Nuclear Energy Hydrogen Program Overview: High Temperature Electrolysis

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Hydrogen and Fuel Cell Technical Advisory Committee Open Meeting
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Increasing Demand for Hydrogen

Near-term

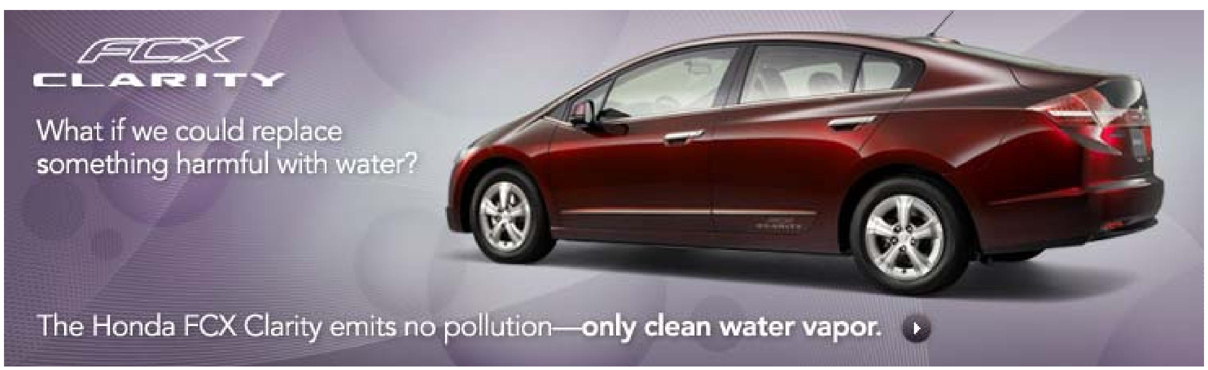
Long-term

We Already Have A "Hydrogen Economy"

- H_2 production: 12 Mton/yr in US
- Ammonia production
- Upgrading of low-quality hydrocarbon resources (e.g. Athabasca Oil Sands, Orinoco heavy crude)
- Synthetic fuels (methanol, synthetic diesel / gasoline) from biomass, coal?
- The "transportation fuel of the future"
  - 28% of US energy is used for transportation
  - Essential for overall CO_2 reduction (assuming CO_2-free hydrogen production)

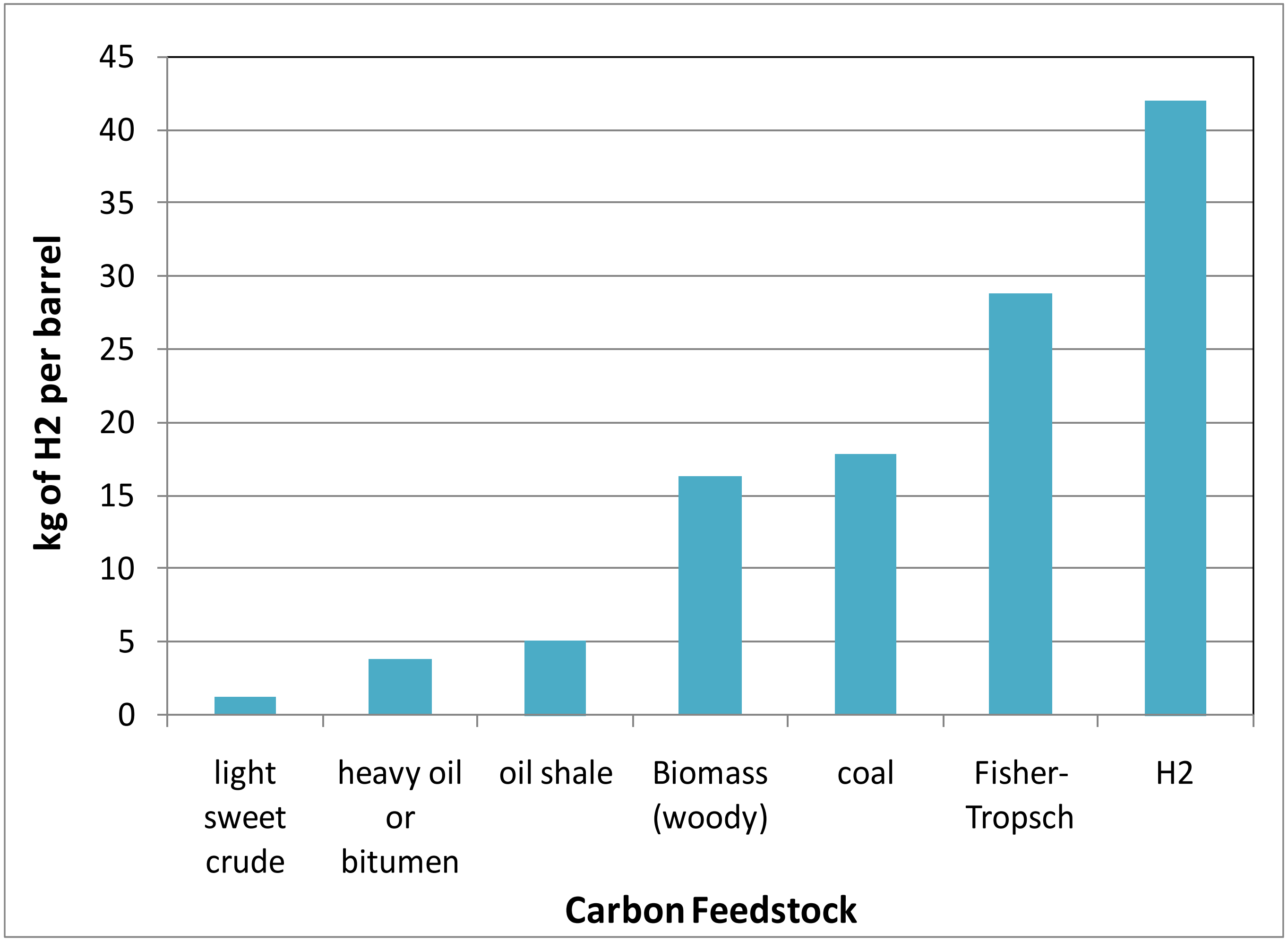
Extraction of oil sands

Air Products SMR Plant near Edmonton~100 million SCFD H_2



Honda FCX – currently in limited availability for lease in Southern CA

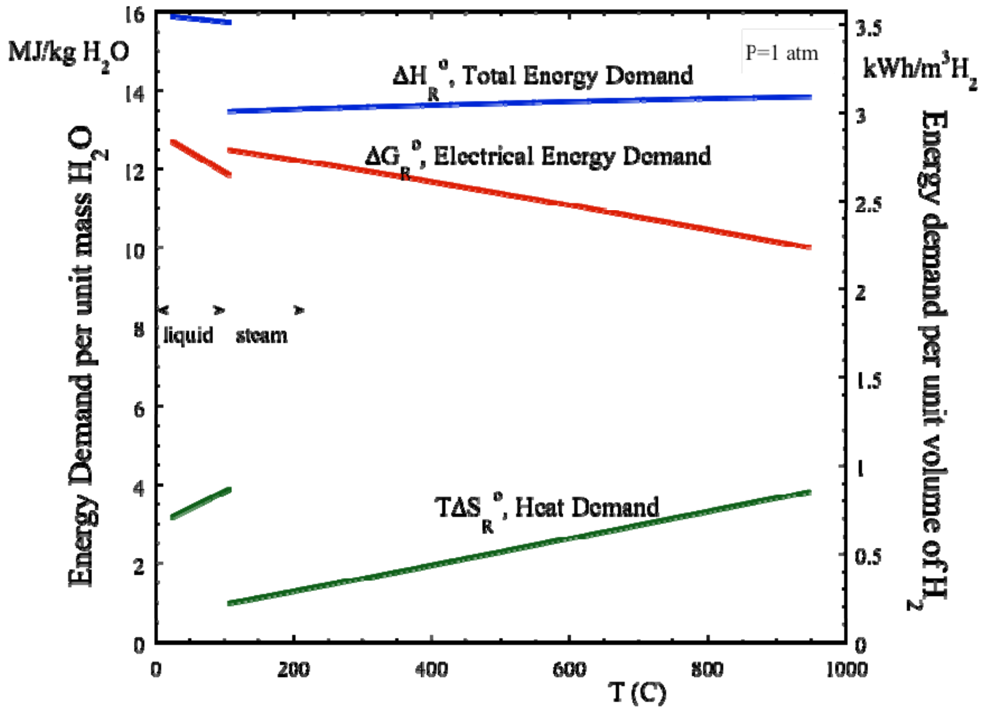
Hydrogen requirements for processing of carbon feedstocks to produce liquids fuels



High Temperature Electrolysis is more efficient than conventional electrolysis

- Overall Thermal-to-hydrogen efficiency >50% (based on HHV)
- Electrical power requirements
  - HTE: ~ 34 kW-hr/kg
  - Conventional ~ 50 kW-hr/kg

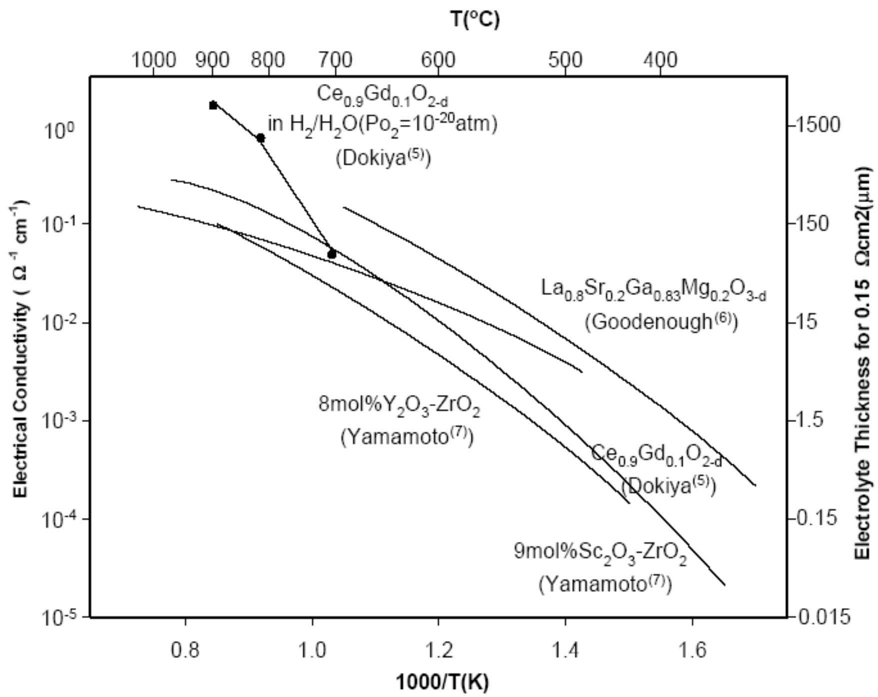
Standard-state ideal energy requirements for electrolysis as a function of temperature



Kinetics

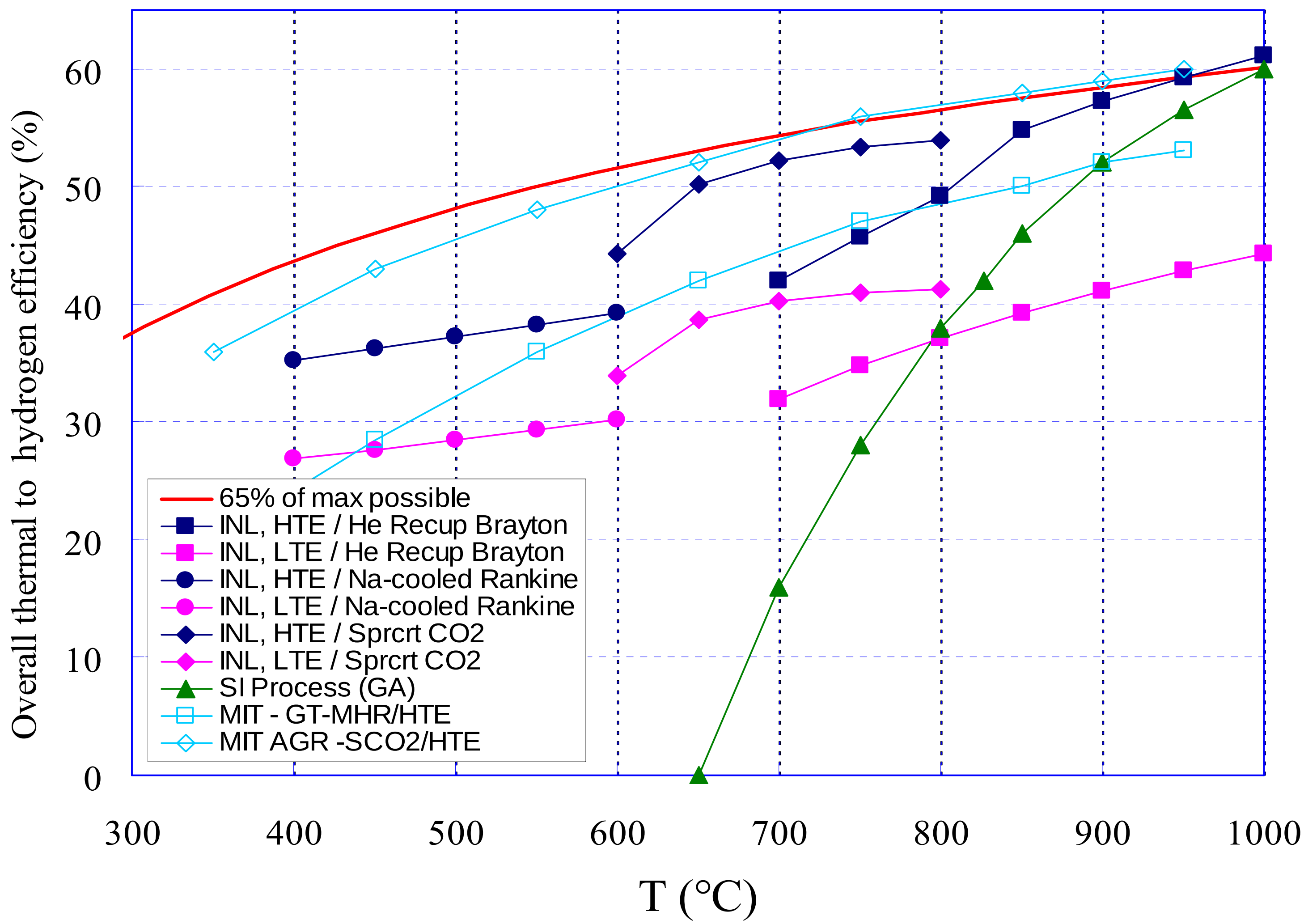
Ionic conductivities increase with T

Low activation overpotentials (no precious metal catalysts needed)



