Solid State Energy Conversion Alliance
2nd Annual Workshop Proceedings
March 29-30, 2001 • Arlington, Virginia

SECA

NETL

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Pacific Northwest National Laboratory
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DISCLAIMER

2ND ANNUAL WORKSHOP PROCEEDINGS
SOLID STATE ENERGY CONVERSION ALLIANCE
MARCH 29-30, 2001

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2ND ANNUAL WORKSHOP PROCEEDINGS
SOLID STATE ENERGY CONVERSION ALLIANCE
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FOREWORD

The National Energy Technology Laboratory (NETL) and the Pacific Northwest National Laboratory (PNNL) are pleased to provide the proceedings of the second annual Solid State Energy Conversion Alliance (SECA) Workshop held on March 29-30, 2001 in Arlington. The package includes the presentations made during the workshop, a list of participants, and the results of the breakout sessions. Those sessions covered stack materials and processes, power electronics, balance of plant and thermal integration, fuel processing technologies, and stack and system performance modeling. The breakout sessions have been reported as accurately as possible; however, due to the recording and transcription process errors may have occurred. If you note any significant omissions or wish to provide additional information, we welcome your comments and hope that all stakeholder groups will use the enclosed information in their planning endeavors.

The SECA industrial teams were selected in July 2001, and will start work imminently. The core technology program solicitation is currently being drafted, and will be released in December 2001. The solicitation will be periodically reissued with revised topics based on stakeholder input. Input from the industrial teams, the first and second annual workshops, the February core technology program workshop, and stakeholders has been carefully reviewed and incorporated into the SECA program.

We sincerely appreciate your active participation in the workshop and breakout sessions. Over 210 participants, representing various stakeholders groups from more than 100 organizations, provided a wealth of information and opinions. This collaboration will undoubtedly enhance the planning for and the ultimate realization of the SECA goals.

The date and location of the third annual SECA workshop is March 21-22, 2002, at the Hyatt Regency Washington on Capitol Hill in Washington, DC. We look forward to your future participation in SECA. Further details and updates will be available at the NETL website: www.netl.doe.gov/scng or the SECA website: www.seca.doe.gov.

Sincerely,

Wayne A. Surdoval
SECA Project Manager
National Energy Technology Laboratory
Strategic Center for Natural Gas

I. PRESENTATIONS

A. OFFICE OF FOSSIL ENERGY PERSPECTIVES ON DISTRIBUTED GENERATION AND FUEL CELL TECHNOLOGY

George Rudins, Acting Assistant Secretary
U.S. DOE, Office of Fossil Energy

Good morning.

I am delighted to be here today at this second annual meeting of the Solid State Energy Conversion Alliance, or SECA as we all know it.

We are convinced that SECA could be one of the most important steps forward in the history of power generation. It could be, if you in this audience are successful, a breakthrough for clean, efficient, and reliable power generation. It could be the stimulus that will make fuel cells the first choice for "home-grown" power generation, or for distributed power for businesses and utilities, as well as for military and transportation uses.

I'm convinced that SECA has to be the breakthrough we need. At the projected prices of today's technology—and we have to be honest about this—fuel cells will probably never advance beyond niche markets. And I am equally convinced that with the power demands we see coming, it is imperative that fuel cells move beyond today's limited applications. Fuel cells need to be in the mainstream of tomorrow's power industry.

It may surprise some people to know that the solid-oxide fuel cell was one of the earliest power technologies studied in our program. It even pre-dates me. In fact, you can go back to the very first set of projects funded by the Office of Coal Research, back in the early 1960s, and find a project for solid oxide fuel cell development.

The technology has come a long way since those early days. But it remains a challenge, an engineering challenge, and certainly an economic challenge.

Yet, at the same time, we see in front of us potential paths to success. We need to work these paths to ensure this technology addresses the growing needs of this country: environmental needs, fuel efficiency needs, and the special challenges of distributed generation.

We need an innovative concept such as SECA to be successful. It won't be easy.

Why do we need SECA? Well, in case you haven't heard, we have a power problem. It didn't happen overnight, and it won't be solved overnight. But we must solve it.
Supply far exceeded demand during much of the last two decades and many utilities stopped building power plants years ago. The U.S. electric power industry did not foresee a decade of rapid economic growth and the forced retirement of aging and dirty plants.

California is not so much an isolated case, as it is a warning sign for the rest of the nation. The state assumed that this supply excess would continue. It didn't add significantly to its power-plant capacity; not since the mid 1980s. So, while restructuring their markets, Californians put too much faith into rosy expectations. And they were ill-equipped when supplies tightened and prices became more volatile.

The rest of the nation cannot be complacent—thinking that California's problems could only happen in California.

In New York City last summer, temperatures were cooler than normal. Yet, wholesale power rates soared 30 percent. New plants are planned, but it will be 2 years or more before they are come on line with sufficient capacity to ease concerns about brownouts and blackouts.

The short-term fix for this coming summer is installation of six turbines within the city limits that run on natural gas. Consolidated Edison spokesman Michael Clendenin said in late February, *"The worst is still ahead for New York, until there's enough power being generated to make deregulation and the free market work."*

So today we need to take a new look at the future of our electrified economy, and recognize that new thinking is required. And new thinking often leads to new technologies.

As I said, the problem didn't appear overnight, and it won't go away in the near future. In 1999, the Energy Information Administration predicted that 300 gigawatts of new capacity would be needed by 2020. Last year, they increased that prediction to almost 400 gigawatts. Now, we are talking about a 44percent increase in the nation's demand for power by 2020.

Our demand for *new* power supplies in the next 20 years will be greater than all the power generated today in Germany and Japan, combined.

As I said, we need new thinking—a new vision—about the make-up and character of tomorrow's power grid. For many people, and I am one of them, this new vision includes distributed generation and fuel cells.

Distributed generation can reduce dependence on the grid. It provides electricity at remote locations where there are no distribution lines, as well as in areas where the distribution system is too overloaded to allow additional connections. It can alleviate the difficulties with constructing longer distance transmission lines. It provides power when and where it is needed.

Many in the electric power industry are embracing DG. Lawrence Downes, Chairman and CEO of New Jersey Resources, representing the Distributed Power Coalition of America, testified before the Senate Committee on Energy and Natural Resources back in May 2000.
He said:

> Distributed generation promises to change the electricity industry in much the same way that personal computers changed the face of computing. Personal computers revolutionized our economy, bringing computing power to the desks of tens of millions of Americans. The same future awaits the electric industry. Distributed generation can bring reliability, power quality, cleaner air, and lower costs to all classes of consumers.

Fuel cells fit hand-in-glove with this new power vision.

Improved Reliability -- the digital economy makes this more important than ever. A commercial bank in Omaha, Nebraska, loses power for one hour, and it writes off $6 million. For every hour an airline can't access its central computers, it loses $100,000.

High quality power on an uninterruptable basis is a critical attribute for our computer-based society. The Electric Power Research Institute estimates that reliability and power quality limitations of the current electricity infrastructure costs the U.S. economy more than $30 billion each year in lost time and revenue.

Fuel cell technologies can provide an onsite solution. Power you can see being generated. Power that is steady, constant, with relatively little distortion. And that makes it ideal for computer-based businesses or hospitals.

Reliability means an awful lot to commercial businesses, but poll after poll shows that even more on the minds of Americans minds is the quality of their environment. The air they breathe, and the air their children will breathe for years to come.

When almost everybody seems to be saying these days, "Not in my backyard," fuel cells are pretty good neighbors. They are clean and quiet—everything you want neighbors to be. Fuel cells are so clean that the South Coast Air Quality Control District, which includes Los Angeles, allows them to be sited without a permit.

Increased Efficiency: Today, we're hearing more and more about efficiency. California's major rate increase this week was intended, in large part, to encourage the efficient use of electricity. Americans became efficiency conscious in the 70s, wavered a little in the 80s and 90s, and now – at least on the West Coast – are beginning to gain a new awareness of the need to use energy more efficiently.

I believe Americans also need to be concerned about energy efficiencies at the "front end" of the power cycle in addition to the end-use of energy.

We have enormous opportunities to make improvements in the way we generate electricity – and I would offer to you that every gain we can make in power generating efficiency only compounds the efficiency benefits when the power is used.

Fuel cells take us to a new plateau of front-end efficiency. We break through the 33 or 35 or perhaps in the best of cases, the 38 or 39 percent efficiencies of today's technologies. Now we can set our sights on 60 or 65 percent efficiencies – and if we can capture and use the thermal energy, we're looking at 70, 75 or 80 percent fuel use efficiencies.

If we want to talk about conserving our natural resources, we should be talking about higher power generation efficiencies. If we want to talk about saving costs for consumers, we should be talking about higher power generation efficiencies.

Fuel Diversity -- Tomorrow's power industry must become a more "fuel diverse" industry – because with diversity comes energy and economic strength. No longer can we say "what should we do for natural gas?" or "what should we do for coal or biomass?" We must ask ourselves "what can we do for ALL our domestic resources? How do we maximize the energy potential of ALL our fuel supplies, especially those we have in most abundance?"

And the answer comes back again: fuel cells.

Today, fuel cells are running off natural gas and landfill gas and a few off various alcohols. Tomorrow, if our efforts are successful, they could be running off coal gas, or gas made from biomass, or perhaps municipal waste.

Yes, we have come a long way since the concept of an all solid-state fuel cell was first conceived in the 1960s. Siemens Westinghouse recently completed a record run on a solid oxide fuel cell, accumulating almost 17,000 hours of operation with essentially no performance degradation. That 100-kilowatt unit is the "Energizer Bunny" of fuel cells – it just kept going and going. And I understand the plans are to keep going at a new location.

Despite all of the progress, there is that final hurdle, the one that must be overcome before the *promise* of fuel cells becomes the *reality* of fuel cells. That hurdle is cost.

If we take a hard look at the last 15 or 20 years, we might have over-promised our capability to introduce fuel cells are reasonable costs. Three or four thousand dollars an installed kilowatt is too much. A thousand dollars a kilowatt is too much for most applications.

We need to get the costs down to the gas turbine range or below, down to the $400 per kilowatt range.

That is what drives SECA. That is the goal. There is no question, it is ambitious. But cost reductions of this magnitude are not unprecedented.

Look at the electronics industry. Look at computers that cost five and six thousand dollars 15 years ago, now selling for $800 or $900 dollars, with orders of magnitude more power. I saw a VCR on sale a few days ago for $70—the price of a pair of run-of-the-mill tennis shoes—the kind that Michael Jordon wouldn't be caught dead in. Who would have imagined that a few years ago?

If mass customization can work for the electronics industry, it can work for its "first cousin" in the energy sector: fuel cells.

That's what we want SECA to set into motion: innovations in mass production that lead to core modules—5 to 10 kilowatts each—that can be mixed and matched in a variety of combinations. From the power units of the military to the power generators of our commercial economy—that is what will push fuel cells beyond today's niche markets.

We won't achieve our goals overnight. We have set aggressive, but achievable targets: $800 a kilowatt by 2005, $600 a kilowatt by 2008, $400 a kilowatt by 2011.

I am convinced that if we achieve those goals, we will watch fuel cells take off at a pace none of us can imagine today.

Now, let me make my final point: SECA stands for Solid State Energy Conversion Alliance. The key to the technological breakthroughs are the first words "Solid State." But the key to ultimate success is the last word: "Alliance."

That is what will make SECA work. An alliance of skills, and a cross-pollination of ideas. Gone are the days when a single company can carry the load. The risks are too great, the challenges are too numerous. Today, it takes the best and the brightest from industry, R&D organizations, universities, and yes, even government agencies, all applying their expertise toward a common goal.

And there is no goal more important to the economic future of this country than our shared vision of reliable, abundant, low cost, and environmentally acceptable electricity. America runs on the power it generates. America competes on the world market because of the way we generate power. America's future depends on reliable, affordable, clean power. We know that today more than ever.

Thank you for being here. And thank you for your dedication and commitment to this new vision.

B. DOE Vehicle Technology Programs

Thomas J. Gross, Deputy Assistant Secretary, Office of Transportation Technologies
U.S. DOE, Office of Energy Efficiency and Renewable Energy

Vehicle Technology Programs

Thomas J. Gross
Deputy Assistant Secretary
Office of Transportation Technologies
Office of Energy Efficiency and Renewable Energy

Solid State Energy Conversion Alliance Workshop
March 29, 2001

Presentation Outline

- OTT Mission
- Vehicle Technology Programs
  - Light-Duty Vehicles
  - Heavy-Duty Vehicles
- Fuels R&D
- Fuel Cell Program
- SECA-Related R&D

OTT Mission

...support the development and use of advanced transportation vehicles and fuels which will reduce energy demand, particularly for petroleum; reduce greenhouse gas emissions; and enable United States transportation to sustain a strong competitive position in domestic and world markets.

Partnerships Are Key to Success

Clean Cities

Bioenergy Initiative

California FUEL CELL PARTNERSHIP

DRIVING FOR THE FUTURE

US AMP

PNGV

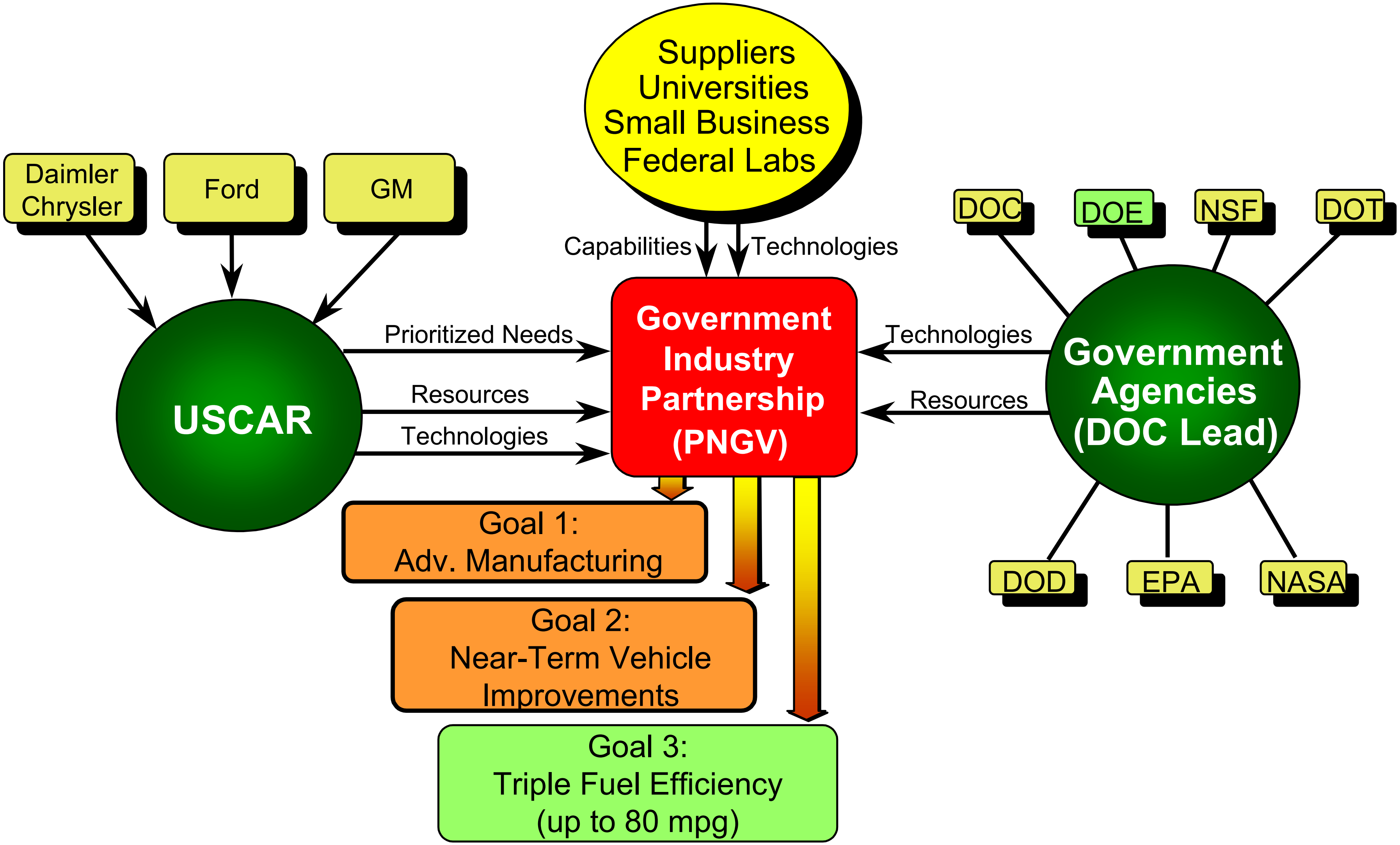
PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

Government-Industry
21st Century Truck Partnership

USABC

SECA

PNGV: An Historic Collaboration Between Industry & Government



Technology Portfolio Continues to Evolve

Engine/Power Sources

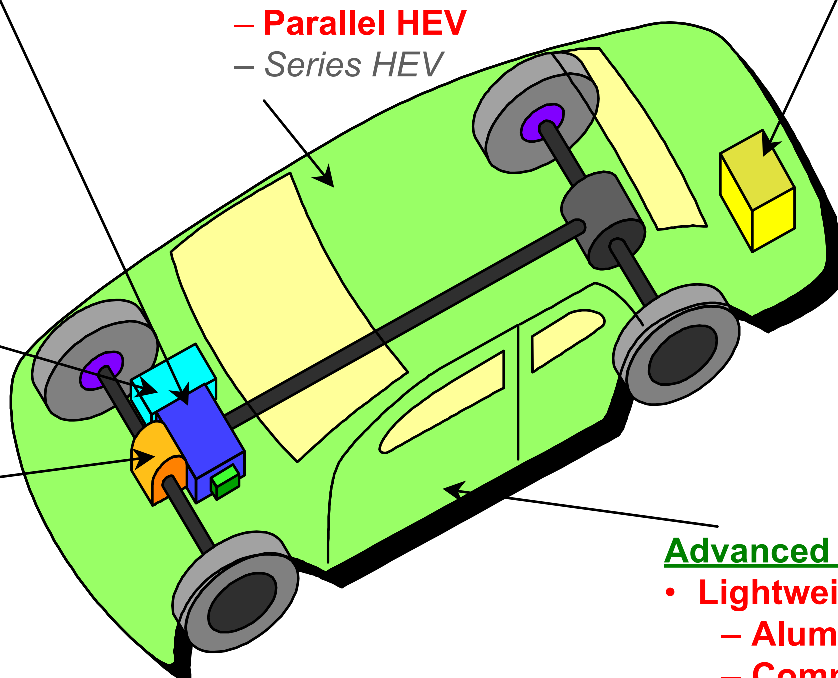
- **Advanced Heat Engines**
  - **DI Engines**
  - *HCCI*
  - *VCR*
- **Combustion and Aftertreatment**
  - **Lean NOx Catalyst**
  - **EGR**
  - **Traps**
- **Fuel Cell**
- **Batteries**
  - **NiMH Battery**
  - **Lithium Battery**
- *Pneumatic/Hydraulic Storage*
- **Power Electronics**
  - **Invertors/Controllers**
  - **Motors**
  - **Ultracapacitors – Electric**

Systems Development

- **Aerodynamics**
- **Rolling Resistance – Tires**
- **Accessory Loads – HVAC**
- **Powertrain Configuration**
  - **Parallel HEV**
  - *Series HEV*

Fuels Utilization

- **Gasoline**
- **Diesel Fuels and Blends (<30 ppm sulfur)**
- **Natural Gas**
  - **Methanol**
  - **Fischer-Tropsch**
  - *Dimethyl Ether*
- **Ethanol**
- *Hydrogen*



Advanced Materials

- **Lightweight Materials**
  - **Aluminum/Composite BIW**
  - **Composite BIW**
- **Propulsion Materials**

(red)	Most promising options
(black)	*Other technologies*

2000 PNGV Concept Vehicles

PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

Ford Prodigy

- Lightweight materials reduce vehicle body structure weight 50%*
- Integrated starter/alternator*
- 33% reduction in aerodynamic drag
- Advanced diesel engine with 35% efficiency improvement projected to exceed 70 mpg (gasoline equivalent)*
- High-power battery *

DaimlerChrysler ESX3

- Body system weighs 46% less*
- Efficient diesel engine, motor, and battery projected at 72 mpg (gasoline equivalent)*
- Cost penalty halved to $7500

GM Precept

- Vehicle body weight reduced 45% *
- World's most energy efficient vehicle lighting system
- Lowest drag coefficient ever recorded for a 5-p sedan
- Dual-axle parallel hybrid achieves 79.6 mpg (gasoline equivalent)

*Government supported technologies

The National Research Council Conducts Annual Reviews of PNGV

- Outstanding effort in meeting the concept car milestone in 2000
- Substantial technical progress noted in:
  - Vehicle engineering
  - Structural materials
  - 4-stroke, direct-injection engines
  - Fuel cells
  - Batteries
  - Power electronics
- Major barriers: costs, emissions, fuels
- Significant progress also observed for Goals 1 and 2

"Considering the magnitude of the challenges facing the program, PNGV is making good progress"

-- NRC Sixth Report of the PNGV

PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

Technology Is Migrating into New U.S. Vehicles

PNGV
PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

- Hybrid-electric drives scheduled for:
  - Dodge Durango in 2003
  - Ford Escape in 2003
  - Chevrolet Silverado in 2004
  - and Ford Explorer in 2005
- 412 pounds of lightweight aluminum in the 2000 Lincoln LS
- Aluminum used for door, deck, and hood panels for Cadillac, Oldsmobile, and Chevrolet vehicles
- 50-pounds lighter composite pickup truck box on the 2001 Chevrolet Silverado
- Production of a new, lighter, recyclable thermoplastic hardtop for the Jeep Wrangler in 2001

Difficult, but Surmountable, Research Challenges Remain to Achieve Very High Fuel Economy

- **Hybrid Systems:** Parallel configuration offers best option to meet 80 mpg. Series configuration may be used with fuel cells. Cost, weight, and packaging remain as challenges.
- **CIDI Engines:** Mature technology with 44% efficiency, but NOx and particulate emissions remain as challenges.
- **Fuel Cells:** Lowest onboard emissions and potential for highest efficiency, but cost, systems integration, and fueling infrastructure are major challenges.
- **Energy Storage:** Considerable progress in developing high-power battery; focus now on cost and cycle life.
- **Power Electronics:** Progress on cost, power-to-weight ratios, and efficiencies needed
- **Light Materials:** Significant weight reductions achieved. Major issues are cost, manufacturability, joining, recycling, and repair.
- **Fuels:** Fuel impacts on infrastructure must be addressed. Thorough evaluation is needed of the effects of fuel composition and physical properties on CIDI and fuel systems' performance.

21st Century Truck Partnership

Industry Participants

Allison Transmission	General Motors
BAE SYSTEMS Controls	Honeywell
Caterpillar	International Truck and Engine
Cummins	Mack Trucks
DaimlerChrysler	NovaBUS
Detroit Diesel	Oshkosh Truck
Eaton Corporation	PACCAR
Freightliner	Volvo Trucks North America

Department of Energy
DOE/EE/OTT Heavy Vehicle Technologies R&D

Department of Defense
Army/TACOM NAC Military Vehicle R&D

Department of Transportation
Intelligent Vehicle and Highway Safety R&D

Environmental Protection Agency
Vehicle Emissions Regulations

21st Century Truck Partnership Declaration of Intent

Trucking industry's future depends on ability to produce affordable, high quality, safe, environmentally sensitive products.

- **Innovation needed** for U.S. truck manufacturers and suppliers to remain competitive worldwide;
- New truck and bus technologies will help truck owners and operators, and their customers, **cut fuel and operating costs and increase safety;**
- DOD would share gains and benefit from **reduced logistic costs** of transporting fuel during operations.

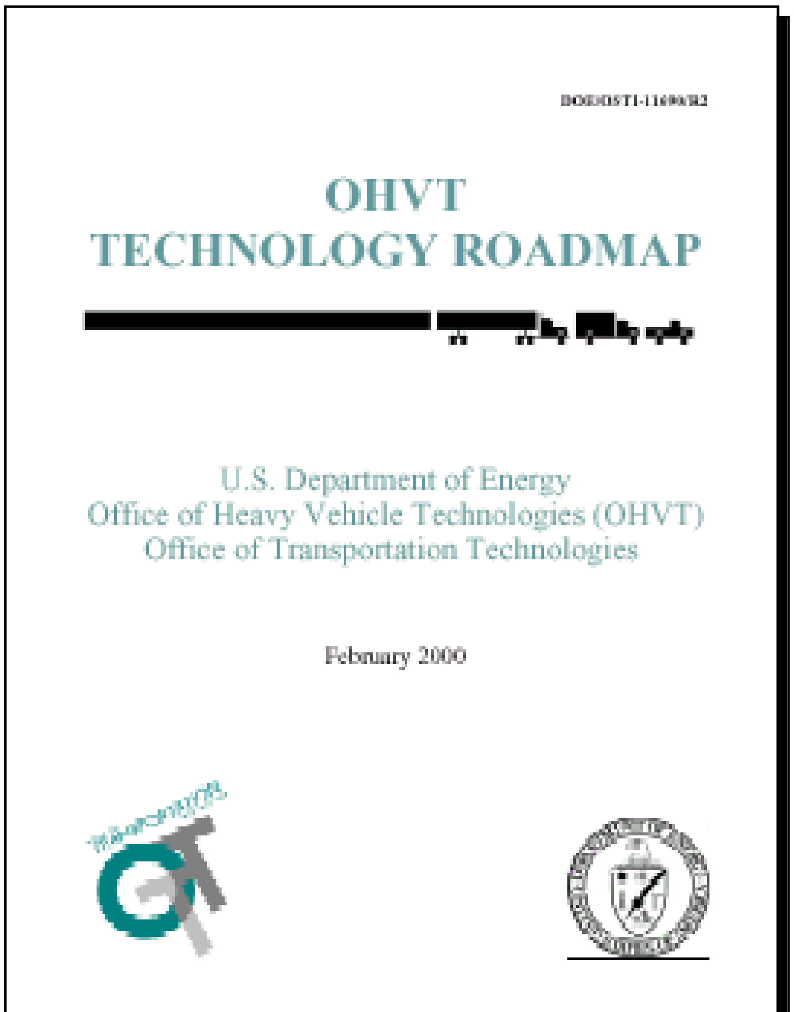
21^{st} Century Truck Partnership Declaration of Intent

Develop production prototype vehicles that:

- **Improve fuel efficiency, specifically, by 2010;**
  - double the Class 8 long-haul truck fuel efficiency*;
  - triple the Class 2b and 6 truck (delivery van) fuel efficiency*; and
  - triple the Class 8 transit bus fuel efficiency*;
- **Exceed expected emissions standards for 2010;**
- **Meet or exceed motor carrier safety goal of reducing truck fatalities by half in ten years; and**
- **Enhance affordability, and maintain or enhance performance.**

* on a ton-mile per gallon basis

Heavy Vehicles Technology Roadmap


OHVT
TECHNOLOGY ROADMAP

U.S. Department of Energy
Office of Heavy Vehicle Technologies (OHVT)
Office of Transportation Technologies

February 2000

R&D needs of three groups of trucks are addressed

- Class 7 and 8, heavy-duty on-highway trucks
- Class 3-6, medium duty trucks such as urban delivery vans and transit buses.
- Class 1 and 2 light trucks (pickups, vans, and sport utility vehicles)

Independent review conducted by the National Research Council.

Heavy Vehicle Technologies R&D Goals

Heavy (Class 7-8) Trucks

To develop by 2004, the enabling technologies needed to achieve a fuel efficiency of at least ***10 miles per gallon*** *(at 65 miles per hour)* and ***meet*** emissions standards prevailing in 2004, using petroleum-based diesel fuel.

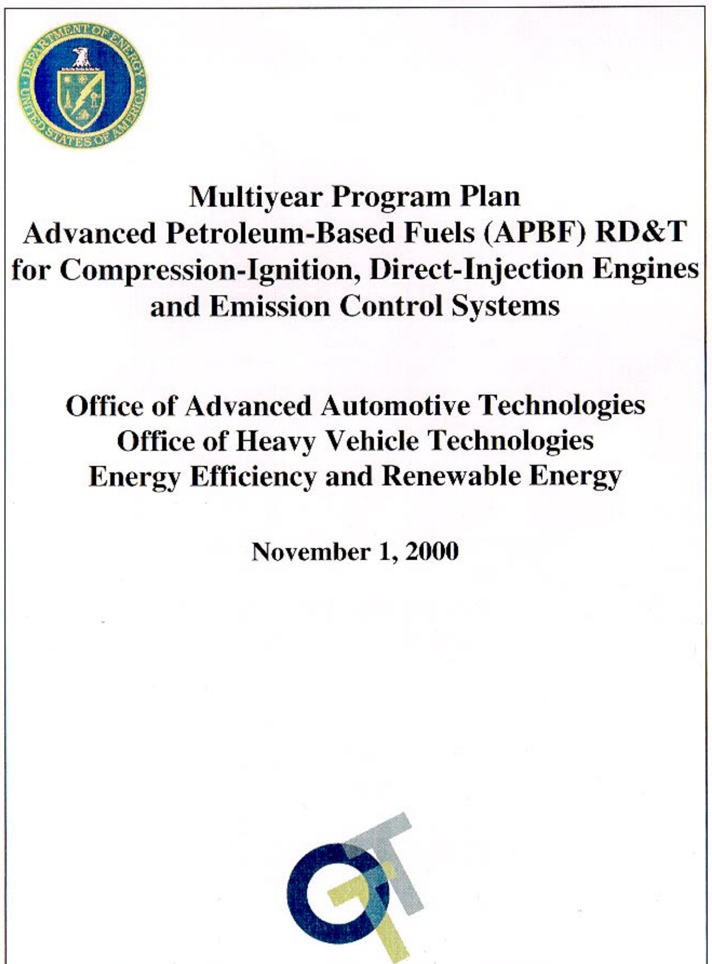
Medium (Class 3-6) Trucks

By 2004, to develop and demonstrate commercially viable vehicles that achieve, on an urban driving cycle, at least ***double the fuel economy*** of comparable current (1999) vehicles, and as a *research goal*, reduce criteria pollutant emissions to at ***least 30 percent below*** EPA standards prevailing in 2004.

Light (Class 1-2) Trucks

To develop by 2004 the enabling technologies for clean diesel engines to be competitive with and ***at least 35-percent more fuel efficient*** than equivalent gasoline engines for light trucks, while meeting Federal and state emissions standards prevailing in 2004.

OHVT/OAAT Advanced Petroleum-Based Fuels Program



Multiyear Program Plan
Advanced Petroleum-Based Fuels (APBF) RD&T
for Compression-Ignition, Direct-Injection Engines
and Emission Control Systems

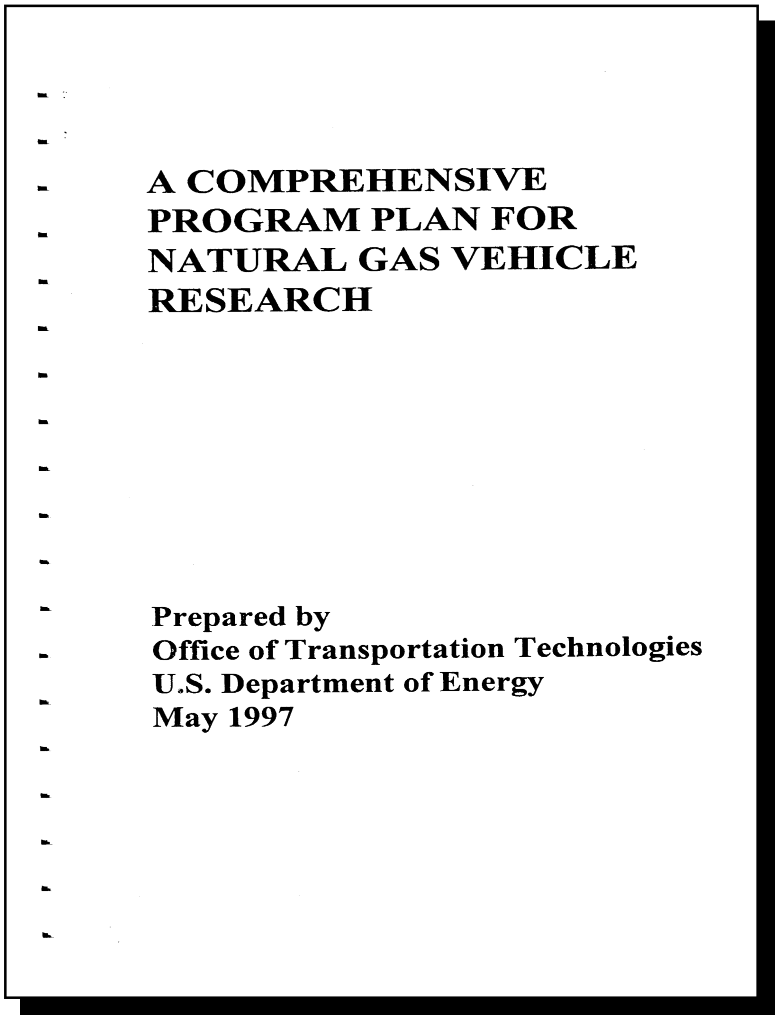
Office of Advanced Automotive Technologies
Office of Heavy Vehicle Technologies
Energy Efficiency and Renewable Energy

November 1, 2000

Mission Undertake, with partners in the energy and transportation industries, research and development which will result in competitive, high performance, low emission fuel options for transportation vehicles.

Goals Identify, develop, and test new fuel formulations for automotive and truck engines that will be needed to simultaneously achieve high fuel economy and low emissions.

Alternative Fuels Program



A COMPREHENSIVE PROGRAM PLAN FOR NATURAL GAS VEHICLE RESEARCH

Prepared by
Office of Transportation Technologies
U.S. Department of Energy
May 1997

Goals

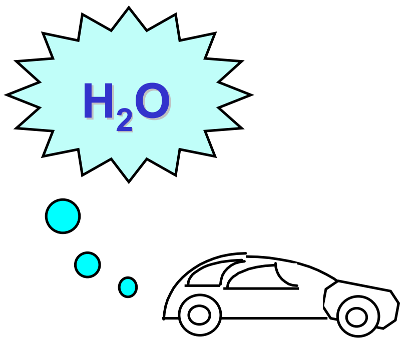
- Develop production-ready prototype vehicles – one Class 3-6 CNG and one Class 7/8 LNG – achieving 2007 emission standards and fully competitive with conventionally fueled counterparts.
- Develop enabling fueling infrastructure technology to promote use of CNG and LNG in medium- and heavy-duty engines.
- Attain capital cost of $70 per DGE for LNG tank.
- Improve average thermal efficiency of NG engines to approach that of diesel engines.
- Understand atmospheric impacts of the use of petroleum-based and alternative transportation fuels.

Fuel Technology R&D Challenges

Alternative Fuels

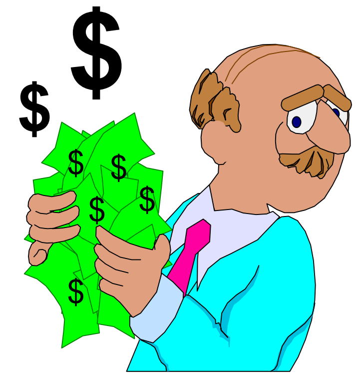
- **Vehicle Integration**
  - A clean-sheet design of Class 3-6 and Class 7-8 trucks will ensure full integration of CNG and LNG technologies in vehicles.
- **Engine Efficiency**
  - Natural gas engines must overcome part-load and throttling efficiency losses to achieve diesel-like efficiencies.
- **Fueling Infrastructure**
  - Advances are needed in cost-reduction, ease of handling, and safety to have full customer acceptance.
- **On-board Storage**
  - Natural gas will have to be stored on-board at considerably lower pressures than current technology to address space and safety concerns.

Fuel Cells For Transportation Program Goal

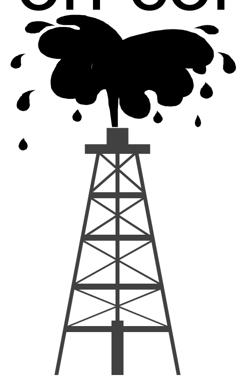


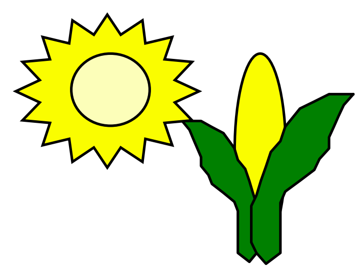
More MPG

Develop highly efficient,
low- or zero-emission,
cost-competitive

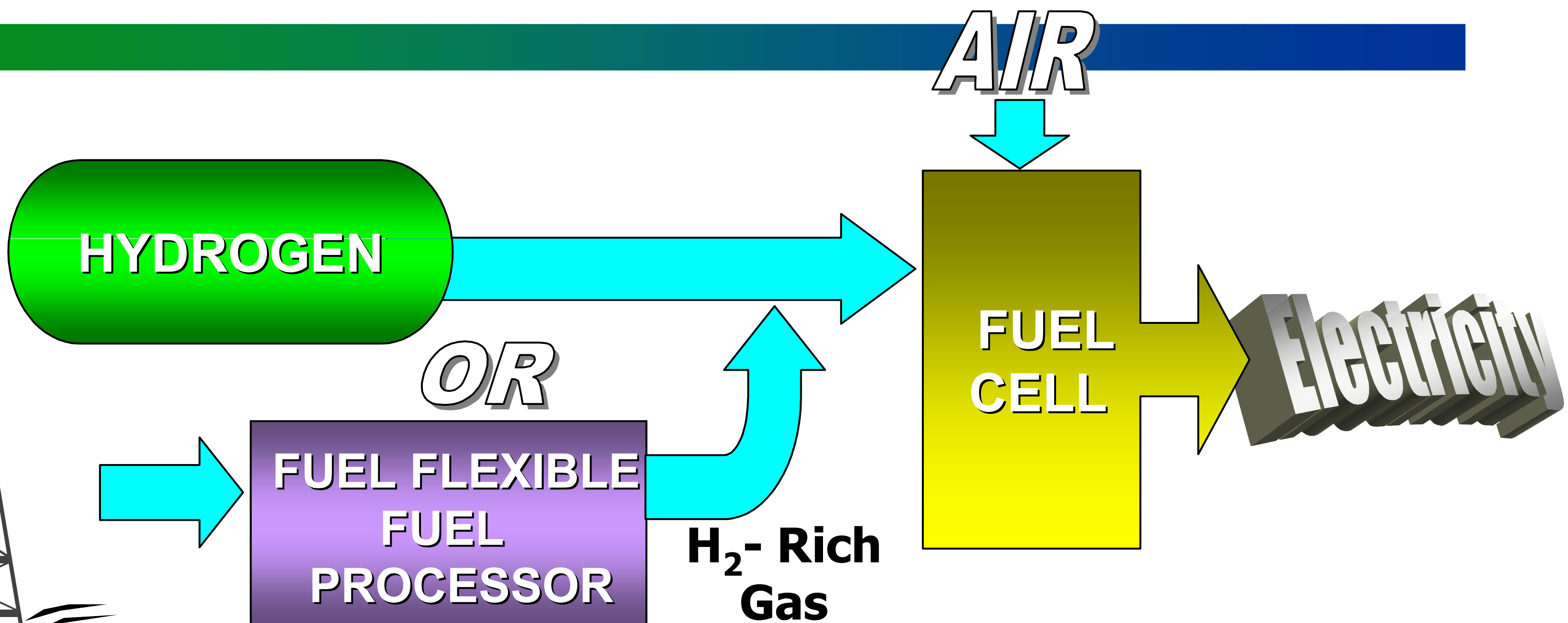


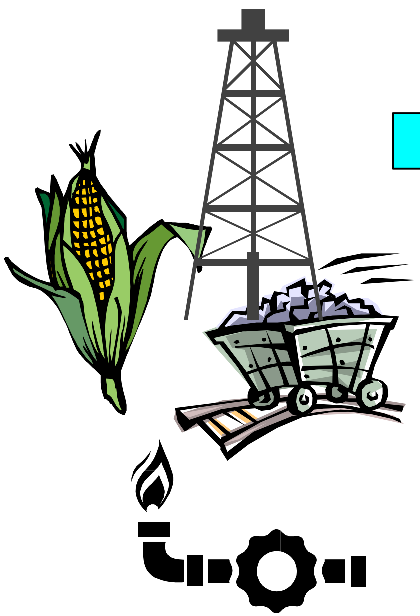
automotive fuel cell power system technologies that operate on conventional & alternative fuels.





Fuel Strategy for Automotive Fuel Cells





- Hydrogen can be stored and supplied directly to the fuel cell: *Storage and Infrastructure Issues*
- Hydrogen can be derived on-board from fuels such as ethanol, methanol, natural gas, gasoline or FT fuels: *Complexity, Cost, and Start-up Issues*

Program is Focused on Critical Technical Challenges

Significant technical and economic challenges will keep fuel cell vehicles from making significant market penetration for up to 10 years.

Major Challenges for Automotive PEM Fuel Cells:

- Cost
- Efficiency (Higher Cell Voltage)
- Air Management (Compressor Technology)
- Startup (Fuel Processor Thermal Mass)
- Thermal/Water Management

Projects and Funding by Budget Category

Systems

- Plug Power/Nuvera
- International Fuel Cells
- Energy Partners, Honeywell
- A.D. Little (Cost Analysis)
- ANL (System Analysis)

FY01: $7.6M

Fuel Processing

- Nuvera
- Hydrogen Burner
- McDermott
- Honeywell
- ADL/Acurex
- ANL, LANL, PNNL

FY01: $21.5M

Stack Subsystem Components

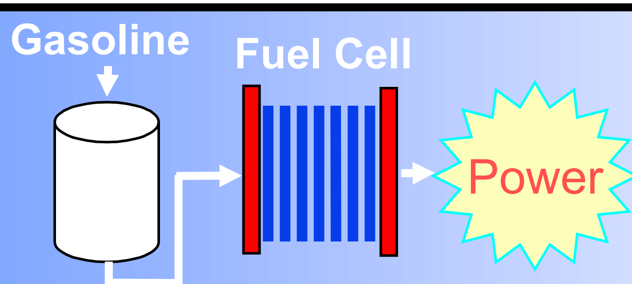
- Energy Partners, AlliedSignal, IFC, Plug Power
- Gas Technology Institute
- 3M, SwRI/Gore, Foster-Miller
- Vairex, A.D. Little, AlliedSignal, Meruit
- LANL, LBNL, NRL, JPL

FY01: $12.4M

Progress in Gasoline Fuel Cell Systems

Full Scale Gasoline Systems Are Being Demonstrated

1997:

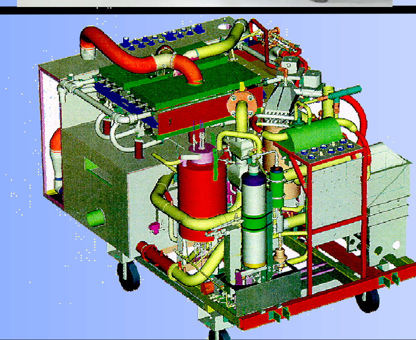


World's First Demonstration of PEM Fuel Cell Power from Gasoline - <1kW

1999:

Plug Power & Epyx (NUVERA) Demonstrate 10kW System on Multiple Fuels Including Gasoline, Methanol, and Ethanol

2000:

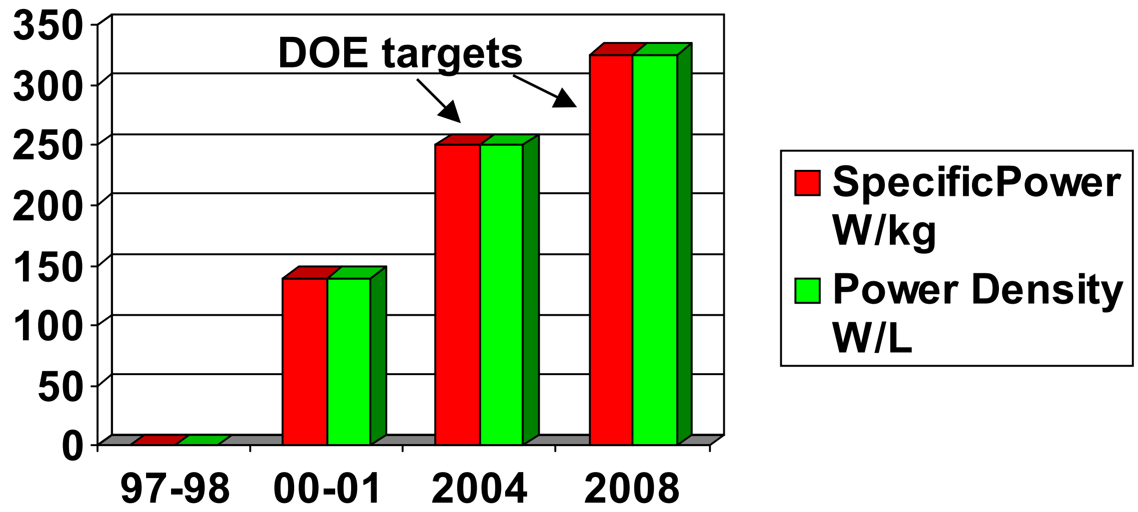


IFC Demonstrates 50 kW, Automated System on Gasoline

Significant Improvements in Fuel Cell System Size and Weight Have Been Made in the PNGV/DOE Program

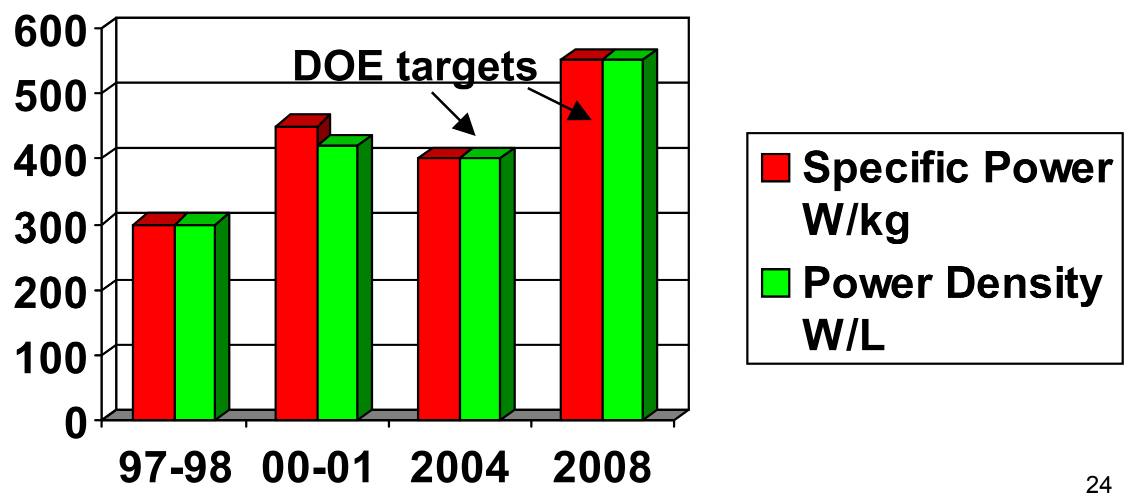
50kW Gasoline Fuel Cell Power System*

- includes stack system, fuel processor, BOP
- gasoline systems and data unavailable in 1997-98



50kW Direct Hydrogen Fuel Cell Power System**

- includes stack, air/water management
- targets are for stack subsystem, i.e. excludes fuel processor, hydrogen storage



*Based on Plug Power

** Based on IFC

DOE is a Member of the CALIFORNIA FUEL CELL PARTNERSHIP

California FUEL CELL PARTNERSHIP

DRIVING FOR THE FUTURE

Goals

- Demonstrate vehicle technology
- Demonstrate the viability of alternative fuel infrastructure technology
- Explore the path to commercialization
- Increase public awareness

Members

- State of California (CARB/CEC/SCAQMD)
- Auto Manufacturers (DaimlerChrysler/Ford/Honda/Hyundai/Nissan/ Volkswagen/General Motors/Toyota)
- Energy Providers (BP/Shell Hydrogen/Texaco/ExxonMobil)
- Fuel Cell Companies (Ballard/IFC/XCELLSiS)
- Associates (Air Products/Methanex/Praxair/Hydrogen Burner/Pacific G&E
- Proton Energy/Stuart Energy/AC Transit/SunLine)
- Federal agencies (DOE/DOT)

SECA-Related R&D

OTT is developing fuel cells for auxiliary power units (APUs) in diesel trucks, and addressing the related technical challenges:

- **Diesel Reforming**
  - eliminate carbon formation
  - remove sulfur and/or develop sulfur tolerant catalysts
- **Solid Oxide Fuel Cells**
  - develop rugged, low cost cell materials
  - reduce startup time

Current R&D efforts are being carried by LANL, NETL, and ANL under the Transportation Fuel Cell Program.
Small businesses and universities will carry out R&D through the Cooperative Automotive Research for Advanced Technology (CARAT) Program.
Analyses of APUs for light and heavy vehicle applications will be conducted.

Summary

- DOE's Office of Transportation Technologies is addressing the key technical challenges in the development of fuel-efficient vehicles for both light duty and heavy duty applications.
- Government-Industry partnerships are critical to the success of OTT's Vehicle Technology Programs.
- OTT's Fuel Cell Program has made tremendous progress; however, major technical challenges remain which prevent the introduction of fuel cell vehicles today.
- The Fuel Cell Program is developing fuel cell and fuel processing technologies in support of SECA.

For more information, visit the OTT Web Site:
www.ott.doe.gov

C. REPORT ON THE SOLID STATE ENERGY CONVERSION ALLIANCE

Joseph P. Strakey, Director, Strategic Center for Natural Gas
U.S. DOE National Energy Technology Laboratory

The Solid State Energy Conversion Alliance

2nd Annual SECA Workshop
March 29th & 30th, 2001

Joseph P. Strakey

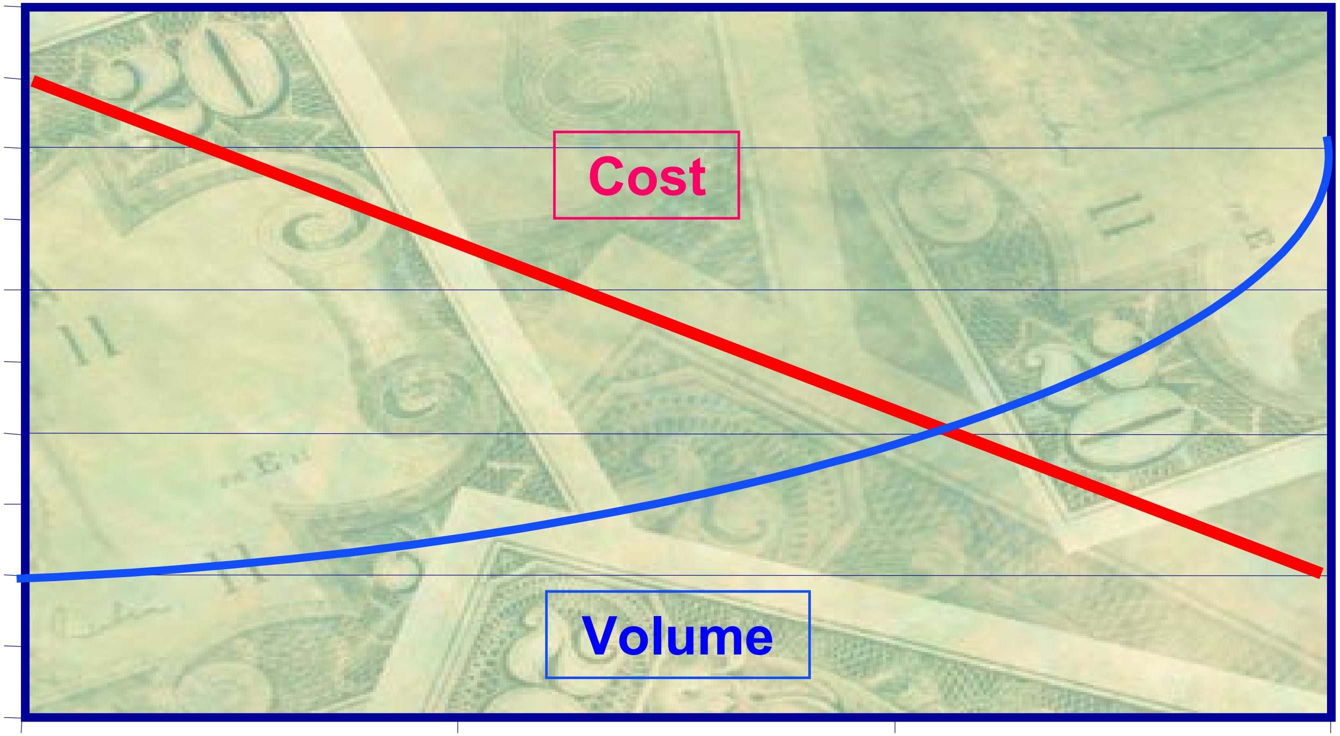
National Energy Technology Laboratory

NETL

Public Benefits

- **Negligible emissions of SO_2, NOx, particulates, VOC using fossil fuels**
- **Double the efficiency of producing power from fossil fuels**
    - **Reduced CO_2 emissions**
    - **Reduced dependence on imported fuels**
- **Reliability of power supply**
- **Multiple fuel capability**

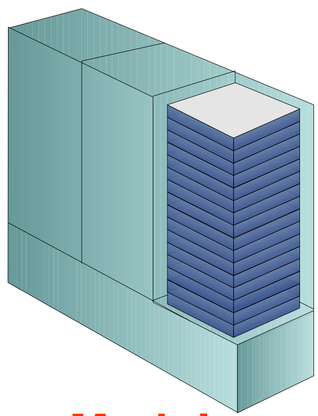
The Vision: *Fuel Cells in 2010*



Low Cost/High Volume
$400/kW/ > 50,000 units/yr

A High Power Density, Low Cost Core Module for Multiple Applications

SECA



Core Module

Transportation

Stationary

Military

Key to Cost Reduction:
Mass Customization of Common Modules

SECA Development: Progressive Applications

2005

- **$800/kW**
- **Prototype ($-Unit) 3 - 10 kW**

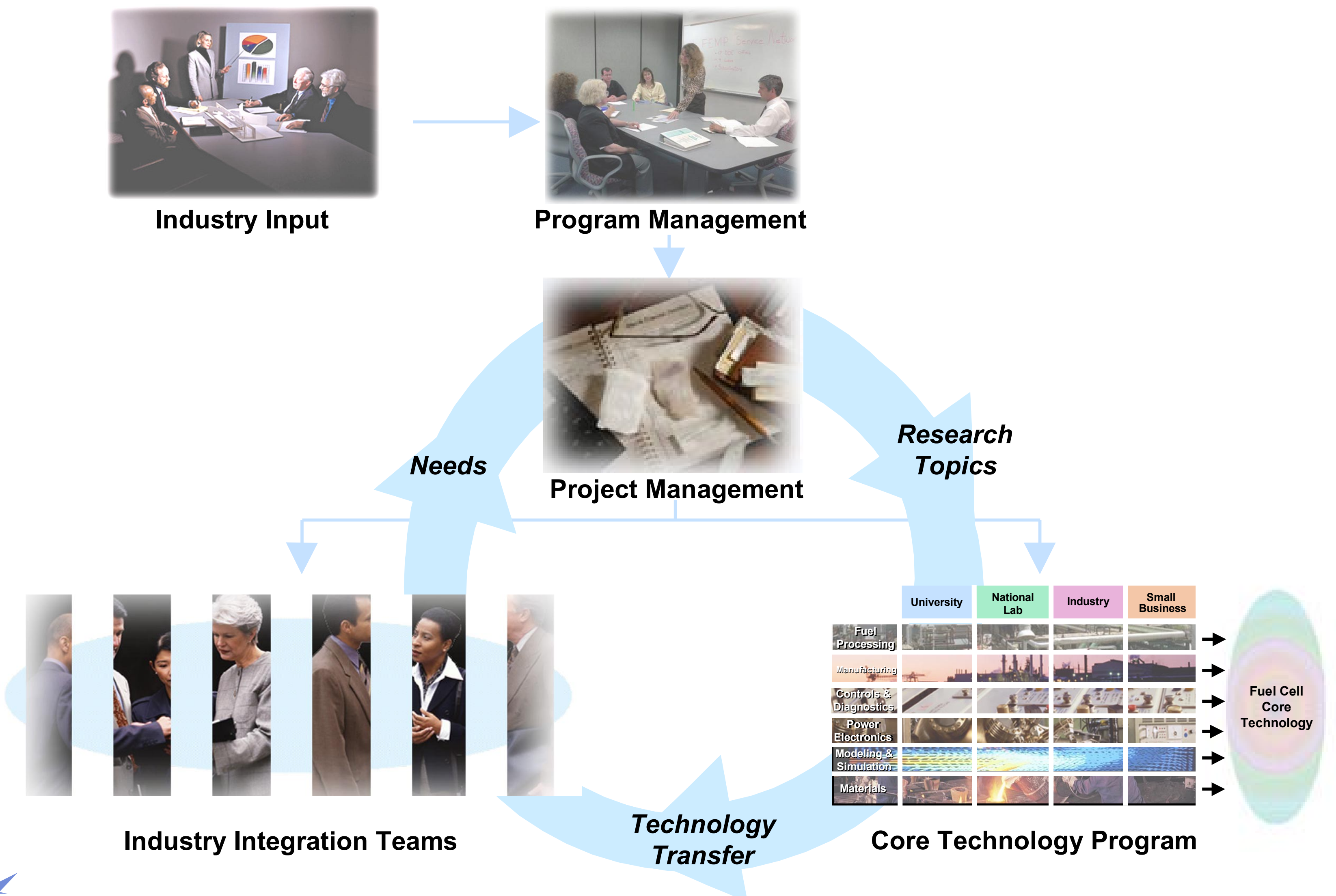
2010

- **$400/kW**
- **Commercial**

2015

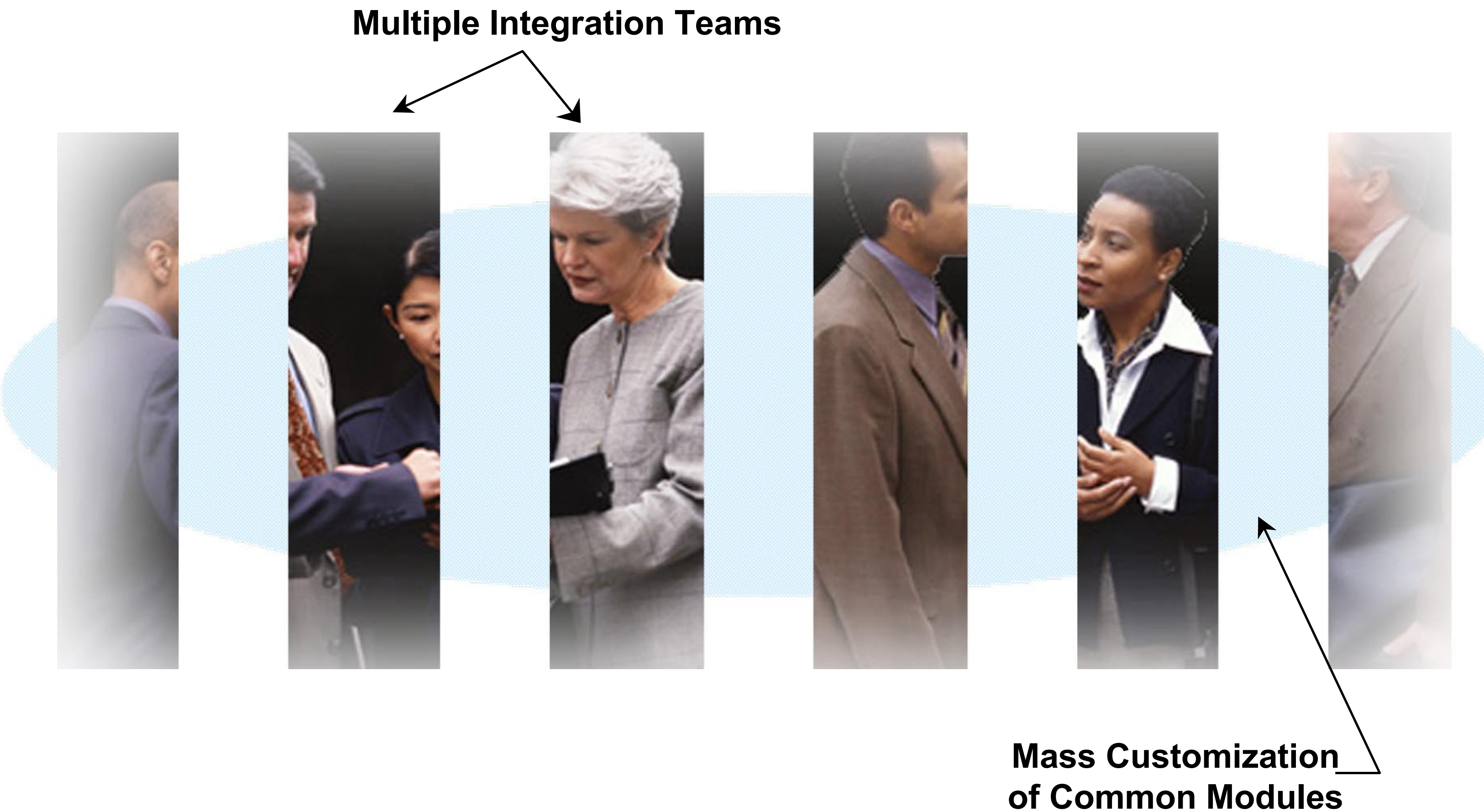
- **Vision 21 Power Plants**
  70-80% efficient plants
- **Propulsion <$200?/kW**

Program Structure



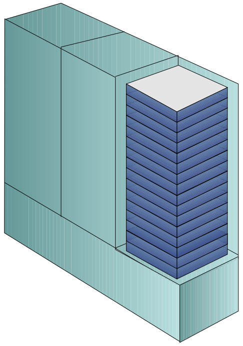
Industry Integration Teams

The Manufacturing Base



Industry Integration Teams

- Three to six competitively selected DOE/DOD teams
- Prototype within four years of award.
- 20% cost share in Phase I 50% in Phase II and III.



Industrial Team Solicitation Components

Technical Approach

Statement of Work,
Milestones,
and Test Plan

Cost Estimate

Capabilities, Facilities,
Team Structure
and Personnel

Market Evaluation and
Applicants
Existing Experience

Industrial Team Minimum Requirements

PHASE III

Power Rating Net	3-10 kW
Cost	$400 / kW
Efficiency (AC or DC/LHV)	30 - 50% [APU] 40 - 60% [Stationary]
Testing (Steady State) :	>1500 hours - 95% availability - Power ≤0.1% degradation/500 hours at a constant stack voltage
(Transient):	>100 cycles defined by application - Power ≤ 1% degradation after 100 cycles at a constant stack voltage

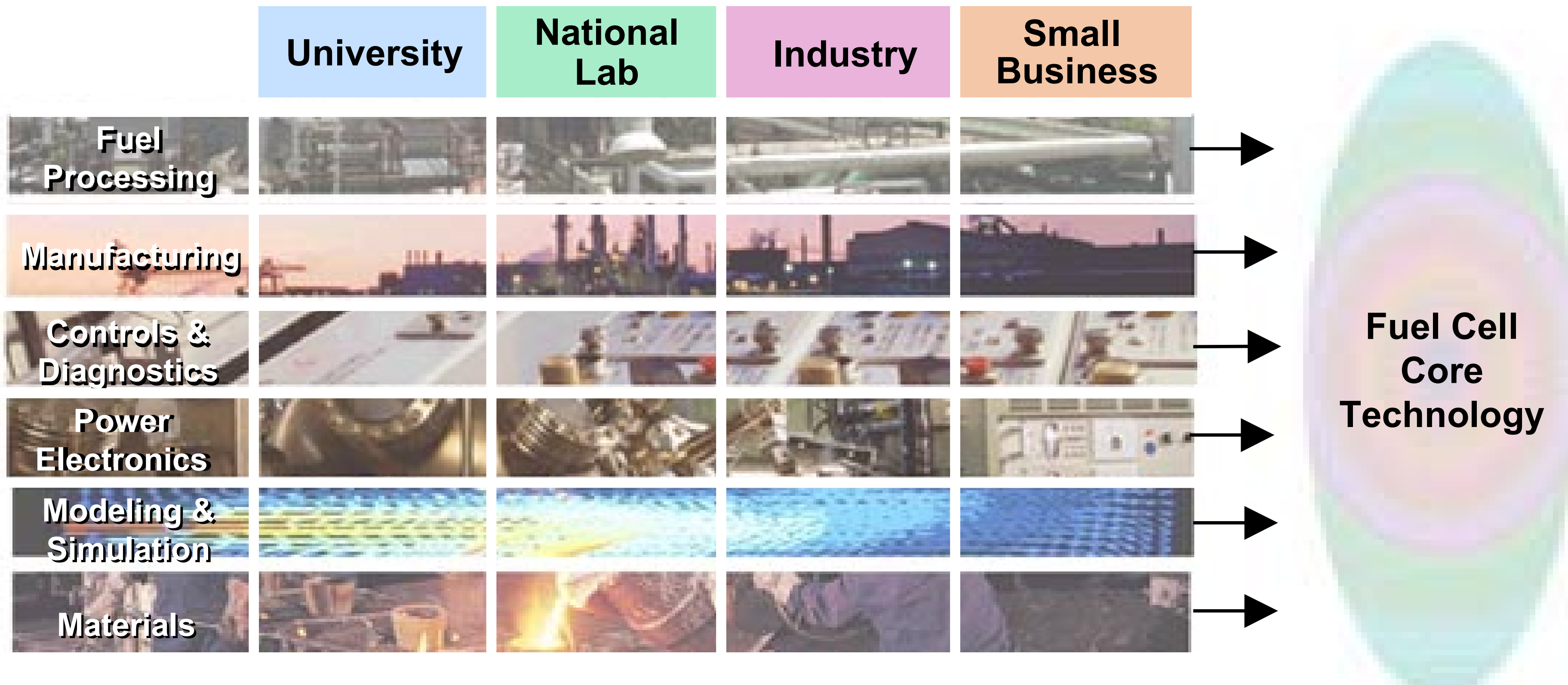
Industrial Team Minimum Requirements

PHASE III

Design Lifetime	5,000 Hours [APU] 40,000 Hours [Stationary]
Maintenance Interval	> 1,000 Hours
Fuels (Current infrastructure)	Natural Gas Gasoline Diesel

Core Technology Program

The Technology Base



Core Technology Program (CTP)

Raising the Technology Baseline.

- CTP developments can benefit all SECA Industrial Teams
- A mix of short (1-2 year) projects that address the needs of multiple Industrial Teams and a few longer term projects that add significant value to all projects.
- Biannual meeting of CTP participants, Industrial Teams, Project Management Team
- Limited Lab Call in FY01
- Solicitation in FY01 for universities and small businesses

Intellectual Property
Cornerstone of the Alliance

- **Non-Exclusive License** — **CTP → Industry Teams**
  - **- Ready market of potential licensees**
  - **- Best designs vs. highest bidder**
- **Promotes Collaboration - Limits Redundancy**

Exceptional Circumstance Provisions

- Each Industrial Team will be offered a non-exclusive license for the IP generated by the Core Technology Program in the SOFC field of use
- Offers must be open for 1 year after issue of a U.S. patent
- Pilot program; reevaluate after 2 years

SECA Players/Efforts

SECA

Universities, National Labs, Industry

McDERMOTT

NEXTECH MATERIALS

Honeywell

ARGONNE NATIONAL LABORATORY

Pacific Northwest National Laboratory

THE UNIVERSITY OF UTAH

NETL

SIEMENS Westinghouse

Arthur D Little

OAK RIDGE NATIONAL LABORATORY

UNIVERSITY OF FLORIDA

BERKELEY LAB

TMI SYSTEMS

UNIVERSITY of MISSOURI-ROLLA

NTCRC

DELPHI

Automotive Systems

NORTHWESTERN UNIVERSITY

Active SECA Projects

- Multi-layered, co-fired, planar, SOFC stack
- Manufacturing technology utilizes high-volume production methods currently employed in the manufacture of multi-layer ceramic packages

Honeywell

- Manufacturing process based on tape calendering for multi-layer planar SOFC using a new Honeywell design concept
- Demonstrate cell performance

Active SECA Projects

Pacific Northwest National Laboratory

- SOFC component development
- SOFC modeling & experimental support
- Prototype small stack testing of developed components and concepts
- Supporting Delphi through CRDA

ARGONNE NATIONAL LABORATORY

- Development of low-temperature cathode materials
- Sulfur - tolerant anode materials
- Metallic bi-polar plates and stack
- Systems modeling

Active SECA Projects

THE UNIVERSITY OF UTAH

- **Theoretical studies and materials work on cathode microstructures while maintaining high-power density performance with standard solid oxide fuel cell materials at reduced temperatures**

NORTHWESTERN UNIVERSITY

- **Revisit the segmented-in-series SOFC design using modern multi-layer manufacturing techniques**

Active SECA Projects

OAK RIDGE NATIONAL LABORATORY

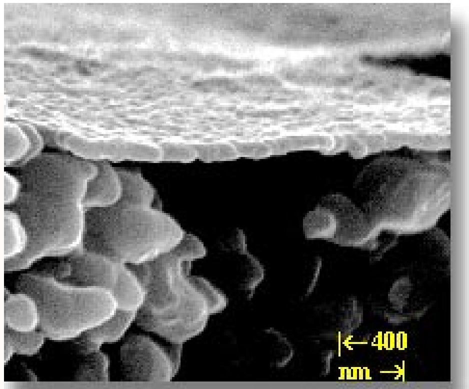
- Anode supported thin film fuel cell development
- Tape casting, screen printing

NETL

- Fuel cell reformer R&D
- Fuel cell modeling and simulation
- Testing of all fuel cell types
- Dynamic hybrid system studies
- Sensors

Active SECA Projects

- Identify, characterize, test new electrolyte materials that have ionic conductivity suitable for use in the 550 - 800ºC range, and are chemically stable at SOFC operating conditions



UNIVERSITY OF FLORIDA

- Develop a stable bi-layer electrolyte for low-T SOFC's
- Develop a detailed kinetic/ thermodynamic/transport model for use in evaluating bi-layer electrolytes and for SOFC cell evaluation

Active SECA Projects

SIEMENS Westinghouse

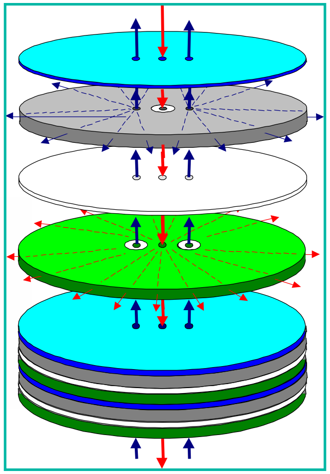
- Evaluate and test the suitability of electrolyte materials for low temperature SOFC operation in combination with cathode materials

NEXTECH MATERIALS

- Research co-sintered electrode supported planar fuel cells, spin coated ultra-thin electrolytes, and co-extrusion of monolithic shapes

Active SECA Projects

TMI SYSTEMS



- Implement a screen-print manufacturing technique for production of complete cells at lower cost

DELPHI

Automotive Systems

- New project selected in FY 2000 (In negotiation)
- PNNL providing technology support through CRDA

SECA Timeline

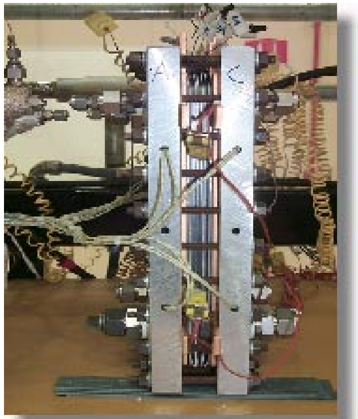
• 1st Annual SECA Workshop	June 1-2, 2000
• Industry Team Solicitation Issued	November 3, 2000
• Proposals Due	January 24, 2001
	January 4, 2002
	January 3, 2003
• SECA Core Technology Program Workshop	February 14 & 15, 2000
• 2nd Annual SECA Workshop	March 29-30,2001
• 2001 Industrial Teams Selected	*May 2001*
• Core Technology Program Solicitation Issued	*May 2001*
• Core Technology Program Review Meeting	*November 2001*

SECA FY01 Funding (millions)

- **FY 2001 Funding - $18.9**
- **Industrial Funding - $ 11.8**
  - FY 2001 Industrial Team Funding - $7.4
  - Multi-Layer Ceramic - $3.7
  - Systems - $0.5
  - Materials - $0.24
- **Core Technology Program - $ 6.7**
  - National Laboratories - $5.4
  - Universities - $0.57
  - FY 2001 - $ 0.68
- **Studies, Workshops, and Support - $0.43**

DOD Interests/Activities

- Core Technology
  - Accelerate development
  - Logistic fuels
- Militarization
  - Survivability, shock & vibration, etc.
- Integration
  - Balance of plant packaging
- Testing
  - Laboratory to field environment



Some SECA-Related Solicitations

- ✓ California Energy Commission PIER Solicitation
- ✓ DOE Office of Transportation Technology CARAT Solicitation
- ✓ NIST Advanced Technology Program
- ✓ EC FRAMEWORK V and VI
- ✓ DOD DARPA Palm Power

EU - US Cooperation

- Transatlantic network supporting research and stimulating co-operation on fuel cells for transportation and stationary applications, including several SECA-related areas:
  - Auxiliary power units
  - Codes and standards,
  - SOFC and high temperature fuel cell hybrid systems
  - Assessment of availability of critical materials for high temperature fuel cells

Responding to the Needs of the Nation

President Bush and I are deeply committed to developing an energy policy that includes . . . developing new technologies that conserve fossil fuels and reduce energy-related pollution.

