Solid State Energy Conversion Alliance

SECA

Workshop Proceedings

June 1-2, 2000 • Baltimore, Maryland

NETL

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

U.S. Department of Energy
National Energy Technology Laboratory

August 2000

Dear SECA Workshop Participant:

The National Energy Technology Laboratory (NETL) and the Pacific Northwest National Laboratory (PNNL) are pleased to provide the proceedings of the Solid State Energy Conversion Alliance (SECA) Workshop held on June 1-2, 2000 in Baltimore. The package includes the presentations made during the workshop, a transcript of the Question and Answer session, additional discussion concerning intellectual property, and the breakout session results that were developed for materials and manufacturing, fuel processing, modeling and simulation, power electronics, and thermal systems. We have attempted to accurately capture all the ideas and comments expressed during the workshop. A list of participants is also included. If you note any omissions or wish to provide additional information, we welcome your comments.

We are analyzing these results and developing the industrial team solicitation. Our current plan is to hold the solicitation open for three years with an opportunity to propose once each year. This will allow both a longer period for formation of teams and the addition of teams corresponding to the available budget and the addition of more government co-sponsors. We hope that all stakeholder groups will use the enclosed information in their planning endeavors as well. In order to permit careful review of the Workshop results and to consider other input, the date for issuing the solicitation for public comment is now mid-to-late August. Further details and updates will be available at the NETL website: www.netl.doe.gov.

We sincerely appreciate your active participation in the workshop and the breakout work sessions. Over 170 participants from more than 100 organizations representing various stakeholders groups provided a wealth of information and opinions. This collaboration among stakeholders groups will undoubtedly accelerate the planning for and the ultimate realization of SECA.

The tentative date for the next SECA workshop is April 2nd and 3rd 2001 in the Washington DC area. We look forward to your future participation in SECA.

Sincerely,

Wayne A. Surdoval
SECA Project Manager

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Solid State Energy Conversion Alliance (SECA)

WORKSHOP PROCEEDINGS

June 1-2, 2000
The Holiday Inn Inner Harbor
Baltimore, Maryland

National Energy Technology Laboratory

Pacific Northwest National Laboratory

Executive Summary

The National Energy Technology Laboratory (NETL) and the Pacific Northwest National Laboratory (PNNL) hosted the Solid State Energy Conversion Alliance (SECA) workshop on June 1-2, 2000 to gather stakeholder input on the opportunities and challenges for achieving the goal of low-cost, broadly marketable fuel cells by 2010. These workshop proceedings include all of the speaker presentations, question and answer (Q&A) documentation, a discussion of the intellectual property issues, and two appendices for the breakout session results and the participant list. The Department of Energy (DOE) will use the breakout group results from the workshop as input to the preparation of technology plans and program solicitations to implement SECA. The proceedings will also be made publicly available.

Background

SECA is envisioned as a collaboration of government agencies, industry, universities, and national laboratories committed to the development of low-cost, high power density, solid-oxide fuel cells for a broad range of applications. Industrial teams, research and development performers, and funding organizations are part of the alliance. SECA has been formed to both accelerate the development of the industrial base needed to commercially produce low-cost solid-oxide fuel cells and to provide a core research program to provide any advancements necessary to achieving the aggressive SECA goals. The two host laboratories, NETL and PNNL, are the driving force behind SECA, providing the leadership, focus, and integration needed to bring solid-oxide fuel cell technology into near-term markets.

A Vision for Fuel Cells in 2010

Low-cost, high-efficiency, solid-state fuel cell systems will be available at less than $400/kW for stationary, transportation, and military applications. This breakthrough will allow widespread penetration into these high-volume markets, ultimately leading to application of advanced fuel cell technology in "Vision 21" central-station power plants. The inherently high efficiencies of these solid-oxide fuel cells will provide significantly reduced CO_2 emissions and negligible emissions of other pollutants.

The basic building block will be a nominally 5 kW solid-oxide fuel cell module that can be mass-produced and used for residential, mobile, or military applications. For applications with larger power needs, the mass-produced core modules will be interconnected much like batteries, thus eliminating the need for custom designed fuel cell stacks to meet a specific power rating. SECA technology will ultimately lead to megawatt size configurations for commercial/light industrial packages and "Vision 21" central-station power applications.

Workshop Breakout Sessions

Seven breakout sessions were held:

- Materials and Manufacturing – Session A
- Materials and Manufacturing – Session B
- Fuel Processing – Session A
- Fuel Processing – Session B
- Modeling and Simulation
- Power Electronics
- Thermal Systems

Through a series of breakout group sessions, over 120 participants collaboratively addressed the following questions:

- What are the scientific and technology issues that exist for achieving the SECA vision by 2010?
- What are the research and development (R&D) opportunities?
- What engineering, development, and research actions are required to address the identified issues and opportunities?

The following definitions were used to characterize the maturity of the different components of the solid-oxide fuel cell technology identified in the breakout sessions:

- Engineering: something that has not been done before but can be solved by existing engineering procedures,
- Development: something that requires development of methodologies or extensive data gathering but a path to solution is clear,
- Research: problem areas for which there is no clear path to success and require new approaches.

Workshop Breakout Sessions Results

For each session, a summary is provided in Appendix A along with the "storyboard" results for issues; R&D opportunities; engineering, development, and research actions needed for implementation; and group "report-outs." Every effort has been made to represent the results of the consensus voting fairly and accurately without any individual influences or biases. Therefore, minimal narrative summary is provided since at some level a more extensive summary would represent an individual interpretation of the results. This results in a relatively "dry" report; however, it is one that we and hopefully others will find useful.

WORKSHOP PROCEEDINGS
SOLID STATE ENERGY CONVERSION ALLIANCE WORKSHOP
JUNE 1-2, 2000

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WORKSHOP PROCEEDINGS
SOLID STATE ENERGY CONVERSION ALLIANCE WORKSHOP
JUNE 1-2, 2000

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APPENDICES

I. PRESENTATIONS

A. FOSSIL ENERGY MISSION AND THE FUEL CELL PROGRAM

George Rudins, Deputy Assistant Secretary for Coal and Power Systems
U.S. DOE, Office of Fossil Energy

1. Introduction

- I'm pleased to be here at the Solid State Energy Conversion Alliance Workshop. I'd like to thank Rita Bajura, Director of the National Energy Technology Laboratory, for inviting me to speak about this exciting new DOE initiative.

- Later speakers will discuss in some detail the structure and applications of the Solid State Energy Conversion Alliance, or SECA. I would like to speak about SECA in a larger context: how it fits into the national energy strategy, and the goals and milestones of the fuel cell program.

2. Comprehensive National Energy Strategy

- The Comprehensive National Energy Strategy, issued in April 1998, set forth five common-sense goals for national energy policy:

  - Improving energy efficiency.
  - Ensuring reliability.
  - Promoting clean energy technologies.
  - Expanding energy choices.
  - Cooperating internationally on energy issues.

- Fuel cells, and SECA, help us meet all five of these important goals:

  - Fuel cells are highly efficient. With thermal recovery, the total efficiency of fuel cell systems could reach 85%.

  - Fuel cells promise to be one of the most reliable power generation technologies, if not the most reliable. They are now being used by hospitals, hotels, and telephone companies as part of critical uninterruptible power systems. SECA will result in distributed generation products that will further increase grid reliability and safety.

  - Fuel cells are clean. They generate no solid wastes, and have dramatically lower emissions of nitrogen compounds, particulates, and greenhouse gases.

  - Fuel cells expand energy choices. They can be used in both distributed and centralized configurations. They provide siting and fuel flexibility. They allow us to use our abundant fossil-fuel resources in an environmentally friendly way.

- Fuel cells address environmental issues of global concern, including emissions of greenhouse gases. They are well suited for developing countries without an existing energy infrastructure, and will help meet a growing worldwide demand for energy. SECA will be an internationally cooperative effort. Through the SECA Core Technology Program, we expect to cooperate with the European Union, and others.

3. Near-Term Distributed Generation Market

- Given fuel cells' strengths, the abundance of fossil-fuel resources, and the need for highly efficient, clean energy technologies, the Department of Energy has funded fuel cell research for over two decades.