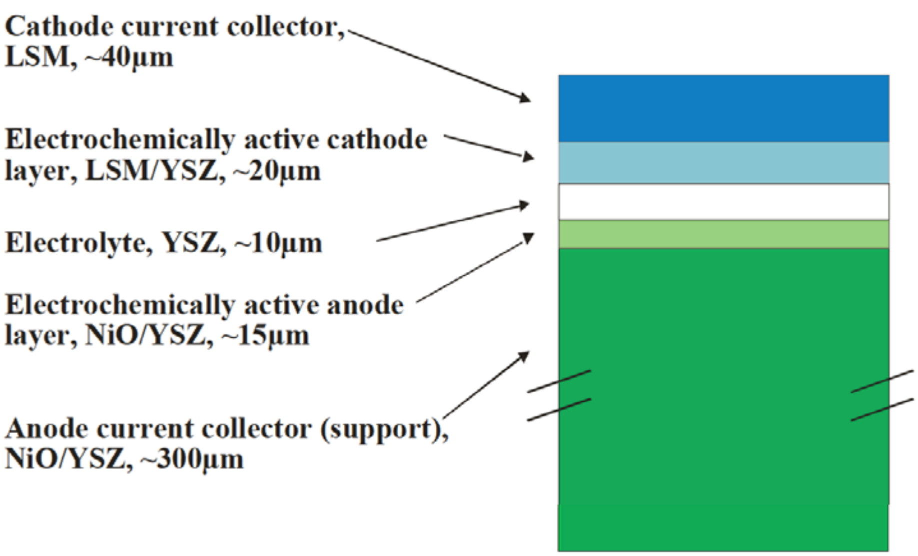
Motivation for High-Temperature Processes

Overall thermal-to-hydrogen production efficiencies based on HHV for several reactor/process concepts, as a function of reactor outlet temperature

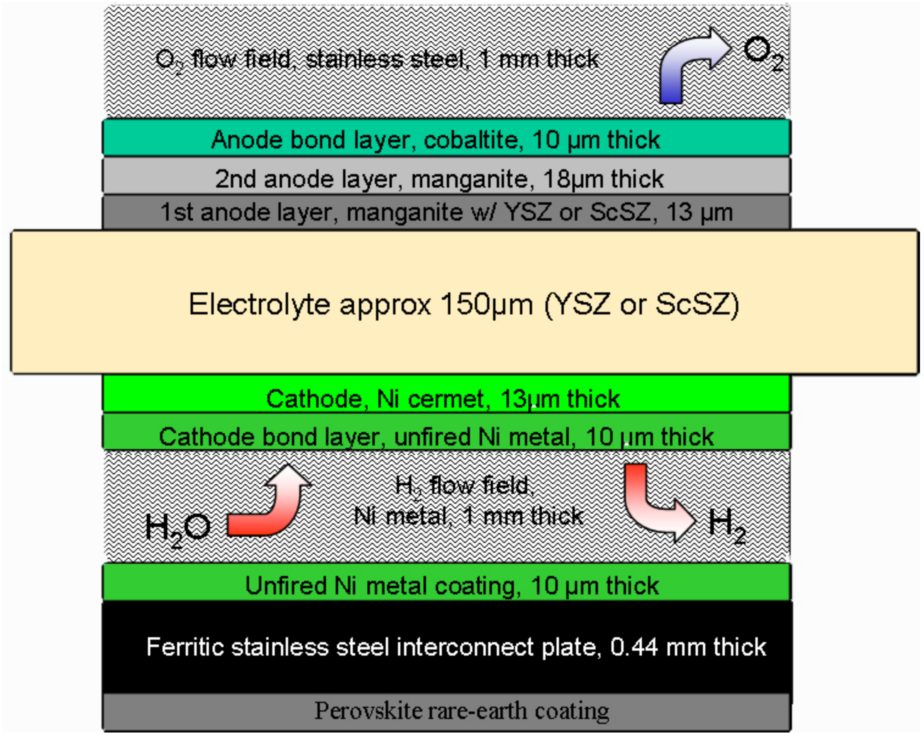


Technology Description -- HTE Leverages Fuel Cell Technology

Layers in a typical electrode-supported cell



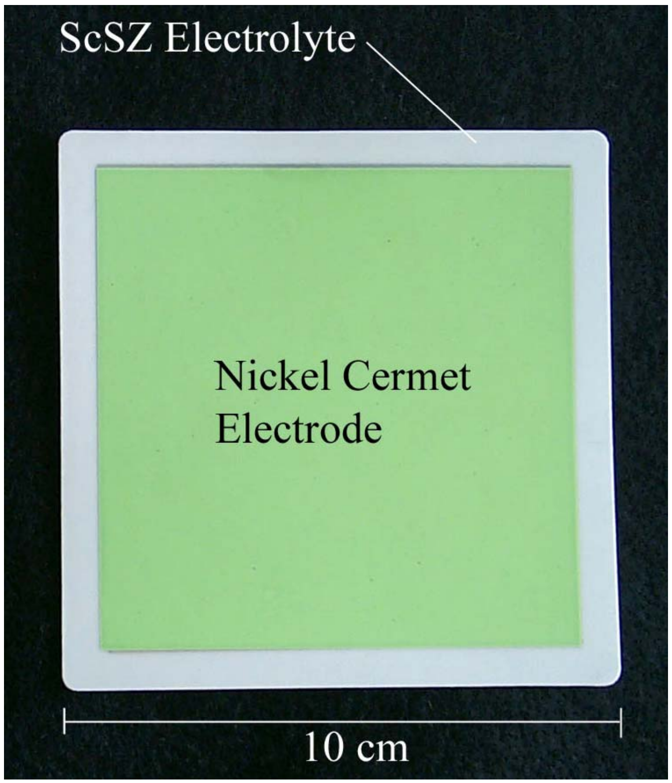
SOEC stack repeat unit



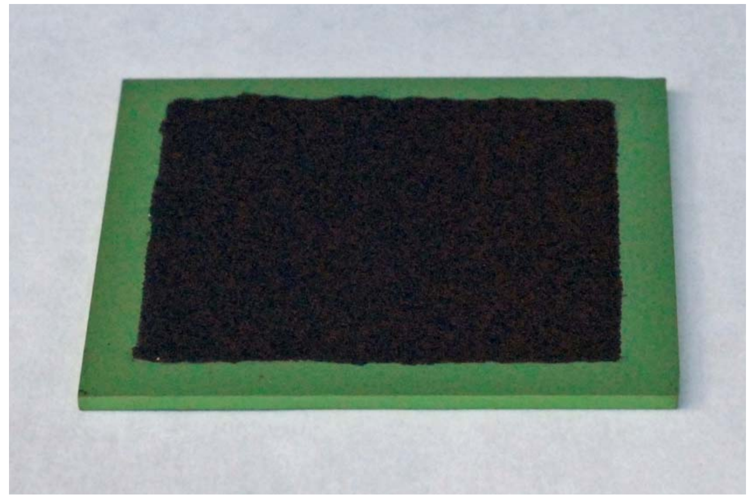
Technology Description

Planar cell types

Tape-cast electrolyte - supported cell with screen-printed electrodes



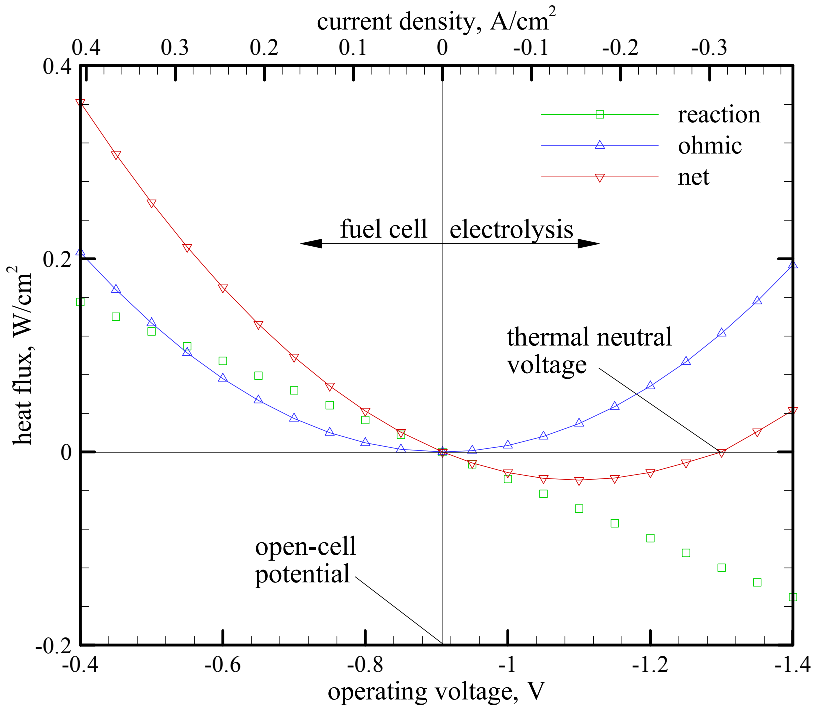
Anode (SOFC) - supported cell, with screen-printed cathode



Typical Layer thicknesses (µm)	Electrolyte-Supported Cell	Anode-Supported (SOFC) Cell
Air/O_2 electrode	40	90
electrolyte	160	10
H_2O/H_2 Electrode	30	1500

Fuel cell mode vs Electrolysis mode – fundamental differences

Energy Budgets in Fuel Cell and Electrolysis Modes



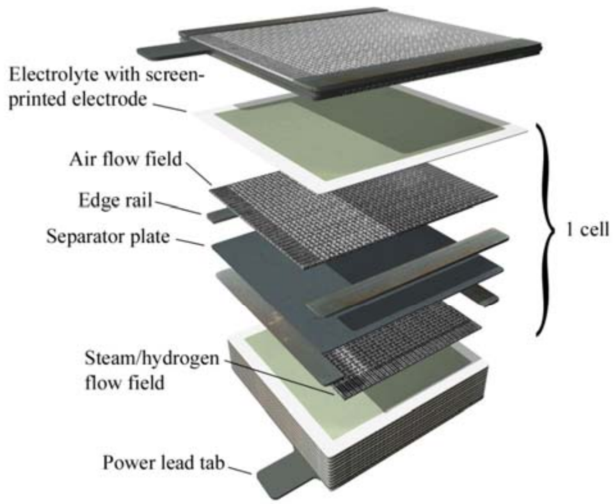
Stack ASR = 1.25,
T = 927 C,
$y_{H2,i} = 0.1$,
$y_{H2,o} = 0.95$

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

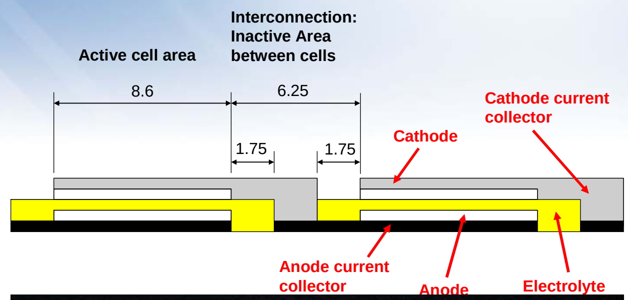
(1.291 V at 1200 K)

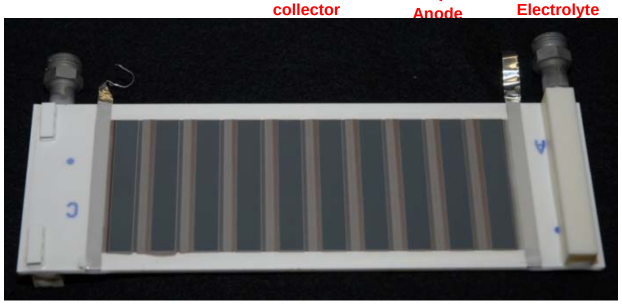
- Direction of mass fluxes
- Heat requirement / rejection
  - We like to operate SOEC near V_{TN}
    - Balance between efficiency, H_2 production rate, and thermal stresses
    - More uniform cell and stack temperature
  - SOEC seals more challenging
    - Higher back pressure on seals due to product collection
    - H_2 diffusion
  - SOEC more corrosive
    - Higher steam content (cathode side)
    - High O_2 content (anode side)
- Performance degradation / lifetime is worse in electrolysis than in fuel cell mode

Stack Designs Studied By INL

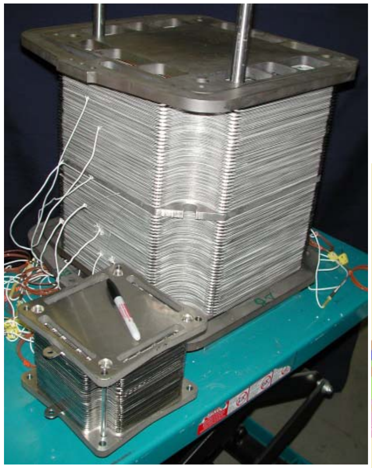


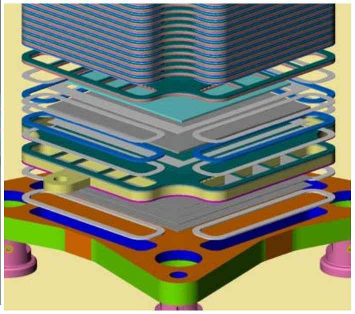
Externally manifolded planar stack, electrolyte-supported cells (Ceramatec)



