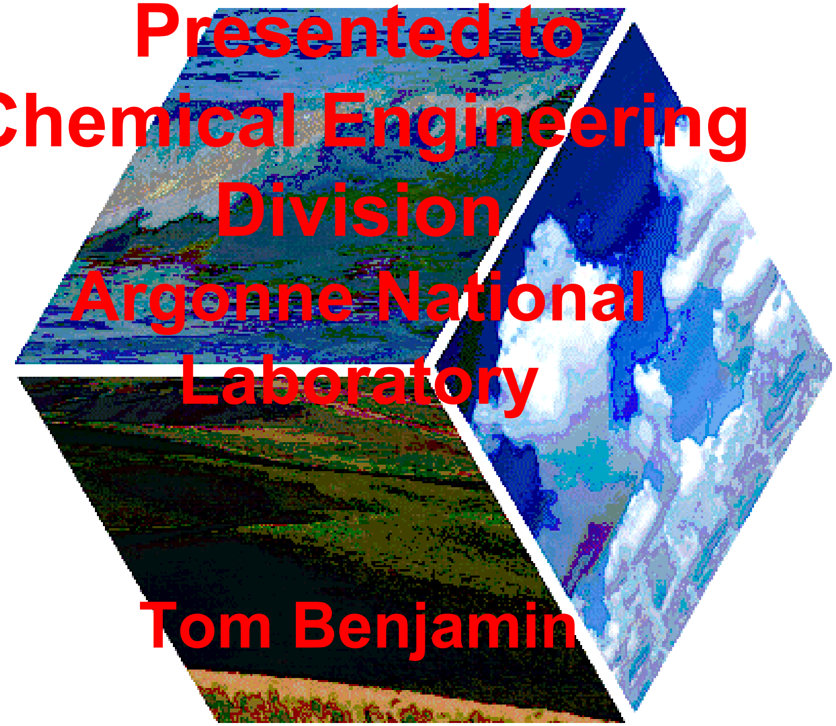
An Overview of DOE's Hydrogen, Fuel Cells, and Infrastructure Technologies Program



Presented to
Chemical Engineering Division
Argonne National Laboratory

Tom Benjamin

April 9, 2003

Outline

- **Introduction/Background**
- HFCIT Overview
- Challenges
- HFCIT Progress
- Resources

Electrochemical Projects Support Group

Purpose: Provide technical and programmatic support to the DOE Hydrogen, Fuel Cells, and Infrastructure Technologies and Advanced Battery Program Managers.

Walt Podolski
Vince Battaglia
Tom Benjamin
Brian Concannon
Carole Read
Bob Sutton
Bill Swift

DOE Fuel-Cell-Related Programs

Office of Energy Efficiency and Renewable Energy (EERE)	⟷	**Office of Fossil Energy (FE)**

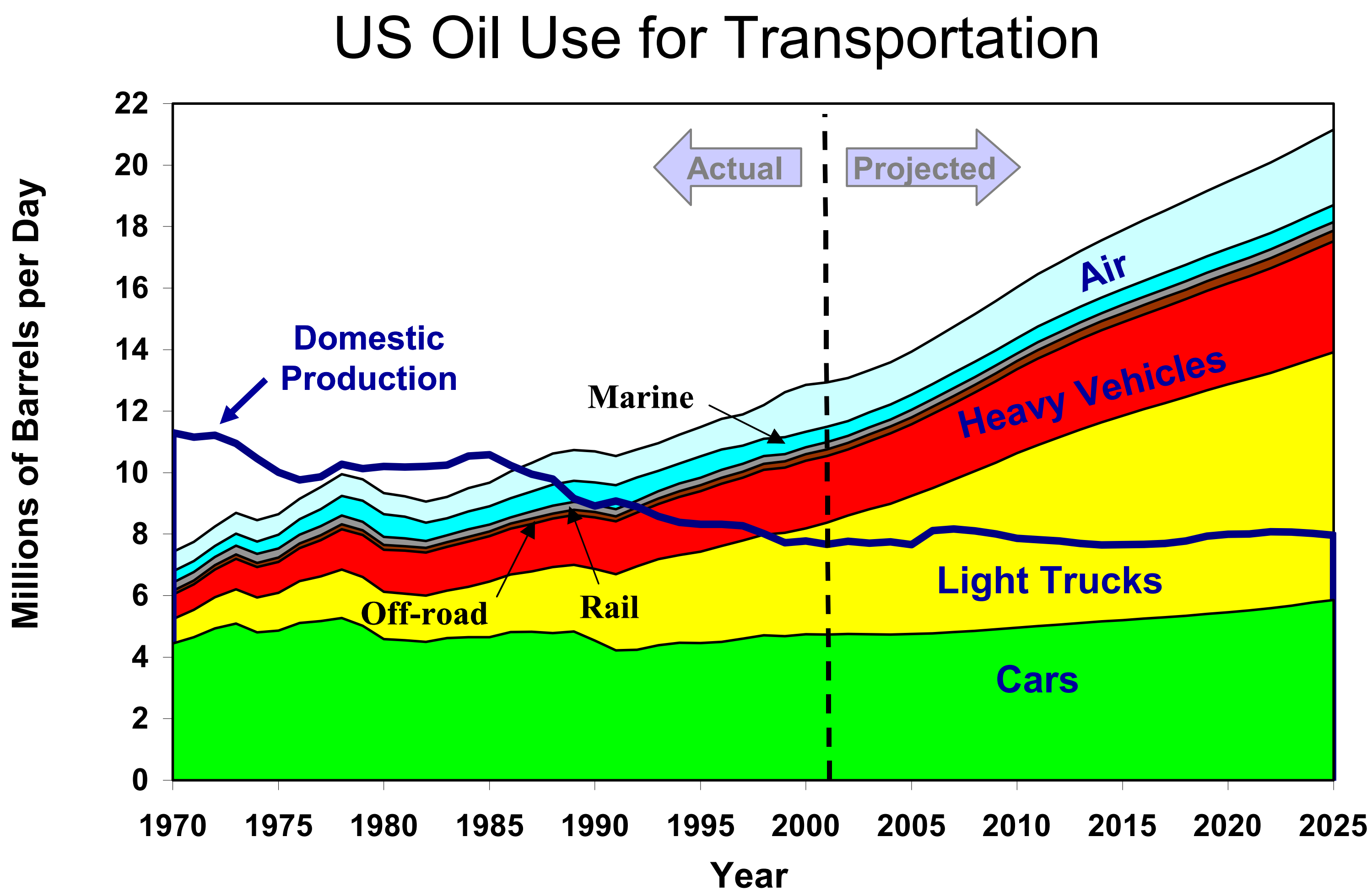
Emphasis on low temperature fuel cells

- **Transportation Applications**
- **Distributed Generation (Building Applications)**
- **Portable Power**
- **Hydrogen Technologies**

Emphasis on high temperature fuel cells

- **Large Stationary Applications**
- **Distributed Generation (Grid)**
- **Hybrid Systems**

U.S. Energy Dependence Is Driven By Transportation



Source: Transportation Energy Data Book: Edition 22, September 2002, and EIA Annual Energy Outlook 2003, January 2003

Program Evolution

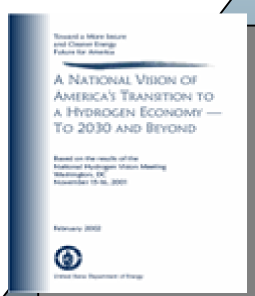
"<u>Hydrogen fuel cells</u> represent one of the most encouraging, innovative technologies of our era. …And so that's why I'm going to work with the Congress to move this nation forward on hydrogen fuel cell technologies" Feb 6

PNGV

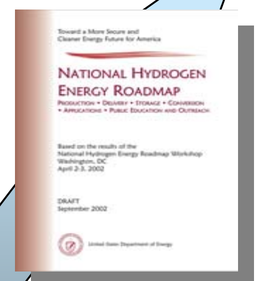
May 16, 2001

January 9, 2002
Secretary Abraham announces the FreedomCAR Partnership

FreedomCAR


A National Vision of America's Transition to a Hydrogen Economy — To 2030 and Beyond