Spencer Abraham, Secretary of Energy

D. European Perspectives for Fuel Cells in the EU/US

Gilles Lequeux, Scientific Officer, Fuel Cells and Hydrogen Technologies
European Commission

FP5 (1999-2002) - The Energy Content - Overview

Clear Policy Targets:

- Energy oriented by doubling the Share of Renewable Energy Sources (from 6% to 12% in 2010 versus 1998) also contributing to the security of our energy supply;
- Environmental incentives to meet the Kyoto Objectives (8% CO_2 reduction between 2008 and 2012 compared to 1990 level);
- Socio-economic measures recognising the impact of energy systems on competitiveness, employment, cohesions of regions,...

ENERGY

Why Fuel Cells is so important ?

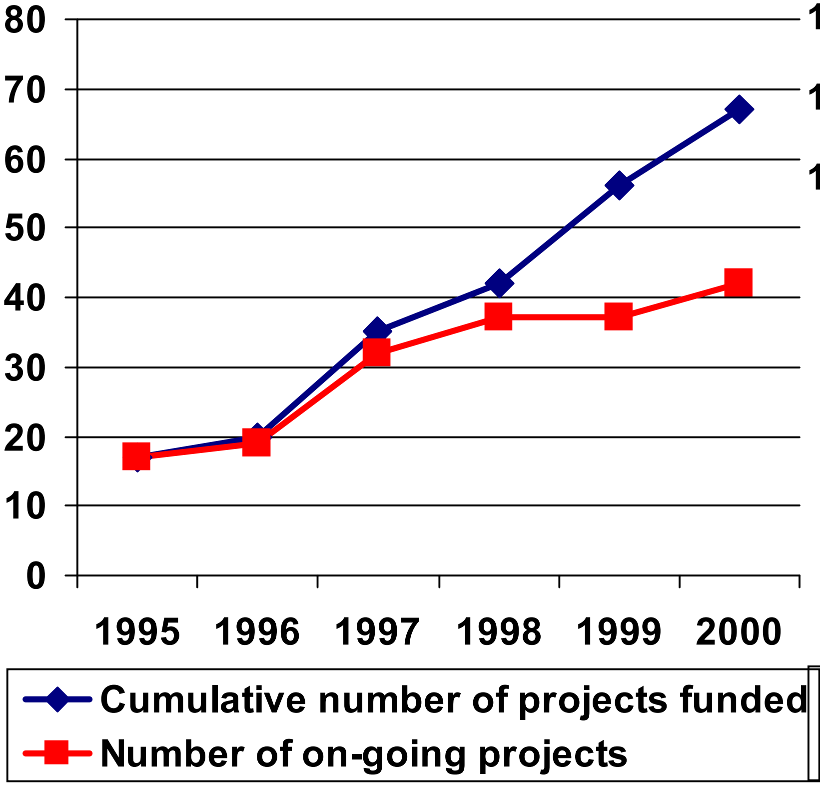
A Cleaner and more efficient technology:

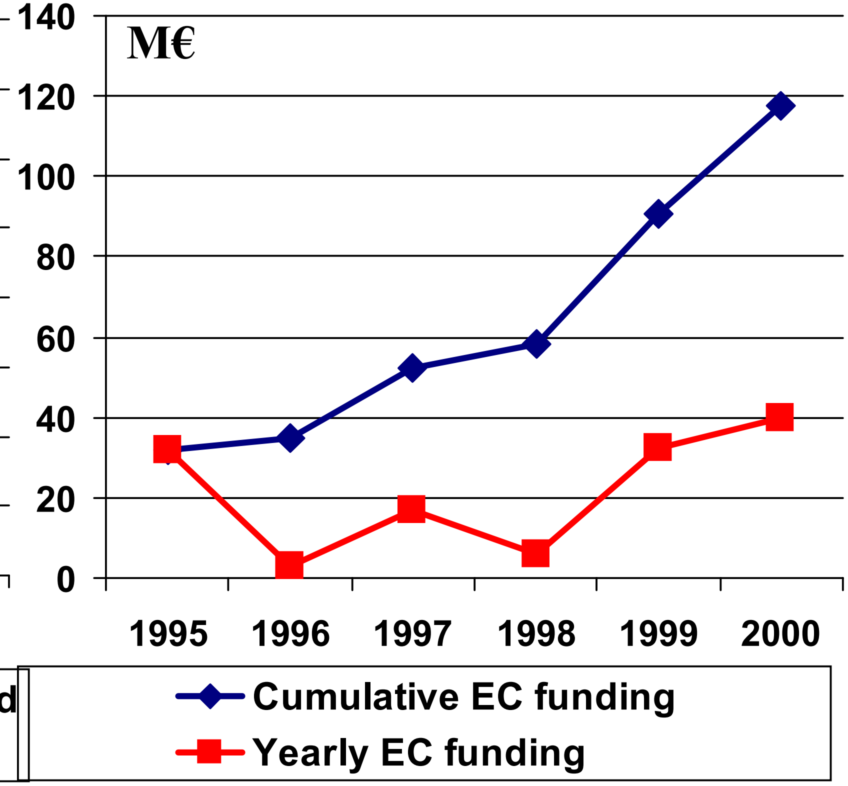
- **Superior to combustion technologies** (Automotive industry, power generation, heat and electricity supply in homes, commercial/business buildings and industries, portable devices);
- **Contribution to the EU Energy policy** (energy savings, environment respectful, sustainable and security of energy supply especially with hydrogen;

The current challenge sill remains

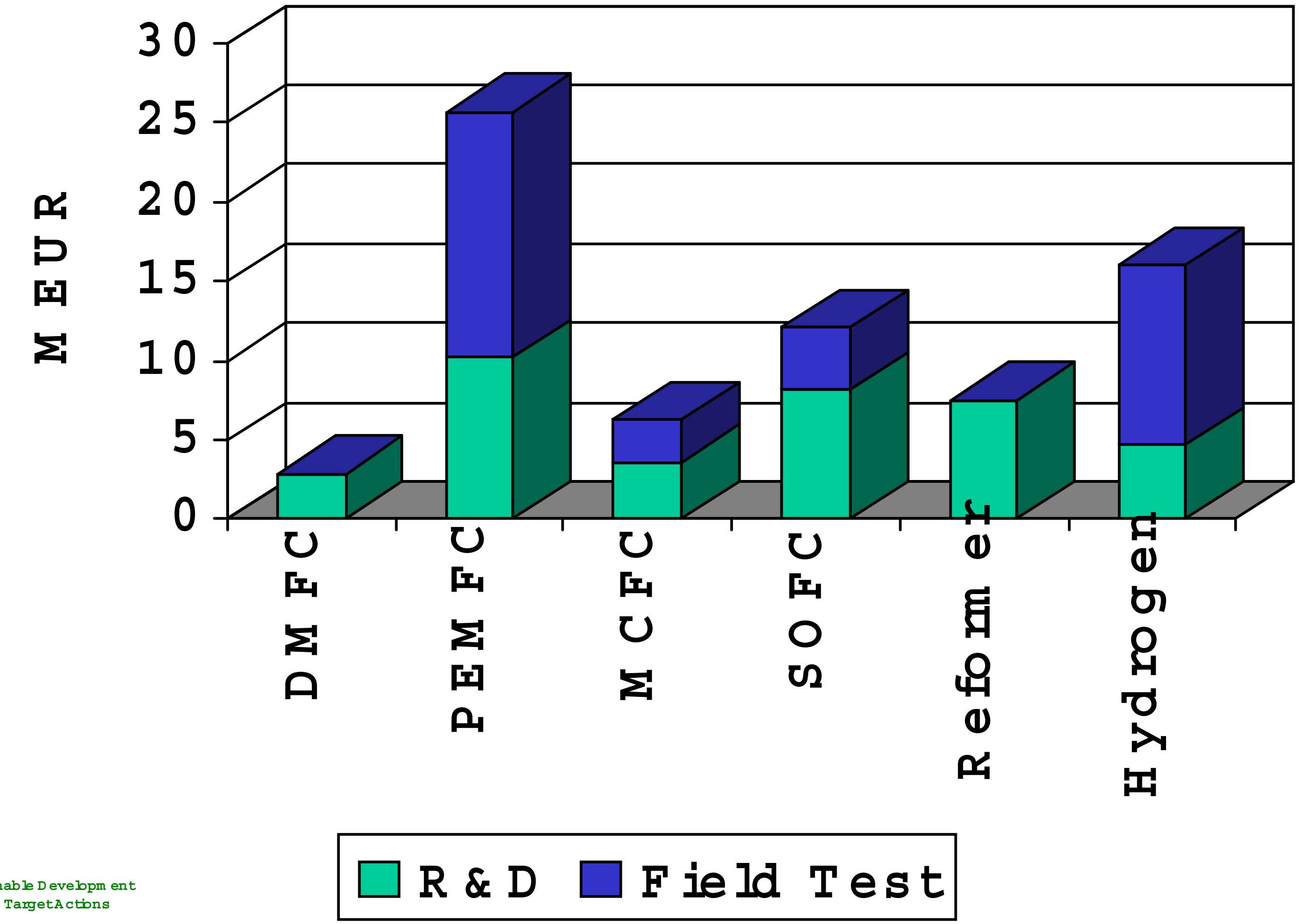
"Cost Reduction"

Dynamic of the Fuel Cell EU support since 1995

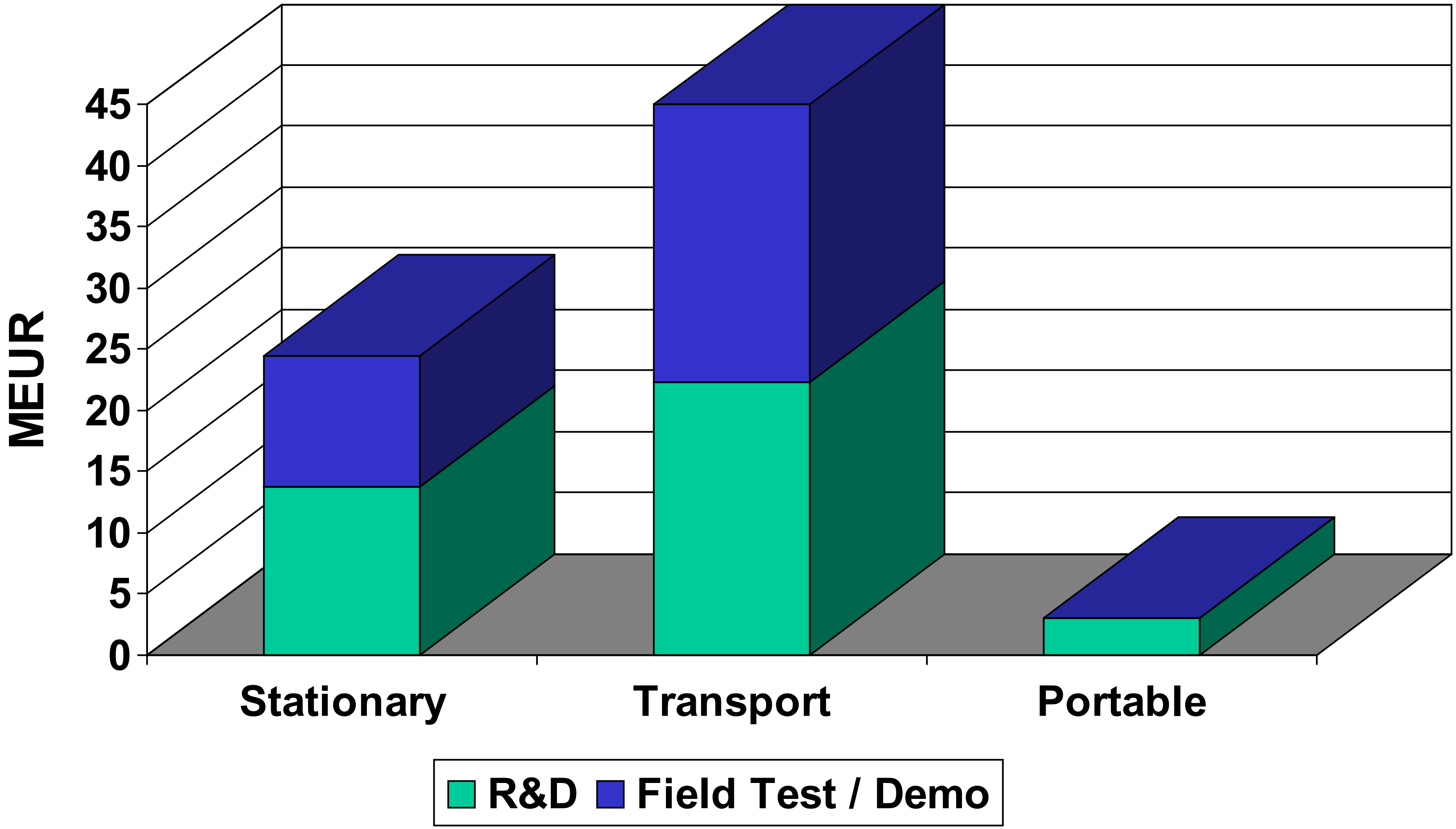




EC support to Fuel Cell and Hydrogen technologies 1999-2000



EC support to Fuel Cell and Hydrogen technologies 1999-2000



Overview of Fuel Cell yearly public funding in Europe (All types)

DE	FR	ES	IT	DK	UK	SE	SW	Total MS(1)	EU (EC)	Total (EU)
MEUR	MEUR	MEUR	MEUR	MEUR	MEUR	MEUR	MEUR	MEUR	MEUR	MEUR
8	**11,5**	**3**	**2,3**	**2,7**	**2(2)**	**0,7**	**1**	**~31**	**~30**	**~61**
SOFC MCFC PEMFC	**All types**	**PEMFC MCFC**	**SOFC, MCFC, PEMFC**	**SOFC**	**SOFC, PEMFC**	**SOFC, MCFC PEMFC**	**SOFC, PEMFC PAFC**		**SOFC, PEMFC DMFC in M/LT All types in ST**	

(1) : European Member States
(2) : New programme 2001-2005 starting

Status of SOFC development in Europe

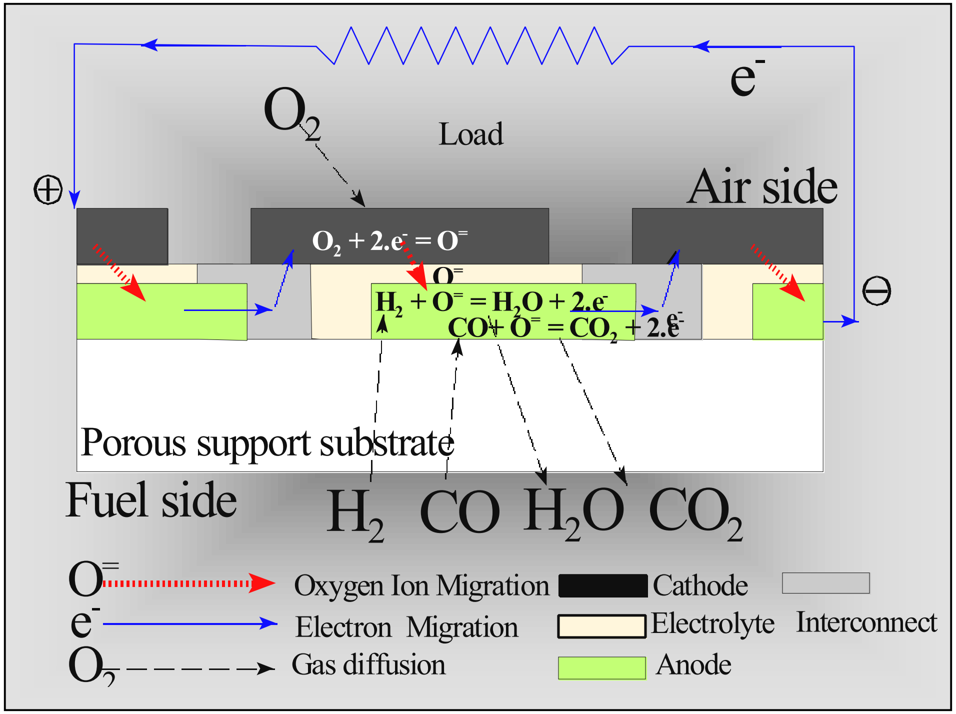
Planar				
One cell per planar surface		**Many cells (matrix or series) per planar surface**		
Metallic inter-connectors		Ceramic inter-connectors	Metallic inter-connectors	Ceramic inter-connectors
Thick electrolyte	Thin electrolyte	Thick electrolyte	Thick electrolyte	Thick electrolyte
Sulzer Hexis (1 kWe, 2000, 70 cells, 270 mA/ cm^2 0.175 W/cm^2 900°C, x% NG) **ECN** (0.09 kW, 2000, 5 cells, 250 mA/cm2, 950 °C, steam ref. NG at SCR=2.5)	**Forshungs Zentrum Juelich** (1.6 kW, 2000, 10 cells, 610 mA/cm^2, 800°C, 44% H_2) **ECN** (0.054 kW, 2000, 3 cells, 250 mA/cm^2, 800^{o}C, 4g/hr/cell ref CH_4 **Risø** (0.47 W/ cm^2, 1999, 1 cell, 560 mA/cm^2,0.7 V 850°C, 97% H_2)	**Risø** (0.5 kW, 1995, 50 cells, 300 mA/cm^2, 1000°C, 40% H_2)	**Siemens (stopped)** (7.2 kW, 1998, 2 stacks of 50x4x4 cells, 400 mA/cm^2, 900°C, 30% H_2)	**Rolls Royce** (1 kW, 2000, 27x 20 cells 385 mA/cm^2, 970°C, x% H_2)

A 5 kWe scale SOFC stack PRoof of Concept (PROCON)

- Investigate critical issues for a 20 kW system
- Develop and test of a 5 kW stack
- Anode supported-cells (~800 °C)
- Period : 2000-2002
- EU support : 1,5 M€

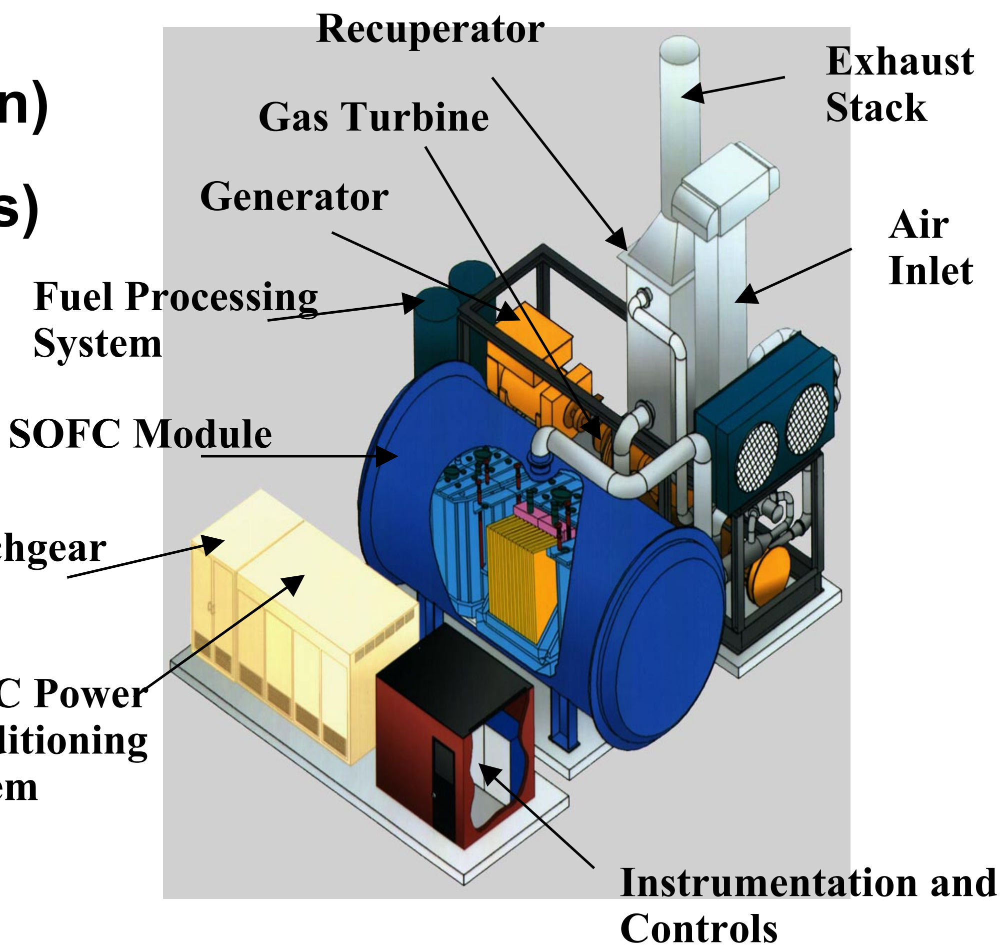
A 20 kWe Multi-Functional SOFC stack (MF-SOFC)

- Design of a power system : 200 - 500 kW
- Develop and test of a 20 kW stack
- Modularity of stack
- Period : 2000-2003
- EU support : 3,5 M€



1 MWe Hybrid SOFC/µGT

- **Demo** (EU/US co-operation)
- **Efficiency > 55 %** (gross)
- **Power system**
- **3 bar Pressure**
- **Period : 2000-2003**
- **EU support : 4 MEUR**



(Copyright from SIEMENS)

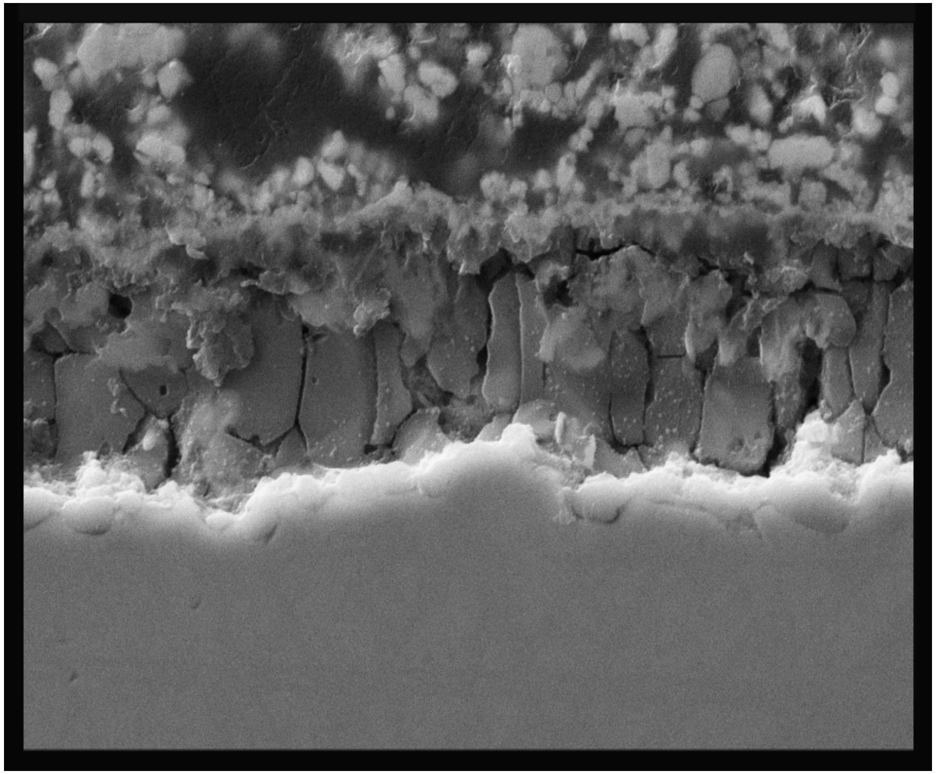
Integrated Modelling Study of Fuel Cell/Gas Turbine Hybrids (IM-SOFC-GT)

- **Assessment of product requirements and viability by combining market understanding and integrated modelling capabilities**
- **Obtain specifications for FC stack and turbo-machinery + key BoP components**
- **Sub-MWe high efficiency distributed generation systems, 1-3 MWe systems for cogeneration, 20-30 Mwe high efficiency systems**
- **Period : 2001-2003**
- **EU support : 1.2 MEUR**

Component Reliability Of SOFC Systems for Commercial Operation

CORE SOFC

- Planar with ferritic steels as interconnects
- Degradation rate
  < 0.75 % per 1000 hrs
- Thermal cyclability
  < 0.75 %degradation
  after 20 temp. cycles
- Period : 2001-2004
- EU support : 2 M€



(Not satisfying interface between interconnect and ceramic)

Stationary small to large scale Heat & Electricity Production, power generation”

Modelling/Simulation Product definition/requirements

IM-SOFC-GT

Industrial Development

Rolls-Royce
Turbec
ABB Turbo
Alstom Power
Turbomeca
Sydkraft
Enel

Applied Research

Univ. Genova
Univ. Lund

SOFC Materials

CORE-SOFC

Industrial Development

ECN/Indec
Rolls-Royce
Haldor-Topsoe

Applied Research

Risoe
FZJ

SOFC System

MF-SOFC

Industrial Development

Rolls-Royce
Advanced Ceramics
Gaz de France

Applied Research

Risoe
Imperial College

SOFC System

PROCON

Industrial Development

Alstom
Prototech

Applied Research

FZJ

Mass Deployment of cheap and reliable modules

'Strategy' Goals for RTD - FP5

- **Qualitative :** Cost reduction
  Improve life time of critical parts
  Contribute to solve the fuelling options
  (fuel choice and re-fuelling infrastructure)
  Pre-normative / socio-economic

- **Quantitative :**

	Stationary	Transport
– System cost	< 1.000 EUR/kW	< 100 (50) EUR/kW
– life time	50.000 - 100.000 hrs	> 5.000 (10.000) hr
– Modularity	< 300 kW	

A FUEL CELL RESEARCH, DEVELOPMENT & DEMONSTRATION STRATEGY up to 2005 (2)

- All fuel cell types are in principle considered (application and problem solving oriented programme);
- Applications for Low temperature FC will address in transport the road, rail, marine + hybrid vehicles and in stationary the co-generation in buildings and decentralised electricity production and portable devices;
- Applications for high temperatures FC (including the combination with turbines) will address de-centralised electricity production and co-generation in buildings and process industry, large scale power generation in stand alone or grid connected mode + possibly APU;

A FUEL CELL RESEARCH, DEVELOPMENT & DEMONSTRATION STRATEGY up to 2005 (3)

- In transport, research should address the fuel choice problem (methanol, NG, gasoline-naphta, diesel) and infrastructure.
- In stationary electricity production and co-generation, the multi-fuel capability and flexibility should be addressed and explored as well as the capturation of CO2 + reversible electrolysers;
- In buildings, special attention should be given to fuel cell applications for co-generation and HVAC, adapting heat and electricity supply to the demand including the integration with heat pumps, electrolysers, storage systems,…
- Socio-economic and pre-normative research

Possible areas for EU/US co-operation

Organisation profile	Industrial Manufacturer	National Laboratories	Academia	End-User / Utility
Potential interest				
Pre-normative research to support the development of standards and norms for : - safety, - quality, - test procedures, -performance measurements…				
Technology mapping				
Market penetration analysis				
Other(s) :				
Field testing				
Stand-alone SOFC				
Advanced hybrid fuel cell system (SOFC/GT)				
Auxiliary Power Units				
Residential fuel cell system				
Other(s) : UPS				
Applied Research				
Optimization of system integration				
Low temperature Solid Oxide fuel Cells				
Anode stability				
Improvement of key materials				
Modeling and simulation				
Power electronics				
Cell & stack Manufacturing				
Other(s) :				
Interconnects				
Specialist GTs for fuel cells recuperators				

Possible areas for EU/US co-operation on SOFC

- Interest from 13 key EU organisations (IN, nat. lab., Univ. End-users);
- Industrial key players
  - ➤ Market penetration analysis
  - ➤ field testing of stand-alone systems
  - ➤ research on BoP optimisation, low temp. SOFC, improvement of key materials, modelling & simulation, cell& stack manufacturing
- End-users
  - ➤ technology mapping, market penetration analysis, pre-normative research, system optimisation
- National lab.
  - ➤ Steel optimisation for interconnects / dev. of SOFC for APU
- Academia
  - ➤ Low temperature SOFC, BoP optimisation & modeling, improved key materials

Forms of possible co-operation

- Coordinated or joint research projects;
- joint studies,
- joint organisation and participation in workshops, seminars with exchange of informations
- setting-up of trans-national networks or setting-up of coordinated platform between US and EU existing or new coming alliances or networks
  - ➤ April-may 2001 : signature of a EU/US implementing arrangement
  - ➤ EU financial support to EU organisations still possible (14/12/01) - see www.cordis.lu

Innovative approach for 2001-2002

- Concentration of ~60% of budget around a core set of Target Actions (including FC)
- General call (covering all types of Fuel Cells) with identification of a limited number of priorities of strategic importance for EU (~40% of budget being part of a general call)
- clear differentiation on problems and technologies to be used within short term (less than 5 years) and medium-to-long term

(*) : TA and the general call concern RTD projects, TN and CA.

Target Actions - FP5 (1999-2002)

Short-term

(Results exploited < 5 years - demo)

- Application driven fuel cells
- Bio-electricity
- Sustainable Communities
- Clean Urban Transport
- Eco-buildings
- Gas Power Generation

Medium to long-term

(Results exploited > 5 years - R&D)

- Fuel Cells and H_2
- Bio-energy
- Integration
- Cleaner fuels for transport
- Storage
- PV

Indicative timetable and budget

Target Actions

60% of total budget (~ 290 MEUR)

Short-Term 50% of total Target Action budget	Medium to Long-Term 50% of total Target Action budget
4th call: ID "TA-ST"	5th call: ID "TA-MLT"
1st closing date: 15.03.2001 Budget: ~70 Meuro	1st closing date: 15.02.2001 Budget: ~70 Meuro
2nd closing date: 14.12.2001 Budget: ~75 Meuro Topics covered: •Application Driven Fuel Cells •Bio-electricity •Eco-buildings	2nd closing date: 14.12.2001 Budget: ~75 Meuro Topics covered: Fuel Cells and hydrogen •Bio Energy •Integration •Cleaner fuels for transport •Storage •Photovoltaic

Short-term (FP5)

Application driven fuel cells

➘ Demonstrate technical and economical viability of innovative FC concepts and of new energy systems combining FC, RES and H_2 infrastructure

- introduction of FC systems in intermediate markets (niche, islands,…); use of FC in industry (CHP, peak shaving, on-site premium power, … benefits due to BoP simplification and on maintenance); domestic/commercial (distributed Fuel Cell networks)
- test-beds for various re-fuelling infrastructures including H2 (production, distribution, storage, safety, standards)

medium to long-term (FP5)

Fuel cells and hydrogen

↘Introduction of fuel cells in a RES and H_2 based supply scenario by reducing cost

- RTD on Proton Exchange Membrane Fuel Cell and related Direct Methanol Fuel Cell and Solid Oxide Fuel Cell and related technologies (reformers, H_2 storage) for stationary, portable and mobile applications (cells, stack, BoP)
- Fuel choice and infrastructure (cost, emissions, safety,…)
- Multi-fuel capability and fuel flexilbility for stationary fuel cells
- socio-economic and pre-normative research (norms and standards on safety, regulation,testing procedures,…)

ENERGY

Indicative timetable and budget

General Call

40% of total budget (~ 215 MEUR)

Short-Term 50% of total Target Action budget	Medium to Long-Term 50% of total Target Action budget
6th call: ID "GEN-ST"	7th call: ID "GEN-ML"
1st closing date: 15.03.2001 Budget: ~45 Meuro Topics covered: short-term actions covering all areas of the WP	1st closing date: 15.02.2001 Budget: ~45 Meuro Topics covered: Medium to long-term actions covering all areas of the WP
2nd closing date: 14.12.2001 Budget: ~50 Meuro Topics covered: short-term actions covering all areas of the WP	2nd closing date: 14.12.2001 Budget: ~75 Meuro Topics covered: Medium to long-term actions covering all areas of the WP

Priorities of Strategic importance to the EU

- Management of Greenhouse Gases emissions and climate change
- Exploiting the potential of new ICTs in energy RTD including e-science issues
- Socio-economic research related to energy technologies and their impact
- International co-operation, co-ordination with MS research programmes and EU wide research networks
- Pre-normative research of interest at EU level

The New Framework Progarmme (2003-2006)

➘Designed to promote the setting up of ERA

❒Status : EC proposal to EU Parliament and Council

❒Overall budget : 16,3 BEUR

❒Fuel Cell content : in Sustainable Development and Global Change (Budget 1,7 BEUR)

- ❒ short term :
  - - RES, energy economies, energy efficiency (urban environment and clean transport)
  - - intelligent transport (rebalancing and integration of intermodality)
- ❒ long term :
  - - Stationary & Mobile Fuel Cells
  - - Hydrogen technologies
  - - solar photovoltaic technologies & biomass

The New Framework Progarmme (2003-2006)

➘Designed to promote the setting up of ERA with 3 main instruments

- ❒ Netrworks of excellence
- ❒ Large-scale integrated projects (> 10 MEUR)
- ❒ Participation of EU in MS research programmes
  - ❒ with stimulation of International co-operation with third countries (particularly S&T agreements)

E. A DARPA PERSPECTIVE ON SMALL FUEL CELLS FOR THE MILITARY

Robert J. Nowak, Program Manager
U.S. DOD, Defense Advanced Research Projects Agency

"A DARPA Perspective on Small Fuel Cells for the Military"

Defense Sciences Office

Presented at the

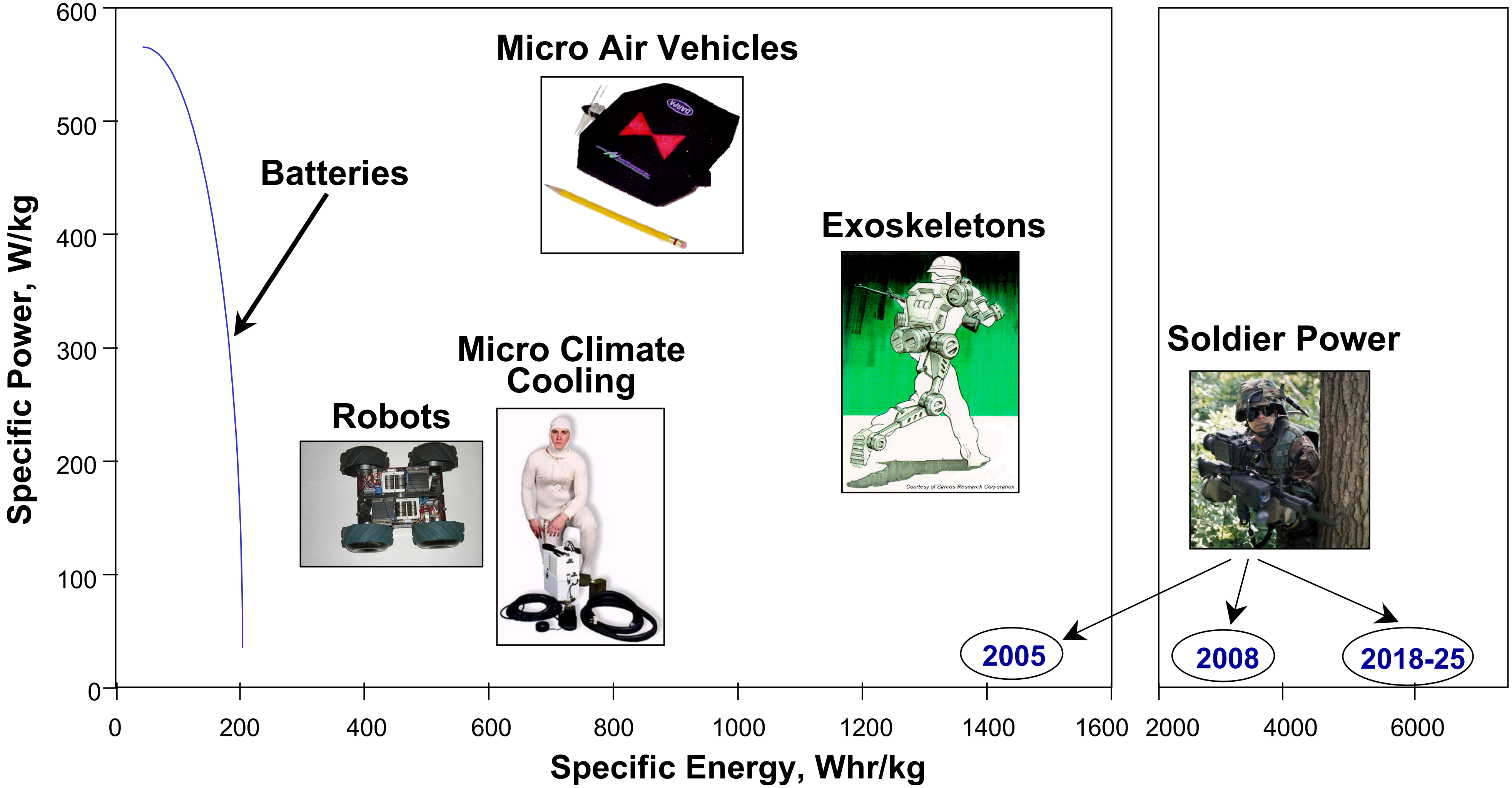
SOLID STATE ENERGY CONVERSION ALLIANCE (SECA) WORKSHOP

Arlington, VA
29 March 2001

Robert J. Nowak, Ph.D.
Defense Advanced Research Projects Agency (DARPA)
Defense Sciences Office
(703) 696-7491 (voice)
(703) 696-3999 (fax)
RNOWAK@darpa.mil

Performance Shortfall for Today's Power Sources

Defense Sciences Office

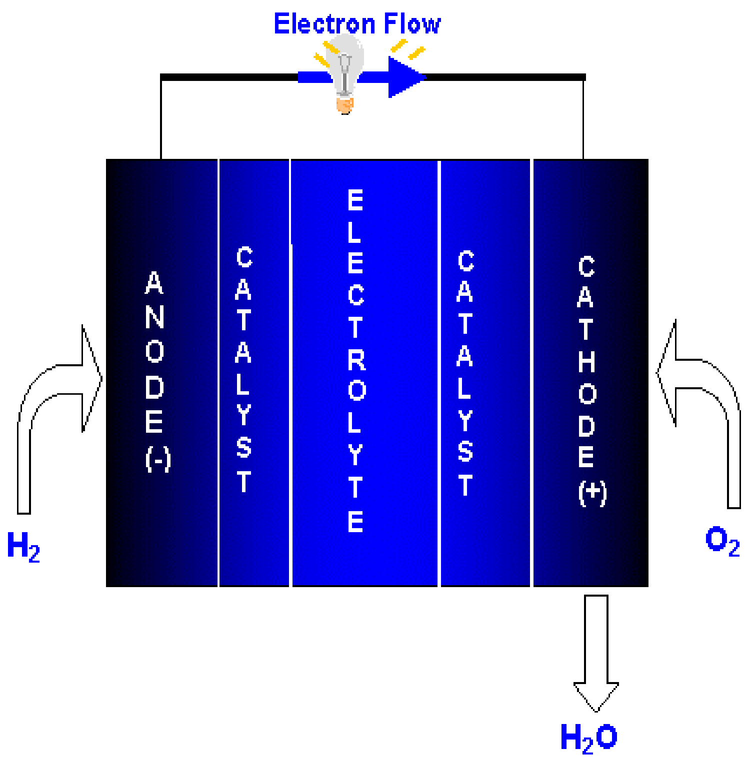


Energy Conversion Technologies Considered For Portable Power Applications

Defense Sciences Office

<u>Electrochemical</u> $\varepsilon \sim 100\ \%$

- Fuel Cells



<u>Heat Engines</u> $\varepsilon = [(1 - T_L/T_H) * 100]\ \%$

Dynamic Systems

- Piston
- Turbines
- Stirling

Static Systems

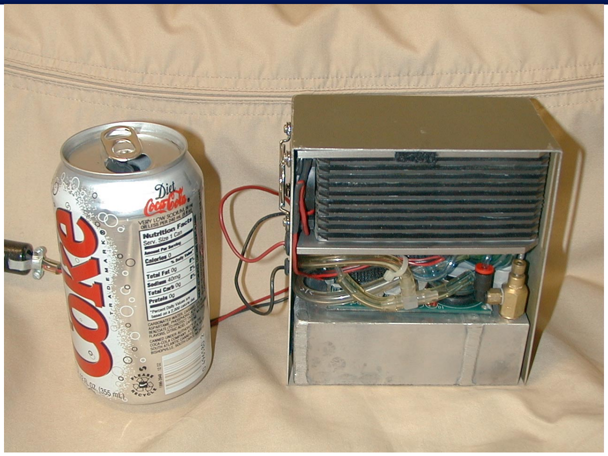
- Thermoelectrics
- Thermionics
- Alkali Metal Thermal to Electric Conversion
- Thermophotovoltaics

Fuel cells promise earliest but not only opportunity

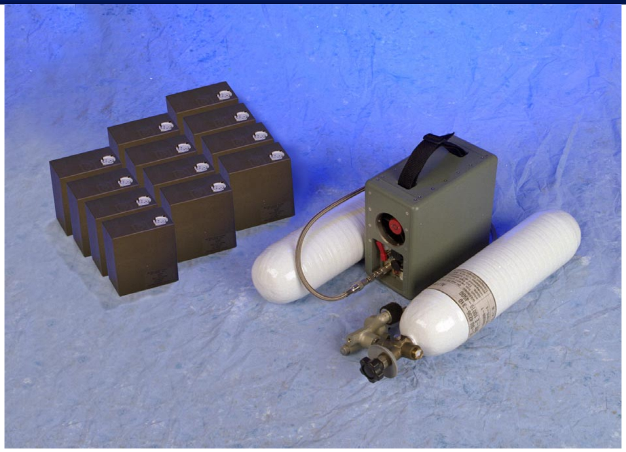
DoD Compact Fuel Cell Evolution

Defense Sciences Office

<u>1992 – H_2 Stack</u>
- 15 W
- 5 pounds



<u>1996 - H_2 System</u>
- 40 W / 90 Wh
- 3.5 pounds
- Metal Hydride



<u>1998 - H_2 System</u>
- 50 W/ 2 Kw-hr
- 7.5 lbs
- Compressed Hydrogen

<u>2000 – DMFC Stack (2001 - System)</u>
- 70 W
- 2.2lbs (goal)

<u>Future - SOFC</u>

The Fuel is ***<u>the</u>*** Issue

Marine Corps Air Ground Combat Center
29 Palms, CA, Fall 1999

TRAINING

Fuel Cells aboard Humvee

PRC-119 Radios

MILITARY EXERCISE

Retransmission Site

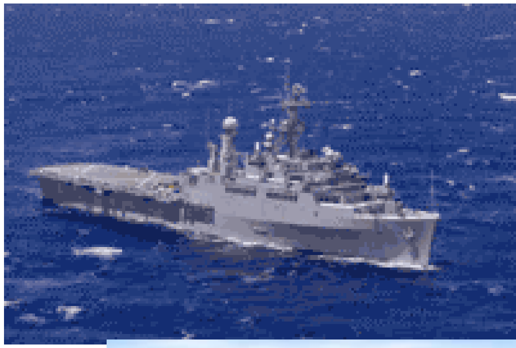
COST ESTIMATE FOR ONE DAY, ONE RETRANS SITE

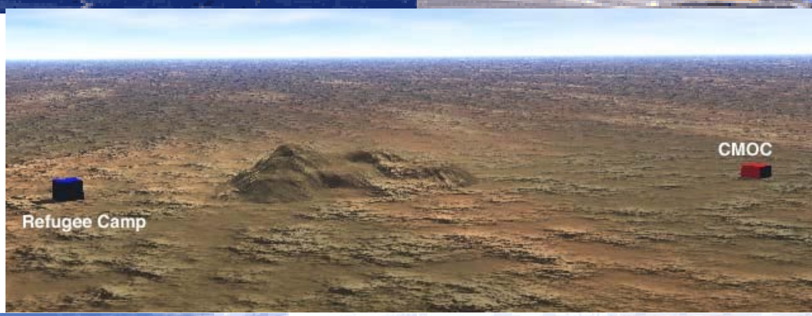
- **BA5590 BATTERIES = $900**
- **FUEL CELLS = $26**

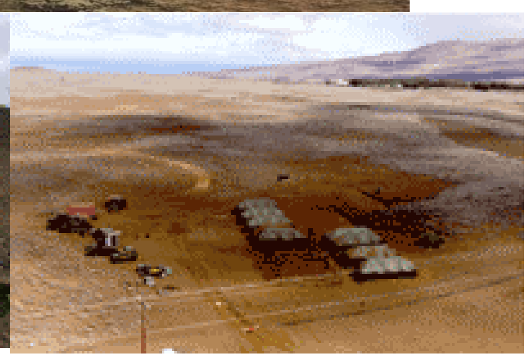
Operation Strong Angel - Humanitarian Exercise
11-15 June 2000, Parker Ranch, HI

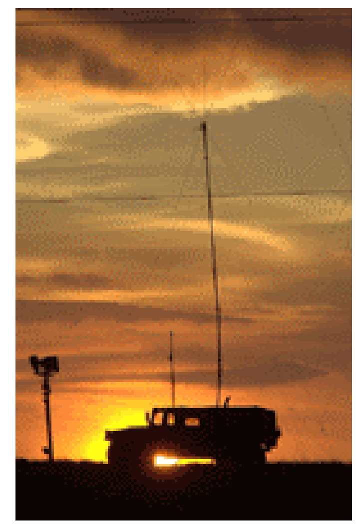
RIMPAC 2000

Defense Sciences Office









UNITED NATIONS
HIGH COMMISSIONER FOR REFUGEES

unicef

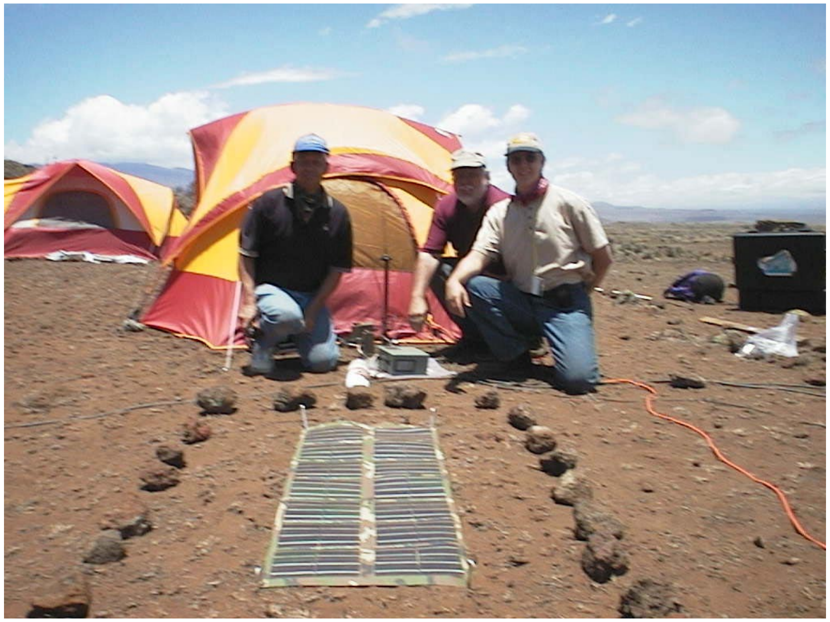
Welcome to the
World Food Programme
The food aid organization of the United Nations

American Red Cross

Operation Strong Angel

Parker Ranch, HI, 11-15 June 2000

Defense Sciences Office



Fuel cells operating laptop Computers, battery chargers In the CMOC area

Hybrid Fuel Cell, photovoltaic, Battery system operating a Ham Radio at the refugee camp

Hydrogen Sources Comparison For Portable PEM Fuel Cells

50 W
PEM Fuel Cell
(2.7 kg)

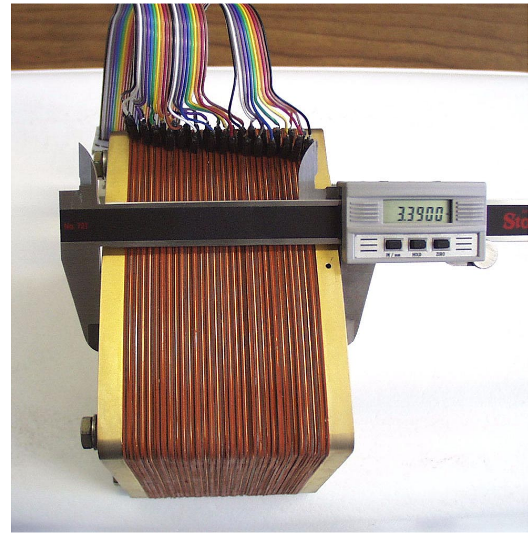
4500 psi H_2
289 Wh/kg
1.7% Storage

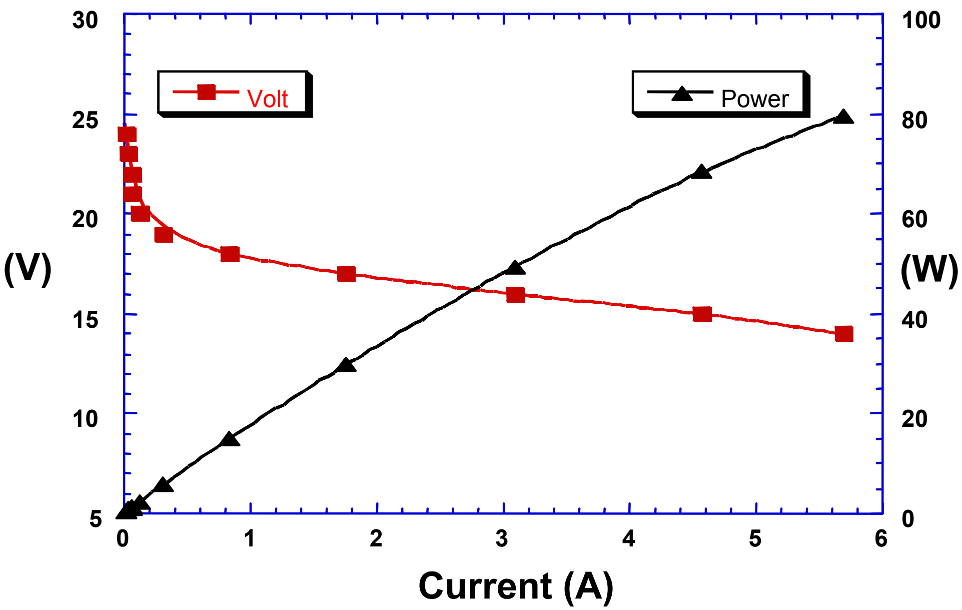
$NH_3 + LiAlH_4 \rightarrow H_2$ + Solid Products
1000 Wh/kg
6% Storage

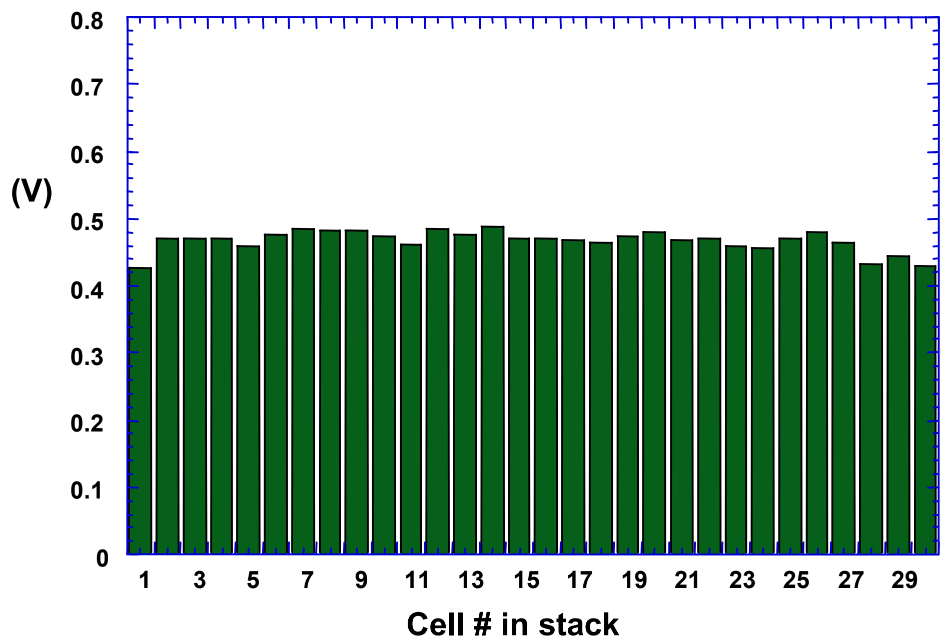
30-Cell Direct Methanol Fuel Cell Stack

Los Alamos National Laboratory

Defense Sciences Office

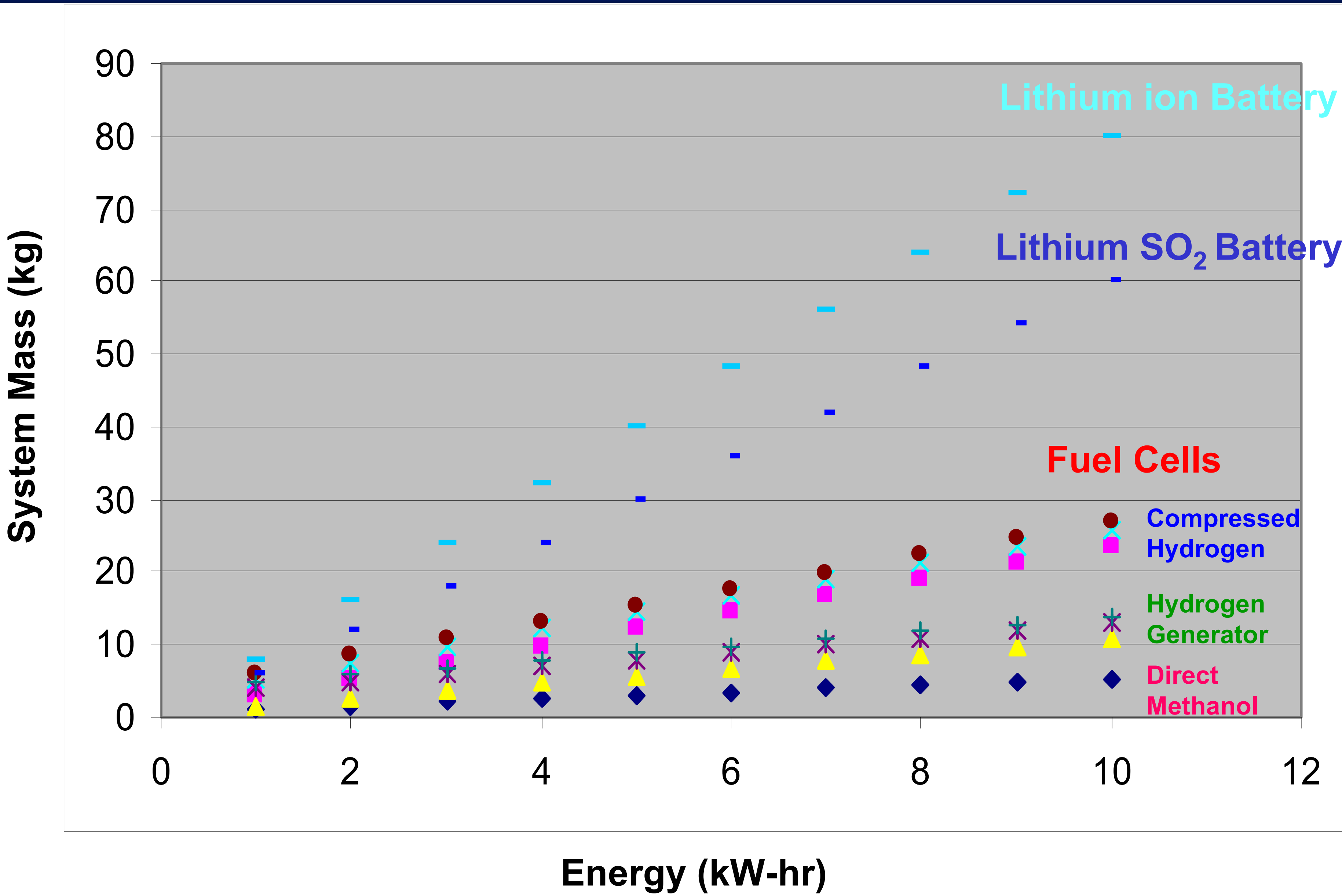






Lithium Battery / Fuel Cell Comparison

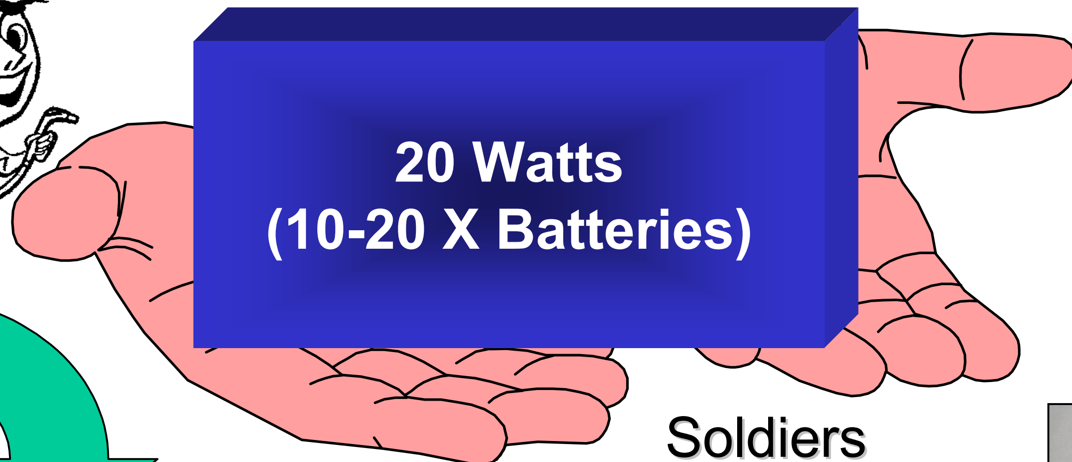
Defense Sciences Office



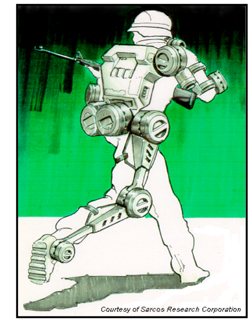
Palm Power Program

Defense Sciences Office

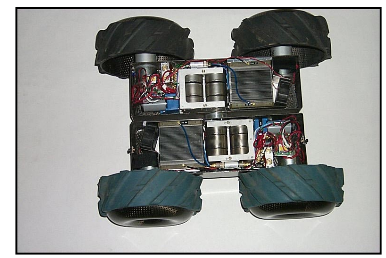
Program Goal



Exoskeletons



Robots

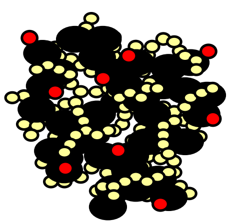


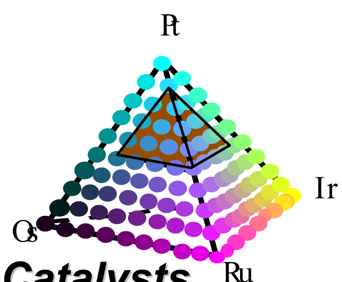
Soldiers

High Energy Content Fuel

Electric Power

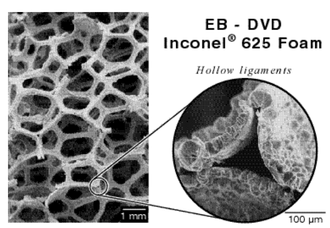
Materials Development





Catalysts

Thermal Management



Thermal Conductors…and Insulators

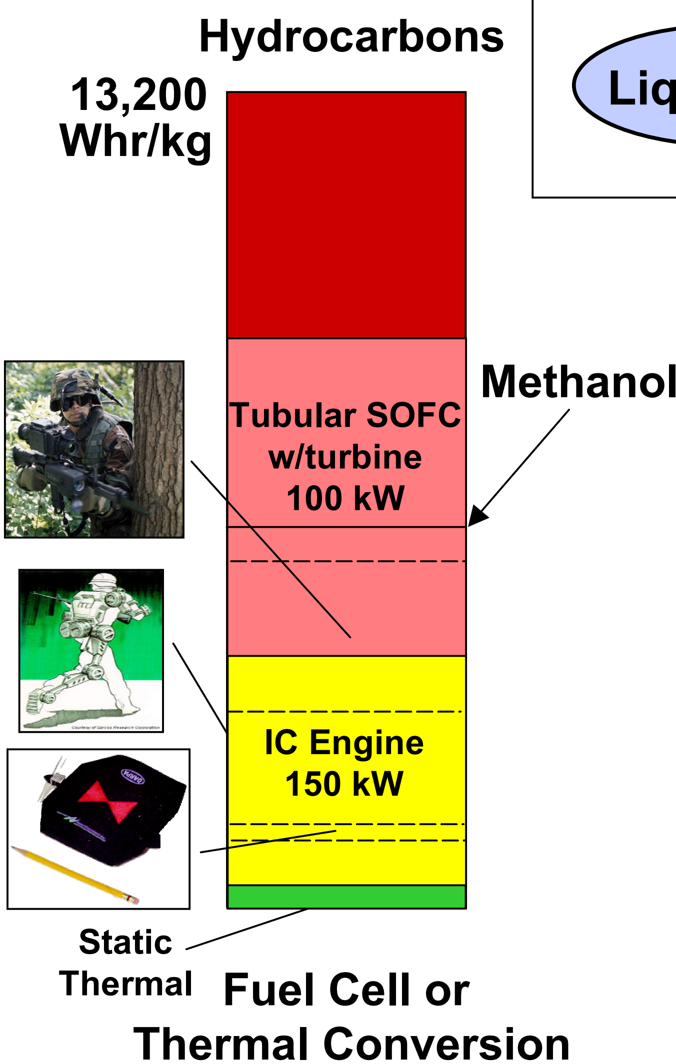
System Integration

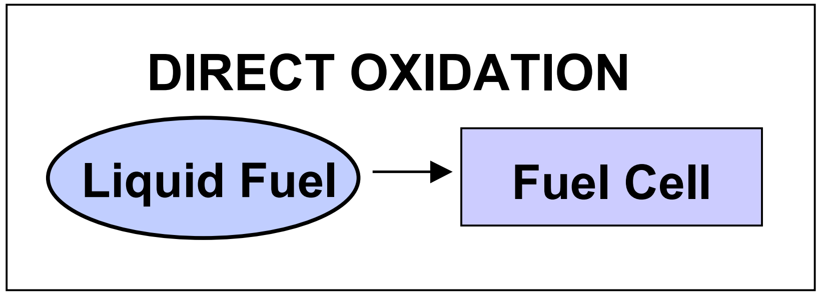
- **Fabrication**
- **Cascading Systems**

High T ***Low T***

The Holy Grail? -
Direct Conversion of Hydrocarbon Fuels

Defense Sciences Office

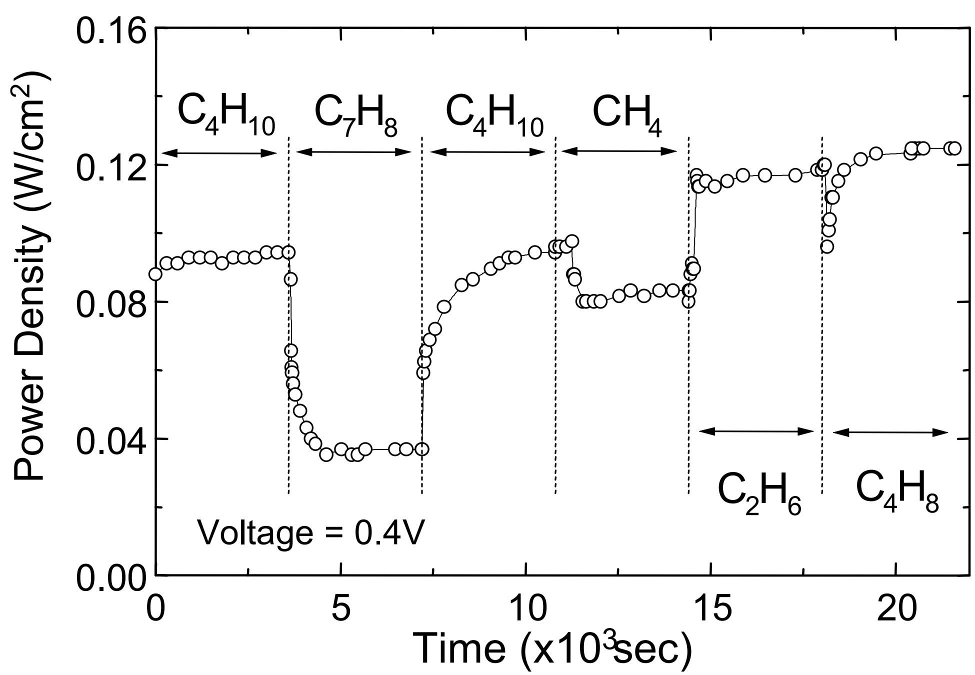




CHALLENGES

- Increase Performance
  - → Catalysts
- Thermal management
- Liquid Fuels

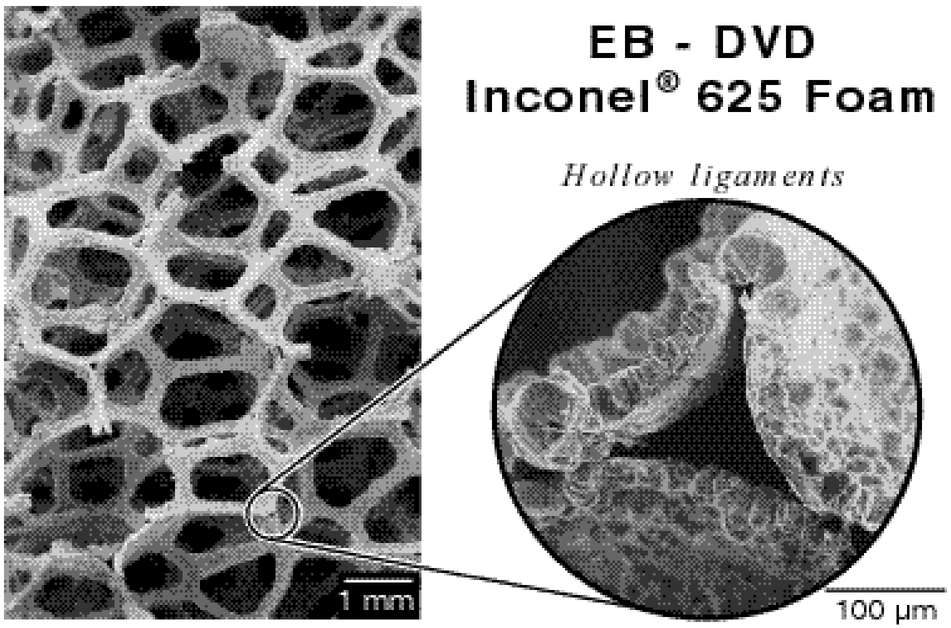
Recent work:



S. Park, J. M. Vohs, and R. J. Gorte, Nature, 404 (2000) 265.

Thermal Management Opportunities

Superthermal Conductors and Heat Exchangers



Aerogel Insulators

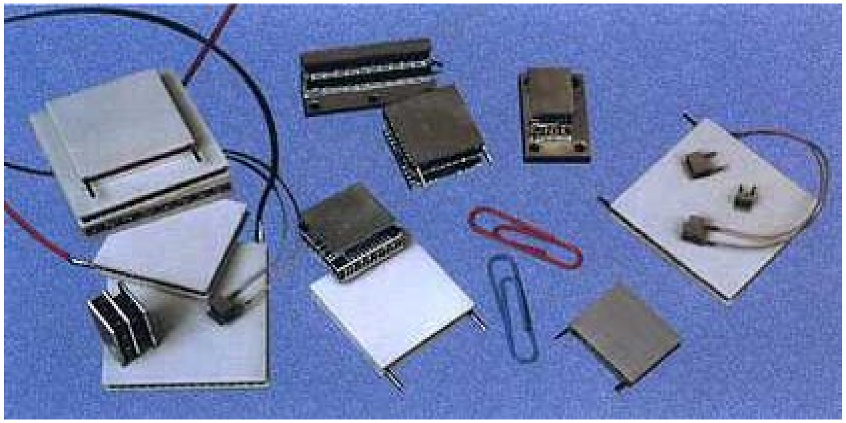
K_{solid} Aerogel = 0.002 W/mK @ 300K
K_{solid} Silica = 1.4 W/mK @ 300K

Thermal Integration Opportunities

Cascading Systems

- **Thermally integrate multiple technologies**
  - ✓ **Design**
  - ✓ **Fabrication**

+



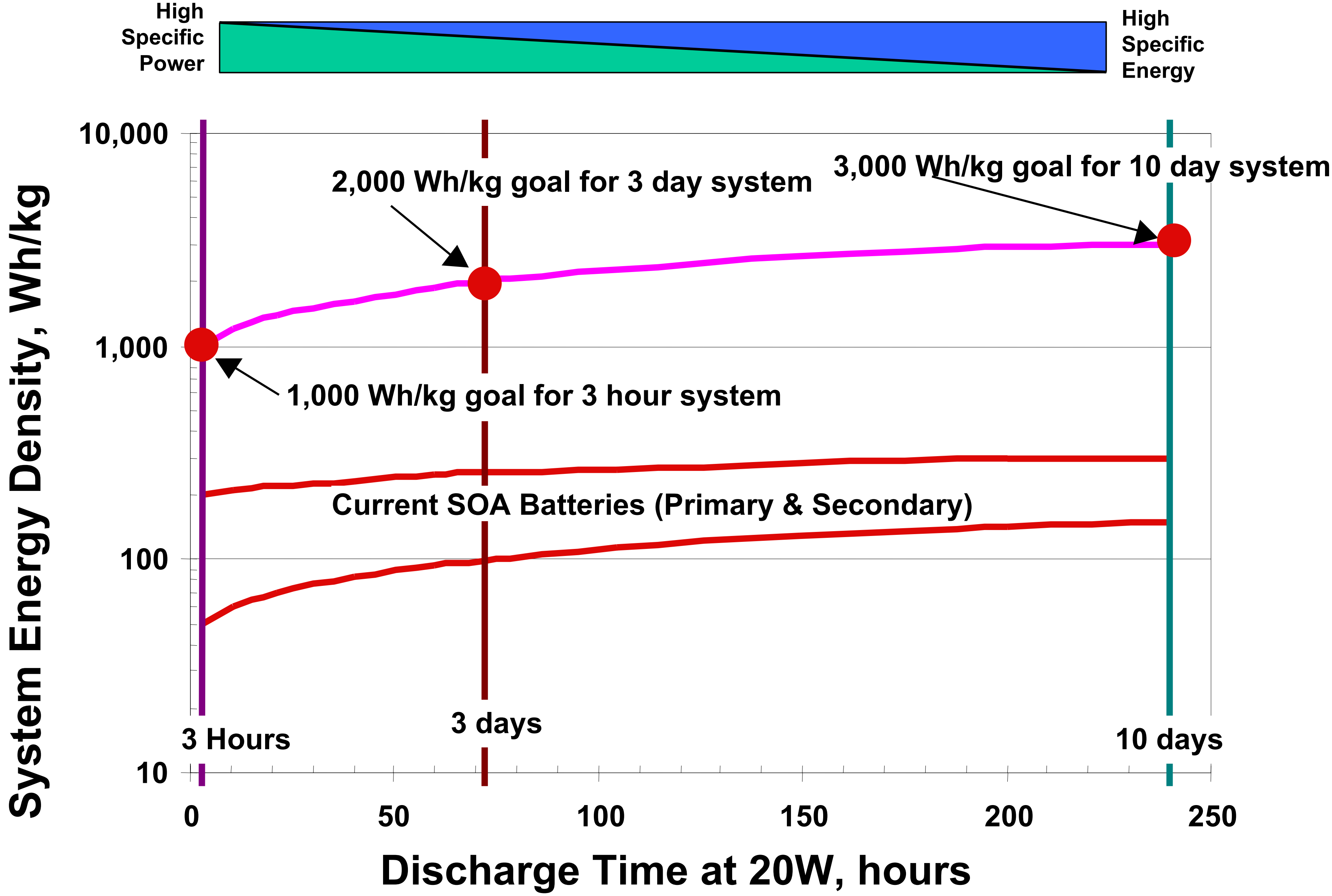
SOLID OXIDE FUEL CELL
1000 - 650 C

THERMOELECTRICS
1000 - 100 C

Integrated Efficiency >> Σ Individual Efficiencies

Palm Power Goals

Defense Sciences Office



http://www.darpa.mil/dso/thrust/md/palmpower/index.html

Power Driven Technology Revolutions

Period	Technology	Specific Power	Revolution
Early 1700's	Steam engines	0.005 W/g	'Industrial'
1890-1960	Steam turbines	0.05-1.0 W/g	'Transportation'
	IC engines		
1950-2000	Turbojets	10 W/g	'Aviation'
	Turbofans		
2000-?	Microcombustors	100 W/g	Use imagination

Information from Prof Alessandro Gomez, Yale University

The Bottom Line

Photo by Sarah Underhill

F. CHALLENGES FOR SOLID OXIDE FUEL CELLS IN THE FUTURE ENERGY SYSTEM

Donald P. McConnell, Associate Laboratory Director
Pacific Northwest National Laboratory

Challenges for Solid Oxide Fuel Cells in the Future Energy System

Presented to the

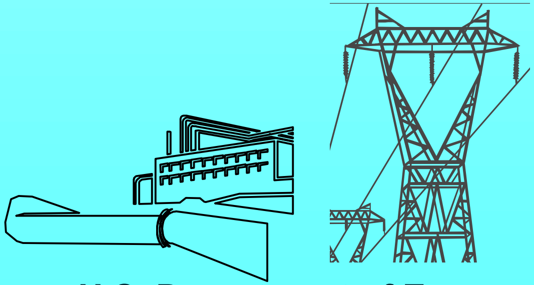
Solid State Energy Conversion Alliance Second Annual Conference

March 29, 2001
Arlington, Virginia

Don McConnell

Battelle Corporate SVP

Pacific Northwest National Lab



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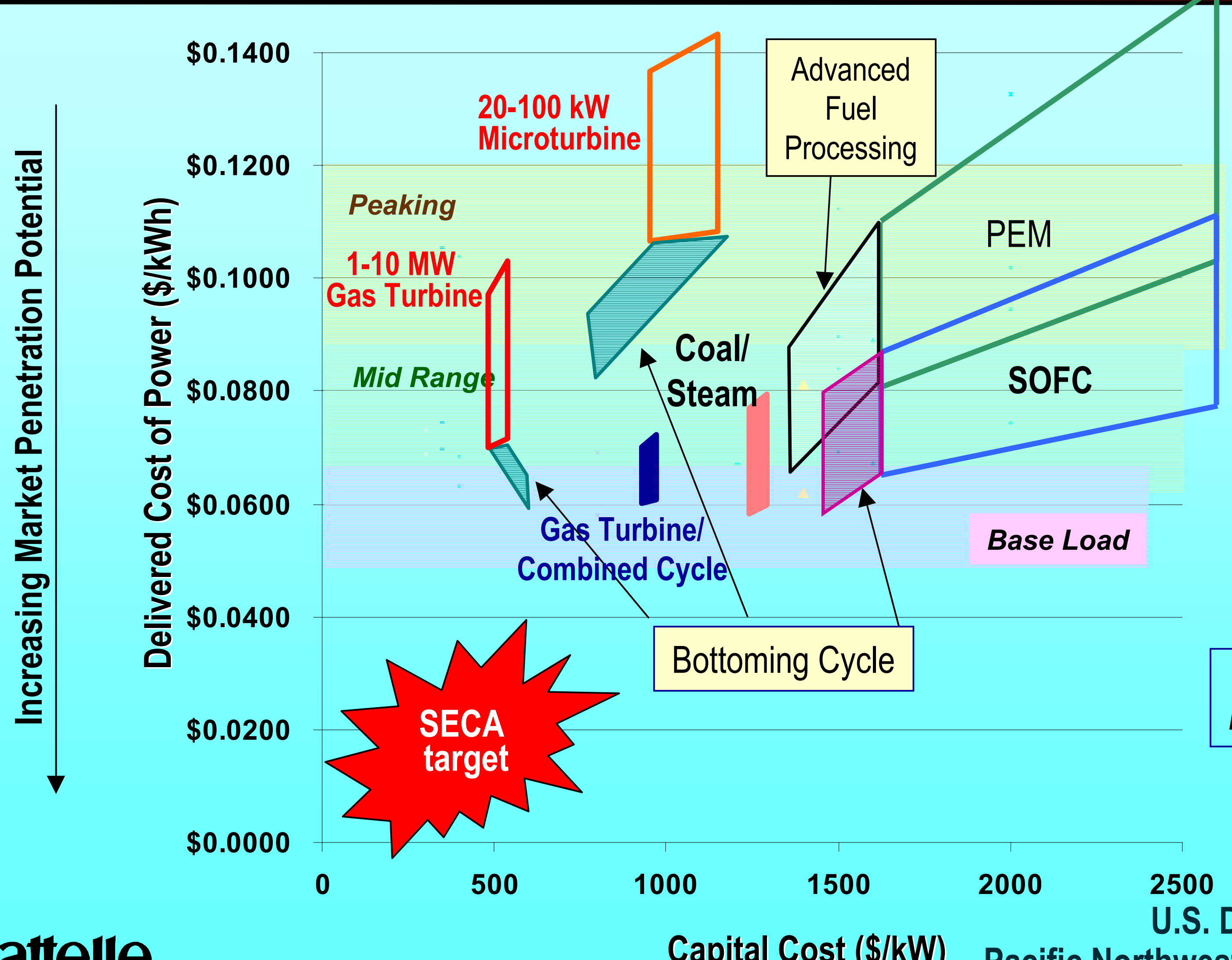
U.S. Department of Energy
Pacific Northwest National Laboratory

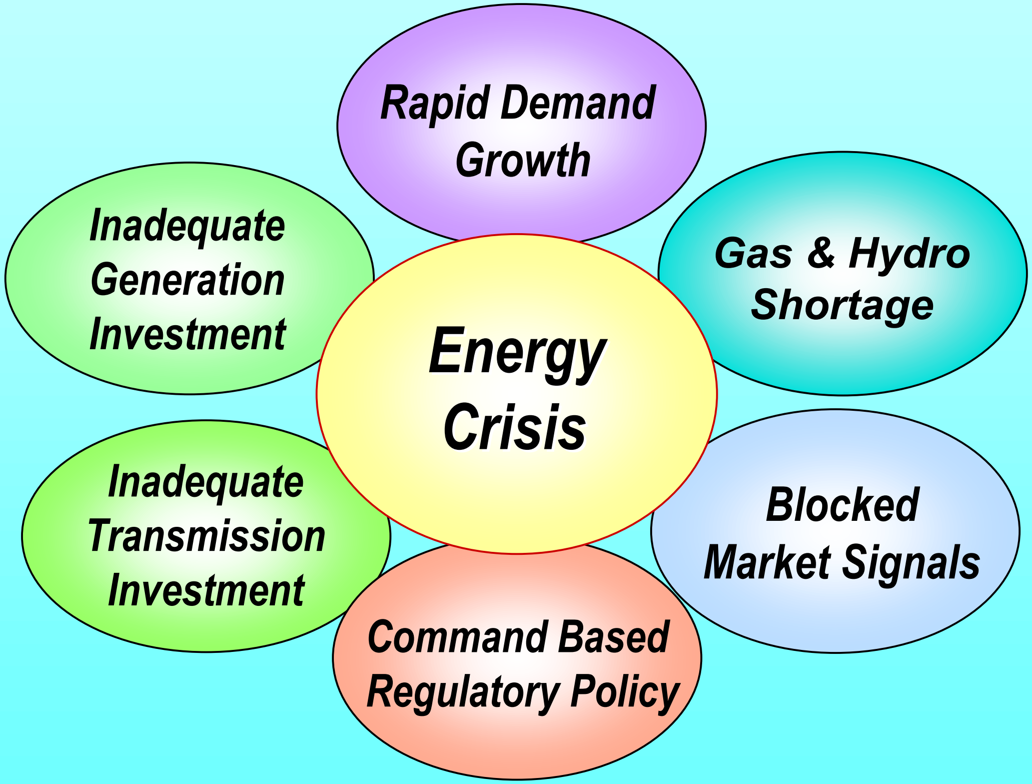
Competitive Cost Positioning for Alternative Power Concepts

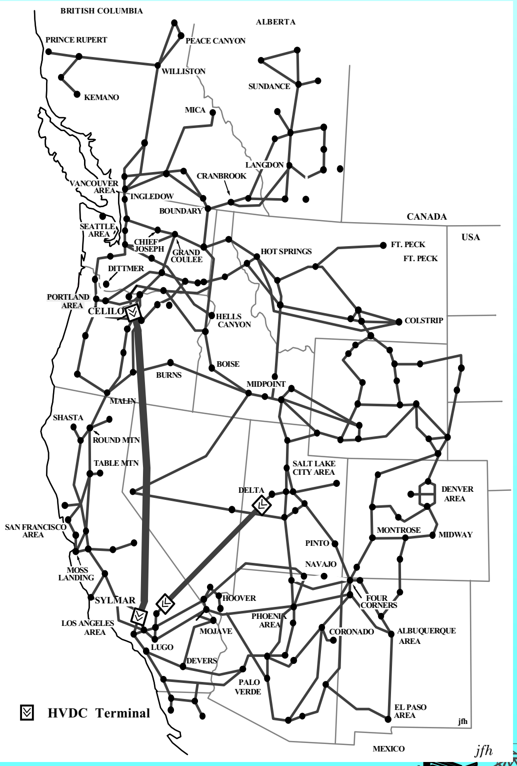


Reproduced Courtesy of Battelle Energy Products

"We're facing, incredibly, another energy crisis!"

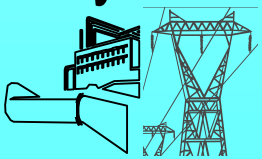
Rep. Billy Tauzin, Chairman, House Energy and Commerce Committee





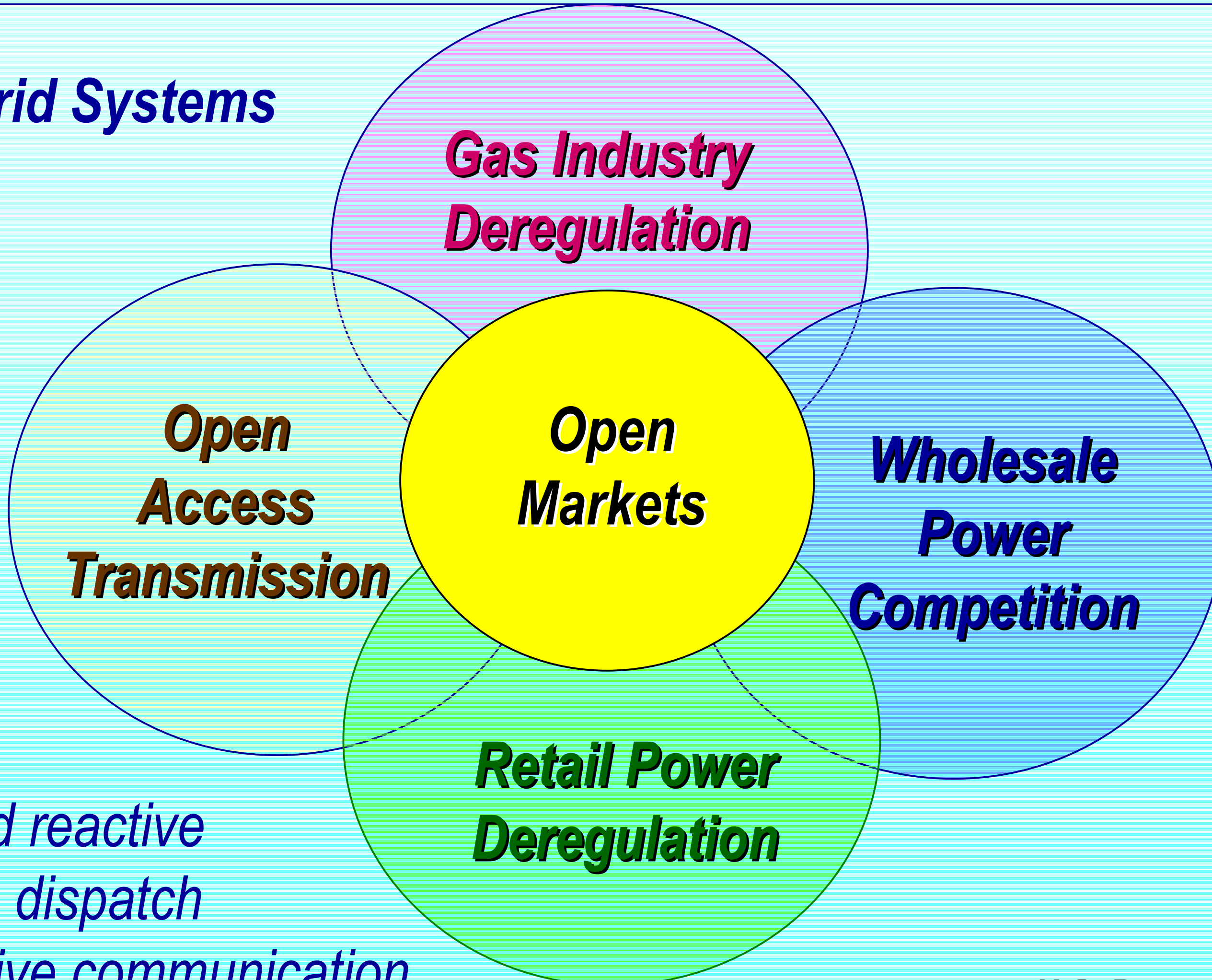
Efficiencies from markets are <u>not</u> automatic…

- FERC Report on Market Power (11/00)
- Price caps in the New England and California markets
- Immaturity of retail markets in all states
- Failures among retail marketers and e-commerce sites
- Lack of effective market signals and transparency
- Lack of consumer response options
- Lack of market based incentives for higher efficiency, cleaner energy conversion sources
- Bottlenecks in distribution resulting in imbalanced availability
- Incentives drive inefficiencies: focus on “islands of standby power” rather than overall power system reliability



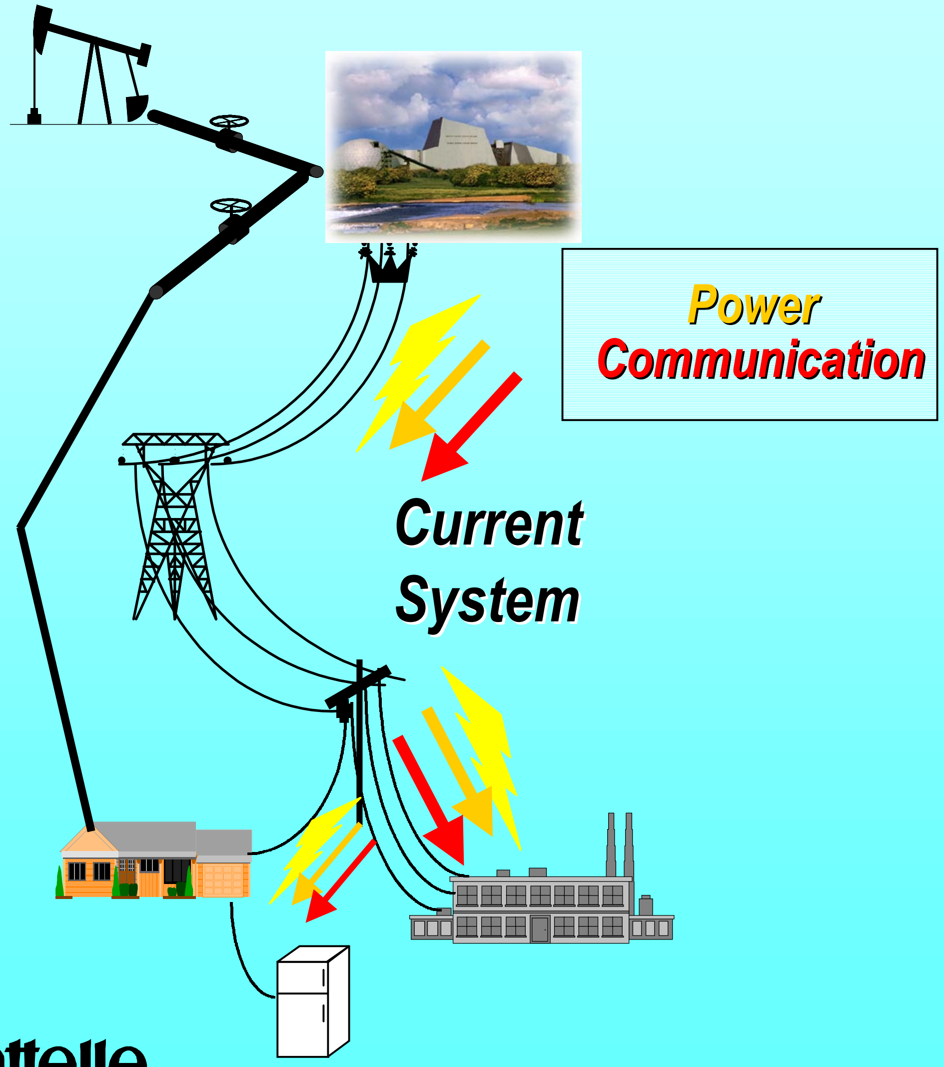
Open Energy Markets: In Theory… Increased Access and Competition Will Improve Efficiency, Reduce Overall Costs and Incentivize Investment

Future Grid Systems

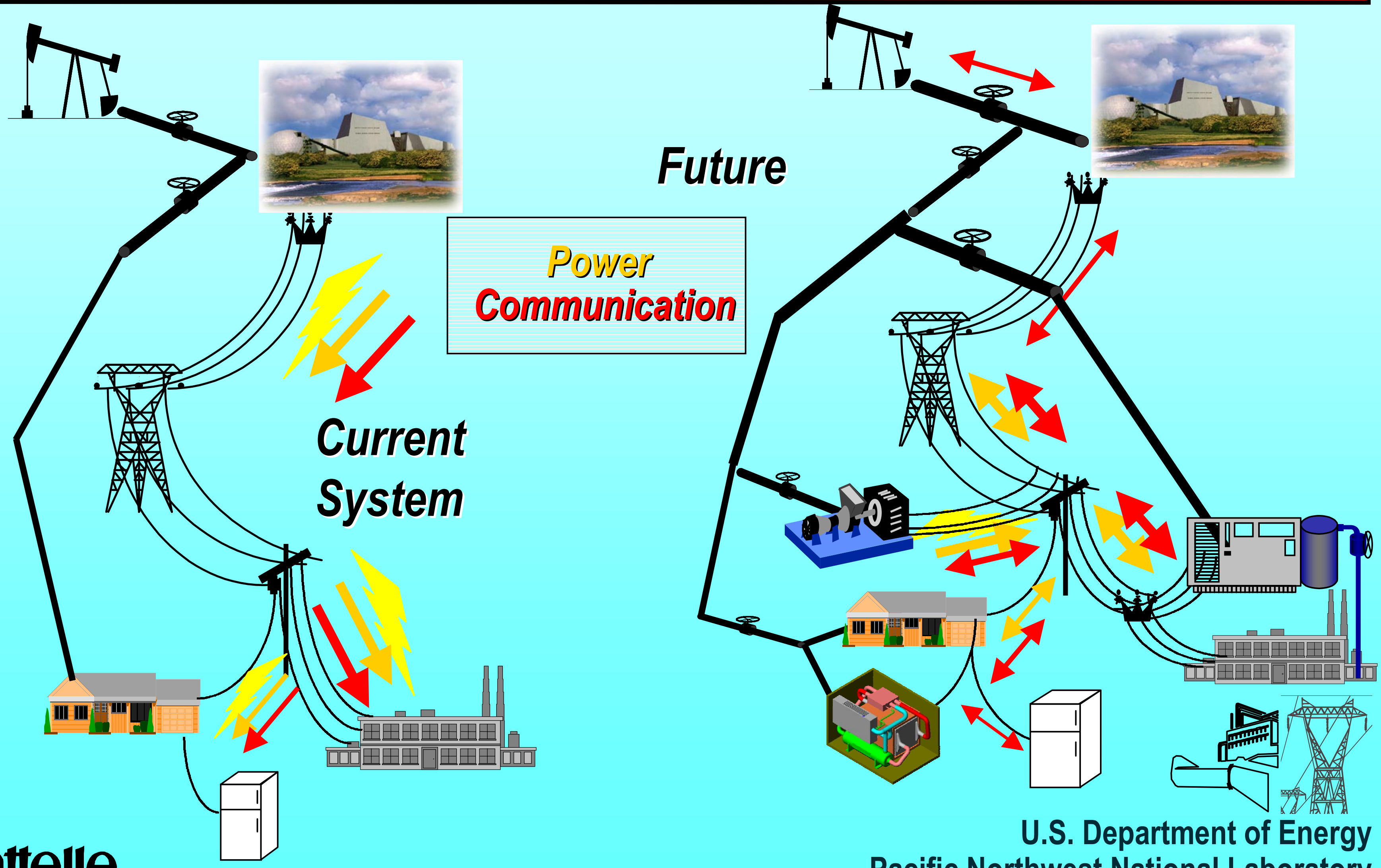


- *Demand reactive*
- *Remote dispatch*
- *Interactive communication*

The current energy system has inherent limitations that impede distributed generation



The Future Energy System Will Evolve to Facilitate Open Markets …



This new energy system embodies the features of a robust, reliable and efficient energy supply.

CURRENT

- Blackouts used to manage market and component failures
- Centralized, top-down control and planning is required
- Unidirectional control frustrates consumer responses and deployment of new technology
- Lack of resiliency can result in cascading system failure
- Layered and serial processes frustrate coordination and real-time responsiveness
- Top-down solutions, with regulatory checks, results in either over- or under-building
- Current system is not environmentally optimized
- Retards market based, efficient system solutions

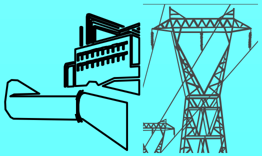
FUTURE

- Stable, reliable, predictable, controllable, manageable, fails gracefully, quality power
- Fuel flexible, resilient, demand responsive, decentralized (markets, generation, control, etc.)
- Expands and contract with markets, distributed vs. central power, absorbs new technologies/ markets/market instruments
- Withstands natural and deliberate threats to infrastructure
- Auditable, builds links between markets and institutions, dynamic system optimization, holistic
- 2nd law efficient, promotes and rewards efficiency, faster, easier to manage and maintain
- Environmentally friendly, incorporates externalities, responds to environmental dispatch
- Higher asset utilization, lower first cost, lower life-cycle cost
- Compatible with existing system, can evolve over time to new paradigm

Demands of the New Energy System on SECA Products

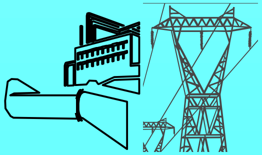
While application specific, typical applications will require:

- Interactive control and telecommunication systems:
  - Dispatch controllers
  - Transaction-based controls
  - Plug and play controls
- Multiple power outputs (AC, DC Mixed)
- Waste heat utilization (CHP)
- Broad range turn down capability
- Remote monitoring, diagnosis and prognosis

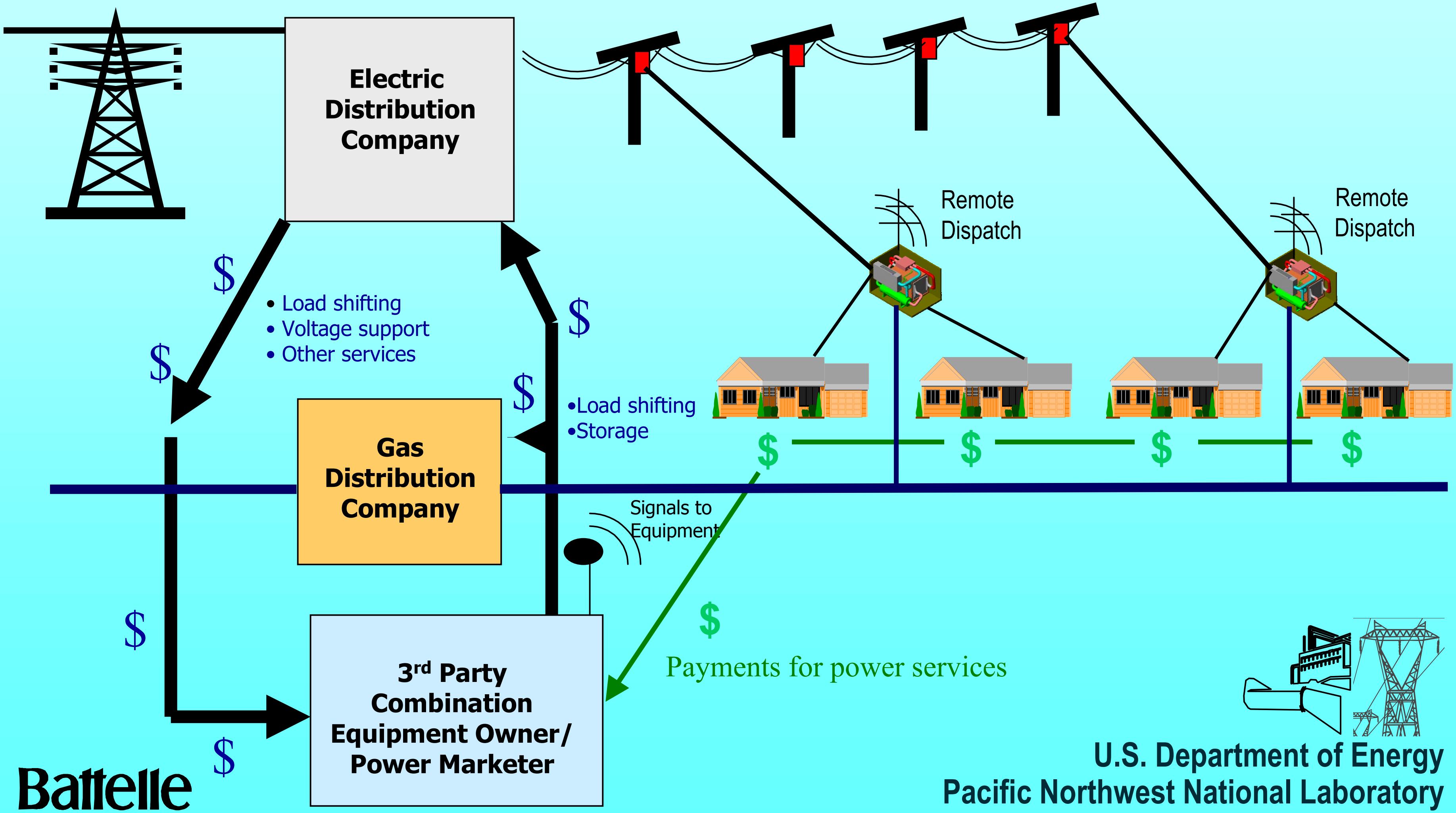


Reducing Demand: Commercial AC/DC Building Bus

- **Scenario**---Office bldg. with grid-connected fuel cell; 1 W/ft^2 DC-plug loads (computers, printers), 2 W/ft^2 fluorescent light ballasts @ 108V 20kHz AC
- **Currently**---expensive, 90% eff. synchronous inverter; 50% eff. DC converters; 90% eff. ballasts
- **Future**---Multiple power outputs provides DC at several voltages, frequencies; direct conversion for lights saves 15%; DC used directly saves 50%; downsized fuel cell & inverter; ballasts and DC converters eliminated
- **Opportunities**---integrated system design (supply, distribution, end-use); conversion technologies; appliances; fuel cell balance-of-plant



Taking advantage of the "Spark Gap": Remotely Dispatched, Fuel Cell Load Balancing



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U.S. Department of Energy
Pacific Northwest National Laboratory

Crosscutting Science & Technology R&D Areas

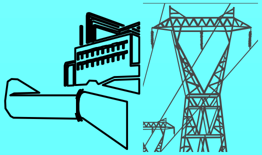
- Complex, adaptive systems theory & applications
- Genetic (and other adaptation) algorithms applied to markets, regulations, controls
- Network topologies and stability
- Control theory for large-scale, dispersed, hierarchical networks
- Simulation of massive, complex, coupled economic/engineering hierarchical networks
- Microtechnology applications in sensors, controls, equipment

NETL

SECA

Solid State Energy Conversion Alliance

LUNCH!



G. Fuel Cell Initiatives and Future Applications in the U.S. Navy and U.S. Marine Corps

Richard T. Carlin, Program Officer
U.S. DOD, Office of Naval Research

Fuel Cell Initiatives and Future Applications in the U.S. Navy and U.S. Marine Corps

Dr. Richard T. Carlin
Office of Naval Research

2nd Solid State Energy Conversion Alliance Workshop

29-30 March 2001, Arlington, VA

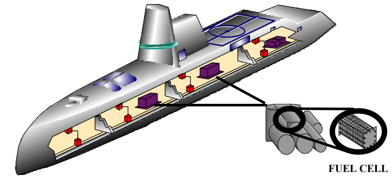
Contact Info: (703)696-5075, FAX (703)696-6887, carlinr@onr.navy.mil

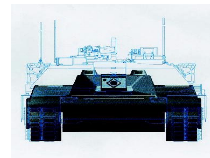
Grand Challenge

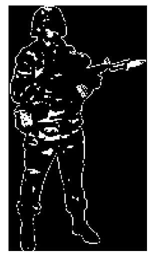
Electric Power Sources for the Navy and Marine Corps

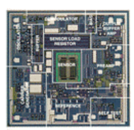
Develop new, safe, efficient, environmentally friendly, non-petroleum based sources of power and power generation concepts that would support portable long-lived power sources for all future Marine-carried equipment and electric power sources required for all-electric ships and other Naval warfighting platforms

No Single Power Source for All Platforms and Applications









1 MWatt

100 KWatt

1 KWatt

100 Watts

1 Watt

Military systems power requirements often follow a “step-function”, and so, different power sources technologies may be better suited for certain applications over others.

Energy Harvesting/Renewable

Batteries/Energy Storage

Fuel cells

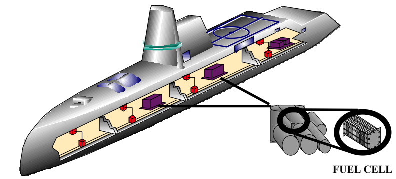
Stirling Engines

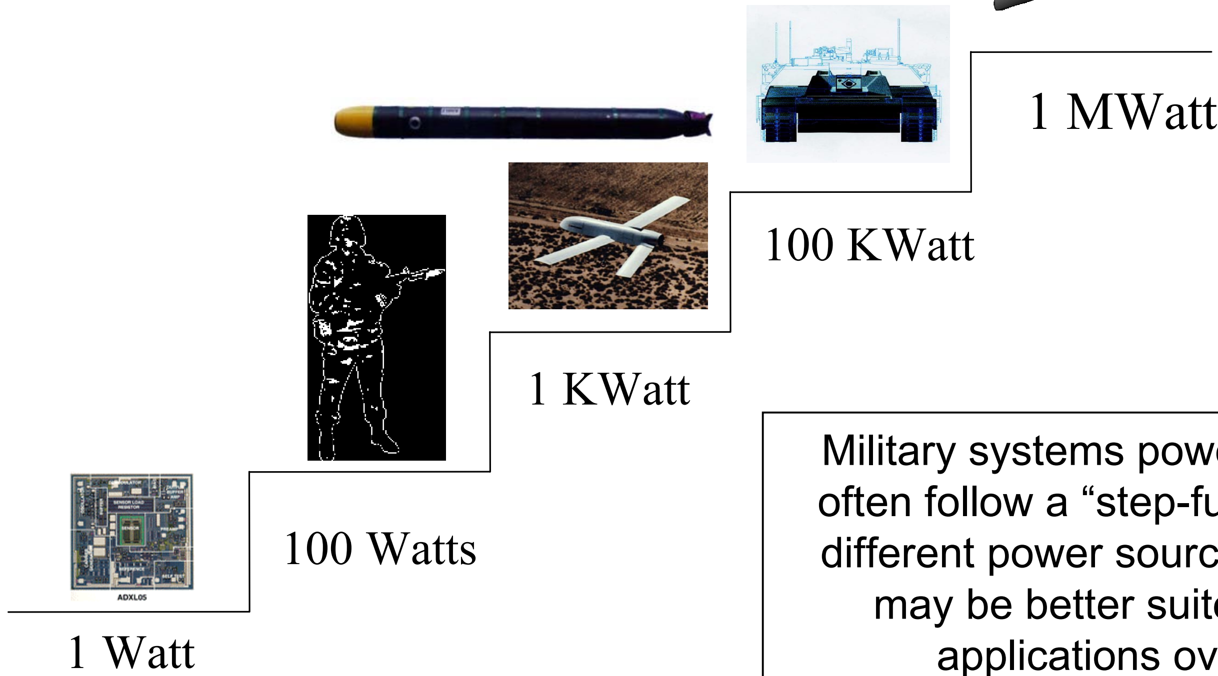
Turbines

Nuclear Power

Systems integration

No Single Power Source for All Platforms and Applications





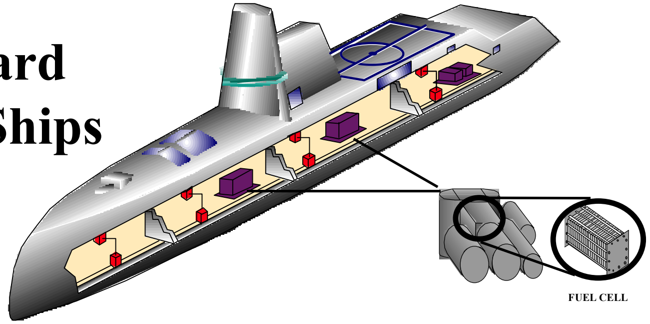
Military systems power requirements often follow a "step-function", and so, different power sources technologies may be better suited for certain applications over others.

←— **Fuel Cells** —→

←— **Systems Integration** —→

Ship Service Fuel Cell Program (SSFC)

Navy, Coast Guard & Commercial Ships



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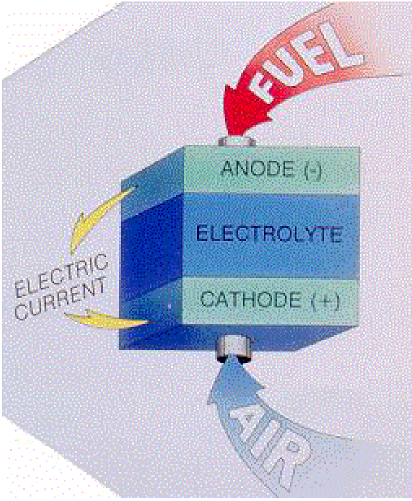


Challenges

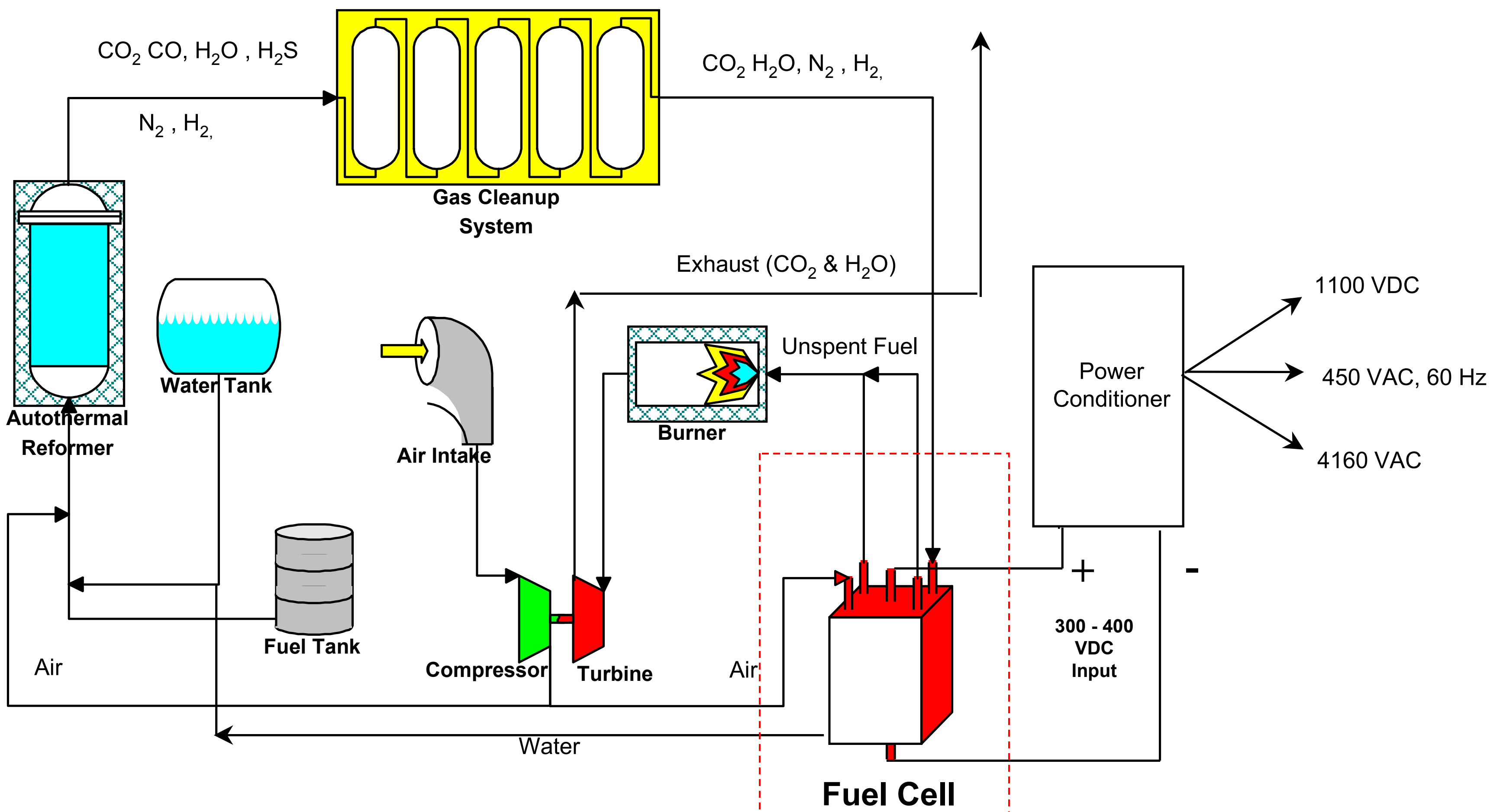
- *Logistic Diesel Fuel Reforming*
- *Reformate Cleanup*
- *Efficient System Integration*
- *High Specific Power*
- *Transient Response*

Payoffs

- ✔ *Increased Fuel Efficiency and Operational Range*
- ✔ *Distributed Power for Increased Survivability*
- ✔ *96% Reduction in NO_x, CO and HC Emissions*
- ✔ *30% Reduction in CO_2 Emissions*
- ✔ *\$0.6M to \$1M/yr/ship Savings*
- ✔ *Reduced Thermal and Visual Signatures*

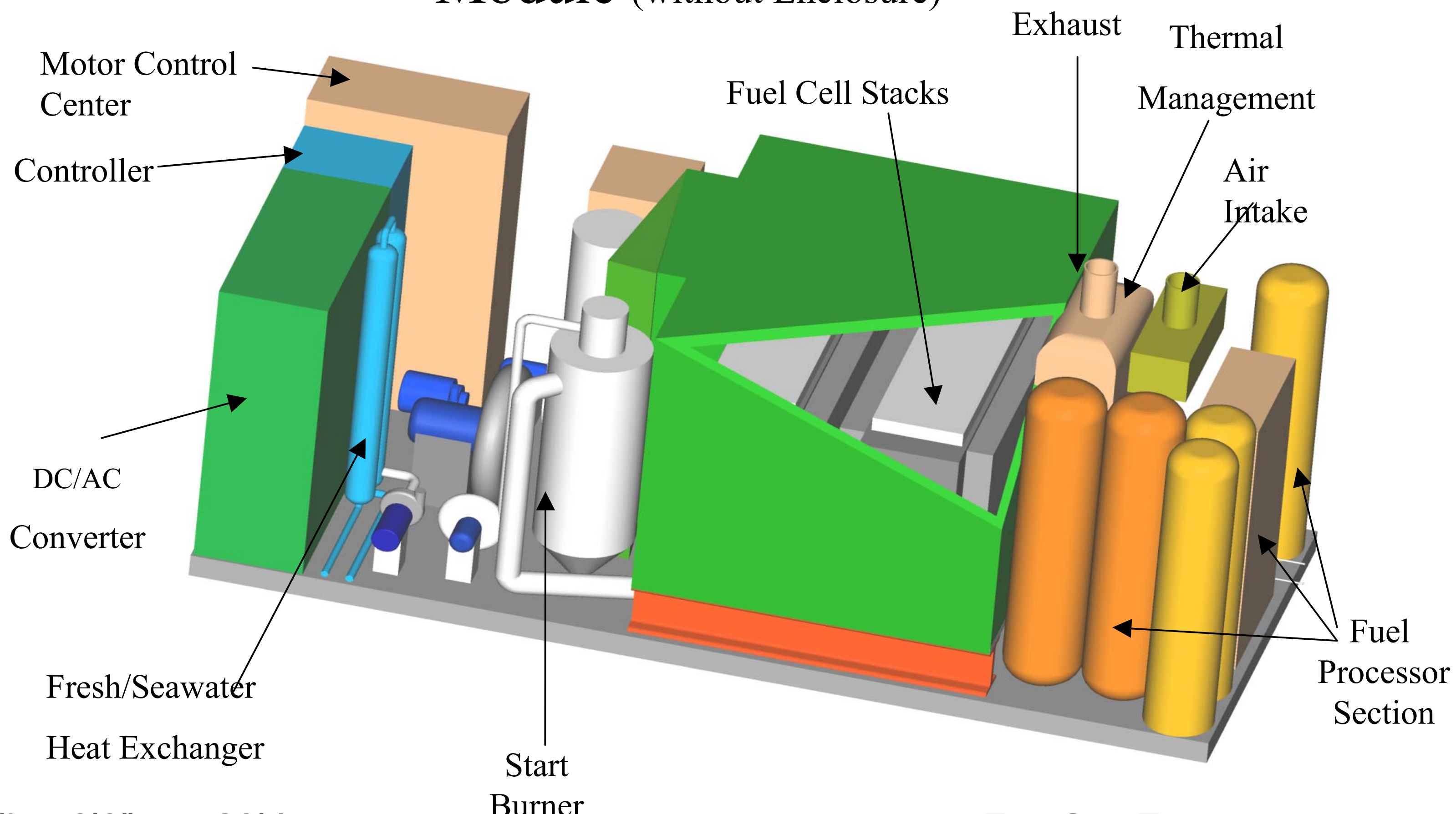
SSFC Fuel Processing Concepts

Fuel Processing is the Key to Fuel Cell Operation!!!



SSFC Scaled Demonstration

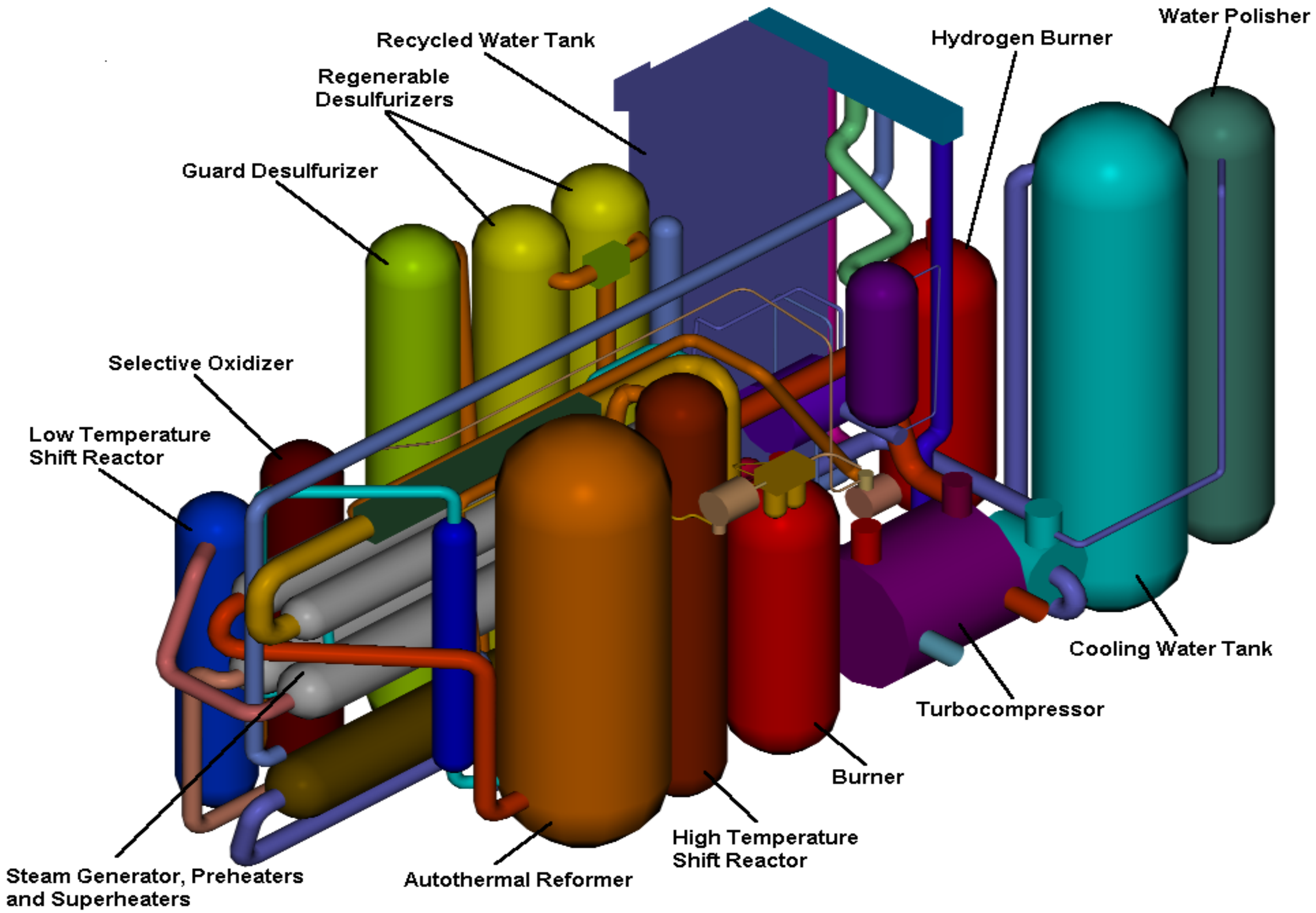
Conceptual 625 kW Molten Carbonate Fuel Cell Module (without Enclosure)



8’h x 8’3” w x 20’ l

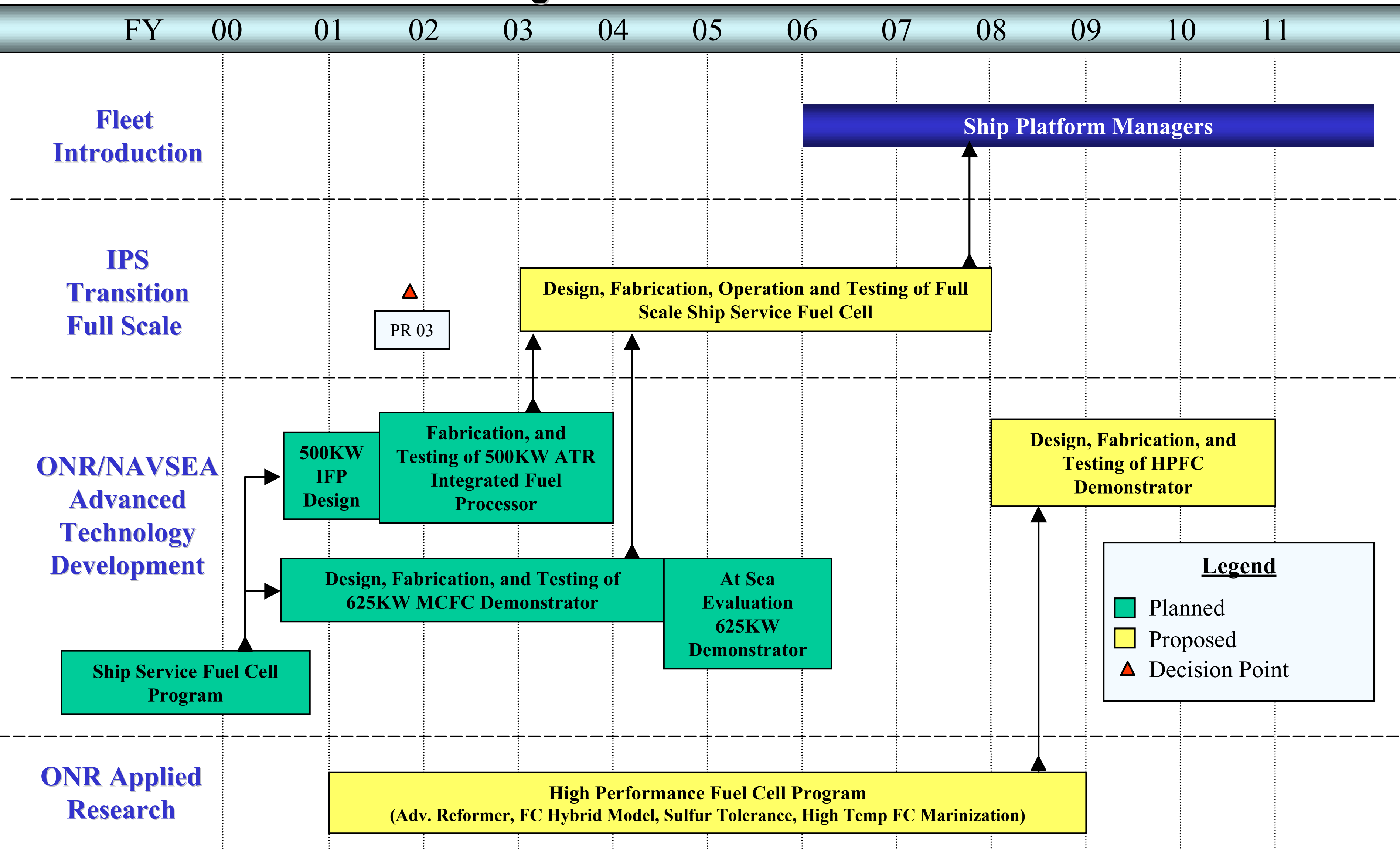
FuelCell Energy, Inc.

McDermott Technology 500kW SSFC Integrated Fuel Processor (IFP)



Navy Shipboard Fuel Cell Program

Program Timeline/Transition



Direct Diesel-to-Electric SOFC

Marine Corps Electrical Power

- Field Generators
- Individual Marine
- Future Vehicles
- Autonomous Vehicles

Penn Engineering™

MARINE CORPS AIR GROUND COMBAT CENTER

29 Palms, CA, 8-10 Oct 1999

Fuel Cells aboard Humvee

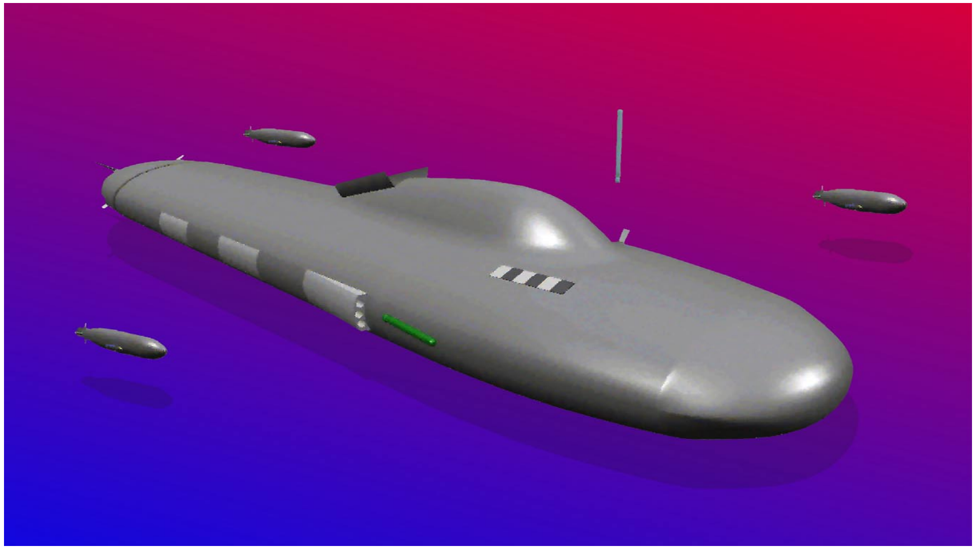
Ten PRC-119 Radios

Ball Aerospace

COST ESTIMATE FOR EXERCISE

- **BA5590 BATTERIES = $1800**
- **FUEL CELLS = $100**

Autonomous Undersea Vehicles (AUVs)



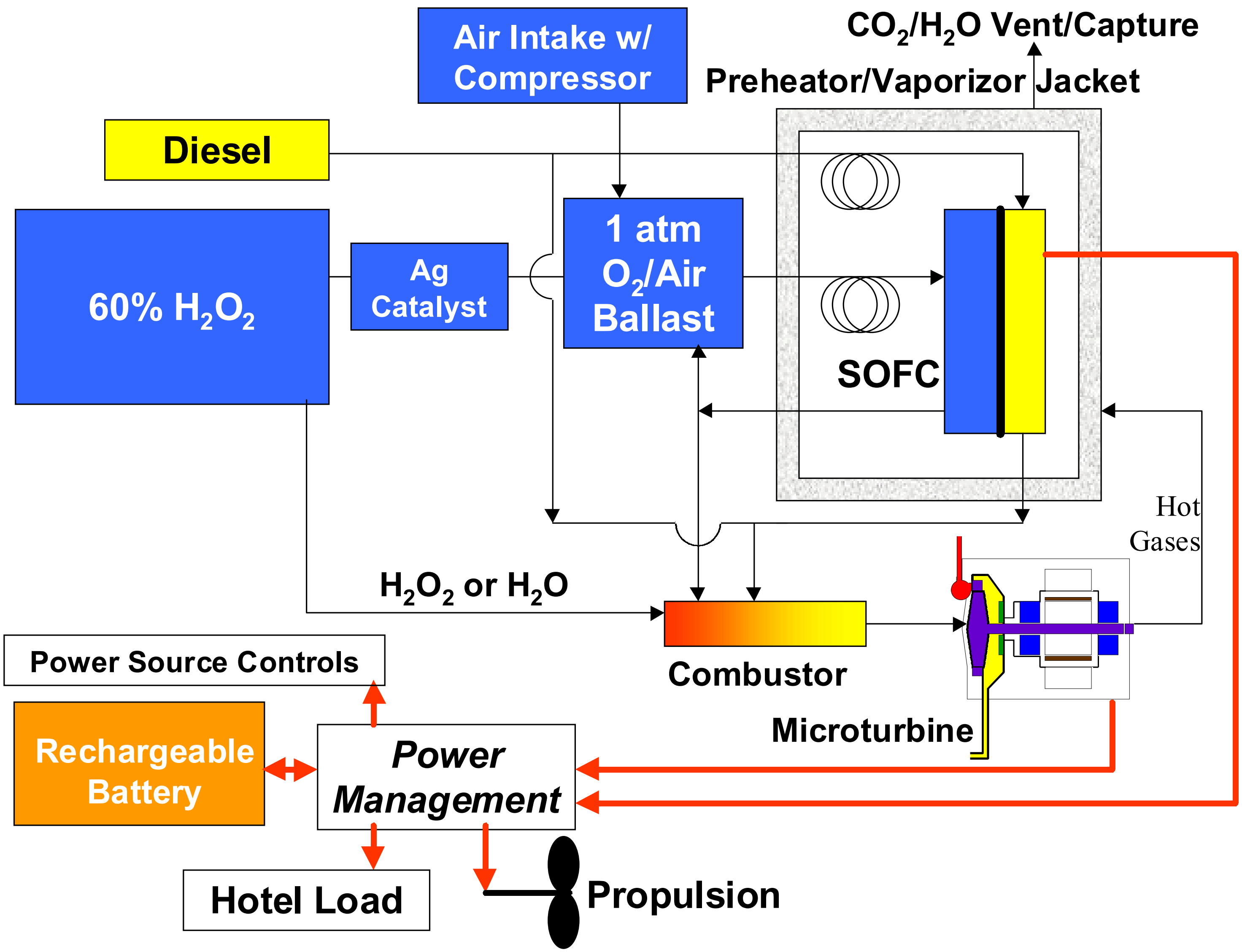
AUV PEM Fuel Cell Operating on Diesel

PEM Fuel Cell System for 4 kW and 100 kWh

Components	Weight (kg)
PEM Fuel Cell	10
Fuel System	
Diesel Fuel	14
Reformer + Pump	31
O_2-generator/CO_2/S-absorber	178 ←
Other Auxiliaries	15
Totals	248
Add 10% for Structure	273
Specific Energy (w-hr/kg)	**350**

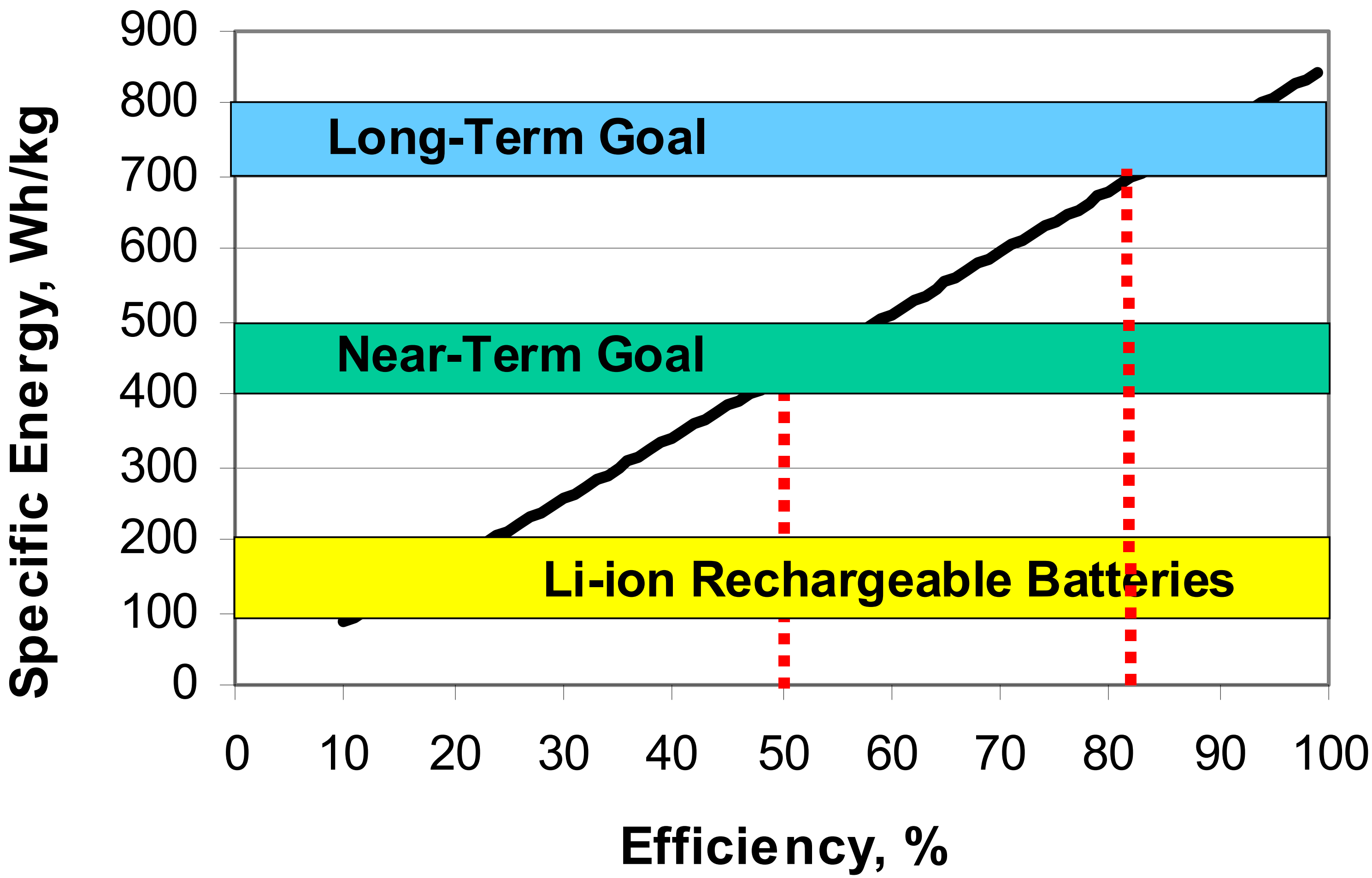
- **O_2 and CO_2/S-Absorbers = >65% Total System Weight**
- **Relatively Low Specific Energy ⇒ 400 Wh/kg Goal**

SOFC Hybrid Concept for AUV



SOFC Hybrid Concept for AUV

SOFC/Microturbine using Diesel/60% H_2O_2



15 kg Diesel, 184 Kg 60% H_2O_2, & 30 kg (SOFC + BOP)

- Fuel Cells Applications
  - Shipboard power
  - Autonomous vehicles
  - Person-portable power
  - Field generators
  - Ground and sea combat vehicles
- Major Challenges
  - Operation on logistics fuels
    - Other fuels under consideration (*e.g.*, synthetic diesels)
  - Operation in anaerobic environments
  - Compact, lightweight, rugged

H. Universities for Fuel Cells

Jacob Brouwer, Associate Director
National Fuel Cell Research Center, University of California, Irvine

SOLID STATE ENERGY CONVERSION ALLIANCE (SECA) WORKSHOP

ARLINGTON, VIRGINIA

NFCRC

JACK BROUWER
NATIONAL FUEL CELL RESEARCH CENTER
UNIVERSITY OF CALIFORNIA, IRVINE
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MARCH 29, 2001

NFCRC

UNIVERSITIES FOR FUEL CELLS

<u>OUTLINE</u>

- INTRODUCTION TO UfFC CONCEPT
- BACKGROUND
  - DESCRIPTION OF CURRENT/PAST ACTIVITIES
- GOALS AND OBJECTIVES OF UfFC
- RELATIONSHIP TO SECA PROGRAM
- NEXT STEPS

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INTRODUCTION

- FUEL CELLS ARE AN “EMERGING” TECHNOLOGY
- RESEARCH AND DEVELOPMENT OF FUEL CELLS IS ALSO “EMERGING”
- FUEL CELL EDUCATION IS NOT WIDESPREAD
- PUBLIC DOESN’T HAVE BASIC UNDERSTANDING OF FUEL CELLS
- ENGINEERS OFTEN HAVE NO BASIC UNDERSTANDING OR BACKGROUND IN FUEL CELLS
- BROAD RANGE OF MULTI-DISCIPLINARY TALENT IS REQUIRED:
  - PHYSICS
  - CHEMISTRY
  - MATERIALS SCIENCE
  - HEAT TRANSFER
  - FLUIDS
  - ELECTROCHEMISTRY

emerging (i mûrj’ ing), *v.i.*, to come forth into view, as from concealment, or, to rise, as from an inferior state

INTRODUCTION

- BRING OPPORTUNITIES INTO VIEW
  - JOINT RESEARCH AND DEVELOPMENT PROJECTS
  - R&D PROGRAMS
  - INDUSTRY, UNIVERSITY, NATIONAL LAB COLLABORATIVES
- RAISE FUEL CELL EDUCATION LEVELS (FROM THEIR INFERIOR STATE)
- BRING FORTH INTO VIEW CONCEPTS AND BREAKTHROUGHS THAT COULD IMPACT FUEL CELLS
- IDENTIFY NEEDED RESEARCH AND DEVELOPMENT ACTIVITIES
- IDENTIFY SCIENTIFIC EXPERTISE AND TALENT AT VARIOUS INSTITUTIONS THROUGHOUT U.S. (WORLDWIDE)
  - ADDRESS REQUIRED R&D
  - ADDRESS FUEL CELL PROGRAM NEEDS
- RAISE GENERAL AWARENESS OF FUEL CELLS

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BACKGROUND

- U.S. DEPARTMENT OF ENERGY WORKSHOP, MORGANTOWN, WV, AUGUST, 1998
- EVENING BREAKOUT GROUPS (UNIVERSITIES GROUP FORMED)
- PROFESSOR J. ROBERT SELMAN LEADING EFFORTS TO-DATE
- SEVERAL INFORMAL MEETINGS
  - AT MAJOR ELECTROCHEMICAL SOCIETY MEETINGS
  - AT JOINT U.S. DOE/EPRI/GRI MEETINGS
  - AT ILLINOIS INSTITUTE OF TECHNOLOGY
- NFCRC JOINED IN LEADERSHIP
- VOLUNTARY AND SELF-SUPPORTED PARTICIPATION