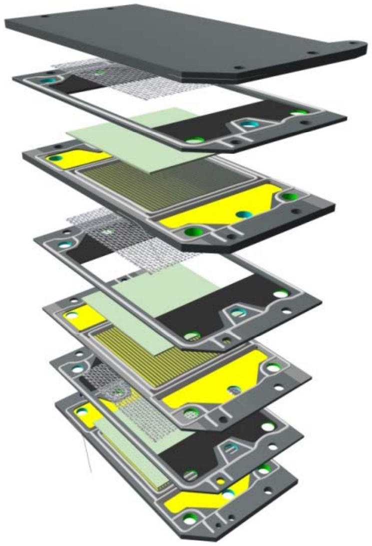


Integrated planar (segmented-in-series) stack, ceramic substrate-supported cells (Rolls Royce)

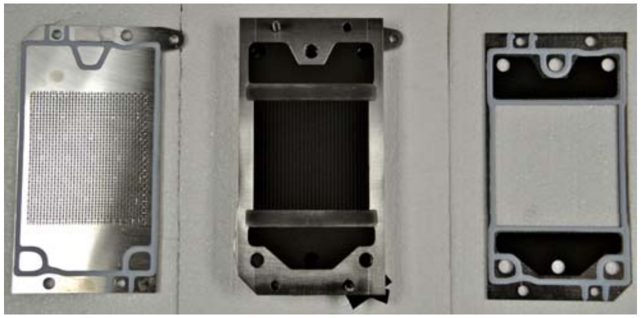




Internally manifolded cross-flow planar stack with anode-supported cells (MSRI, Versa Power)



Stack components at INL

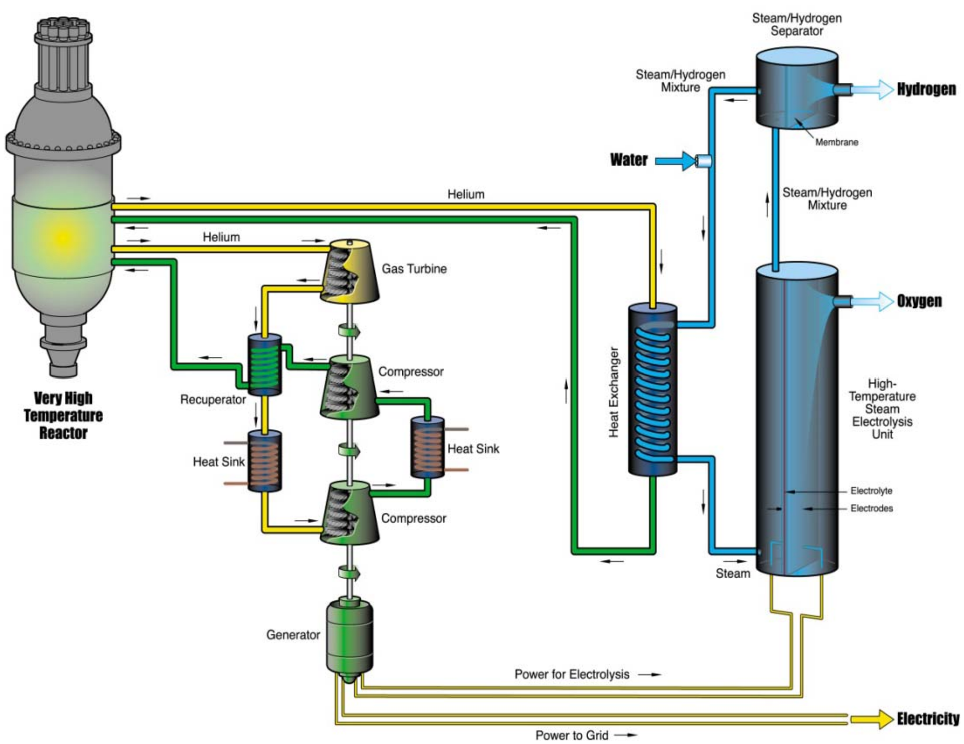


Internally manifolded counter-flow planar stack with anode-supported cells (St. Gobain/FZ Julich)

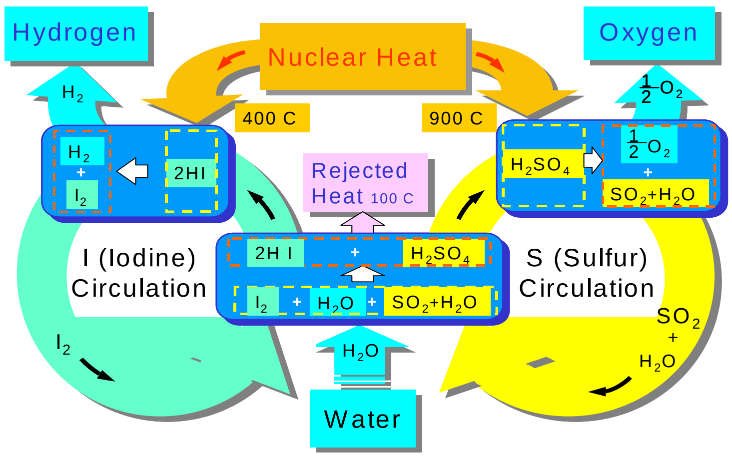
DOE Nuclear Hydrogen Initiative (NHI)

- established in 2003 to support research and development on advanced high-temperature large-scale nuclear hydrogen production methods

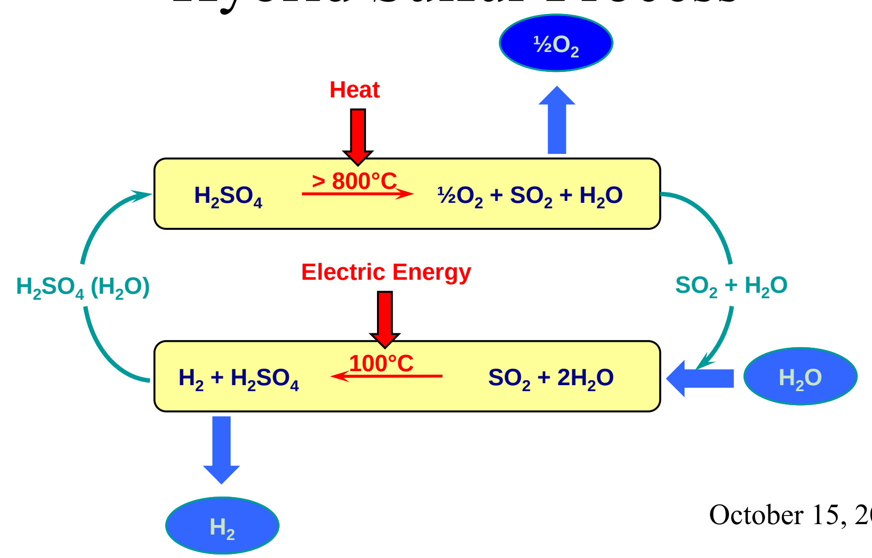
High Temperature Electrolysis



Thermochemical Sulfur Iodine Process



Hybrid Sulfur Process



INL HTSE Program History and Status

- From 2003 – 2009, INL served as the lead laboratory for High-Temperature Electrolysis (HTE) research and development, under the DOE Nuclear Hydrogen Initiative (NHI)
  - Demonstrated the feasibility of HTE for efficient H_2 production, using solid oxide cells
  - Built and operated a 15 kW Integrated Laboratory Scale HTE unit (>5000 NL/hr,1080 hrs)
- In 2007, the INL HTE team was recognized with the Stoel Rives and Federal Laboratory Consortium awards for coelectrolysis work
- During FY09, HTE was selected by DOE as the primary nuclear hydrogen production technology for early deployment (based on the recommendation of an external independent review team)
- FY10-11 HTE activities are now funded under NGNP
  - Focus on performance degradation
  - INL subcontractor (VersaPower) demonstrates ~2%/1000 hours performance

INL HTE Research Scope

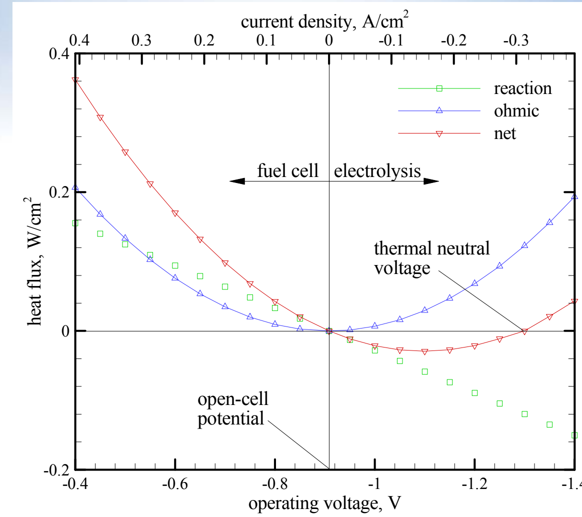
Fundamentals

Small-Scale Experiments

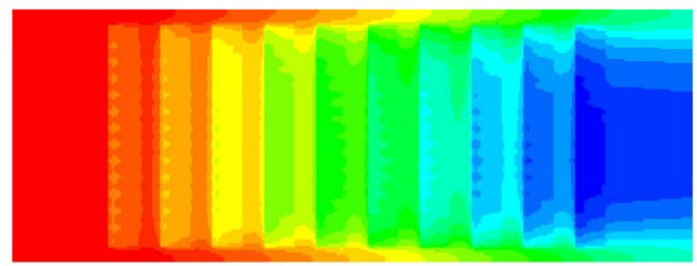
CFD Simulation

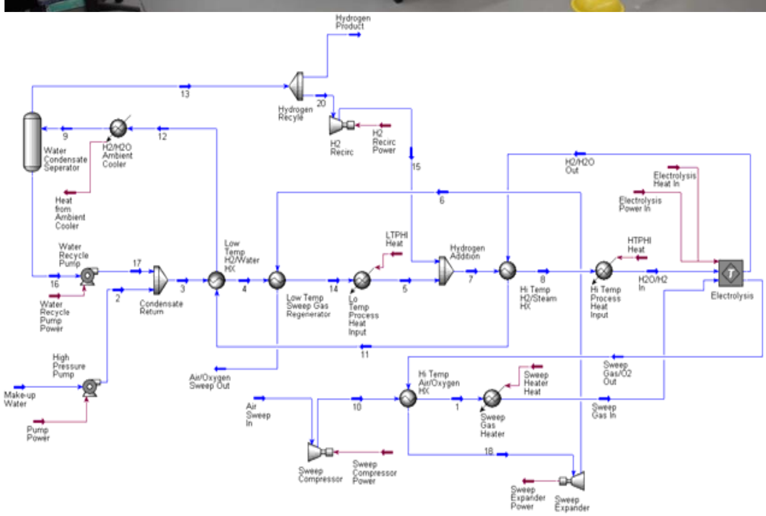
System Modeling

Technology Demonstration



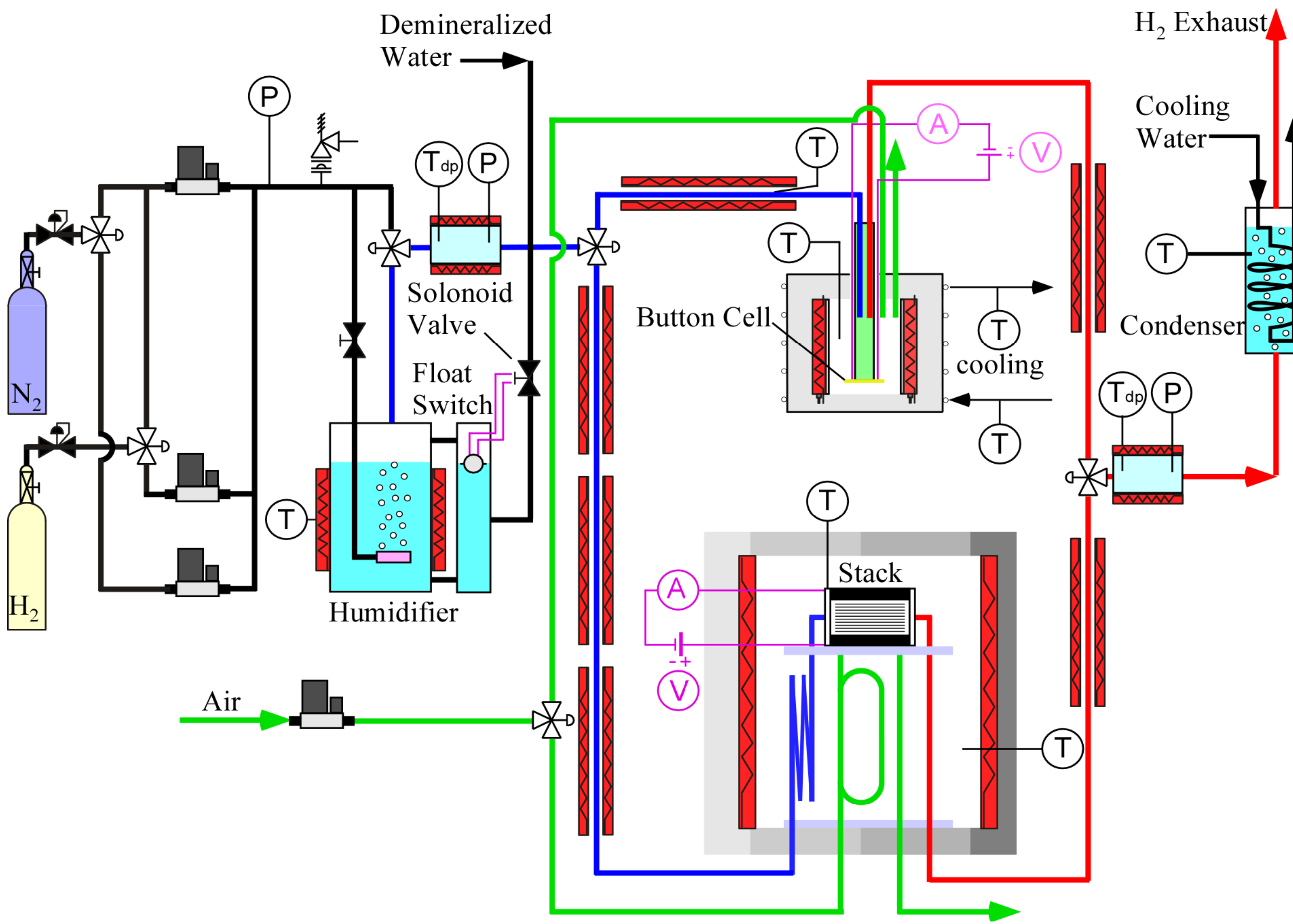
Hydrogen mole fraction, top of porous tube, FC mode