National H_2 Vision
February 2002


National Hydrogen Energy Roadmap

National H_2 Energy Roadmap
November 2002

January 28, 2003
President Bush
FreedomCAR and Fuel Initiative
H_2


Hydrogen, Fuel Cells and Infrastructure Technologies

5-Year Research, Development & Demonstration Plan

MYPP
Summer 2003

Outline

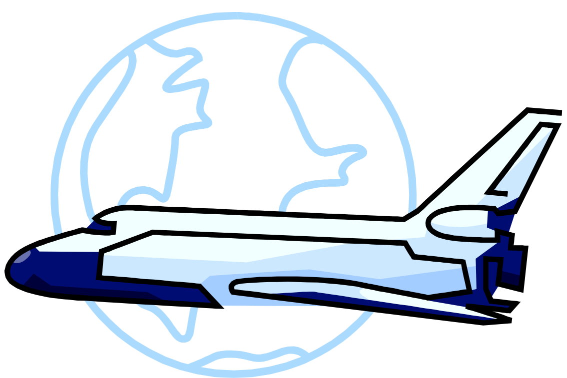
Introduction/Background

HFCIT Overview

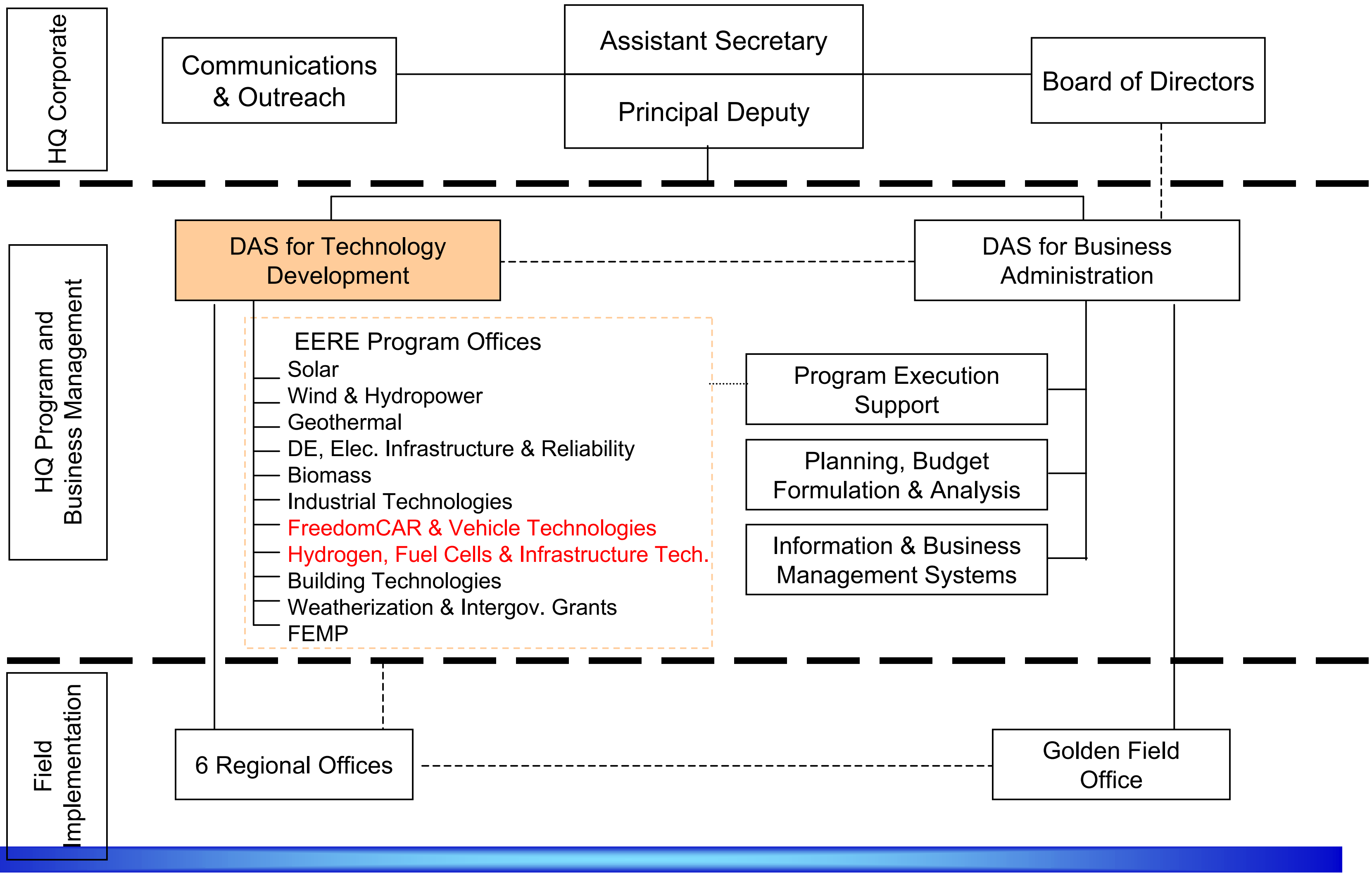
Challenges

HFCIT Progress

Resources



The New EERE


HQ Corporate
Communications & Outreach
Assistant Secretary
Principal Deputy
Board of Directors
HQ Program and Business Management
DAS for Technology Development
DAS for Business Administration
EERE Program Offices
Solar
Wind & Hydropower
Geothermal
DE, Elec. Infrastructure & Reliability
Biomass
Industrial Technologies
FreedomCAR & Vehicle Technologies
Hydrogen, Fuel Cells & Infrastructure Tech.
Building Technologies
Weatherization & Intergov. Grants
FEMP
Program Execution Support
Planning, Budget Formulation & Analysis
Information & Business Management Systems
Field Implementation
6 Regional Offices
Golden Field Office

HFCIT Organization Structure and Management

Hydrogen, Fuel Cells and Infrastructure Technologies Program

Steven Chalk, Program Manager

Technology Validation –	Sigmund Gronich	202-586-1623
Safety & Codes/Standards –	Neil Rossmeissl	202-586-8668
Education –	Christy Cooper	202-586-1885

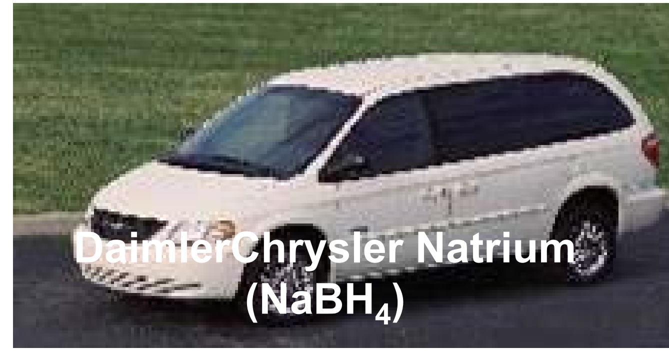
Hydrogen Production
Peter Devlin
202-586-4905

Hydrogen Storage
JoAnn Milliken
202-586-2480

Fuel Cells
Patrick Davis
202-586-8061

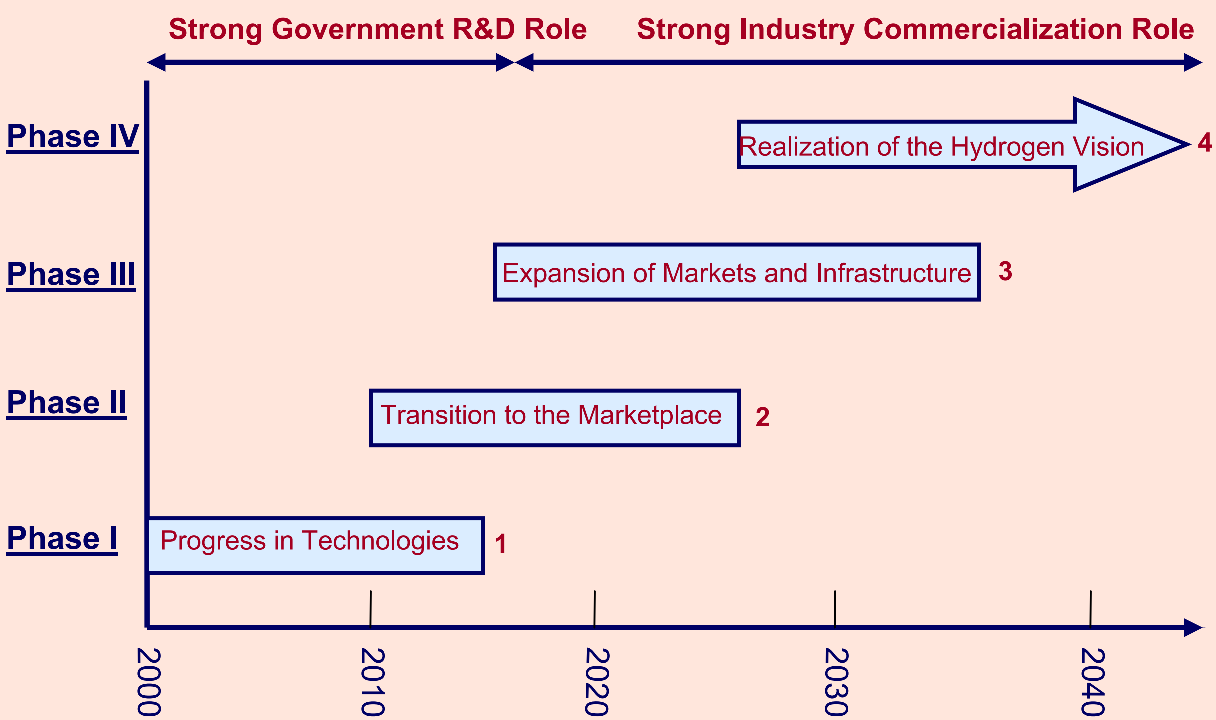
HFCIT Program Focus

Research, develop, and validate fuel cell and hydrogen production, delivery, and storage technologies for transportation and stationary applications



Overview of DOE Strategy

Technology Today → Long-Term Vision



Major Milestones

1 – H_2 power and transport systems available in select locations; limited infrastructure

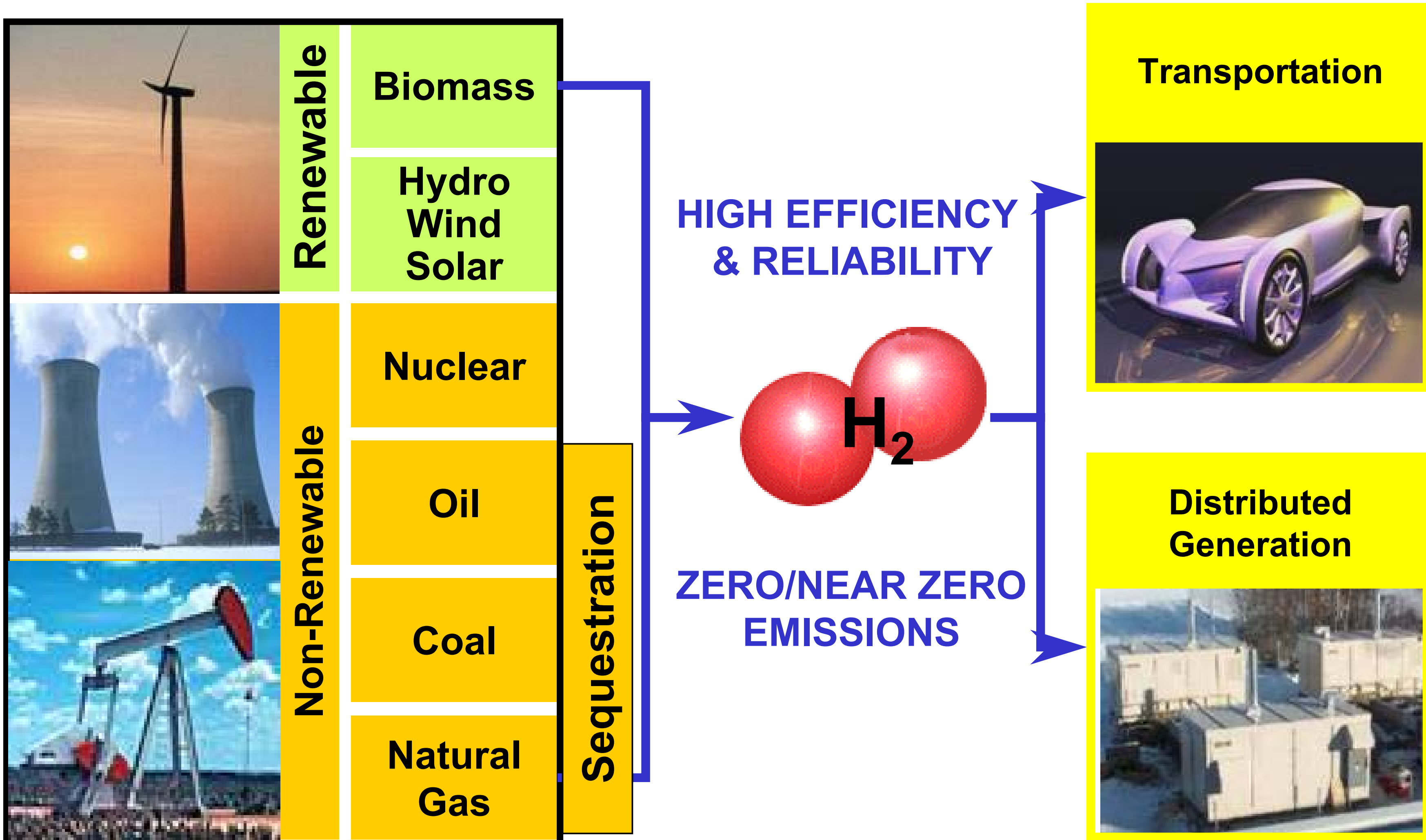
2 – H_2 power and transport systems <u>commercially</u> available; expanded local infrastructure