- The current fuel cell program is aimed at the near-term distributed generation market. The near-term market includes premium power applications: computer centers, hospitals, and other facilities that must have a reliable supply of high-quality electricity and are willing to pay for it.

- The current FE fuel cell program, now in the last phase of development, has two parts:

  - development of molten carbonate fuel cell systems, by Fuel Cell Energy, and
  - development of tubular solid oxide fuel cell systems, by Siemens Westinghouse.

- The program's goals are:

  - Commercialization of solid oxide fuel cell and molten carbonate fuel cell power plants in the 200-kW to 3-MW range by 2003.

  - Costs of $1,000 to $1,500 per kilowatt.

  - Efficiencies of 50 to 60%.

  - To have at least 50 MW per year of U.S. molten carbonate fuel cell manufacturing capacity, and to have at least 30 MW per year of U.S. solid oxide fuel cell manufacturing capacity by 2003.

- The U.S. and European growth and replacement market for near-term distributed generation is expected to approach 10 GW per year over the next decade. Globally it is expected to be 20 GW per year.

- The near-term developers, Fuel Cell Energy and Siemens Westinghouse, have had impressive test performance, and each plans multiple demonstrations within the next few years. Collectively, they could be capturing 1 to 2 GW per year of the global market by the end of the decade.

4. The Mature Distributed Generation Market

- To penetrate the mature distributed generation market, lower cost fuel cells are required. Distributed generation technologies must have low introductory and installation costs, and they must be reliable.

- SECA, which Ms. Bajura will describe in more detail, is a mechanism to build and integrate the industry base for low-cost fuel cells to penetrate the mature distributed generation market. SECA will build an alliance of government agencies, commercial developers, universities, and national laboratories to develop solid oxide fuel cells with the capability for immediate commercial success. SECA will build on the great progress to date in developing fuel cells and will assure a dramatic reduction in fuel cell cost down to $400/kW for stationary power applications, which in turn should guarantee a very large market share for fuel cells.

  The alliance will provide a focal point, an "organizational center" for the development of

  - stationary power applications,
  - auxiliary power units for military applications, and
  - auxiliary power units for transportation applications.

- All three applications will benefit from the free flow of leveraged fuel cell technology development. SECA's cost goal for stationary applications is $400 per kilowatt by 2010. Long-term cost goals for military and transportation applications are $50 to $200 per kilowatt. Efficiencies for all applications will be greatly improved over current state-of-the art.

- The results of this program will also provide early low-cost power systems for mature distributed generation market applications, and will feed directly into the Vision 21 Fuel Cells Program.

5. Vision 21

- Fossil fuels currently provide 85% of global and U.S. energy supply. Even under a climate change scenario, we will need to use fossil energy well into the future. But we need to use it smarter. The goal of Vision 21 is to wring every possible bit of useful energy out of carbon-based feedstocks to produce energy products, while eliminating all environmental concerns regarding electricity generation, and doing so at comparative costs.

- The Vision 21 fuel cells segment will develop advanced fuel cell modules that would be integrated with other Vision 21 advanced technology modules, and would be tailored to meet specific market needs. Fuels cells are needed to obtain the 60% efficient coal-fueled and the 75% gas fueled Vision 21 power plants of the future.

- To reach these high efficiency targets, a hybridized, high-efficiency fuel cell is required. Getting the cost of the fuel cell power module to $400 per kW is a key factor in deploying Vision 21 systems by 2015. If this can be done, fuel cell/turbine hybrids could replace turbines as the power block in integrated gasification combined-cycle applications.

- These highly efficient combined systems, in multi-megawatt sizes, would have no environmental impact outside their own footprint. The goal is to make these modules ready for use in integrated systems by 2015. This program segment will accept additional technology input from the SECA program segments as solid state fuel cells become available.

- Fuel cells also have an advantage in Vision 21 sequestration applications. Fuel cells have inherently high efficiency and can also be configured to produce concentrated CO2 streams. Under the recent Vision 21 solicitation, Siemens Westinghouse received an award to reconfigure their tubular solid oxide fuel cell to produce a concentrated CO2 stream for use in enhanced oil recovery and other applications.

6. Conclusion

- Part of the Department of Energy's mission is "to foster a secure and reliable energy system that is environmentally and economically sustainable." Fuel cells, and SECA, will help us meet this challenge.
- Fuel cells, with their roots in the space program, have the potential to truly revolutionize power generation. SECA is a natural extension of the existing fuel cell program, a logical next step.
- Thank you for joining us as we take this step into the future.

B. KEYNOTE ADDRESS: THE SOLID STATE ENERGY CONVERSION ALLIANCE (SECA): ITS STRUCTURE, TARGET APPLICATIONS, AND ROLE IN DOE'S STRATEGIC PLAN

Rita A. Bajura, Director
U.S. DOE, National Energy Technology Center

Slide 1
The Solid State Energy Conversion Alliance:
A Paradigm Shift in Technology Development

Good morning. I'm pleased to be here. It is my privilege to present an overview of the Solid State Energy Conversion Alliance, or SECA. I will discuss:

- A vision for the future of fuel cells.
- What the SECA alliance is.
- The concept behind the alliance.
- The proposed structure of the alliance.
- Next steps to initiate the SECA program.

Slide 2
The Vision: Fuel Cells in 2010

Let me start by sharing a vision of the future, a vision of solid-state fuel cell systems in 2010.

- These systems will be low cost: $400 per kilowatt in the multi-kilowatt size range, a remarkable accomplishment in this small size range. The price trajectory will be downward, such that a $50 per kilowatt system for transportation applications is on the horizon.

- Fuel-to-end-use efficiencies will be high: nearly twice as high as today's conventional technologies, again a remarkable accomplishment in the multi-kilowatt size range. These high efficiencies translate to reduced greenhouse gas emissions.

- Given a fuel, there will be a fuel-cell system that can operate on it. Fuel cells will be able to operate on natural gas, gasoline, diesel fuel, landfill gas, hydrogen, and defense logistics fuels.

Early movers in the fuel-cell industry will have commercialized them as auxiliary power units for the nation's cars and trucks, distributed generation units for homes, and field power units for military operations.

Slide 3
The Vision: A Core Module for Multiple Applications

The core of this vision is a 5-kilowatt, low-cost, high power-density, solid-state fuel-cell stack. The core module measures approximately 4 by 4 by 12 inches. It can be mass produced because it can be used in multiple end-use markets. Because it is a standard core module, the cost to customize it for multiple markets is cheap.

This concept of "mass customization of common modules" eliminates the Catch-22 of commercialization:

- High-volume production is needed to reduce costs,
- but low costs are needed to create a large market.

The 5-kilowatt core modules can be combined (like batteries) for applications with larger power needs. This "building block" approach enables low-cost customization. This is the Gateway or Dell computer concept applied to fuel cells. Gateway and Dell keep personal computer costs low and meet the exact needs of their customers by applying using the concept of mass customization.

Ultimately, the SECA concept could lead to megawatt-size fuel-cell systems for commercial and industrial applications and Vision 21 energy plants.

This vision is achievable, but it will take a new approach to technology development.

Slide 4
SECA — Realizing the Vision

That approach is SECA – the Solid State Energy Conversion Alliance.

SECA is an alliance of

- industrial teams, who individually plan to commercialize solid-state fuel-cell systems;
- R&D organizations involved in solid-state activities; and
- government organizations, who provide funding.

SECA is a national program that provides a forum to bring these entities together. All are interested in low-cost, high power-density, solid-state fuel-cell systems for some application. All are committed to the concept of "mass customization" as the route to reducing costs.

The high power-density requirement of the SECA program is a critical driver for transportation applications. This sector presents some of the most challenging requirements for the use of fuel cells. For example, a 5-kilowatt unit for auxiliary power must fit into a volume of 50 liters. (The "unit" includes the stack, reformer, and all other balance-of-plant components.) The 5-kilowatt unit must also weigh less than 50 kilograms, and have a surface temperature less than 45 °C.