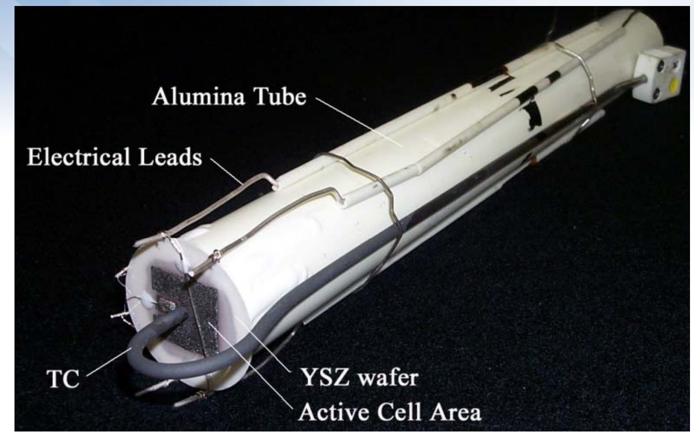


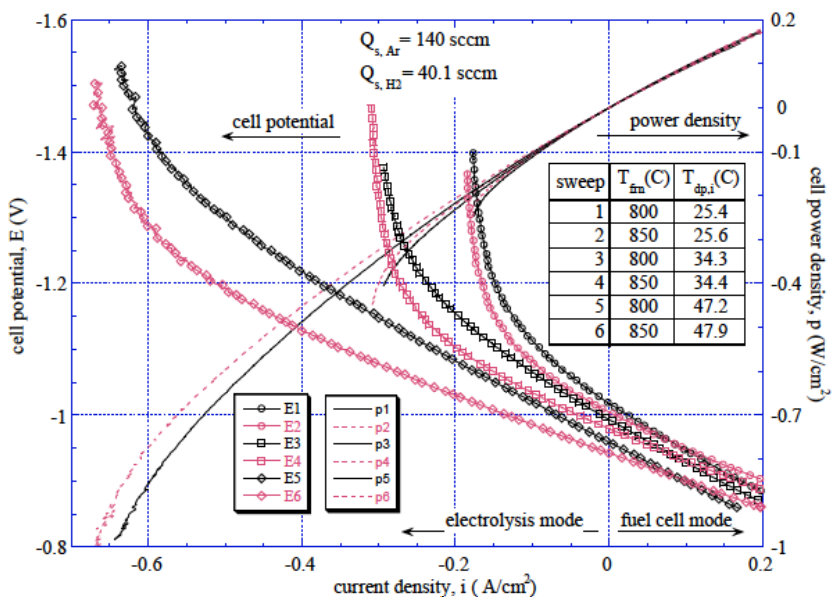
Bench Scale Testing

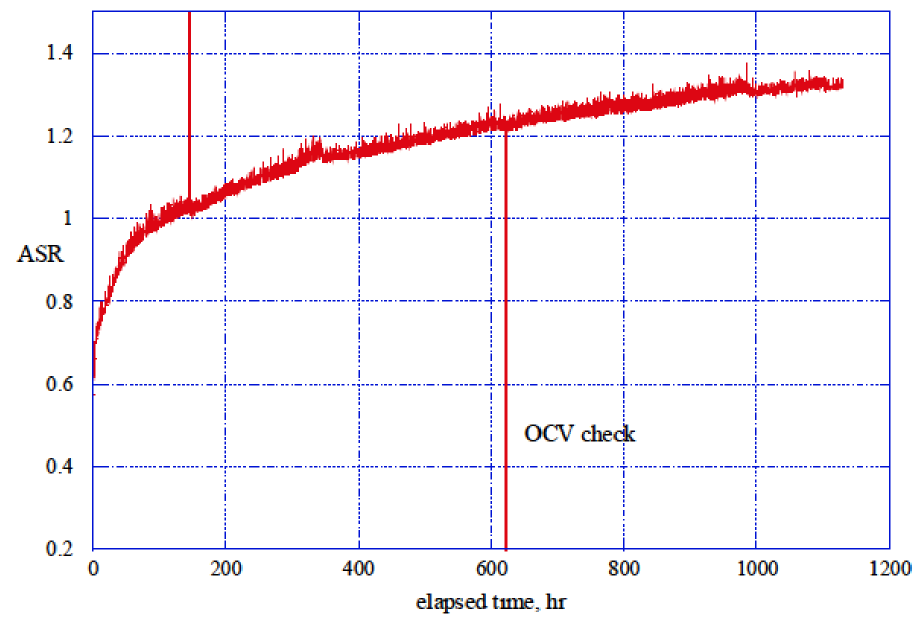
Typical INL Test Schematic



Button Cell Tests



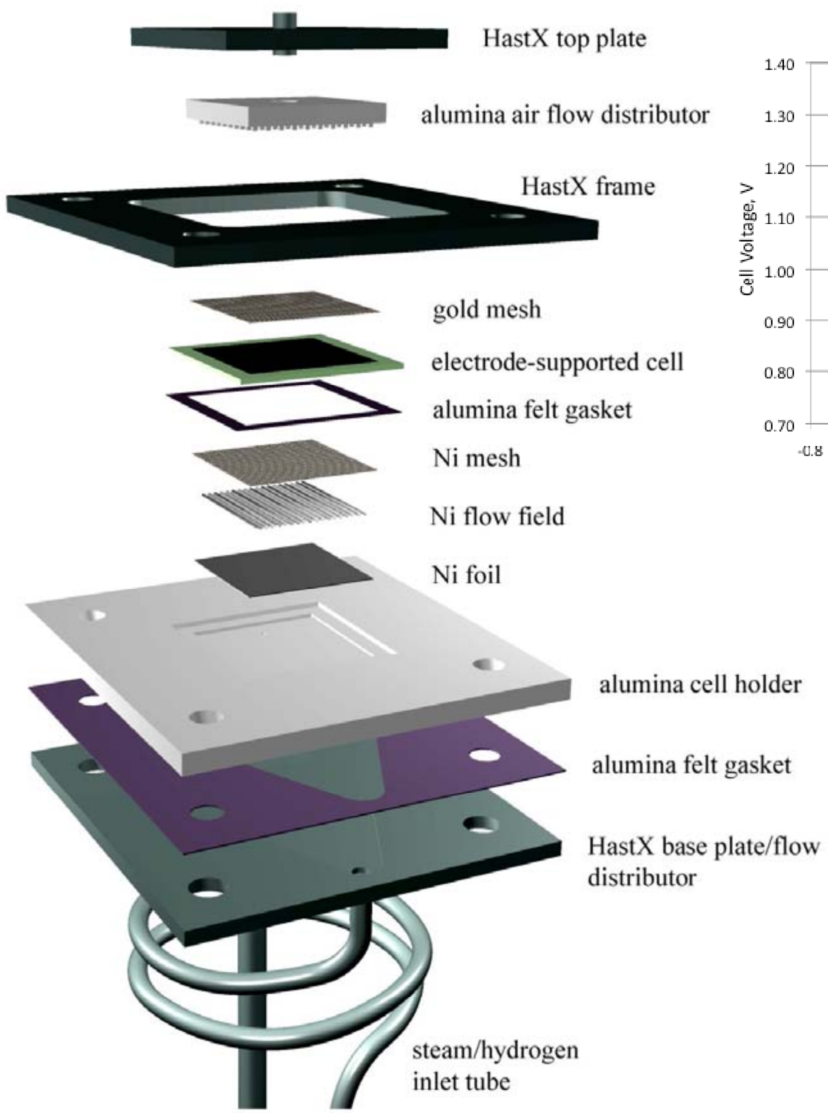




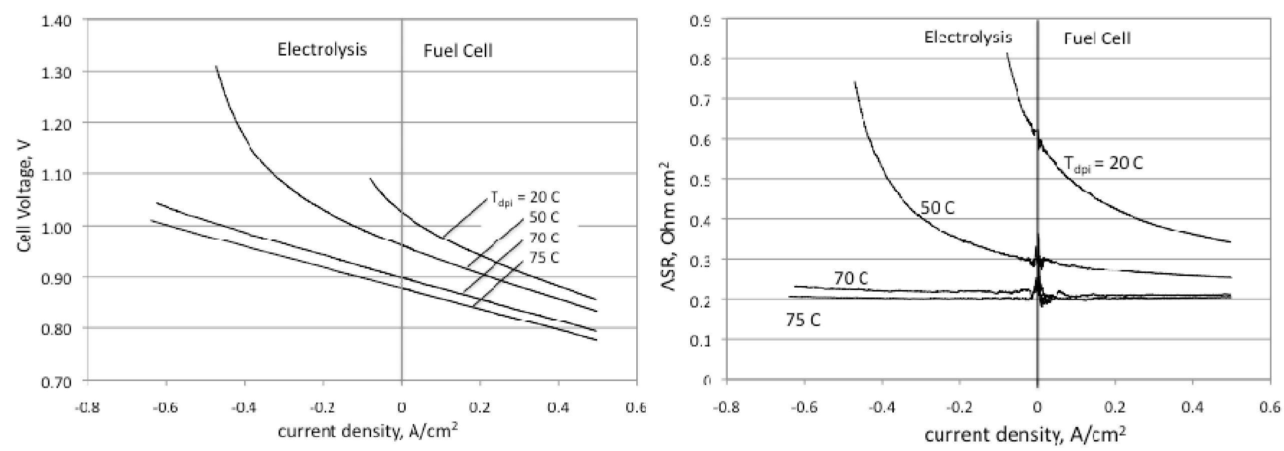
- Button cells typically used to characterize performance of new cell materials
- Button cells are an idealized test geometry
  - Fuel flow impinges upon cell surface
  - Cells do not include interconnects

SOEC performance characterization – small scale tests

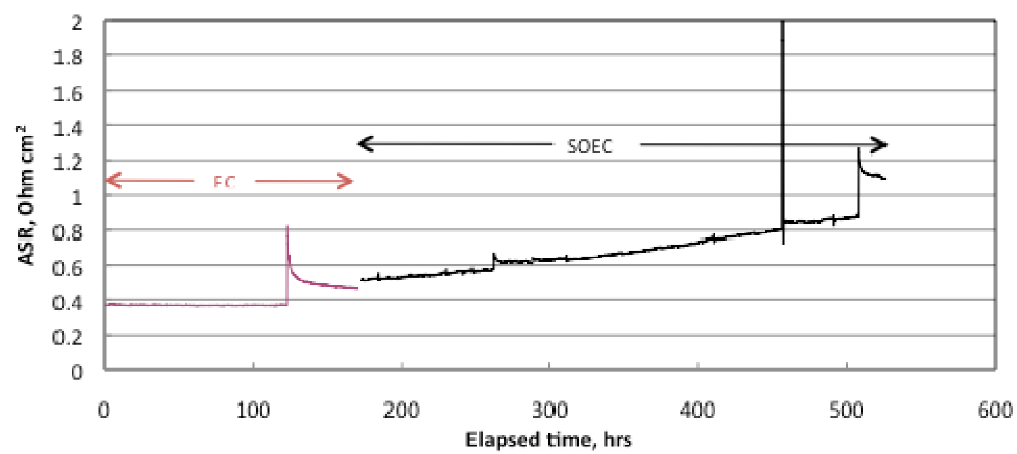
Single-cell test apparatus



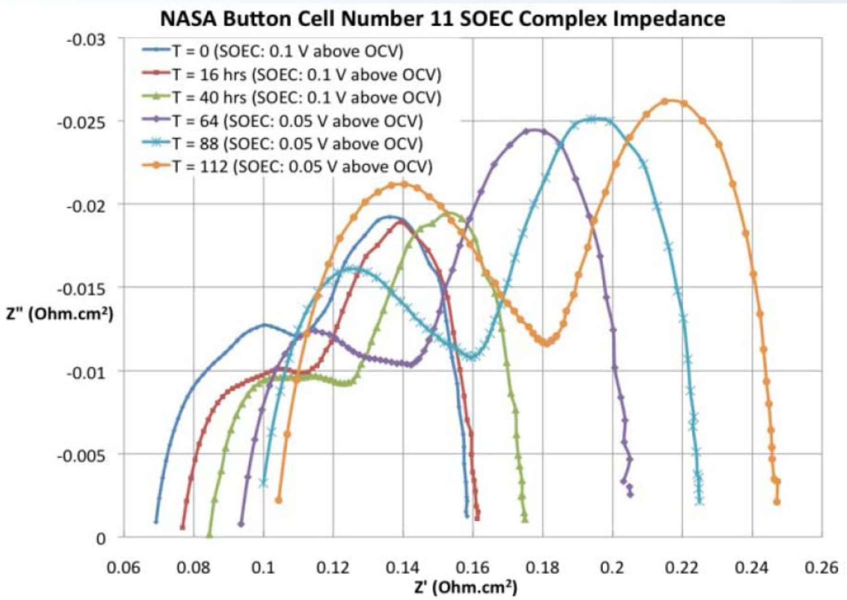
Initial polarization curves – electrode-supported cells, effect of steam content