3 – H_2 power and transport systems <u>commercially</u> available; regional infrastructure

4 – H_2 power and transport systems <u>commercially</u> available in all regions; national infrastructure

DRAFT: Work in Progress

Hydrogen from Diverse Domestic Resources

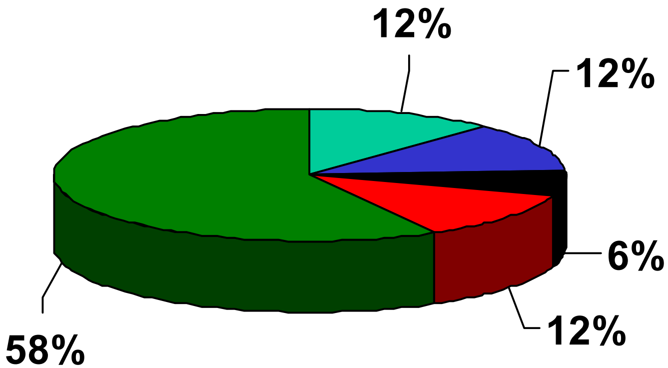


2010 FreedomCAR and Fuel Initiative Technology - Specific Goals

	Efficiency	Power	Energy	Cost*	Life	Weight
Fuel Cell System	60% (hydrogen) 45% (w/ reformer)	325 W/kg 220 W/L		$45/kW (2010) $30kW (2015)		
Hydrogen Fuel/ Storage/ Infrastructure	70% well to pump		2 kW-h/kg 1.5 kW-h/L	$4/kW-h $1.50/gal (gas equiv.)		
Electric Propulsion		$\geq$55 kW 18 s 30 kW cont.		$12/kW peak	15 years	
Electric Energy Storage		25 kW 18 s	300 W-h	$20/kW	15 years	
Materials						50% less
Engine Powertrain System**	45% peak			$30/kW	15 years	

***Cost references based on CY2001 dollar values. ** Meets or exceeds emissions standards.**

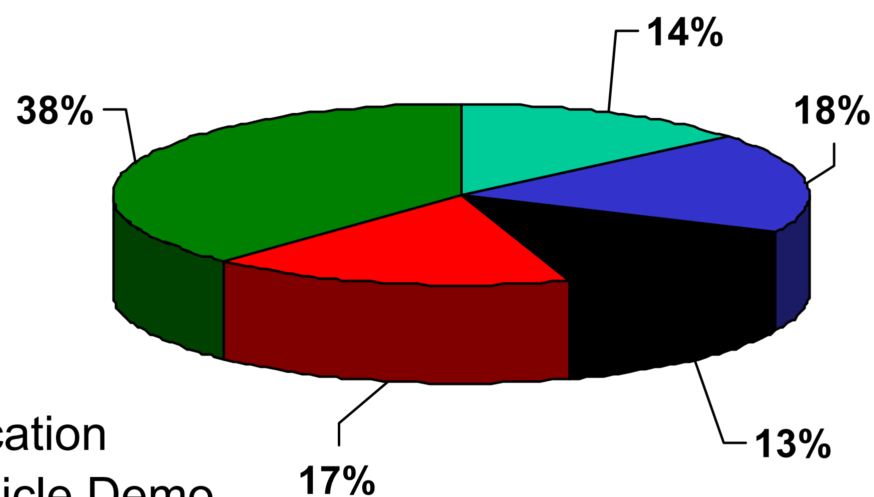
HFCIT Budget Trends



FY 2003 Appropriation
$ 97M

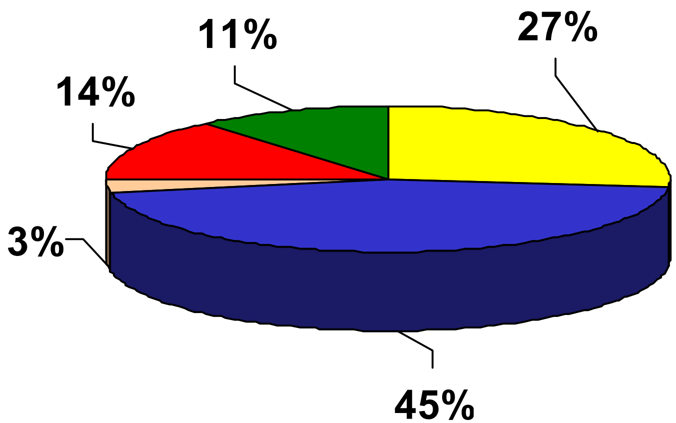
FY 2002
Appropriation
$ 76M

FY 2004 Request
$ 165M



- Fuel Cell Systems and Components
- Hydrogen Production and Delivery
- Hydrogen Storage
- Safety, Codes & Standards, and Education
- Hydrogen Infrastructure/Fuel Cell Vehicle Demo

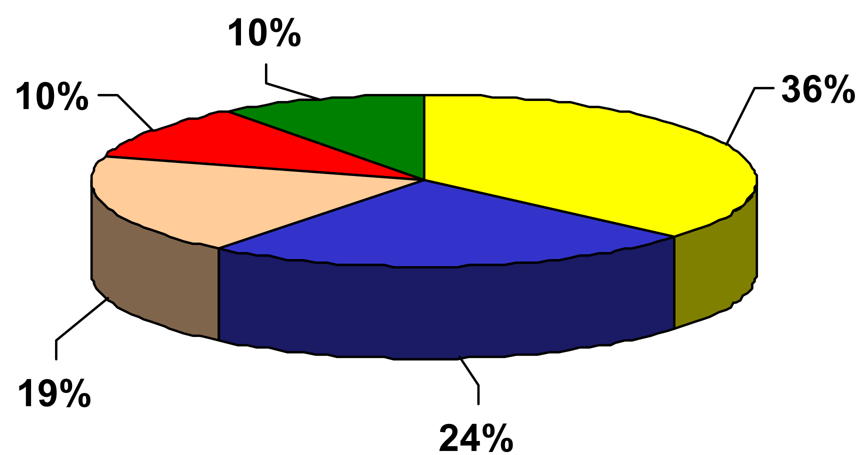
Fuel Cell Budget Trends



FY 2002 Appropriation
$ 47M

FY 2003 Appropriation
$ 55M

FY 2004 Request
$ 77.5M



- Stack Components
- Transportation Systems
- Fuel Processing
- Technology Validation
- Distributed Energy

Projects – Fuel Cells

Membranes & Electrodes

3M – MEAs and Production Techniques
3M – Improved Cathodes and High-Temp MEA
DeNora/DuPont – Advanced MEAs
Fuel Cell Energy – High-Temp Membrane
UTC Fuel Cells – Improved Cathodes and High-Temp Membrane
Superior Micropowders – Low Pt Cathode
SWRI/Gore – Pilot Production Methods
ANL
LANL
LBNL

Fuel Processing

Catalytica – Plate Reformer
Nuvera – STAR Fuel Processor
Nuvera – Hi-Q Fuel Processor
U. Of Michigan – Microchannel
UTRC – Hydrogen Enhancement
Ohio State U. – H2 Enhancement
McDermott – Autothermal Reforming
ANL
PNNL
LANL

Projects – Fuel Cells (cont.)

Bipolar Plates/Components

Porvair – Low Cost, Mass-Produced Plates
Honeywell - Sensors
UTC Fuel Cells - Sensors
ORNL

Systems Integration

UTC Fuel Cells
Caterpillar – Ethanol
GE Honeywell

Studies

TIAX – Costing, Pt Cost and Availability, Fuel Effects
Breakthrough Technologies Inc – Foreign Transportation FC Programs
Directed Technologies Inc – Transportation FC Costs

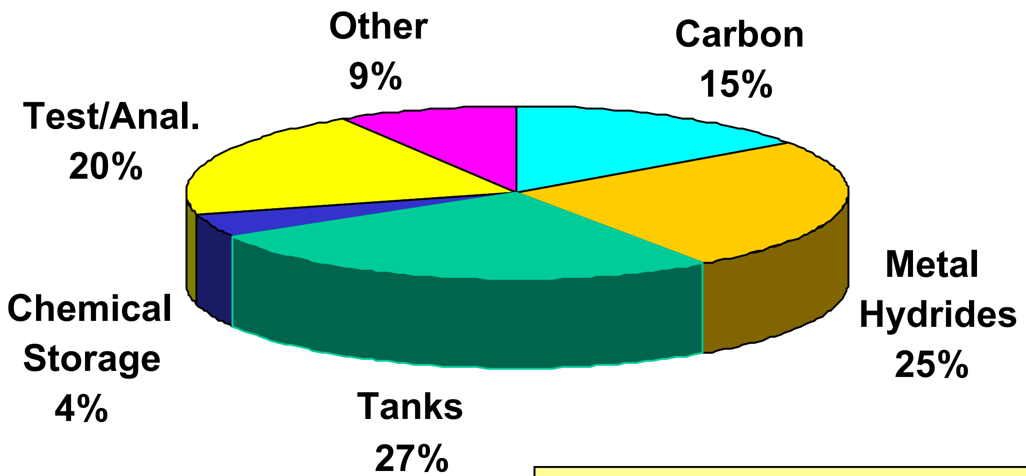
Air Management

Honeywell – Turbocompressor
Mechanology – TIVM
UTC Fuel Cell – Blowers
TIAX - Hybrid

Hydrogen Storage Budget

FY 2002
Appropriation
$ 6M

FY 2003 Appropriation
$ 11M



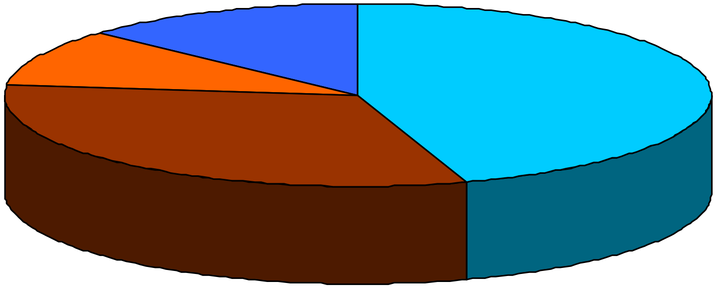
FY 2004 Request $ 30M

Hydrogen Production Budget

FY 2004 Request $ 38.5M

<u>Coal</u> - $5 million
•Separation of pure hydrogen gas from synthesis gas (carbon monoxide and hydrogen)
•Technologies also applicable to biomass feedstocks

Nuclear - $4 million (using heat from either nuclear power or solar collectors)
•High temperature water splitting
•High temperature chemical cycles



<u>Natural Gas</u> - $12.2 million
•Small, distributed systems to begin making hydrogen available at local refueling stations