High power-density is not as critical for stationary applications. However, by addressing these challenging requirements for the transportation sector, stationary developers may be able to substantially reduce their costs. Over the course of this workshop, I invite your thoughts on these draft requirements for the transportation sector.

The SECA program develops an integrated strategy to address the technical barriers of solid-state fuel-cell systems. SECA also focuses research performers on the breakthrough technologies needed to achieve the program goals.

Two national labs coordinate the SECA program: the National Energy Technology Laboratory (NETL) and the Pacific Northwest National Laboratory (PNNL). They provide the leadership, focus, and integration needed to achieve the goals of the SECA program.

Slide 5
SECA Structure

SECA represents a new model for joint government and private-industry technology development. Through annual workshops such as this, interested stakeholders help develop program goals. This information flows — through the program managers at NETL and PNNL — to the project management at NETL. The project managers coordinate the activities of the Industry Integration Teams and the Core Technology Program.

Each of the vertical bars in the viewgraph represents one Industry Integration Team. Each team is developing a fuel-cell system that they intend to commercialize.

The Core Technology Program (lower left in the viewgraph) consists of a "patchwork quilt" of R&D performers. Their projects address crosscutting technical issues in solid-state fuel-cell systems.

The blue arrows show a "circular" relationship. The Industry Integration Teams communicate their technology development needs to the project managers. The project managers translate these needs into research topics for the Core Technology Program. Participants in the Core Technology Program develop solutions that are transferred back to the Industry Integration Teams.

Slide 6
SECA Industry Integration Teams

Each Industry Integration Team is developing the capability to commercialize a solid-state fuel-cell system. It can be for stationary and/or transportation and/or military applications.
The teams are independent. They compete with each other. However, all are committed to the concept of mass customization as a route to reducing the cost of fuel-cell systems.

These "vertical teams" are competitively selected and will receive funding from interested government organizations, such as DOE's Office of Fossil Energy (FE). Our hope is that DOE's Office of Energy Efficiency and Renewable Energy (EE), and various organizations in the Department of Defense (DOD) will also decide to fund a suite of Industry Integration Teams. We are discussing the possibility of shared funding with EE and DOD, and are delighted that they are participating in this workshop.

FE is currently developing its first solicitation for Industry Integration Teams. Wayne Surdoval from NETL will discuss this solicitation later this morning. We anticipate that FE will fund two or three Industry Integration Teams as a result of this solicitation. Our hope is other funding organizations will join in this solicitation or issue their own solicitation(s). The number of Industry Integration Teams ultimately selected will depend on the number of government agencies sponsoring the SECA program and their level of commitment.

DOD's Tank Armament and Automotive Command (TACOM) may choose to issue a solicitation for a solid-state fuel-cell module for tanks or other military vehicles.

The SECA program has momentum! "Pre-SECA" R&D work is already underway. Three industry projects in our present program are on a "SECA pathway." They are the Delphi, Honeywell, and McDermott projects. You will hear presentations from these companies later this morning. These organizations are either under contract with us, have a CRADA with us, or have been competitively selected for an award under a previous solicitation. The three projects are likely to be absorbed into the SECA program as Industry Integration Teams.
These three plus an additional two or three give a total of five or six possible Industry Integration Teams funded by FE.

Slide 7
SECA Core Technology Program

R&D performers in the Core Technology Program address the crosscutting technology development needs of the Industry Integration Teams. R&D performers may be:

- universities,
- national labs,
- industry, and
- small businesses.

They will conduct basic and applied R&D. The list of technology development categories we think the R&D performers will need to address includes:

- fuel processing,
- manufacturing,
- controls and diagnostics,
- power electronics,
- modeling and simulation, and
- materials.

This list is draft. I invite workshop participants to tell us if we have the right list of R&D needs.

The projects in the Core Technology Program are competitively selected, and are supported by the same government agencies that fund the Industry Integration Teams. The target funding split is 40 percent for the Core Technology Program and 60 percent for the Industry Integration Teams.

FE has pre-existing contracts and awards that are relevant to the Core Technology Program. For example, we have projects with the University of Utah and the University of Missouri, and materials work with Honeywell. Our intent is to absorb these projects into SECA.

As a side note, we are successfully using the research model outlined here in our gas turbine program. The Advanced Gas Turbine Research Program is establishing the scientific foundation for 21th century gas turbines. The program is industry driven and involves 95 universities in 37 states. Both FE and EE fund the program. Pre-competitive research areas are defined by an Industry Review Board — the gas turbine manufactures. The South Carolina Institute for Energy Studies coordinates the program for DOE.

Slide 8
Intellectual Property — Cornerstone of the Alliance

SECA's treatment of intellectual property is the cornerstone of the alliance. It is a pilot program. DOE hopes this pilot will become the model for other technology development programs.

In the SECA program, DOE anticipates that all members of the alliance will be granted rights to own any inventions they make under the program. The intellectual property (IP) rights of the Industry Integration Teams are complete. However, those of the Core Technology Program are slightly limited. Participants in the Core Technology Program must be willing to license their patented technologies to any of the Industry Integration Teams, within reasonable time limits and other constraints.

Why this approach to IP? The SECA concept is based on the development of a common fuel-cell core module. This common module is essential to reducing the cost. The core module will be expedited if the technologies developed in the Core Technology Program are available for licensing to the Industry Integration Teams. We believe the Industry Integration Teams will be more likely to identify research needs if they are assured that all solutions will be within reach. This intellectual property approach will open the doors to collaboration!

There are other advantages:

- Technologies developed in the Core Technology Program can be incorporated into any designs that will benefit from them — not just into the designs of the highest bidder.
- Research performers in the Core Technology Program will have a ready market for their inventions. They will reap royalties if an Industry Integration Team commercializes a fuel-cell system with their invention.
- This intellectual property arrangement increases the value of a technology. If a technology is important, all of the Industrial Integration Teams will need it to remain competitive.

Slide 9
Solid-State — The Choice for the New Millennium

- I want to examine some underlying questions about the SECA concept. First: Why solid-state? Solid-state fuel cells have several potential advantages:

- Solid-state fuel cells have inherently high efficiencies — up to 60 to 70 percent hydrocarbon-to-electric efficiency. Hybrid or staged systems can have efficiencies up to 80 percent.

- Their high temperature simplifies high-temperature reforming of hydrocarbon fuels. The reformer and the fuel cell can be coupled.

- Solid-state fuel cells have easier head management and simpler control systems.

They lend themselves to low-cost manufacturing.

Slide 10
SECA — Now is the Time

Why is now the time for SECA? Recent technology breakthroughs have set the stage for low-cost solid-state fuel cells. These breakthroughs include:

- Advances in thin-film manufacturing of solid-state materials; for example, tape casting and multi-layer ceramic processing.
- Innovations in planar designs, such as anode-supported electrolytes.
- Compact fuel-processing technology, such as micro-channel reforming.
- Low-cost invertors.
- Advances from related industries; for example, semiconductor manufacturing.

Market forces make it the right time for SECA. Deregulation is opening the door for distributed generation technologies like fuel cells — domestically and internationally. There is a growing demand for more electric power in the transportation sector.

The environmental spotlight is extending small-scale applications. The superb environmental performance of fuel cells makes them a leading contender for market share of small-size systems.

Slide 11
Status of the Market — Stationary

I would like to touch on the status of markets for solid-state fuel cells. Other speakers will discuss markets in more detail.

In the stationary market, there is a movement from central station to distributed power. This is the mainframe-to-personal-computer analogy. Customers want individual control and reliability. Penetrating the distributed generation market beyond niche markets applications will require costs at or below $400 per kilowatt. We need breakthrough technologies to reduce costs to this level. Environmental concerns are driving distributed generations toward very clean systems such as fuel cells.

Slide 12
Status of the Market — Transportation

In the transportation market, solid-state fuel cells offer the potential of low cost systems that can operate using the existing fuel infrastructure. These fuel cells offer both very high efficiencies and low emissions. Auxiliary power units for long-distance trucks may be an early market applications for solid-state fuel cells.

