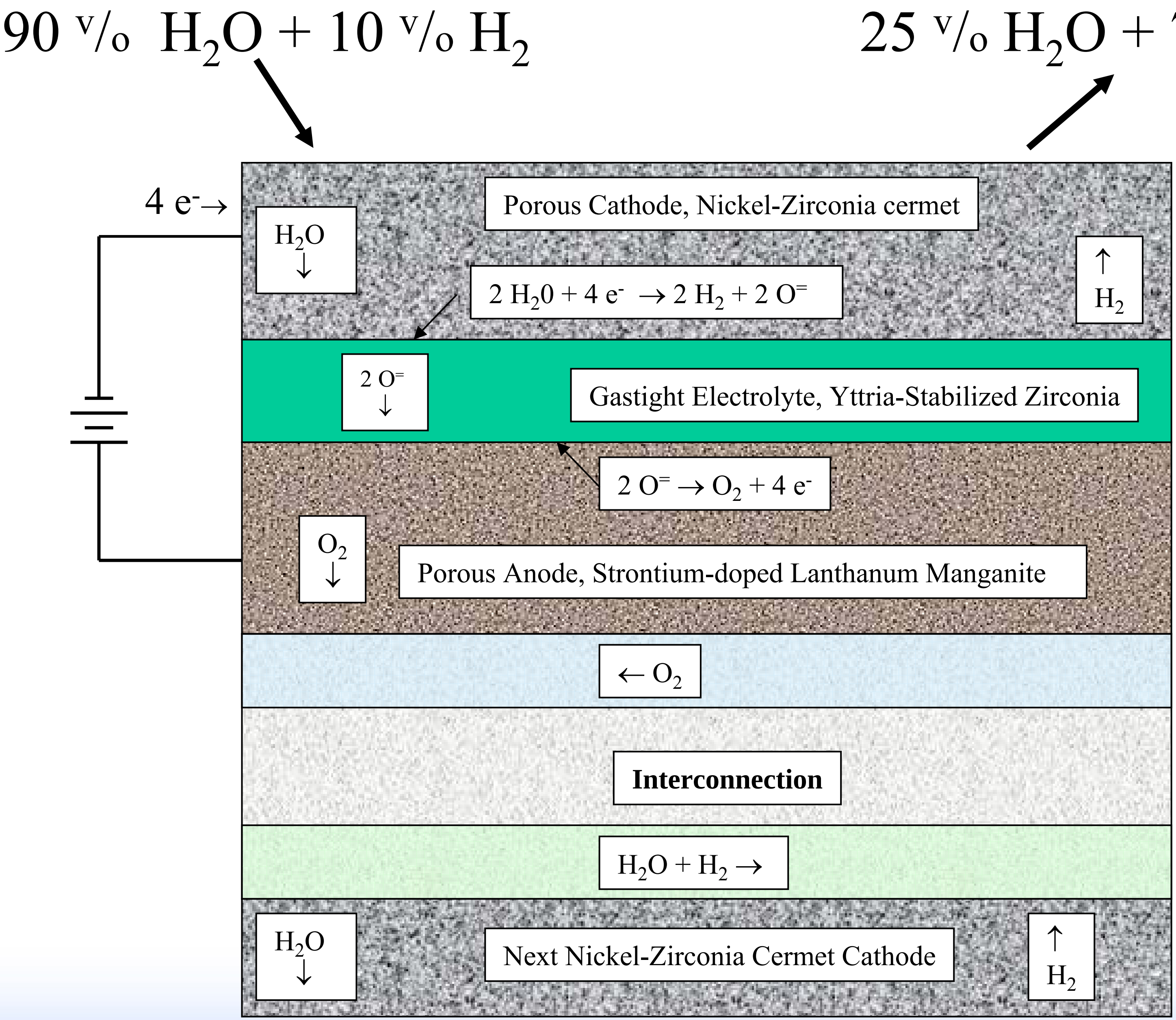


This can be the proverbial "chicken" for the Hydrogen Economy

- Replacing present US transportation fuels (gasoline, diesel, jet fuel) with hydrogen would require a 17-fold increase in our hydrogen production.
  -Would consume >100% of our natural gas supply, or
  - Would require ~500 1000-MWe power plants to provide the energy for water splitting