Renewables - $17.3 million
•Direct water splitting using solar energy
•Thermal processes using biomas
•Advanced electrolysis from wind power

DOE Offices of Energy Efficiency and Renewable Energy ($23M), Fossil Energy, and Nuclear Energy are collaborating on hydrogen production research

Projects – Hydrogen Technologies

Hydrogen Production

NG-based refueling stations: (Air Products, GTI, GE-EERC)
Hydrogen production/purification: (Praxair, Air Products, InnovaTek)
Thermocatalytic CO_2 (FSEC)
Supercritical water biomass gasifier: (General Atomics)
Waste fermentation processes: (U. Iowa)
Electrolyzers: (Stuart Energy, LLNL, INEEL)
Photocatalytic: (UCSB, U of Hawaii, SRI)
Marine organisms: (UC Berkeley)

Office of Science major areas of current research:

- Catalysts and mechanisms for hydrogen production
- **Hydrogen storage- hydrides, nanofibers, and nanotubes**

Hydrogen Storage

Alanate Storage Materials: (UTRC, U. Hawaii, SRTC, SNL)
Carbon Nanotubes: (NREL)
Test protocol for storage materials: (SwRI)
High Pressure Tanks: (JHU/Lincoln, Quantum LLNL, INEEL)
ThermoCompressor: (Ergenics)

Codes & Standards

National Hydrogen Association
SNL, NREL

Education/Outreach/Analysis

TIAX
NREL

HFCIT National Laboratory Priorities - PEMFC

Laboratory	Priority
Argonne	Systems Analysis Fuel Proc Catalysts Fast-Start Fuel Proc
Brookhaven	Low-Pt Electrodes
Oak Ridge	Hydrogen Production Stack Materials Stack Components
Lawrence Berkeley	Electrocatalysts
Lawrence Livermore	Sensors Hydrogen Storage

Laboratory	Priority
Los Alamos	Sensors Improved Cathodes High-Temp Membrane Durability Studies Fuels Effects
Energy Technology	Fuel Processing
Renewable Energy	Vehicle Analysis Hydrogen Production Hydrogen Storage
Pacific Northwest	Microchannel Fuel Processing
Sandia	Hydrogen Purification Hydrogen Storage

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Fuel Cells and Hydrogen – The Critical Challenges

Fuel Cells:

- Cost
- Durability
- Fuel Processing
- Air/Thermal/Water Management
- Codes & Standards

Hydrogen:

- Storage
- Fuel Infrastructure
- Hydrogen Fuel Cost
- Codes & Standard

The Challenge – ≤ $45/kW for 50-kW Gasoline-Fueled PEMFC Integrated System

Subsystem	2005 Target[a]	2010 Target[a]	2003 Status[a,b]
Fuel Cell	**$100**	**$35**	**$200**
Fuel Processor	**$25**	**$10**	**$65**
BOP/ Assembly	(c)	(c)	**$35**
Total[d]	**$125**	**$45**	**$300**

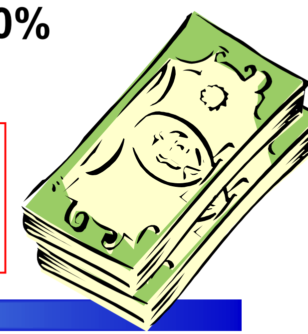
a. HFCIT MYPP Draft March 2003
b. Based on Tiax (A.D. Little) and Directed Technologies cost studies
c. BOP/Assembly in fuel cell & fuel processor
d. High-volume projections

Show Me The Money

$ **MEA and bipolar plate materials and fabrication techniques**
20-30%

$ **Increased stack power density by operation at lower voltage, higher current (also lowers system efficiency)**
20-25%

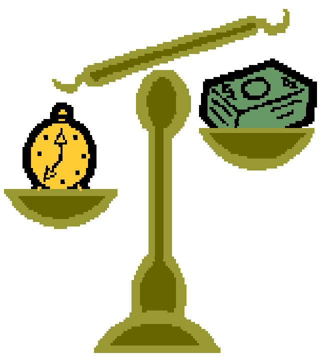
$**Reduce Platinum Group Metals in stack and fuel processor**
15-20%



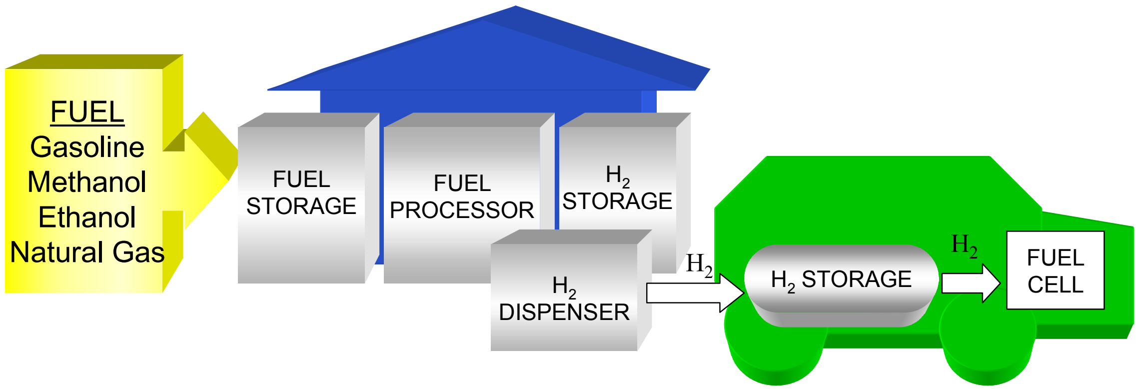
Non-PGM Electrocatalyst Workshop March 21-22, 2003

The Challenge – Start-Up Time

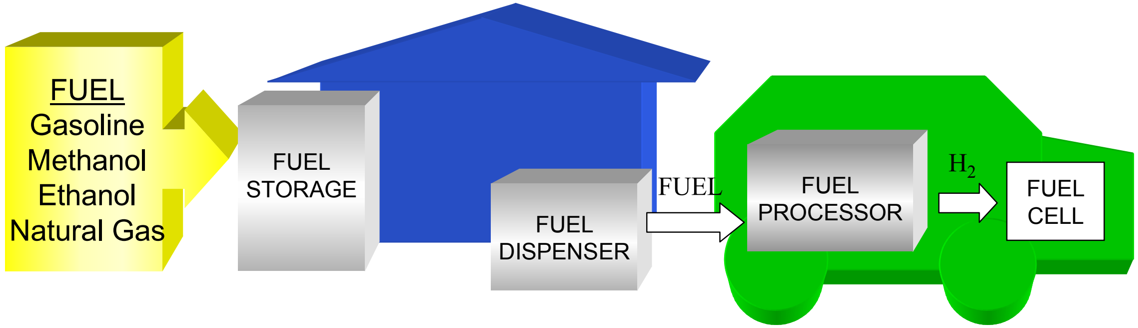
Dual Path Fueling Strategy



Off-Board Fuel Processing & Hydrogen Storage



On-Board Fuel Processing



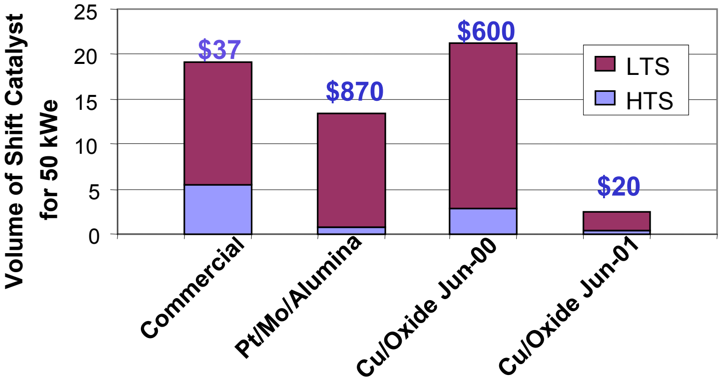
Onboard fuel processing Go/No Go decision in 2004

Onboard Fuel Processing Go/No Go Milestone

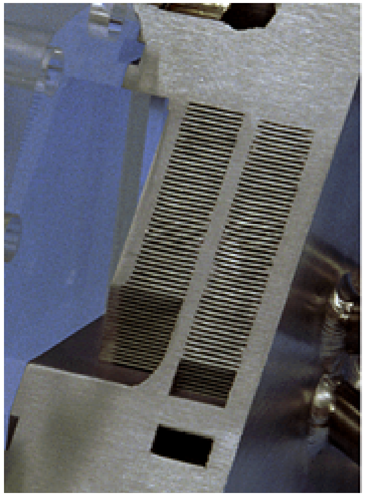
- **Major Go/No Go decision planned for 2004 that will result in either:**
  - **Ending on-board fuel processing work**
  - **Changing scope and redirecting activity**
- **Prime criteria for Go/No Go will be start-up time and how it impacts:**
  - **Fuel efficiency**
  - **Cost and complexity**
- **Have initiated process to determine Go/No Go criteria**
  - **NREL vehicle modeling working in conjunction with Argonne fuel processing work.**

Technical Solutions – Fuel Processor Start-Up Time

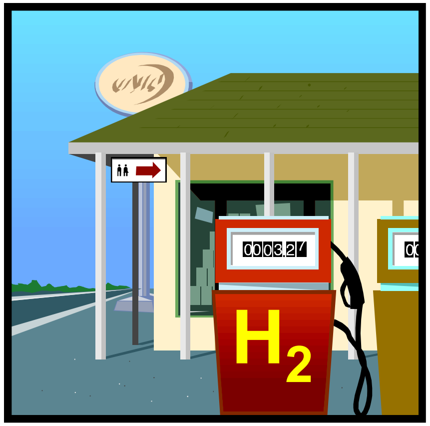
- ***Improve Water-Gas Shift catalysts (ANL, U. Michigan, NexTech, Nuvera, Catalytica)***
  - ***Significantly reduce size/weight***
  - ***Eliminate one stage of shift reactor and/or the preferential oxidizer***
- ***Develop microchannel fuel processing technology (PNNL, U. Mich.) to achieve dramatic size reduction (1/10 conventional systems)***
- ***Develop infrastructure in support of hydrogen-fueled fuel cell vehicles***