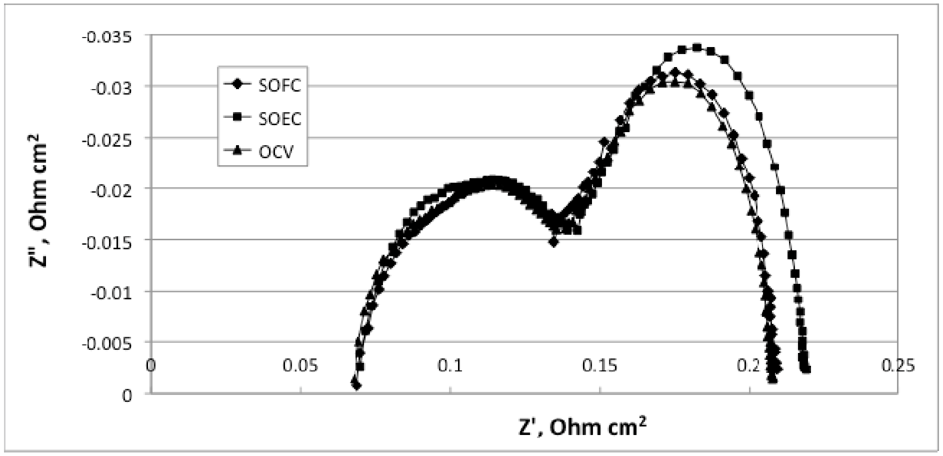
Degradation accelerates in the SOEC mode



Fuel Cell & EIS Characterization

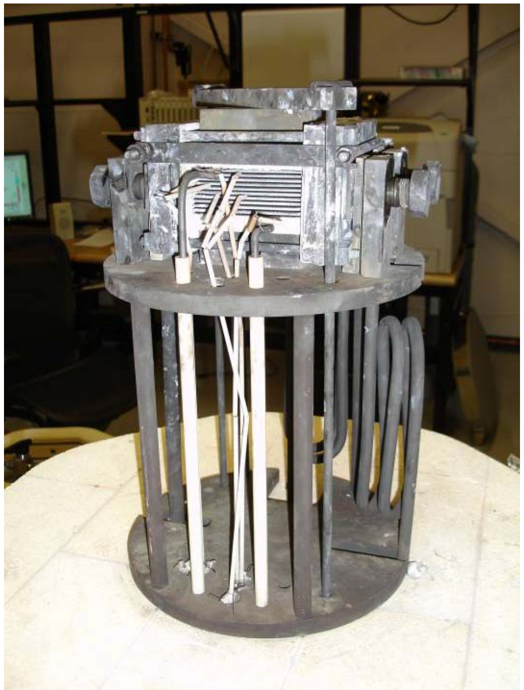


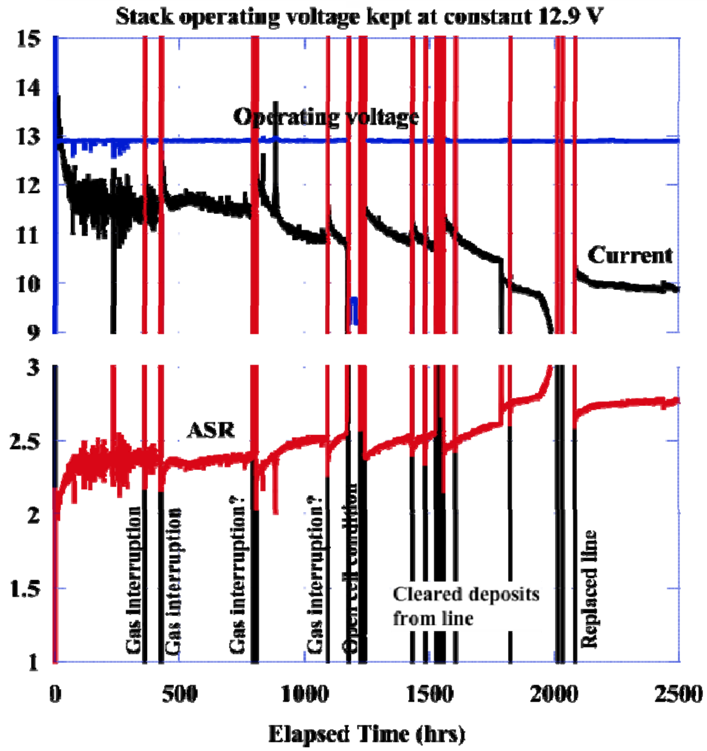
Impedance Spectra, single electrode-supported cell



EIS measurements can provide insight into the relative contributions of various polarization and degradation mechanisms

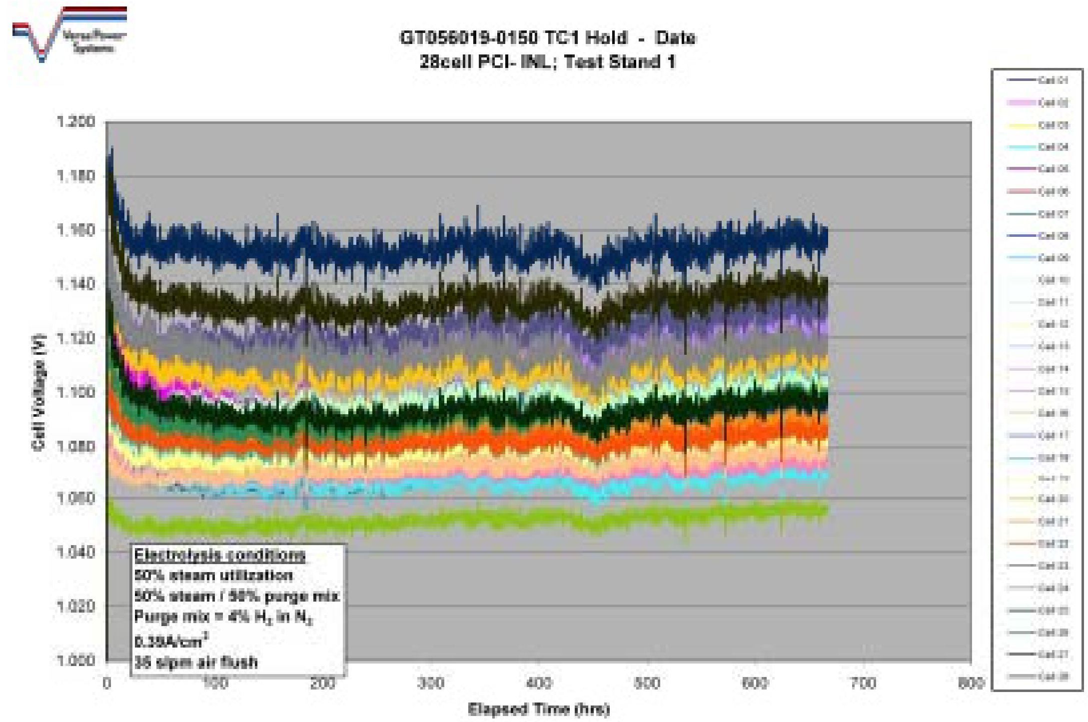
10-Cell Stack 2500 Hours Results





- Many test disruptions
- Average degradation rate <8%/1000 hours
- Experiment linked to separate methanation experiment
    - Electrolysis hydrogen product used to produce methane

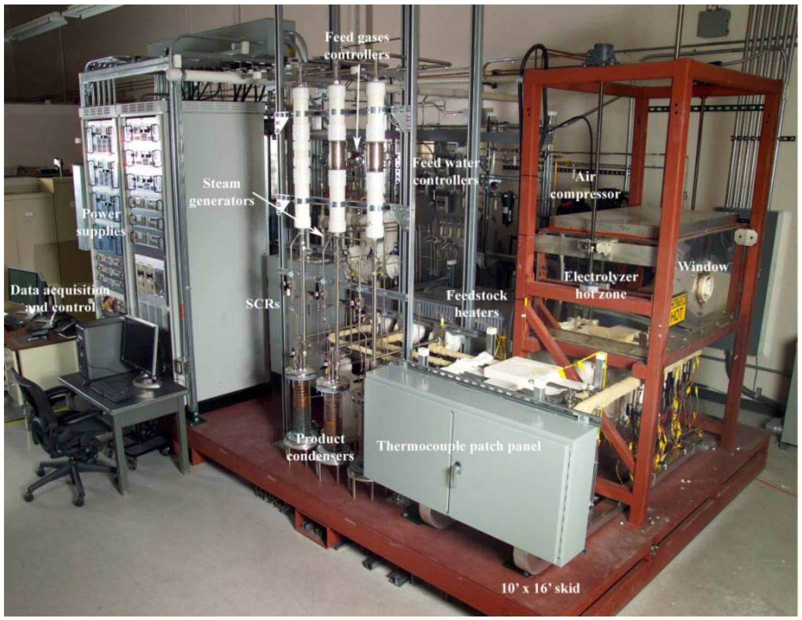
VersaPower 28 Cell Electrolysis Test

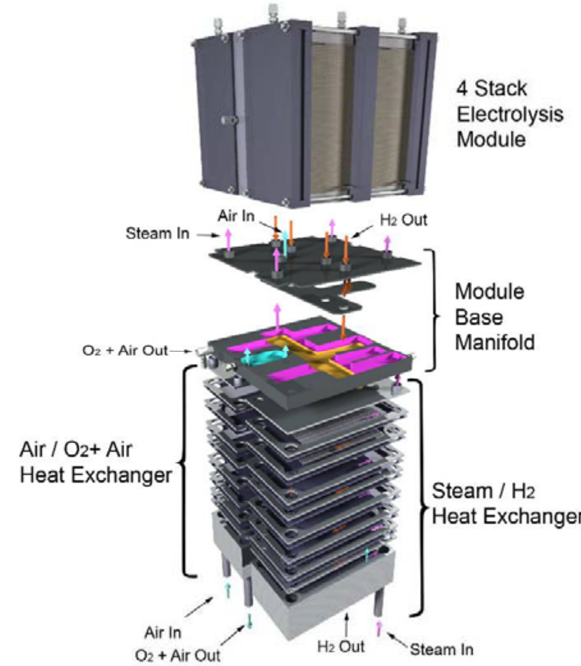


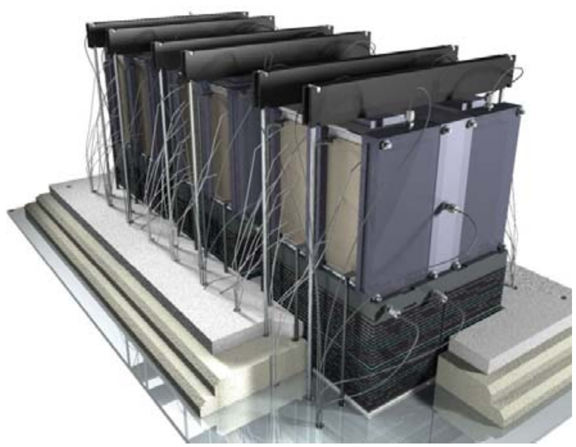
- Under subcontract to INL
- 1.4 kWe stack
- 660 hours test time to date
- Equivalent degradation rate 0.9%/1000 hours
- Earlier electrolysis stack tests demonstrated 3.8%/khr and 1.5%/khr

Large scale SOEC demonstration:
15 kW Integrated Laboratory Scale test facility at INL

- Initial hydrogen production rate > 5000 NL/hr
- Demonstrated heat recuperation and hydrogen recycle

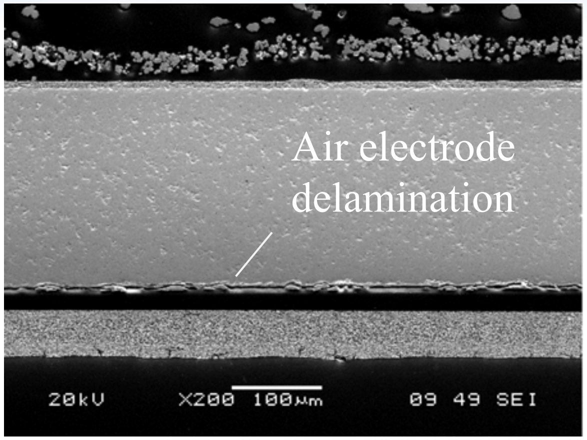




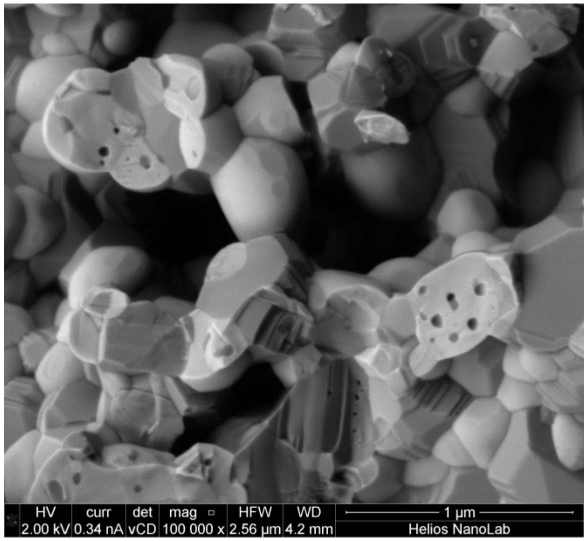


SOEC Performance Degradation

- Possible degradation mechanisms include:
  - chromium migration
  - corrosion of metallic components
  - morphology change (coarsening) in electrochemically active layers
  - electrode delamination…
- No accepted definition as to how it is measured
  - When does long duration test really start?
  - Skip cell conditioning phase?
- Degradation is worse in electrolytic mode of operation (vs FC mode)
- In general, Single Cells outperform Single Repeat Units
- Single Repeat Units outperform Stacks
- In general, cell performance is not 100% repeatable
  - Cell-to-cell variations in construction
- Materials of construction, BOP, test conditions, test disruptions all affect degradation
- Bottom line is H_2 production cost ($ / kg), not efficiency or degradation