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GOALS AND OBJECTIVES

- **SUPPORT UNIVERSITY-BASED FUEL CELL ADVANCEMENT**
- **SUPPORT MAJOR U.S. DOE PROGRAMS THAT ARE ADVANCING SOLID STATE FUEL CELLS**
- **PROVIDE AN INFORMATION CONDUIT BETWEEN AND AMONGST UNIVERSITIES, NATIONAL LABS, AGENCIES, INDUSTRY**
- **EDUCATE PUBLIC ON FUEL CELLS IN GENERAL AND SOLID STATE FUEL CELLS IN PARTICULAR**
- **PROVIDE A FORUM FOR INFORMATION DISSEMINATION AND THE DEVELOPMENT OF EDUCATIONAL MATERIALS**
- **FOSTER INCREASED PARTICIPATION OF SCIENTISTS AND RESEARCHERS IN THE EMERGING FIELDS REQUIRED**

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RELATIONSHIP TO SECA

- **SECA PROGRAM NEEDS A STRONG CONTINGENT OF UNIVERSITY RESEARCHERS**
  - CRITICAL EXPERTISE
  - REQUIRED RESEARCH AND DEVELOPMENT CAPABILITIES
- **SECA PROGRAM (AND OTHERS) ARE VERY BROAD**
  - FUEL CELLS AND FUEL CELL MATERIALS
  - FUEL PROCESSORS
  - INVERTERS AND POWER ELECTRONICS
  - WATER AND THERMAL MANAGEMENT
  - SYSTEMS MODELING AND SYSTEM INTEGRATION
  - MANUFACTURING
- **SECA PROGRAM HAS AMBITIOUS COST TARGETS**
  - BREAKTHROUGHS AND DISCOVERIES

NEXT STEPS

- DESIRE IS FOR VERY LOW OVERHEAD OPERATION
- NO COMPLEX STRUCTURE, NO LARGE TIME COMMITMENT (VOLUNTARY PARTICIPATION)
- FOCUSED EFFORTS (JOINT WORKSHOPS, BROCURE, WEB-SITE, WHITE PAPERS)
- SUPPORT ALLIANCE BUILDING
- ATTRACT A MORE BROAD CROSS-SECTION OF UNIVERSITY PARTICIPANTS
  - E.G., UNIV. OF WISCONSIN, VIRGINIA TECH, OTHERS EXPERTISE IN POWER ELECTRONICS
- SERVE AS INFORMATION CONDUIT
  - INDUSTRY INTEGRATION TEAMS
  - CORE TECHNOLOGY PROGRAM

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NEXT STEPS

RESEARCH AREA WORKSHOPS

- EXCHANGE OF INFORMATION
  - STATUS AND CURRENT RESEARCH ACTIVITIES
  - FUNDING OPPORTUNITIES ARE REVIEWED,
  - JOINT EFFORTS ARE ESTABLISHED FOR FUNDING.
- DEVELOP TECHNOLOGY TRANSFER MATERIALS
- SUPPORT DOE PROGRAMS
- SUPPORT INDIVIDUAL AND JOINT UNIVERSITIES' PROGRAMS

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NEXT STEPS

INFORMATION DEVELOPMENT/DISSEMINATION

- ESTABLISH A WEB-SITE
- GENERATE/IDENTIFY RESEARCH AREA NEEDS
- GENERATE BROCHURE
  - LAY AUDIENCE
- GENERATE WHITE PAPER(S)
  - OBJECTIVE INFORMATION
  - PERSUASIVE SCIENTIFIC INFORMATION

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NEXT STEPS

REQUEST TO YOU:

- **HELP US IDENTIFY INTERESTED PARTIES**
  - **YOU AND YOUR UNIVERSITY ORGANIZATION**
  - **COLLEAGUES, ACQUAINTANCES**
  - **GROUPS OR INDIVIDUALS YOU KNOW ABOUT**

- **SEND TO:**
  - **JACK BROUWER, JB@NFCRC.UCI.EDU**

I. U.S. DOE Sponsored Study on SOFC Applications in the Transportation Industry

Michael Krumpelt, Section Head, Fuel Cell Technology, Argonne National Laboratory
and John Hirschenhofer, Parsons

U.S. DOE Sponsored Study on SOFC Applications in the Transportation Industry

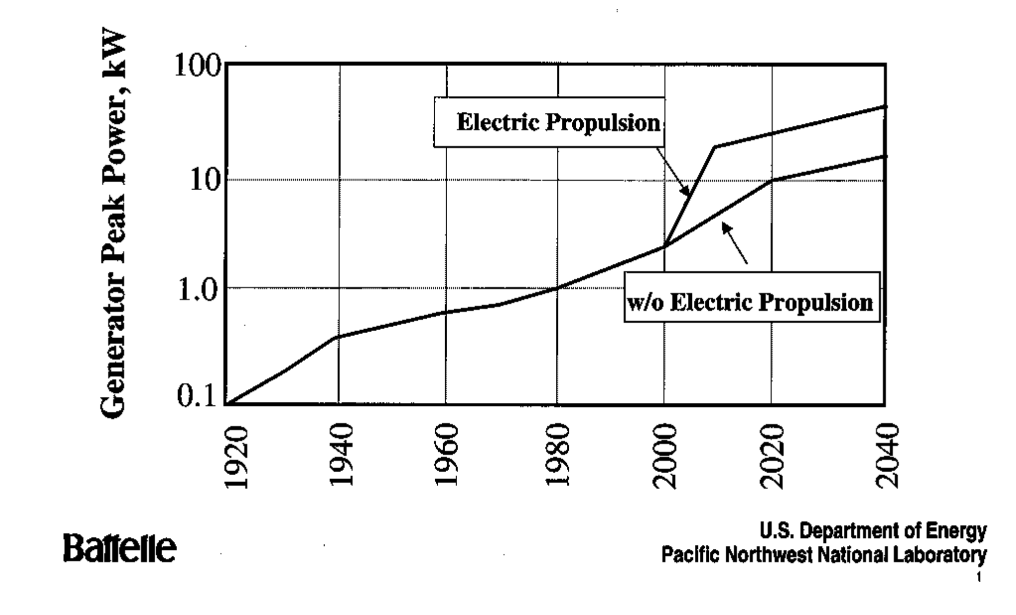
presented by
Michael Krumpelt
Argonne National Laboratory

John H. Hirschenhofer
Parsons

2nd Solid State Energy Conversion Alliance Workshop
March 29-30, 2001
Arlington, VA

Motivation

- Auxiliary Power Units (APU) are becoming interesting to the Automotive Industry because:
  - Power Requirements in Passenger cars are increasing
  - Anti-idling bans for trucks may be legislated



Perceived Challenges for SOFC in Transportation

- Start-up time
- Fuel consumption during start-up
- Mechanical and thermal ruggedness
- Power density of system

Objectives of Study

- Assess planar SOFC technology status
- Evaluate planar SOFC in transportation vehicles
- Estimate fuel savings and emissions avoidance
- Identify critical R&D issues

Approach

- Define a "Representative" planar SOFC based on discussions with
  - Ceramic Fuel Cells Limited
  - Honeywell
  - McDermott Technology
  - Materials and System Research
  - Sulzer-Hexis
  - Rolls Royce
  - Forschungzentrum-Jülich
- Select a best suited diesel reformer based on technology from
  - Nuvera
  - Hydrogen Burner
  - McDermott
  - Johnson Matthey
  - Argonne National Laboratory

Approach (continued)

- Conceptualize and simulate system
- Identify conventional technology or practice for a representative heavy duty vehicle
- Compare fuel consumption and emissions

Typical Planar SOFC Characteristics

- 850°C cell average temperature
- 0.7 volts/cell
- 0.85 fuel utilization
- 100°C cell oxidant temperature rise
- 10 cm by 10 cm active area
- System electric output is 12V DC (voltage regulator)

Typical Fuel Processor Characteristics

- ATR selected processor
- Temperature: 1000°C

  Steam/Carbon: 3.1

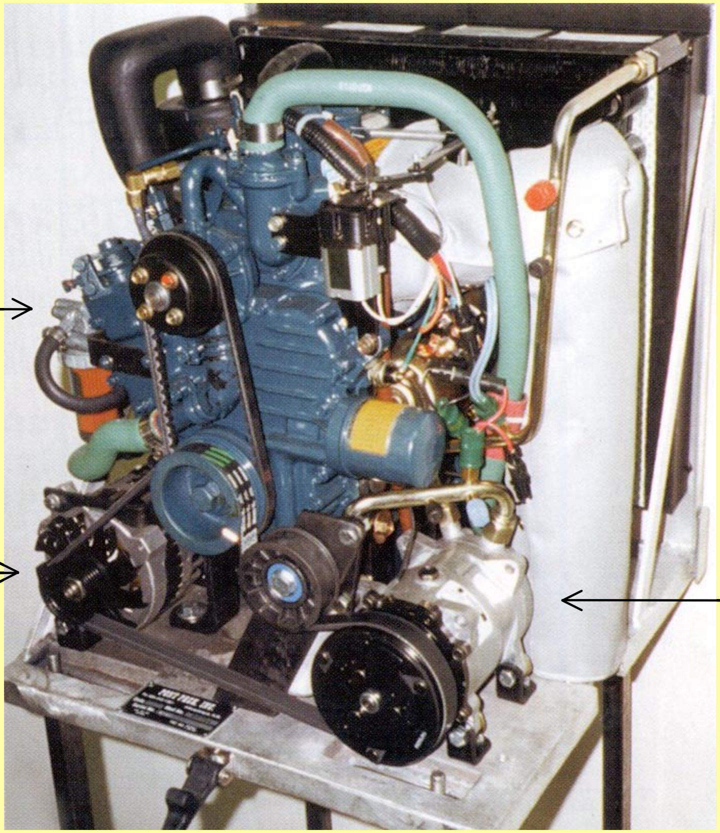
  Oxygen/Carbon: 0.38
- 1,825 Btu/lb LHV (94 Btu/SCF)
- Gas content (vol%):

- 1.4 CH_4	- 9.4 CO_2
- 5.2 CO	- 37.8 H_2O
- 23.4 H_2	- 22.8 N_2

Typical, Conventional Equipment

- Prime Power, Mack EM7-300 Engine
  - 300 HP (~224 kW)
  - 46.4% (LHV) (engine/rad.)
  - 1,530 liters
  - ~1,100 kg
  - ~$100/kW
  - Other parameters
- Auxiliary Power Unit, Pony Pack
  - 0.50 to 0.89 kW electric
  - 3.73 kW electric equivalent air conditioning
  - 29.8% (LHV)
  - 8 cu ft (227 liters)
  - 300 lb (136 kg)
  - $5,600 basic, $1,000 to $2,000 installation

Pony Pack Auxiliary Power Unit



Comparison

	Efficiency % LHV	CO_2 Emissions kg/kWh
Fuel Cell	39.6	.68
Pony Pack	29.8	.90
Truck engine at idle	11.0	2.44

Auxiliary Power Application Conclusions

- SOFC versus idling:
  - Total US, Class 8 fleet fuel savings is ~420 million gallons of diesel annually
  - 4.6 million tons CO_2 reduction annually
- SOFC versus conventional auxiliary power unit:
  - ~48 million gallons of diesel saved annually
  - 0.63 million tons CO_2 reduction annually
  - Fuel cell unit twice volume & 16% heavier

- Planar SOFC is competitive compared to idling & to conventional aux power unit

Needed Technology Improvement

SOFC

- Adapt existing planar SOFCs to transportation environment (robust cells – e.g., via thermal expansion compatibility of cell components)
- Design SOFC stack for quick start
- Conduct improvement program: reduce volume, reduce weight, improve performance, lower cost
- Demonstrate endurance & reliability
- Initiate alternatives: 150°C ΔT cell, 700°C cell

Fuel Processor

- Design for quick start; examine transient issues
- Examine catalyst issues (deactivation from liquid HC)
- Demonstrate endurance & reliability
- Conduct improvement program: reduce volume, reduce weight, improve performance, lower cost

J. SOFC Core Development Activities at PNNL

Prabhakar Singh, Director, Fuel Cell Development Secretary,
Transportation Technologies
Pacific Northwest National Laboratory

SOFC Core Development Activities at PNNL

Prabhakar Singh

Presented to :

The Second Annual SECA Conference, Arlington, VA

March 29, 2001

Technology Focus Areas

- *Cell / Stack Materials and Fabrication Processes*
- *Stack and System Performance Modeling*
- *Related SOFC Development Programs at PNNL*

Cell/Stack Materials and Fabrication Processes Development

Technology development

- Tape casting and co-sintering
- Ni base anode electrode
- Non Ni red/ox tolerant anode
- High performance cathode
- Corrosion resistant interconnection

Low cost tape casting and co-sintering processes

Anode formulations consisting of Ni - ZrO_2 - Al_2O_3

- CTE match with the electrolyte
- Cost reduction- substitution of ZrO_2 by Al_2O_3
- Dimensional control & less warpage

Co-sintering of the anode and electrolyte layers in air

- Bi-layer composites fabricated and tested
  - 5 to 10 uM dense YSZ &~ 600 to 1000 uM porous Ni- Cermet

Advanced red/ox tolerant anode development

Goal : Develop alternatives to Ni-based anodes that offers higher tolerance to oxidizing environments to allow fuel to be turned off during shut down.

- ***Limited choice of materials***
- ***Selected Perovskites, fluorites,Spinels, Pyrochlores identified with:***
  - *High electrical conductivity*
  - *Chemical and structural stability - oxidizing / reducing environments*
  - *Good TEC match*
  - *Very slow redox kinetics*

Development Status

- *Mixed valence transition metal oxides.*
- *Measured conductivity : 1-300 S/cm at 1000^{o}C at pO_2= 10^{-18} atm.*
- *TECs : 10 -12 x 10^{-6} C^{-1} during Oxidation & Reduction Cycles.*
- *Full reduction-oxidation cycles demonstrated.*

Further Characterization and cell tests in progress.

SECA

High Performance Cathode

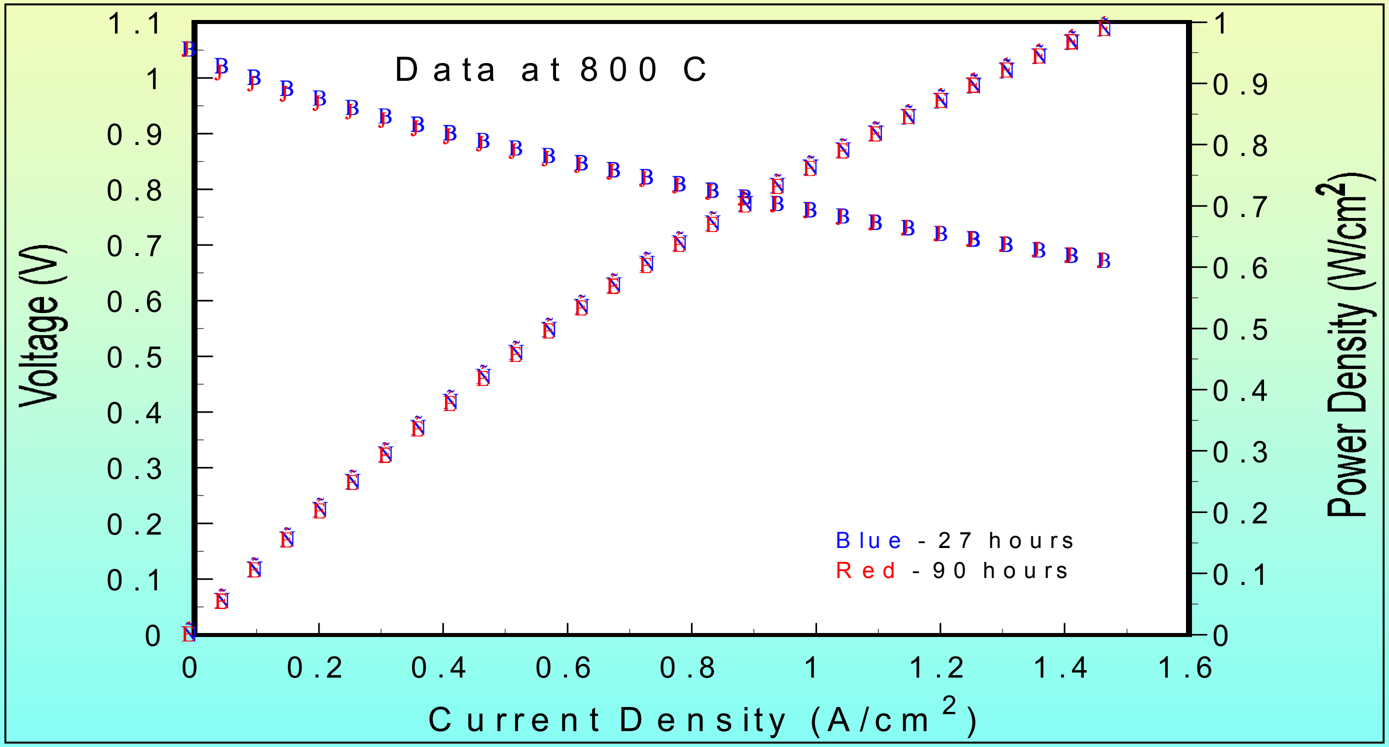
Goal : Develop and optimize intermediate temperature chemically stable cathode for high power density operations under isothermal and thermal cyclic exposure conditions.

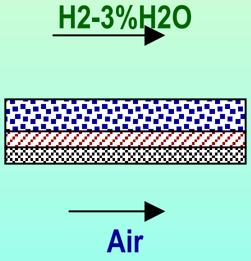
- A large historical data base available on doped ABO_3 Perovskites

- Improved performance & stability demonstrated for $La_{1-x}Sr_xFeO_3$

- Structural and compositional optimizations (bulk and interfacial modifications) in progress

Improvements in Cell Performance





Anode – Ni-Al_2O_3-ZrO_2 (600uM) Cathode – $La_{.8}$ $Sr_{.2}$ FeO_3(50uM) Electrolyte - YSZ(10 uM)

SOFC interconnection development

Two fold objective:

- *Identify degradation processes*
- *Develop a cost effective material (bulk and /or coatings) for intermediate temperature operation.*

SOFC exposure conditions remain complex:

- **Multi component gas streams (H_2O, CO_2, O_2 etc.)**
- **Changing fuel composition (fuel utilization)**
- **Simultaneous fuel and oxidant gas exposures**
- **Isothermal and thermal cyclic exposures**

SOFC interconnection development

Status:

•Identified corrosion processes :

- Conjoint attack
- Molecular diffusion through scale imperfections / defects
- Oxide defect chemistry - anion or Cation stoichiometry
- Short circuit diffusion
- Vaporization

•Developed metallurgical data base :

- Oxidation and oxide properties (conductivity, PB ratio, defect structure)
- Joinability and fabricability (hot & cold rolling, welding, brazing)
- Carburization & sulfidation behavior (metal dusting, low mp eutectic)

Approach

- ***Pre-Screen Evaluation***
  - Thermal expansion coefficient
  - Linear rate of oxide scale growth at 800°C
  - Creep rate at 800°C
  - Potential for hydrogen embrittlement
  - Potential for corrosion due to sulfidation
  - Initial estimate of raw materials costs

- ***Screen Testing***
  - Electrical Screen
  - Chemical Screen
  - Mechanical Screen
  - Fabrication Screen
  - Cost Analysis

- ***Collaborative Development Effort***
  - National Laboratories
  - SOFC Manufacturers
  - Materials Manufacturers
  - Academia

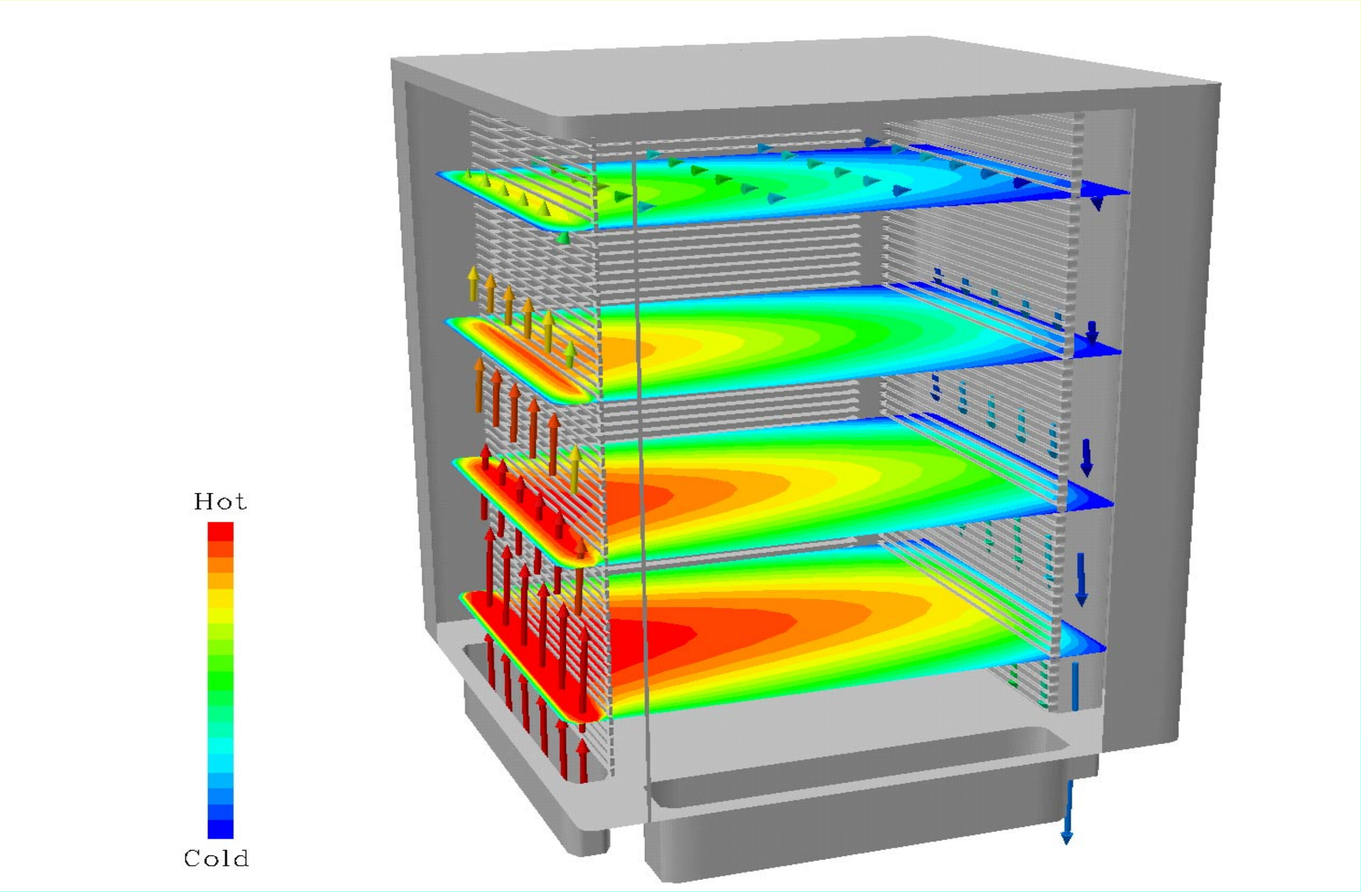
Stack and System Performance Modeling

Goal : Develop and optimize advanced engineering modeling tools and cell and stack designs.

Predict thermal, stress, flow and electrical performance during cell / stack startup and cool down as well as steady state and transient operation (Electro-thermo-chemical analysis)

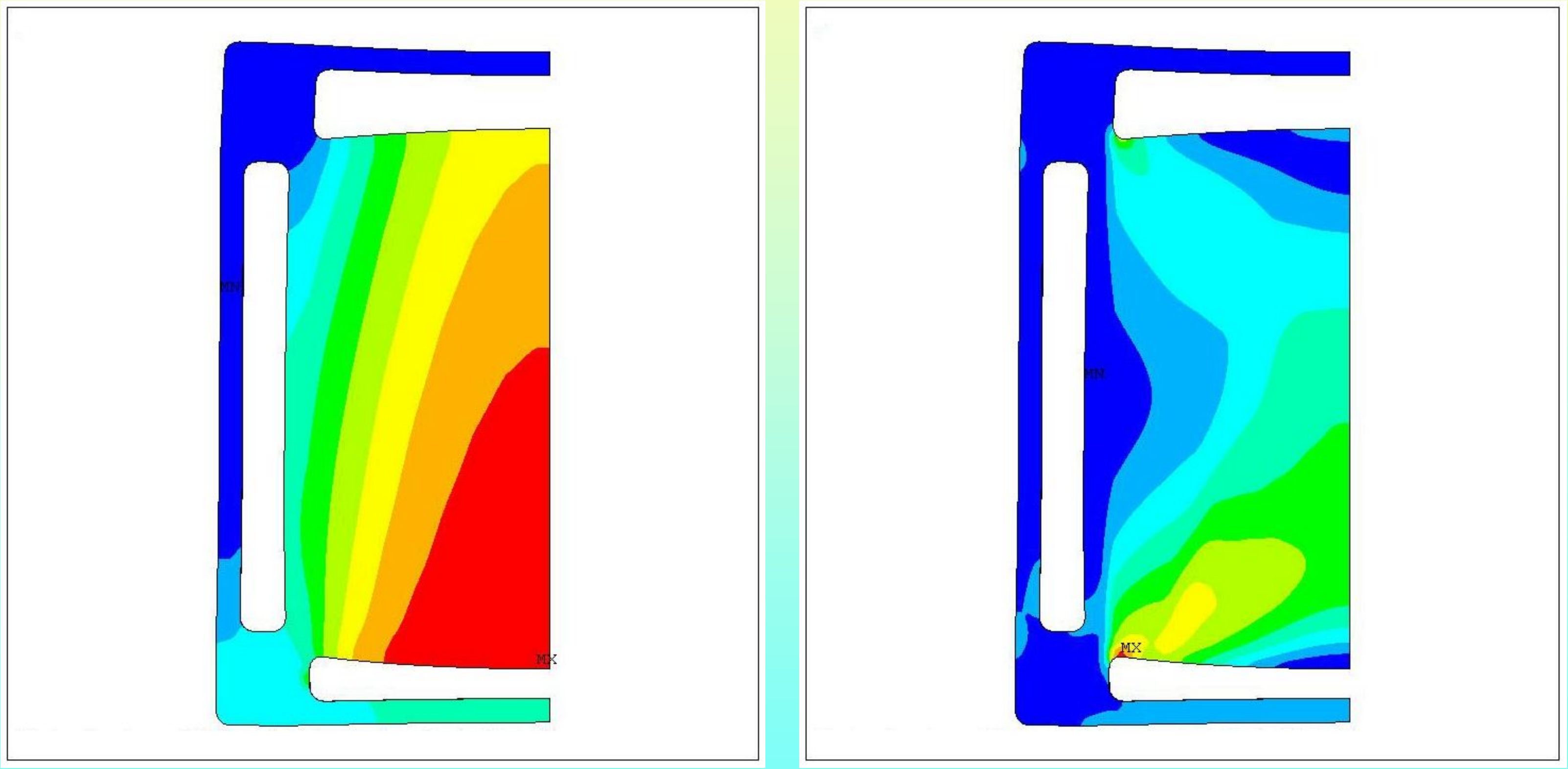
- ***Stress analysis***
- ***Computational flow analysis***
- ***Electrochemical analysis***

Thermal-Fluids Model



Prediction of flow and temperature distribution.

Thermal-Structural Model:



Prediction of thermal stresses and planar deflections

Animation of stack heat up

Related SOFC Development Programs at PNNL

LDRD :

- *Fuel Cell Observatory*
- *Advanced FC Systems & Functional Integration*

AR&TD :

- *Basic Electro-ceramic Materials for Fuel Cells and Gas separation membranes, Glass seals*

CRADA :

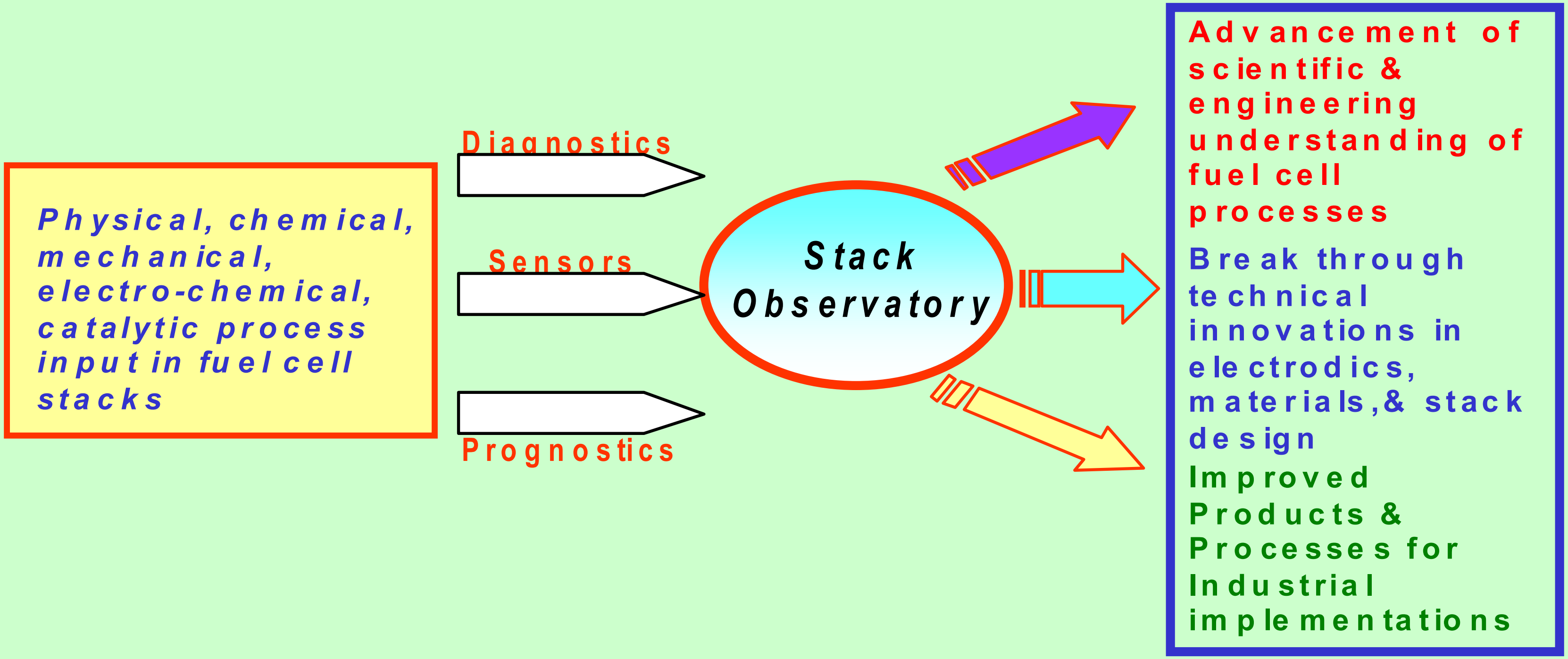
- *Collaborative SOFC Technology development with Delphi Automotive for Automotive Auxiliary Power*

DARPA :

- *Collaborative SOFC Technology Development with Honeywell for "Palm Power"*

SOFC Stack Observatory Concept

Solid oxide fuel cell stack observatory



U.S. Department of Energy
Pacific Northwest National Laboratory

K. SOLID OXIDE FUEL CELL RESEARCH AT ARGONNE NATIONAL LABORATORY

Romesh Kumar, Group Leader, Transportation Applications in the Electrochemical Technology Program
Argonne National Laboratory

Solid Oxide Fuel Cell Research at Argonne National Laboratory

R. Kumar, R. Ahluwalia, T. Cruse, J. Ralph, X. Wang, and M. Krumpelt

2nd Solid State Energy Conversion Alliance Workshop
Arlington, VA
March 29-30, 2001

Task areas

- Low-temperature cathode materials
- Sulfur-tolerant anode materials
- Metallic interconnect (bipolar) plates
- Cell, stack, and systems modeling

Low-Temperature Cathode Development
Overview

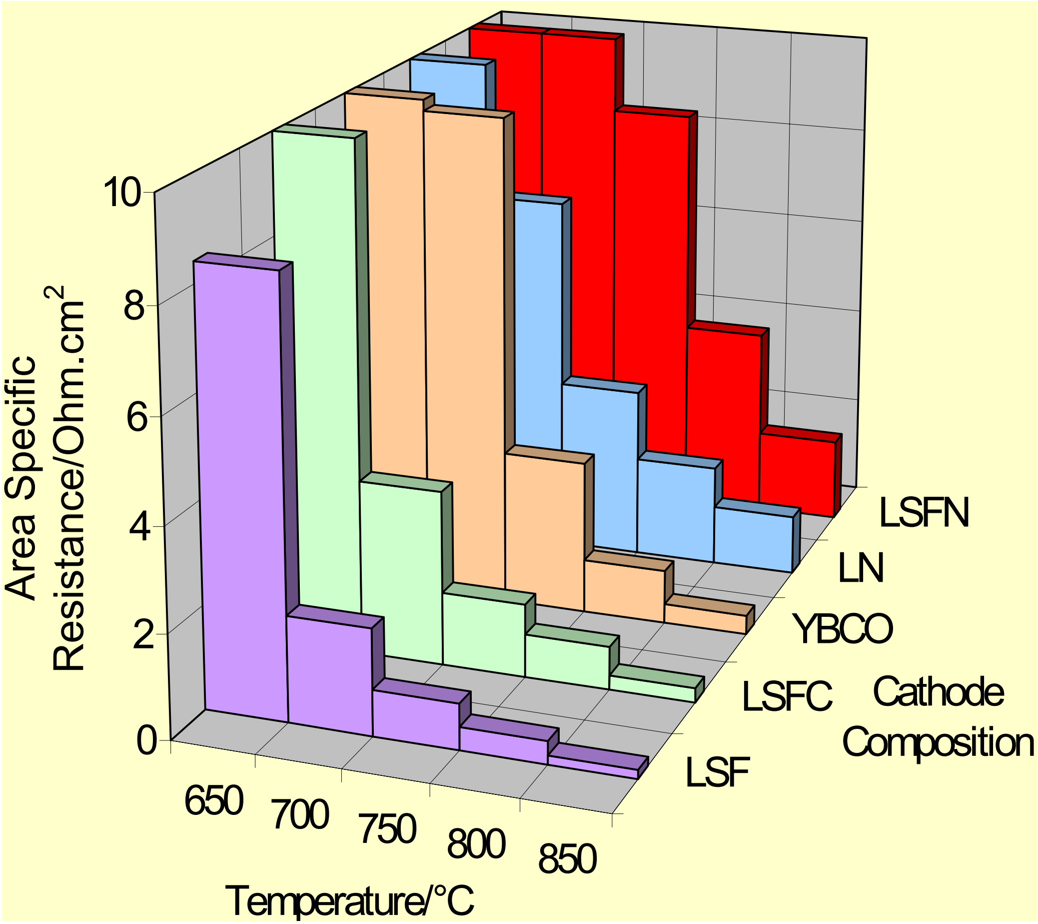
- LSM is a poor cathode material at <900^{o}C, even as LSM/YSZ composite
- Need to develop a mixed conducting material to achieve better power densities at $\leq$800^{o}C
- Options:
  - replace Mn in LSM by Co, Fe, or Ni
  - move to differently structured materials
- La(Sr)FeO_3 (LSF) has proven to be the most compatible and best performing cathode with YSZ

Low-Temperature Cathode Development

Perovskite-based cathodes

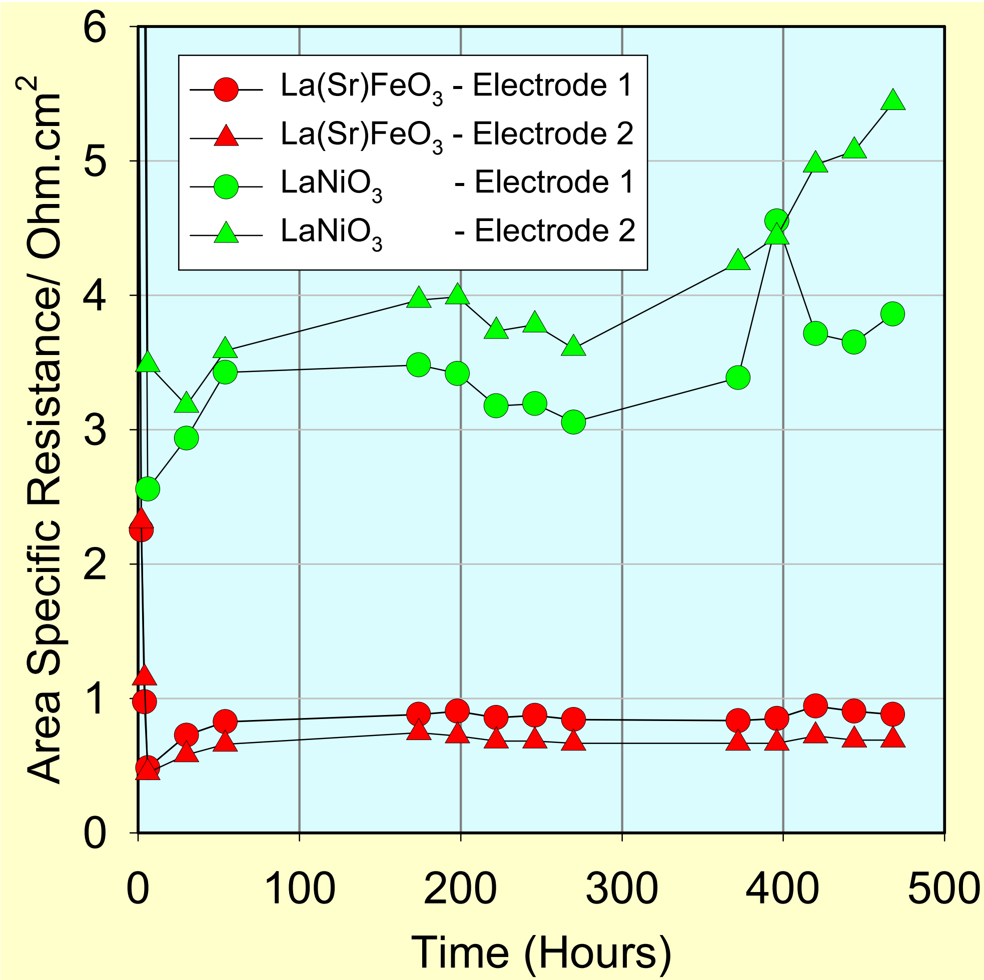
Composition	Electronic Conductivity (Scm^{-1}) at 800°C	Ionic Conductivity (Scm^{-1}) at 900°C
$La_{1-X}Sr_XCoO_3$	1000-2000	8×10^{-1}
$La_{1-X}Sr_XFeO_3$	400-500	1×10^{-2}
$La_{1-X}Sr_XNiO_3$	500	-
$La_{1-X}Sr_XMnO_3$	100-200	10^{-7}
$La_{1-X}Sr_XCrO_3$	<100	$<10^{-7}$

Low-Temperature Cathode Development
Area-specific resistances on YSZ



- Ferrite-based perovskites display best performance at all temperatures (initial target ASR is <1 Ω cm^2)
- Layered structures show good performance at ≥850°C but high activation energies preclude use at ≤800°C
- Nickelate-based perovskite has potential <u>if</u> the structure can be stabilized when doped

Low-Temperature Cathode Development
Long-term ASR on YSZ at 800^{o}C

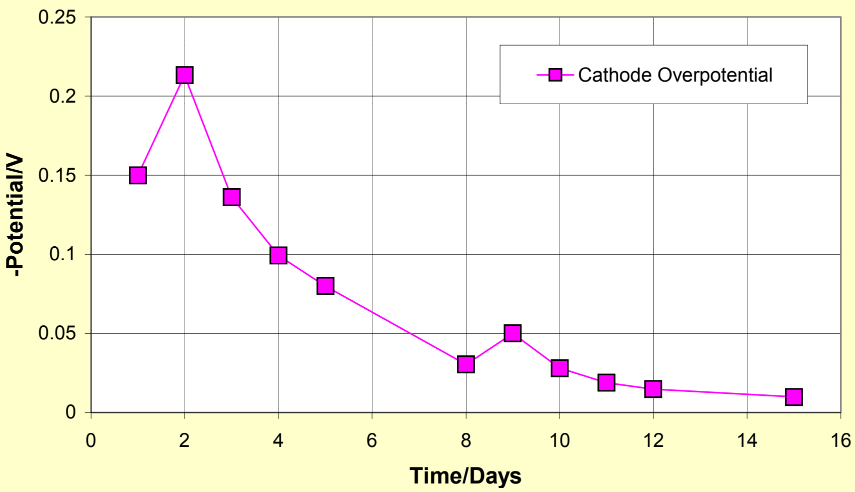


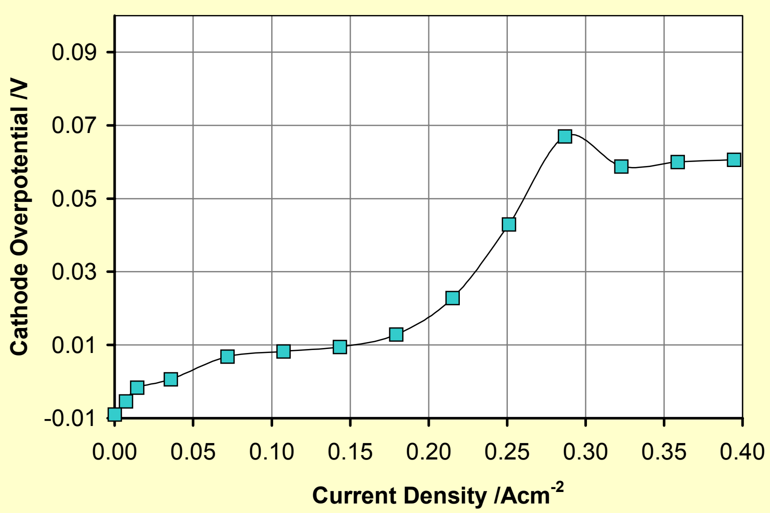
- LSF displays the most stable performance with an ASR of <1 Ω cm^2
- LN has too high an ASR at 800^{o}C

Low-Temperature Cathode Development

Polarization curves for La(Sr)FeO$_3$ on YSZ

- Current conditioned for ~330 h at 250 mA cm^{-2} at 800^{o}C
- Overpotentials decreased with time over the 16 days
- Values for LSF at 800^{o}C are similar to LSM at 1000^{o}C



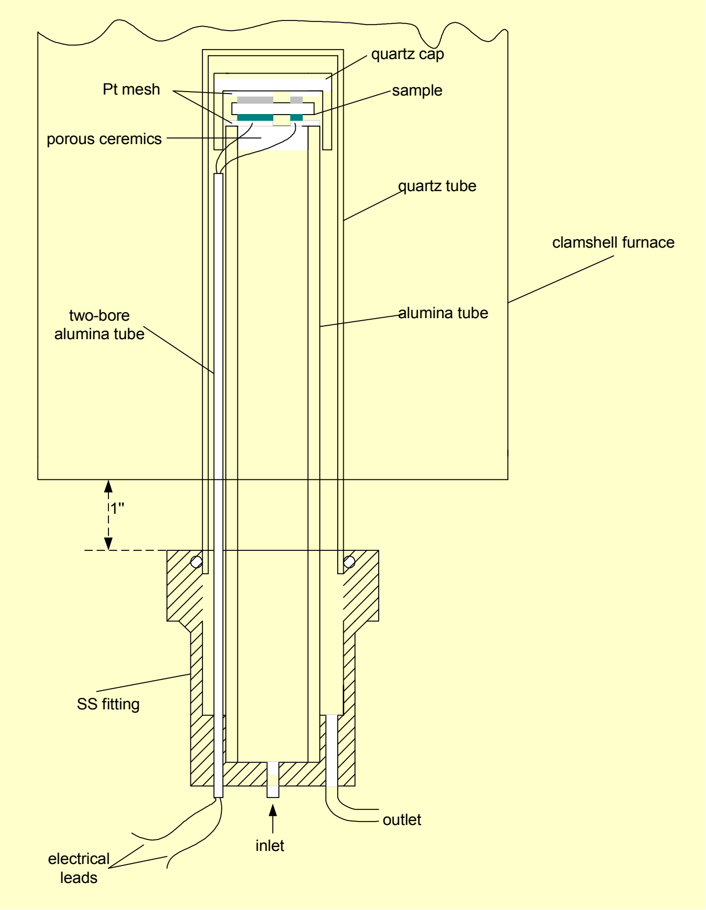


Sulfur-Tolerant Anode Materials
Approach

- Modify conventional anode material with an additive that has suitable redox chemistry
  - additive captures H_2S in preference to Ni; the H_2S is subsequently oxidized to SO_2
- Replace the Ni in Ni-YSZ with other metal or alloy active for electrooxidation of H_2 but resistant to poisoning by H_2S
- Investigate new classes of materials based on carbides and/or sulfides

Sulfur-Tolerant Anode Materials
Status

- Several candidate anode materials have been coated on commercial YSZ disks for half-cell tests
- Testing will get underway within the next few weeks with fuel gases containing 0-100 ppm H_2S



Test Apparatus Schematic

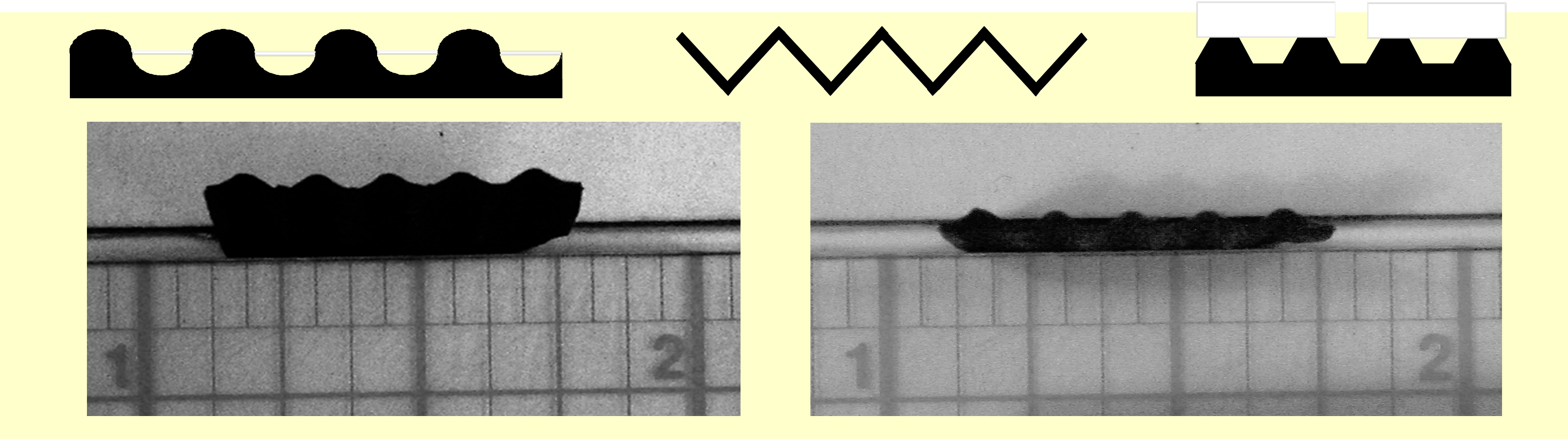
Metallic Interconnect Development

Materials requirements

- Electronically conductive
- Chemically stable under under both anodic and cathodic conditions
- Coefficient of thermal expansion similar to the other fuel cell materials
- Formable (for internally manifolded stack designs)

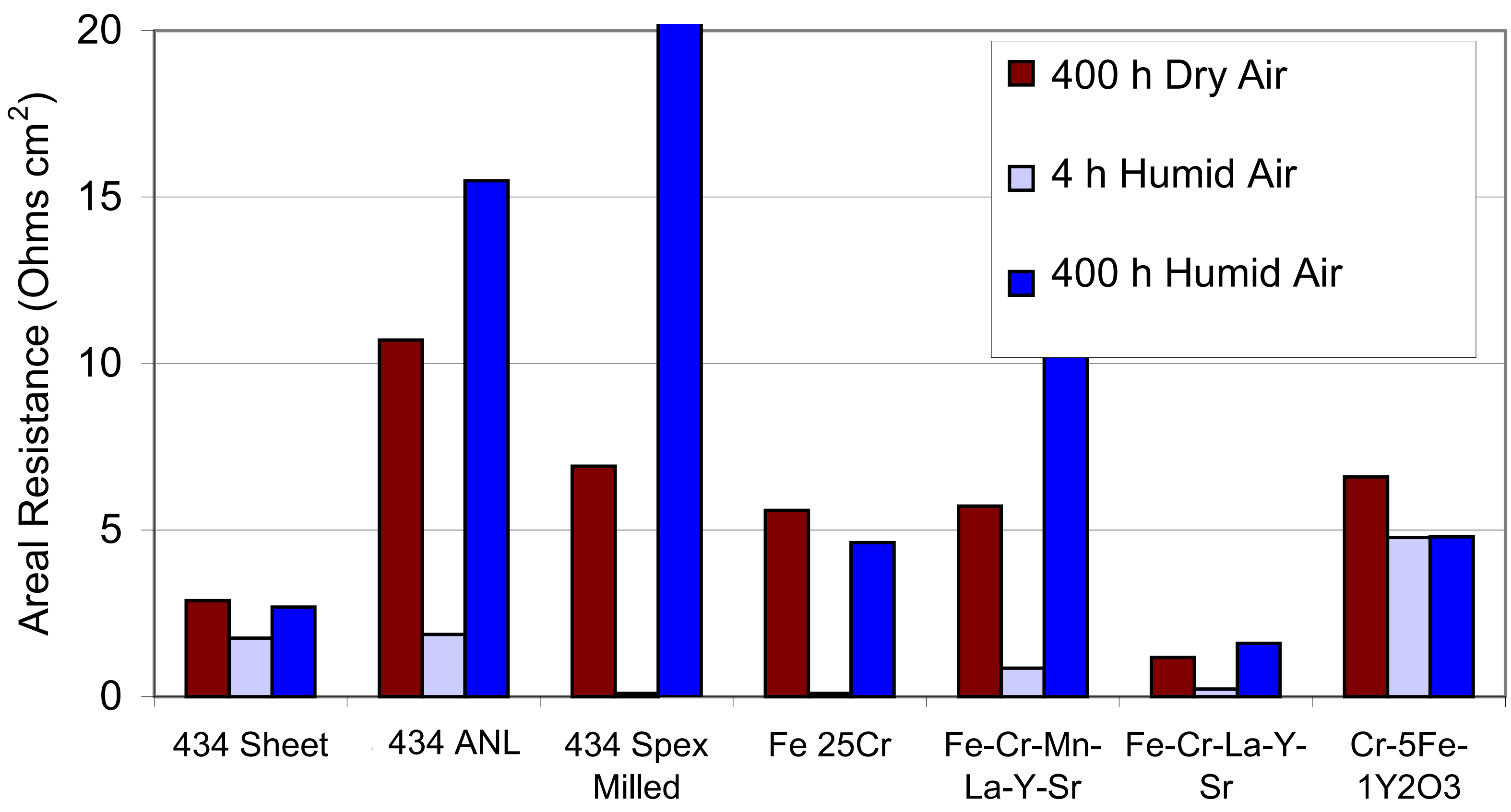
Metallic Interconnect Development
Approach

- Alloys similar to ferritic stainless steels
  - reduce Cr, other elements that can degrade fuel cell performance
  - additives to improve properties and protective scale
- Coated materials to impart chemical stability
- Powder production by mechanical alloying techniques
- Processing technique can yield almost any desired shape
  - flat, corrugated, textured, functionally graded



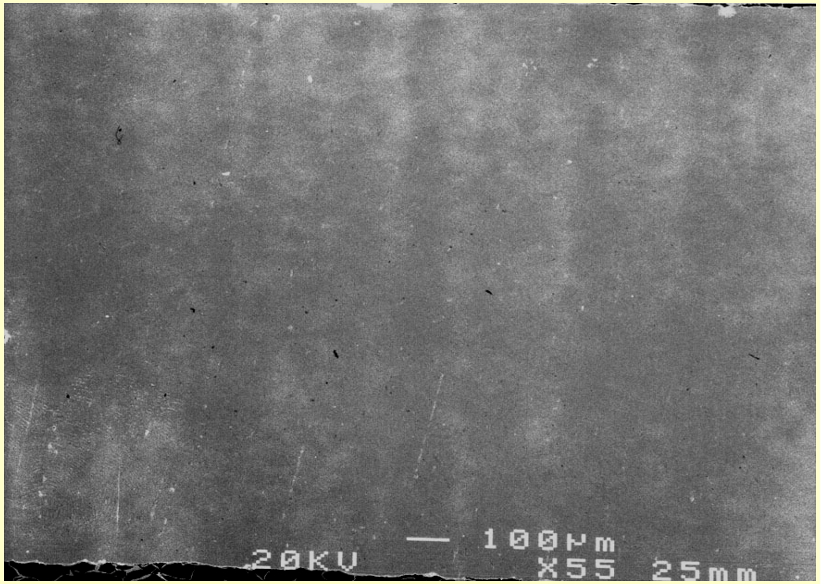
Metallic Interconnect Development

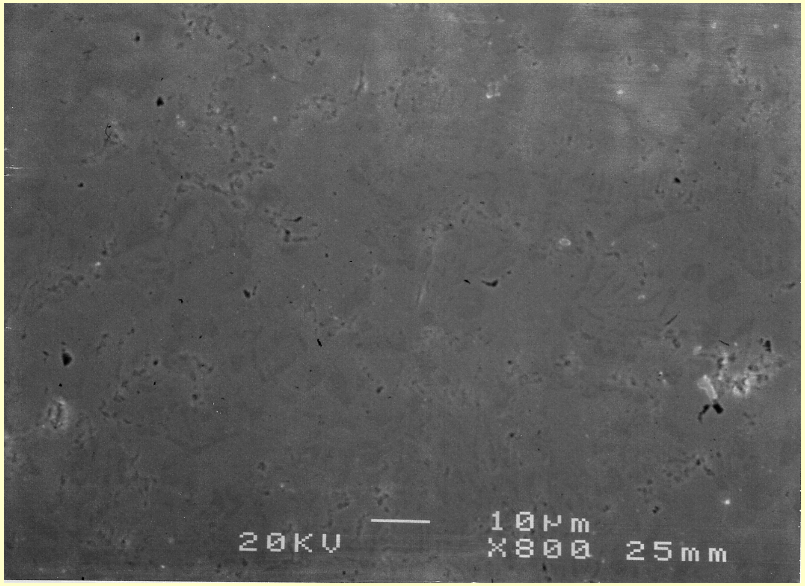
Electrical resistance of the oxide scale



Metallic Interconnect Development

Multi-layer plates show excellent bonding





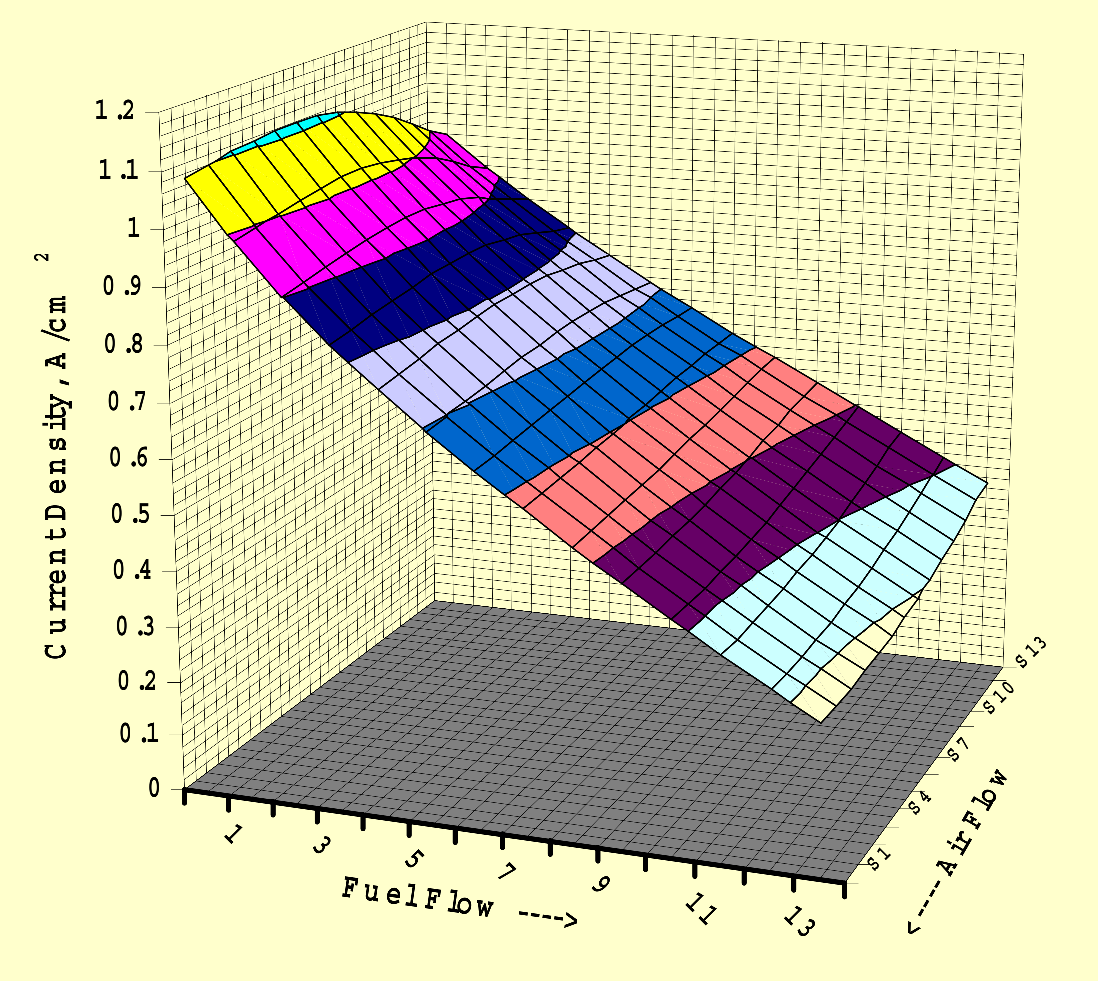
10 layers of ferritic stainless steel alloy

Each layer ~140 µm thick

(Fe-Cr-La-Y-Sr)

Cell, Stack, and Systems Modeling
Current density distribution, 0.7 V, 85% u_f

- Single cell model: sample results
- Current density can vary by a factor of 5



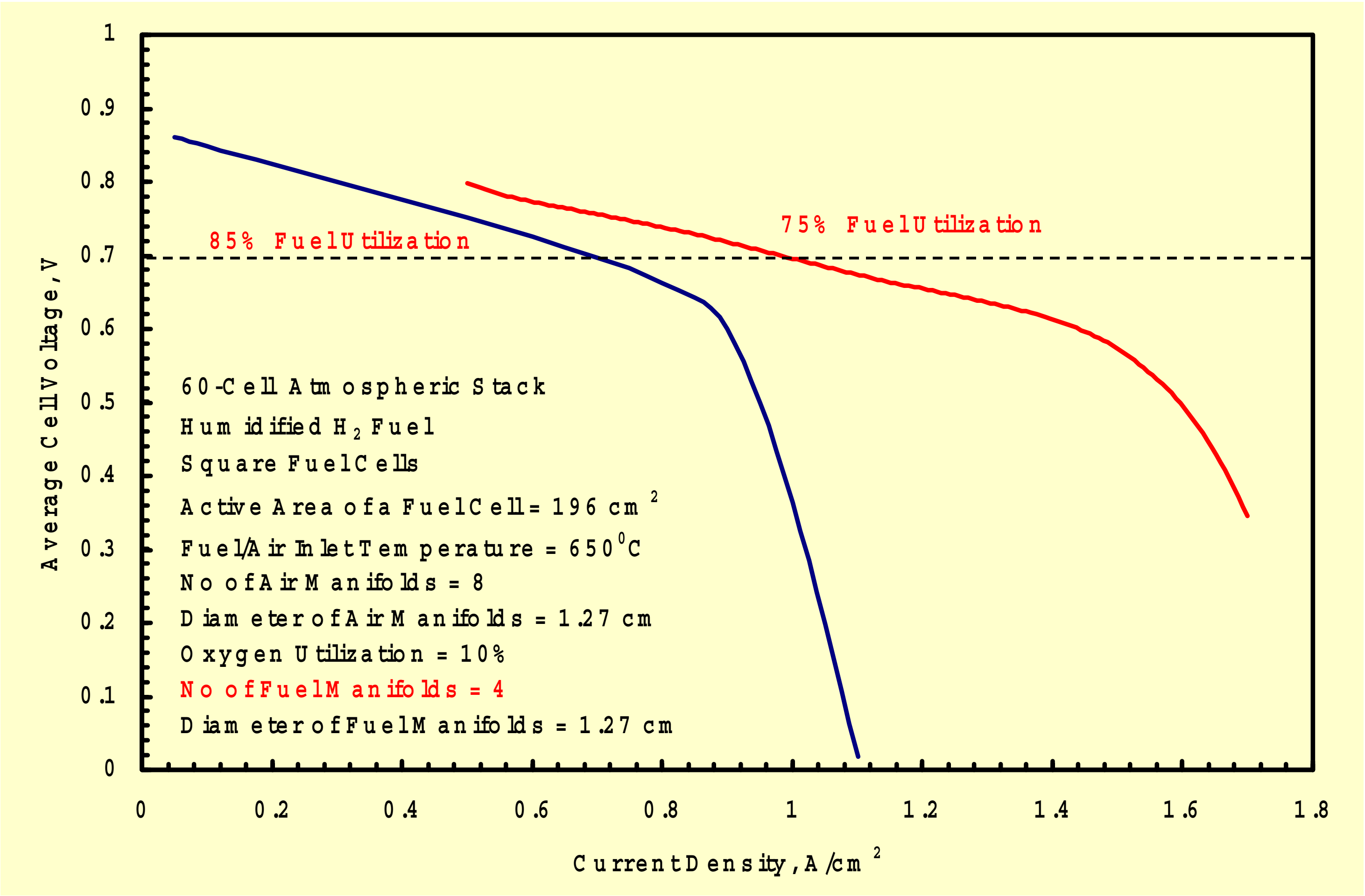
Cell, Stack, and Systems Modeling

Cell performance change with reformate

	Humidified H_2	Reformate
Active Cell Area	196 cm^2	196 cm^2
Fuel Composition	95.2% H_2	59.2% H_2
	4.8% H_2O	19.3% H_2O
		4.2% CH_4
		10.3% CO
		7.1% CO_2
Inlet Temperature	650 ^0C	650 ^0C
Max Cell Temperature	804 ^0C	800 ^0C
Fuel Utilization	85.30%	85.30%
Oxygen Utilization	7.30%	9.40%
Call Voltage	0.7 V	0.7 V
Avg Nernst Potential	0.86 V	0.84 V
Avg Current Density	0.65 A/cm^2	0.518 A/cm^2
Gross Power	89.4 W	71 W
Net Power	87.1 W	70.1 W

Cell, Stack, and Systems Modeling

Stack performance vs. fuel utilization



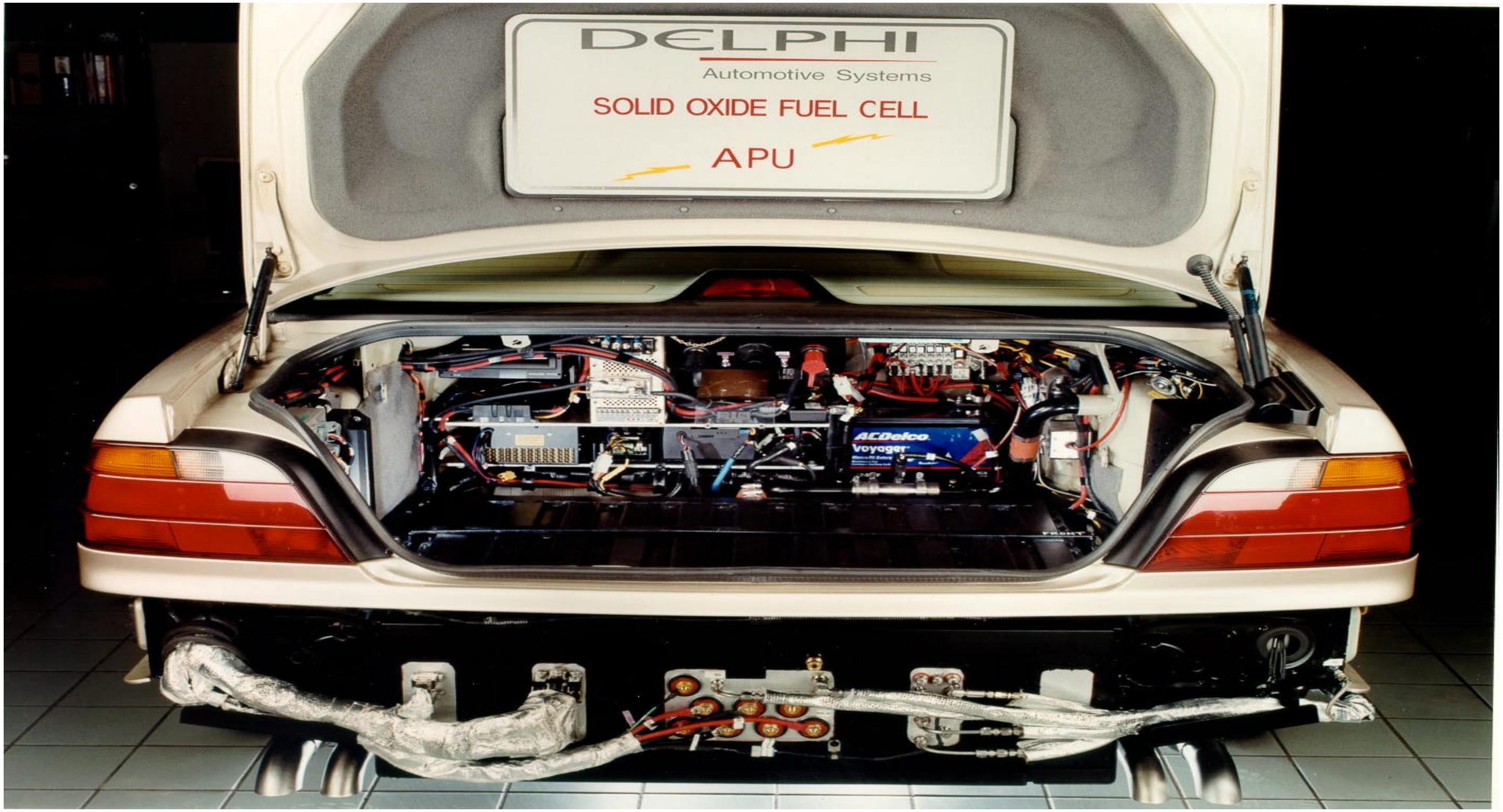
Summary
Current and future work

- Micro-engineer the cathode-electrolyte interface to further improve cathode performance
- Evaluate anode materials with 0-100 ppm H_2S in fuel gas
- Characterize oxide scale on metallic bipolar plates for growth rates and electrical conductivity
- Test developed materials in full cell and short stack configurations, as appropriate

L. SOFC Status and Challenges

Chris DeMinco, Manager, Advanced Systems Development
Customer Solutions Center
Delphi Automotive Systems

SOFC Status and Challenges



Chris De Minco & Dr. Subhasish Mukerjee
Delphi Automotive Systems

Introduction

- Delphi Automotive Systems is developing Solid Oxide Fuel Cell (SOFC) technology for transportation applications - primarily as an on-board Auxiliary Power Unit (APU).
- Paradigm shift in the supply of electric power for transportation.
- Highly efficient and low emissions.
- Consistent with the increasing demands for electrical power in the new era of more comfort and convenience, safety along with low emissions environmental friendliness.

Outline

- Why a SOFC APU
- SOFC APU System Mechanization
- Key Subsystem Development
  - Stack
  - Reformer
  - Waste Energy Recovery
  - Battery Pack
  - BOP
- Current APU and Technical Challenges
- Future Vision and Conclusions

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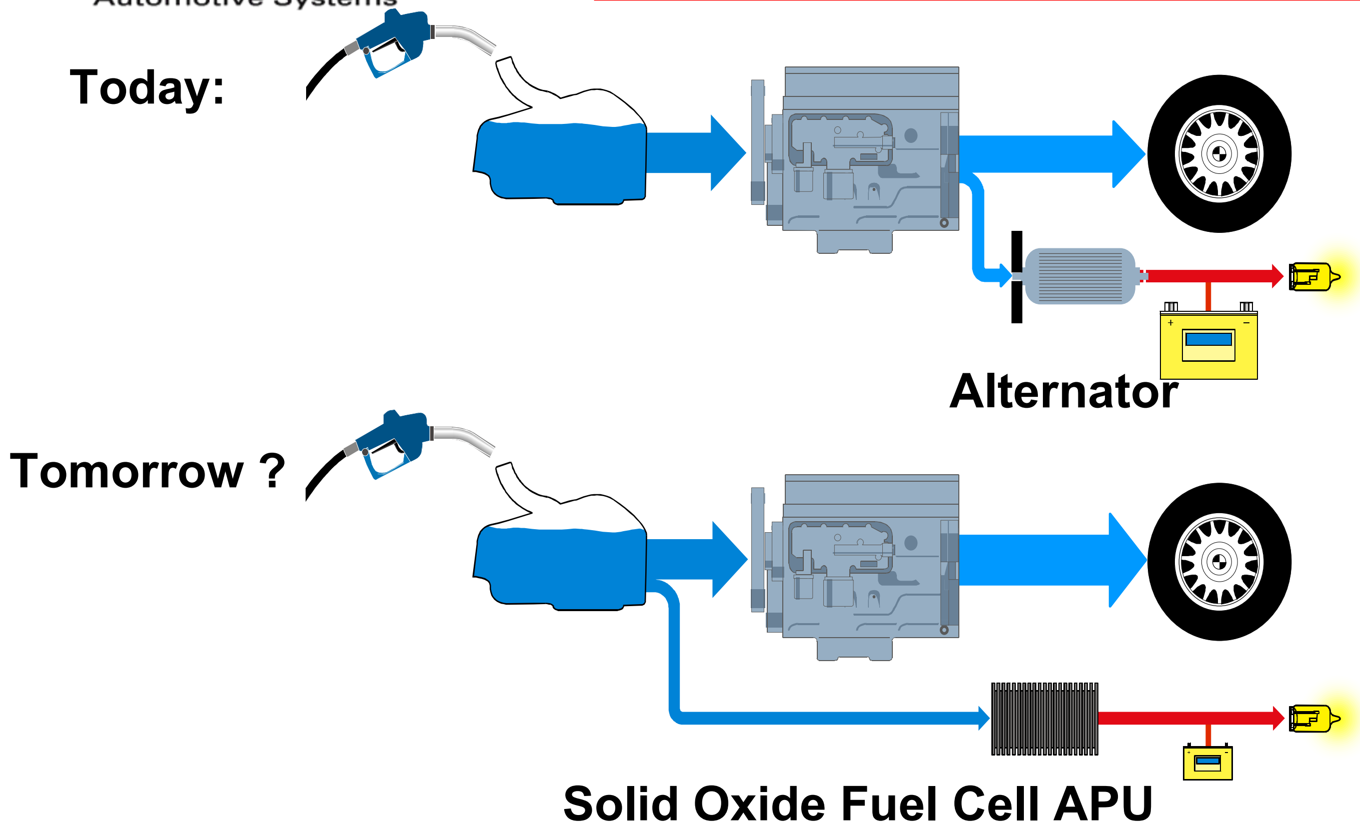
Fuel Cell APU for Gasoline Cars



Why a SOFC APU?