Potential for Size/Wt Reduction with ANL Cu/Oxide Catalyst



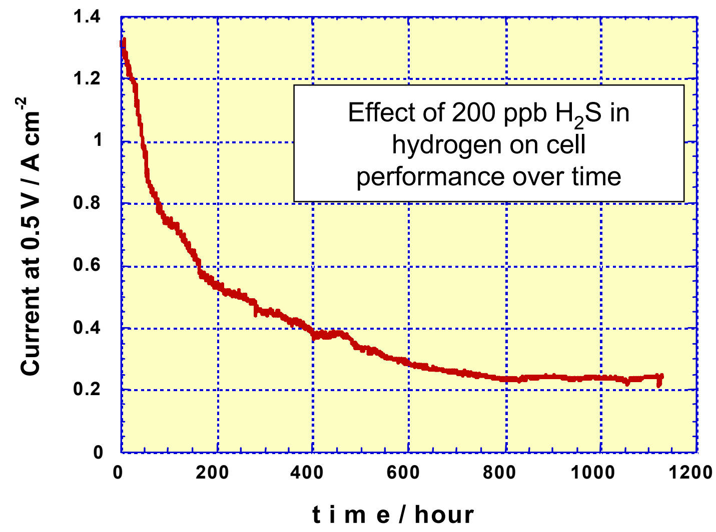
PNNL Microchannel Technology

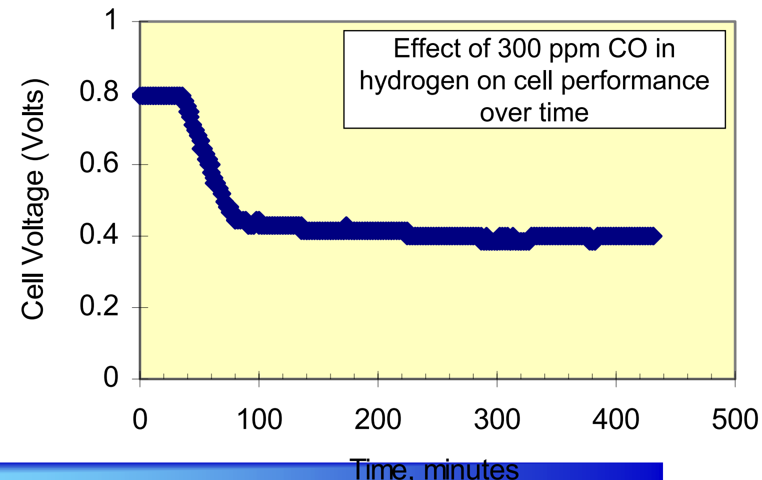


The Challenge – System Durability

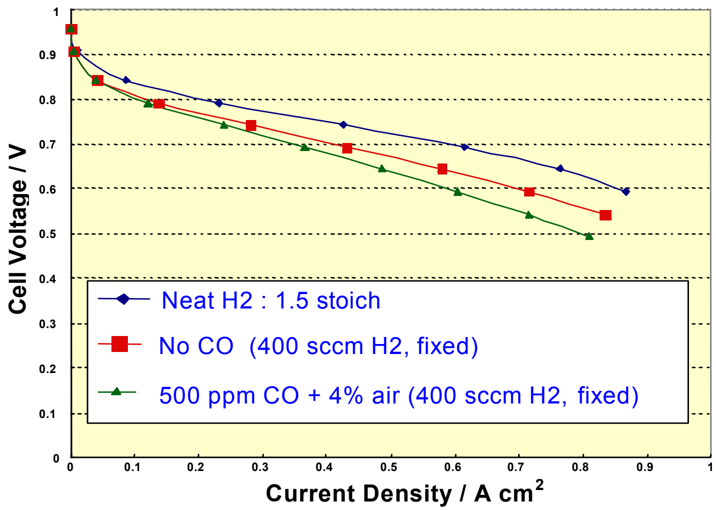
Issue: Current lifetime of transportation fuel cell systems (~1000 h vs. target of 5000 h) – dominated by issues related to fuel choice and the fuel processor.

- **The sulfur content of today's gasoline is sufficient to reduce the activity and lifetime of the on-board fuel processor and fuel cell catalysts**
  - **coke formation in fuel processor**
  - **lower H_2 in reformate**
  - **higher HC breakthrough**
  - **higher CO in reformate**
  - **reduction in fuel cell power density**
- **The CO in reformate can also limit the lifetime and activity of the fuel cell catalyst**
- **Shortage of long-term test data**





Technical Solutions – System Durability



H_2 Refueling Station at CaFCP

- ***Develop technologies (e.g., PROX) for reducing CO in reformate***
- ***Develop sulfur tolerant reformer catalysts and CO tolerant fuel cell catalysts***
- ***Develop higher temperature membranes (at 150°C, CO tolerance increases from ~10 ppm to 1% CO***
- ***Anode air-bleed for increased catalyst CO tolerance***
- ***Improve reactivity and loading capacity of sulfur adsorbents***
- ***Address fuels issues:***
  - ***Introduction of low sulfur gasoline (<85 ppm) and diesel (10 ppm)***
  - ***Infrastructure to support hydrogen-fueled fuel cell vehicles***

The Challenge – Air Management

Issue: Fuel Cells require a large quantity of air

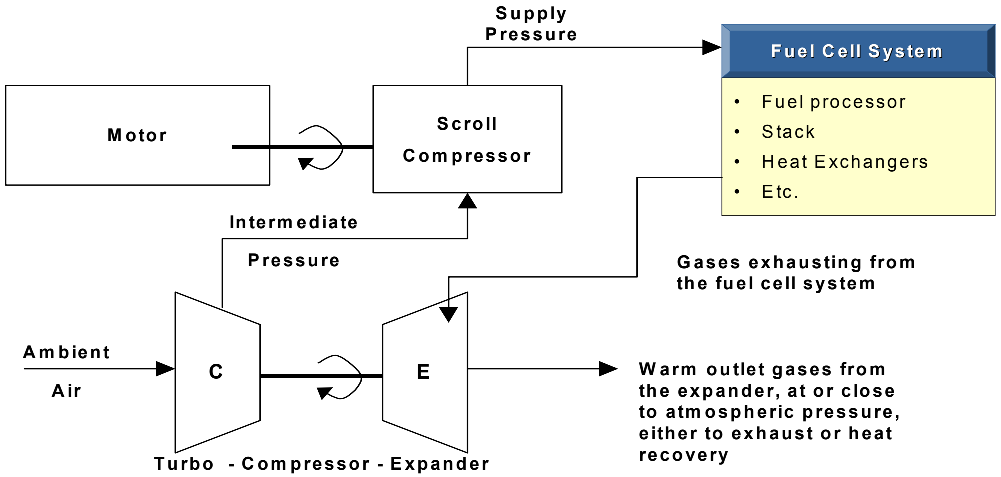
Amount of Oxygen needed

Amount of air needed

Amount of air being pumped

- **Net effects:**
  - Excess air in the fuel cell stack lowers system efficiency and enlarges the stack size, weight, and cost.
  - Air is often supplied at pressure (2-3 atm), resulting in a significant parasitic pumping loss on the fuel cell system.
  - Off-the-shelf compressor/expander machines for transportation fuel cell systems do not exist.

Technical Approach – Air Systems

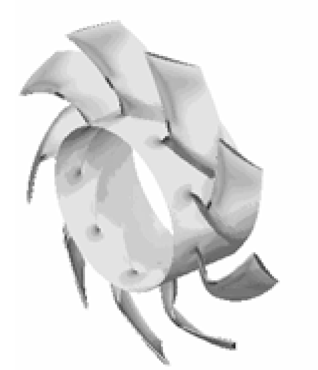


Turbocompressor/Expander: Compact and light, new mixed flow blade and Variable Nozzle Technology performs well during turndown

Blowers: New compact, more efficient devices for 1-5 psig ambient fuel cell systems

Hybrid Scroll-Turbocompressor/Expander-Module Concept: Compact, more efficient

Toroidal: Potentially meets weight and volume targets, but still immature. Near-Frictionless Coatings help friction issues.