Initial H_2 electrode microstructure



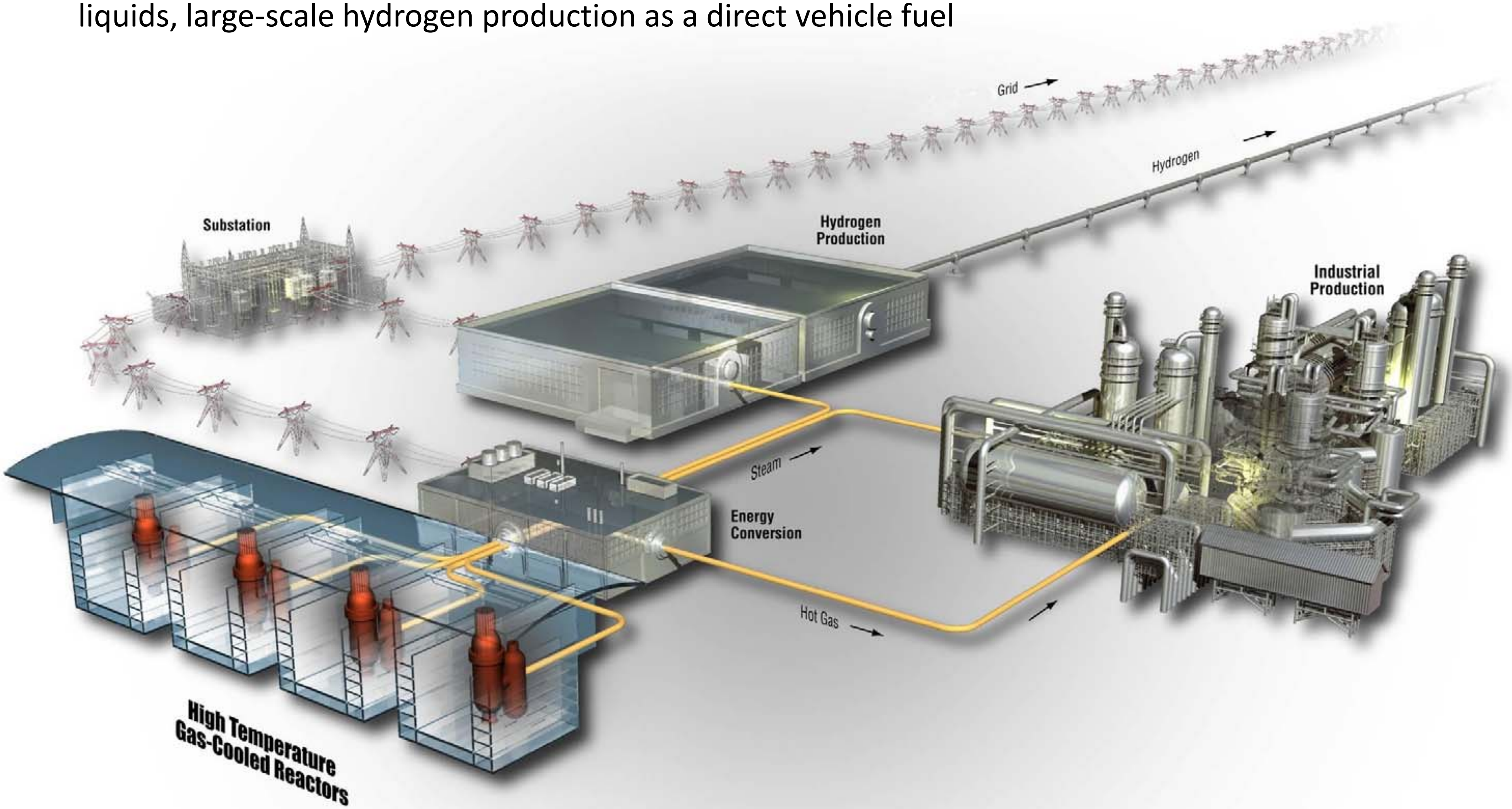
INL HTE Technology Path Forward

- Continue to improve initial performance and durability of HTE cells
- Promote development of larger format cells
- Development concepts of HTE and coelectrolysis linked to nuclear and renewable energy sources
- Demonstrate high pressure operation of HTE
- Pilot scale demonstration (200 kW?)

Deployment Strategies

Large-Scale Centralized Nuclear Hydrogen Production

- directly coupled to an advanced high-temperature reactor
- 600 MWth reactor could produce ~85 million SCFD (similar to a large SMR plant)
- potential applications include petroleum refining, ammonia production, biomass or coal-to-liquids, large-scale hydrogen production as a direct vehicle fuel



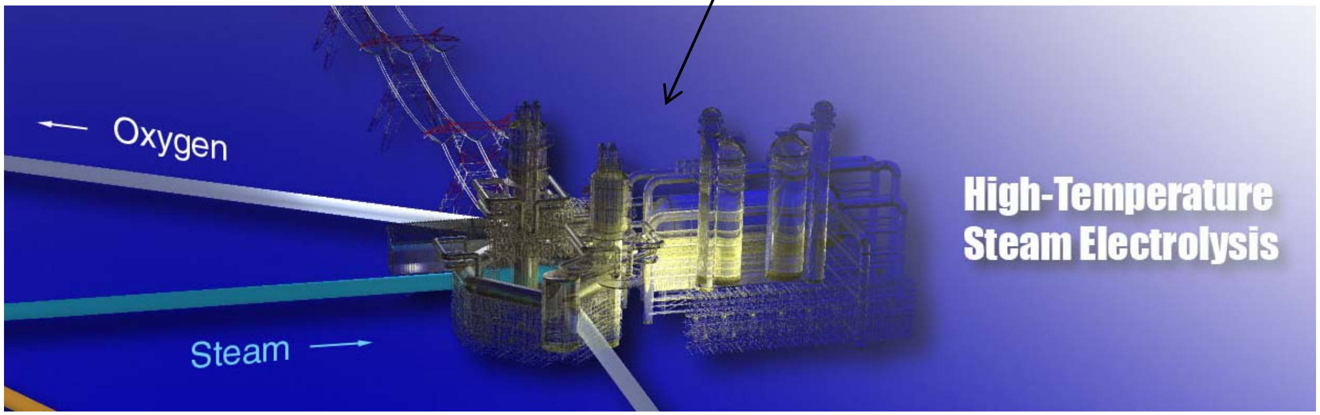
Deployment Strategies

Distributed Hydrogen Production

- powered by grid electricity, with supplemental heat requirement
- can be employed for load leveling, producing H_2 (and O2) during low-cost off-peak time periods

Grid Power

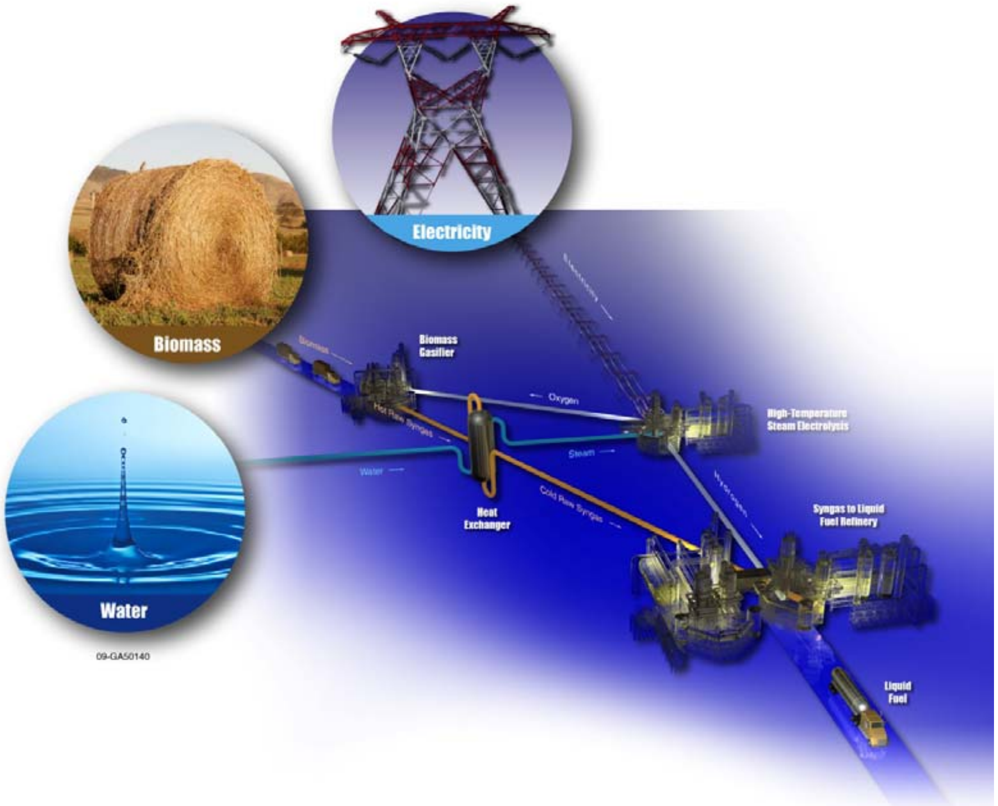
Supplemental High Temperature Heat
(e.g. natural gas-fired)

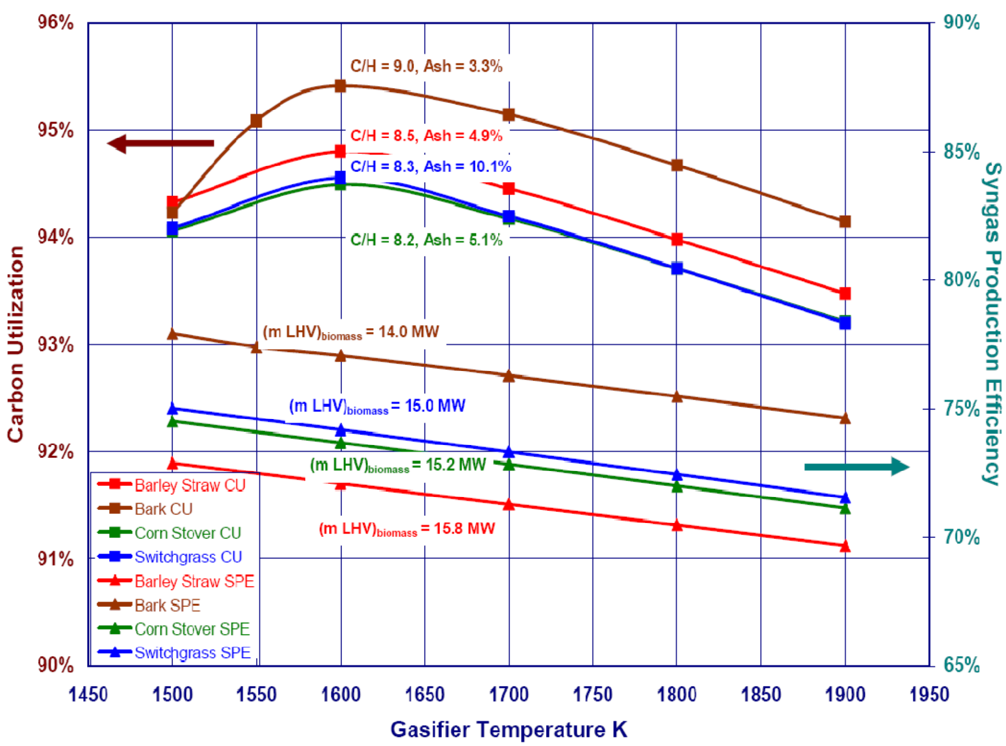


Hydrogen

Deployment Strategies

Distributed Biomass-to-Liquids Concept





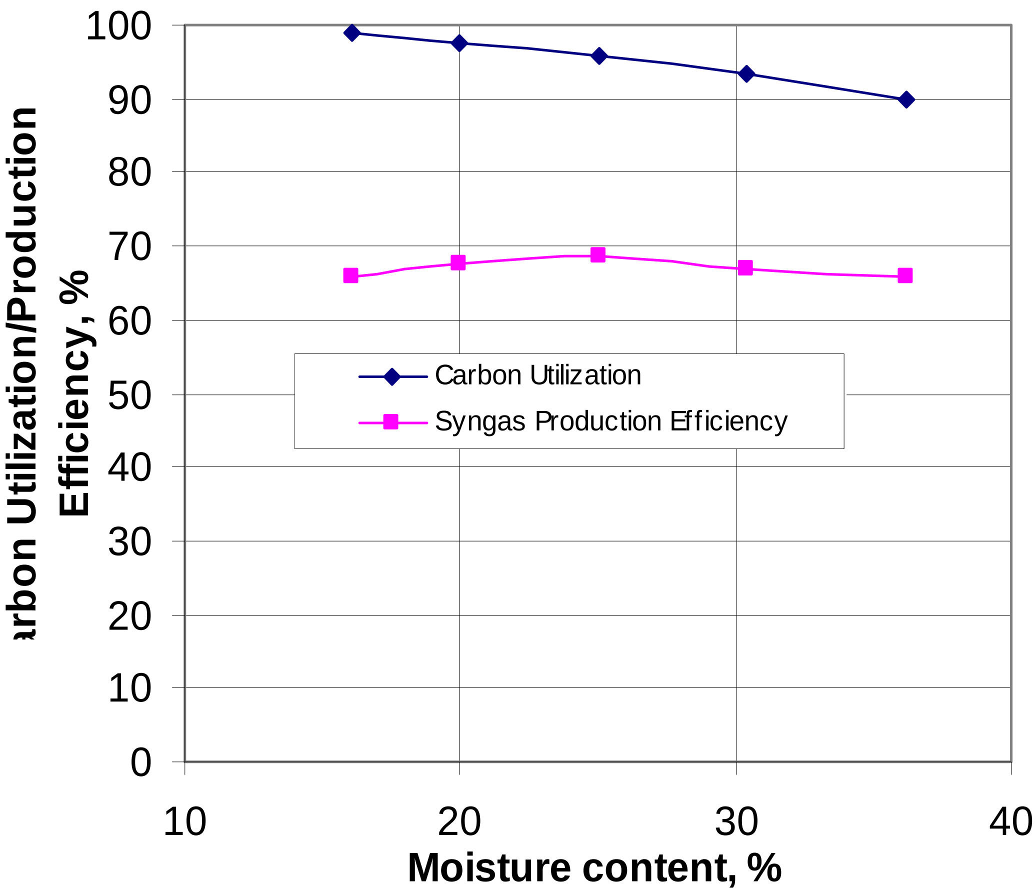
- powered by grid electricity
- HTE produces supplemental H_2 to maximize carbon utilization, plus O_2 for the gasifier
- high temperature process heat for HTE supplied by the gasifier