Slide 13
Status of the Market — Military

In the military market, fuel logistics are critical. Fuels represents 70 percent of the weight of materials moved in a military logistical deployment. DOD needs high-efficiency power sources compatible with defense logistic fuels. Systems need to be quiet, rugged, and have low thermal signatures. Field power units may be one of the early market applications for fuel cells in the military. The navy's decisions to use electric drive on new ships increases the potential size of the market.

Slide 14
A Paradigm Shift

Predicting the future is an inexact art. There is a Chinese proverb that says: "He who lives by the crystal ball will die from eating broken glass." With that said, a book was published recently that gives a view of the future. It is called *The Long Boom, A Vision For the Coming Age of Prosperity*. The authors are Schwartz, Leyden, and Hyatt.

The book describes several scenarios that might take place in the first two decades of this century. One scenario is named after the title of the book — the Long Boom. It depicts an unprecedented period of continued economic growth and world peace. But it is very clean, high-tech economic growth. Three to four billion people in developing countries move to the middle class. They want very clean energy: clean cars, clean electricity. Distributed power generation takes off. It is the beginning of the hydrogen infrastructure. And fuel cells can play a major role in this scenario.

This is a scenario that many of us would love to see play out. But even in the less optimistic scenarios, fuel cells can begin to play a major role. I believe fuel cells represent a major shift in how we produce electricity and power and power. Using the buzz words, fuel cells represent a paradigm shift, or a disruptive technology that will change the market dramatically. SECA accelerates this paradigm shift. It starts with the end in mind. It capitalizes on industry's willingness to cooperate across traditional lines.

Slide 15
Public Benefits

As a result, the public benefits. When advanced, ultra-clean, fuel cells move from niche markets to widespread use:

- Their high efficiency will result in significantly reduced emissions.
- Grid stability and reliability will be enhanced.
- We will have the option of continuing to use our low-cost domestic energy resources in an environmentally friendly way. We will be "greener sooner" using fossil fuels.

Slide 16
Responding to the Needs of the Nation

Assistant Secretary for Fossil Energy Bob Gee noted that "mass customization of fuel-cell components for stationary, mobile, and military applications can lead to mass manufacturing and in turn, to much lower unit costs."

This approach, the SECA approach, helps the Department of Energy fulfill its mission "to foster a secure and reliable energy system that is environmentally and economically sustainable."

As a new business model, SECA provides "the break with traditional ways of thinking" that author Stephen Covey said is necessary to make significant technological breakthroughs. SECA responds to the needs of the nation by providing the means to commercialize clean, low-cost, solid-oxide fuel-cell technology.

Thank you.

The Solid State Energy Conversion Alliance: A Paradigm Shift in Technology Development

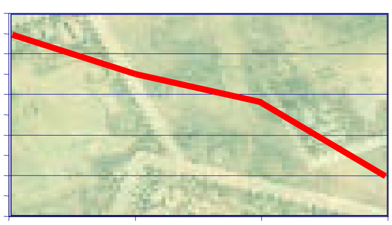
Solid State Energy Conversion Alliance Workshop

June 1-2, 2000

Rita A. Bajura, Director
National Energy Technology Laboratory

NETL

The Vision: *Fuel Cells in 2010*



Low Cost
$400/kW

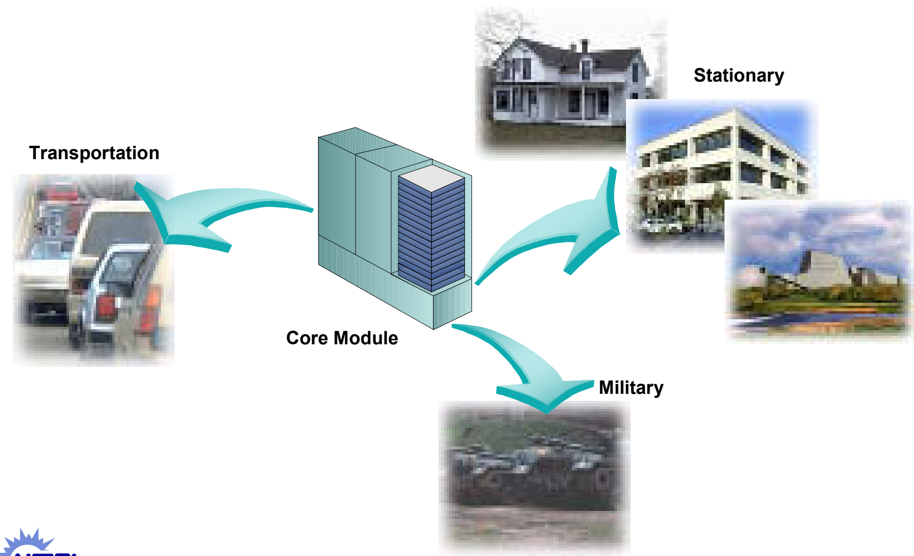
Multiple Fuels

Reduced CO_2 Emissions

NETL

2K- 5/00

The Vision: *A Core Module for Multiple Applications*



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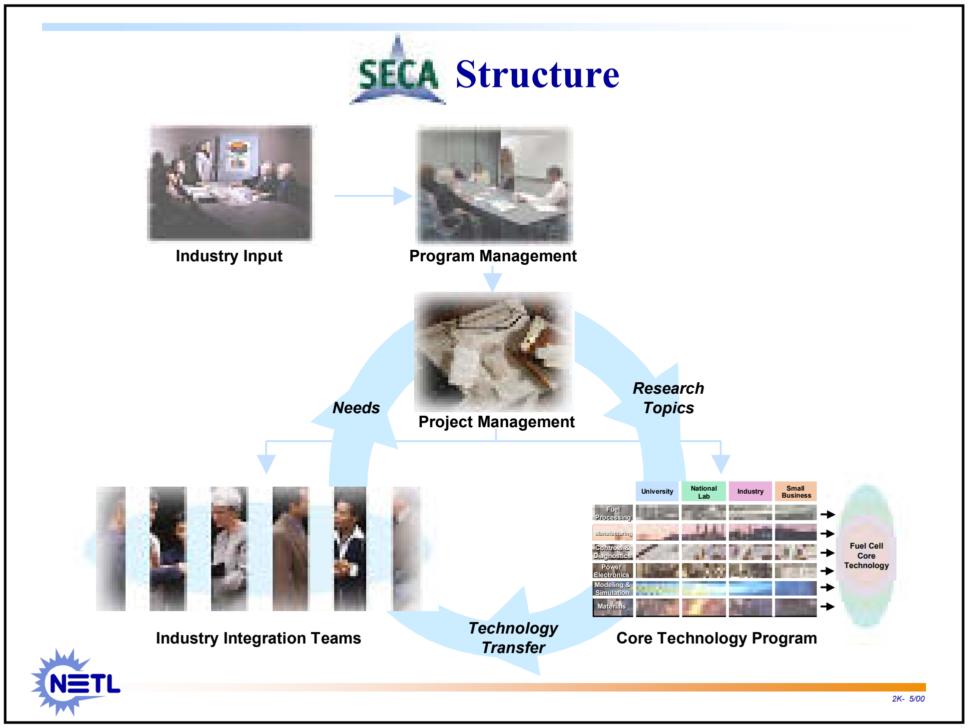
SECA - Realizing the Vision

SECA:

- An alliance of industry teams, R&D performers, and government funding organizations
- Develops an integrated strategy
- Focuses research