High Temperature Electrolysis Plant

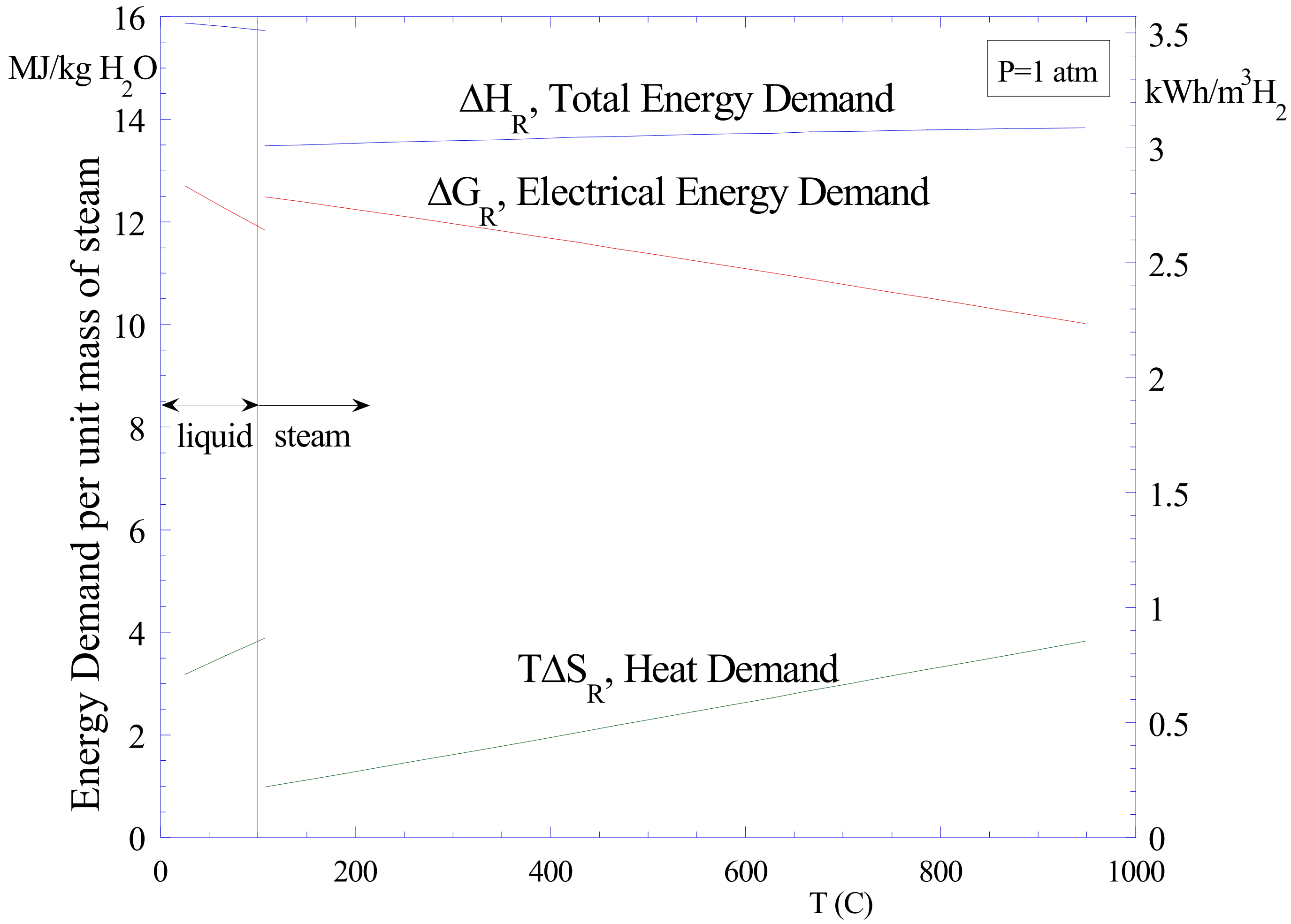




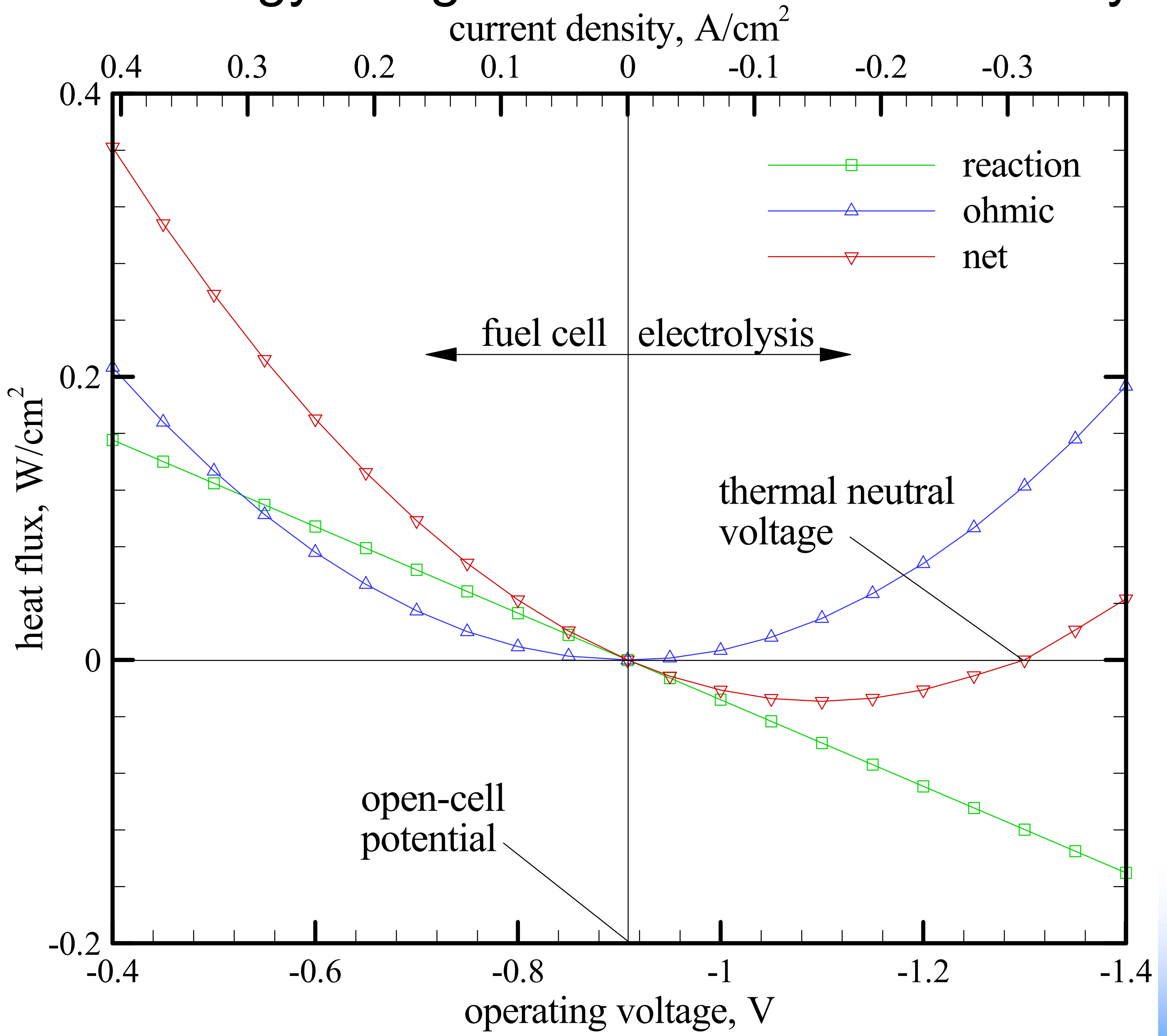
Typical thicknesses

Electrolyte-supported	Cathode-supported
0.05 mm	1.500 mm
0.10 mm	0.01 mm
0.05 mm	0.05 mm
1 – 2.5 mm	

Electrolysis at High Temperatures requires less Electricity



Energy Budgets in fuel-cell and electrolysis modes

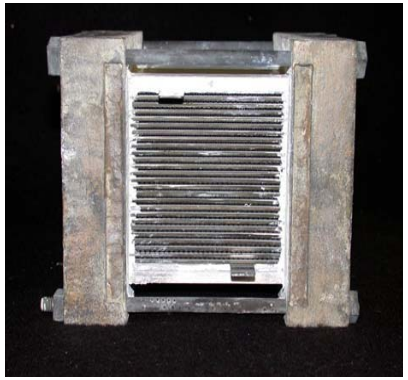


Stack ASR = 1.25,
T = 927 C,
$y_{H2,i} = 0.1$,
$y_{H2,o} = 0.95$

$$V_{tn} = \frac{-\Delta h_R}{2F}$$

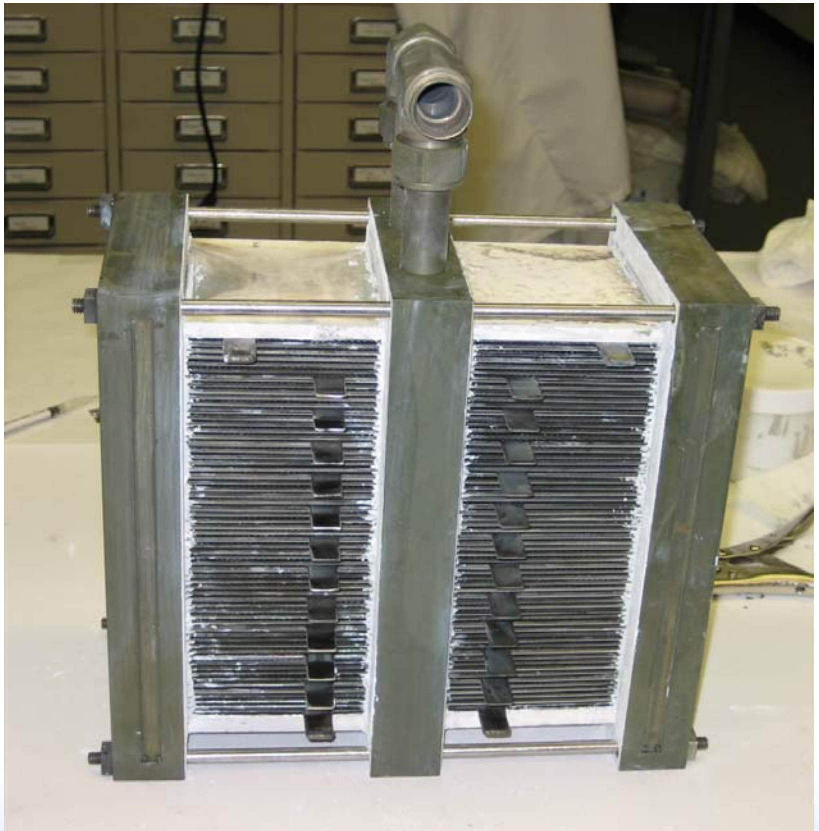
(1.291 V at 1200 K)

25-cell stack used in 1000-hour test
0.177 Nm^3/hr average
Jan. 4 – Feb. 16, 2006



2 x 60-cell stacks tested at Ceramatec, SLC

Initial rate: 1.2 Nm3 H2/hr
final: 0.65 Nm3 H2/hr
2040 hours, ended 9-22-06
>800 hrs in co-electrolysis