Carbon utilization and syngas production efficiency for various biomass feedstocks as a function of gasifier temperature

Deployment Strategies

Nuclear Assisted Coal to Liquids

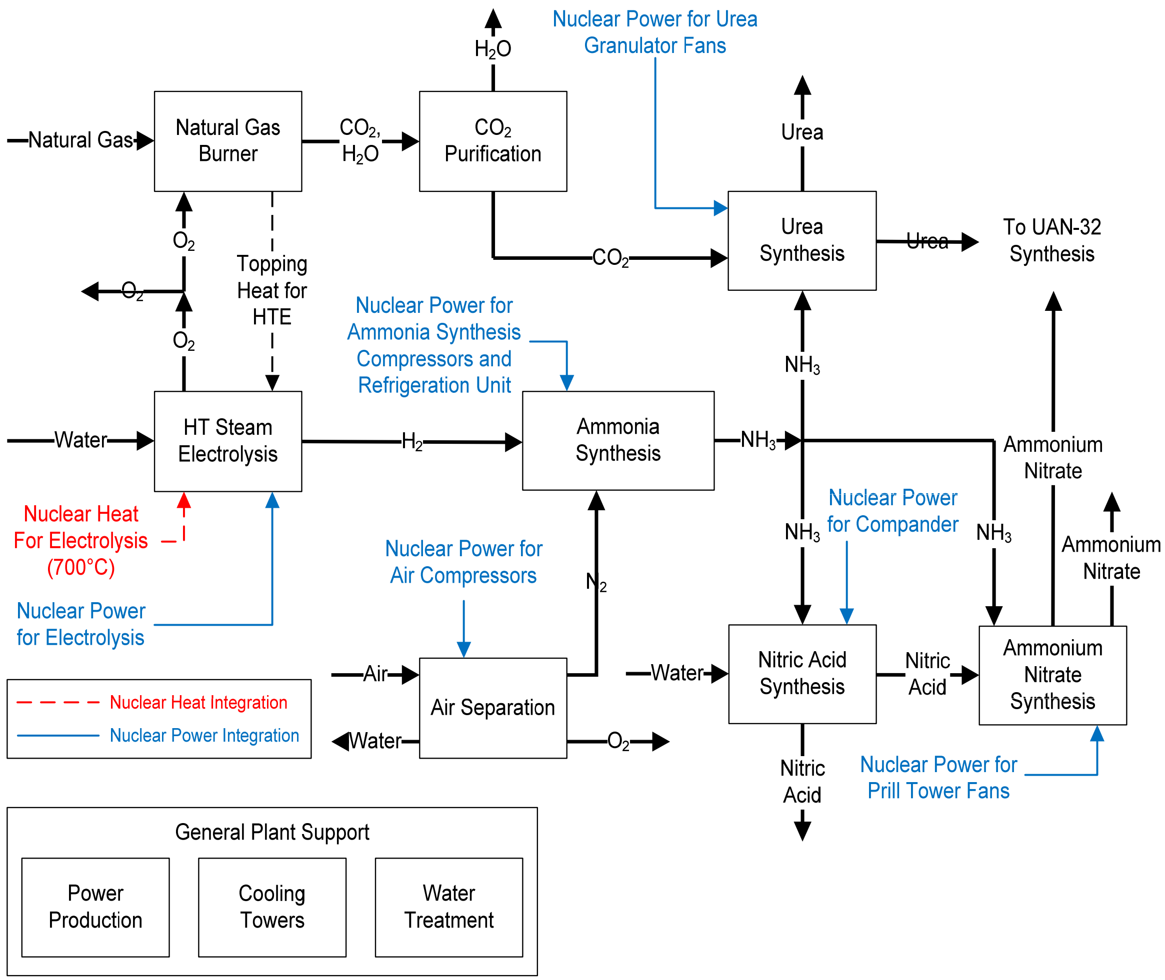
Carbon utilization and syngas production efficiency for CTL as a function of coal moisture content



Note: Traditional coal-to-liquids technology results in only 1/3 of the carbon in the coal ending up in the liquid fuel. With nuclear-assisted (H2 + process heat) coal-to-liquids, almost all of the carbon in the coal can end up in the synthetic liquid fuel! Similar benefits for biomass conversion…

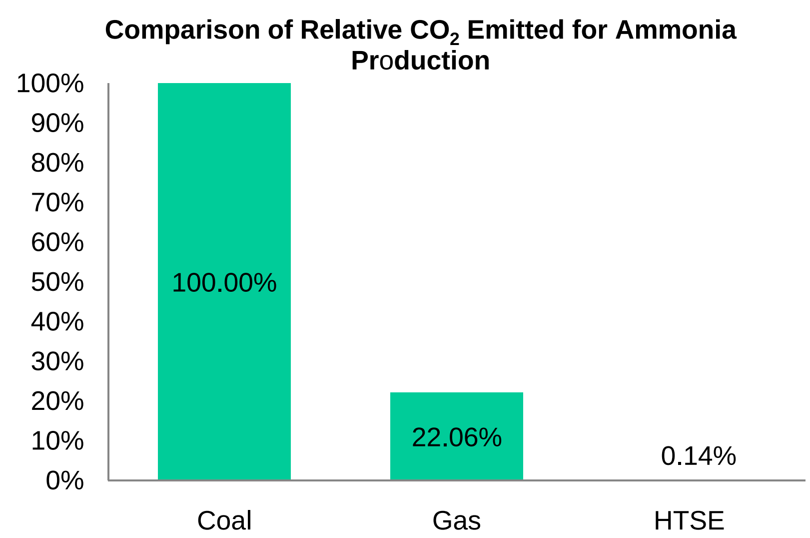
Also: the O_2 can be used in the gasifier!

Ammonia Production using HSTE and Nuclear Heat & Power

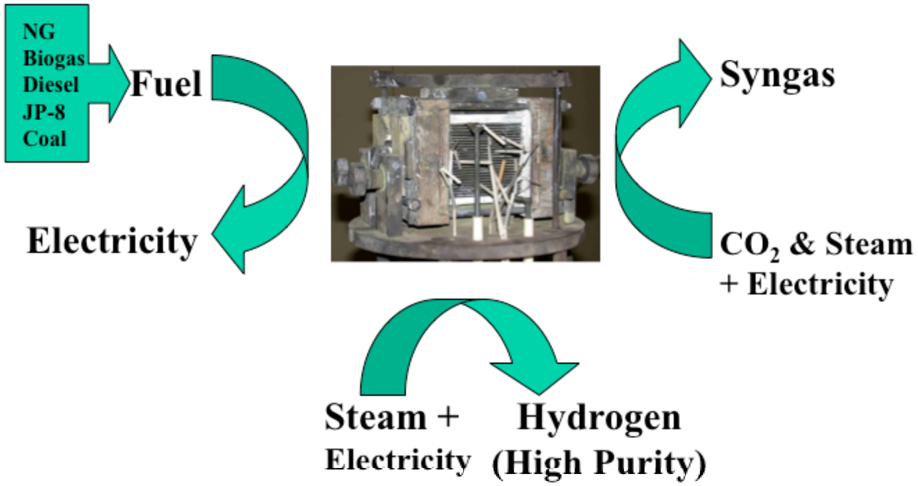


For 3,000 tons/day of urea with 3,800 tons/day of ammonium nitrate production:

- Conventional coal produces 8,000 tons/day of CO_2 using 4,600 tons/day of coal
- Conventional gas produces 1,760 tons/day of CO_2 using 88 MMSCFD of natural gas
- HTSE produces 11 tons/day of CO_2 using 77 MMSCFD of natural gas



Extended Application of HTE
One Technology, Multiple Modes of Operation



Coelectrolysis of H_2O and CO_2 for Direct Production of Syngas

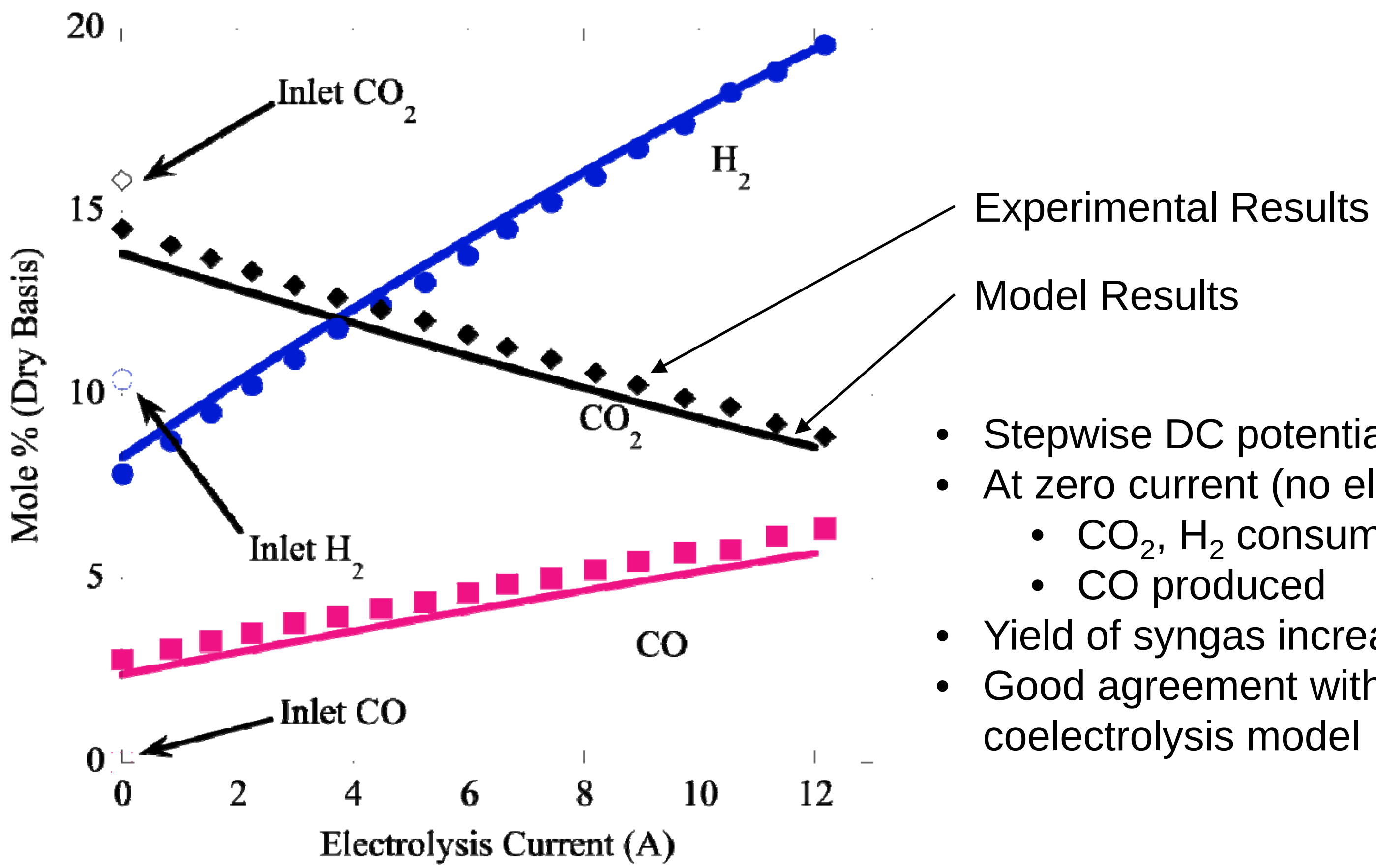
electrical power + heat

$$\underbrace{H_2O + CO_2 \rightarrow H_2 + CO}_{\text{cathode side}} + \underbrace{O_2}_{\text{anode side}}$$

Coelectrolysis chemistry is complicated by the Reverse Shift Reaction (RSR)

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

Typical Coelectrolysis Stack Results



- Stepwise DC potential sweeps
- At zero current (no electrolysis)
  - CO_2, H_2 consumed
  - CO produced

  } Reverse shift reaction
- Yield of syngas increased linearly with current
- Good agreement with INL-developed coelectrolysis model

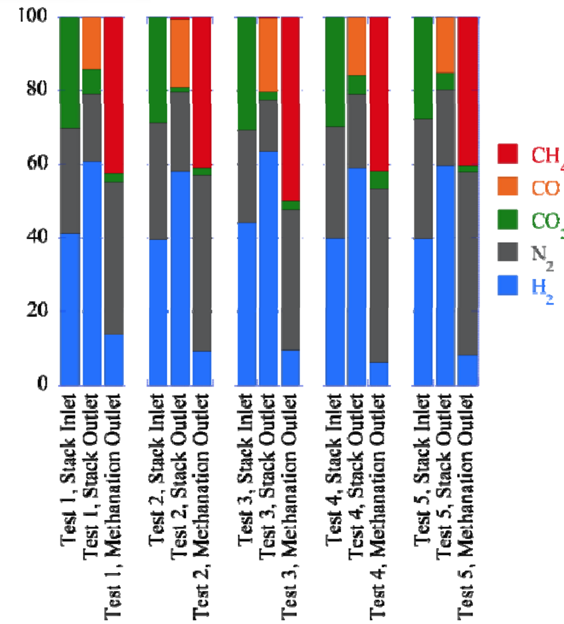
Extensions of Coelectrolysis

Methanation of coelectrolysis products

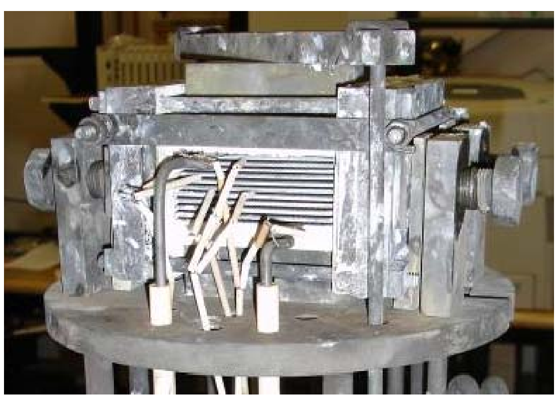
Electrolysis cell
- •Water splitting $4H_2O \rightarrow 4H_2 + 2O_2$
- •RSR $CO_2 + H_2 \rightarrow CO + H_2O$