- The APU is not competing with the IC Engine but complements it.
- Highly efficient generator providing power with the engine off
- The SOFC utilizes simple reforming technology
- Less stringent fuel requirements (uses CO as a fuel)

Fuel Cell Technologies

	PEM	SOFC
Electrolyte	Polymer	Ceramic
Operating Temperature	80°C	700-1000°C
Fuels	H_2 / Reformate	H_2 / CO / Reformate natural gas, light HC fuels
Reforming	External	External / Internal
Oxidant	O_2 / Air	O_2 / Air
Efficiency	> 50%	> 50%
Commercial	Ballard, GM, Toyota	Westinghouse [Delphi]
Current Applications	Portable electronics / Automotive / Utility	Utility [Automotive]

Reformer Complexity - SOFC vs PEM

Gasoline Autothermal / Steam Reformer

> 900 °C

High Temperature Shift Reactor

Low Temperature Shift Reactor

Preferential Oxidation (CO clean-up)

PEM Fuel cell stack

80 °C

Gasoline Partial Oxidation Reformer

800 °C

Solid Oxide Fuel Cell Stack

800 °C

SOFC

SOFC reformer and stack run at similar temperatures and can be closely coupled.

PEM

PEM reformer + stack run at very different temperatures. A complex, multi-stage reformer system must be carefully thermally managed at each step.

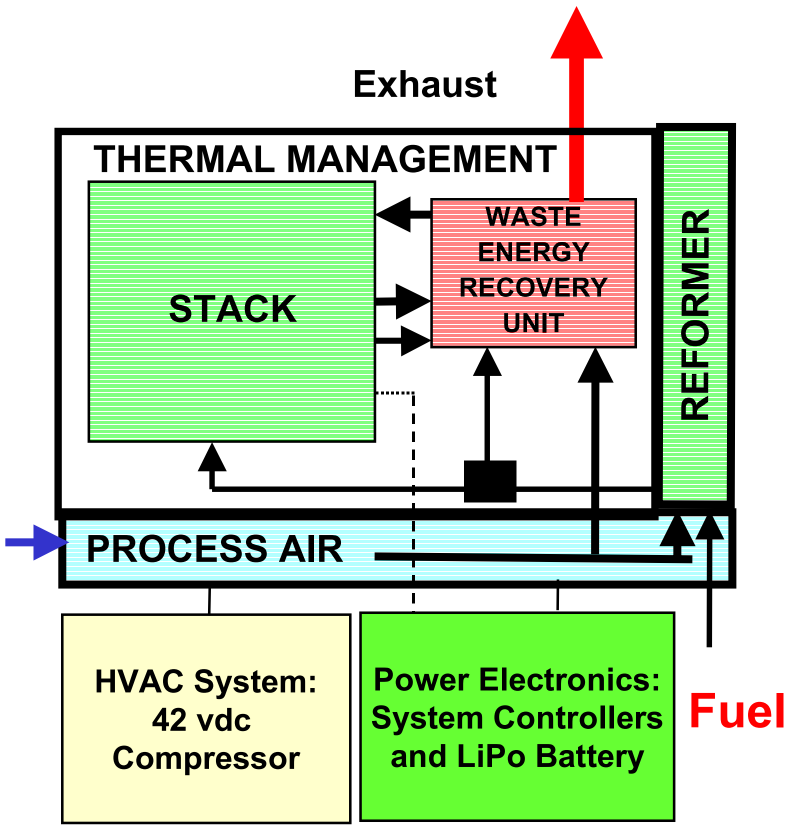
Solid Oxide Fuel Cell APU System Overview

Auxiliary Power Unit (APU) Parts:

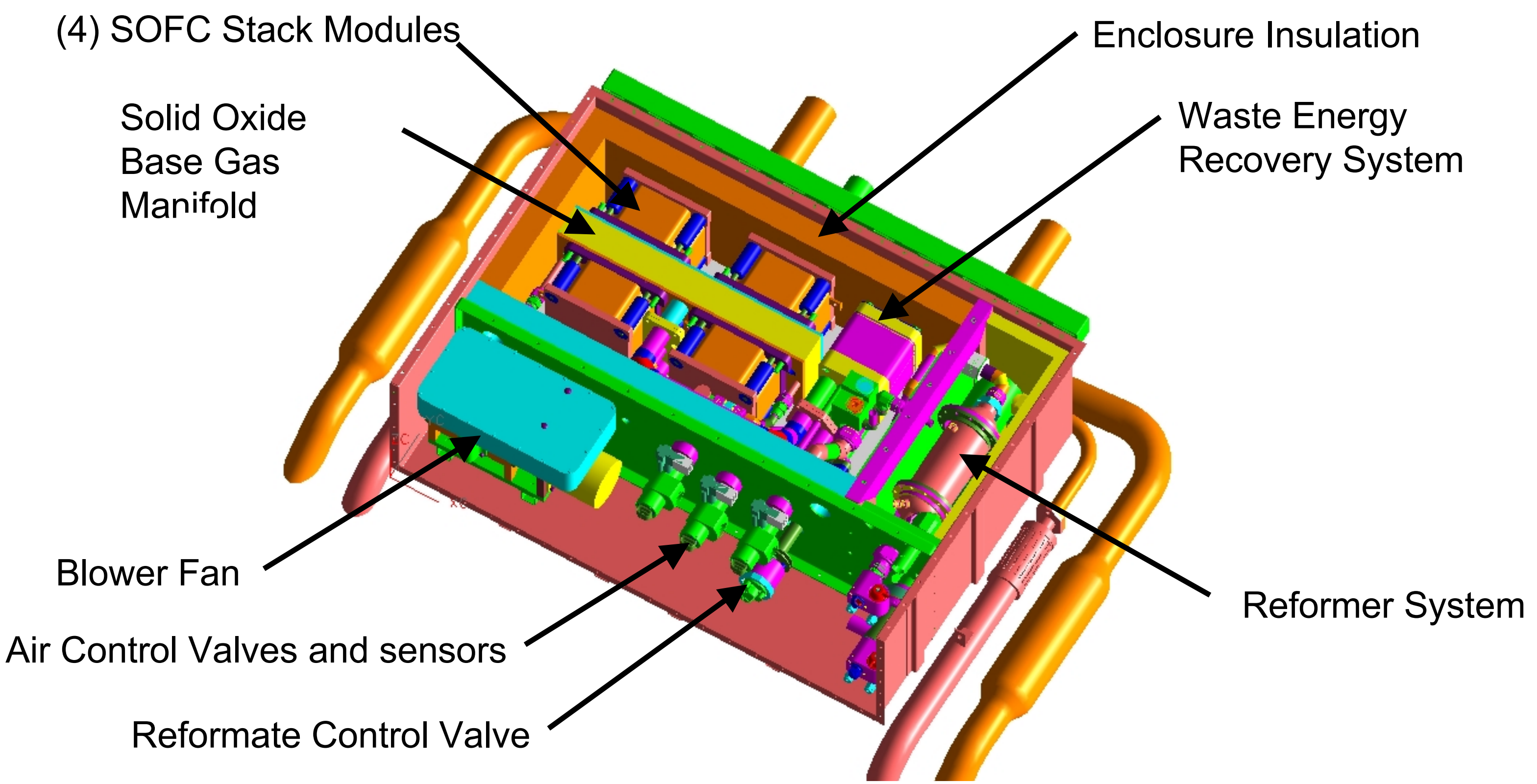
- SOFC Stack subsystem
- Fuel Reformer subsystem
- Balance of Plant (BoP)
  - Process Air Supply
  - Thermal Management
  - Waste Energy Recovery
  - Power Electronics / Controls
  - HVAC subsystem

Expected Customer Benefits:

- Can supply electric power with engine on or off, with high efficiency and essentially zero emissions
- Permits operation of any electrical accessory
- Possible enabler for high power-consuming advancements (e.g., PVT)



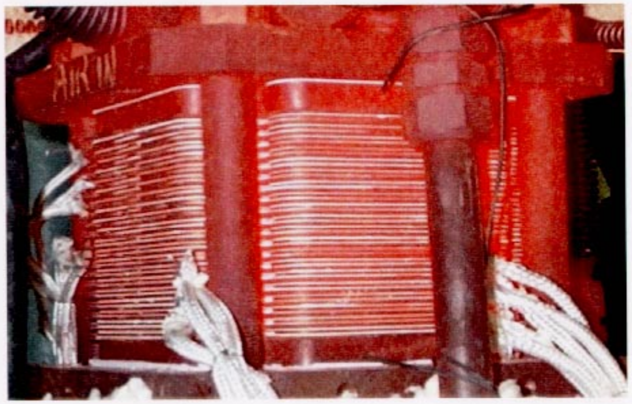
Proof of Concept
Vehicle Integrated APU Layout



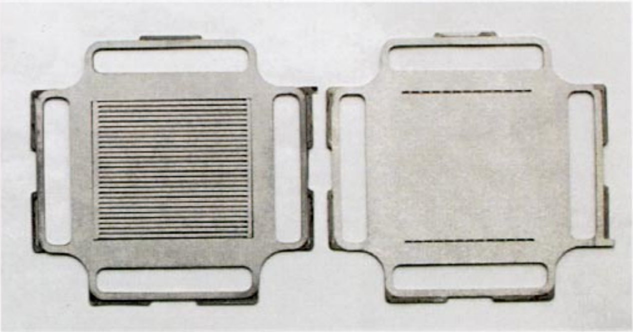
Solid Oxide Fuel Cell Stack

- Stack developed by Global Thermoelectric
- Planar anode supported technology for high power density.
- Metallic interconnects for low cost.
- Compression seals for thermal cycling.

20 Cell - 800 deg. C.



Metal Interconnect Plates



Source: Global Thermoelectric

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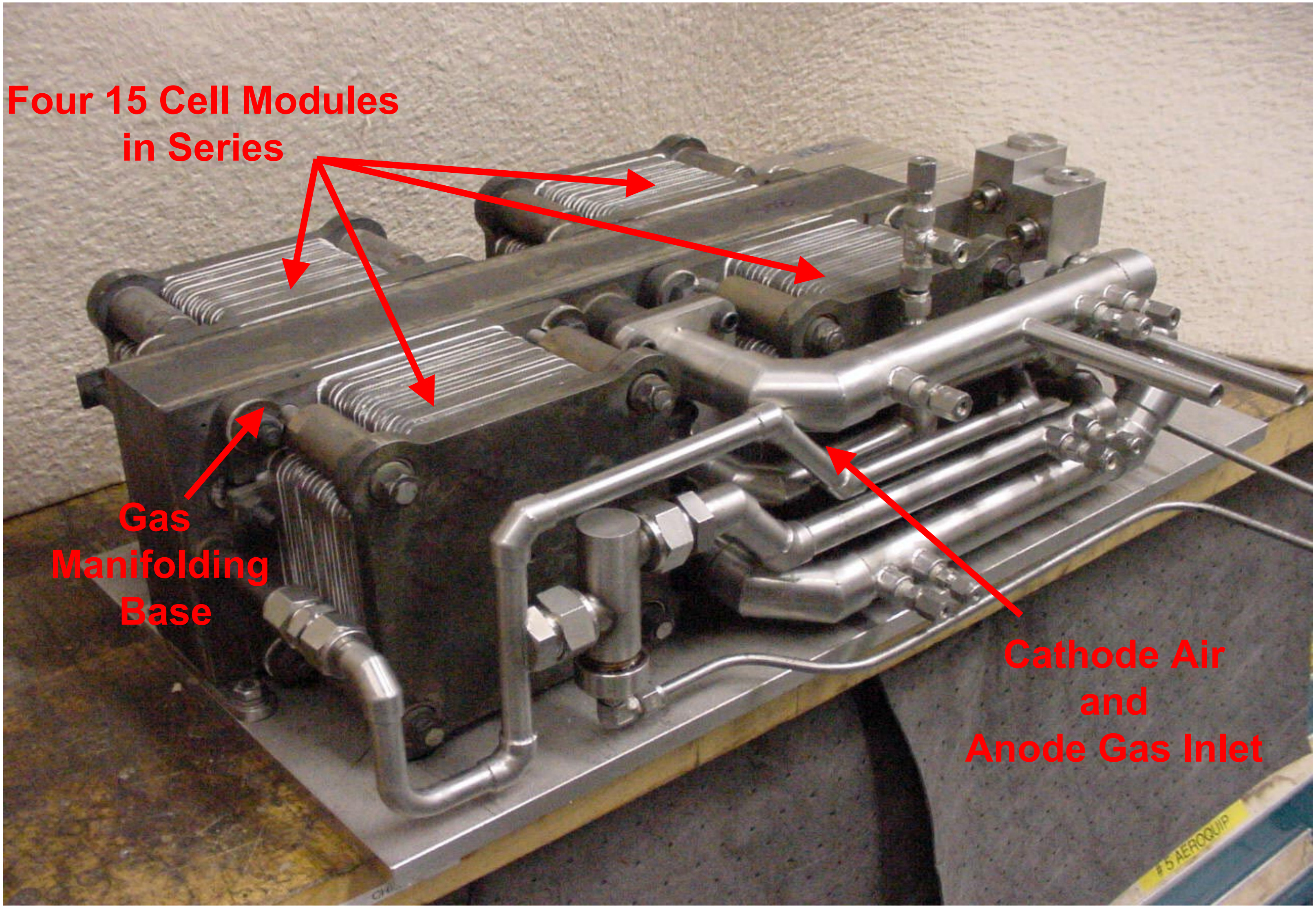
SOFC
"BOXER" 15X4 Stack Plate



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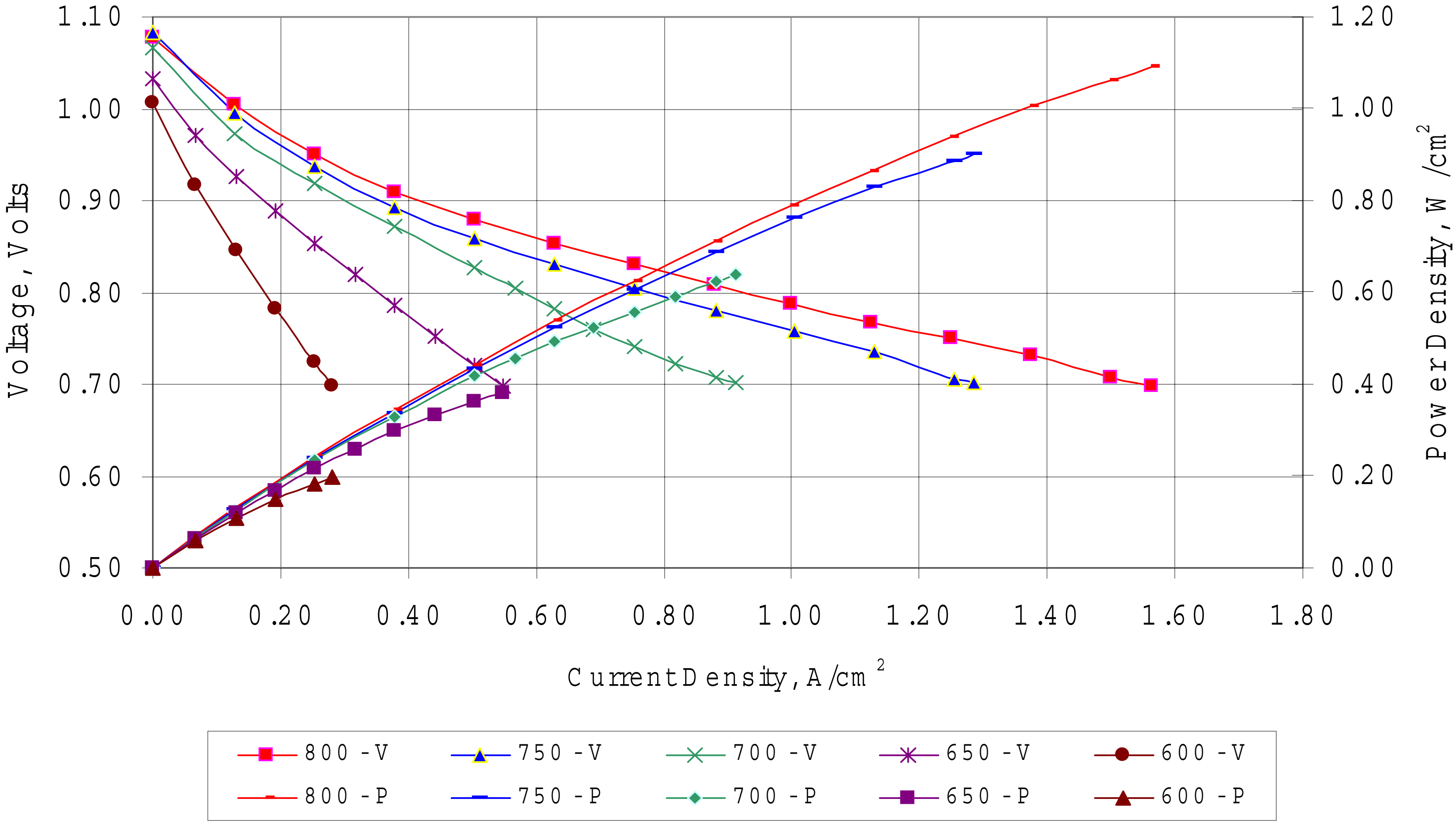
Single Cell Power Density with Hydrogen

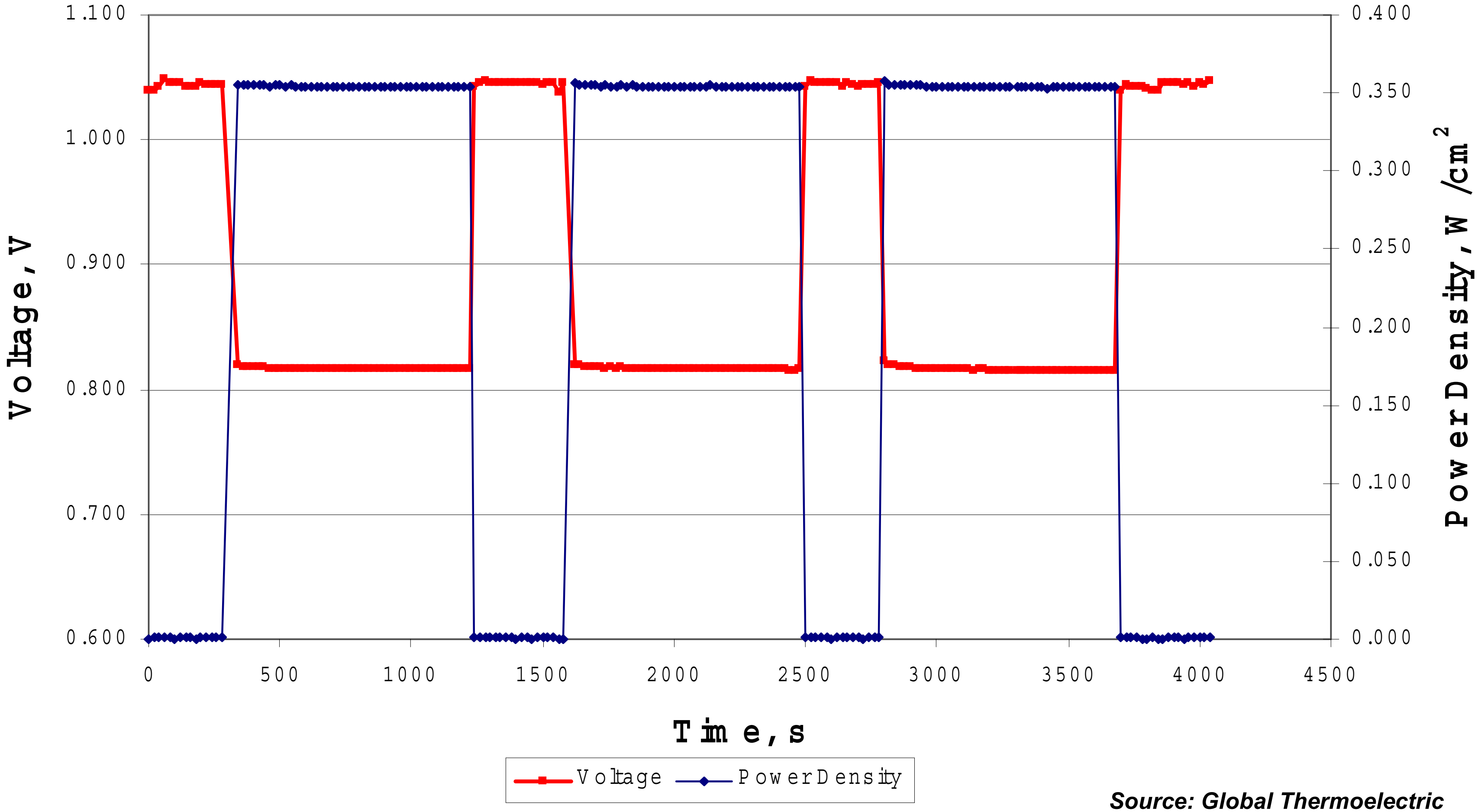
Fuel = hydrogen



Source: Global Thermoelectric

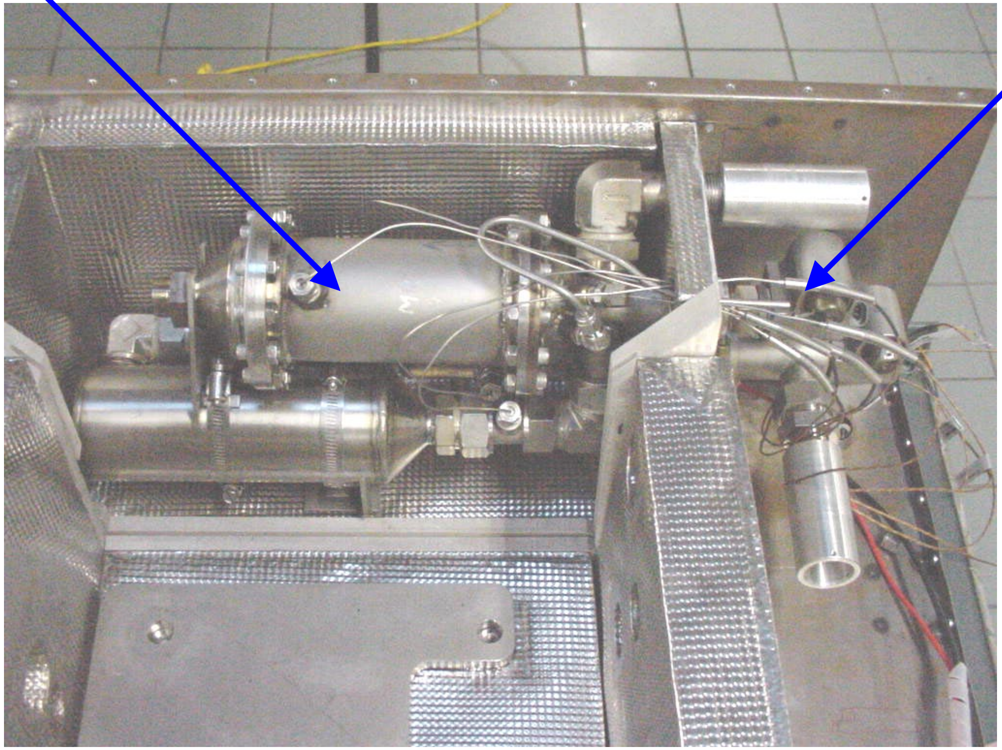
Load Profile Tests

T=750°C, Fuel = 45%hydrogen,rest argon; Fuel Utilization 60%



Source: Global Thermoelectric

SOFC Reformer Prototype



Capacity: 10 kWt Reformate
Catalysts: Automotive Derivative
Air / Fuel Actuators: Standard Automotive
Start-up time: < 10 minutes (to SOFC purity reformate)

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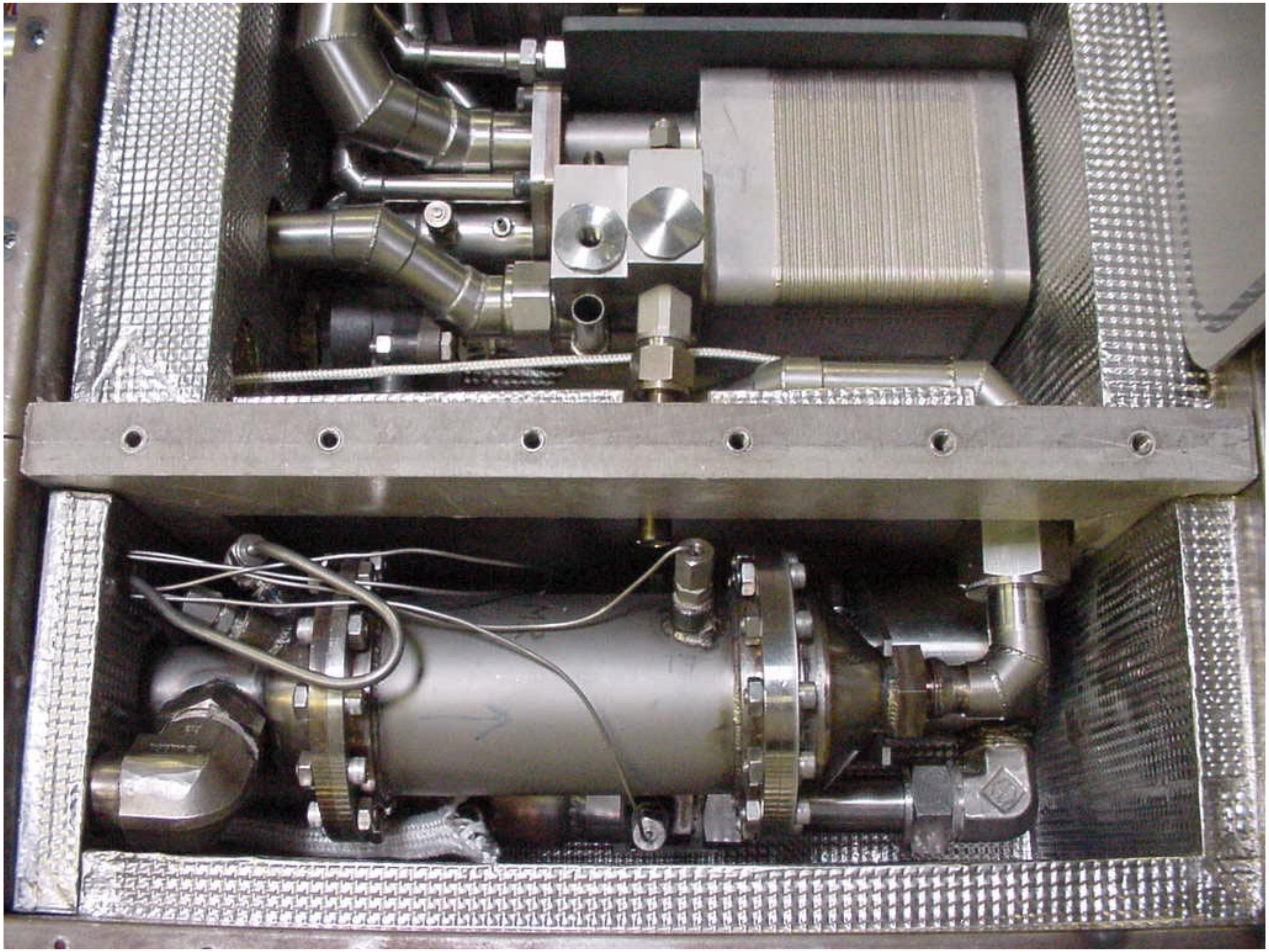
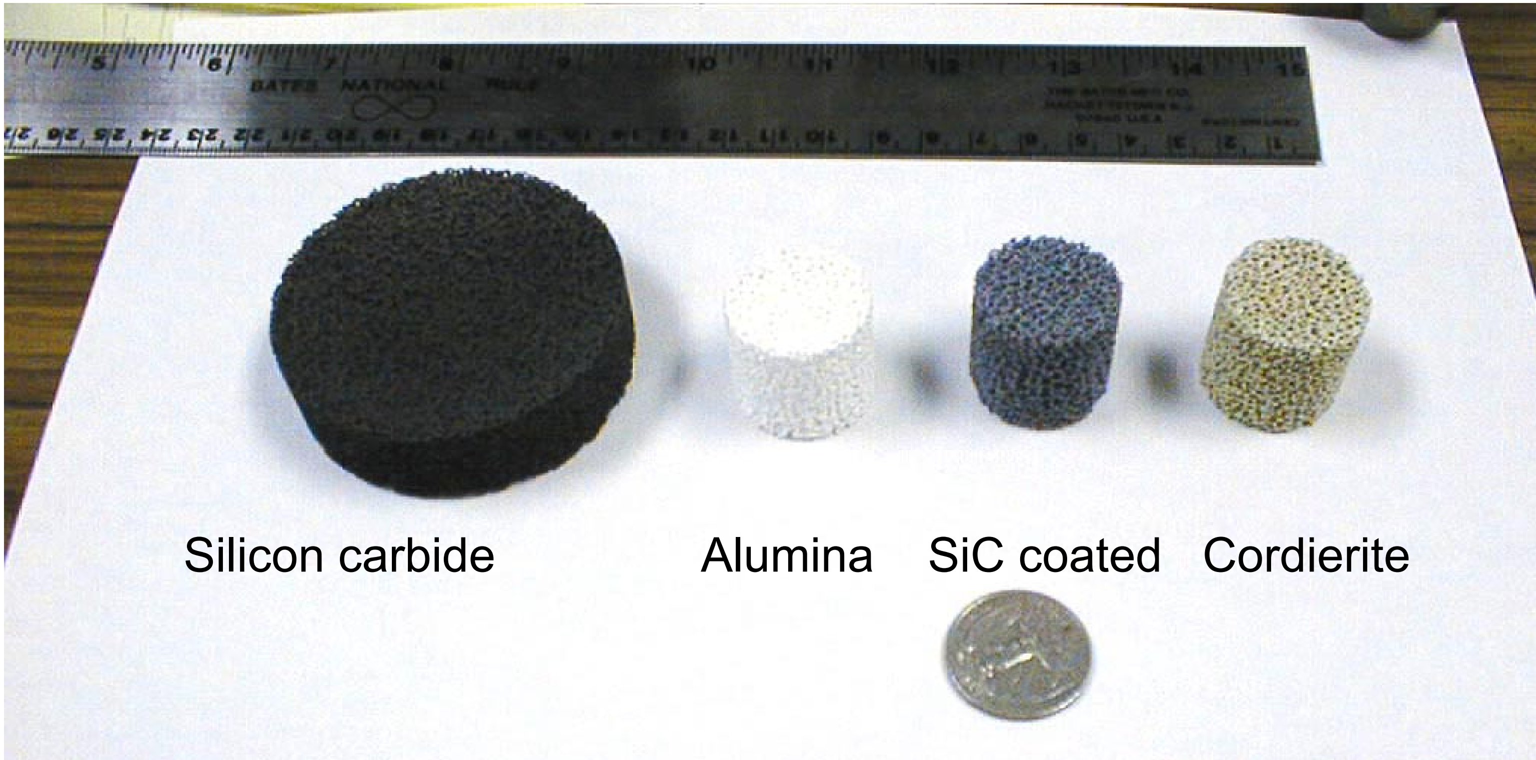
Layout of Vehicle APU

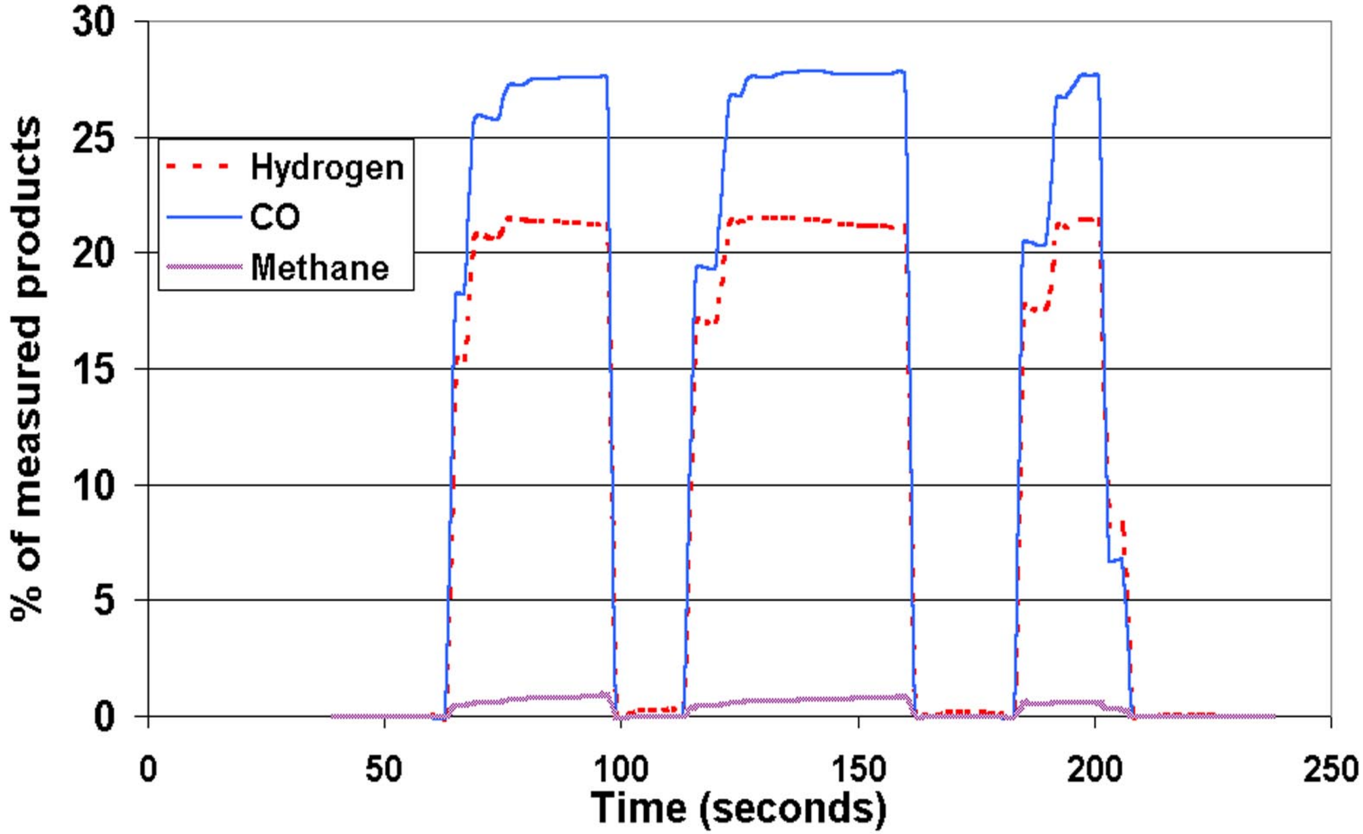


Solid Oxide Fuel Cell APU
Alternative Catalyst Supports

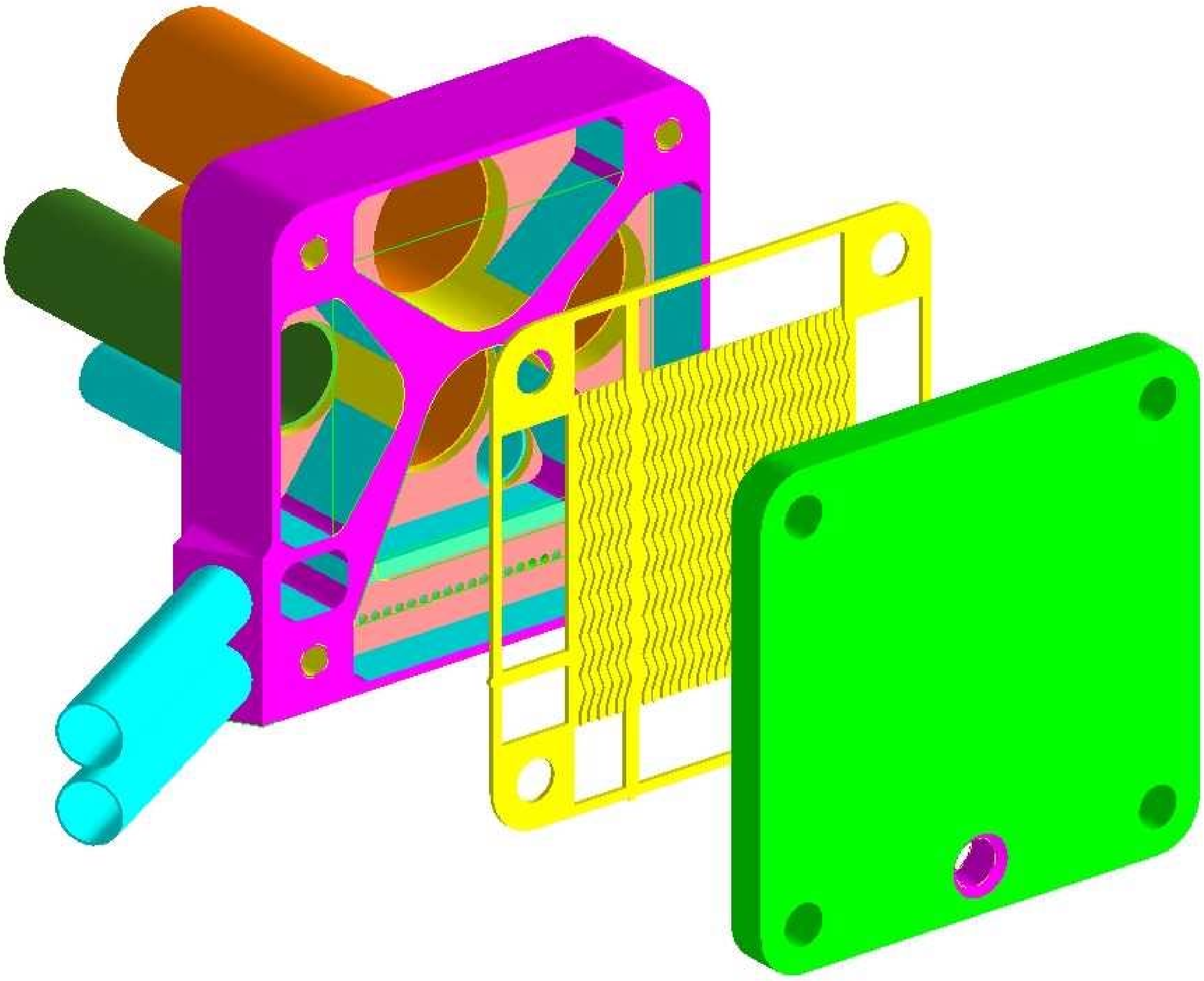


- Catalysts and Supports are Being Developed at Lab Scale within Delphi.
- Lab Scale Reactors Support Catalyst Development (For Both SOFC and PEM)
- Full Scale System Integration and Controls Labs Support Reformer System Development

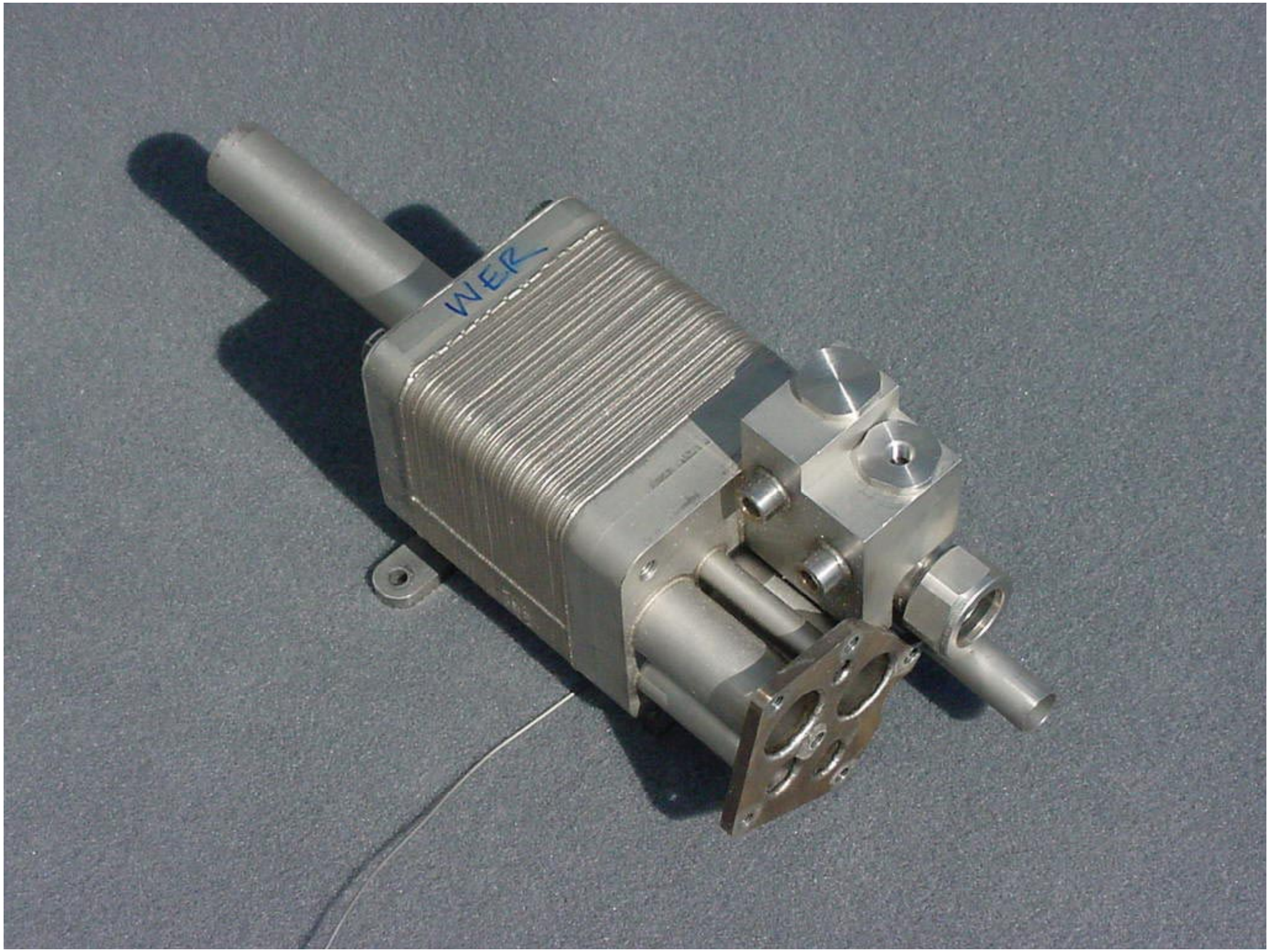
Reformer Cycling



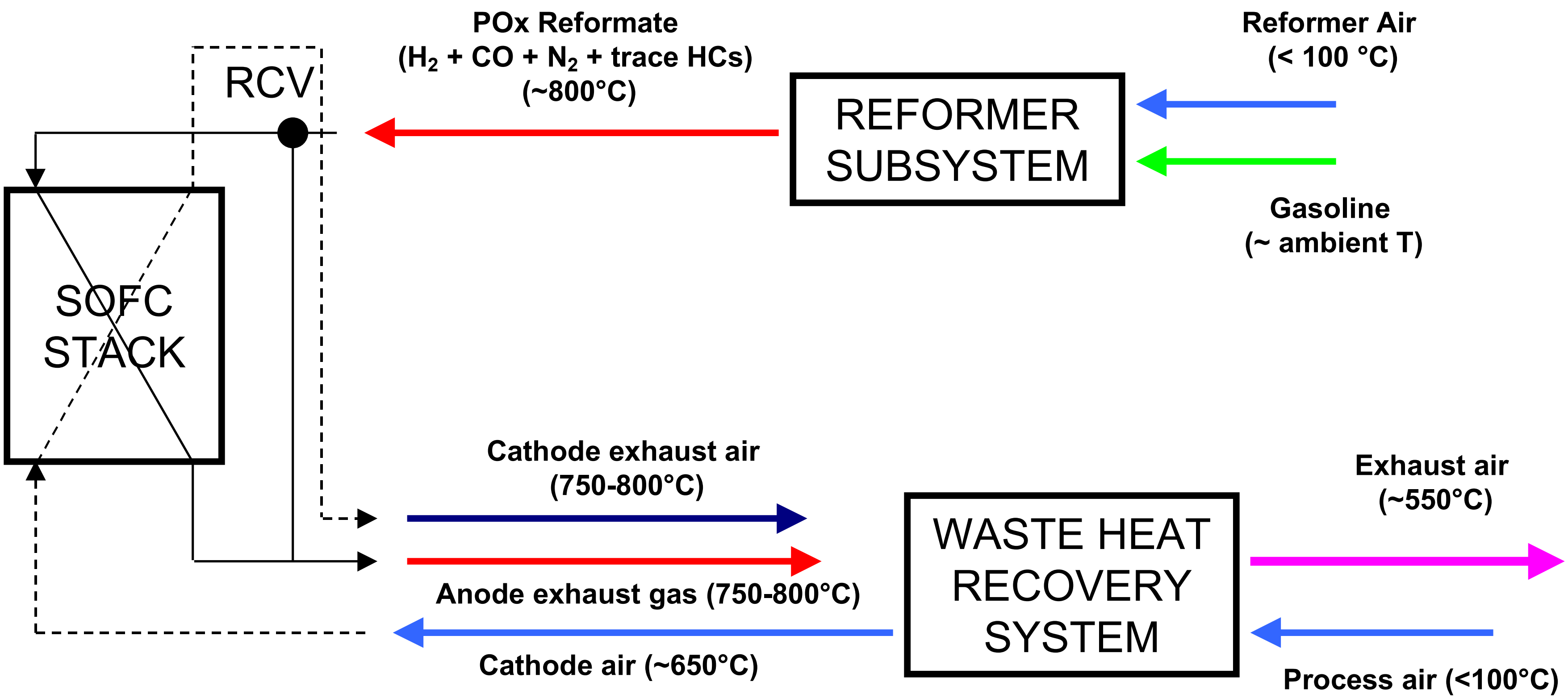
Waste Energy Recovery Unit



Waste Energy Recovery Subsystem



Reformer / Waste Heat Recovery Integration



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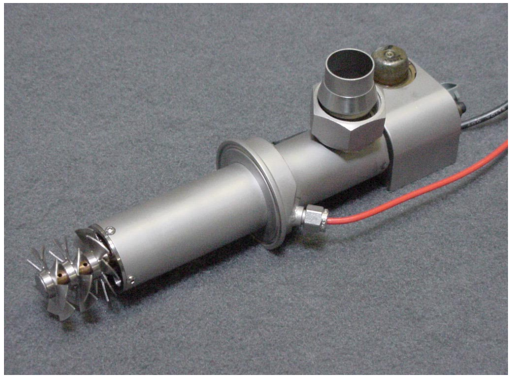
PoC SOFC APU
Gasoline Fuel Reformer Subsystem



PTC Fuel and Air preheating, mixing and vaporization

Reformer catalyst inlet flame arrestor / radiation shield

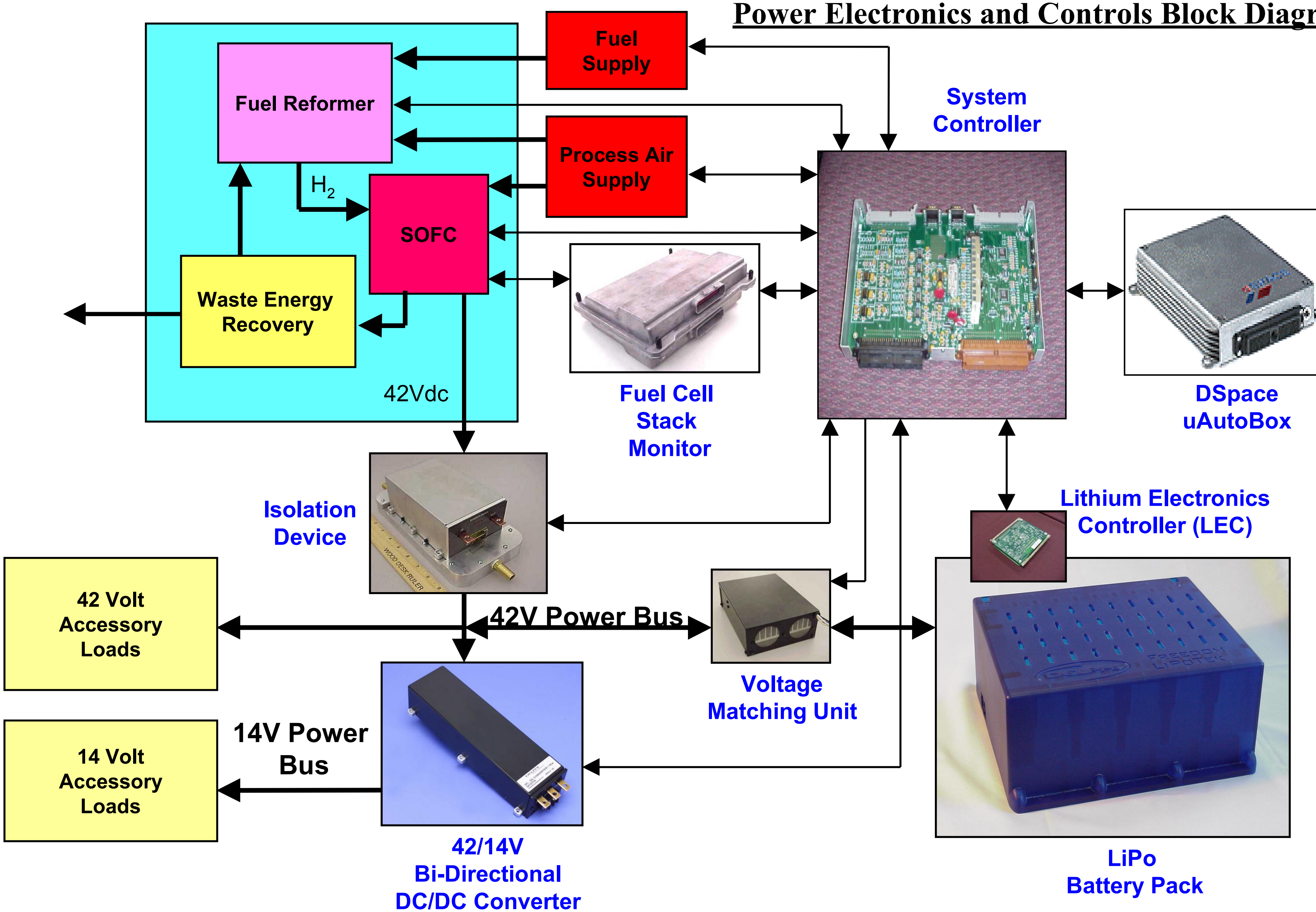
Catalyst formulation, loading and substrate development

Electrically heated catalyst and start-up strategy development

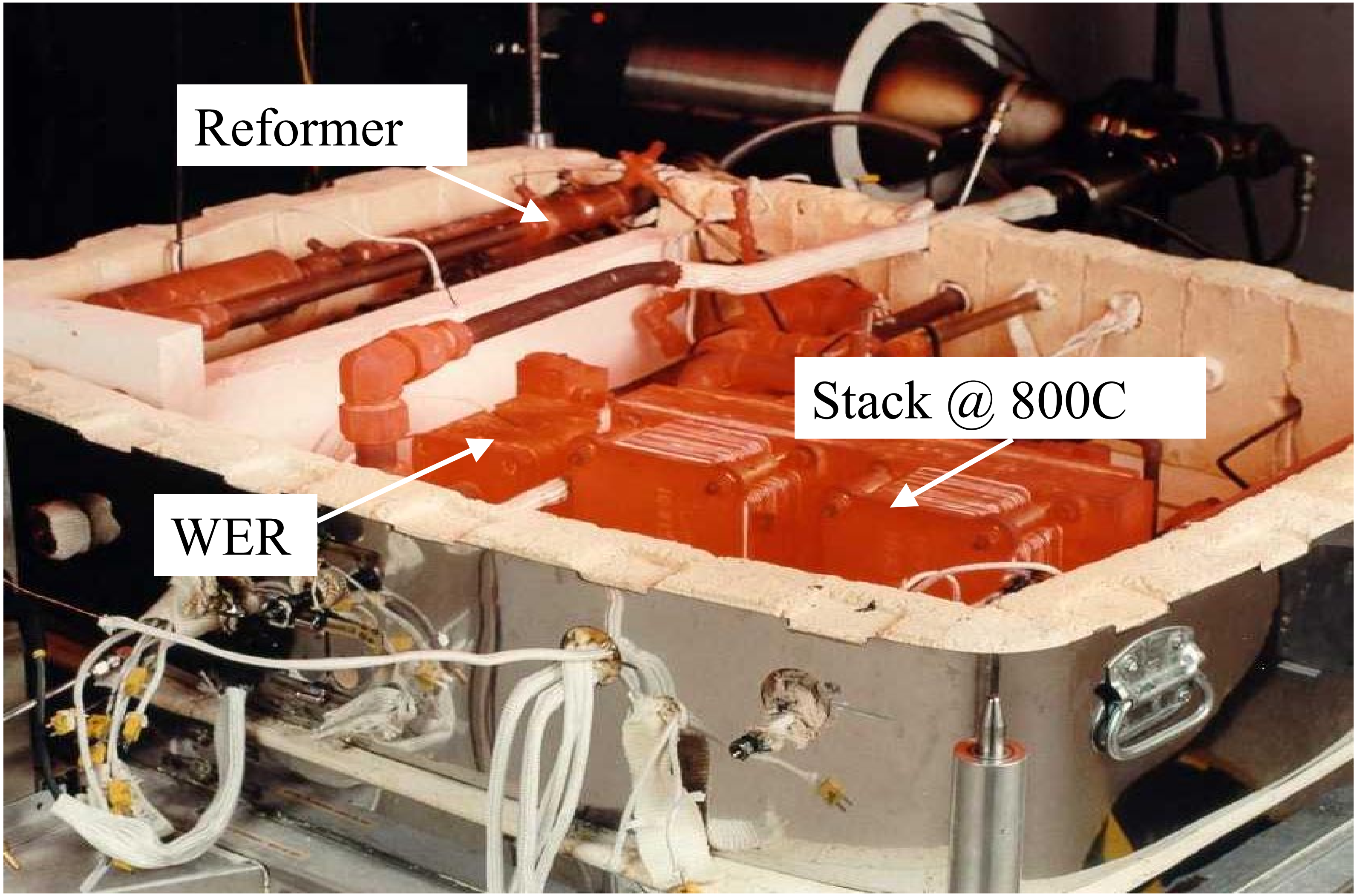
Fuel metering, vaporization and mixing assembly

PoC SOFC APU
Power Electronics and Controls

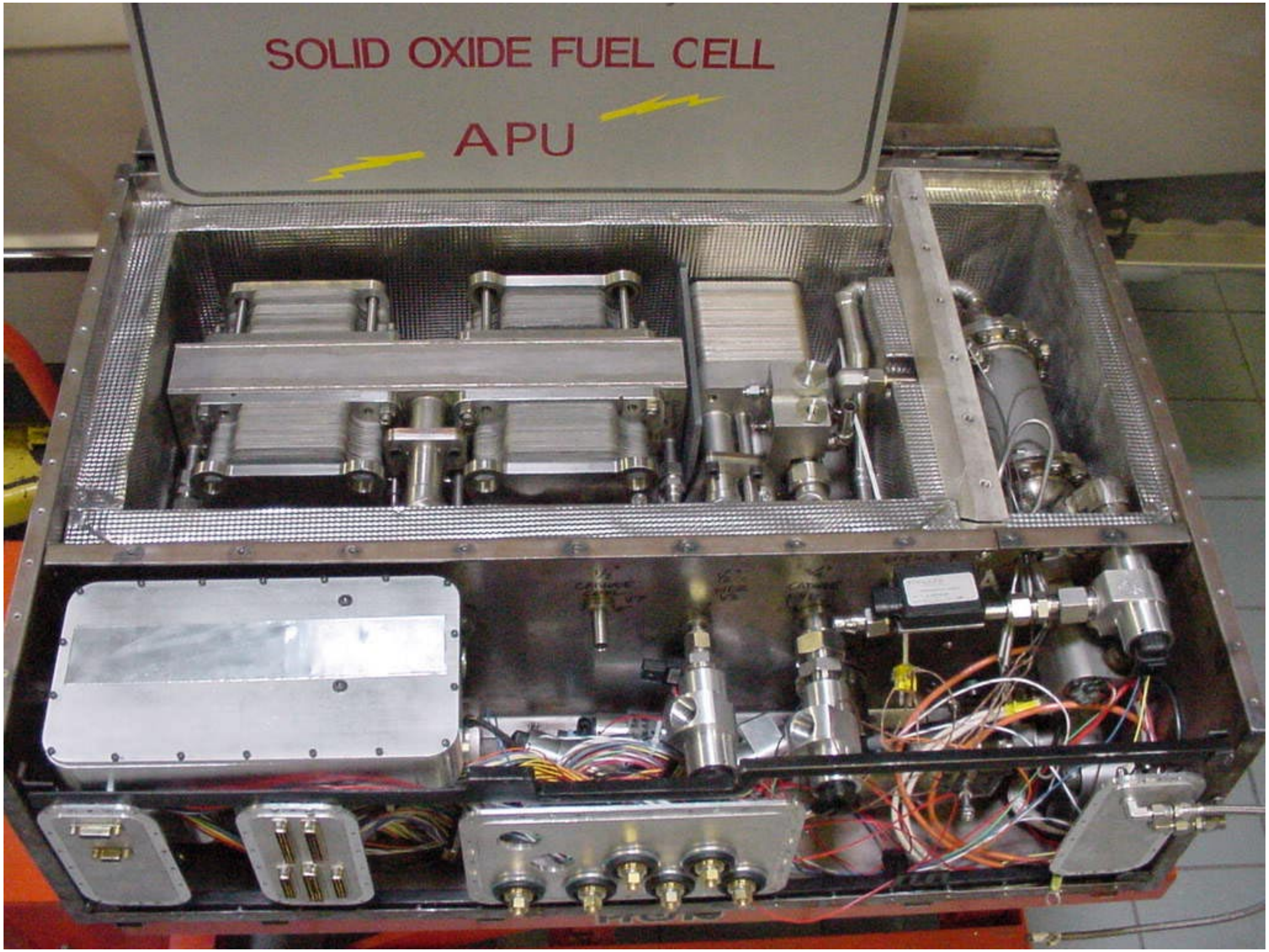
Power Electronics and Controls Block Diagram



Solid Oxide Fuel Cell APU
30 cell Stack / WER Combustor / Reformer



Layout of Vehicle APU



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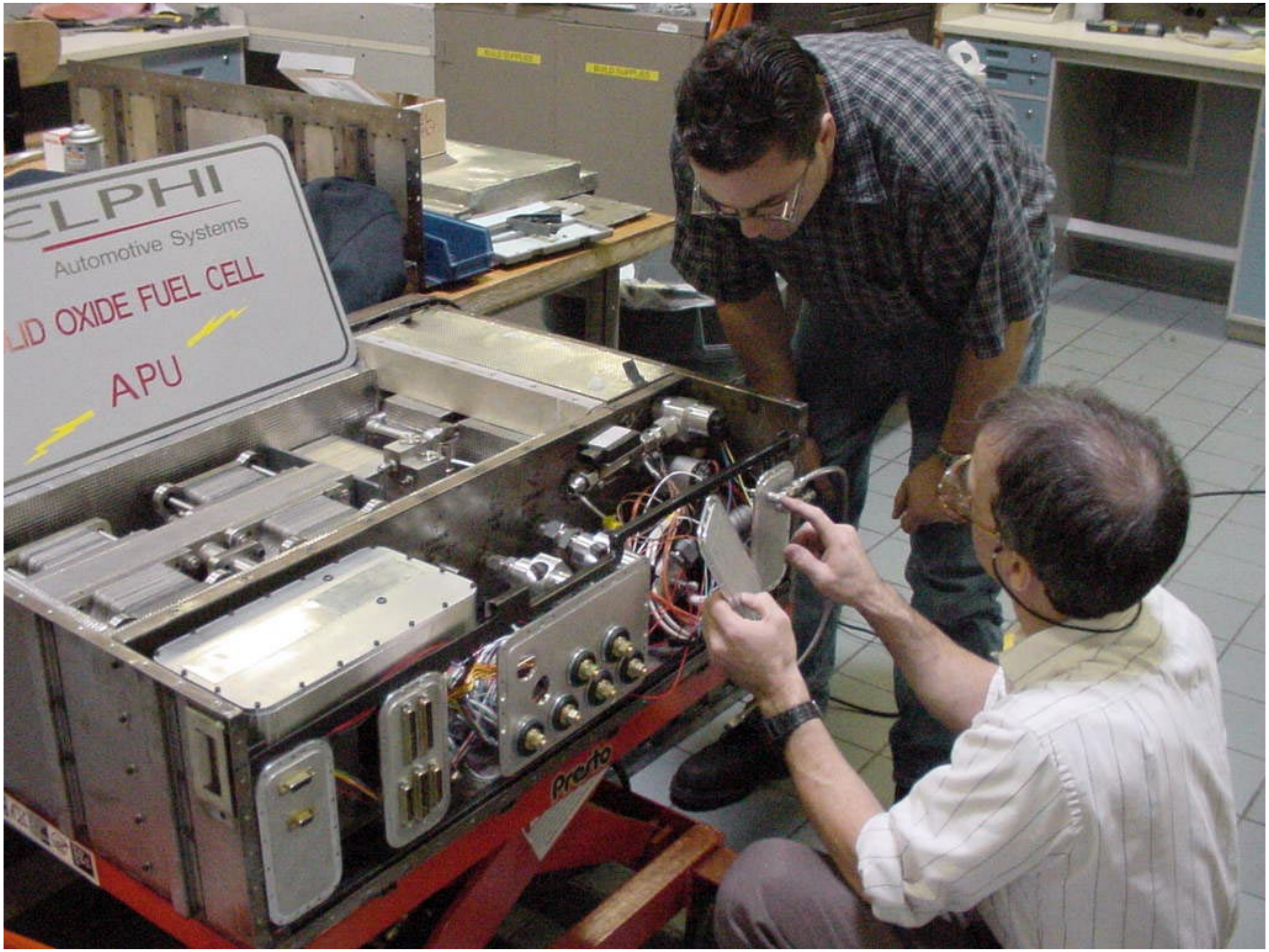
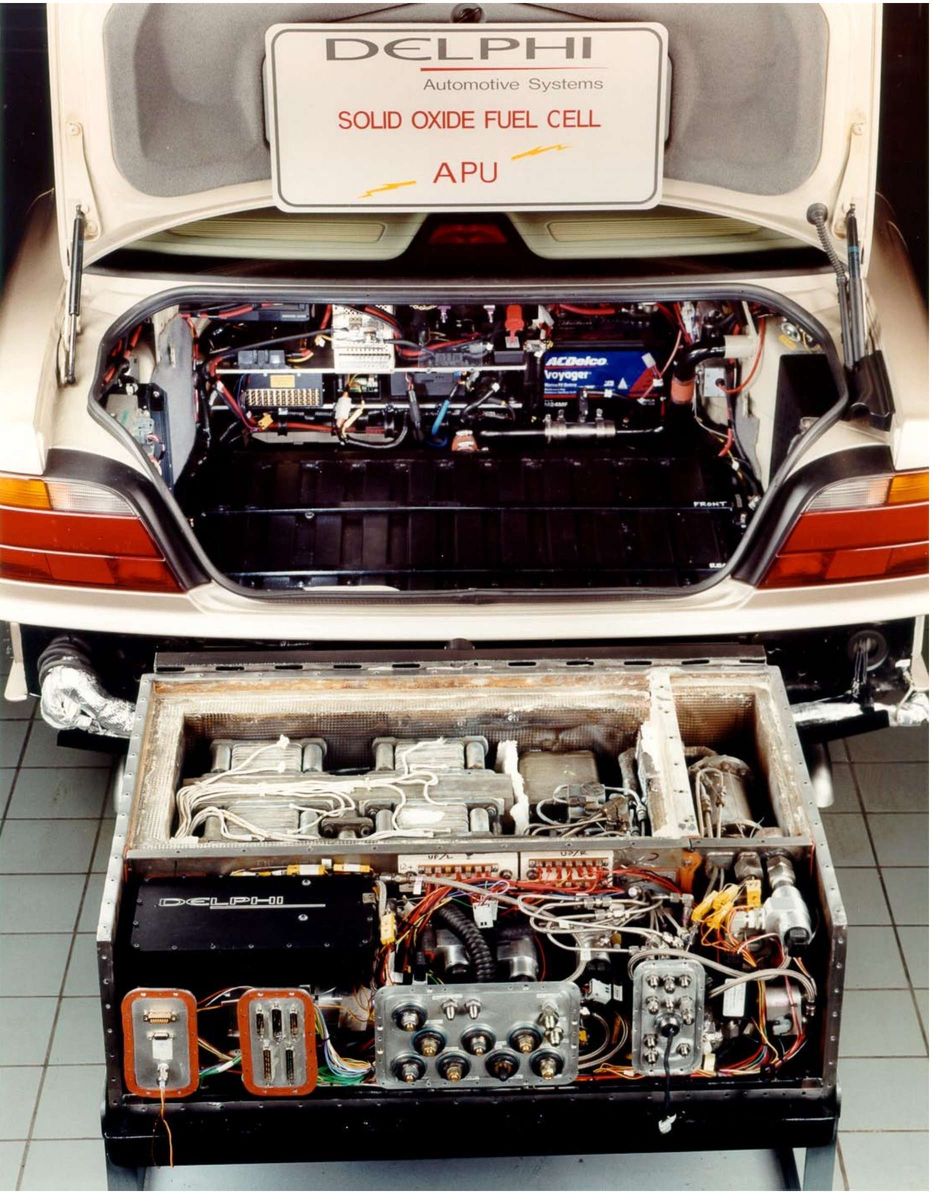
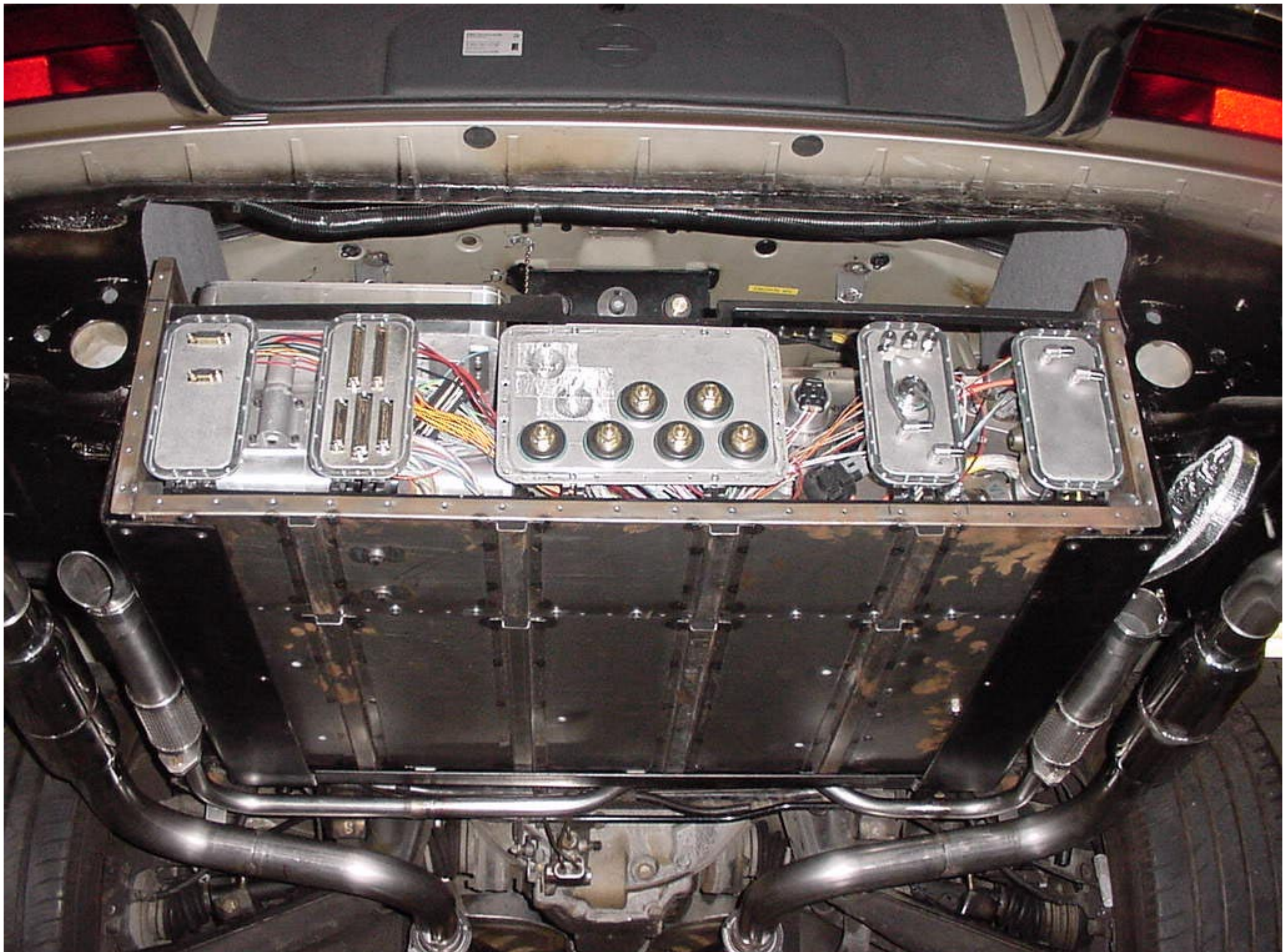
Layout of Vehicle APU



PoC SOFC APU
Integration into vehicle



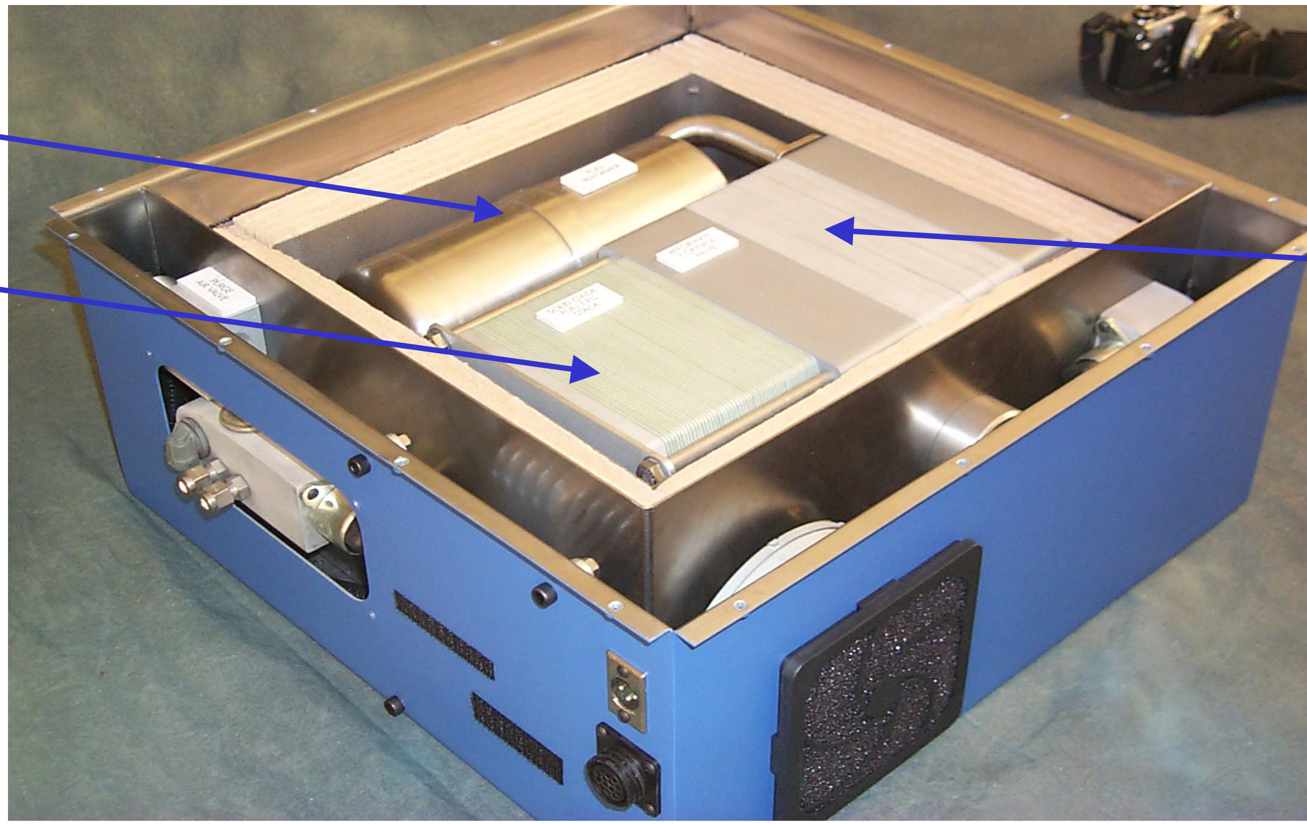
PoC SOFC APU
View from Underside of Vehicle



SOFC Has Many Challenges To Be Viable As An Automotive Technology:

- Cost, Cost, Cost.
- Power density
- Higher efficiency.
- High performance, low cost insulation.
- Robust balance-of-plant components.
- Fast startup and thermal cycling.
- Automotive levels of robustness.