The Challenge – Onboard Hydrogen Storage

Higher Energy Density is Required to Meet Customer Needs

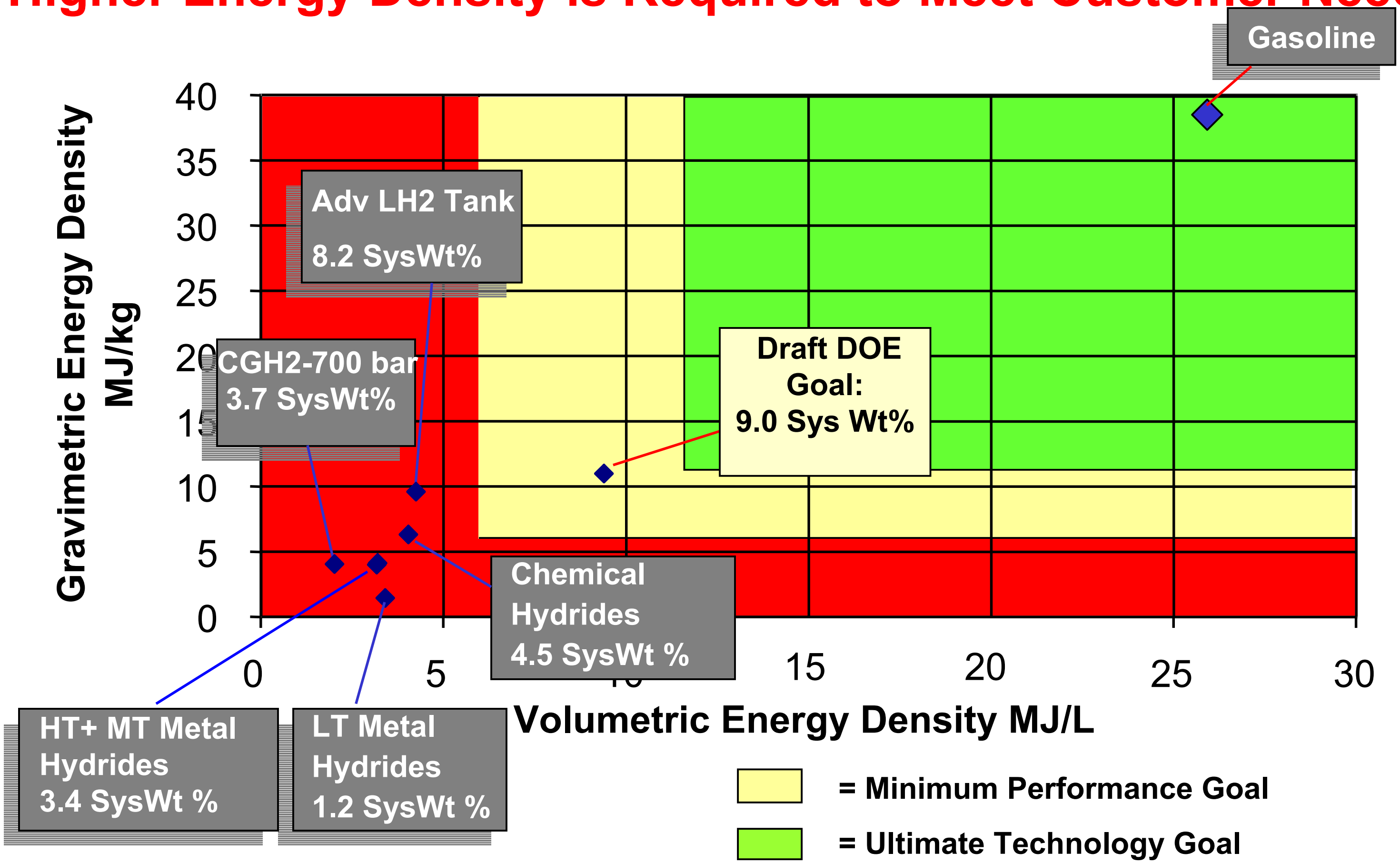
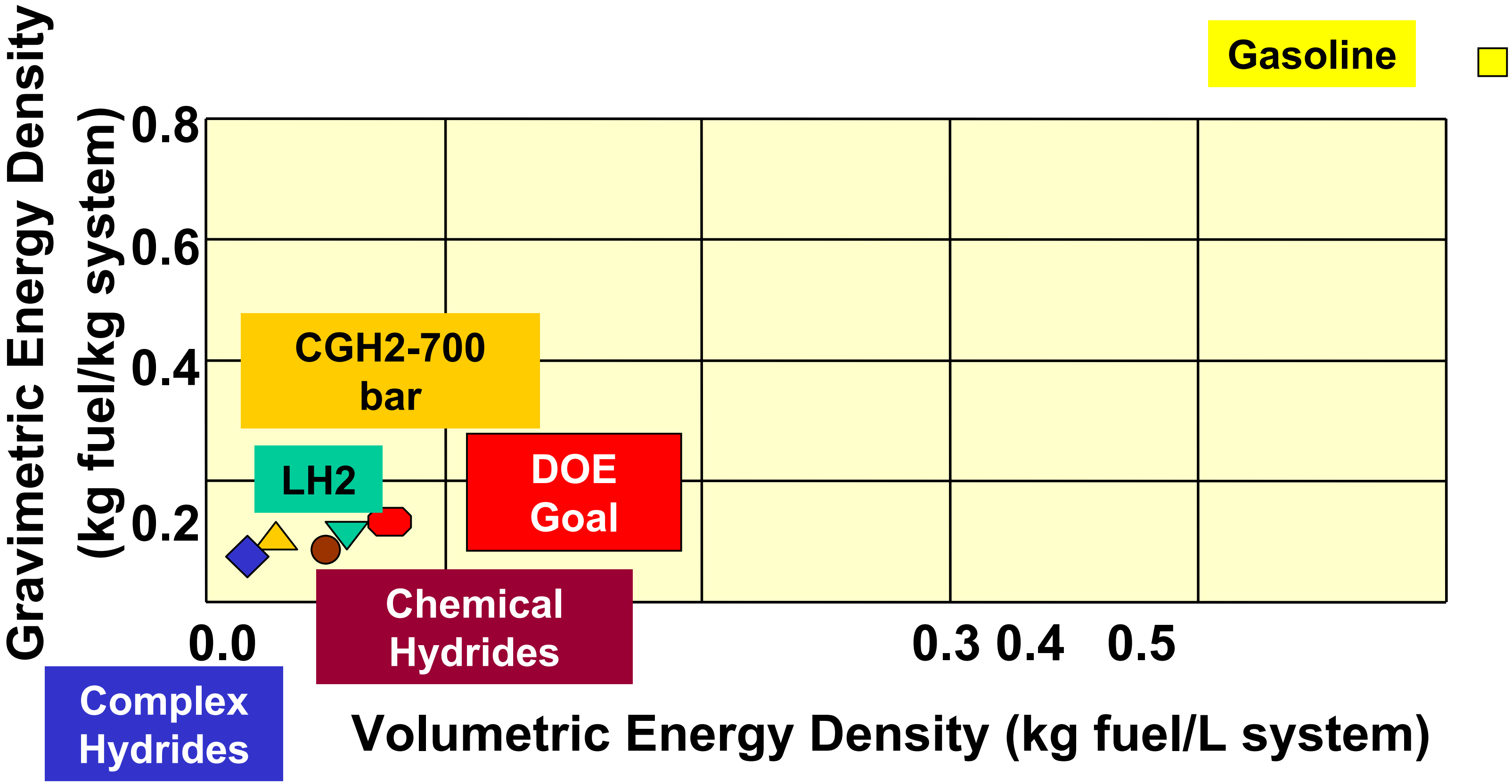


Chart Source: General Motors

Technical Barrier: Onboard Hydrogen Storage

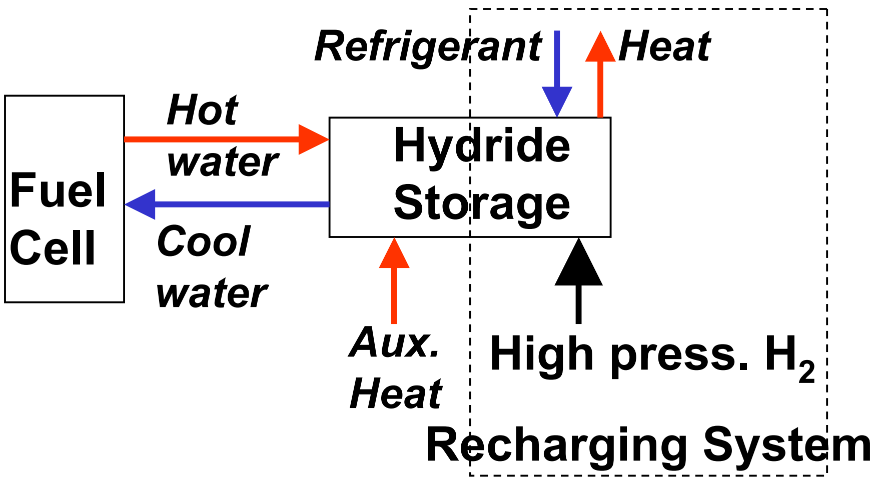
Storing enough hydrogen on vehicles to achieve greater than 300 miles driving range is difficult.



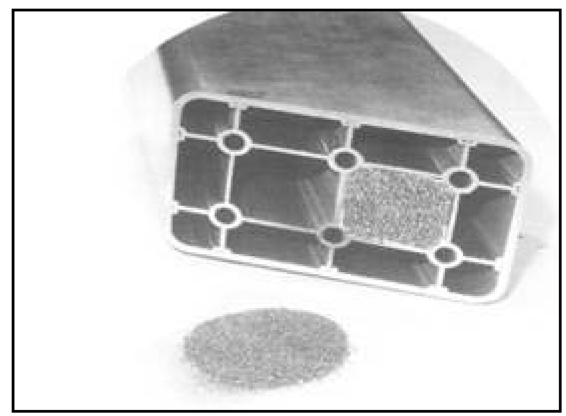
Technical Approach – Onboard Chemical Storage

Charging or absorption: $M + xH_2 \rightarrow MH_{2x}$ + heat

Discharging or desorption: MH_{2x} + heat $\rightarrow M + xH_2$



Ti-catalyzed sodium aluminum hydrides can store 4-5 wt.% hydrogen at 1 atm and 125°C.



Desorption at <100°C (PEM) is still slow.
Cost is high.

Technical Approach – Other Onboard Storage Technologies

• Liquid/slurry hydrides such as sodium borohydride provide safety and improved storage density but require off-vehicle regeneration of reacted/depleted fuel.

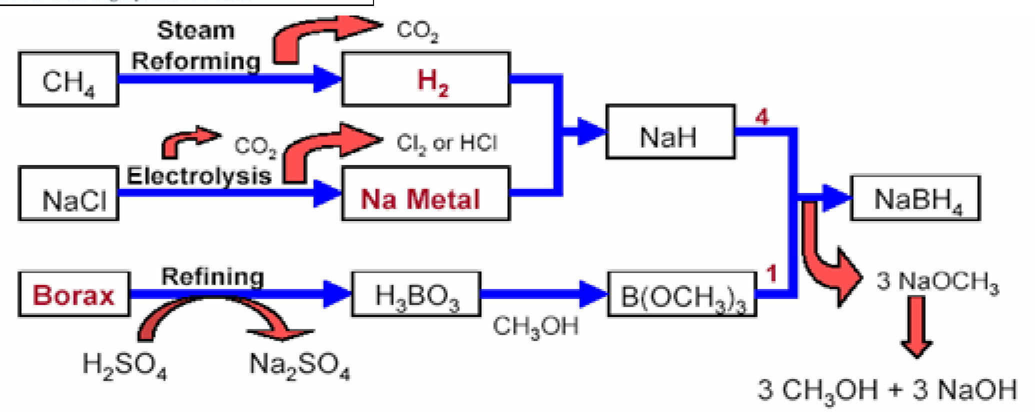
$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 + \textbf{heat}$$

Figure 95 - Second Generation of Hydride Reactor

Figure 112 - Pouring Hydroxide Waste

Final Report DOE Contract DE-FC02-97EE50483, "Advanced Chemical Hydride-Based Hydrogen Generation/Storage System for Fuel Cell Vehicles", ThermoPower Corp, 03/01

Current $NaBH_4$ Synthesis



Hydrogen Storage Materials Workshop

Complex Metal Hydrides

- Continue fundamental studies on $NaAlH_4$ as model system
- Identify other hydride materials that have greater storage capacity

Chemical Hydrides

- Identify improved/new process chemistry for regeneration
- Complete full lifecycle analysis of $NaBH_4$

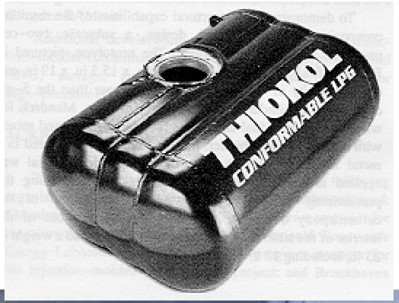
Carbon

- Conduct definitive experiments to show where and how hydrogen is stored in nanotubes
- Better understand the science to engineer carbon for H_2 storage

Advanced Concepts

- Discuss advanced storage concepts further to refine recommendations and to resolve controversial aspects

Compressed/Liquid H2 Storage



- Type IV all-composite tanks are available at 5,000 psi (350 bar)
- Prototype 10,000 psi tanks completed EIHP-based certification tests

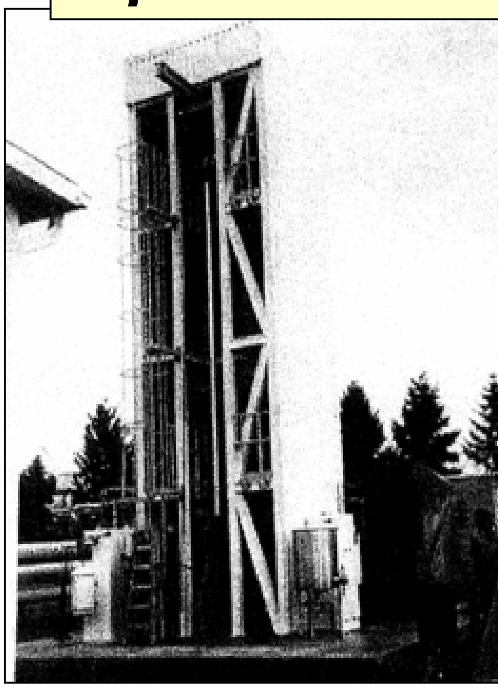
Liquid H2 Storage

- BMW has demonstrated automotive liquid H_2 storage
- Pressurized cryogenic tanks are being developed by LLNL.
- Liquefying H_2 requires substantial energy (40% of HHV)
- Boil-off is an issue for non-pressurized insulated tanks

Packaging volume is still a concern.