NETL

2K- 5/00


SECA Structure
Industry Input
Program Management
Project Management
Needs
Research Topics
University
National Lab
Industry
Small Business
Fuel Processing
Manufacturing
Controls & Diagnostics
Power Electronics
Modeling & Simulation
Materials
Fuel Cell Core Technology
Industry Integration Teams
Technology Transfer
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SECA Industry Integration Teams
The Manufacturing Base
Multiple Integration Teams
Mass Customization of Common Modules
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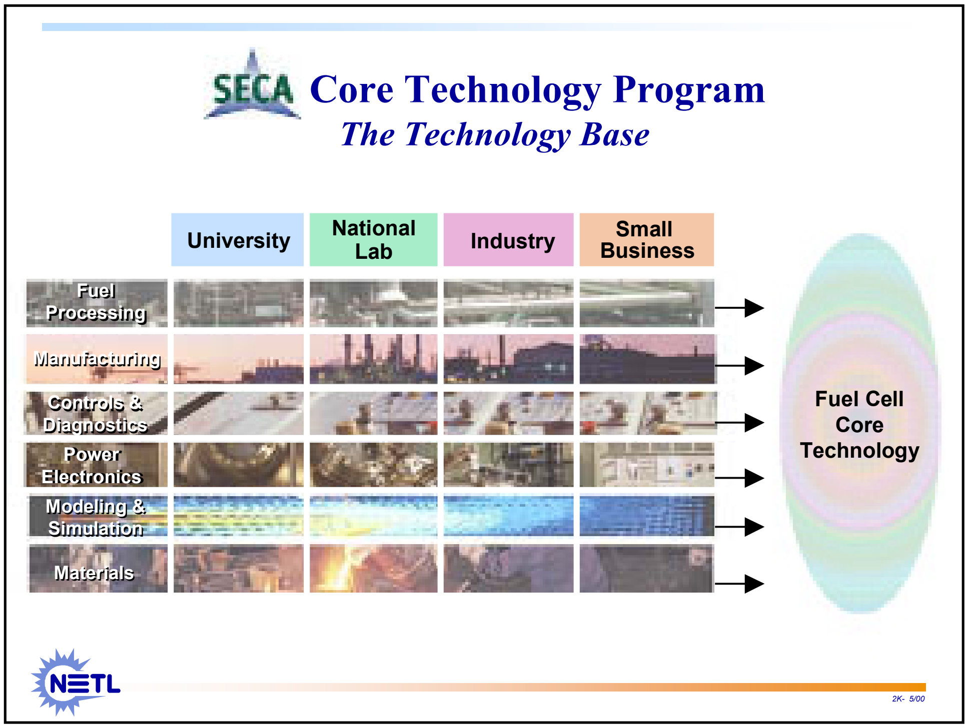
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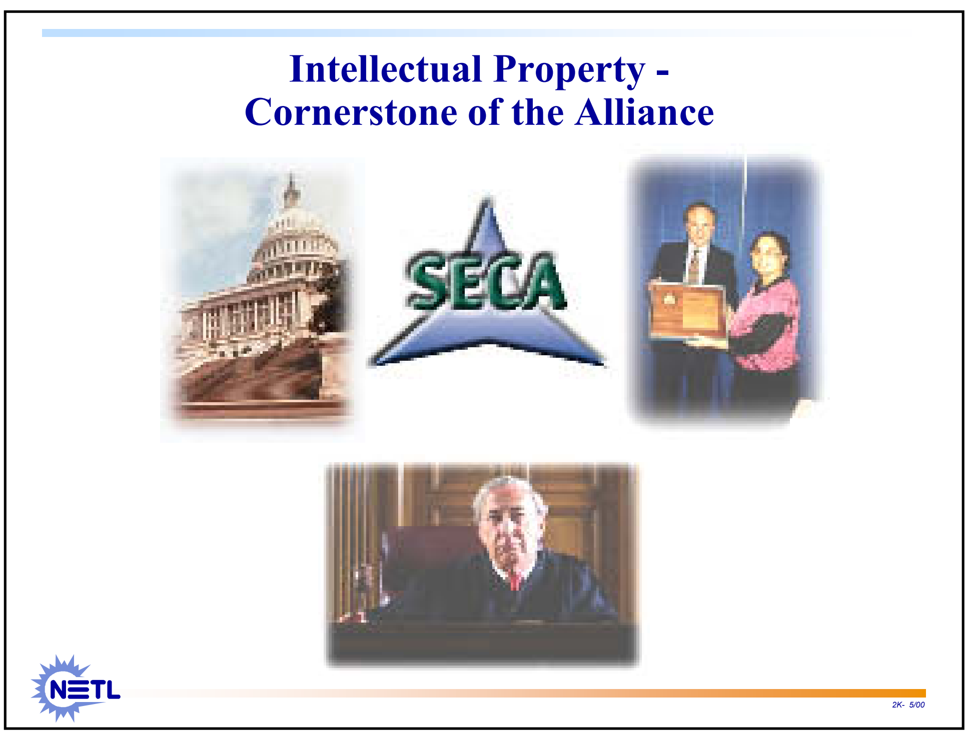
Intellectual Property -
Cornerstone of the Alliance
SECA
NETL
2K- 5/00

Solid State - The Choice for the New Millennium

- Inherently high efficiency
- Couples with high-temperature reforming
- Simple and efficient heat removal designs
- Low-cost manufacturing

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2K- 5/00

SECA - Now is the Time

- Breakthrough in materials, designs, and manufacturing
- Market forces
- Environmental concerns

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2K- 5/00

Status of the Market
Stationary

- Major market penetration requires cost $\leq$ \$400/kW
- Breakthrough technologies needed to reduce costs
- Environmental concerns driving DG to very clean systems

NETL

2K- 5/00

Status of the Market
Transportation

- Potentially low system costs operating on available fuels
- Adaptable to standard transportation fuels
- High efficiencies
- Low emissions

NETL

2K- 5/00

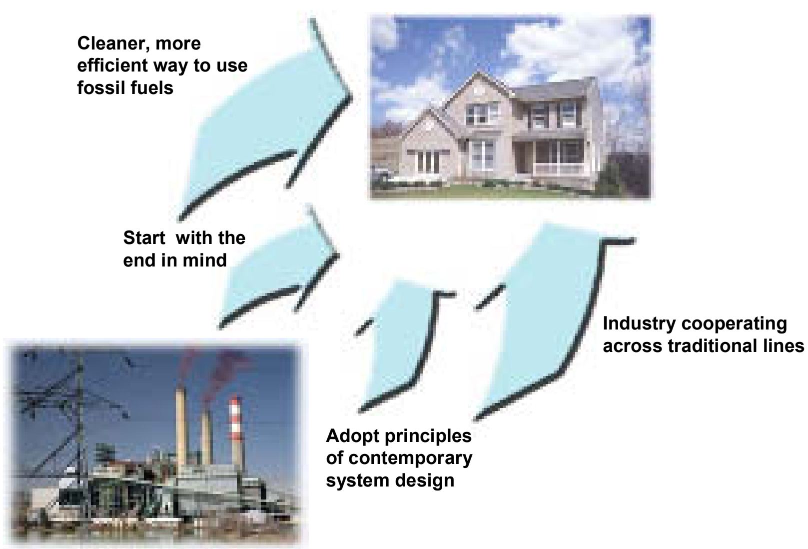
Status of the Market
Military

- Requires high efficiency, low signature power systems
- Fuel logistics are critical
- Electric drives/field power increasingly important