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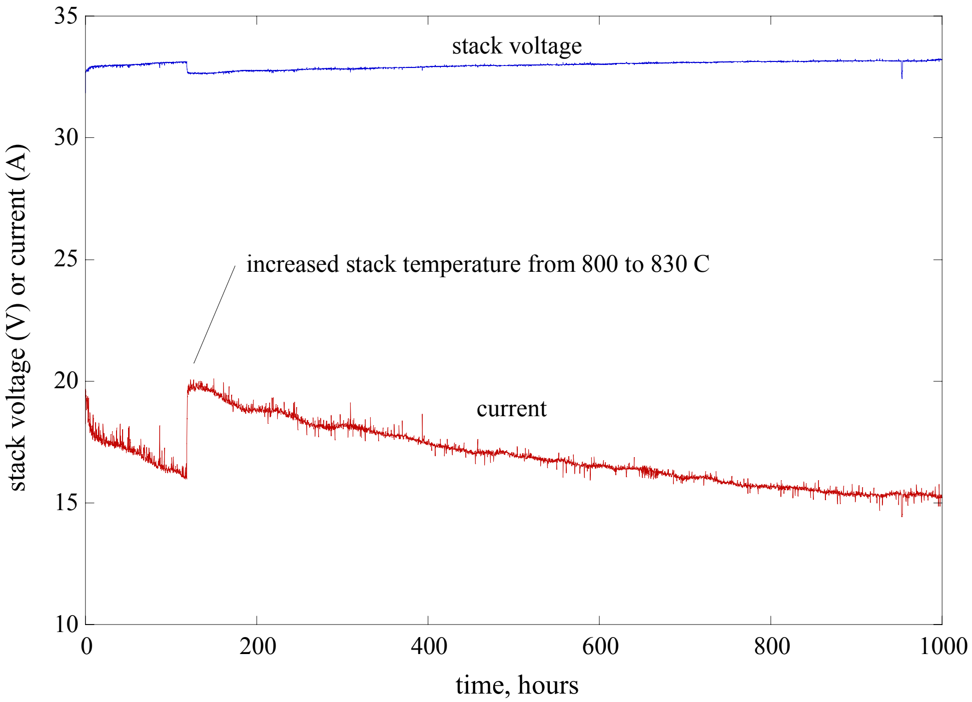
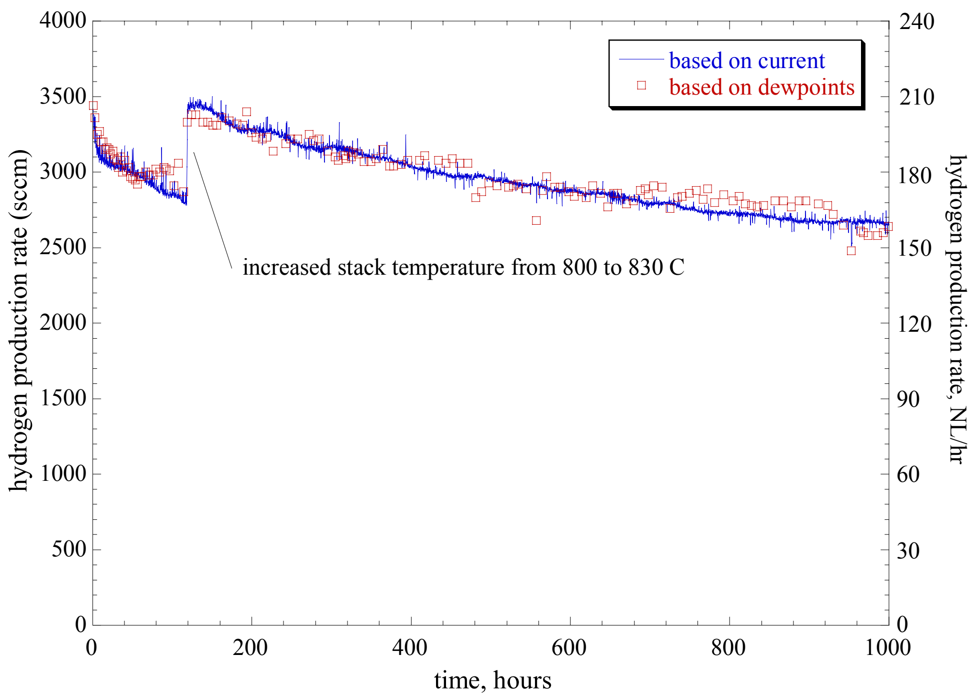
1000-hour electrolysis test, 25-cell stack