Tubular reactor
Ni catalyst
- •Methanation $CO + 3H_2 \rightarrow CH_4 + H_2O$

- •Net Reaction $CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$
- •Tests performed by Ceramatec for INL



INL studying hybrid energy systems
- Linked electrolysis / co-electrolysis to natural gas, methanol, and DME production



+

= Synthetic Methane,
Liquid Methanol,
DME

Potential Impact

Direct use of Nuclear Energy in the Transportation Sector

- Responsible for ~40% of US oil consumption
- contribute ~ 62% of all US transportation-related GHG emissions
- contribute about 17% of all US GHG emissions

Nuclear energy can contribute **directly** to the transportation sector in a completely carbon-free manner in two ways:

1) Auxiliary power generation for electric vehicles

2) Power generation for hydrogen production

Supplemental power required to replace all US light-duty vehicles with hydrogen fuel cell vehicles

$$\overset{(1)}{2.68 \times 10^{12} \frac{miles}{yr}} \div \overset{(2)}{60 \frac{miles}{kg}} \times \left(\overset{(3)}{45.6 \frac{kW \cdot hr}{kg}} + \overset{(4)}{3.3 \frac{kW \cdot hr}{kg}} \right) \times \frac{1 yr}{8760\, hr} = 249\ GW$$

Notes

1) US light-duty vehicle miles, 2008 [US EIA].
2) In November, 2009, Toyota, Honda, and Nissan participated in a 706-mile demonstration run of their prototype FCVs in Japan, achieving an average 73.6 miles/kg. Based on these tests, an assumed average FCV fuel efficiency for future production vehicles of 60 miles/kg is reasonable.
3) Energy requirement for hydrogen production using conventional electrolysis (LTE) [Norsk Hydro Fact Sheet]; this energy requirement is reduced to ~32 kW hr/kg for HTE.
4) Compression work for hydrogen to 30 MPa.

If the hydrogen production is based on HTE, this total power requirement is reduced to 180 GW

Estimates of Power Requirements for Electric/Fuel Cell Vehicles

If all light-duty vehicles had a 40-mile electric range, as much as 63% of light-duty vehicle miles could be provided by battery power alone [1, 2]

Corresponding supplemental power needed for recharging batteries:

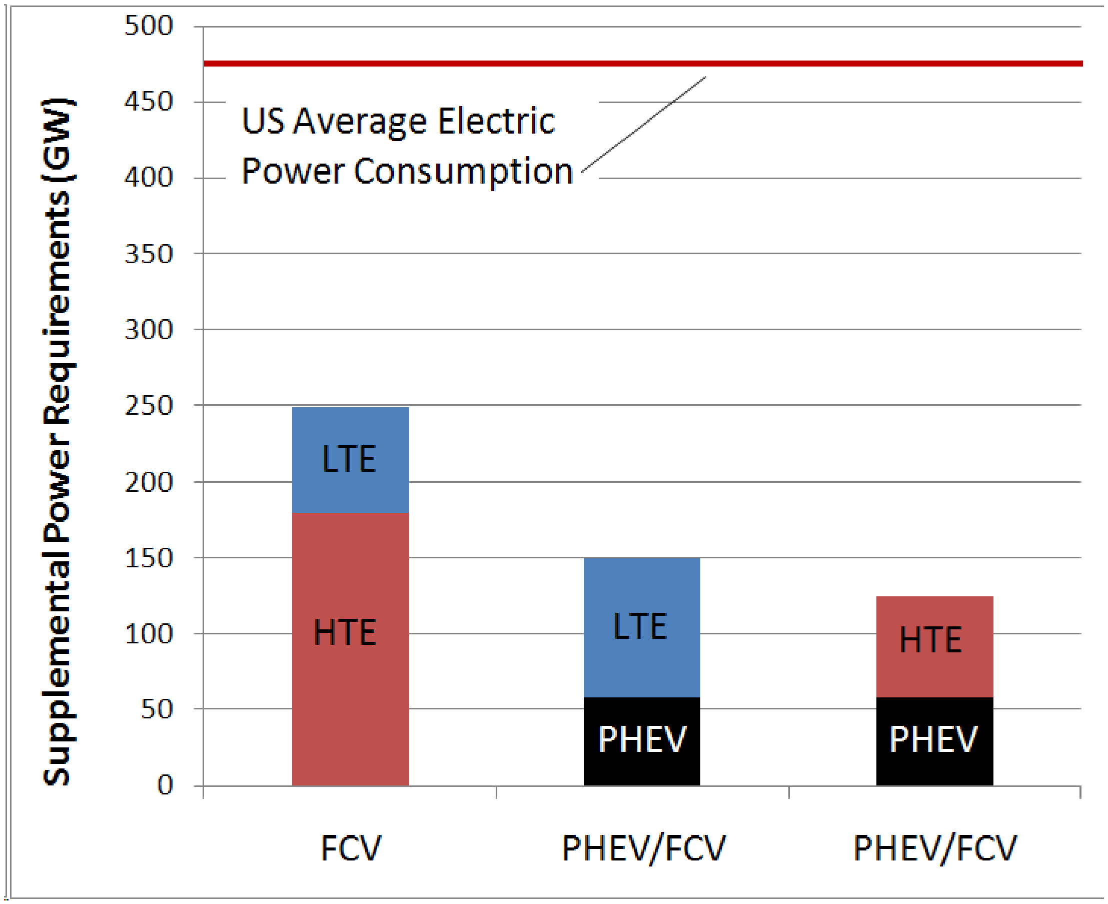
$$2.68 \times 10^{12} \frac{miles}{yr} \times 0.63 \times \frac{12\, kW \cdot hr}{40\ miles} \times \frac{1 yr}{8760\, hr} = 57.7\ GW$$

<u>Notes</u>

1) Specifications for the Chevy Volt, to be available for purchase in 2011, indicate that the pure-electric range of the vehicle will be 40 miles, with a full-recharge energy requirement of only 8 kW·hr. Here we assume a fleet average of 12 kW hr/ 40 miles
2) Supplemental power required for hydrogen production is reduced by 63%.

1. Vyas, A. and Santini, D., "Use of National Surveys for Estimating 'Full' PHEV Potential for Oil-Use Reduction," presented at PLUG-IN 2008 Conference in San Jose, CA, July 2008.
2. American Physical Society, "Energy Future: Think Efficiency, How America Can Look within to Achieve Energy Security and Reduce Global Warming," September 2008.

Supplemental power requirements for light-duty vehicles based on FCVs or PHEV/FCVs.



Total installed nameplate electrical generating capacity in US is 1088 GW (2007), so a significant percentage of the required supplemental power could be provided by increased utilization of installed capacity (of course, new nuclear or renewable capacity is preferable from the standpoint of emissions)

Comparison – Wind Power

1.5 MW Wind turbine near Idaho Falls

If this electrical power for the PHEV/FCV option were generated using wind power, 409,000 large 1.5 MW windmills (assumed capacity factor of 0.25) would be needed. These windmills would be distributed over a land area of about 45,000 square miles (70 acre footprint per windmill).

Economics

	$/kg
Conventional Electrolysis (> 1000 kg/day)[1]	4.15
Dedicated nuclear HTE plant[2]	$3.23
Off-peak grid electricity ($0.05/kW hr), HTE	$2.50
Large-scale SMR[3]	$1.50

1. Ivy, J., "Summary of Electrolytic Hydrogen Production," NREL Report NREL/MP-560-36734, September, 2004; $0.0483/kWhr electricity price
2. Harvego, E. A., McKellar, M. G., Sohal, M. S., O'Brien, J. E., and Herring, J. S., "System Evaluation and Economic Analysis of a Nuclear Reactor Powered High Temperature Electrolysis Hydrogen Production Plant," *Journal of Energy Resources Technology,* 2010.
3. directly dependent on the cost of natural gas, no carbon tax

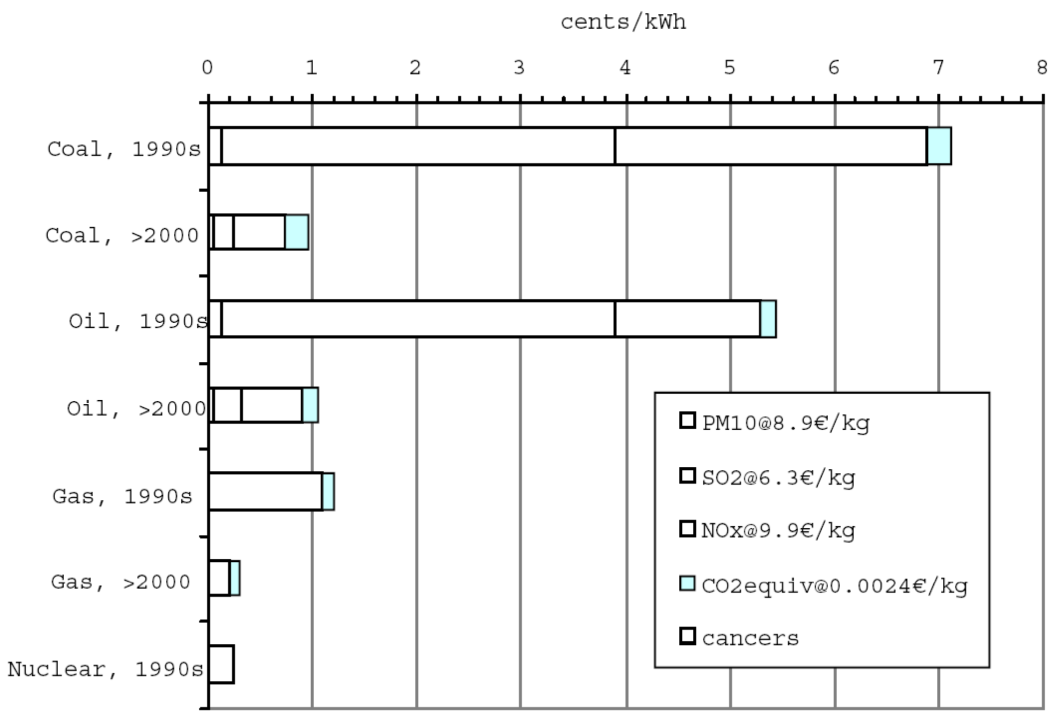
Conclusions

- Development of large-scale carbon-free methods for hydrogen production are needed to meet energy security demands, especially in the transportation sector
- INL has established itself as the world leader in demonstrating the feasibility of HTE for efficient hydrogen production from steam; degradation remains an issue, but significant improvements have been noted in recent tests
- Nuclear energy can impact the transportation sector:
  - indirectly by supplying supplemental hydrogen for upgrading petroleum and synthetic fuels
  - directly to the transportation sector through electrical power for recharging electric vehicle batteries and through hydrogen production for fuel cell vehicles
- Power requirements for new nuclear (or renewable) plants to fully fuel all US light-duty vehicles with carbon-free H_2 is not unreasonable

Thank you!

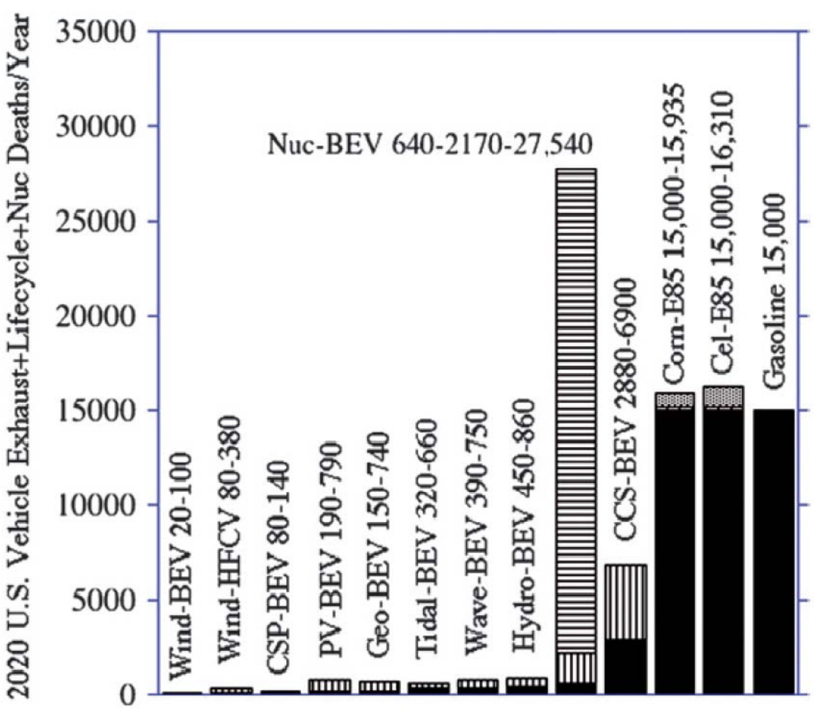
Nuclear Energy – Low Life Cycle Cost

External costs (quantified from various impacts including mortality, morbidity, effects on crops, climate change, etc.)for electric power production (ExTernE Project, EC)



Friedrich, R., Rabl, A., and Spadaro, J. V., "Quantifying the Costs of Air Pollution: the ExternE Project of the EC," *Pollution Atmospherique*, pp. 77 – 104, Dec. 2001.

Estimates of future (ca. 2020) premature deaths due to onroad vehicle air pollution associated with various potential gasoline/diesel substitutes (from Jacobsen [29]).



Jacobsen, M. Z., "Review of Solutions to Global Warming, Air Pollution, and Energy Security," *Energy and Environmental Science*, Vol. 2, pp. 148 – 173, 2009