NETL

2K- 5/00

A Paradigm Shift
Overcoming the Pull of The Past

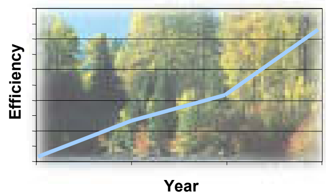


NETL

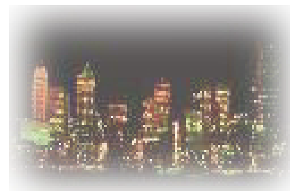
2K- 5/00

Public Benefits

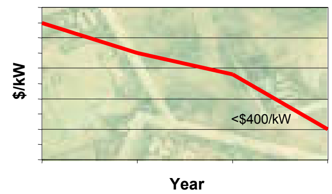
High Efficiency



Grid Stability



Cost Reduction



NETL

2K- 5/00

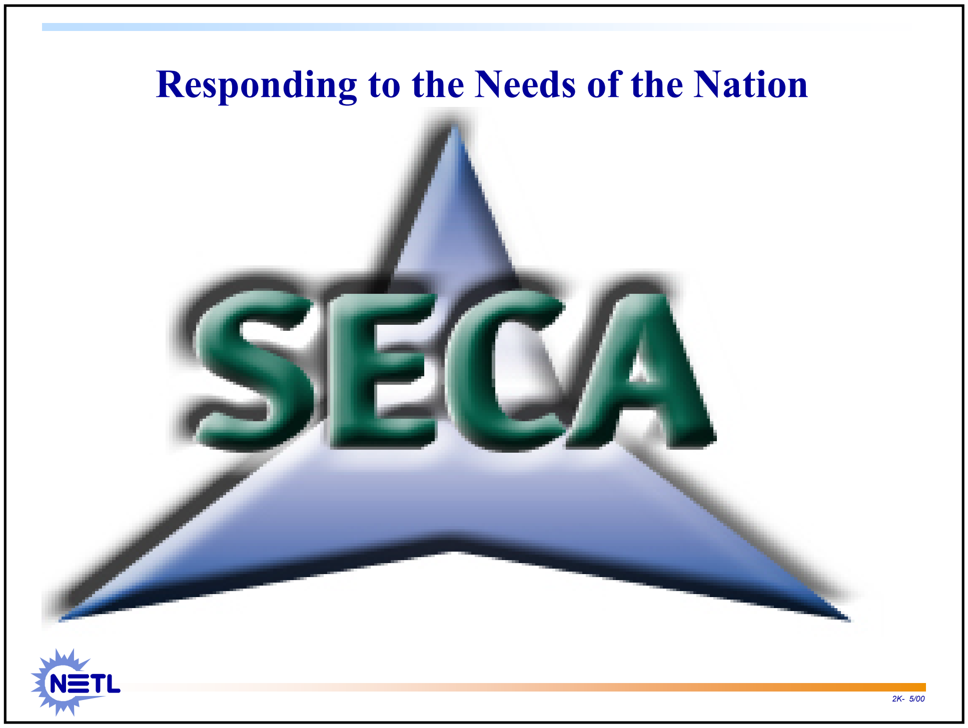
Responding to the Needs of the Nation

"Mass customization of fuel cell components for stationary, mobile, and military applications can lead to mass manufacturing and in turn, to much lower unit costs."

Bob Gee, Assistant Secretary for Fossil Energy

NETL

2K- 5/00


Responding to the Needs of the Nation
SECA
NETL
2K- 5/00

C. U.S. DOE, Office of Transportation Technology, Fuel Cells for Transportation Program

Patrick Davis, Program Manger
U.S. DOE, Energy Efficiency & Renewable Energy

Proton Exchange Membrane (PEM) Fuel Cells for Transportation

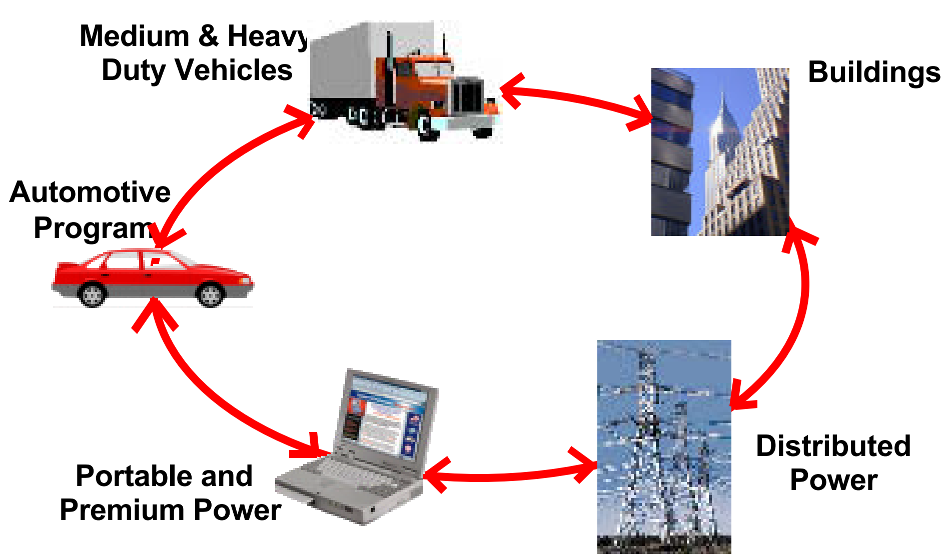
Energy Efficiency and Renewable Energy
Office of Transportation Technologies

Patrick Davis

Solid State Energy Conversion Alliance Workshop
June 1, 2000

EERE PEM Fuel Cell Development Efforts Benefit Multiple Applications

Fuel Cells



Projected Fuel Cell Vehicle Performance (PNGV-Class Series Hybrid)

Fuel Cells

Projected Mileage, MPG

	Gasoline Fueled	Hydrogen Fueled
Urban Fuel Economy	79	101
Highway Fuel Economy	97	128
Combined	**86**	***111***

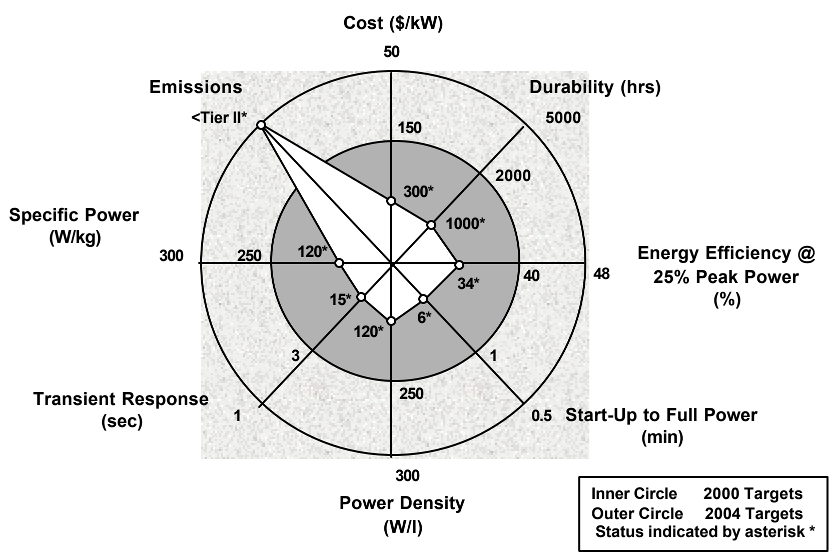
Note: Based on NREL/ADVISOR system modeling using target fuel cell efficiencies.

108 mpg

Status vs Technical Targets

50-kW Gasoline-Fueled Fuel Cell System

Fuel Cells



DOE Transportation Fuel Cell Program
Fuel Strategy

Fuel Cells

Simultaneously pursue parallel paths for near- and long-term

Near-term: Fuel flexible fuel processor

Primary focus ⇨ Advanced petroleum-based fuel

⇨ Methanol, Ethanol, Natural Gas

Long-term: Renewable hydrogen

Primary focus ⇨ On-board vehicle storage

Advanced fuel is "gasoline-like," facilitates on-board processing, and is compatible with existing infrastructure. Gas-to-liquids, methanol, and ethanol may be used as blending constituents.

Structure of DOE Transportation Fuel Cell Program

Fuel Cells

USCAR
System Requirements
System Analyses
Technology Goals
Technical Reviews
R&D Priorities

US DOE
Program Management
Procurement
Budgeting & Resource Allocation
Technology/Program Assessment

ADVISORS/ STAKEHOLDERS
Fuel Providers
Federal/State Govt
Stationary/Building

Universities/LABS
R&D on most critical technical barriers
Assist Suppliers
Independent T&E
Advanced Concepts
Analysis & Modeling

SUPPLIERS
PEM fuel cell system development
Fuel-flexible fuel processor development
Component development

AUTOMAKERS
EV Powertrain Design
Vehicle Engineering/
Packaging Design
Vehicles

→ ***User Customer***

Technology Development Flow

Program is Focused on Technical Barriers

Fuel Cells

There are significant technical and economic reasons that will keep fuel cell vehicles from making significant market penetration for 10 years.