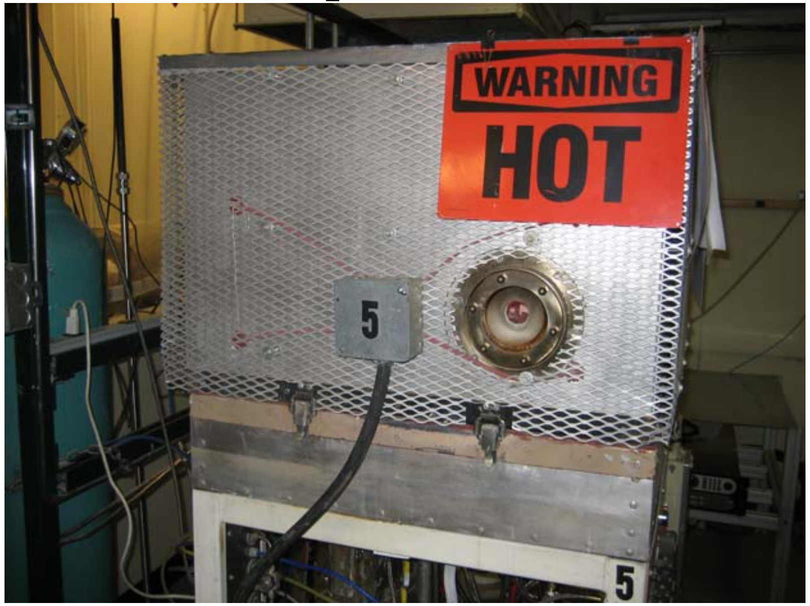
Stack voltage and current

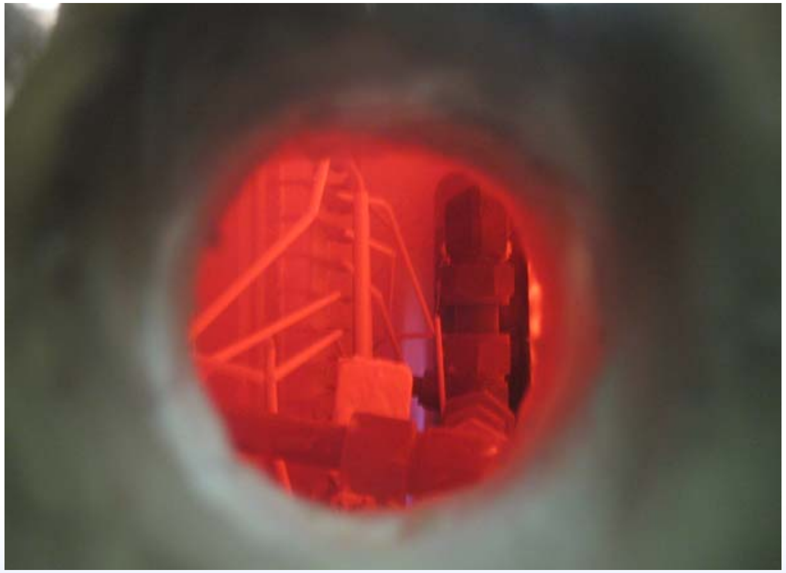


Hydrogen production rate

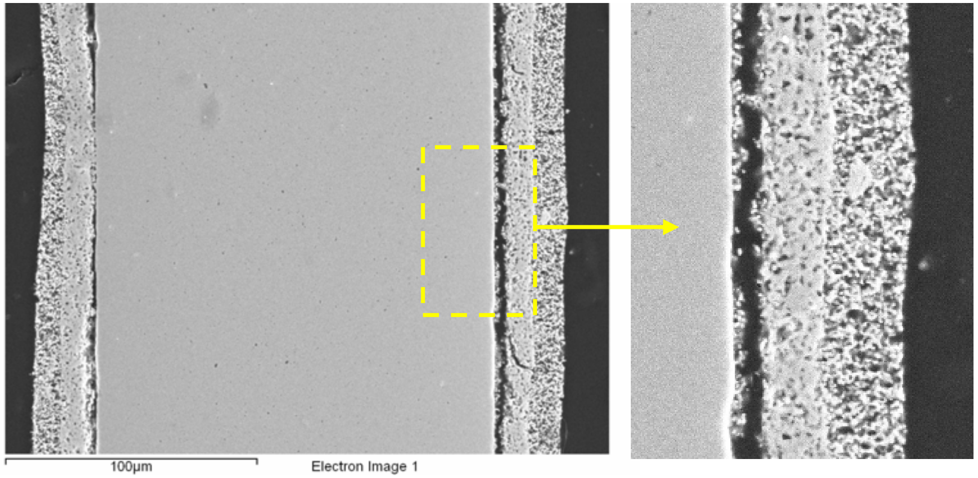


Views of Half-Module in Operation

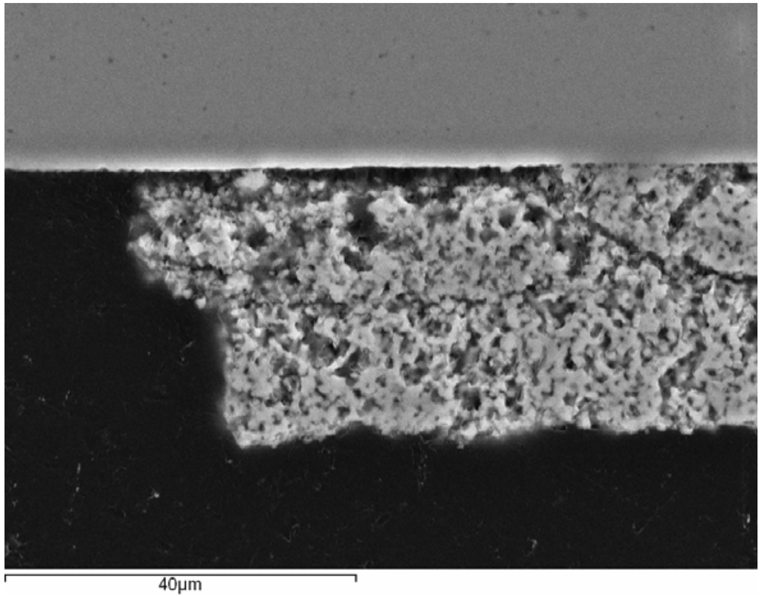




Results of Post-test evaluations (ANL)



SEM image of CER11, showing delamination at the electrolyte-electrode interface, and over-sintering of the inner layer active electrode. Both the delamination and over-sintering can lead to short-term and long-term performance loss at the electrode.



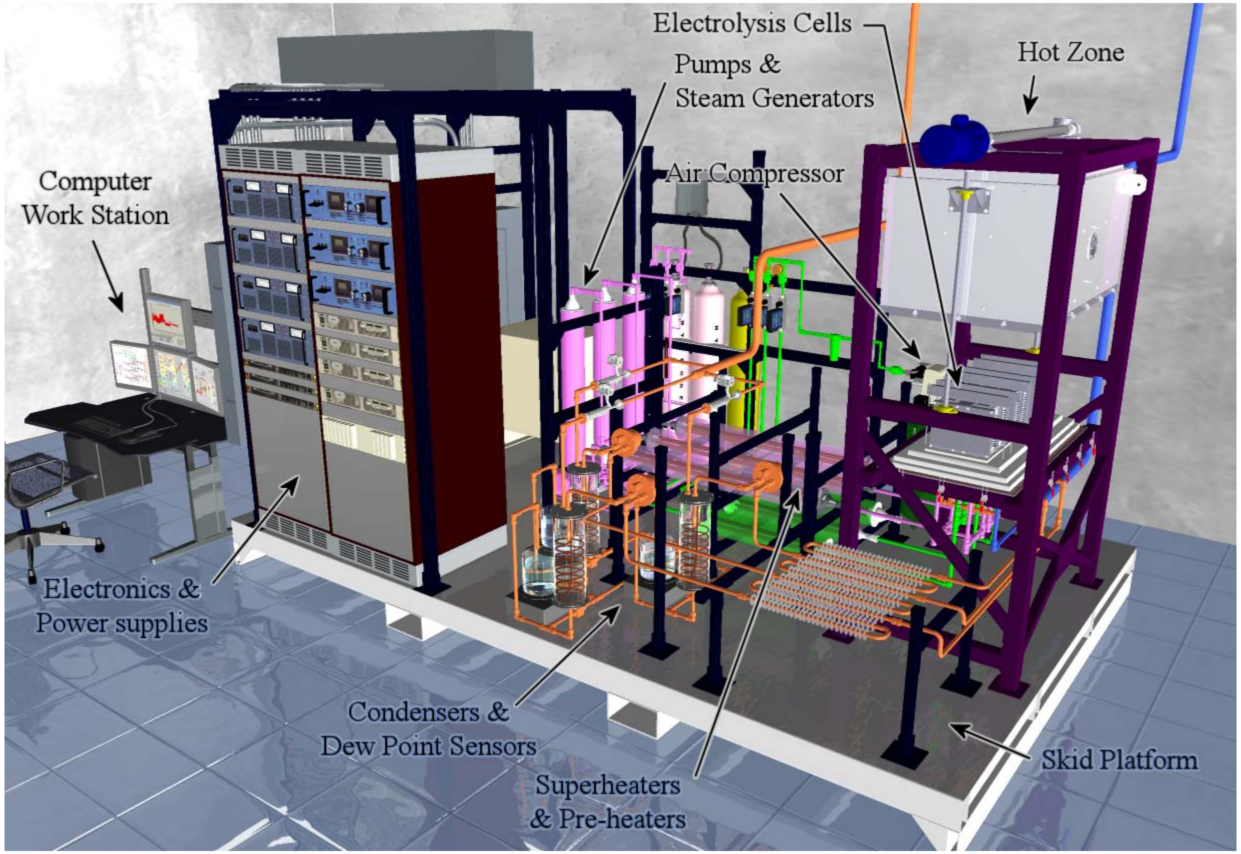
Apparent delamination and cracking of the air electrode near the sealed edge of the 25-cell stack. The gray area at the top of the picture is the zirconia electrolyte.

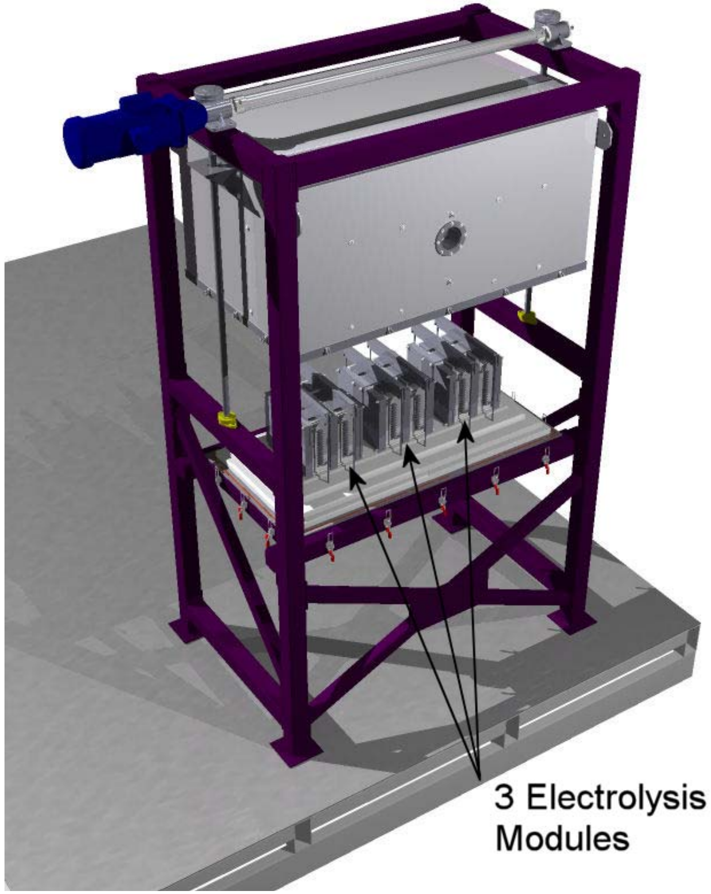
Delivery of Initial ILS module

INL researchers Carl Stoots and James O'Brien accept delivery of first High Temperature Electrolysis Integrated Laboratory Scale module from Ceramatec (March 21, 2007).