Mockup - Future Concept for APU



Automotive SOFC Mechanizations

- APU / generator
  - high efficiency electric power with engine on and off
  - super low emissions (engine off)
  - enabler for electric accessories
- APU / generator / reformer
  - high efficiency power with engine on and off
  - enabler for electric accessories
  - enabler for very high engine efficiency
  - enabler for zero emissions with an internal combustion engine (ICE)
- Series hybrid range extender
  - compact, quiet efficient APU
  - waste heat for cabin heating
  - super low emissions

Conclusions

- SOFC is an attractive ,efficient, alternative source of power generation for : transportation,military, remote and distributed power. It will enter the market as an APU - a paradigm shift in supply of electric power .

- It is not likely to replace the ICE but will complement it.

- It has other future mechanizations which support the trend to essentially zero toxic emissions and much reduced CO_2 emissions

Delphi Automotive Systems with its partners are working toward bringing this key technology to the various market.

"THE TEAM "

M. SOLID OXIDE FUEL CELL SYSTEM DEVELOPMENT

Nguyen Q. Minh, Manager, Fuel Cells
Honeywell

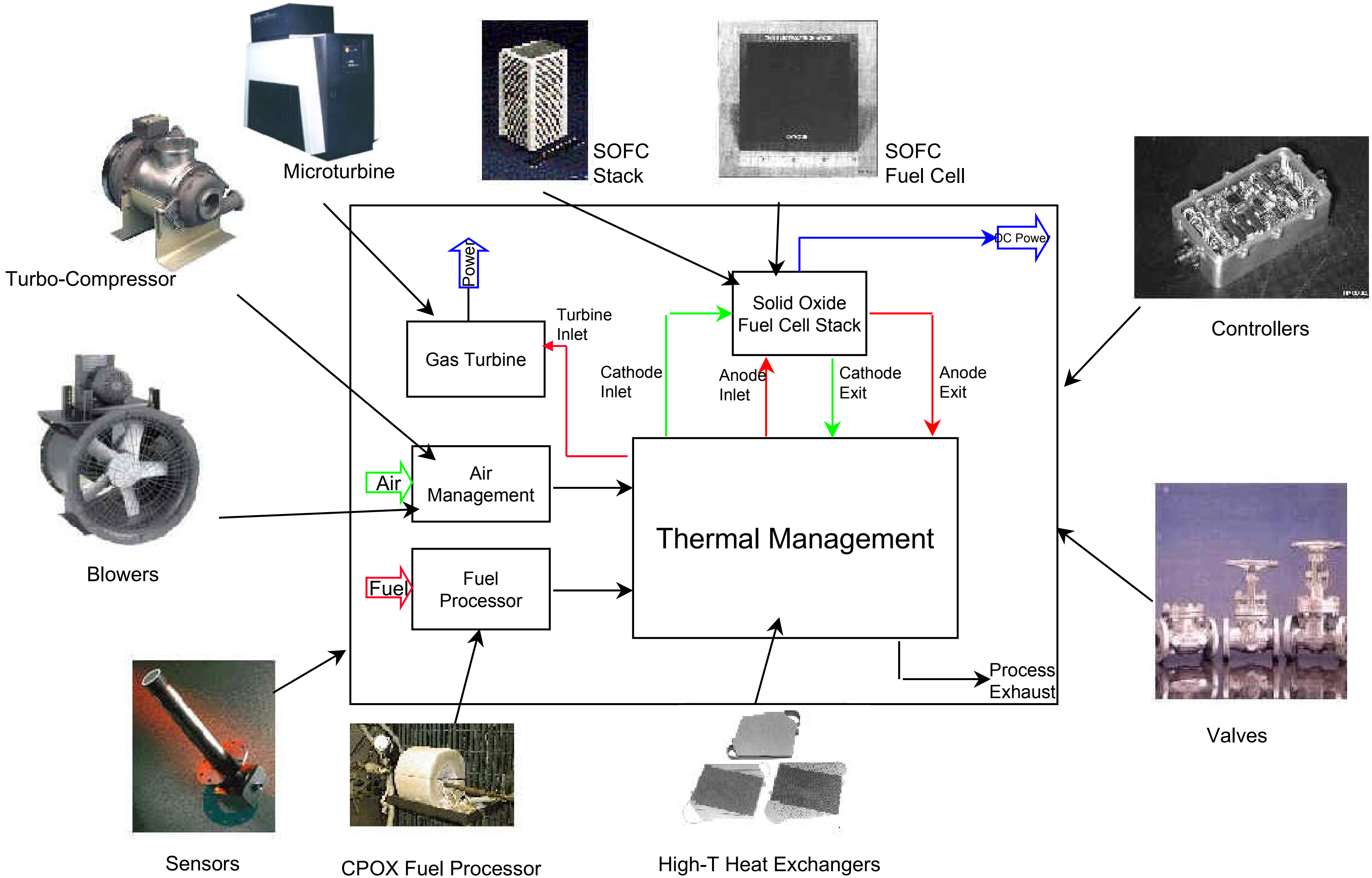
Honeywell

Solid Oxide Fuel Cell System Development

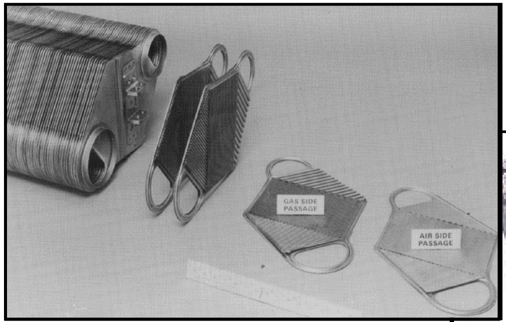
Nguyen Minh

2nd Solid State Energy Conversion Alliance Workshop
March 29-30, 2001
Arlington, VA

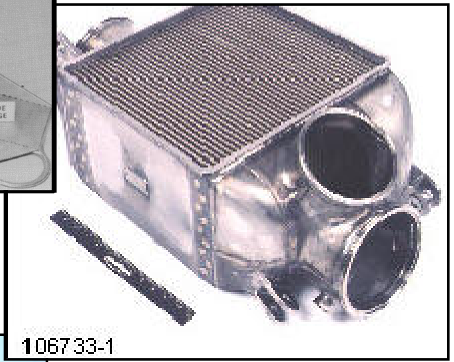
Simplified SOFC System & Components



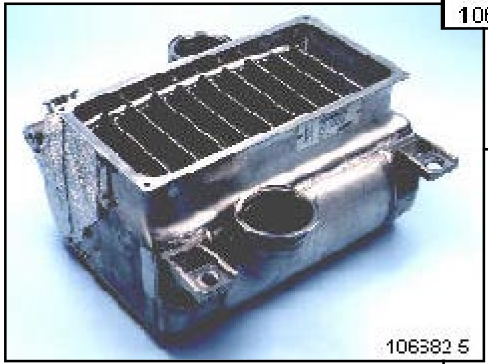
Heat Transfer/Thermal Management



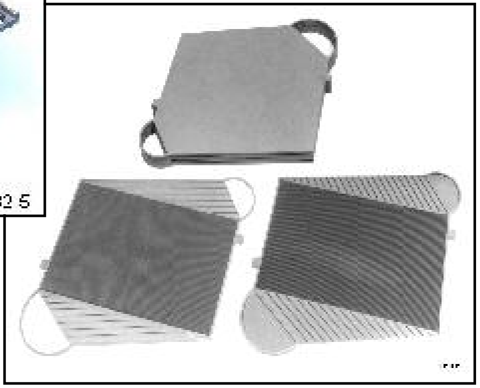
Commercial Recuperators



757-300 RR Precooler



F22 Primary Heat Exchanger

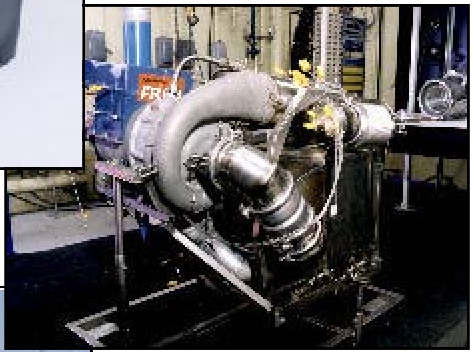


Si_3N_4 Ceramic Heat Exchanger

- Extensive experience with thermal management of complex systems
- Broad spectrum of heat exchanger products
- Thermal management systems for a wide range of operating environments

Turbomachinery

RAH-66 Fan



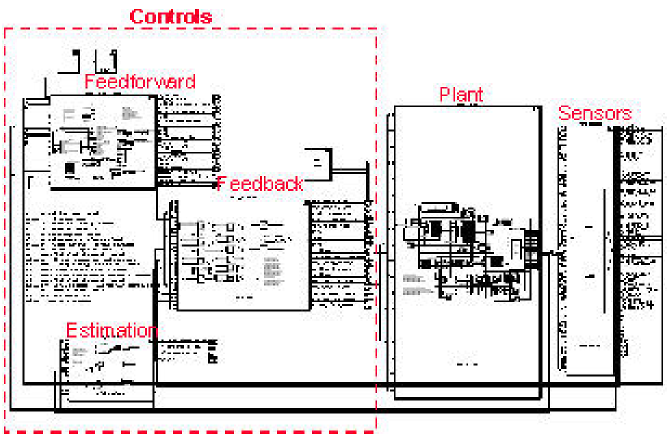
50 kW Turbogenerator

Trident Gas Hydraulic Assembly Turbopump

PEMFC Turbocompressor

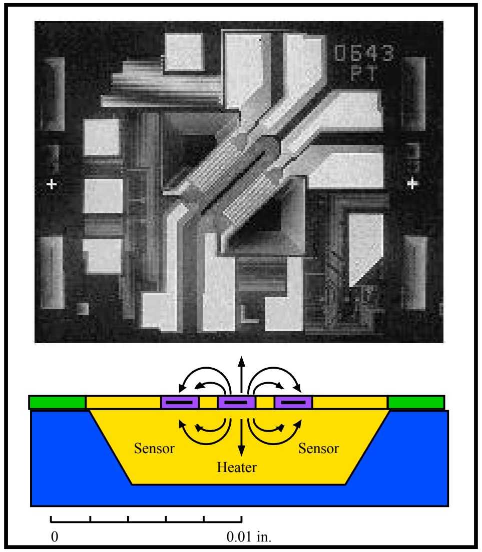
- Expert knowledge in positive displacement and dynamic pumps, compressors, and turbines
- Wide range of turbomachinery products
- Development of turbocompressor for PEMFC systems

Controls and Sensors



Control Schematic

Hydrogen Sensor



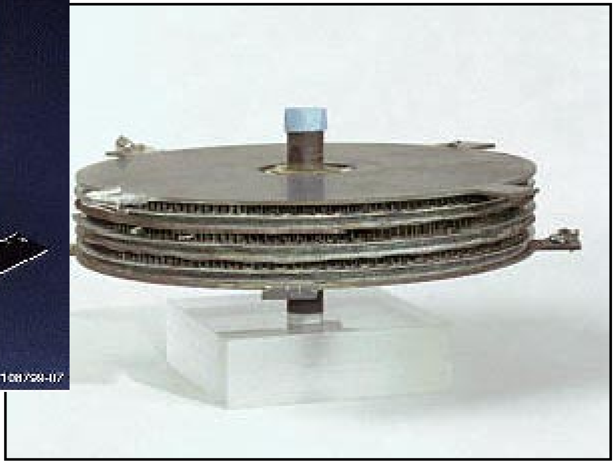
Top view and cross section of Mass Air Flow Sensor

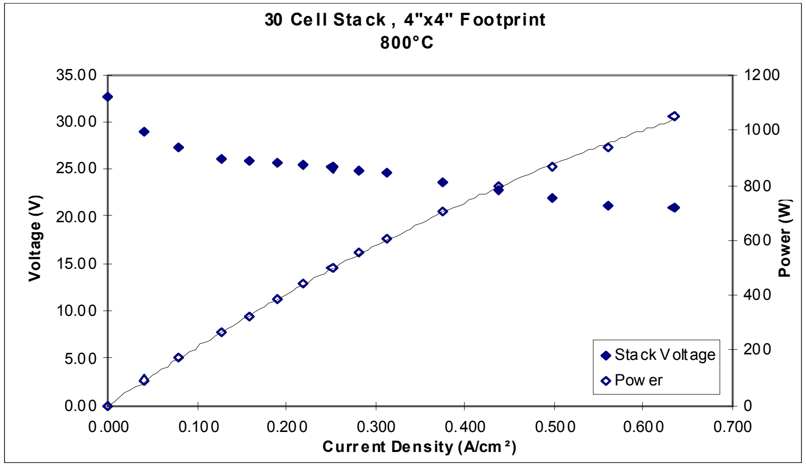
- **Controls**
  - Model-base control and optimization algorithms including Fuel Cell Dynamics Component Library
  - Rapid prototyping
  - Load following control system for PEMFC systems
- **Sensors**
  - Relative humidity
  - Mass air flow
  - Hydrogen
  - Carbon monoxide

System Development Approach

- **Low-cost fabrication processes and materials along with compact, lightweight component designs**
  - **SOFC:** Tape calendering fabrication process, stack designs incorporating thin-electrolyte cells and thin-foil metallic interconnects
  - **Fuel processor:** Catalytic partial oxidation (CPOX)
- **Component designs based on system requirements and other design methodologies (e.g., design-for manufacturing, design-to-cost)**
- **Focus on lessons learned from small (50 W to several kW) system operation**

SOFC Stack Metrics

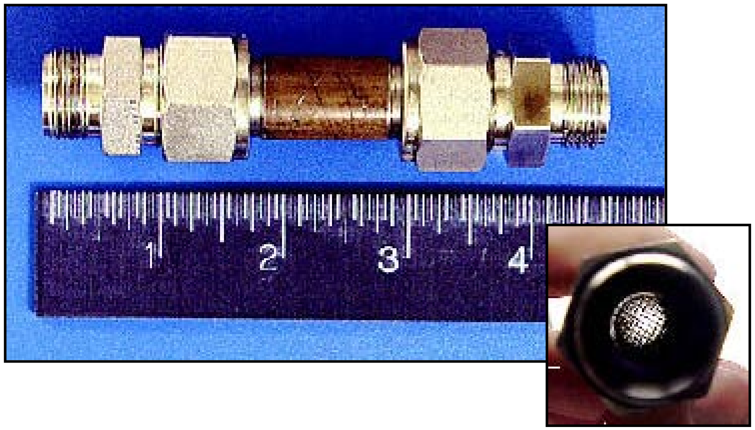


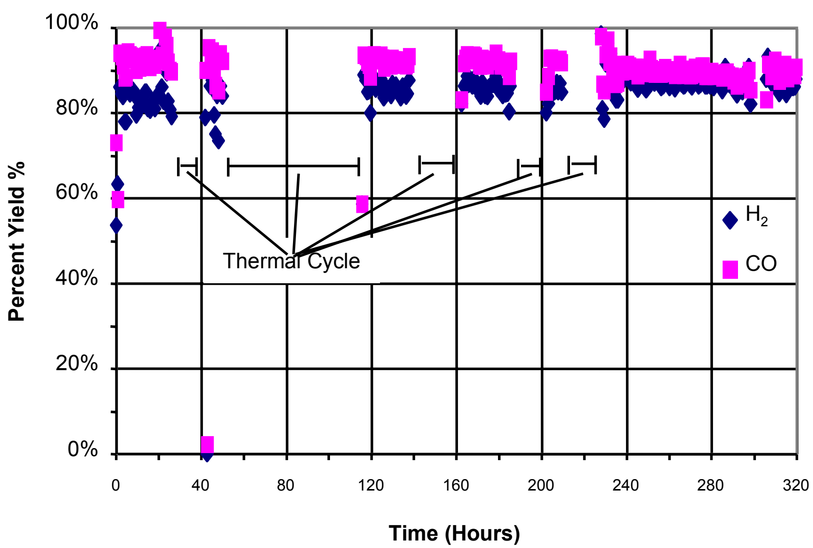


- Fabrication and operation of multi-cell stack of various sizes (up to kW size)
- 800°C operation at ambient pressure and up to 3 atm
- Thermal cycling
- Start-up and shut-down
- Power density:
  - 0.6 W / cm² with hydrogen
  - 0.4 W / cm² with syngas from JP-8

Honeywell

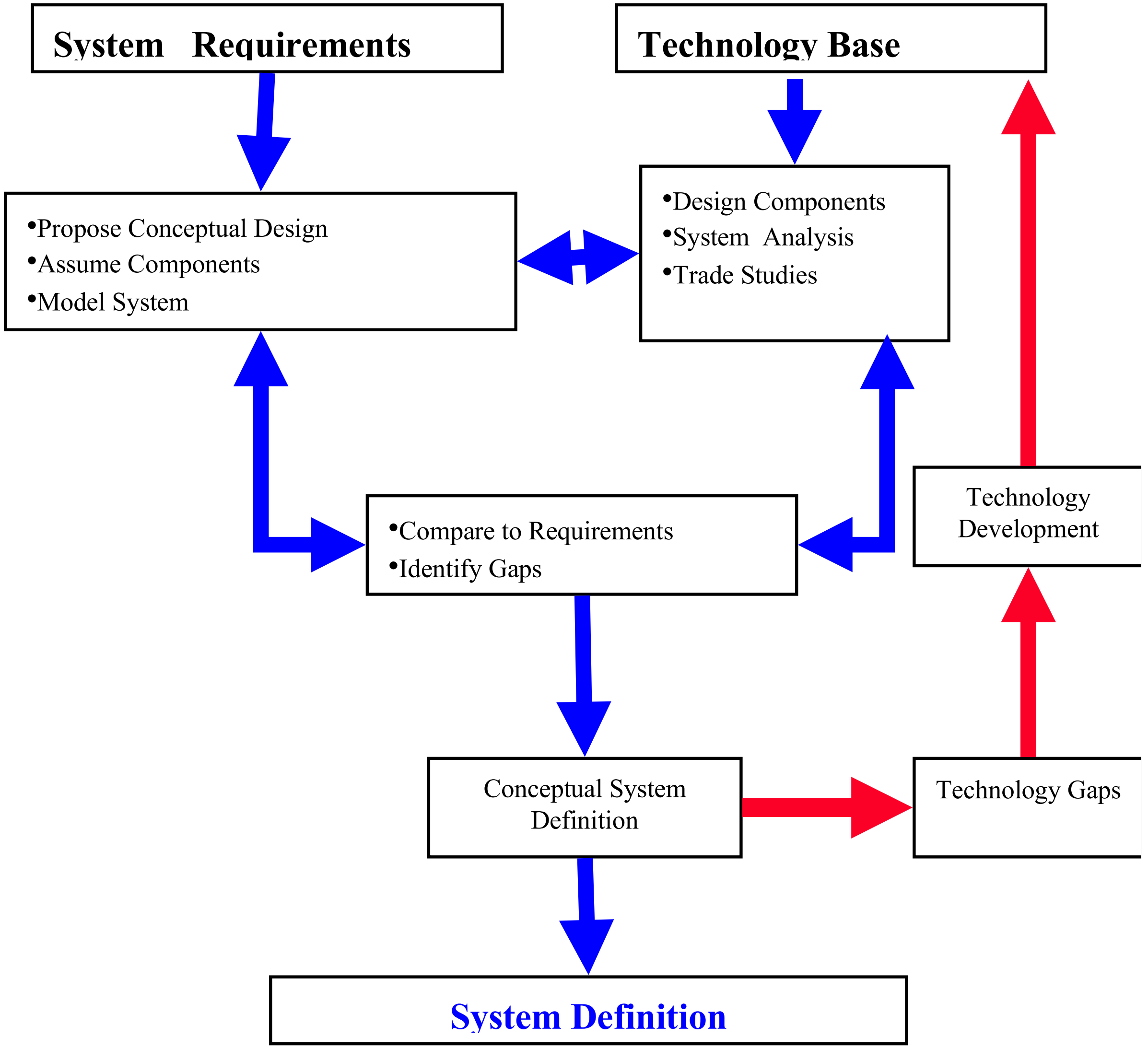
CPOX Performance Metrics



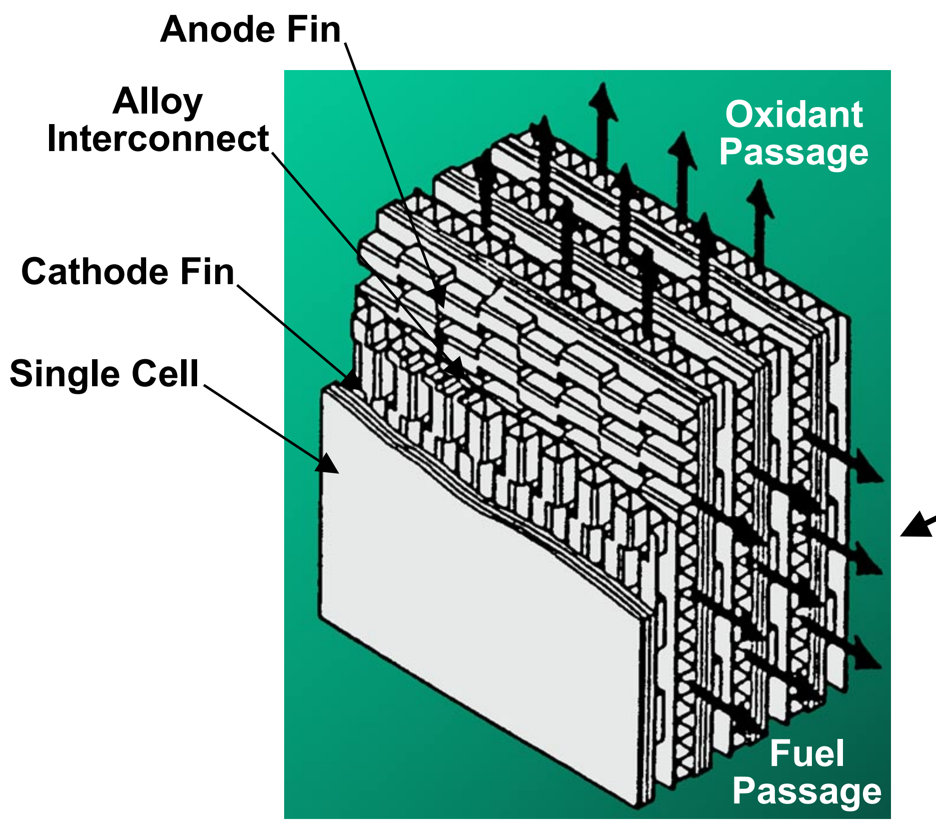


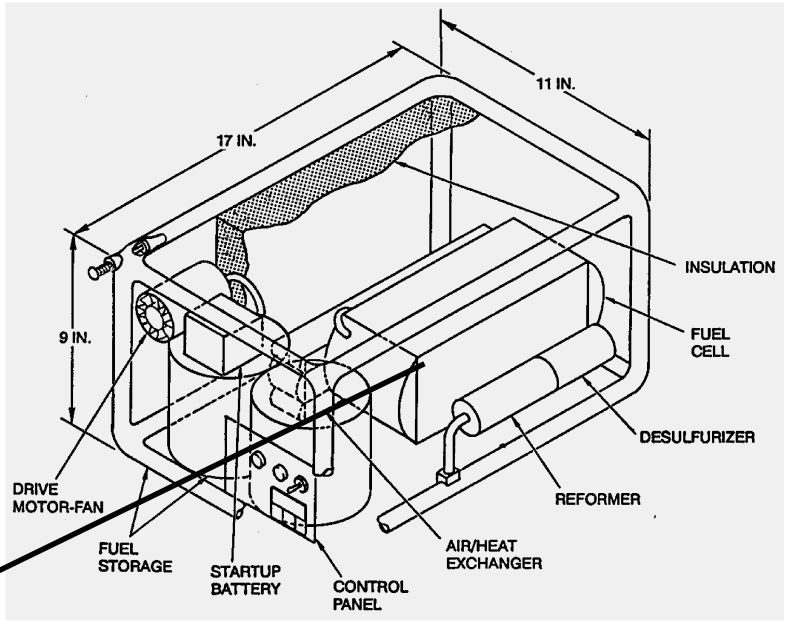
- Duration: 700 hours to date
- Thermal cycles: 10
- Sulfur tolerance: 1000 ppm dibenzothiophene in JP-8
- Yield: 70-80% of LHV in JP-8

System Design Methodology



Solid Oxide Fuel Cell Battery Charger

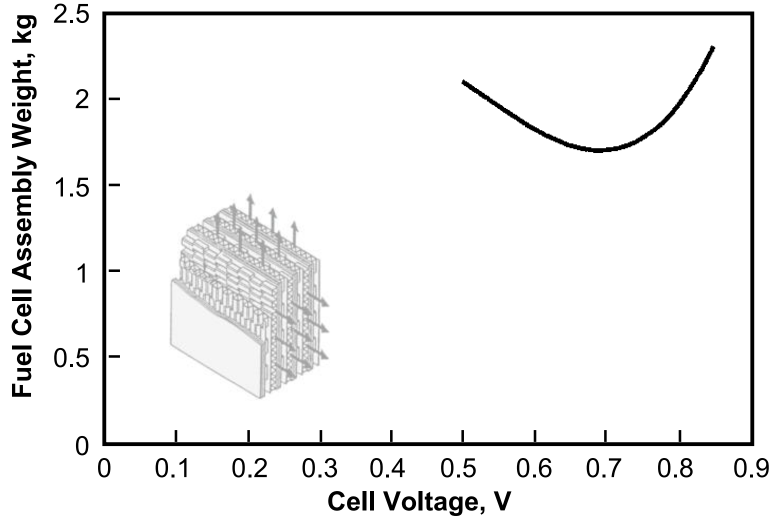


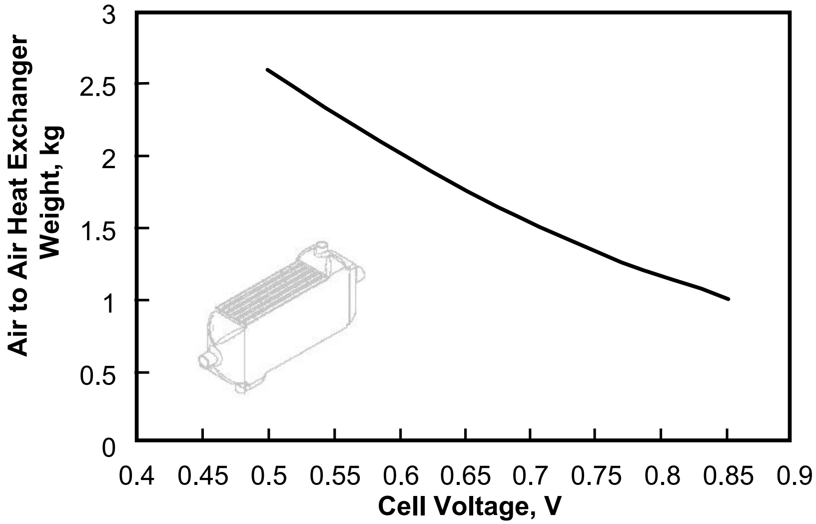


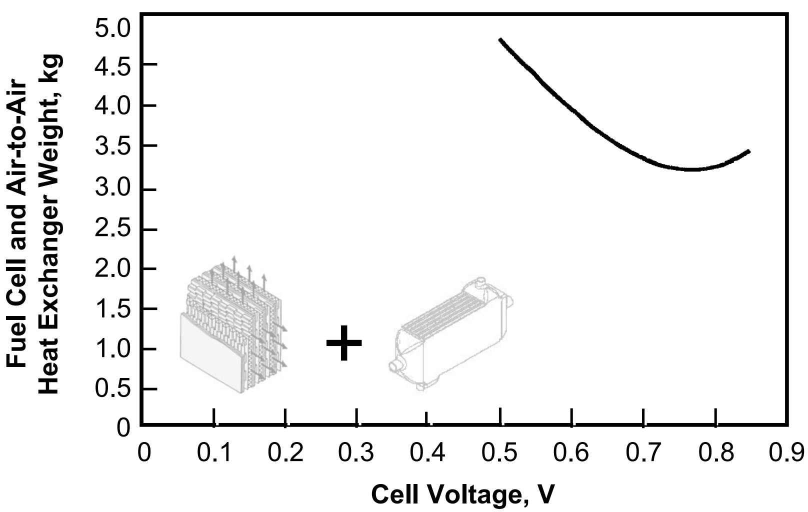
Requirements

- 7 kg
- 500 W at 28 VDC
- Operation on logistic fuels (JP and diesel)

System Weight Optimization





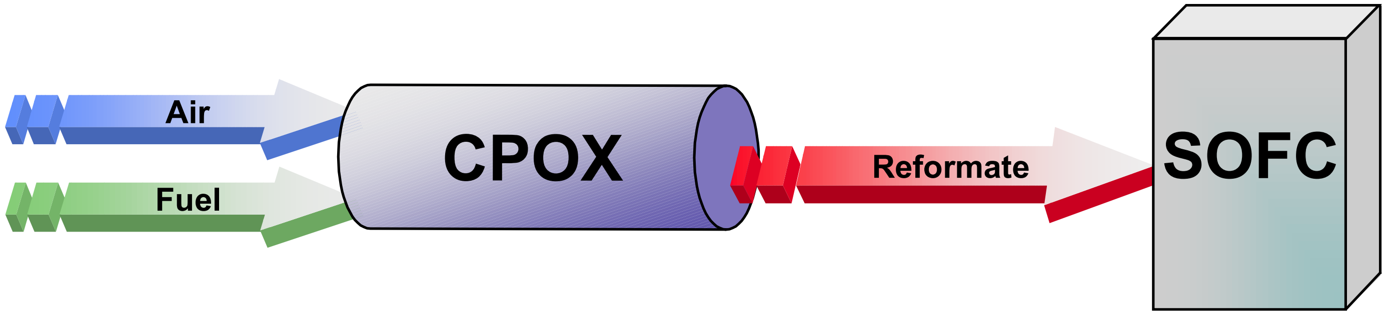


- **500 W, 28 VDC output**
- **Hydrogen utilization of 0.8**
- **Minimum weight at cell voltage of 0.75 V**

CPOX/SOFC Integration - Key Parameters

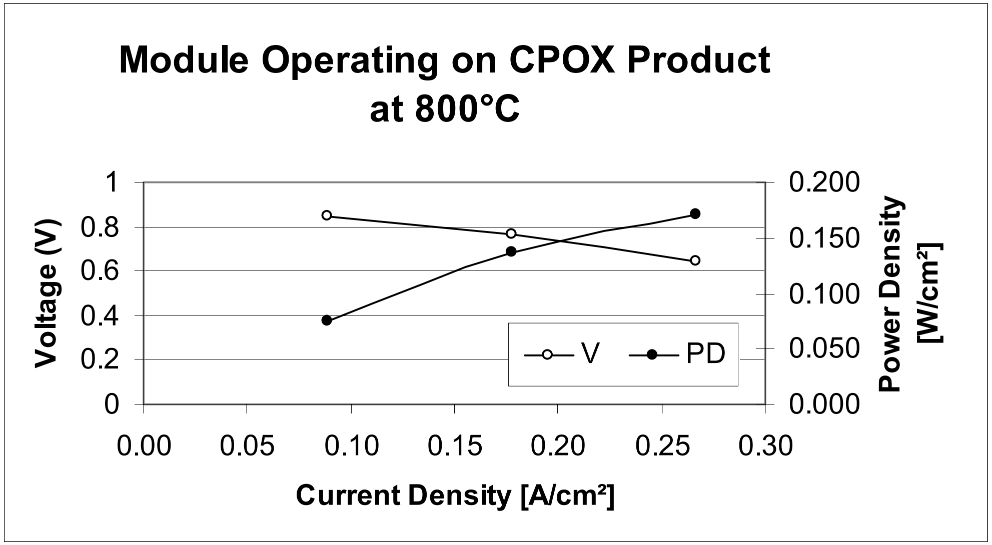
- Start-up and shut-down procedures
- Range of operating parameters
- Pressure drop
- Thermal management
- Transient characteristics

Integrated CPOX-SOFC Operation



CPOX

Input	Output
JP-8	17.3% H_2
Air	21.0% CO
	0.7% CO_2
	11.0% H_2O
	50.0% N_2



Demonstration of multicell SOFC operation on JP-8 syngas

System Demonstration

- Demonstration of key component integration
  - Integration of system components, especially CPOX fuel processor and SOFC stack
- Operation characteristics
  - Startup
  - Thermal integration
  - Propane and JP-8 fuels

Concluding Remarks

- **Low-cost fabrication processes and materials along with compact, lightweight components developed for SOFC systems**
- **Demonstration of component integration and operation of small systems**
- **Near-term activities consistent with SECA plan**

N. THE IMPACT OF MLC MANUFACTURING ON FUEL CELL COMMERCIALIZATION

William P. Schweizer, Manager, Solid Oxide Fuel Cell Development
McDermott Technology, Inc.

The Impact of MLC Manufacturing on Fuel Cell Commercialization

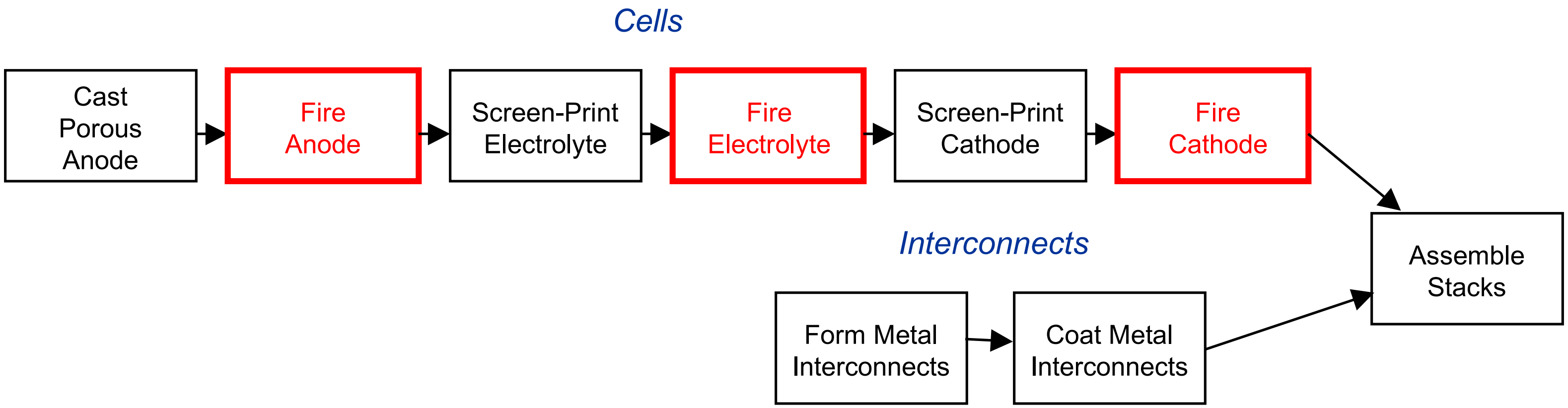
Presented at the 2nd Annual SECA Workshop
Arlington, VA
March 29, 2001

Traditional Methods vs. MLC

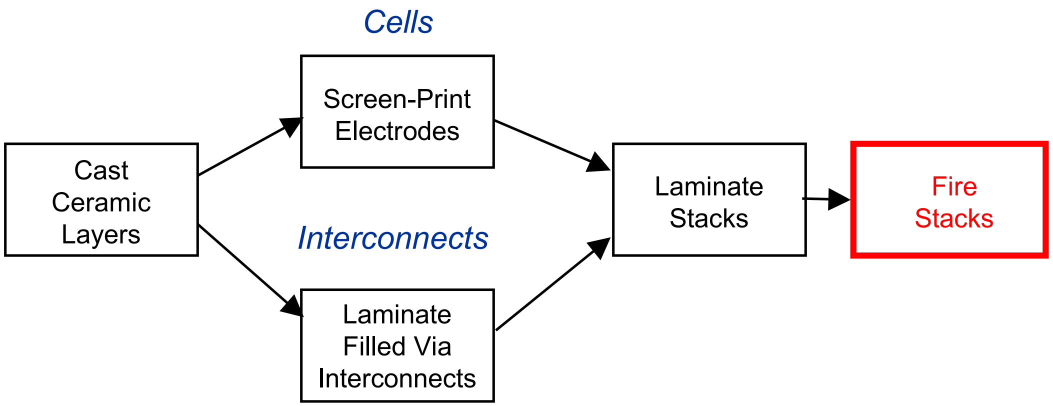
- Traditional Methods
  - Electrolyte or electrode supported with subsequent application of additional cell layers
  - Multiple firings
  - Metal interconnects
  - Labor intensive stack assembly
- MLC Method
  - Co-fired repeat units consisting of anode, cathode, electrolyte and interconnects
  - Single firing step
  - 3rd generation ceramic interconnects
  - Limited stack assembly required

Traditional Methods vs. MLC

Traditional Process



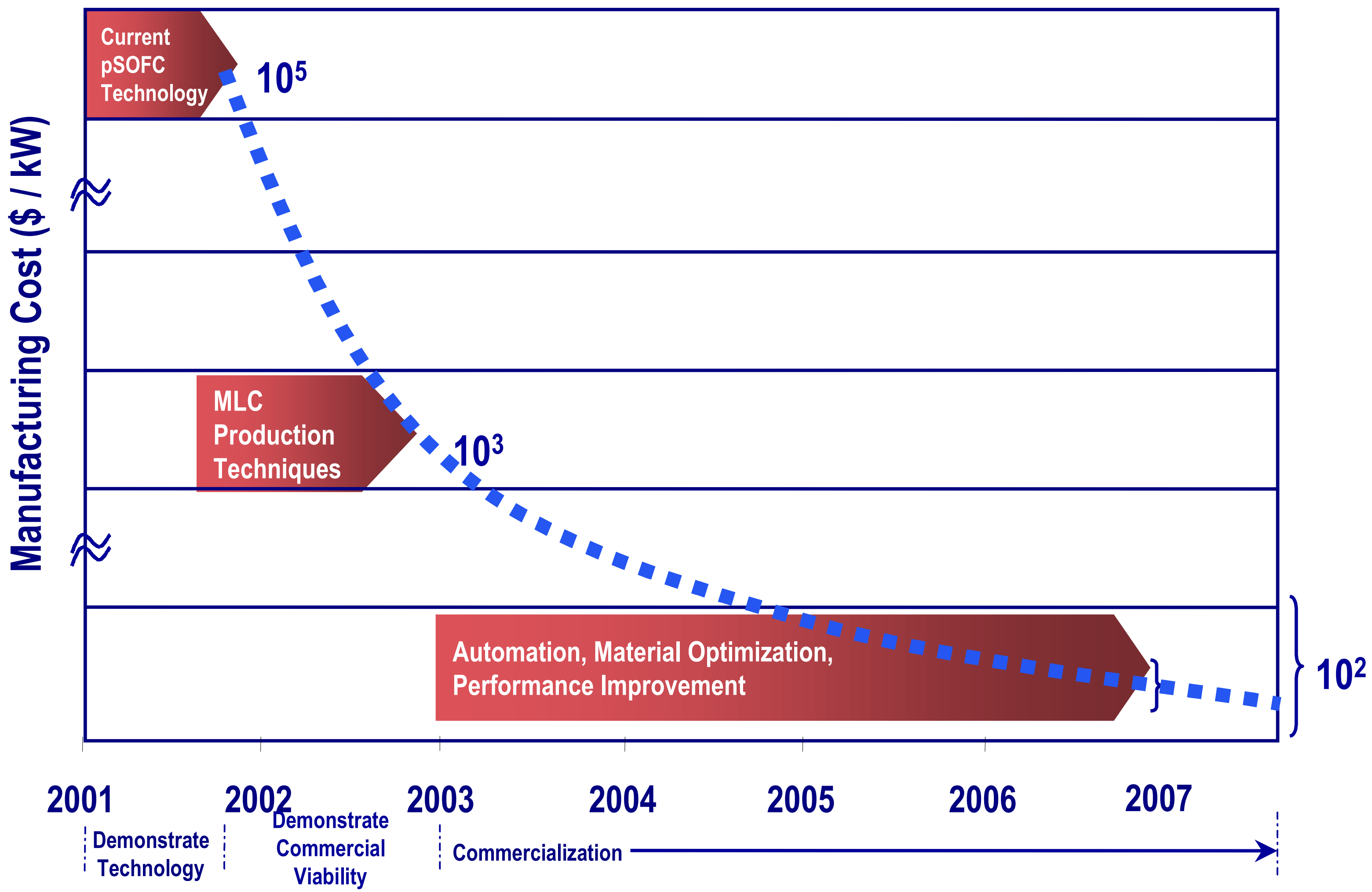
MLC Process



Advantages of MLC Co-fired Approach

- Process time savings
  - Single firing step
  - Reduced stack assembly
- Performance Gains
  - Intimate electrode contact - low polarization losses & contact resistance between interconnects
  - Improved seals
  - Minimizes thermal mismatch & corrosion
- Established high-volume, low-cost, high-quality production methods

Cost Reduction Roadmap



Buffalo Manufacturing Facility

O. LOW-COST MANUFACTURING OF MULTILAYER CERAMIC FUEL CELLS

Scott Swartz, Director of Technology
NexTech Materials, Ltd.

Low-Cost Manufacturing of Multilayer Ceramic Fuel Cells

Scott L. Swartz, Ph.D.
Director of Technology
NexTech Materials, Ltd.

2nd Annual SECA Workshop
Arlington, Virginia
March 29-30, 2001

NEXTECH MATERIALS

MULTILAYER FUEL CELL ALLIANCE

Low-Cost Manufacturing of Multilayer Ceramic Fuel Cells

DOE Contract No. DE-AC26-00NT40706

Program Manager: William Dawson, NexTech Materials

Principal Investigator: Scott Swartz, NexTech Materials

NETL Project Manager: Tom George

Advanced Materials Technologies   EMTEC   Gas Technology Institute   Iowa State University   Michael A. Cobb & Company
NexTech Materials   Northwestern University   Oak Ridge National Laboratory   Ohio State University   University of Missouri-Rolla

Program Plan

<u>Phase I (3 months)</u>

Manufacturing Cost and Risk Assessment

Michael A. Cobb & Co.
Advanced Materials Technologies
Gas Technology Institute

<u>Phase II (12 months)</u>

Development of Fabrication Processes for Planar Cells

NexTech Materials
Oak Ridge National Laboratory
University of Missouri-Rolla

<u>Phase III (9 months)</u>

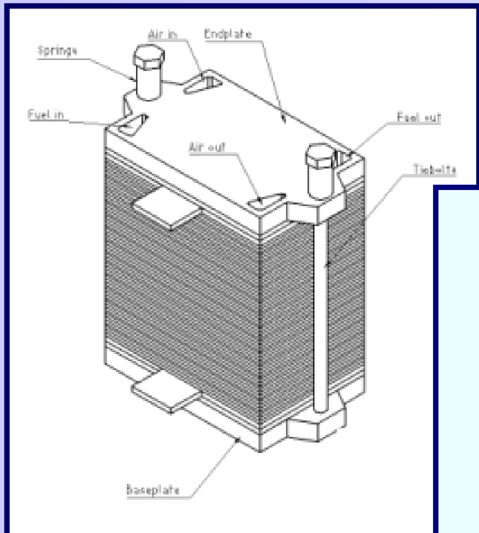
SOFC Testing, Destructive and Non-Destructive Testing

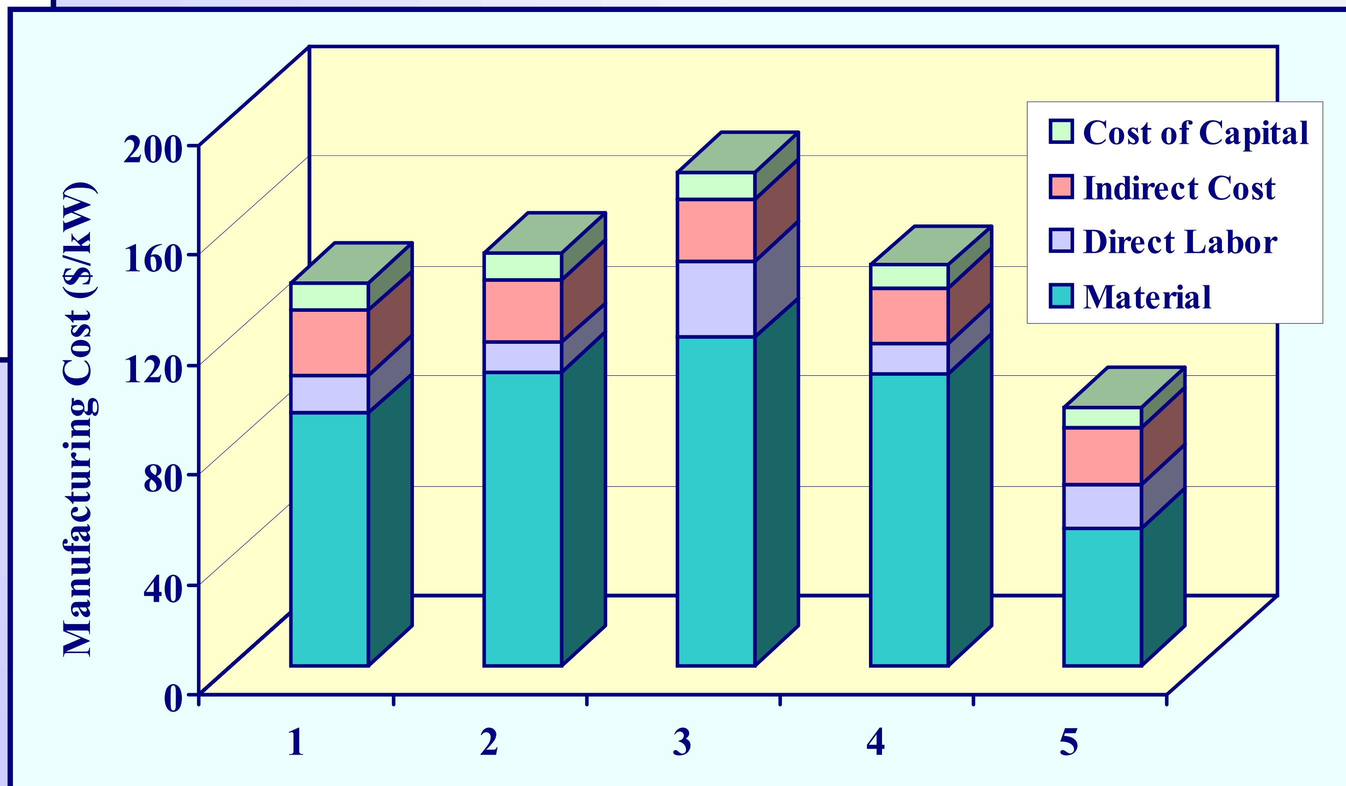
Northwestern University
Gas Technology Institute
Ohio State, Iowa State

NexTech Materials

MULTILAYER FUEL CELL ALLIANCE

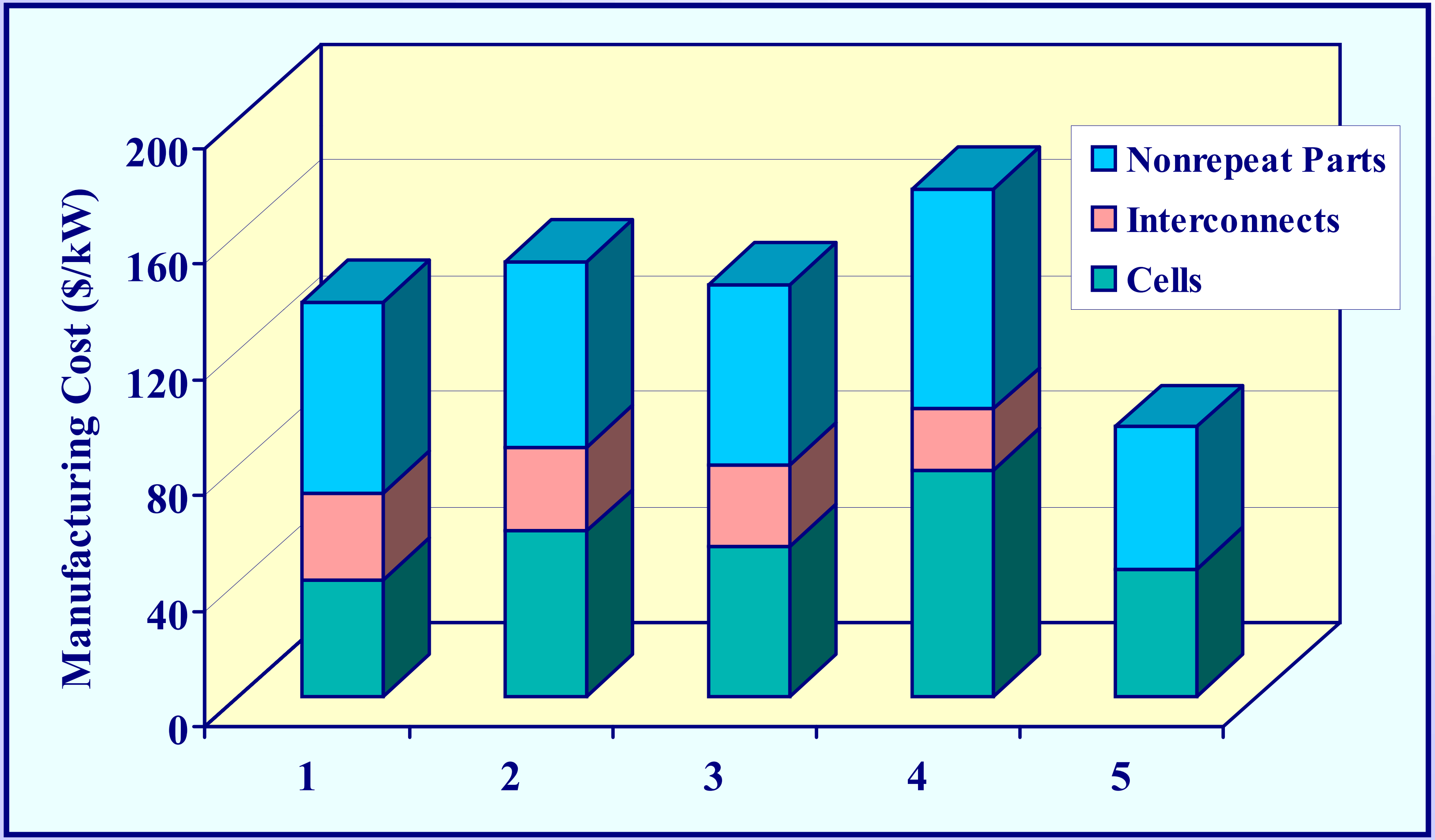
Manufacturing Cost





Advanced Materials Technologies EMTEC Gas Technology Institute Iowa State University Michael A. Cobb & Company
NexTech Materials Northwestern University Oak Ridge National Laboratory Ohio State University University of Missouri-Rolla

Manufacturing Cost



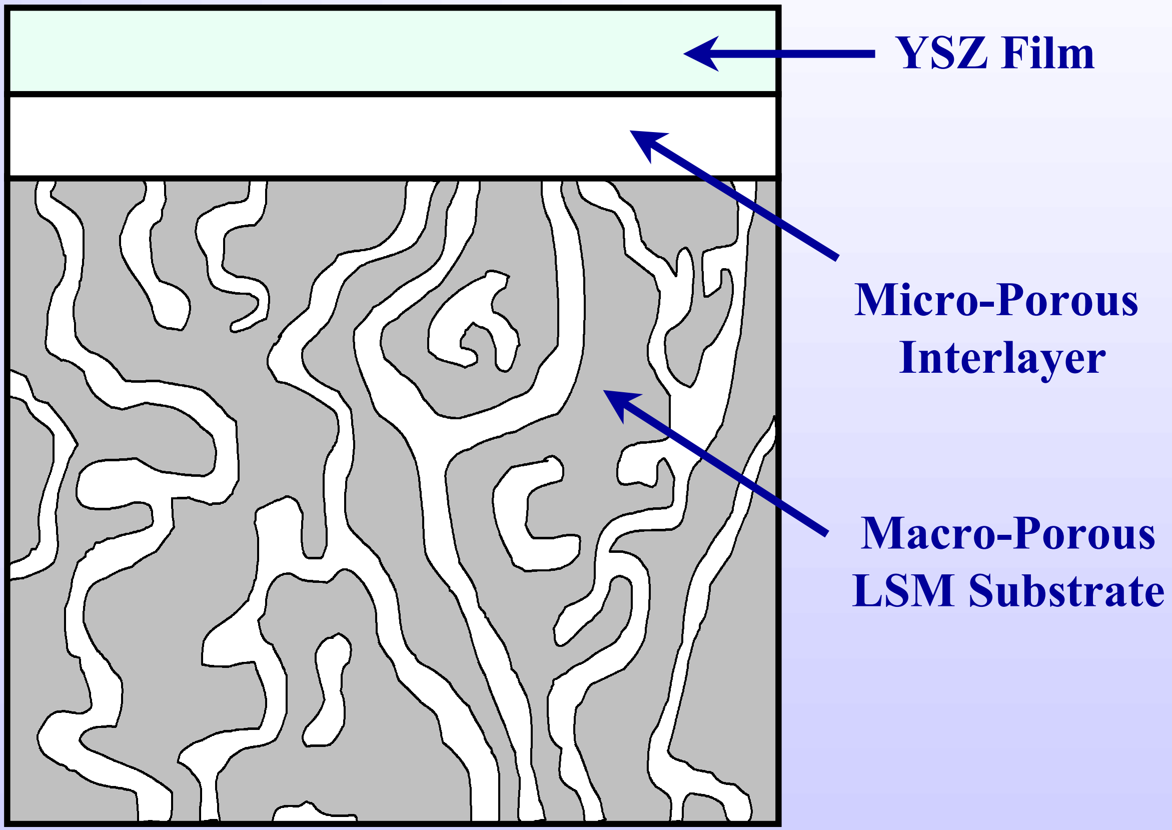
Technical Approach

Tape Casting (Cathode)

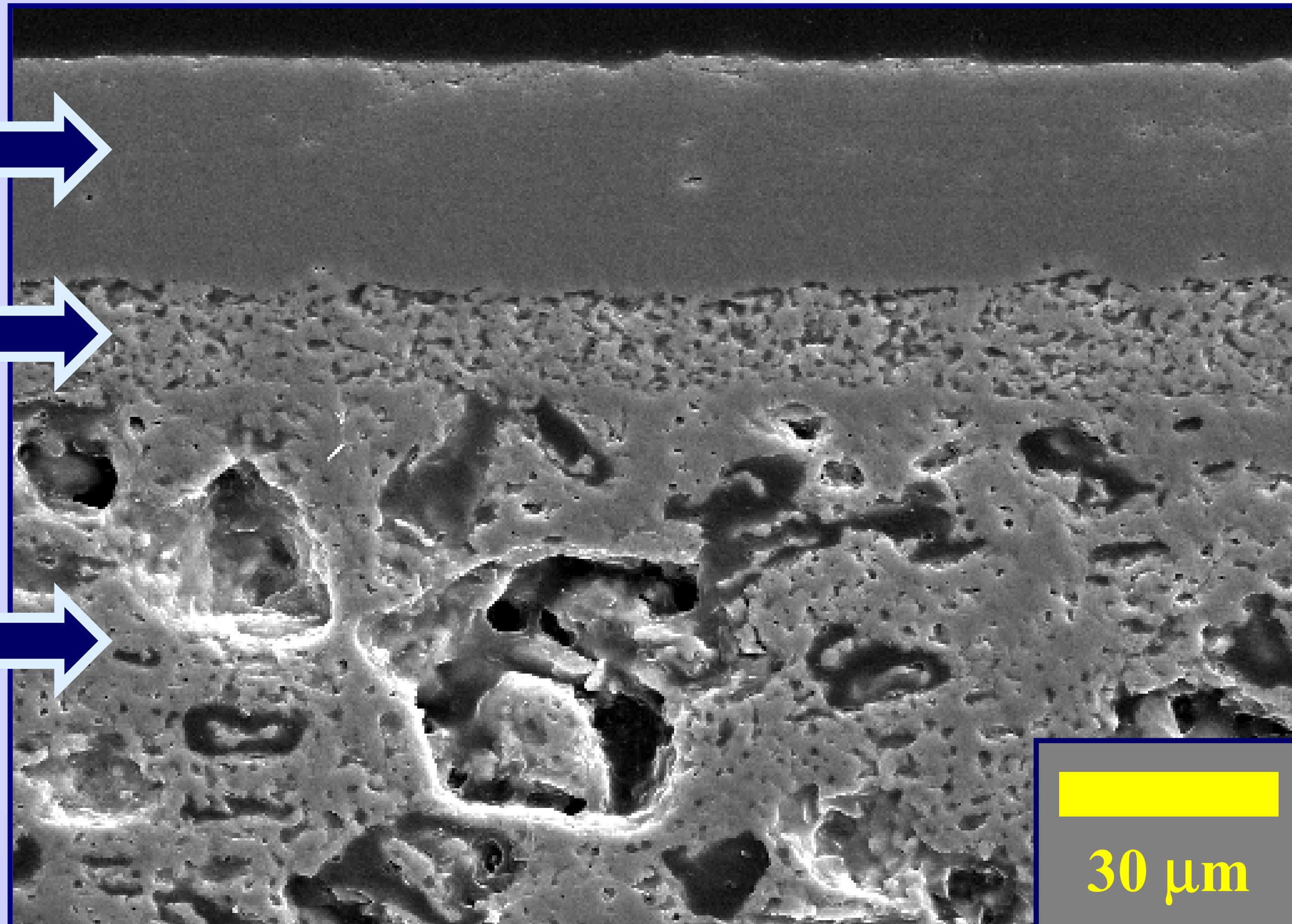
Colloidal Spray (Electrolyte)

Co-Sintering

Screen Printing (Anode)



Current Status



Technical Approach

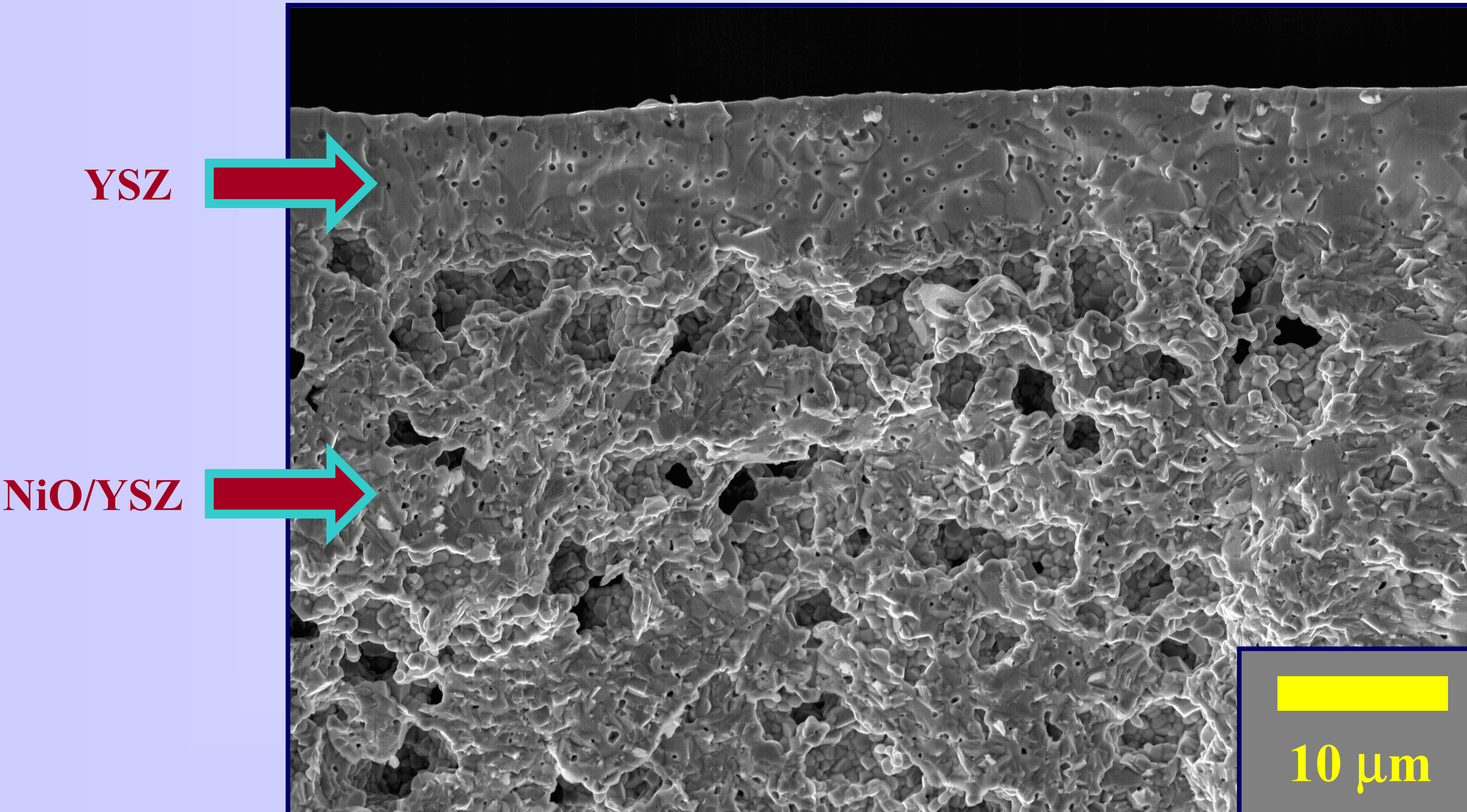
Tape Casting (Anode)

Screen Printing (Electrolyte)

Co-Sintering

Screen Printing (Cathode)

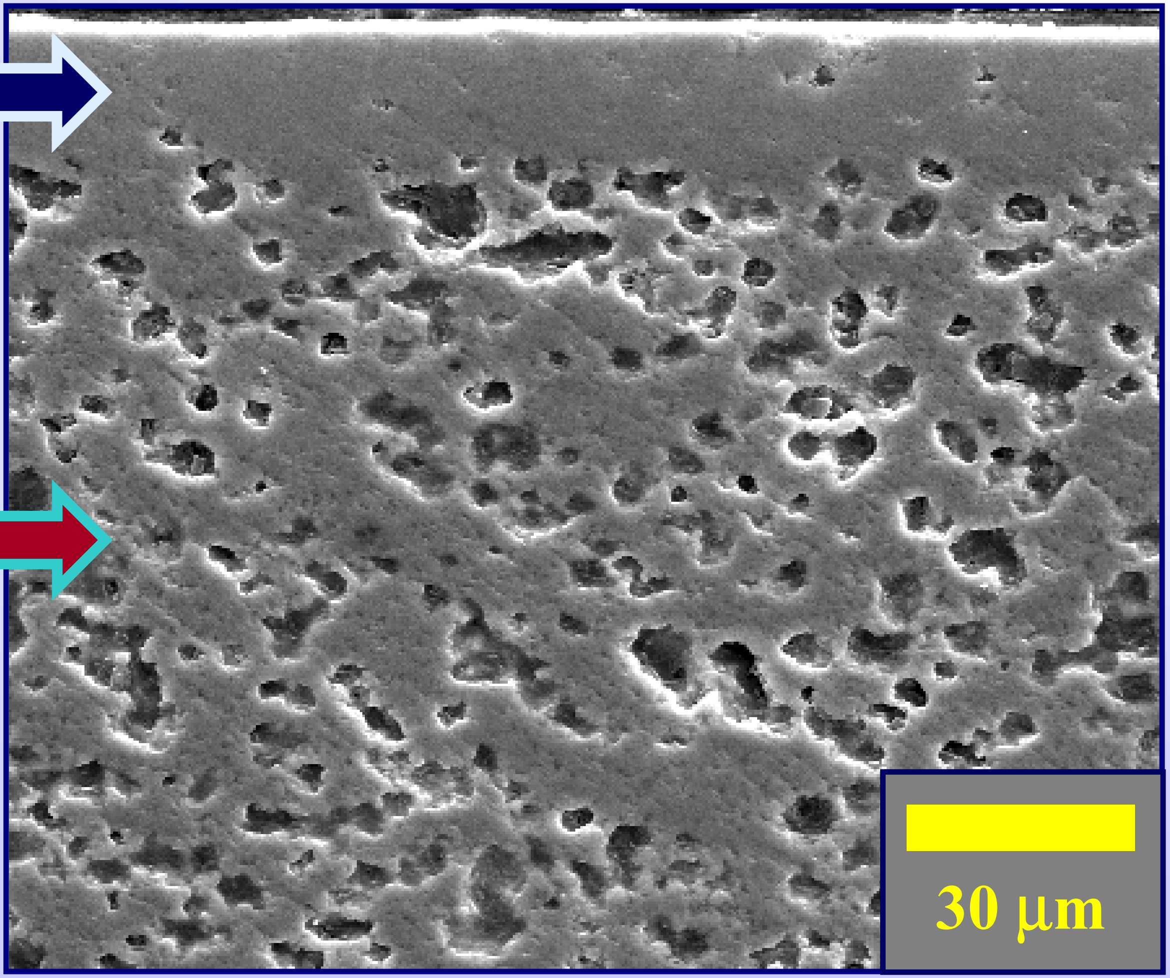
Current Status



Collaboration

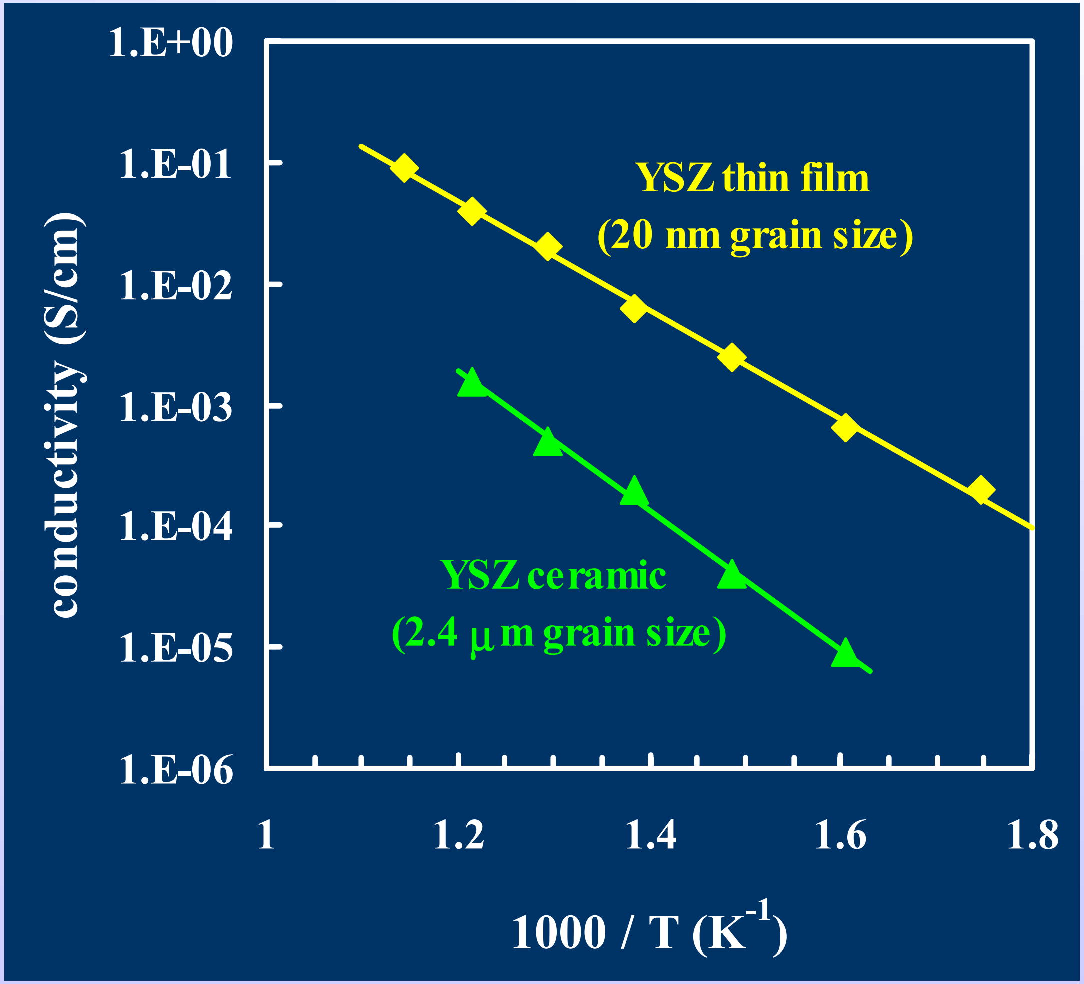
Colloidally deposited YSZ Film (NexTech)