The Challenge – Hydrogen Production

Issue: Hydrogen costs about $3.50 for the energy equivalent of a gallon of gasoline.



- Advanced fuel processing technologies with higher efficiency are being developed for various feedstocks.
- Reformer systems are being designed for ease of manufacture and reduced capital cost.
- Improved electrolyzers that cost about $300/kW ($10,000/kW currently) are being developed.

The goal is $1.50 with well-to-pump efficiency of 70%.

The Challenge – Hydrogen Infrastructure

- **Capital cost is enormous for a national system**
- **Uniform codes and standards are being developed for refueling stations to facilitate placement and reduce cost.**
- **Vehicle/station refueling interface standards are being developed.**
- **On-site or central H_2 generation? Transportation costs, electricity co-production**
- **FreedomCAR hydrogen fuel cell vehicles and infrastructure demonstrations are planned.**

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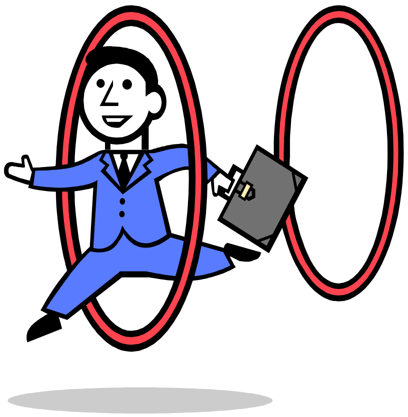
HFCIT Progress

Resources



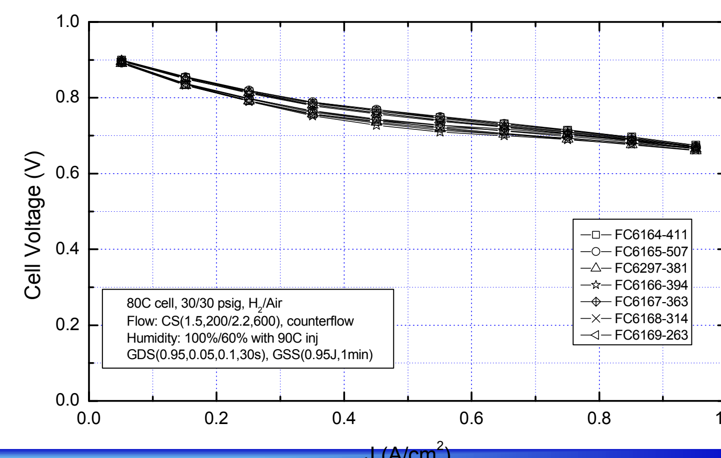
Accomplishments – 3M

Goal: Develop a set of high-performance, matched PEM fuel cell components and pilot manufacturing processes to facilitate high volume, high yield stack production.

- Fabricated PtA binary catalysts that have higher ORR activities than Pt, ("A" is a non-precious metal)
- Discovered a PtAB ternary which gives the same performance as Pt but with half the amount of precious metal.
- Demonstrated process for high speed/ high yield catalyst transfer to form MEAs

Cross-sectional view of whiskers 50,000 x.

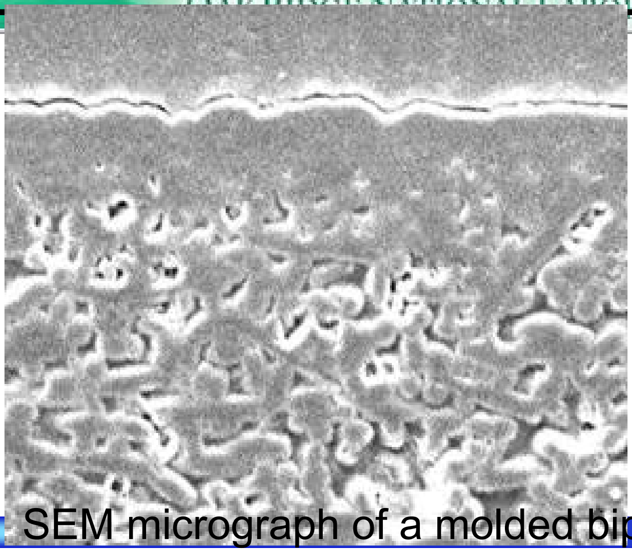
Rolled-Goods MEAs Reproducible



Accomplishments – Porvair/ORNL

Goal: Develop a slurry molded fiber material with a carbon chemical vapor infiltrated surface as a bipolar plate material (ORNL); design and construct a pilot scale production line to demonstrate high volume, low cost manufacturing.

- Developed carbon composite material w/ graphite particulate filler appropriate for fuel cell bipolar plates. (ORNL)
- Improved mechanical strength and wetting of baseline material. (ORNL)
- Qualified initial material and processing equipment (Porvair)
- Meets DOE technical goals

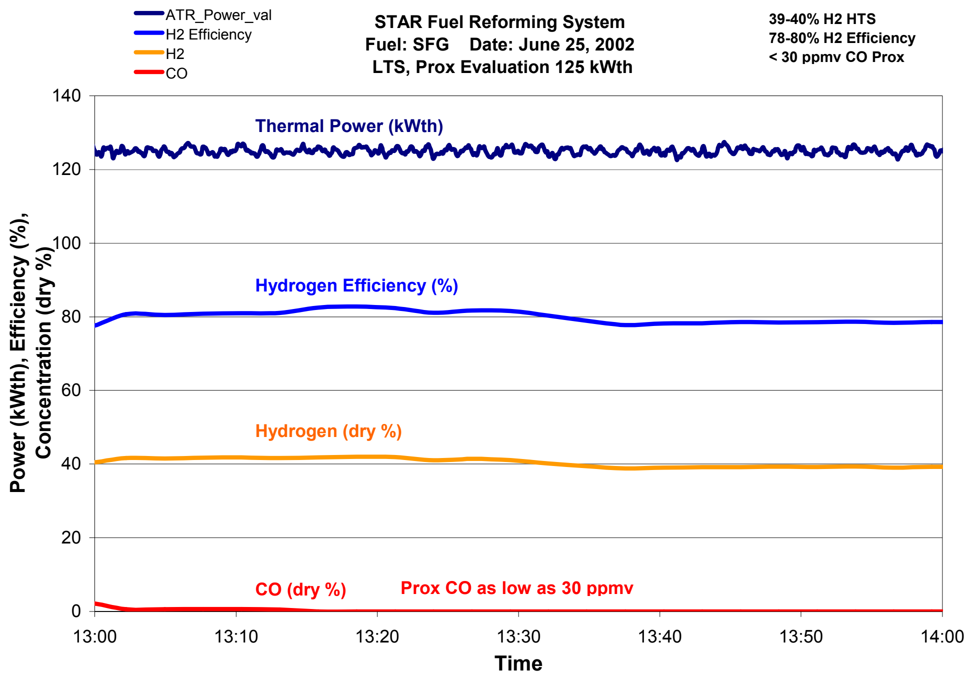


SEM micrograph of a molded bipolar plate

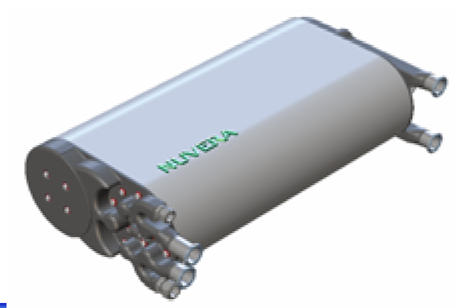
Accomplishments – Nuvera

Goal:

- Develop and demonstrate SOA automotive multi-fuel processor to meet DOE targets
  - Monolithic catalyst, compact heat exchangers, low thermal mass
- Develop system control strategies

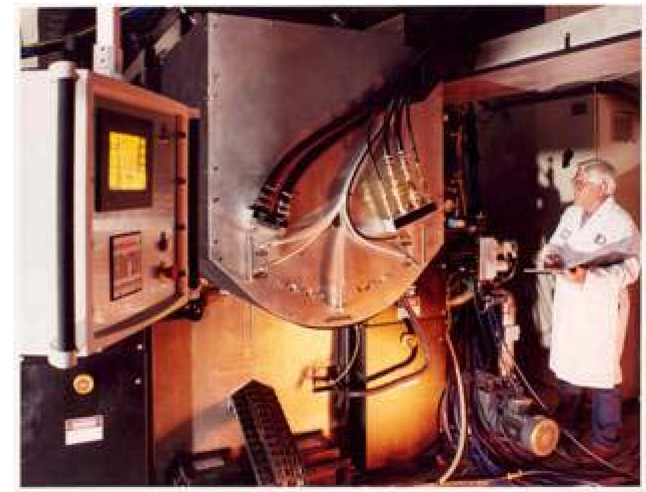


- 200kWth
- 78% efficiency
- 40% hydrogen



Accomplishments – Southwest Research Institute

- **Southwest Research Institute and W.L. Gore, Inc. demonstrated a pilot manufacturing plant for low-platinum electrodes:**
  - **Loading of 0.2 mg/cm^2 is better than the DOE 2005 target of 0.3 mg/cm^2 (0.6 g/kW)**
  - **Capacity of 10,000 m^2 of electrode material per year (several thousand vehicles)**
  - **Projected to meet $10/kW MEA target**
- **Technology is being validated in 10-kW stacks built and tested by GM**
- **Future work will focus on durability testing**



SwRI Pilot Manufacturing System for Fuel Cell Electrodes

GM 10-kW Stack

Accomplishment - Las Vegas Hydrogen Station

- Completed 5-year project for design, construction, and demonstration of a multi-purpose refueling station with:
  - on-site H_2 production (natural gas reforming)
  - hydrogen/electricity co-production system operating a 50kW PEM FC
  - H_2/CNG blends and pure H_2 vehicle dispensers.
- Future plans are to evaluate operability, reliability, economic feasibility, and certify integrated power generation (50 kW PEM) and vehicle refueling designs.
- November 15, 2002 dedication ceremony