Closeup of the four stacks

Integrated Laboratory Scale experiment





Inevitable Comparison:

Liquid hydrocarbons are very good fuels for transportation

- **Liquid over range of ambient temperatures**
- **Pumpable: gas pump: 20 liters/min = 11 MW_{th}**
- **Energy dense: 34 MJ_{th}/liter at 0.1 MPa**
  - **H_2 gas: 9.9 MJ_{th}/liter at 80 MPa,**
  - **H_2 120 MJ_{th}/kg, gasoline: 40 MJ_{th}/kg**
- **Storable: little loss, fire hazards understood**
- **Transportable by pipeline: 0.91 m oil pipeline: 70 GW_{th}**

Hydrogen will be used primarily to enhance gasoline, diesel and jet fuel production until the on-board storage problem can be solved.

Co-Electrolysis

- Primarily a "proof-of-principle" research project
- Investigate the feasibility of producing syngas

Syngas

$2H_2$ and CO

- using high-temperature co-electrolysis of H_2O and CO_2

$$2\ H_2O + CO_2 \rightarrow 2\ H_2 + CO + 1.5\ O_2$$

- while taking advantage of solid oxide fuel cell technology.

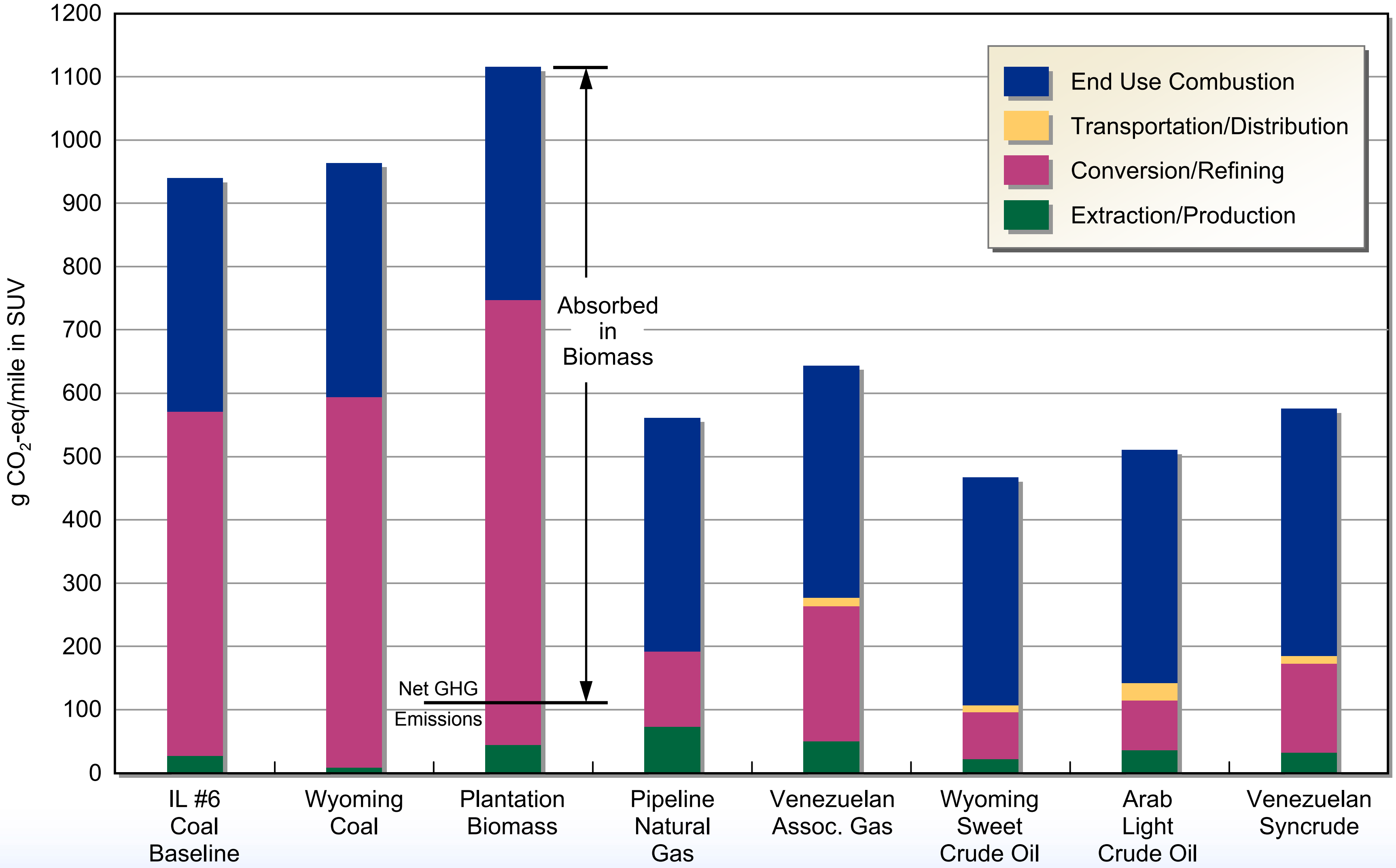
SYNTHETIC FUELS

- Nothing New About Synfuels
  - Produced via the Fischer-Tropsch process

    Syngas

    - $nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$
    - Discovered before WWII
    - Pressure primarily determines *n*
- Production of Synfuels requires Syngas
  - Previous H_2 production releases large amounts of CO_2

Full Diesel SUV Life-Cycle Greenhouse-Gas Emissions for Crude Oil and Other Feedstocks with Fischer-Tropsch Conversion



Source: Charles Forsberg, ORNL, Mar 07

Table 2: Summary of Syngas Conversion Processes and Conditions

Process	Catalyst	Process Conditions			% conv	Product	Selectivity
		T (°C)	P (bar)	H_2:CO	(CO basis)		
Fischer-Tropsch Synthesis	Fe	300-350	10-40	1.7:1	50-90% with recycle	α-olefins gasoline	ASF -48% (max) 15-40% actual
	Co	200-240	7-12	2.15:1		Waxes diesel	ASF - 40% (max)
	Ru					Waxes	
Methanol Synthesis	ZnO/Cr_2O_3	350	250-350	3:1	99% (25% max/pass – 4-7% actual/pass)	Methanol	> 99% with recycle
	$Cu/ZnO/Al_2O_3$	220-275	50-100				
Ammonia	Fe/FeO + additives	430-480 (550 max)	100-500	2-3:1 H_2:N_2	10-35%/pass	Ammonia	> 99% with recycle
	Alkali/ZnO/Cr_2O_3	300-425	125-300	1:1	5-20%	Branched primary alcohols	
	Alkali/Cu/ZnO(Al_2O_3)	275-310	50-100	2-3:1	20-30%	Primary alcohols	30-45% C_{2+} 17-25% CO_2
	Alkali/CuO/CoO	260-340	60-200	0.5-4:1	5-30%	Linear primary alcohols	ASF
	Alkali/MoS_2	260-350	30-175	1:1	10%	Linear alcohols	75-90% C_{2+} in liquid product
Oxosynthesis	Co carbonyl	110-200	200-300	1:1 + olefin			
	Co – P modified	160-200	50-100	1:1 + olefin		C_{11}-C_{14} alcohols	
	Rh – P modified	60-120	7-25	1:1 + propylene		C_4 aldehydes	> 90%
Isosynthesis	ThO_2	400-450	100-1000 (300)	0.85:1	40-50%	*i*-C_4	
	ZrO_2	300-425	350	1:1	30%		15
Steam Methane Reforming	Ni	850	15-30	na	100% CH_4 conversion	Syngas/ hydrogen	