Tape Cast Anode Substrate (ORNL)

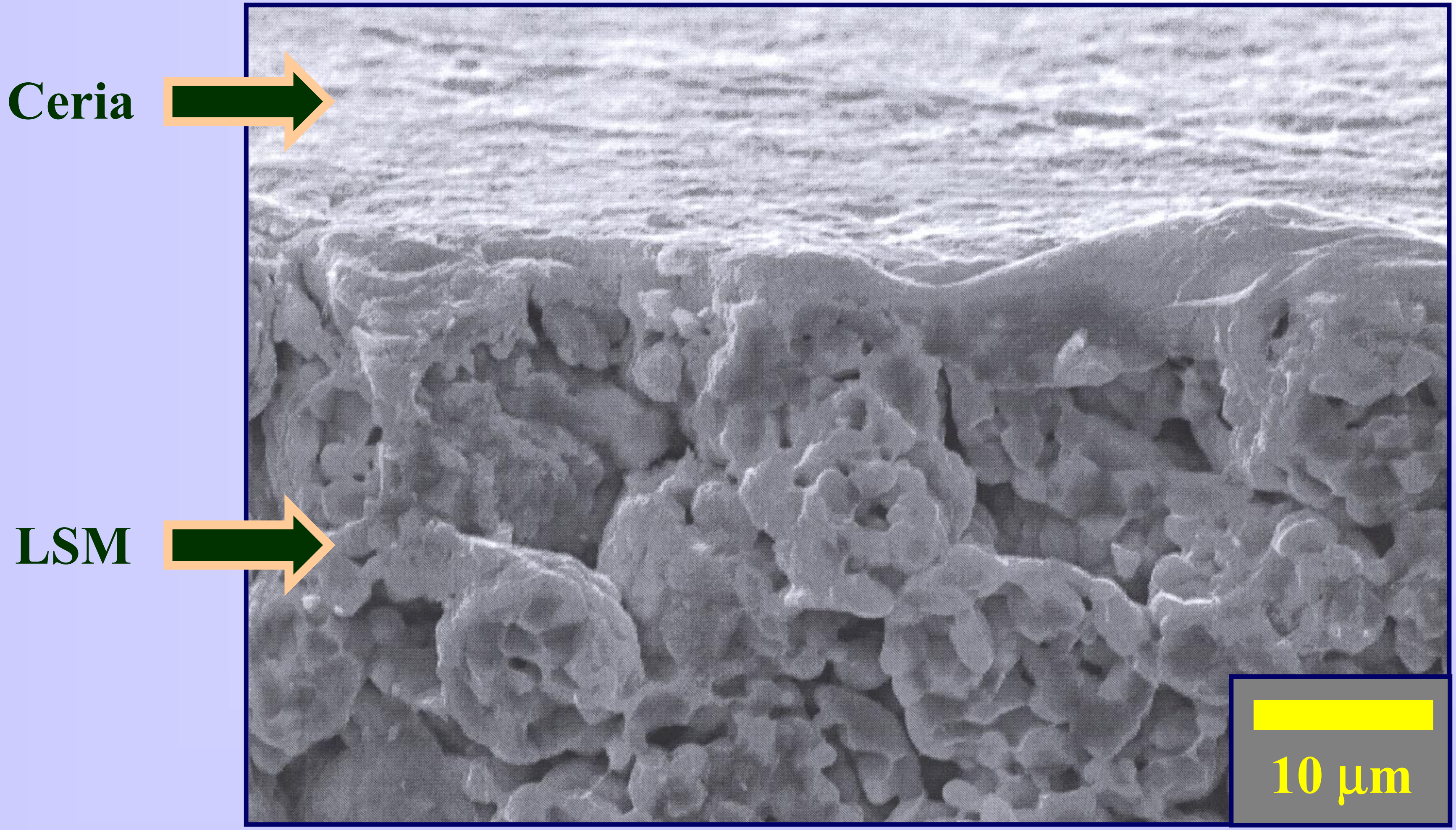


Technical Approach

- **Tape Casting (Cathode)**
- **Sintering**
- **Spin Coating (Electrolyte)**
- **Screen Printing (Anode)**



Interlayer Development



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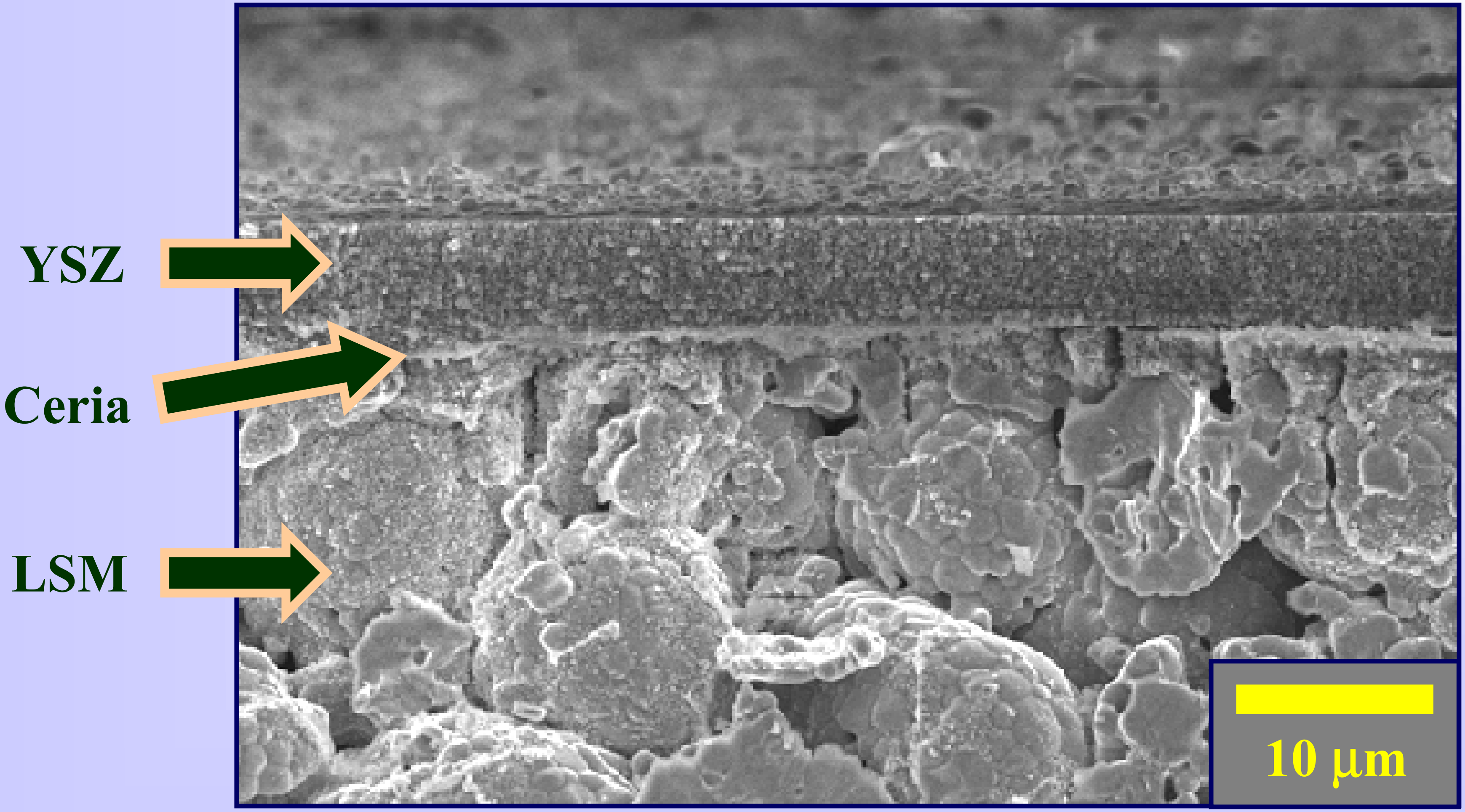
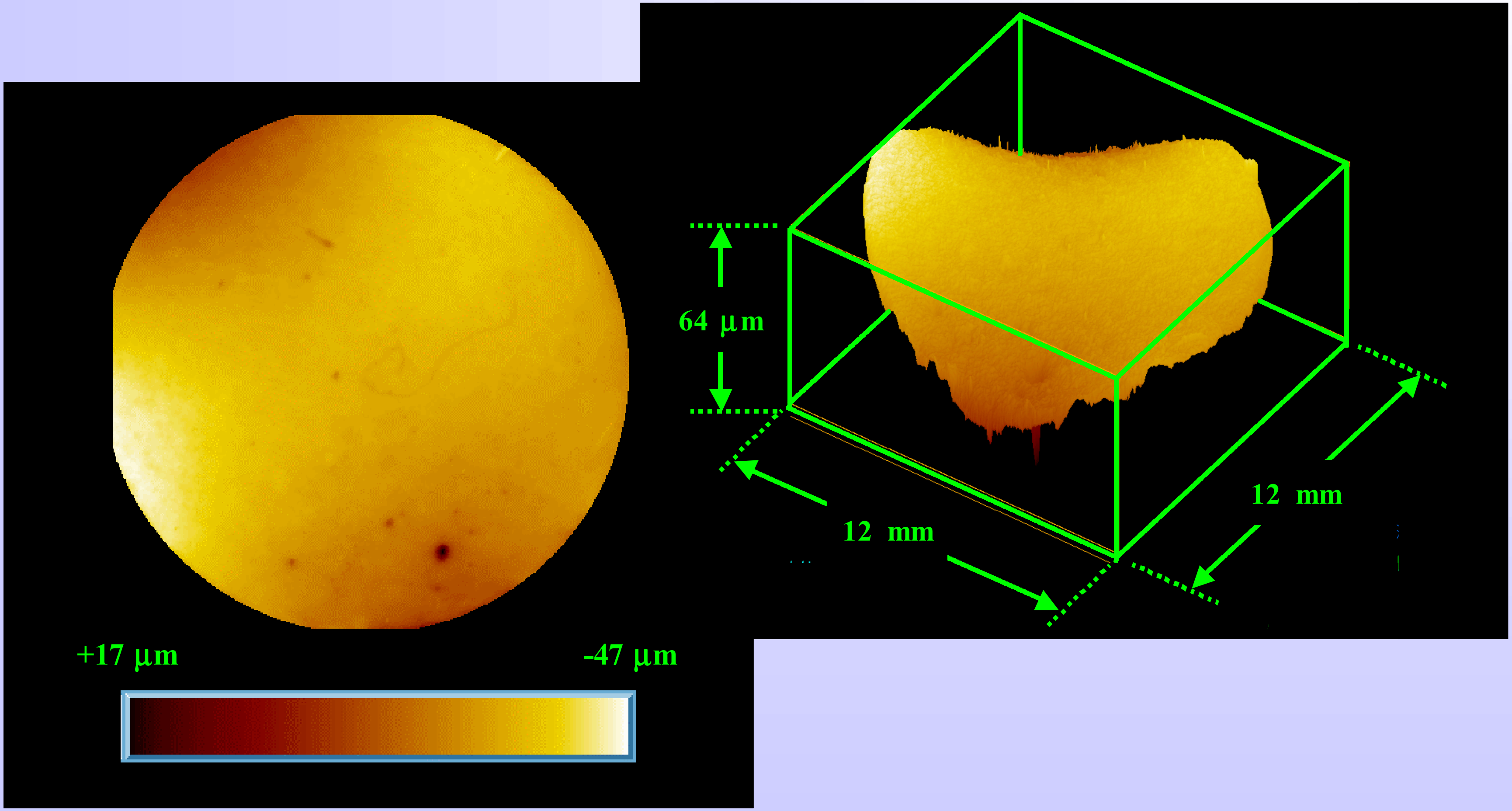
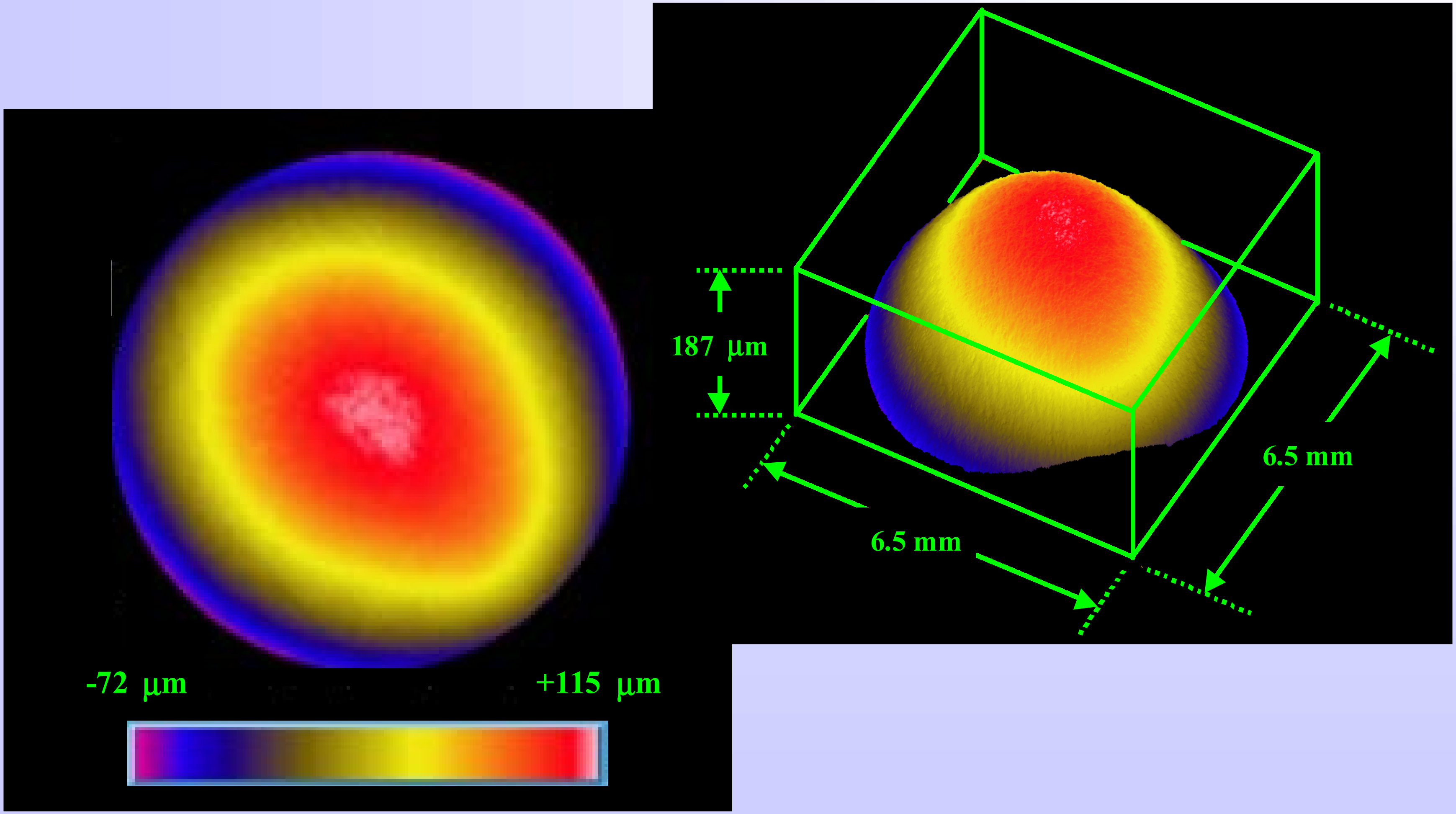


Optical Profilometry



Optical Profilometry



Commercial Focus

- SOFC materials (cathodes, anodes, electrolytes).
- Evaluation of low-cost manufacturing methods for planar, thin-film electrolyte SOFCs.
- Co-sintering technology.
- Evaluation by SOFC developers.
- Listing of products on *FuelCellMaterials.com*.

FuelCellMaterials.com

- Nanoscale YSZ and Ceria electrolyte powders.
- Nanoscale YSZ and Ceria coating suspensions.
- Low-temperature cathode powders and inks.
- Advanced anode powders and inks.
- Anode-supported planar elements.
- Cathode-supported planar elements.

Future Work

- Scale-up of fabrication to 100-cm^2 areas.
- Screen printing of top electrodes.
- Single-cell and long-term SOFC performance testing to evaluate materials and process modifications.
- Development of non-destructive evaluation methods:
  - Optical profilometry
  - X-ray computed tomography
  - UV fluorescence spectroscopy
  - X-ray radiography

Acknowledgments

- Mike Cobb and Kirby Meacham (Cobb & Co.)
- Jim Stephan (Advanced Materials Technologies)
- Bob Remick (Gas Technology Institute)
- Tim Armstrong (ORNL)
- Harlan Anderson and Wayne Huebner (UMR)
- Scott Barnett (Northwestern)
- John Lannutti (Ohio State University)
- Chris Schilling (Iowa University)
- Russ Bennett and Gary Kapp (EMTEC)

Thanks to DOE, NETL, and the State of Ohio!

P. Low Cost Multi-layer Fabrication Method for Solid Oxide Fuel Cells

Christopher Milliken, Materials Group Leader and
Benson P. Lee, President
Technology Management, Inc.

2nd Annual Solid State Energy Conversion Alliance (SECA) Workshop

Low Cost Multi-layer Fabrication Method for Solid Oxide Fuel Cells

DE-AC26-00NT40707

Dr. Christopher Milliken

Technology Management, Inc.

Cleveland, Ohio tmi@stratos.net

Tom George, NETL Project Manager

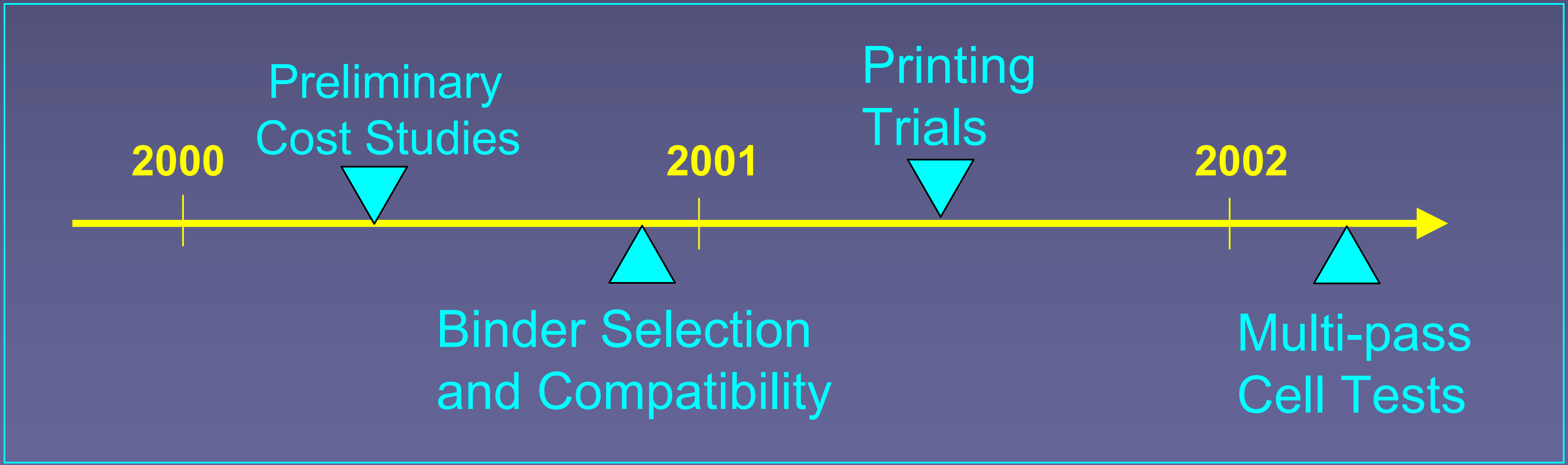
Background of TMI

- Organized in 1990 to commercialize low cost planar SOFC technology
- Engineered compact, integrated, systems.
- Designed for multi-use applications and simplified field service.

- Operated on common fuels- multiple 100 Cell stacks on CH_4 /JP-8

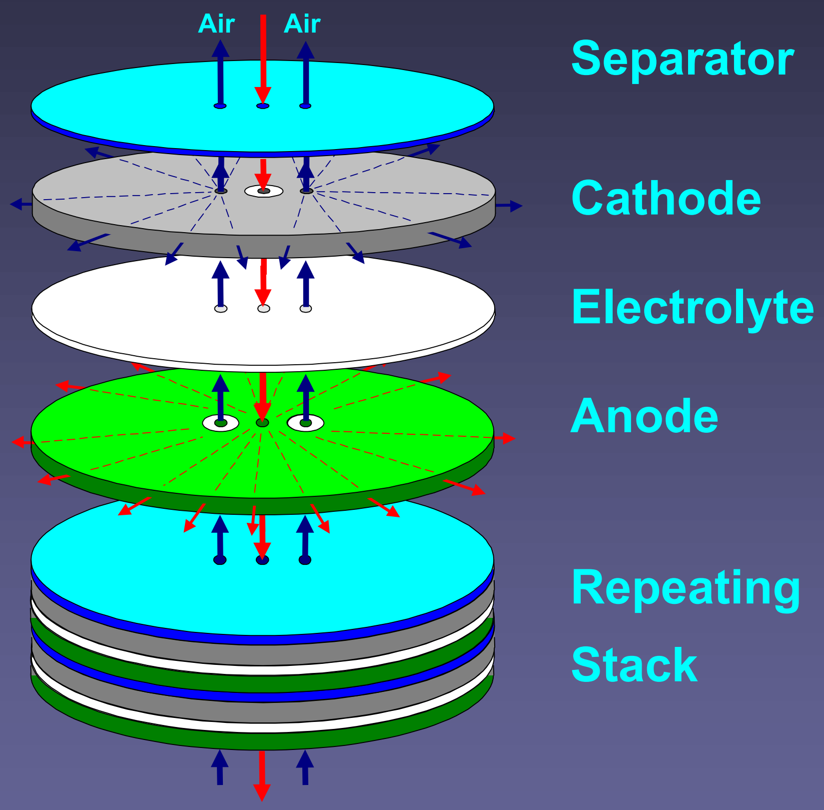
Overall Program Objectives

- *Large demand for low cost SOFC systems.*
- *Multi-Pass Screen Printing* -mature, low cost fabrication technique adapted to the TMI SOFC radial-flow design



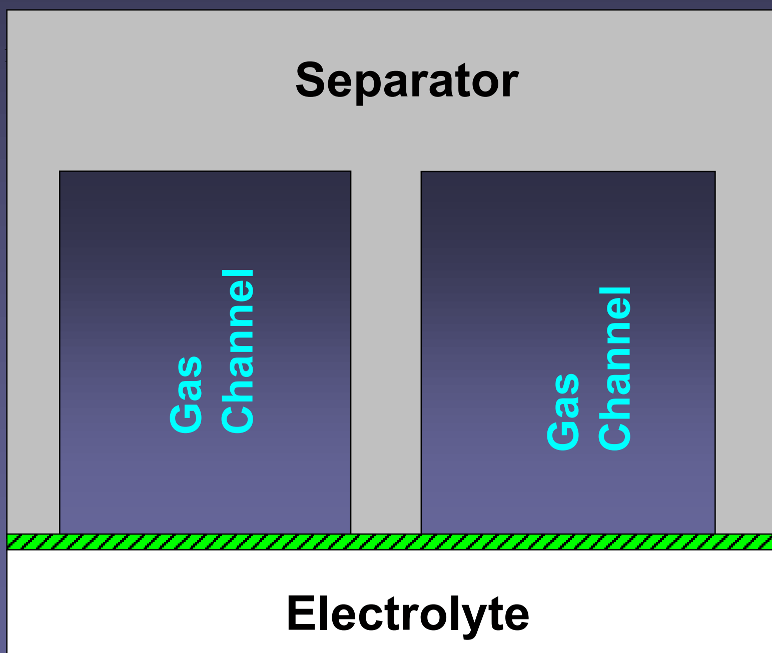
TMI Cell Design

- Simple Geometry
- Small, central seals
- Radial Co-flow
- Low Cost (vs. Performance)

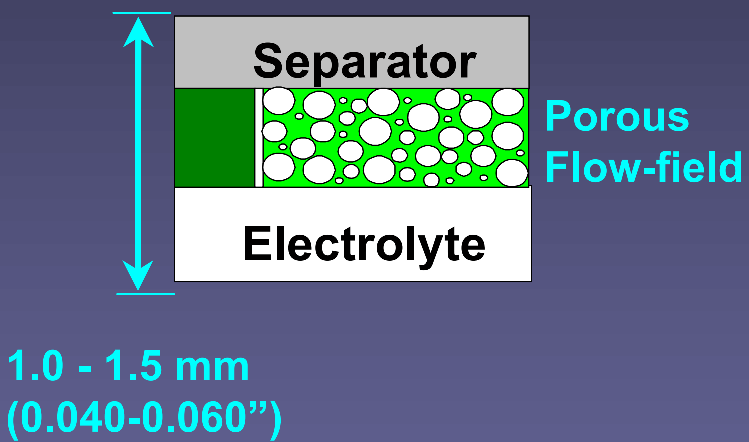


Compatible Flow Strategy

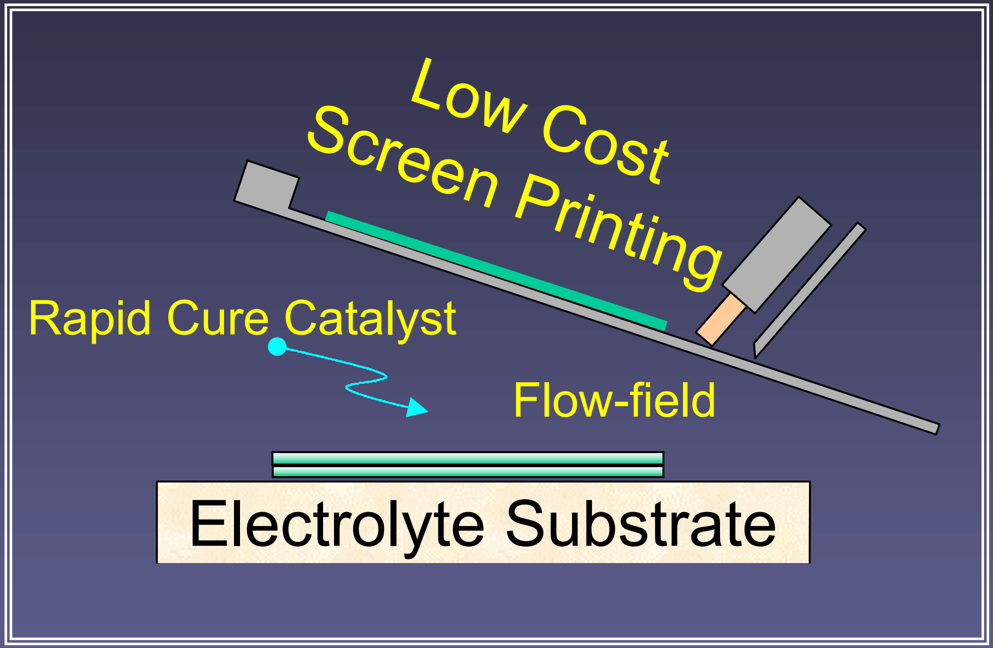
A Common Planar Design



TMI Design



Low Cost Manufacturing Strategy



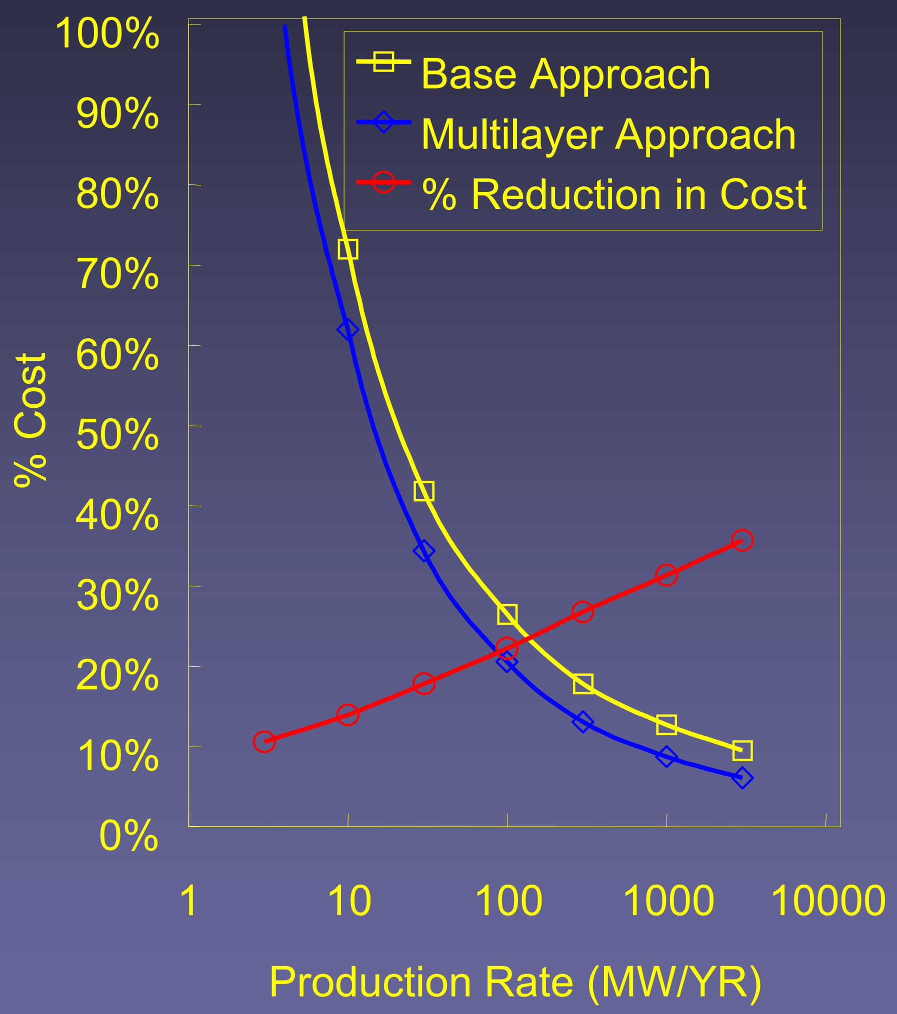
Automated Commercial Screen Printer

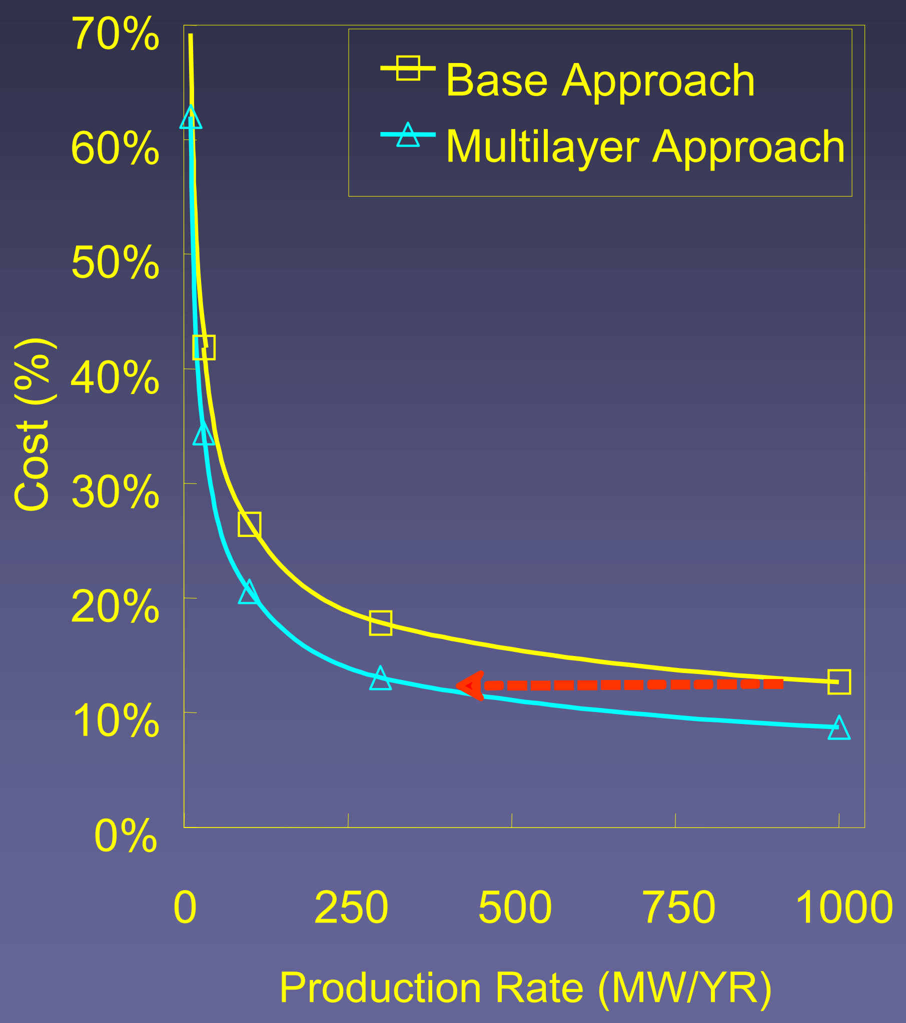
Task 1. Cost/Benefit Estimate

- Cost Build-up:
  - Direct Materials, Labor and Overhead
  - Indirect
  - Amortization of Capital Costs

- Benefits
  - Reduced Stack Cost
  - Increased Power Density (volume and weight)

Lower Per-Unit Costs





Task 2. Binder Systems

- Identified Candidate Binders
- Characterized Seven different systems
  - Reactivity/Contamination
  - Sensitivity/Hardness
- Four systems ranked by Compatibility.

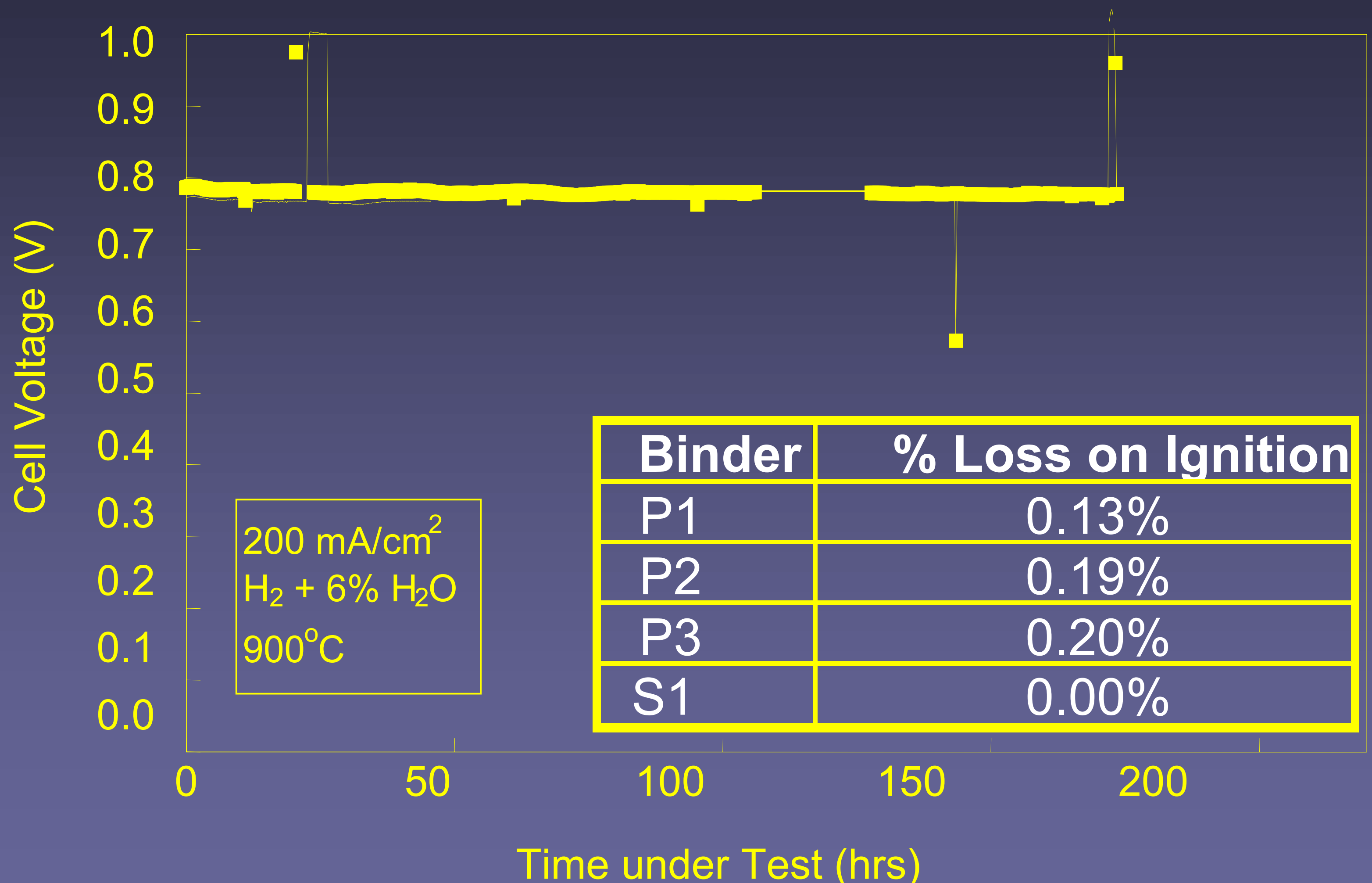
Reactivity Analysis

Binder	Cathode Powder	Seal Glass	Anode Powder
*Sample S1**	None	None	None
Sample C1**	None	None	None
Sample C2	None	None	None
Sample P1	None	None	None
Sample P2	None	None	None
Sample P3	None	None	None
Sample P4	Slight	Slight	Slight

* Reacted > 24 hrs with Cathode

** Reacts in ambient conditions

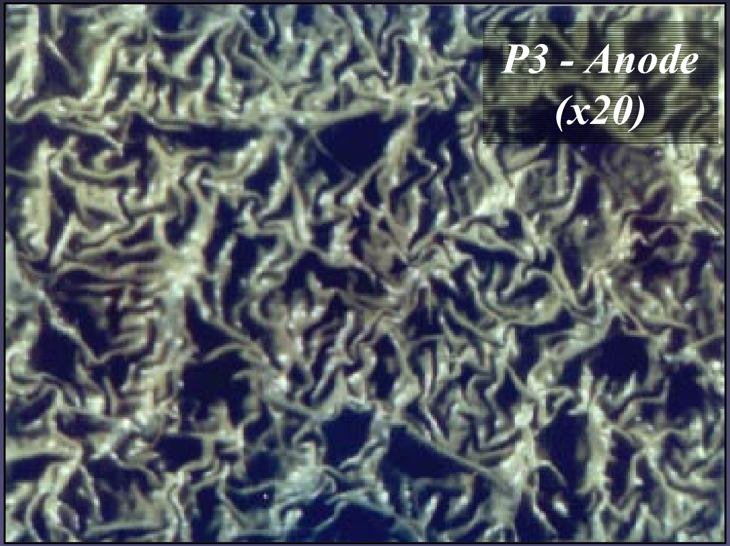
Cell Performance
(a Contamination Indicator)

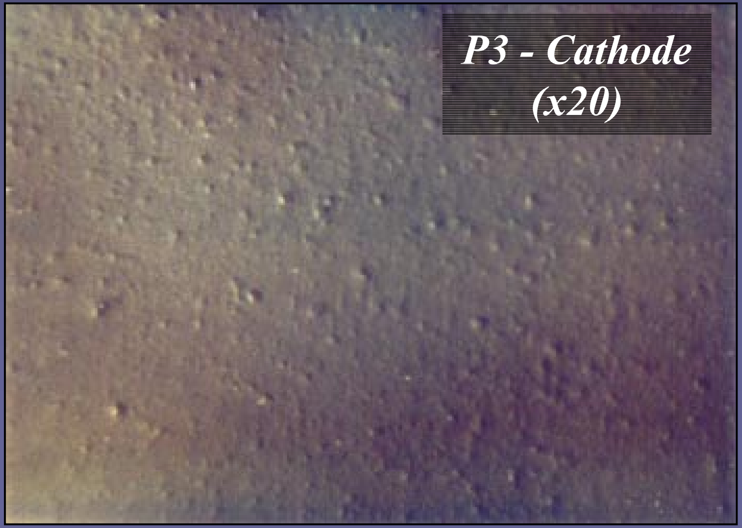


Binder	% Loss on Ignition
P1	0.13%
P2	0.19%
P3	0.20%
S1	0.00%

Task 3. Ink Curing Quality

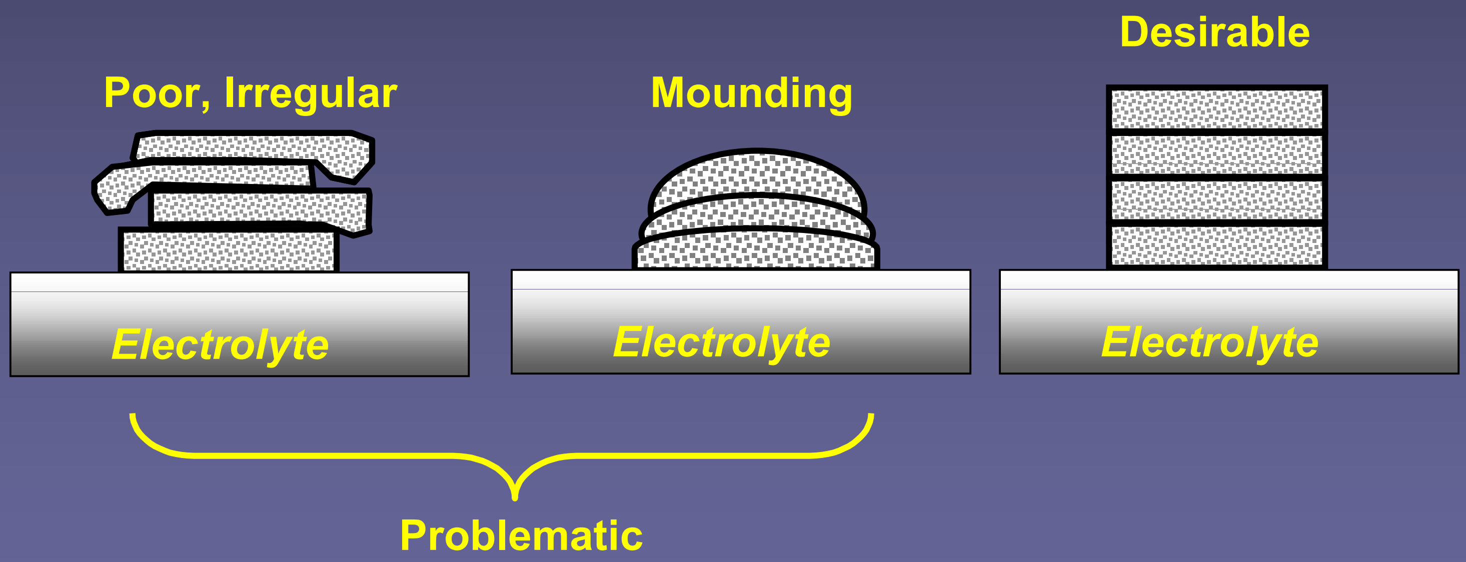
- Curing quality & rate depends on powder, thickness, and catalyst
- Challenges
  - Voids / Pockets
  - Incomplete curing



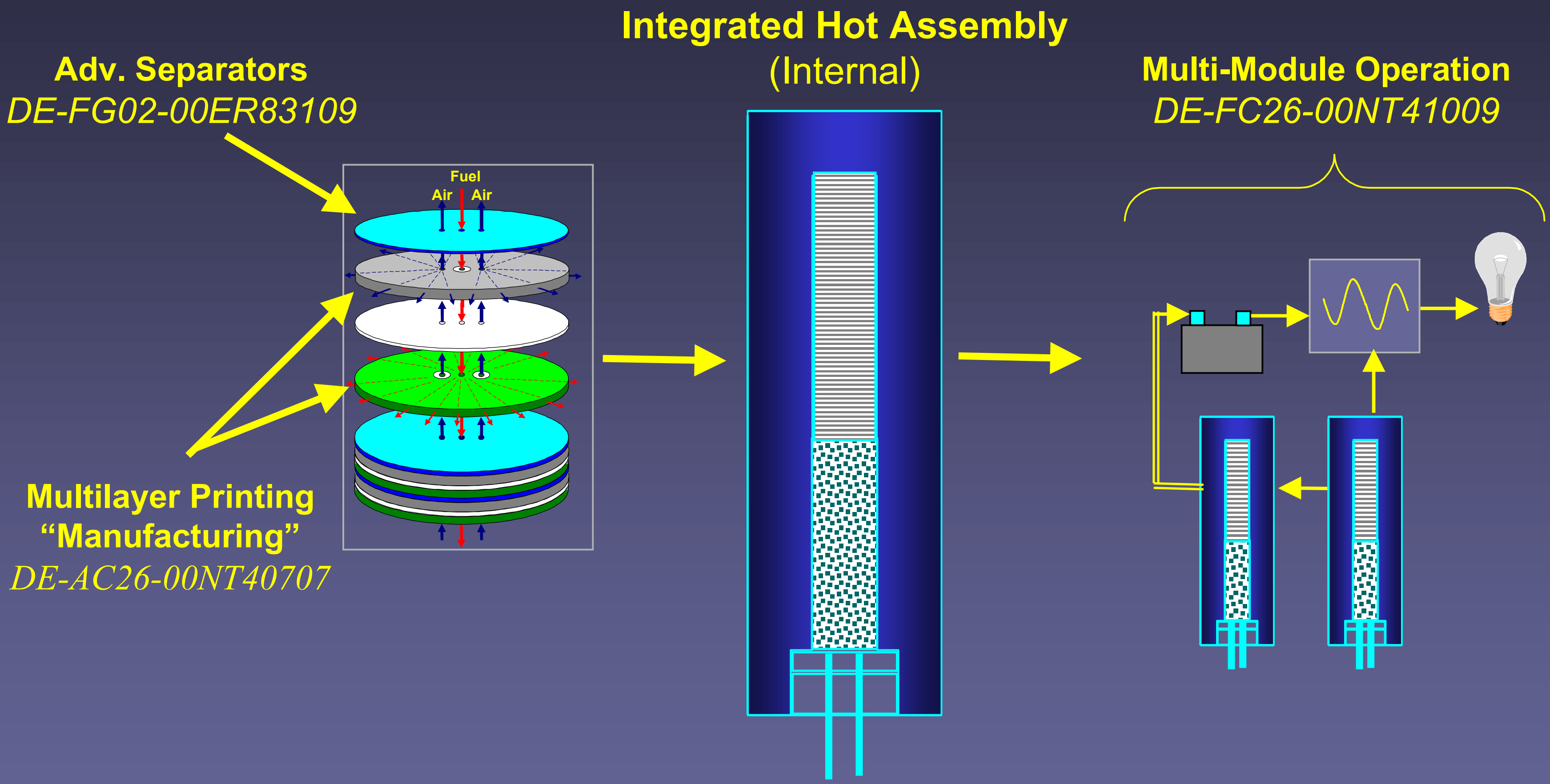


Current Challenges

- Trade-offs among rate of cure, thickness, and catalyst.
- Multi-pass Printing



Low Cost Strategies



Summary

- Completed Cost Estimate.
- Identified Binders
  - Reactivity and Contamination Studies Initiated.
  - Trade-offs among rate of cure, thickness, and catalyst.
- Multi-pass tests (Phase III).

Q. PLANAR POX/SOFC DESIGN

Carole Read
Arthur D. Little, Inc.

Planar POX/SOFC Design

Presentation at

SECA Workshop

March 2001
Washington, DC

Arthur D Little

Advances in SOFC technology now appear to enable broad small-scale applications in both stationary and transportation markets.

- Planar, thin electrolyte, electrode-supported configuration improves performance significantly
  - Increases in power density (~500 mW/cm^2 or greater)
  - Lower operating temperatures (650-850°C)
  - Lower cost metallic separator plates
  - Elimination of very high temperature molten glass seals
  - Potential for higher stack efficiency
  - Reduced heat losses from lower operating temperature
- Potential for economy of scale for manufacturing
  - Geometry lends itself to high volume, low cost manufacturing techniques
  - Broad applicability is consistent with high-volume manufacturing

Effective system design and integration has not yet received sufficient attention and is critical for the development of competitive products.

Objective

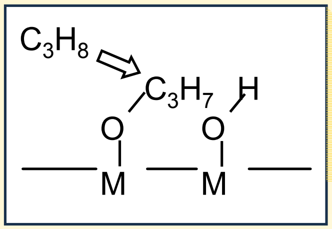
DOE/NETL/SECA asked Arthur D. Little to develop a conceptual design package and cost estimate for a planar anode supported SOFC system.

System Performance	Physical Characteristics	System Cost Targets
◆ Efficiency greater than 35% at peak power (LHV) ◆ Rating, 5 kWe net ◆ Operating life greater than 5000 hours ◆ Cold (25°C) start-up time < 10 minutes ◆ Voltage – 42 VDC ◆ No external water supply needed	◆ Volume goal less than 50 liter ◆ Mass goal less than 50 kg ◆ Operating temperature 800°C ◆ Surface temperature of system package less than 45°C	◆ Cost of balance of plant goal less than $400/kW ◆ Ultimate goal $400/kW for system

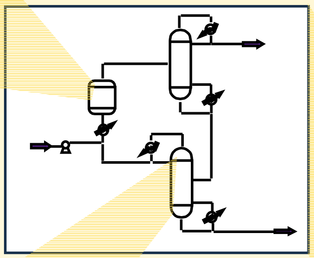
The target application for this module is an auxiliary power unit (APU) for on-road vehicles such as trucks.

We used our multi-level, model-based development methodology to design a POX/SOFC system for auxiliary power unit (APU) applications.

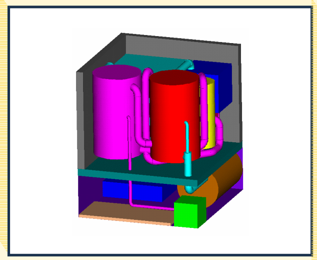
Fuel Cell Performance & Cost Model



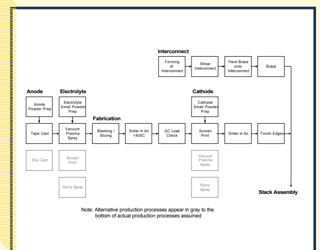
Reformer model



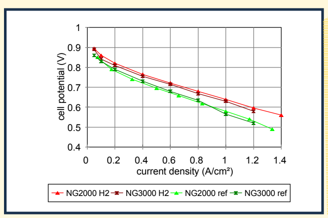
Thermodynamic System Model



Conceptual Design and Configuration



Manufacturing Cost Model



Fuel Cell Model

We used thermodynamic models coupled with detailed manufacturing cost models to identify the key design and cost drivers for planar technology.

Individual components have been distributed among the major sub-systems.

Reformer	Fuel Cell	Recuperators	Balance-of-Plant
◆ Homogeneous gas phase POX reformer[1] ➢ POX air preheater ➢ Air, fuel, recycle mixer ➢ Eductor ➢ Primary cathode air preheater ◆ ZnO sorbent bed	◆ Fuel Cell Stack (Unit Cells)[3] ◆ Balance of Stack[4]	◆ Anode recuperator ◆ Tailgas burner[2] ➢ Fuel vaporizer ◆ Secondary cathode air preheater	◆ Startup power ➢ Start-up battery ➢ Blower for active cooling ➢ Switching regulator for recharging ◆ Control & electrical system ➢ System sensors ➢ Controls ➢ System logic ➢ Safety contactor ◆ Rotating equipment ➢ Air Compressor ➢ Fuel Pump ◆ System insulation ◆ System piping

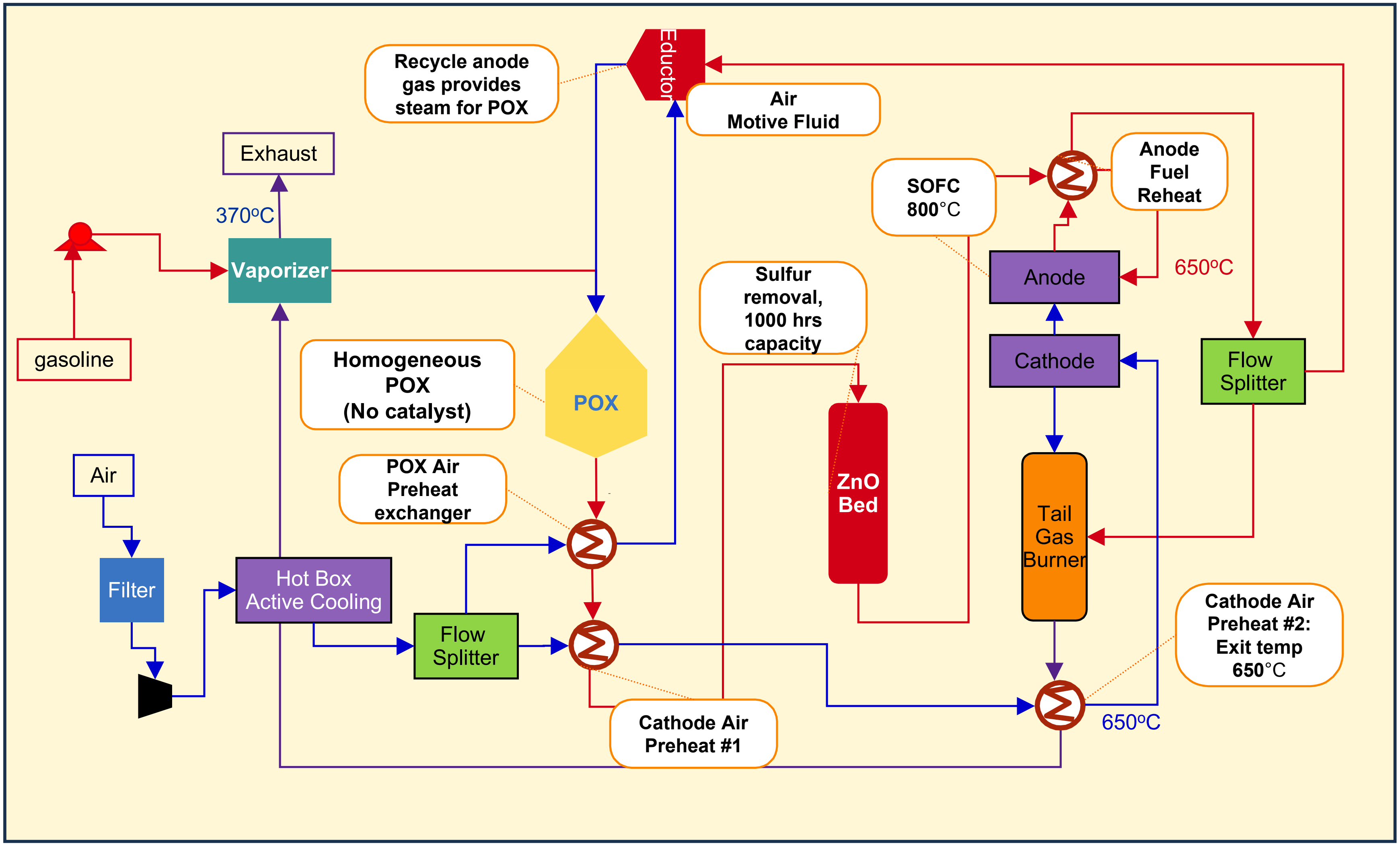
1. The reformer also incorporates the POX air preheater, primary cathode air preheater, air/fuel/recycle mixer, and eductor integrated inside.
2. The Tailgas burner incorporates the fuel vaporizer, and in case 2 the secondary cathode air preheater integrated inside.
3. The fuel cell stack includes cathode, anode, electrolyte, interconnects, and layer assembly, and stack assembly
4. The balance of stack includes endplates, current collector, electrical insulator, outer wrap, and tie bolts. It is assumed that the stack is internally manifolded.

Five separate cases were modeled to investigate the effects of different assumptions about operating conditions and fuel type.

	Base Case	Case 1 Improved Stack Performance	Case 2 Poorer Stack Performance	Case 3 Higher Power Density	Case 4 Sulfur-free Diesel Fuel
Cathode Inlet Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
Anode fuel Utilization	90%	90%	70%	90%	90%
Fuel	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	0 ppm S Diesel
Power density, W/cm^2	0.3	0.6	0.3	0.6	0.3

NOTES.
1. Case 3 has the same performance (efficiency) as the base case except that the fuel cell stack operates with a higher power density (0.6 W/cm^2 compared with 0.3 W/cm^2).
2. Case 4 has the same power density as the base case except that the fuel is sulfur-free Fischer-Tropsch Diesel.

The SOFC system flow diagram shows that equipment for heat removal (and recovery) and fluid movement plays a critical role in the system.



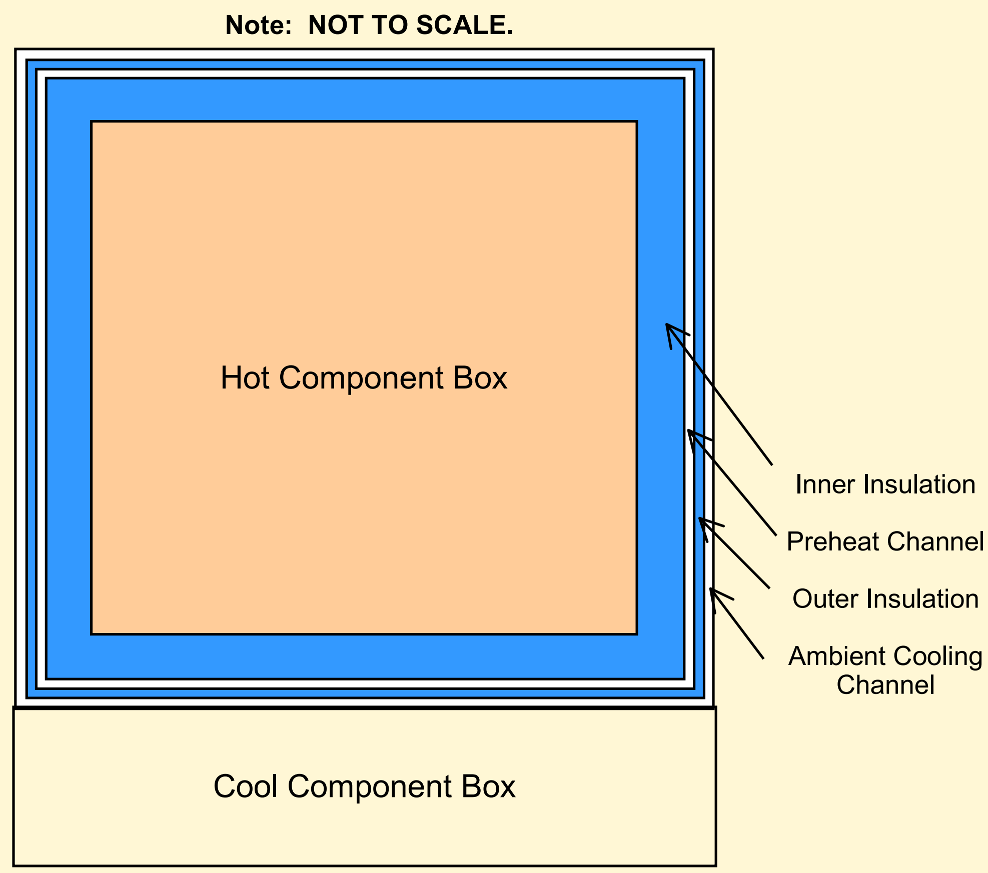
System efficiency targets of 35 percent can be met with sufficient stack thermal management[5].

	Base Case	Case 1	Case 2	Case 3	Case 4
Anode Fuel Utilization	90%	90%	70%	90%	90%
Fuel Cell Efficiency[3]	49%	49%	38%	49%	49%
POX Effluent Temperature	890ºC	890ºC	940ºC	890ºC	910ºC
Estimated POX (with recycle) Efficiency[1]	87%	87%	91%	87%	87%
Cathode Inlet Air Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
Required Cathode Excess Air	760%	330%	1,100%	760%	750%
Required Compressor Pressure[2]	1.28 atm	1.19 atm	1.39 atm	1.28 atm	1.29 atm
Parasitic Loads	**750 W**	**260 W**	**1,700 W**	**750 W**	**770 W**
Exhaust Temperature	370ºC	590ºC	370ºC	370ºC	380ºC
Resultant Overall Efficiency[4]	**37%**	**40%**	**26%**	**37%**	**37%**
Required Fuel Cell gross power rating, kW	**5.75**	**5.26**	**6.70**	**5.75**	**5.77**

1. LHV of the POX outlet stream divided by the LHV of the fuel inlet stream not including the anode recycle inlet. Does not include internal fuel cell reforming.
2. Required pressure to overcome air side pressure drops. Slightly different tube diameters and geometries were used in each case to keep the pressure requirement as low as possible without incurring large volume increases.
3. Fuel cell efficiency is defined as the product of the fuel utilization, voltage (electrical) efficiency and thermodynamic efficiency. Fuel cell efficiency is equal to (Fuel utilization) * (operational voltage/open cell voltage) * (ΔG_{rxn}/LHV fuel). Assume an open cell voltage of 1.2 volts for all anode reactions.
4. Overall system efficiency is defined as (fuel cell efficiency * reformer efficiency) - (energy required for parasitics)/(total energy input to system)
5. Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power. Thermal management of the stack refers to the maximum allowable temperature gradients allowable in the stack due to thermal stress. Thermal management also encompasses the amount of fuel that can be internally reformed at the anode which can serve to regulate the temperature in the stack.

The system is divided into a hot component box with active air cooling to decrease insulation requirements, and a cool components box.

NETL SOFC System Layout



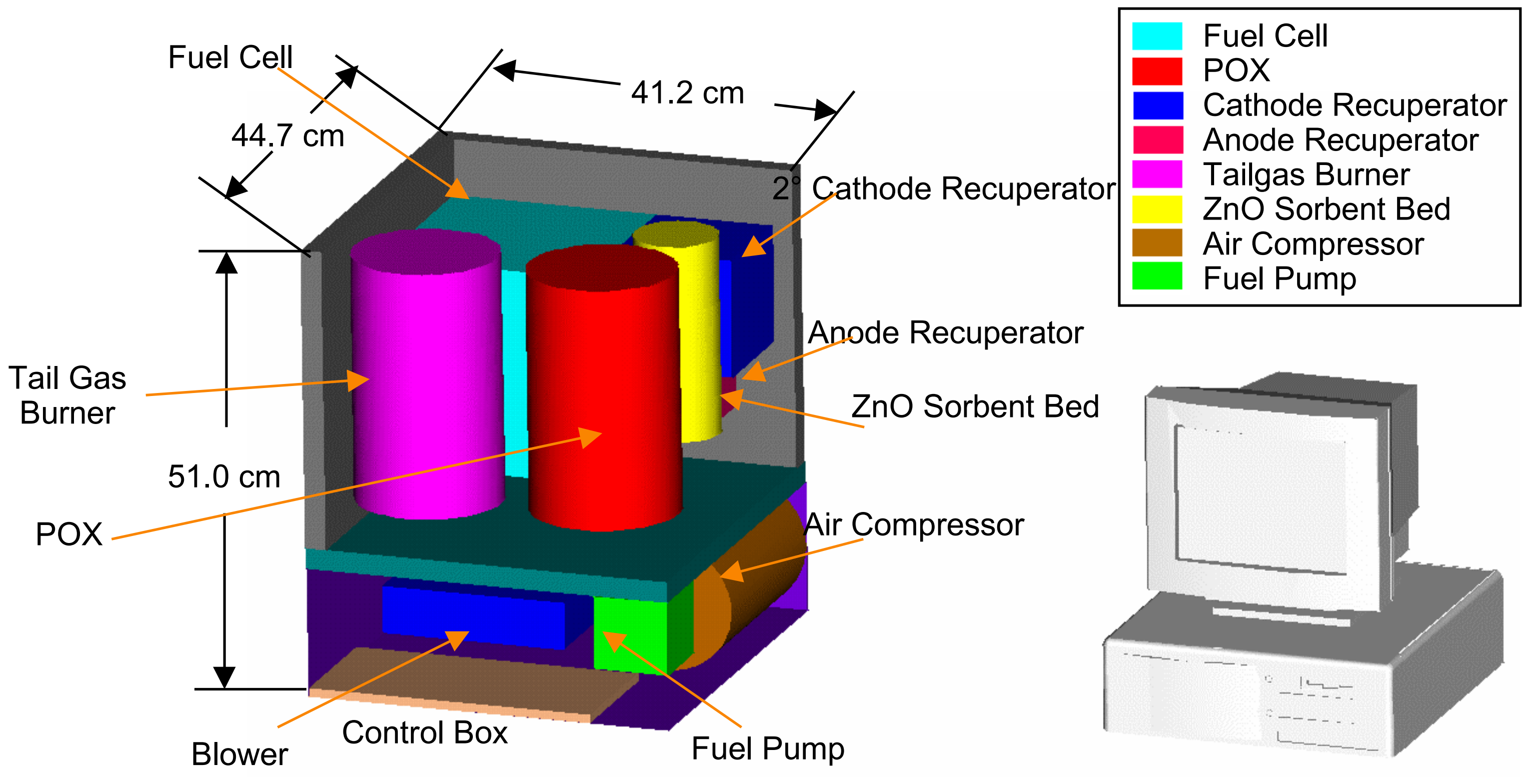
Hot Component Box:

- Fuel cell stack
- POX reformer
- Anode fuel heat exchanger
- Tailgas burner
- ZnO bed (sulfur removal)
- Recuperator heat exchangers
- Eductor

Cool Component Box

- Control system
- Air compressor and filter
- Fuel pump and filter
- Air blower for active cooling
- System battery

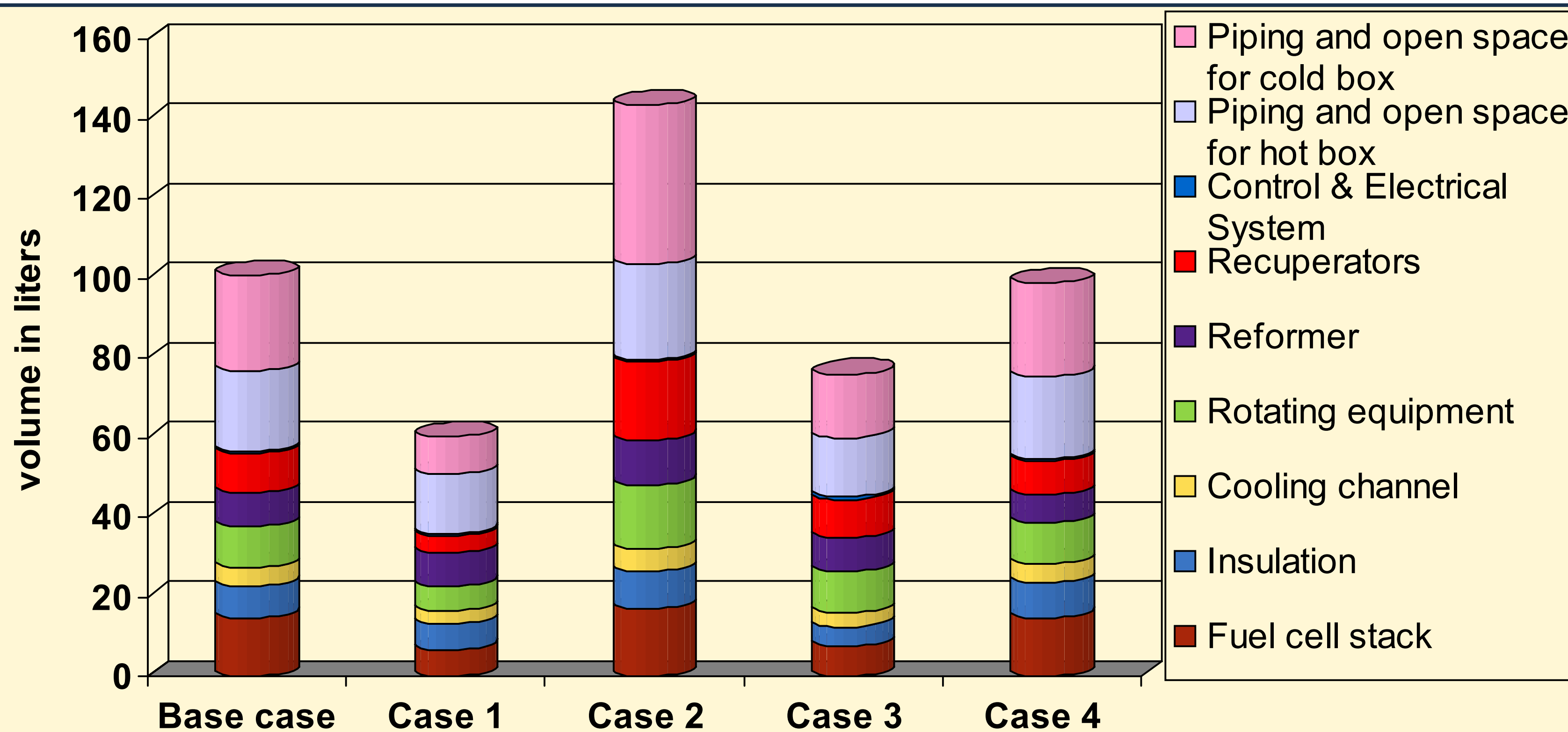
In the first generation configuration, the hot component box and the cool component box have the same footprint.