- **Technical Barriers**
  - **Platinum Usage**
  - **Durability**
  - **Air Systems**
  - **Start-up**
  - **Fuel Infrastructure**
  - **Cost**
- **Economic Barriers**
  - **Competition from other technologies**
  - **Fuel Cell Cost**
  - **Economics of fuel introduction**
  - **Cost of fuel**

Projects and Funding by Budget Category

Systems

- Plug Power/Epyx
- IFC
- Energy Partners, AlliedSignal
- ANL

FY00: $6.0M

Fuel Processing

- NUVERA
- Hydrogen Burner
- McDermott
- Plug Power/UOP
- AlliedSignal
- Arcadis
- ANL, LANL, PNNL

FY00: $17.0M

Stack Subsystem Components

- Energy Partners, AlliedSignal, IFC, Plug Power
- IGT, Electrochem
- 3M, SwRI/Gore, Foster-Miller
- Vairex, A.D. Little, AlliedSignal, Meruit
- Spectracorp
- LANL, LBNL

FY00: $14.0M

Accomplishments

Systems

- Demonstration of first gasoline to PEM experiment (1997), first 10kW gasoline system (1999).
- IFC Hydrogen Sys.
- MeOH (GM) system led to Zafira demonstration

Fuel Processing

- Epyx gasoline fuel processors - 50kW
- PNNL microchannel steam reformer
- ANL autothermal catalyst development
- GM MeOH steam reforming.
- Los Alamos PROX.

Stack Subsystem Components

- Los Alamos low platinum electrode, reconfigured anode.
- Inst. Of Gas Tech. $10/KW bipolar plate.
- Sensors and controls
- AlliedSignal stack demonstrated in JLG boomlift.

Office of Transportation Technologies Interest in Solid Oxide Fuel Cell Technology

Fuel Cells

- **Applications of interest in transportation**
  - **Auxiliary Power for Heavy or Light Duty**
  - **Propulsion for Heavy Duty**
- **Recently completed study by Parsons Infrastructure and Technology indicates auxiliary power application particularly of interest.**
- **OTT will continue to investigate application of solid-oxide fuel cell technology to transportation and support R&D where appropriate.**

<u>Barriers to transportation applications:</u>

Heavy Duty - Cost, Maturity, Durability/Robustness
Light Duty - Cost, Maturity, Start-up, Thermal Cycling

Summary

Fuel Cells

- PEM fuel cell technology leverages multiple applications to achieve significant benefits in energy efficiency.
- Major technical barriers exist that prevent the introduction of PEM technology into today’s light duty transportation options.
- The Office of Transportation Technology Fuel Cell for Transportation program is addressing critical technical barriers.
- Solid Oxide technology may find a role in transportation applications, but, like PEM, has significant technical and economic barriers to overcome.

D. SECA: TRANSPORTATION APPLICATIONS

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

Transportation Applications for Solid Oxide Fuel Cells - Auxiliary Power

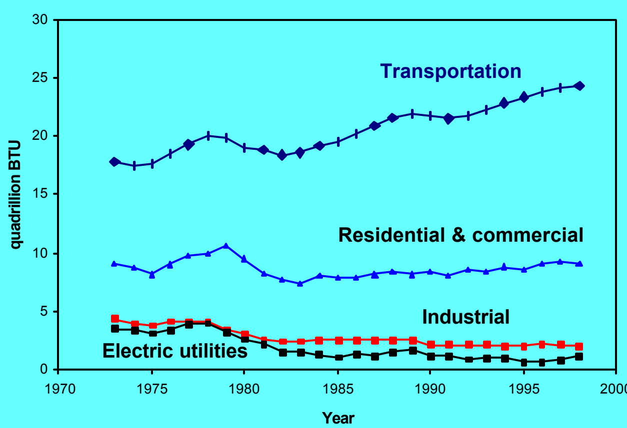
June 1, 2000

Don McConnell
Corporate Senior Vice President
Associate Lab Director, Energy
Pacific Northwest National Lab

Battelle

U.S. Department of Energy
Pacific Northwest National Laboratory

Consumption of Petroleum by End-Use Sector, 1973-1998



- **Transportation is major petroleum end-user**
  - **more people**
  - **more vehicles**

Source: Transportation Energy Data Book: Edition 19

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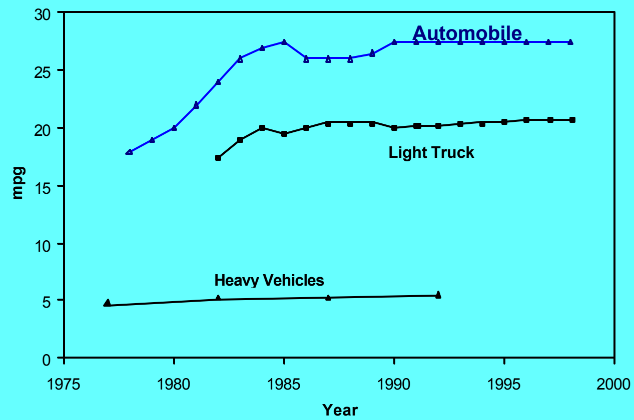
Pacific Northwest National Laboratory

Transportation Fuel Economy



- Significant increase in overall vehicle efficiency has been realized:
  - more efficient engines
  - lightweight vehicle

Source: Transportation Energy Data Book: Edition 19

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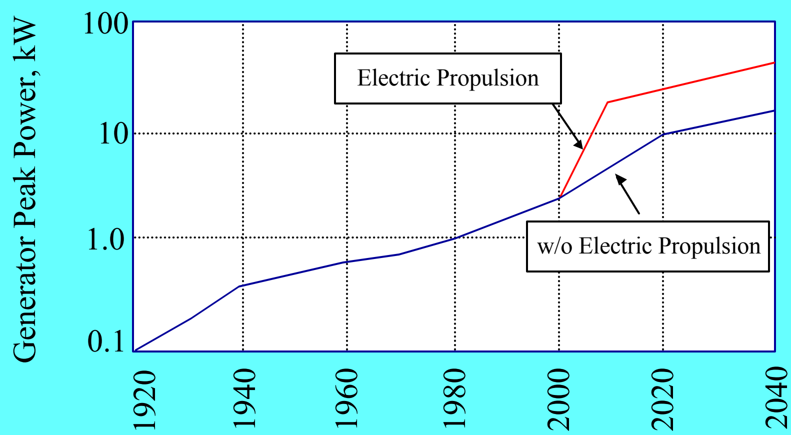
Pacific Northwest National Laboratory

Automotive: Increasing Electrical Power Requirements



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Automotive Auxiliary Power Market Drivers

Peak Power Requirements	kW
Electric suspension	12.0
Heated windshield	2.5
Electric valve control	2.4
Electric power steering	1.3
Anti-lock brakes systems	0.67
Catalyst Heater	0.6
Diesel direct Injection	0.47
Electric coolant pump	0.3
Compartment Fan	0.3
Total Expanding Demand	**20.5 kW**

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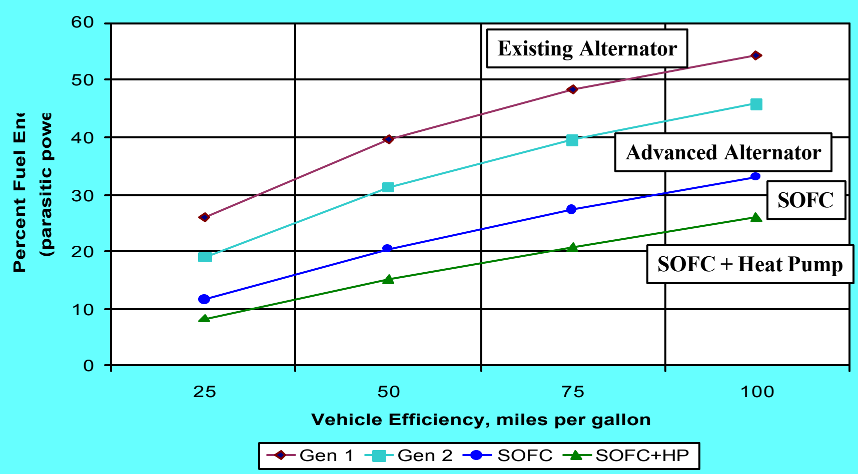
5 kW Vehicle Auxiliary Power: Impact on Estimated Fuel Usage