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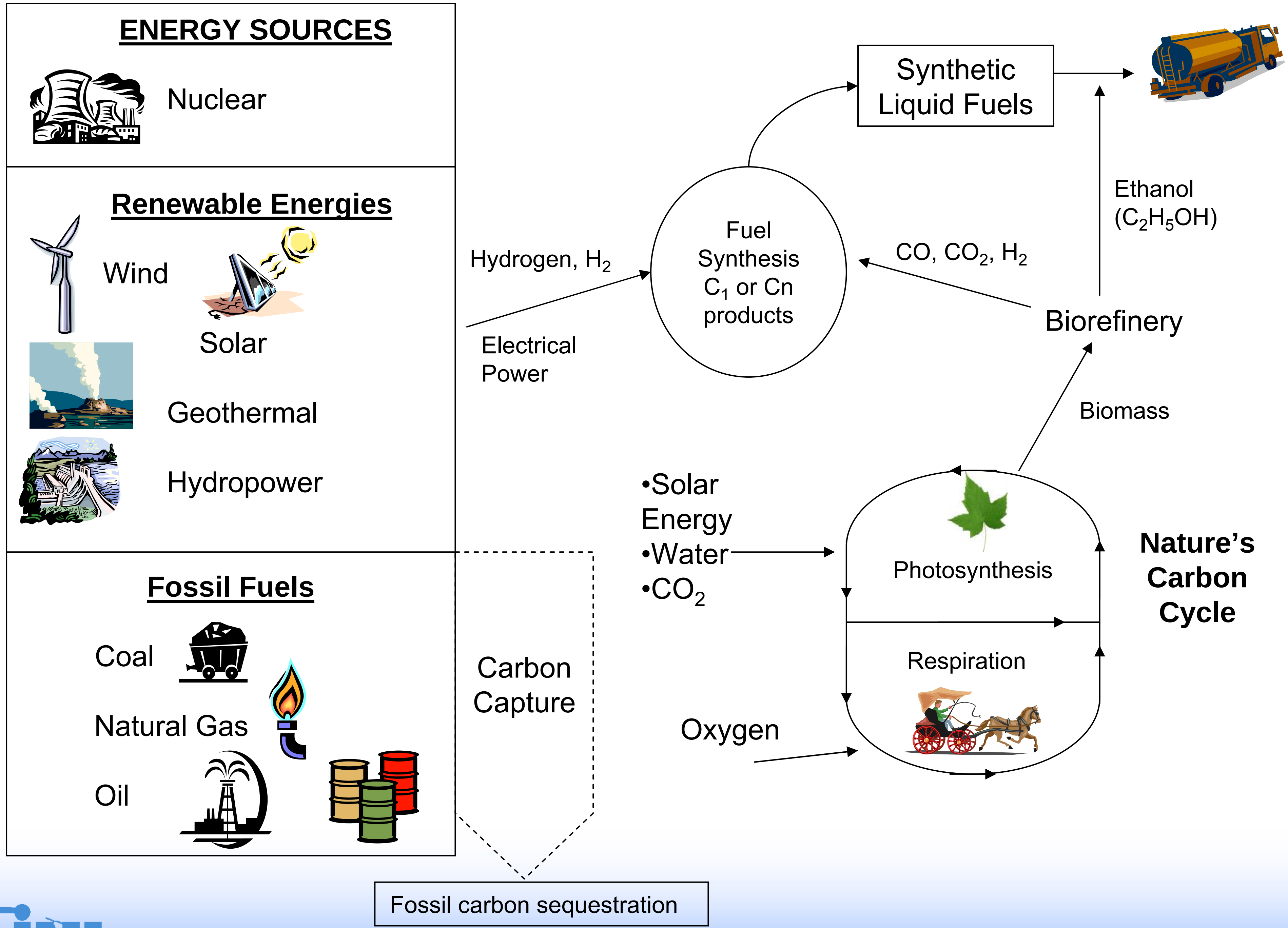
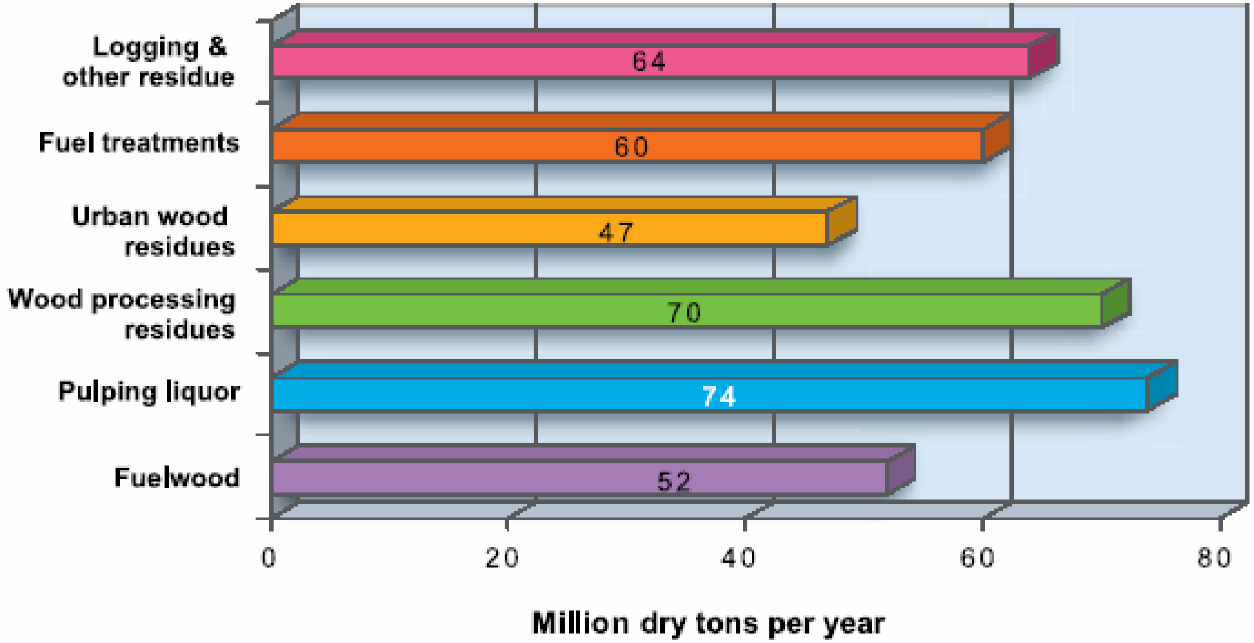
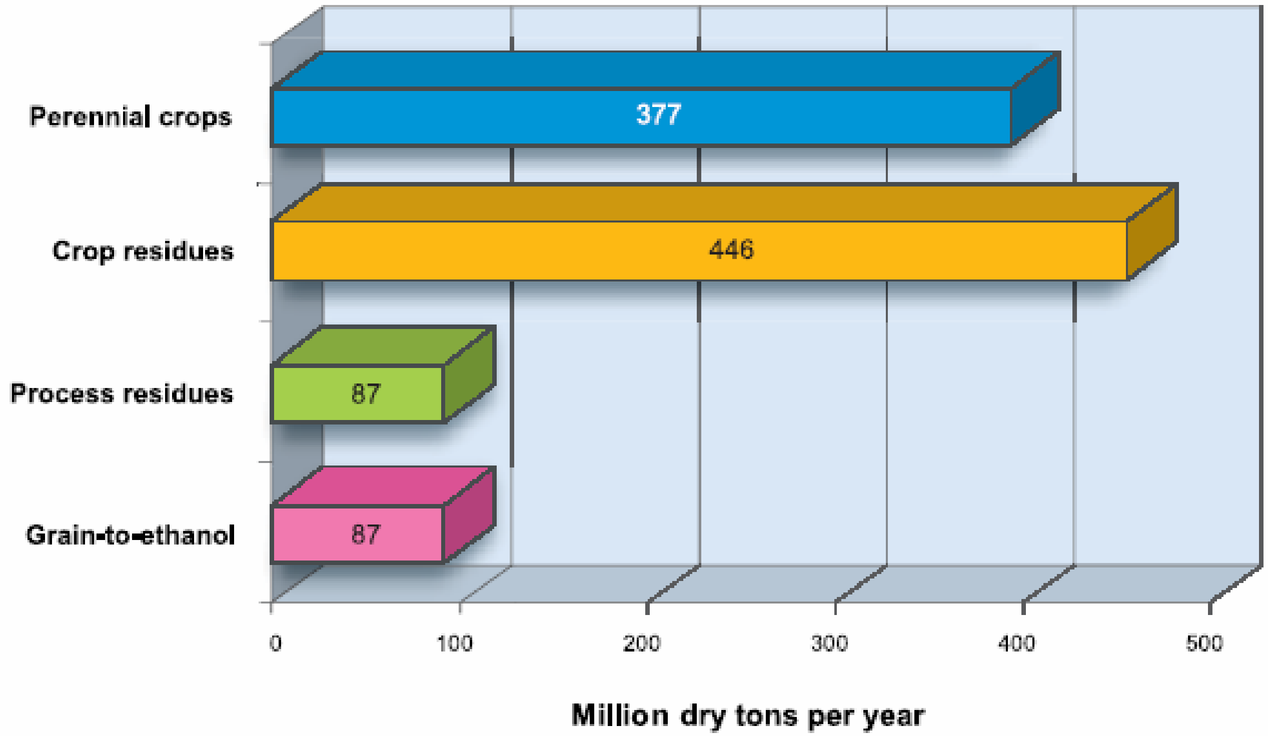