System package volume 94 liters

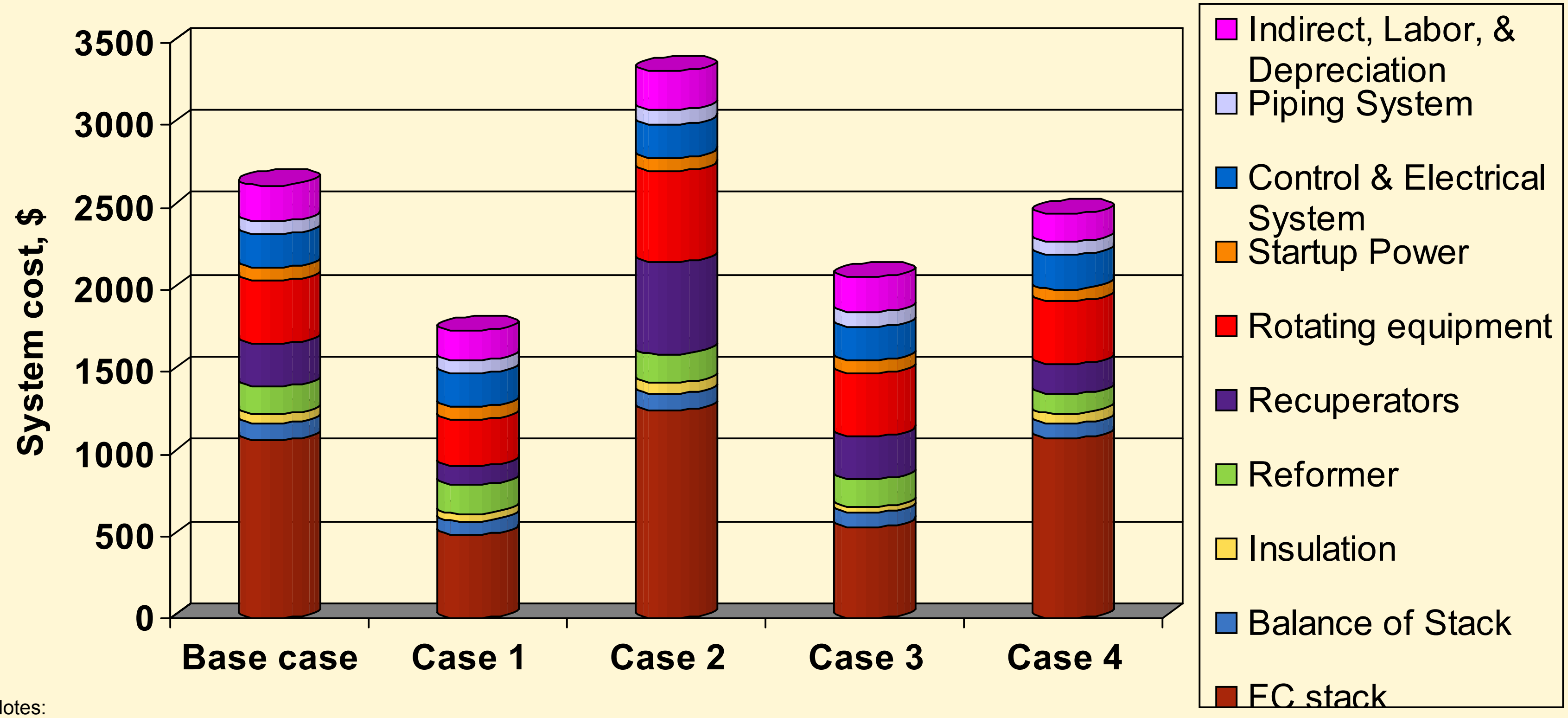
Comparison for Scale

Sufficient stack power density and thermal management are required to approach the volume target of 50 liters (results were 60 to 145 liters).



Notes:
1. The fuel cell stack line items does not include insulation or external manifolding.
2. The system insulation includes high and low temperature insulation
3. The reformer includes volume for the POX reformer, POX air preheater, the primary cathode air preheater and the zinc bed (except for case 4)
4. The recuperators include the Tailgas burner, vaporizer, primary and secondary cathode air preheaters and the anode preheater (except in case 4)
5. Rotating equipment includes the air compressor, fuel pump, and air blower for active cooling
6. The anode preheater and the secondary cathode air exchanger are configured as compact finned cross flow cube heat exchangers
7. In the base case, assuming all the volume of manifolding is in the hot box, the 20 liters includes 14.6 liters of piping for 5.4 liters of open space in the base case hot box.
8. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.
9. Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power.

A system cost of $2500 or less (or $500/kW) appear achievable; the fuel cell stack cost represents 27 to 44% of the system cost.



Notes:
1. The fuel cell stack cost does not include protective conductive coatings on the metallic interconnect, which if needed, could increase stack costs by 5-10%.
2. The fuel cell stack line items does not include insulation or external manifolding.
3. The fuel cell stack balance includes end plates, current collector, electrical insulator, outer wrap, tie bolts, FC temperature sensor, and cathode air temperature sensor
4. The system insulation includes high and low temperature insulation and metal cost for manifolding of active cooling jacket
5. The reformer includes cost for the POX reformer, POX air preheater, the primary cathode air preheater and the zinc bed (except for case 4)
6. The recuperator includes the Tailgas burner, vaporizer, primary and secondary cathode air preheaters and the anode preheater (except in case 4)
7. Rotating equipment includes air compressor and fuel pump
8. Startup power includes cost for battery and active cooling blower
9. Indirect, Labor, and Depreciation includes all indirect costs, labor costs, and depreciation on equipment, tooling, and buildings
10. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

System efficiency targets can be met under most circumstances but heat-up time targets are unrealistic without further technology improvements.

- System efficiency of greater than 35% is easily achievable[1]:
  - Typical efficiency 37%
  - 40% efficiency appears achievable (even at this scale)
  - Stack thermal management can significantly impact efficiency
- Use of sulfur free fuel does not dramatically change system performance or cost from base case sulfur containing fuel operation
  - Alternative reforming technologies such as steam reforming or fully internal reforming were not considered
  - The sulfur free fuel case represents a conservative impact of possible sulfur-free alternative fuels
- A 10 minute start-up time appears unrealistic with current technology:
  - Thermal mass of stack would require significant additional heating and air movement capacity, with significant size (30%) and cost (15%) penalties
  - Materials thermal shock resistance issues will further increase start-up time
  - Minimum practical start-up times from a system perspective is about 30 minutes
  - Heat-up time will also be dependent upon sealing technology used for stack

1. The system efficiency was set by a using a 0.7 Volt unit cell voltage, a POX reformer, and required parasitics. Higher efficiency is achievable at higher cost by selecting a higher cell voltage

Our analysis indicates that achieving the 50-liter volume target will be challenging without further improvements in stack technology.

- System volume estimates range from 60 to 145 liters[1].
- The balance of plant represented by the reformer, recuperators, and rotating equipment represent the largest fraction of the physical equipment
- The actual fuel cell stack and insulation volume occupies between 24-31% of the total system volume
- For the first generation system layout, the largest single volume element was spacing between the components to account for manifolding
- Aggressive stack thermal management and internal reforming will have the greatest impact on volume reduction by impacting the size of required heat recuperators
  - Decrease cathode air requirement
  - Allow more component integration
  - Decrease manifolding and insulation requirements
- Some savings may be obtained by closer packing of rotating equipment and controls and further overall component integration and optimized layout

1. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Achieving the $400/kW system cost target appears feasible with high power density stack performance and good stack thermal management.

- System cost estimates range from $351 to $666 per kW for 5 kW SOFC APU systems
- Fuel cell stack cost and balance of plant (reformer and recuperators) are the key cost drivers for the 5kW net system
- As achievable power density increases, the cost of purchased components such as rotating equipment becomes a key cost driver
- Increasing the power density from 0.3 W/cm^2 to 0.6 W/cm^2 saves $112/kW assuming similar system efficiency
- Aggressive stack thermal management could save $64/kW while poor stack performance and thermal management can result in a penalty of $139/kW
  - Aggressive stack management reduces recuperator area and air movement requirements
- Using low/no sulfur fuel can save $35/kW from simpler system configuration (not considering alternative reformer technology)
  - A zinc sulfur removal bed is not required
  - An anode recuperator is not required

The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Stack thermal management and power density are critical issues impacting the cost and performance of reformer/planar SOFC systems.

How can reformer / planar SOFC systems be applied to truck APUs and how much will they cost?

	System Performance[1]	Cost	Volume & Weight
Internal Stack Thermal Management[2]	●	●	●
Power density / Operating Voltage	●	●	●
Stack Fuel Utilization	●	◒	◒
Stack Thermal Mass[3]	●	○	○
Recuperator	○	●	●
Parasitic power	◒	●	●
Reformer efficiency	◒	◒	◒
Insulation	○	○	●

● Critical ◒ Important ○ Not Leveraging

1. System performance refers to e.g. system efficiency, start-up and shut-down time.
2. Stack thermal management refers to the maximum thermal gradients allowable and degree of internal reforming possible at anode.
3. Critical if provisions must be made to meet tight start-up specifications.

Stack thermal management directly impacts recuperator and parasitic requirements and system volume.

Performance, cost, and size of planar SOFCs offer significant opportunity in a wide range of applications.

- Estimated performance and cost appear:
  - Very competitive for APUs and distributed generation technologies
  - Very attractive for stationary markets
- Performance, size and weight may have to be further improved for key transportation markets
- The impact of lower volume production must be considered for some markets
- The impact of system capacity (modules of 5kW stacks units) should be considered for larger-scale applications
- First order risk exists in that publicly available information of a stack demonstration of a planar anode supported architecture operating at 650-800°C does not exist

In order to direct future development efforts most efficiently, SECA should consider the following issues and their implications.

- Impact of fuel choice (e.g. natural gas, propane)
- Impact of manufacture volume
- True limitations of thermal management and utilization versus attainable voltage/current
  - Modeling of stack to understand internal reforming, etc.
  - Thermal and reaction modeling of SOFC stack under different operating conditions
  - Start-up time verification (impact of thermal shock)
- Impact of internal reforming on system operation and prospects for “designer” fuels
- High performance insulation materials and systems
- Development of integrated components
- Sealing technology for the fuel cell stack
- Long term and cyclic system testing

R. SECA Core Technology Roadmap Development

Gary L. McVay, Deputy Associate Laboratory Director
Pacific Northwest National Laboratory

SECA Core Technology Roadmap Development

March 29-30, 2001

Arlington, VA

by

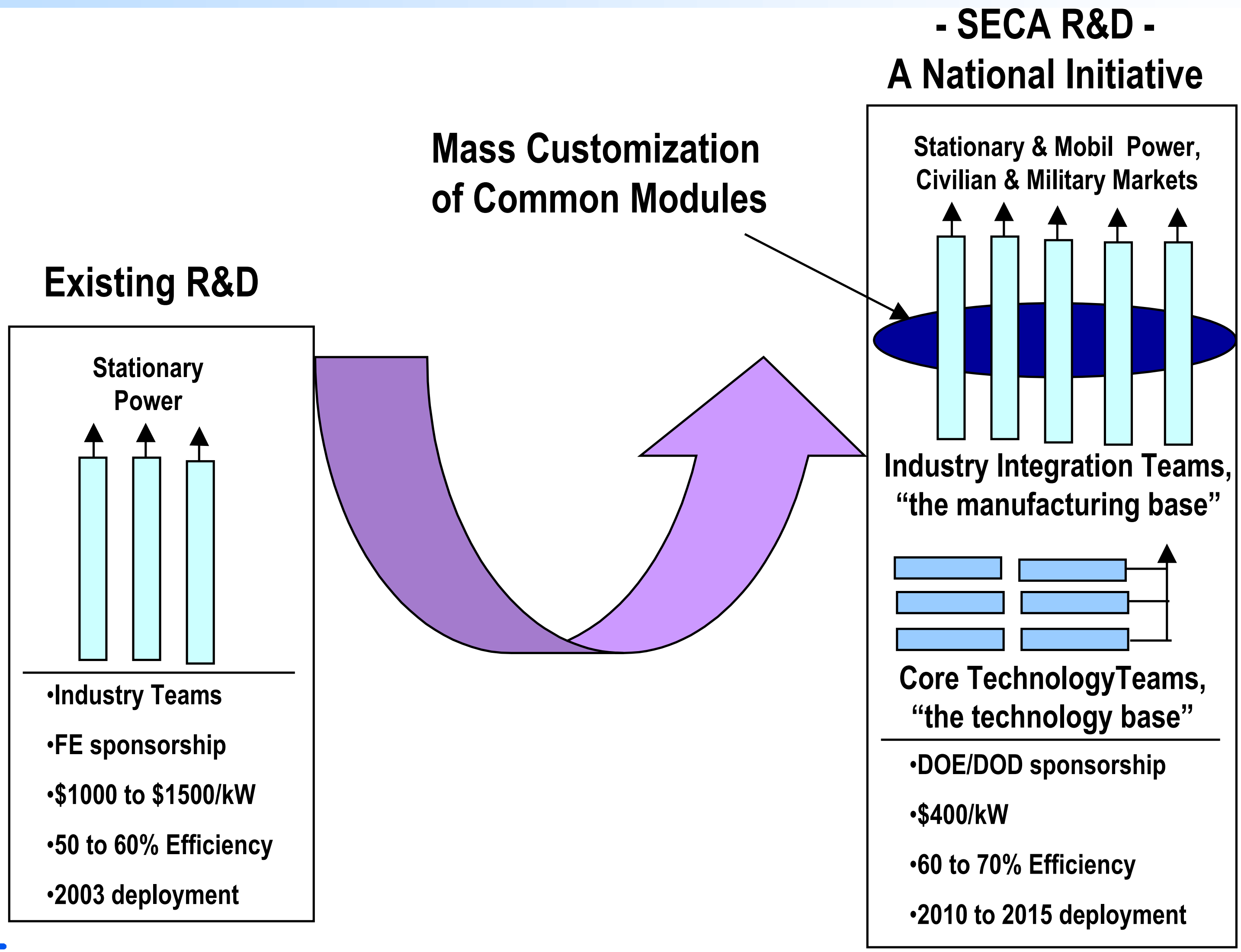
Gary L. McVay

Prabhakar Singh

Battelle

U.S. Department of Energy
Pacific Northwest National Laboratory

SECA VISION
Solid State Energy Conversion Alliance

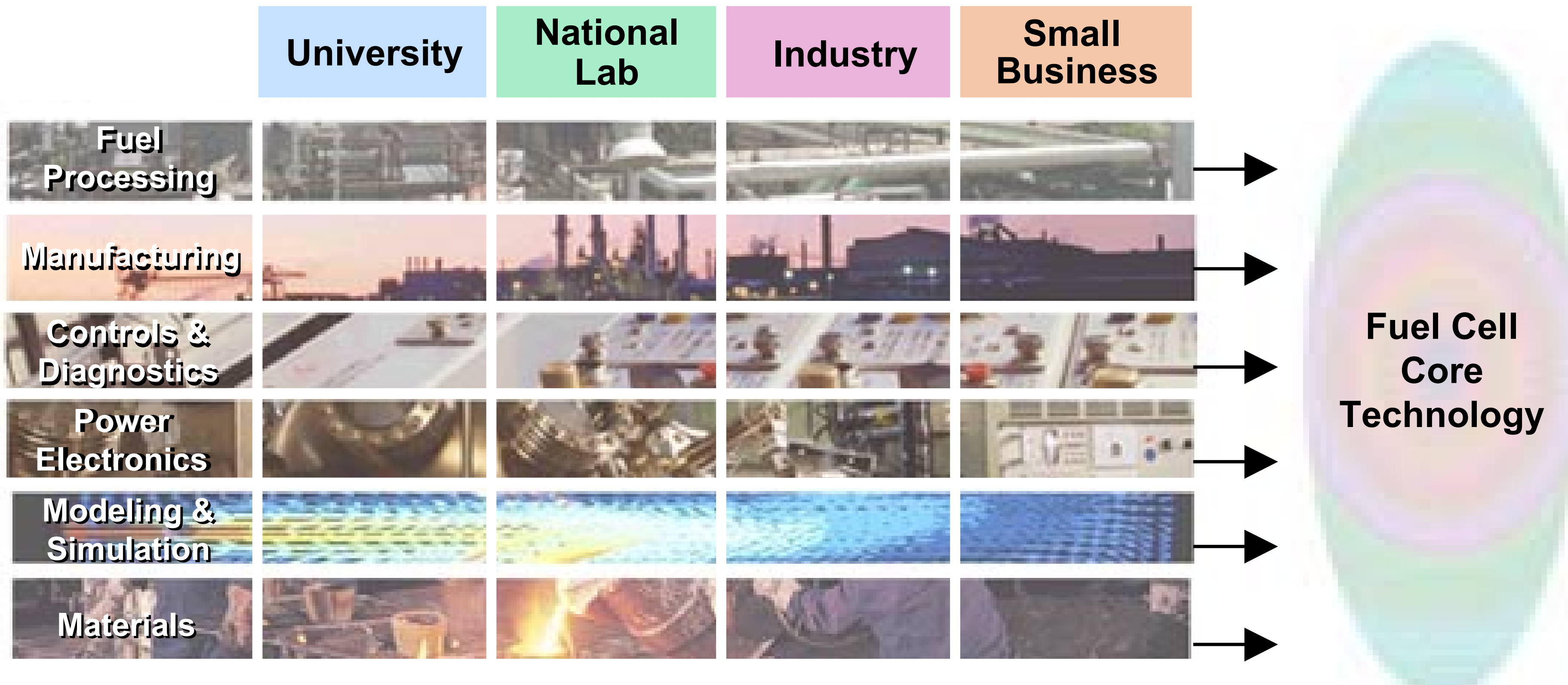


SECA Core Technology Program

- Overcome Technology Barriers That Enable Industrial Teams to Rapidly Progress Toward Low Cost SOFC System Development Consistent With SECA Goals
- Information Shared With All Industrial Teams
- Can Include Universities, National Laboratories, and Industries

SECA Technology Program

The Technology Base



Summary of SECA Core Technology Program Planning Workshop

February 14-15, 2001

Atlanta, GA

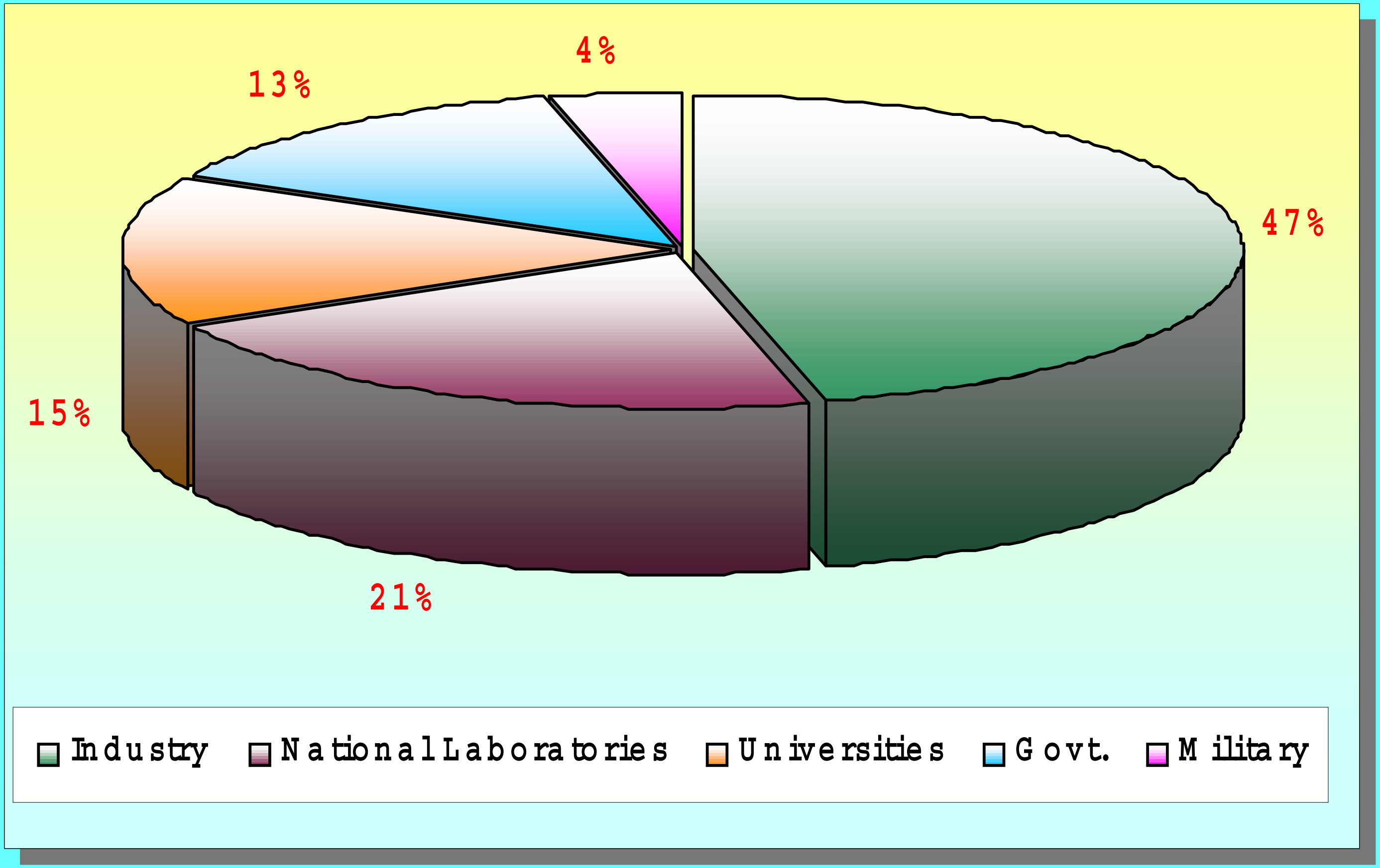
Attendance: 54

Battelle

U.S. Department of Energy
Pacific Northwest National Laboratory

Workshop Results:

Workshop Participation by Affiliation



Workshop Objective

- To identify critical fuel cell and related system technology development needs to meet the SECA cost and performance targets of the advanced solid oxide fuel cell (SOFC) power generation systems

Procedure

- Establish current level of understanding
- Present "strawman" of technology needs or gaps between where we are and SECA goals
- Audience modifies strawman to reflect their perspective (predominantly industry)
- Prioritize
- 2nd day summarize and last chance to modify
- Prioritize overall technology gaps/needs

Next Steps

- Present results of this meeting to 2nd SECA meeting (March 29-30) to get broader perspective—modify if appropriate
- Use as a basis for core technology solicitations

Topic Areas

- Fuel processing technologies
- Cell/stack materials and manufacturing processes
- Stack/system performance and modeling
- Power electronics

Establish Current Level of Understanding

- Fuel Processing Technologies
  - "Fuel Cells for Transportation: Fuel Processing Technology," Patrick B. Davis DOE-OTT Office of Advanced Automotive Technologies
  - "Natural Gas Fuel Processing Experience and Issues," Pinakin S. Patel, FuelCell Energy, Inc.
  - "Diesel Reforming for Solid Oxide Power Generation," David L. King, Pacific Northwest National Laboratory
- Cell/Stack Materials and Manufacturing Processes:
  - "SOFC Materials and Processing Issues," Anil V. Virkar, Materials and Systems Research, Inc.

Establish Current Level of Understanding (cont).

- Stack/System Performance and Modeling:
  - "Solid Oxide Fuel Cell System Development and R&D Needs," Nguyen Ming, Honeywell, Inc.
  - "Solid Oxide Fuel Cell Auxiliary Power Unit: Status and Challenges for Automotive Applications," Subhasish Mukerjee, Delphi Automotive Systems
- Power Electronics:
  - "Lower Cost Power Electronics Systems Blocks for DG and Automotive Applications," Chris Kambouris, Ecostar

Rankings

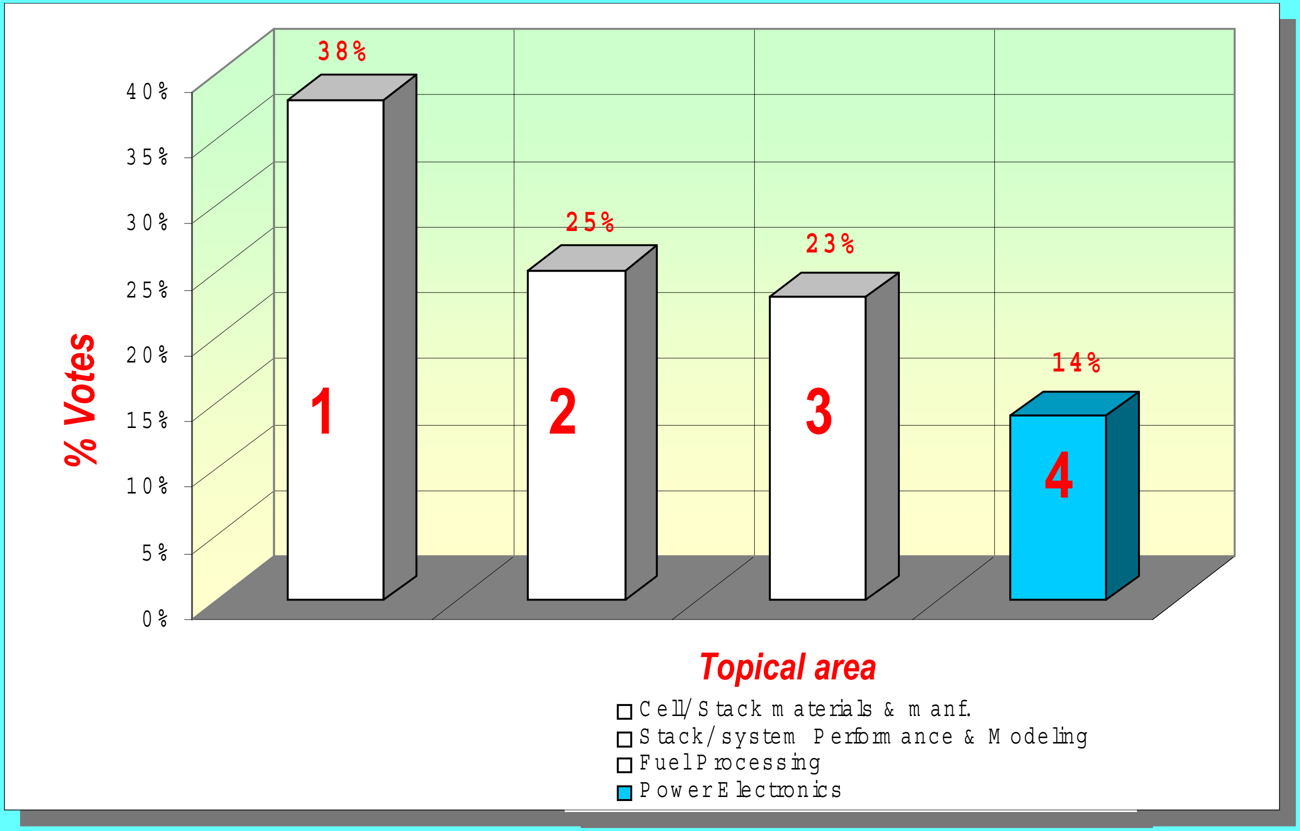
- Fuel Processing:
  - Catalyst kinetics, parameters, deactivation
  - Fuel pre-reforming catalyst and methods
  - Sulphur-tolerant anodes
  - On-anode fuel utilization
  - Water and steam management
- Cell/Stack Materials and Manufacturing:
  - Stable interconnect
  - Fuel/oxidant seals
  - Cathode electrode/electrolyte interface
  - Thermomechanical modeling and tools
  - Internal reforming/direct oxidation

Rankings (cont.)

- Stack/Systems Performance & Modeling:
  - Cell and stack performance model; electrical and chemical model
  - Low-cost HX, insulation, blowers, sensors
  - Fast start-up and thermal cycling
  - System steady state and dynamic model
  - Start-up methods and materials to accomplish fast start-up
- Power Electronics:
  - Fuel cell/PE interface
  - Packaging
  - Sensors, diagnostics, and prognostics
  - Modeling: electrical interface
  - Materials and fabrication processes

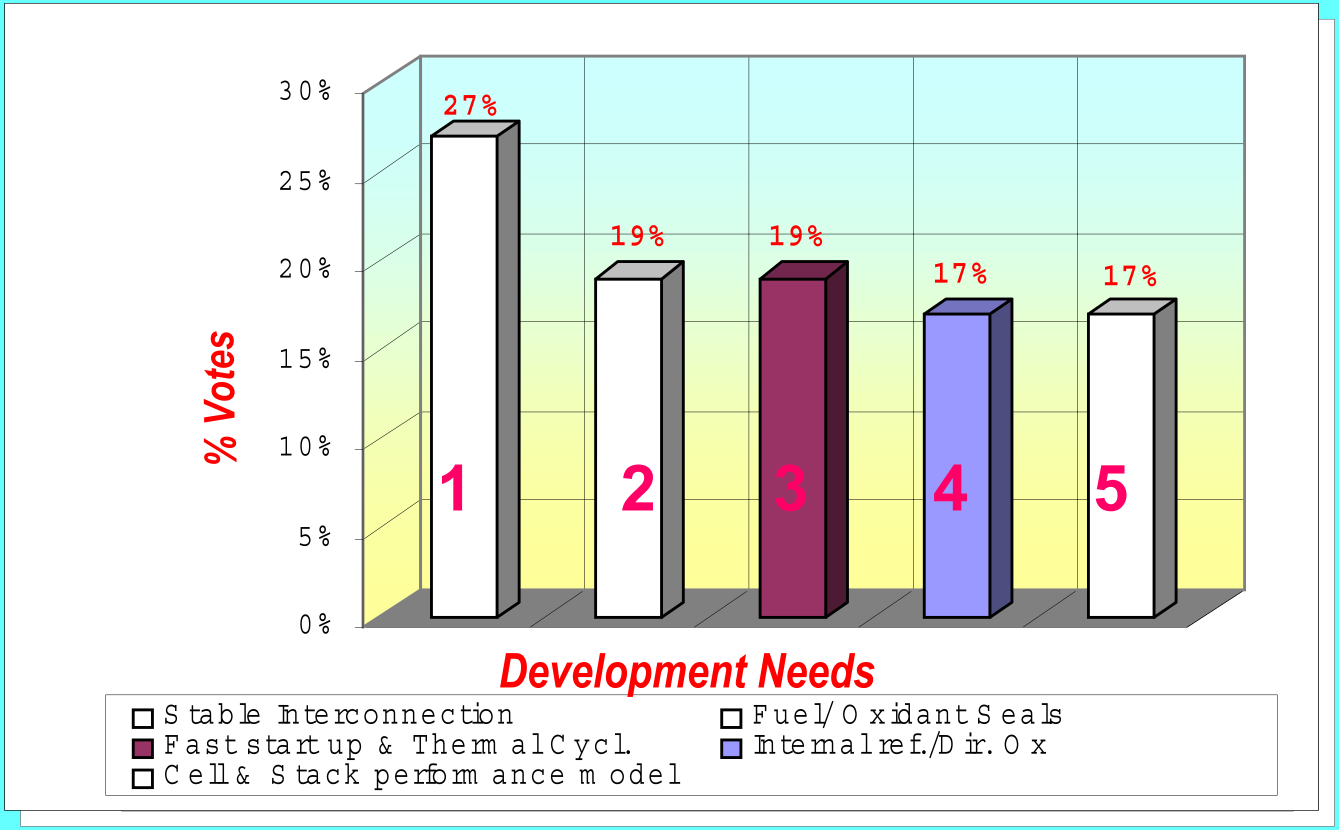
Workshop Results:

Ranking of Topical Area (All workshop Participants)



Workshop Results:

Top 5 Development Needs Identified at the CTP Workshop (All Participants)



Next Steps

- Have summarized the Core Technology Program Planning Workshop…Now would like your input

  ---Breakout Sessions

APPENDIX A
BREAKOUT SESSION RESULTS

STACK MATERIALS & PROCESSES – BREAKOUT GROUP A

Breakout Group A held an open discussion about cell and stack materials and processes. The group considered current research problems and future development, and although the discussion was not rigidly structured, it centered on four interweaving areas:

- oxidation
- temperature
- material
- research goals

They began their discussion with a focus on oxidation within the anode cavity of a fuel cell. Oxidation of nickel, which is a primary candidate for anodes, is temperature dependent. Research has shown that cooling the cell stack below 400°C slows the kinetics and causes anode oxidation, yet current methods to protect the anodes are expensive.

Sulfur tolerance of metallic versus ceramic anodes was also discussed. Currently, the primary candidate for the anode is nickel metal in powder form, which creates a porous matrix. However, nickel is the active anode material, catalyzing an electrochemical reaction. Nickel can be irreversibly contaminated by sulfur, so the core technology program is searching for alternative materials. Researchers have found some ceramics that have substantial electronic conductivity, but as of yet, none are as electrochemically active as nickel. Composites are also being developed that optimize structure and performance. Initial performance studies show that these composites are performing for at least 10,000 hours.

Participants
Stack Materials & Processes – Breakout Group A

NAME	ORGANIZATION
D.C. Agarwal	VDM
Gerry Agnew	Rolls-Royce
Harlan U. Anderson	University of Missouri at Rolla
Scott Barnett	Northwestern University
Donald F. Beal	Performance Ceramics
David Bell	University of Wyoming
Raymond Benn	UTRC
Glen Benson	Aker
Jeff Bolebruch	Blasch precision Ceramics
Larry Chick*	PNNL
Vince Coppolecchia	VDM
William J. Dawson	NexTech
Duane Dimos	Sandia
Stephen W. Freiman	NIST
Randall S. Gemmen	NETL
Don Gerhardt	Ingersol Rand
Robert Glass	LLNL
Bruce Godfrey	Australian SOFC
Sossina M. Haile	Caltech
Mark Hammond	Sarnoff
Michael Hanagan	Precision Glass and Ceramics
Diane Hooie	NETL
Xinyu Huang	Genentech
Rod Judkins	ORNL
Ken Lux	DOE
Radenka Maric	MicroCoating Tech
Jon Ward	SAIC

*Moderator

RECORDER: Rose Dakin, Energetics

The group discussed whether sulfur deposits on the anode tended to increase as temperatures were lowered. The consensus was that unless they reached the low melting point, lower temperatures did not exacerbate the problem. Formation of deposits is dependent on more than temperature. For example, hydrogen activity in the anode chamber and very high fuel concentrations both affects sulfur tolerance and could cause oxidized sulfur formation.

Reducing sulfur from diesel fuels and other fuels used in cell operating technology would help solve the problem, but would also limit the lifetime of the rejuvenation process. This ties in with temperature dependency, which is one of the previously identified problems for the core technology area. If sulfur removal occurs at lower temperatures than fuel cell operation, temperature fluctuations may be an issue. One way to address the problem is to first desulfurize, then reform. However, because of new fuel regulations, sulfur may not be a widespread long-term problem. States are requiring a low sulfur content for electrical power management (EPM) diesel fuel and gasoline, and both fuels can be used in cells. Still, stack developers called for internal reformation.

Nickel-based anode cells can be run on methane fuel. One participant stated that any kind of higher hydrocarbon fuel is almost impossible to use with anode-supported cells, and he called for moving away from hydrocarbon fuels. This led the discussion into cathode cells, and the observation that one cathode limitation is that new cell materials must be developed for lower temperatures.

The group agreed that emerging ceramic technology allows for an increase in the operating term, which leads to better performance. Solid oxide fuel cells have been designed so that 80-85 percent of the mass of the cell is due to the interconnect. Currently, stable metal interconnects cost about $9.00 per kilo or $4.00 per pound. Ceramic technology has changed such that a finished ceramic piece with the same properties as the metal interconnects is available for less than $4.00 per pound.

Other technologies are also emerging. Cathode supported cells were considered viable options, but rather than limiting the discussion to just electrolyte, anode, or cathode supported cells, the group contemplated a tri-layered self-supported cell. This cell would fire at lower temperature, with the morphology and size required of particles coming inward. At low temperature firing, it would be possible to coal fire all the tri-layers at the same time. It was noted that the bi-layer's crystal phase is anywhere from 600^{o}C, with very fine particulates (1-2 nanometers), up to high temperatures of up to 1400-1500^{o}C.

The group discussed metal dusting at this temperature range. Metal dusting is metal wasting phenomena in which a catastrophic form of carbonization forms dust on the surface of the interconnect and thins out the metal. Dusting erodes the surface and penetrates inward. It was noted that pure nickel dusts readily in the cell atmosphere. Coating the interconnect could prevent dusting, but without changing the chemical structure of the nickel, dusting would be inevitable and would continue to be a significant problem in a hydrogen atmosphere.

One participant felt that at low temperatures, the resulting low reactivity in the electrochemical areas would lead to very heavy catalyst loading, which defeats the role of sulfur oxide fuel cells (SOFC). In order to maintain electrochemical activity, the temperature would have to be 550-700^{o}C. Sigma solvents create another temperature dependent situation when using metal interconnects. A high chromium alloy (22-23 percent) in the interconnect creates significant sigma phase embrittlement, and would necessitate operating above the sigma solvent temperature to keep the metal from becoming glass. Running 1000 hours at below sigma solvent temperatures creates glass and destroys the metal interconnect. To allow for a higher chromium content, operation must be above 600-700 ^{o}C degrees. Alternatively, a ceramic interconnect can be used.

The call for high temperature was not unanimous. A representative from academia set the target goal at 400°C, which corresponds to hydrocarbon pyrolysis temperature. Below 400°C, higher hydrocarbons could be used and a wealth of catalyst technology could be applicable. Other factors motivating low-temperature technology included applications outside the SECA program, SOFC current temperatures, small transportation devices, and portable power supplies. It was also noted that many of the final applications would require a standby mode at a lower temperature to allow for quick start-up, and that perhaps a thin series of electrolyte conductors (3-5 microns) could accommodate these lower temperatures.

The need for fundamental data concerning barriers to the development of materials, cathodes, anodes, and stack applications was stressed. There was a desire to define what is known and unknown about predictability of phase equilibria, delivery, material processes, atmosphere, etc. Some information is known about materials processes; for example, the thermomechanics of an anode is hydrogen microstructure and nickel processing. Although the basics of nickel and alumina thermal properties are known, surprises in anode development are still occurring and development could be enhanced with exploration into these fundamental areas.

Seal materials (glass seals, compressive seals, load frames) were also discussed in detail. Creep (pressure on compressive seals) is a problem on larger units. High temperature chemistry allows for the use of design technologies already in place. In a controlled atmosphere, at reasonable temperatures, current materials work well. One requirement noted is that hermetic seals can not have detrimental chemical interactions over long periods of time. If a cell is run at 800°C, C-seals (or C-rings) can be used even if the temperature fluctuates. Two problems were noted: the 750 is electrically conductive, so a thin insulating film needs to be used where the C-seal fits, and the C-seal can not be used on all designs. A glass seal that transitions to ceramic, creating a rigid seal, must be used with rigid structures. Compression and glass seals are both operational-specific, with design-specific chemistry composition. With a cathode-supported cell, choice of materials is restricted, but many designs, especially for the anode-supported cell, have separate operation. Applications also depend on use. Likewise, design and material selection is dependent upon how often and in what environment the cells are used.

Because SECA can not progress unless vertical teams produce and market low-cost technology, such as seals and other design specific technologies, the breakout group called for these to be left as topics for the vertical teams. However, group members noted that without defining design performance, design could not proceed.

While no firm resolutions were reached, it was decided that in phase one of the core technology program, the types of work should be narrowed to answer development problems. Without an operating cell, there will be no system. During phase two, the program should move into manufacturing and product development. For the initial materials of the SOFC, a generational change would occur during the second phase; however, some initial technologies and materials would stay through the transition phase.

STACK MATERIALS & PROCESSES – BREAKOUT GROUP B

Breakout Group B met to discuss cell and stack materials and manufacturing. Their goal was to gather input that would then be added to comments from a previous meeting, and would ultimately help direct SECA's resources and guide the development team's production. Their results were tempered, however, by the difficulty of structuring the core program without developers in place, and without knowing what those developer's needs would be.

The group concurred that the best they could do was to identify generic, short-term issues and note the difficult long-term issues.

The moderator began by having the group members look over a list of priorities set for the core technology group; this list had been generated at a previous meeting. The priorities focused on anode and electrode problems, electrolyte improvements, materials processes, and low-cost, high-volume manufacturing. At the top of the list, and previously voted as most pressing, were the issues of interconnect seals, cathodes, and thermal-mechanical modeling tools.

After reviewing the list, the participants agreed that the following were notable omissions:

- redox tolerant anodes
- oxidation resistance
- sulfur toxicity
- peat and clay chemistry
- materials
- interconnects
  - temperature-electrolyte
  - metal versus ceramic
  - thin film versus thick
- interconnect-seal interdependency
- robustness

Participants
Stack Materials & Processes – Breakout Group B

NAME	ORGANIZATION
Ed Beyma	Parsons Corp.
Joep Huijsmans	ECN/InDEC
Elihu Jerabek	GE Distributed Power
Thomas Johansson	IF"Q" Ceramics AB
Kevin Krist	Gas Technology Institute
John Loughhead	Alstom
Elise Marucchi-Soos	Exxon-Mobil
Brian B. Mathewson	CAM-LEM, Inc.
Kirby Meacham	New Gen Fuel Cells, LLC
Gregg Millman	Uniqema
Nguyen Minh	Honeywell
Subhasish Mukerjee	Delphi Automotive Systems
Hiroshi Nomura	Nihon University (now IIT)
Raymond Roberge	H Power
Bill Schweizer	McDermott
Marvin Singer	U.S. DOE FE
William Cary Smith	U.S. DOE-NETL
Richard Spaeh	DaimlerChrysler
Jeff Stevenson*	PNNL
Anil Virkar	Materials & System Research, Inc. University of Utah
Eric Wachsman	University of Florida
Conghua Wang	Sarnoff Corp.

*Moderator

RECORDER: Lori Hollidge, Energetics

Although stable interconnects appeared at the top of the previously generated list, it was noted that no material was proposed. Most previous interconnect discussions emphasized metals and the challenge of finding protecting metals at the required temperatures. Metallic interconnects have the advantage of reduced cost, and are probably more compliant than ceramic; however, methods for achieving lower temperatures, thinner films, and lower costs should be investigated. The group identified this as an important issue for both the core technology program and the industry vertical teams.

Participants felt that the core technology program should value production, and that power manufacturing must be taken into account when considering the listed items. The moderator noted that DOE has determined not to fund any work without an identifiable and cost-effective product path. There was concern that identifying product-specifics during the fabrication technique stage would be difficult; thus, generics were needed. It is not possible to decide a particular path (for example, a cathode supporter versus anode supporter, or when point interconnects are added) at an early stage. It is in the later stages—when the vertical teams solicit opinions on shorter-term goals—that specific product paths become clearer. Because of this, communication between the technical science aspects and commercialization is important. There needs to be a link between fundamental development work and the manufacturer to ensure that the development can be translated into a high volume process.

If the core program addresses only the specific needs of a few developers, there may not be the opportunity to continue long-term contributions to basic development programs. Even so, an academic researcher called for development of new materials for cell electrolytes and electrodes, believing that the way to allow for lower temperatures is to develop new and better materials. The group concurred; the core technology program should focus on both short-term and long-term goals, and should develop a funding ratio that supports the core team. One possibility is to split the core team's total funding, allocating about half to long-term work and half to short term goals. This, along with quarterly core technology review meetings, would help create a link between fundamental development work and manufacturers, and would allow for translation of development into high-volume processes. It would also allow those involved to view their projects in the context of a system, and would allow the developers to tailor components to actual usage in the stack.

One generic way for the core technology group to look at material, chemical, and mechanical properties would be for them to consider thermomechanical modeling. It would allow them to build a database and start applying the data towards models, which would then allow developers to forecast their systems under a variety of circumstances. Another valuable forecasting tool would be to use "real world" worse case scenarios, generated from industry. The members of the breakout group felt that it was important to communicate to the core program that these examples were extremely relevant, and that the ability to foresee possible problems is imperative to creating final products.

The group hoped that a continuing dialogue would occur between the materials developers and the designers. They suggested a mechanism be in place that would keep the dialog between the horizontal and vertical teams open, because new needs will be discovered from the solutions these teams forge.

Robustness, from stack to system, was also identified as an area of focus. A group member defined this as "one button operations." The belief was that if a stack works with single on/off button, robustness would trickle down into decisions made from development and materials to manufacturing. The specifications need to be identified early in the design stage—that robustness must cover the stack, which plays a role in an entire system.

Although the group wanted to delay design-specific decisions, they were interested in setting specific priorities because each area interacts in some way with the others. For example, the choice of interconnect material influences the selection of sealing material; because seals are such a critical part of the specific design concept, it is necessary to deal with interconnects-seal interdependency. Thus, developing better materials at the core technology level is more important than defining specific goals. These broad goals imply manufacturing capabilities, materials, microstructures, and more.

POWER ELECTRONICS – BREAKOUT GROUP C

Breakout Group C held an open discussion to identify power electronic issues that should be addressed by industry. The group reviewed and expanded on related lists, compiled at previous meetings.

Prior to this meeting, a workshop was held in Knoxville that focused on the holistic view of power electronic. Another workshop in Atlanta focused on SECA.

At that Atlanta workshop, four topical areas were evaluated: cell/stack materials and manufacturing systems, performance modeling, fuel processing, and power electronics. For each area, five priorities (20 in all) were selected. In the power electronics area, these priorities were, in the order of importance:

- fuel cell and power electronics interface
- packaging
- sensors, diagnostics, and prognostics
- modeling of electrical interface
- materials and fabrication processes

Participants
Power Electronics – Breakout Group C

NAME	ORGANIZATION
Don Adams	ORNL
Doug Alderton	Solectria Corporation
Douglas Gyorke	USDOE/NETL
Joe Iannucci	Distributed Utility Associates
Roy Kampmeyer	Power Electronic Systems, Inc.
Tim McDonald	Pinnacle West Capital/APS
Gary McVay	PNNL
Eric Potter	Global Thermoelectric
Steve Satzberg	ONR
Prabhakar Singh*	PNNL
John Weber	Delphi

*Moderator

RECORDER: Kevin Moore, Energetics

A second ballot was then used to rank these priorities, along with priorities from the other four areas. Although none of the power electronics priorities ranked in the top five of the final list, the top three list items influenced new power electronics priorities. These were:

- fuel cell and power electronics interface
- materials and fabrication processes
- modeling of electrical interface

Participants agreed that these were priorities, but believed the areas could be refined and items could be added. They concluded:

- that models should include entire systems, rather than specific components.
- that common specifications should be designed.
- that plug-and-play interfaces should be considered.
- that manufacturers and developers should discuss common goals early in the design process.

Because SECA is a 5-to-10 year program, and at the end of 10 years performance costs must be $400/kw, the group focused on short-term goals and tried to define needs in terms that would be useful to industry teams. During their discussion, they kept in mind the three program phases: phase I, lasting four years, and resulting in a prototype that is demonstrable by industry teams and meets specific requirements; phases II and III, ending at the seven and ten year marks respectively, each phase carrying additional requirements. The electronics processes must meet each set of requirements at each phase, while also meeting the final goal.

Much of the discussion focused on the need for commonality to achieve SECA's goals: common uses, common specifications for applications, and common objectives. Identifying these parallelisms (similarities between automotive and stationary applications, for example) would capitalize on the mass-customization strength of the SECA program. Although the core modules for different applications have different requirements, and generating one set of power electronics for these modules is not possible, the basic architecture around a stack or reformer would be, largely, the same. The differences would depend on fuel requirements, but the problem could be solved with the ability to reconfigure a system depending on fuel cell source. However, interconnection standards are being developed for stationary interconnected applications, and the safety issues of differences in voltage are important to look at before common ground can be found.

Interface modeling was also tied to the need for commonality. Most group members believed that modeling should not be just for fuel cell output or DC regulator controls, but that entire systems should be modeled. Industry often calls for a certain voltage, which leads to developers trying to solve individual fuel cell problems, rather then look at the larger picture. Modeling could provide a tool from the power-electronics side that demonstrates the speed from input into the modules, fuels, and other aspects of the modules. When interfaces and fuel cell output are not well defined, an alternative to modeling entire systems would be to model and design several pathways.

The caveat in designing for commonality is that the system may not be flexible enough to power all the different applications. To some participants, there seemed to be a tradeoff between building for flexibility and building for a modular core. Another shortcoming is that there can be many different views of what is common between applications; because of this, some thought that finding a "best mix" would be the better solution. One way to solve the dilemma may be to look at all applications simultaneously, find the common ground, and then design with both that common ground and "real world" problems in mind.

The module and link should have common aspects defined, and a modeling scheme may allow for the best configuration for common DC output. Hybrid systems for distributed generation also call for common DC bus units, with a single inverter or final voltage power conversion device for the application and system. The common DC bus is a good system, if it works together and if it is based on a model.

The commonality issue was also brought up in relation to grid-interface specifications. It was noted that these specifications were left off the list, and that the omission could create a roadblock to getting products to market. The process of design-to-market is a chain that begins with the common specifications and technical initiative. This would allow for high volume manufacturing and would reduce costs in production. Although some requirements may differ (shock, vibration, and packaging, for example), if industry defined common components then these components could be integrated into production. The group felt SECA could act as the go-between: someone from the system perspective could relate important specifics to the power electronics people. Working together, and having each side understand the other, would reduce costs. Designing with specific temperature and voltage requirements would help industry to decide if the costs were worth the design effort. In this area, industry teams must be responsible for working with the customer community and understanding what that community needs.

Modeling could help with those decisions. Using a model, all parameters and constraints can be considered. For example, although running a cell or stack at 120°C might reduce costs, there is a system development cost implication. The subsystem may be efficient and cheaper, but the system overall is relatively expensive. Modeling would provide an advanced glimpse of problems like this, and would highlight the common modules. Participants called for the ability to stimulate the power electronics package model with input, simulating power electronic responses under different conditions and ultimately being able to have individual models connected to simulate systems. They believed looking at the problems holistically creates not only better-prepared designers, but also smarter consumers.

There was also a call for "plug and play" type power electronics. A participant defined this as having two aspects:

> *"There is the control of the system—from the fuel cell to other sources. Then there is the application, where it matches up to the load. You can have your power electronics control subsystems in the fuel cell, and then take that power and supply it the grid. The cell and reformer need to know how much you need to be doing at the time, based on the load."*

Despite the call for commonality on so many different fronts, the group did agree that reaching common footing on inverters would be difficult. SECA is trying to be the output for the delivery system, collaborating if they do not have the ability to do the work in-house. The result is that SECA has had to deal with meeting performance requirements for the system. Fuel cell manufacturers, thus far, have not used power electronics, but have in-house capabilities for technology transfer. SECA is looking to the core team for experts, and will then develop an integrated transfer approach. Some believed that even within that team, the problems would be hard to address without all the partners working together.

The level of integration depends upon where the fuel cell developers are in the development stage. The stack is sometimes worked on internally, and the power electronics piece doesn't fall into place until the end of the project. This can create rush jobs. On the other hand, these rush jobs are sometimes unavoidable. Given the timeframe for development of breakthrough technology, system level decisions tools must become available so tradeoff choices can be made. One of SECA's goals is to encourage people to consider the project before the end stages, and depend on core technology as backup.

Balance of Plant & Thermal Integration – Breakout Group D

Breakout Group D met to discuss balance of plant and thermal integration issues, specifically issues that were overlooked at the previous workshop in Atlanta.
The participants were told that the discussion should be within, but not restricted by, the framework of a 5 kW solid oxide fuel cell stack as targeted by SECA. However, they were encouraged to discuss any issues they felt were relevant.

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Balance of Plant & Thermal Integration – Breakout Group D

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*Moderator

Recorder: Christina TerMaath, Energetics

This group concluded that the most important balance of plant issue is system modeling. Other core program technology gaps include:

- gas compressor (5kW)
- low cost heat exchangers
- manifolding materials (gas transport)
- motors
- systems integration
- safety systems (unscheduled shutdowns)
- codes and standards
- definitions of technology issues
- gas recycling (anode recycling)
- high temperature blowers/seals
- heat recovery
- program integration
- hybrid systems
- ganging 5 kW units

The group initially approached balance of plant issues by application, splitting their topics into automotive, stationary, mobile, and marine applications. They did this because stack modules vary depending on application. From the beginning of the session, however, modeling was thought to be imperative, because it can highlight how everything is affected by systems and stacks operation.

There was some disagreement as to how the group should approach the topics. Although the workshop focused on a 5 kW unit, some felt that it was necessary to look at balance of plant in a holistic view, beginning with modeling. This would allow for discussion of the common ground in systems (controls and reformers, for example). Others felt a matrix approach was better—that talking about goals is difficult without looking at specific intended uses. These members believed strongly that the balance-of-plant components are dependent on use. The compromise was to recognize that some applications are steady state and some have a transient component. The group believed that balancing a plant might ultimately be easier when planning for the goal of a module that can be used for multiple applications.

Having agreed upon this, the members continued to refine their issues, looking for common ground within each of the applications. The common issues, as defined by this group, include:

- controls
- fuel processing
- combustion
- inverter
- system modeling
- systems integration
- packaging
- thermal air/gas management
- process integration
- start-up/shut-down
- cyclic operation
- transition

Using these common-ground items as a jumping point, the discussion shifted focus to the matrix created by these items and the other core technology program topical areas. For example, they recognized that the "controls" area would include diagnostics, and that "inverters" would fall into the power electronics area (which was being discussed in another breakout group). One member estimated that at least six of the topical areas contain issues related to balance of plant. For clarity, they identified many, although not all, of these areas.

From the <u>Fuel Processing Technologies</u> topical area:

- sulfur removal from natural gas propane
- liquid fuel sulfur removal
- water recovery and self-sufficiency
- steam management and inventory reduction
- efficient regenerable sulfur adsorbent
- liquid fuel preheating and component introduction/mixing to minimize carbon deposition
- methodology for pre-reforming,
- high-temperature hydrogen sulfide adsorption

From the <u>Stack/System Performance and Modeling</u> topical area:

- low-cost heat exchanger material and insulation
- start-up methods in materials to accomplish fast start-up
- sensing and control technology and improved performance/cost
- advanced modeling for control development and information processing
- high efficiency blowers
- high performance low-cost insulation
- fuel cell power/inverter interface

From the <u>Cell Stack Material</u> topical area:

- thermal mechanical modeling.

Despite the overlap in these areas, the group felt that many of these items should relate to the overall system. Participants were concerned that some items may be overlooked because they did not fall precisely within the realm of a specific group. The participants felt these items should be included, because system modeling is important in both the core area and industry. Many saw modeling in the core group as important to industry, and that industrial modeling is a gateway for the integration of models into working systems.

This discussion led to the problem of proprietary property, an issue that became more apparent as the group discussed modeling. Specifically, some members saw the automotive industry working on applications from a systems perspective, drawing on fuel processing technology. Manufacturers would most likely want to keep their resulting system modeling and integration proprietary. This would be one argument for doing system modeling within the core technology program. This modeling would allow for identification for various applications, and offer an opportunity to comment and input in an open environment without necessarily revealing proprietary signs and applications.

Some members felt work needs to be done within the core technology program to develop requirements for components based on system modeling specific applications. Modeling would have the benefit of directing the component work. Systems modeling efforts would not only include the fuel cell, but also hybrid versions of such so that fuel-processing requirements would be identified, and stack design would be influenced. There is currently lack of attention to the system modeling and work needs to be done in systems modeling to make sure that the ranges of parameters in the R&D component are valid.

Countering that, others felt that balance of plant for specific applications should be left to the industrial communities. This would relieve the core technology program of the burden, and reduce costs by at least half as compared to the stack. The core technology group is based on the principle that creation of mass-produced advanced market items would bring costs down, and then specific requests could be made by users while working within those mass-produced boundaries. However, users often want input into the finished product. System modeling may solve this problem, creating a bridge between users, developers, and producers. Commonality can be found, although the real balance of plant will still look very different depending on the application.

Group members called for research to find common ground and to identify components that do not currently exist. Systems modeling and systems integration should be top priorities for the core technology group, and the DOE should be looking at their overall programs and putting integration mechanisms into place. Participants felt specific applications (automotive, marine, stationary, etc) should be selected for modeling, with allowances for the manipulation of different variables. The group concluded, agreeing that systems modeling is an effective way to communicate with potential users without requiring proprietary information from those users.

FUEL PROCESSING TECHNOLOGIES – BREAKOUT GROUP E

Breakout Group E met to define important issues relating to fuel processing, and to identify technologies that may have been overlooked by the core technology group.

The moderator began the discussion by noting redundant items on the list of topical. These included similarities between quantification of catalyst activity, composition, and cost and kinetic catalyst parameters over a wide operating range. There was also some overlap in the sulfur areas.

The breakout group felt that instead of prioritizing items, it would be better to broaden the scope of the core technology program. However, they did agree that the following issues, although not inclusive, were important for the core technology group to consider:

- Thermal cycling
- Removal of sulfur from liquid phase
- Sulfur management systems for fuel processing
- Heat integration
- Modeling techniques
- Fabrication costs and materials
- High temperature sulfur absorbents
- Regenerative absorbent systems
- Stack anode absorbent systems
- Vaporization of liquid fuels
- Sulfur tolerant anodes

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Fuel Processing Technologies–
Breakout Group E

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*Moderator

RECORDER: Ndeye K. Fall, Energetics

The group began by identifying SECA's target efficiency goals, and by agreeing that SECA is not limiting reformer technology in the core program. Although a specific efficiency must be reached, core technologies need to be generic in order to be integrated into a system. While the group agreed that these generic technologies must be developed, they were not able to delineate which areas should be core technology and which areas should be system development. They agreed that the core technology program should focus on basic materials science and the development of broad applications materials, but they acknowledged that those categories might be different even among their peers (e.g. military, academia, government laboratories, systems developers).

There was a feeling that core technology development teams are focusing on a single aspect of a system rather than the system as a whole. The processor-related issues should be more holistic, because focusing on a single issue (sulfur tolerance, for example) may be feasible when looking at basic processing, but not when the cell gets to the stack. The focus, then, should be on integrating the fuel cell system and various configurations, because if smart integration is not considered from the beginning, other goals may not be achieved. The call was for SECA to establish a horizontal reintegration rather than integration just at the final industrial-team level.

Specific processor issues were discussed. In particular, there was a discussion about high temperature processing specifically relating to the operating temperature of zinc oxide, and about sulfur as it related to processing. Auto-thermal reforming catalysts are somewhat sulfur tolerant, and can be used when sulfur is in the fuel. This is useful in basic processing, but sulfur becomes an issue when it gets to the stack. A participant believed the problem was an issue for military applications, but that it was a maintenance issue rather than an operating issue for fuel cell stack. Steam reforming and liquid sulfur removal were also considered, and the group discussed basic strategies for approaching fuel processing. One group member believed that the core technology program did not have the specific task of supporting the development of a fuel processor. Yet another believed that the removal of sulfur from the liquid phase *is* a function of the core program.

Group members saw sulfur tolerance as an issue, and one that reappears whenever similar discussions take place. The consensus was that sulfur tolerance is an important area for the core technology program, and that the program should consider a broad range of fuels. Although the group agreed on this point, they did not agree that sulfur tolerance is a long-range issue. Those who argued it is not long-term issue noted that the catalytic technology in internal combustion engines would not work with high levels of sulfur. Because of this, a major drop in sulfur content will occur, even without the core technology program specifically addressing the issue. Others pointed out that even if sulfur levels are reduced to levels as low as 15 parts per million (ppm), it would still be too high for stack reforming. The counter-argument was that if a metal catalyst is used in the reformer, 15 ppm is not too high.

Sulfur also came up in the fuel pre-reforming discussion. For example, in the pre-reformer, C1s that may be processed on the stack are produced. This led to the group questioning whether sulfur materials can be pre-reformed although processing is a low temperature process.

Part of the problem, as the group saw it, is that SECA is looking holistically at the stack. As the temperature of the stack decreases to the 900-950 degree range, sulfur becomes more of an issue. Nickel catalysts work well at this range, however. Yet the move is to reduce the operating temperature of the stack even more, thus, the impact of fuel processing on the stack itself must be considered.

Temperature was also brought up in relation to materials. The core technology program should look at construction for high temperature environments in the stack (as material electrodes or end plates, and as fuel processing components). The core program should also consider fabrication costs and materials used in reformers. As an example, one participant said his first reformer was built with 512 inches of welding, using extensive steel and operating at high temperatures. He called for low-temperature alternatives to the materials used in reformers. Others agreed, and said the core program needs to consider materials at the modeling and design stages.

The core technology program should also consider techniques that are applicable to low-production volume characteristics. Ultimately, manufacturers will be faced with the vertical team's limits in regards to fuel cell systems. If cost and production are considered together, technology will be able to be brought to the marketplace within financial limits.

The group did not come to any firm conclusions, and felt that setting solid priorities would be too restrictive. Participants wanted to broaden the scope rather than listing a few specific items for the core technology program. In part, this was because funding had not been specifically designated, and also because it was difficult to define cross-cutting issues when priorities were dependent upon who was making the list (industry as opposed to developers, for example).

STACK & SYSTEM PERFORMANCE MODELING – BREAKOUT GROUP F

Breakout Group F met to discuss stack and system performance modeling. The group analyzed their topic and voted on modeling priorities to submit to the core program. They also voted on specific modeling priorities for cell technology and for stack technology. The voting results are shown below.

Top priorities:

- stack performance models and experimental validation
- system dynamics of steady state submodels and experimental validation
- cell models
- other component models (reformer)
- cost and life cycle models
- controls

Cell Priorities:

- internal reformation
- optimization of materials
- detailed microstructure based on electrochemistry/material code

Stack Priorities:

- electrochemistry and engineering codes
  - steady state
  - thermal cycling
  - life
  - coupling of electrochemistry
- thermomechanical data
  - PEM
  - metal
  - seals
- validation
- failure mechanism
- failure criteria

Participants
Stack & System Performance Modeling – Breakout Group F

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*Moderator

RECORDER: Lauren Giles, Energetics

The discussion opened with the acknowledgment that there are many unknowns about various subsystems. Subsystem leaders are often not sure of their priorities, so those in charge of controls must sometimes make a 'best guess' and experiment to find the right subsystem. Modeling tools that will allow for quick decisions about interconnect designs, concepts, and seals must be created. By looking at an entire system, one could determine where modeling could make major impacts.

It is important to be able to look at the entire stack and identify the challenges for the system as a whole. It is important to determine how the stack interacts with other components, system designs, and system controls, and then to be able to model the dynamic part of the system. According to one participant, the important question in modeling may be: "*what are the tools and do they exist in a way that can be used from an engineering design perspective?"*

Another group member felt the best way to look at modeling would be to determine what one is trying to accomplish with the models, rather than to begin with a specific thermal or mechanical goal. However, cost must be an important parameter; models that will very quickly allow for the determination of stresses and thermal cycling will also allow for the calculation of the cost of various systems. The models still end up being electrical in nature, while measuring physical processes. Participants felt that modeling should not be about tradeoffs between the different components; instead, it should focus on the establishment of component requirements.

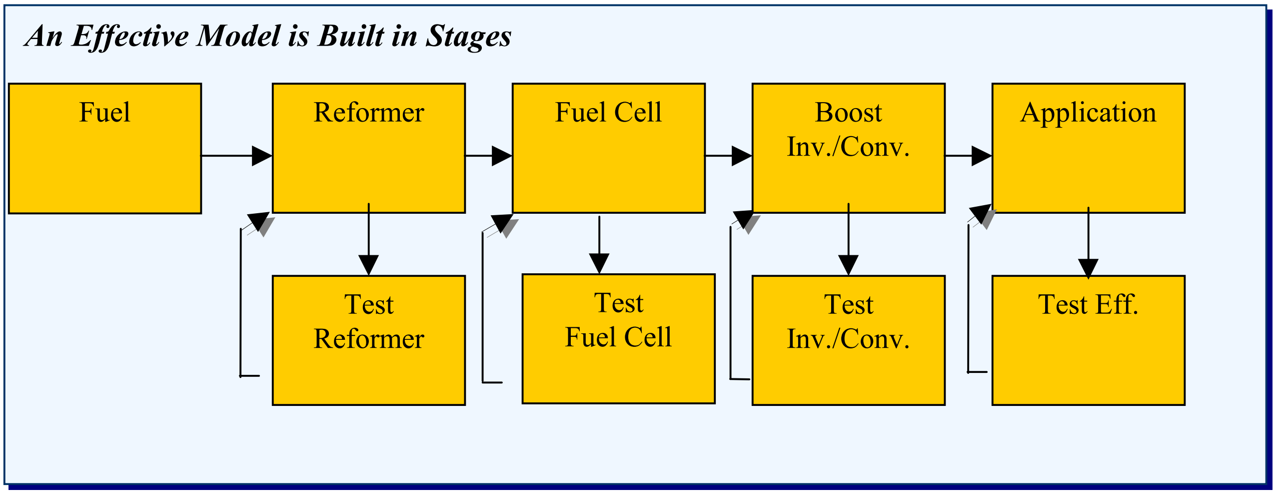
The discussion then moved to the goals and objectives of different system and component models. SOFCs should be looked at early on because these fuel cells are high-temperature and can be used in many applications. The models should get to a point in the structure that will permit fast start-up and allow for considering thermal stress within the stack itself. Another participant pointed out that what was being called for was two layers of modeling: stress modeling and cost analysis.

This breakout group recognized that determining high-level requirements would be difficult, because every member had different requirements based on their industry. Yet, having a common system-efficiency goal would allow for calculation and determination of thermal losses, size of fuel pump and injectors, or the size of various heat exchangers. Basing models on some high level parameters would allow one to determine the inputs and outputs of the subsystem. After those inputs and outputs are determined, the focus should shift to engineering models that will mold cost studies and help to refine the system. The next group of models, fuel-reforming models for example, should analyze the interaction. The difficult part, again, is defining the initial high-level requirements.

There is precedence in the process industry for process models. Too much of the Aspen model is "black box." Fundamentally, the Aspen model is a good starting point, because it is a set of integrated models and is used to design a system rather than a fuel cell or specific components. Aspen can be used to set a research and development plan, but a second set of models are then needed to achieve more detail. This requires addressing both the fuel cell type and the application. Today's system models, particularly the stack mode, have to be based on physics and chemistry. Thus, SECA may have a role in initiating the dialog between those developing requirements and those people developing the stack.

A difficulty is that there may be only four or five initial high-level requirements: power density, weight, volume, and fuel type, for example. Yet, when the next environment is modeled, many more inputs specific to the system may be required (the salt content of the air or fuel quality, for example). Thus, what might be a viable solution for a particular application may not be appropriate for similar systems and may not be cost effective.

To illustrate effective modeling, the following chart was sketched.



An effective model must be built in stages, beginning with fuel and the reformer. In order to optimize the reformer for use with specific sulfur types or to minimize the sulfur to a specific point, each stage must be followed. After the reformer stage, it is important to then optimize what is coming out of the fuel cell—using whatever method necessary. Haynes stated that this example is good modeling from both a system standpoint and an individual model standpoint. This view of modeling develops learning curve, and, because it predicts in stages, predicts how individual components will contribute to overall system efficiency.

Another participant believed the diagram represents an evolving paradigm. A developing Vision 21 project involves using Fluent to build a flow sheet model with Aspen and to provide more detail. It is this type of modeling arrangement some would like to see for fuel cell development. It would allow one to look at the reformer in the fuel cell in an integrated sense, but would also allow analysis of specific details as they pertain to transience and load.

At this point, the group began to define the tools needed and their objectives. They believed that knowledge comes from the connection between chemical engineering and physical chemistry. It is important to use modeling for engineering algorithms, and to have a dynamic university-based program in which the fundamentals of the stack are studied. For example, heat transfer specifics are not well known in small units, and thus it is necessary to model and build a program of models for small units.

Current models are fundamentally based on assumptions; some developers believe those assumptions are generally incorrect. Yet, most vertical teams are reluctant to communicate what is incorrect about the models. To have a reasonable modeling program, there must be an experimental validation program and a program that generates input data. One alternative may be to insulate the vertical team from the core team. The group believed that the core team is effective, and that it should be integrated in such a way that the vertical team can take advantage of the tools created rather than having the core team develop model-specific designs.

Participants also felt that the core program should provide tools, knowledge, and data that can be used regardless of design. One specific tool should be commercial codes. In order to make progress within

SECA's timeframe, the codes should allow for additions and modifications. Specifically, electrochemistry codes related to the flow of thermal properties could be added to the engineering codes and manipulated at the stack level. These need to be appropriate while not too fundamental, and would require an agreement with industry teams.

Validation modeling input is also important, and the technology program should build in credible and detailed benchmarks. A comprehensive initiative from industry is needed to provide input and benchmark geometry.

One participant spoke of current work that looks at fundamental electrochemical behavior, heat transfer, and mass transport in a system. Using that data, behavior of the components can be predicted based on codes, and predictions of battery voltage out of the cell can be expanded to the stack. The chemistry and fundamental kinetic source of each battery type (lead-acid and lithium ion) is known, so all that is required is changing the geometry. This work should be applicable to a fuel cell system.

At the stack level, electrical, dynamic and thermal systems should all be looked at separately, so that objectives and subsystem requirements can be established. At the cell level, existing codes and new codes could be built. Internal reformation is an area that should be studied to provide optimization of materials, and microstructures should be another. These studies require a detailed microstructure data of electrochemistry and materials. If such a code exists, it would help with the optimization and design of materials.

Fundamental chemistry should also be considered. This chemistry may help explain microstructural issues as well as direct the optimization of other properties. For example, often the microstructure of the materials determines what the ion activity is, so experimental results could be affected. Without this knowledge, it could be difficult to optimize the development of these materials. This issue, again, is related to validation, and there was a call for software vendors to support the vertical teams in providing that validation.

APPENDIX B
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