Accomplishments – ANL/CMT

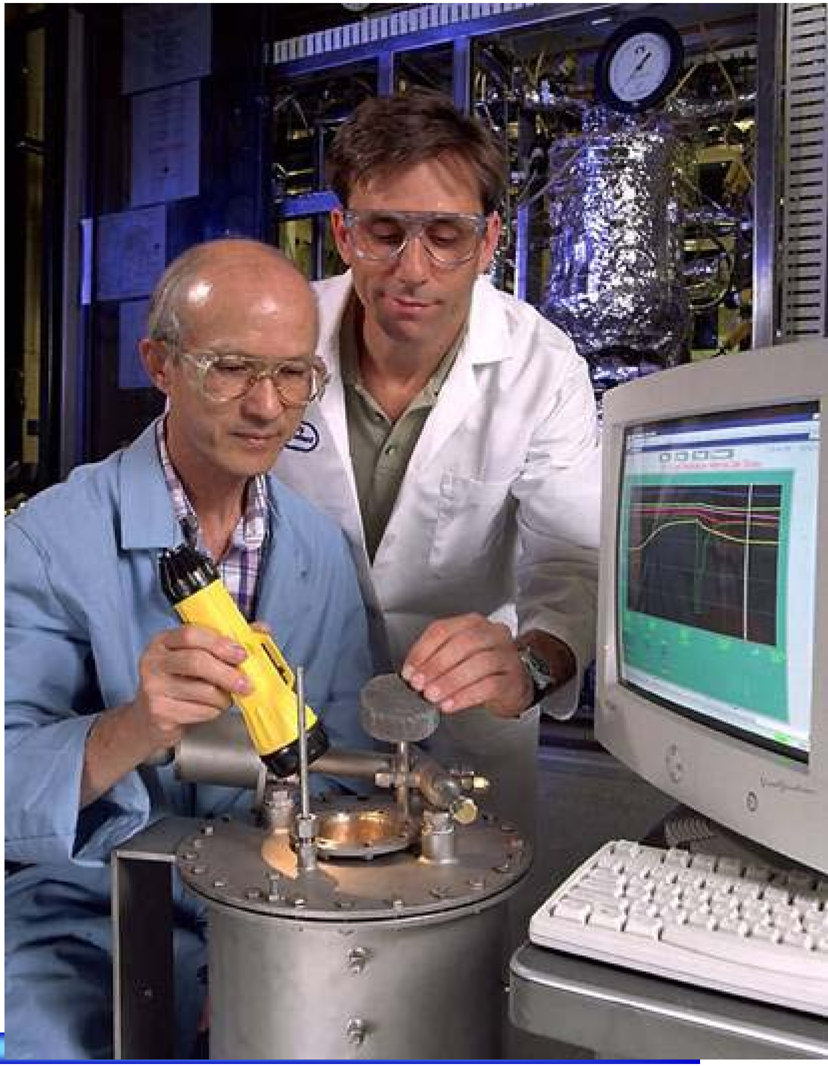
- **Demonstrate a FP capable of 60 second start-up**
- **Identify tech barriers for rapid start**
- **Engineering scale (10 kWe) FP using ATR, WGS, PrOx**
- **Consortium of national laboratories (ANL, LANL, ORNL, PNNL), private companies, and universities**

Study rapid-start capability of on-board FPs

Accomplishments – ANL/CMT

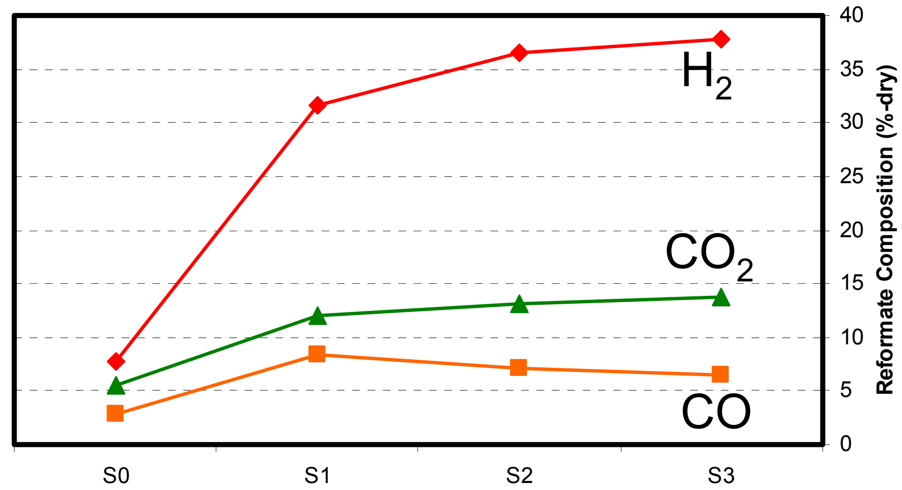
- **Converted natural gas to PEMFC-quality hydrogen**
- **5 kWe capacity for stationary applications**
- **CRADA project with H2fuel**
- **Tech transfer**

Integrated fuel processor demonstration

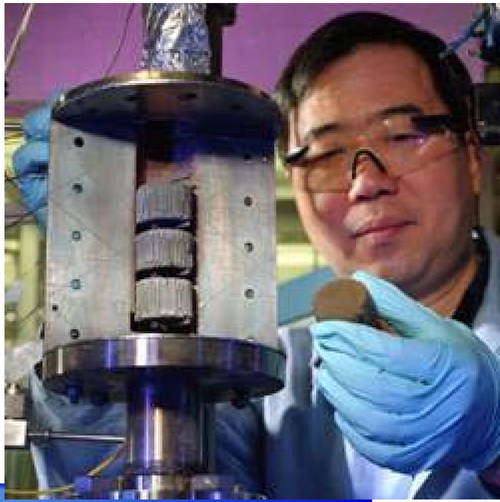


Accomplishments – ANL/CMT

- **3-fluid nozzle developed for ATR**
- **Demonstrated conversion of diesel surrogates**
- **1 kWe reactor for auxiliary power units, NOx reduction**



Demonstrated diesel reforming with liquid injector



Accomplishments – ANL

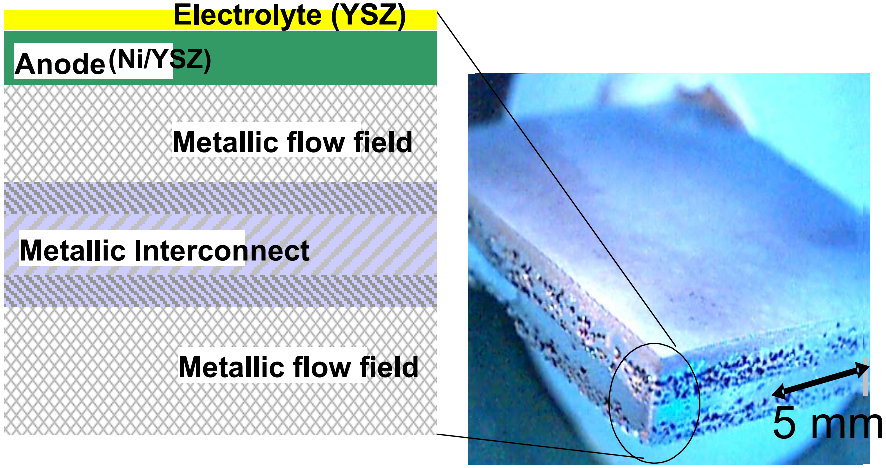
Goal: **To develop an improved SOFC for Auxiliary Power Units (APUs)**

SOFCs pros

- **High power density and efficiency**
- **Fuel versatility/simplified fuel processing**
- **Highly favorable duty cycle**

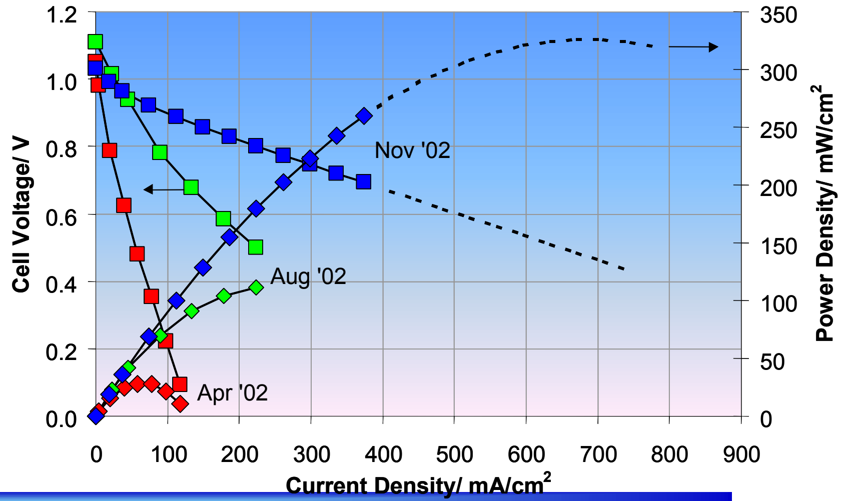
SOFC issues

- **Startup time, resistance to temp cycling**
- **Vibration and shock resistance**
- **Manufacturing cost**



Metallic Bipolar Plate-Supported SOFC (TuffCell)

- **Sintered in a single step**
- **Reduces manufacturing cost**
- **metal layers provides high strength**
- **Single contact plane between stack units**
  - **Reduces contact resistance**



Outline

Introduction/Background

HFCIT Overview

Challenges

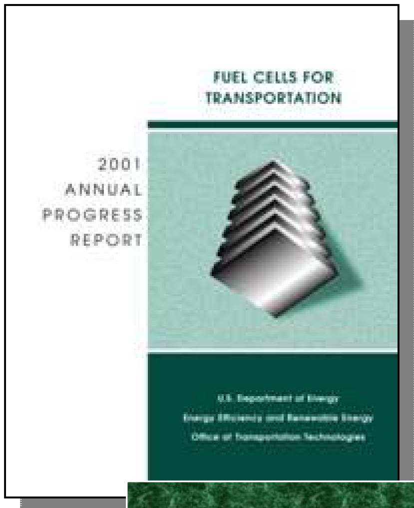
HFCIT Progress

Resources

HFCIT Planned Solicitations & Workshops

- **Stationary & Transportation Fuel Cell Solicitation (closed 03/27/03).**
  Contact: Kathi Epping, 202-586-7425
- **Fuel Cell Portable & Auxiliary Power. April 2003 release.**
  Contact: John Garbak 202-586-1723
- **Vehicle Demonstration, Infrastructure, and Co-production: April 2003 release.**
  Contact: Sig Gronich, 202-586-1623
- **State Energy Program Fuel Cell topic: Stationary & vehicle demonstration with education plan. Closes 05/09/2003.**
  Contact: Christy Cooper, 202-586-1885
- **Hydrogen Production & Delivery : Late spring release. Notice of Program Interest to review ideas for solicitation topics (January 2003).**
  Contact: Roxanne Danz, 202-586-7260
- **Hydrogen Storage: Early summer release.**
  Contact: JoAnn Milliken, 202-586-2480
- **Basic Research for Hydrogen Production, Storage, and Use Workshop, May 13-16, 2003, Washington, DC**

http://www.eere.energy.gov/hydrogenandfuelcells



Proceedings of the 2002 DOE H_2 Program and Fuel Cells Annual Program/Lab R&D Review