ENERGY SOURCES
Nuclear
Renewable Energies
Wind
Solar
Geothermal
Hydropower
Fossil Fuels
Coal
Natural Gas
Oil
Hydrogen, H_2
Electrical Power
Fuel Synthesis C_1 or Cn products
Synthetic Liquid Fuels
Ethanol (C_2H_5OH)
CO, CO_2, H_2
Biorefinery
Biomass
•Solar Energy
•Water
•CO_2
Photosynthesis
Respiration
Oxygen
Nature's Carbon Cycle
Carbon Capture
Fossil carbon sequestration

U.S. Biomass-to-Ethanol Resource Base





Carbon comparison
1.3 Gt cellulose = 520 Mt_c/yr

20 m bbl/d crude = 647 Mt_c/yr

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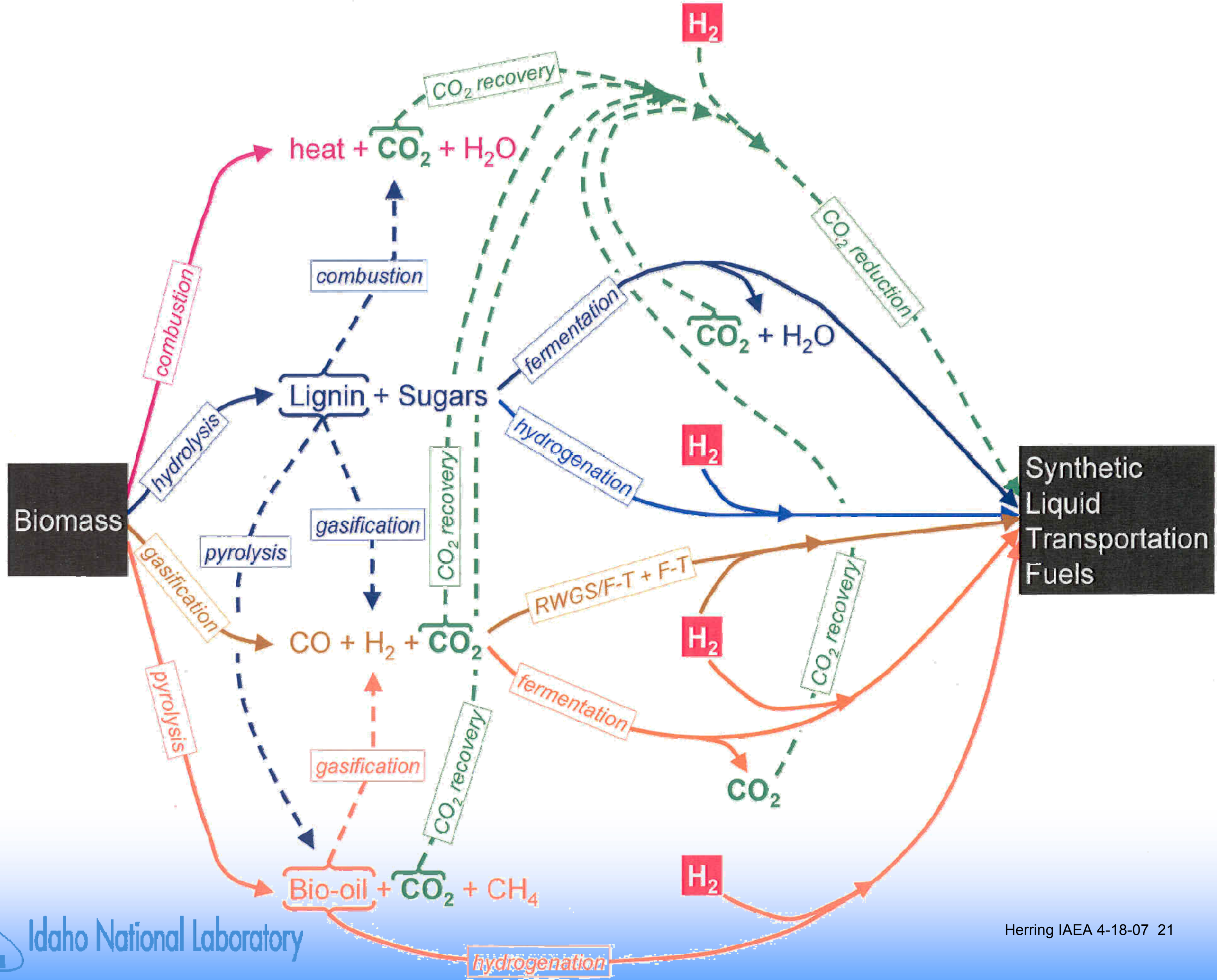
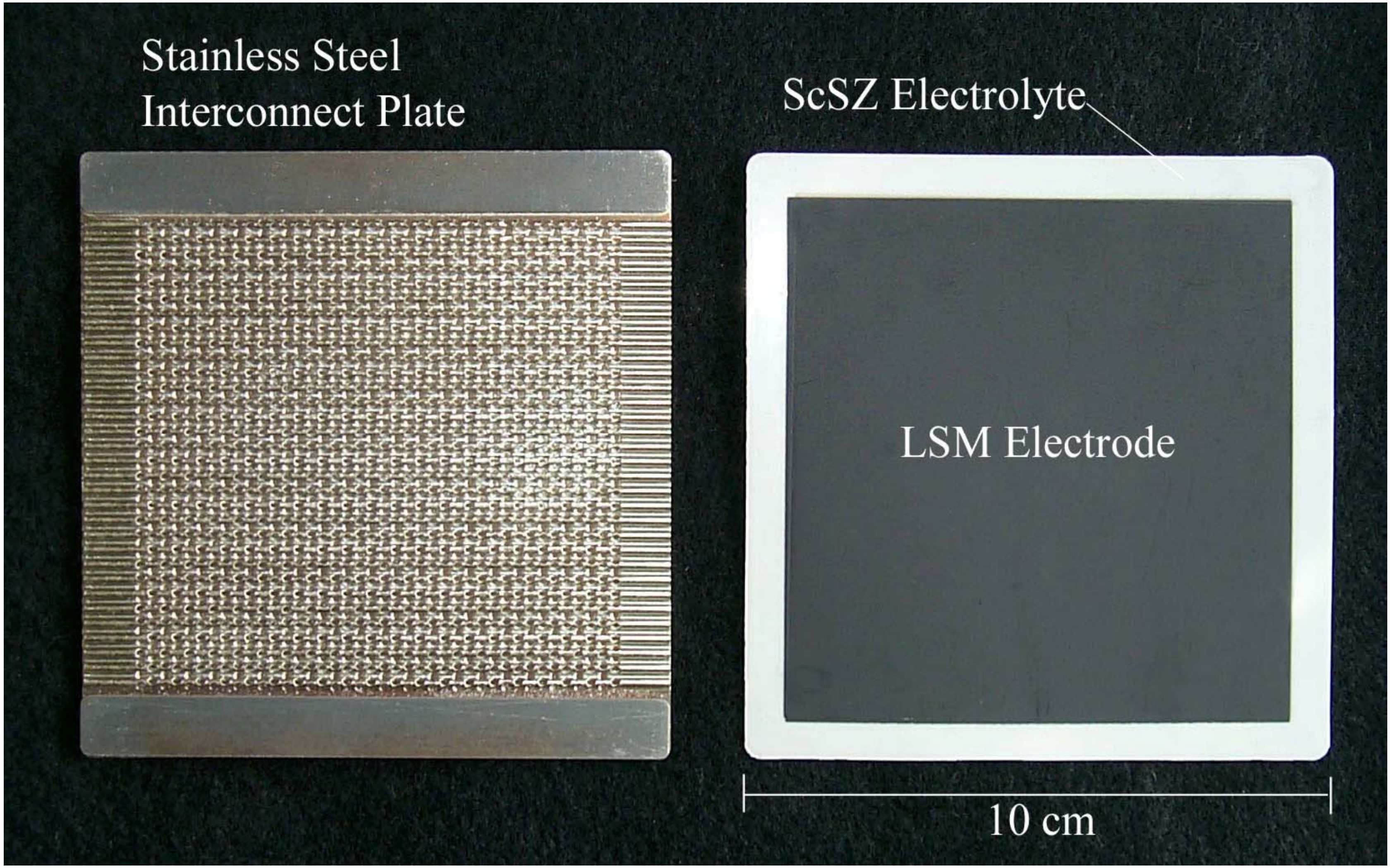
Biomass to Liquid Fuels Pathways



Conclusions

- **Conventional electrolysis is available today**
- **High temperature electrolysis is under development and will be more efficient**
- **HTE Experimental results from 25-cell stack and 2x60-cell half-module, fabricated by Ceramatec,**
  - **Hydrogen production rates in excess of 160 normal liters/hour were maintained with a 25-cell solid-oxide electrolysis stack for 1000 hours**
  - **Hydrogen production greater than 800 normal liters/hour are now being achieved in the half-module test**
  - **An Integrated Laboratory Scale experiment is now being build, which will produce about 5,000 normal liters/hour**
- **In the near-term hydrogen from nuclear energy will be used to upgrade crude and later to synthesize conventional gasoline and diesel fuel from renewable carbon sources**
- **In the long-term pure hydrogen from nuclear energy will power vehicles directly through fuel cells**

Stack Internal Components



Thermal Water Splitting Efficiencies, from Yildiz and Kazimi (MIT)

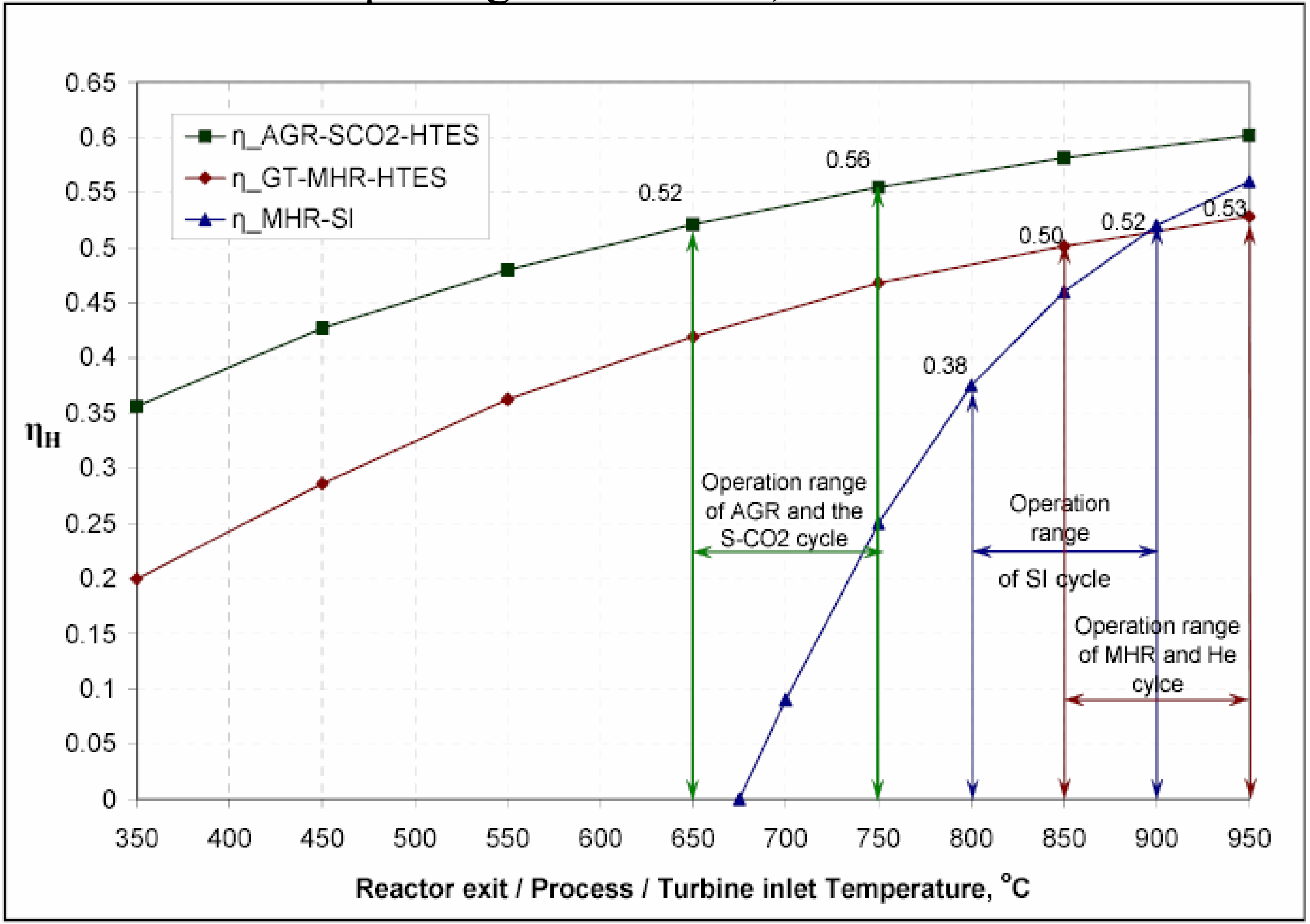


Figure 14: Comparison of the thermal-to-hydrogen efficiency of the HTES and SI related technologies as a function of temperature

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Economic Comparison

Hydrogen Production Cost					
Process	Energy Source	Reactor Core Outlet Temp., °C	Process Max. Cycle Temp., °C	H_2 Cost w/o O_2 Credit, $/kg	H_2 Cost with O_2 Credit, $/kg
High Pressure Electrolysis	Gas Turbine-HTGR	850	80	$ 2.45	$ 2.29
Steam Methane Reforming*	Natural Gas	NA	700	$ 1.35	--
Steam Methane Reforming*	Process Heat-HTGR	850	700	$ 1.20	--
Sulfur-Iodine	Process Heat-HTGR	1000	900	$ 2.07	$ 1.91
High Temperature Electrolysis	HTGR	1000	850	$ 2.31	$ 2.15

source: EPRI 1009687, Oct 2004

* natural gas:$5.60/million BTU, sequestration: $4.09/MT CO_2

The U.S. Biomass Resource Base