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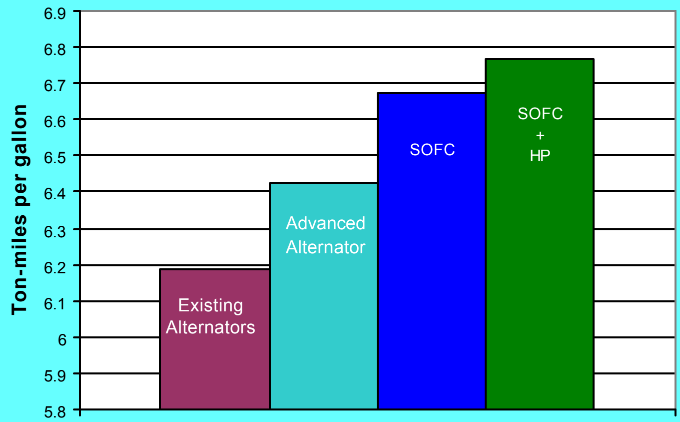
Auxiliary Power:
Ton-Mile Efficiency for Class 8 Truck



- Assume 5 kW continuous
- Assume a New York to Los Angeles, 60 mph
- 8 hours idle per day

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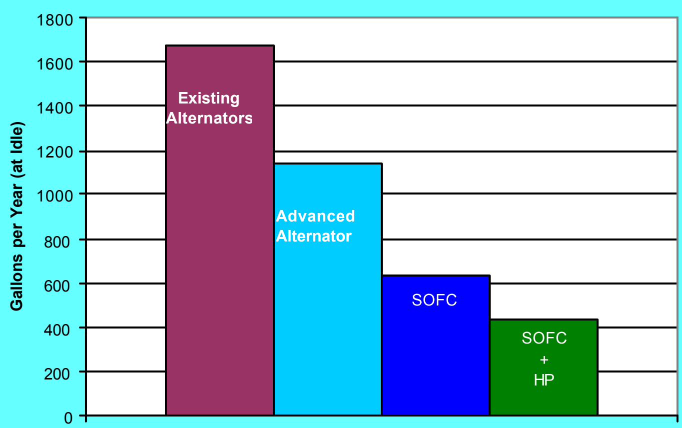
Estimated Idle Fuel Usage per Year, Class 8 Truck



- Significant fuel saving as APU efficiency increases
- 250 days in a year
- 8 hours idle per day

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Pacific Northwest National Laboratory

Mobile Electrical Power Generation

- **Engine/Generator**
  - **Fuel Energy ->Mechanical Energy->Electrical Energy**
    - Low overall efficiency = 12-17% peak, 5-7% idle
    - Inexpensive & reliable
- **Potential of Fuel Cells**
  - **Fuel Energy -> Electrical Energy**
    - High overall system efficiency > 40 %
    - Expensive, unreliable and (as yet) unproven
    - Environmentally friendly, reduced emissions
- **Fuel Cell Combined with Heat Pump**
    - Overall system efficiency >65%
    - Full independence of auxiliaries from engine operation
    - Minimizes emissions from auxiliaries

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Advantages of Fuel Cell for Auxiliary Power

- Electricity without combustion
- Continuous production of electricity as long as fuel is supplied
- Environmentally clean
- High efficiency, > 60 % stack efficiencies
- Low Noise
- Modular and compact
- Potential for low cost

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“Generic” Automotive APU Specification

Power	5 kW net
Rated voltage	42 Vdc
Mass Target	< 50 kg (0.1 kW/kg)
Volume Target	< 50 liter (0.1kW/liter)
Operation life	>5000 hrs
Cold Start Required	>3000 times
Warm Starts Required	SOFC < 10 minutes
Maintenance Required	>> 1000 hrs (30 ppm S)
Efficiency	> 40 %
Surface Temperature	< 45 degrees celsius

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High Efficiency, Low Cost APU System

R&D Advances Required in:

- Solid Oxide Fuel Cell Stack
- Fuel Reformation
- Integrated Balance-of-Plant
- Thermal Control Subsystem
- Waste Energy Recovery Subsystem
- Power Electronics and Energy Storage Subsystem
- Entire System Cost must be driven down

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Potential APU Markets

- Luxury Vehicles
- Recreational Vehicles
- Heavy Duty Trucks
- Short Haul Trucks
- Passenger Vehicles

$1000/kW

$600/kW

$200/kW

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E. Solid Oxide Fuel Cells and Department of Defense Applications

Herbert Dobbs, National Automotive Center, TACOM

TACOM
Mobility and Firepower for America's Army

Solid Oxide Fuel Cells and Defense Applications

Presented to the

Solid State Energy Conversion Alliance (SECA) Workshop

1 June, 2000

Herbert H. Dobbs, Jr.
Team Leader, Alternative Fuels and Fuel Cells
TACOM National Automotive Center

Tank-automotive & Armaments COMmand

SOFC's and Defense Applications

Outline

- Armed Services Interests
- Fuel - The sulfur problem
- Efficiency - A key logistic issue
- PEM versus SOFC
- A way forward in ground vehicles
- Wrap up

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SOFC's and Defense Applications

Military Fuel Cell Applications

- Navy
  - Ship service power
  - Ship Propulsion
- Air Force
  - Bare Base - tent city power
  - Flight line generator replacement
- Army and Marines
  - Ground vehicle APUs and propulsion
  - Mobile Generators
  - Soldier Power

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SOFC's and Defense Applications

Fuel - The sulfur problem

- Navy
  - Ship fuel allows up to 10,000 ppm sulfur
  - JP-5 jet fuel allows up to 4,000 ppm
- Air Force and Ground Forces
  - JP-8 is the single peacetime and battlefield fuel
  - 3,000 ppm S limit
- Overseas fuels can have very high sulfur levels
- Historically low JP-5/8 sulfur levels are increasing

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SOFC's and Defense Applications

Efficiency and Emissions

- The U.S. has moved from forward basing to force projection
- Logistic support structures must be kept small
  - Less vulnerable supply systems
  - Faster to deploy
  - Less expensive in peace or war
- 70% of the Army's bulk supply burden is fuel
- Emissions are a real military concern
  - Most military activity is peacetime
  - Military trucks are affected now - ships and aircraft later

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SOFC's and Defense Applications

PEM: Advantages and Issues

- Advantages
  - PEM fuel cells are available
  - Good efficiency
  - High rate of commercial investment in PEM technology
- Issues
  - Difficult cooling in high ambient temperature
  - Noble metal catalysts - cost and scarcity
  - Complex reformer
    - Poor sulfur tolerance
    - Must remove carbon monoxide
    - Penalizes efficiency and power density

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SOFC's and Defense Applications

SOFC: Advantages and Issues

- Advantages
  - Excellent integration with simplified reformer
  - Potential efficiency of combined cycle
  - Heat rejection is much easier
    - Promotes high power density propulsion systems
    - Long term military vehicle propulsion candidate
- Issues
  - Much less mature than PEM
  - Scale up to large vehicle systems
  - Slow startup

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SOFC's and Defense Applications

A Way Forward in Ground Vehicles

- SOFCs offer excellent features for future heavy vehicles, especially military vehicles
- Commercial success of SOFCs is the key to broad military adoption
- Long haul truck Auxiliary Power Units (APUs) are a major commercial entry point for SOFCs
  - Solution to anti-idling restrictions
  - Support for separately-powered engine accessories
- The APU builds the base for SOFC engines

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SOFC's and Defense Applications

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F. Solid Oxide Fuel Cells and Stationary Applications

W. Peter Teagan, Arthur D. Little, Inc.

Arthur D Little

Solid Oxide Fuel Cells and Stationary Applications

Presentation to:
Solid State Energy Conversion Alliance (SECA)

June 1-2, 2000
Baltimore, MD

Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390 U.S.A.

Peter Teagan
Johannes Thijssen
Sean Casten

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Arthur D Little June 2000 CAM STC/SECA.ppt 1

SECA 2000 Market Segments Requirements

Several distinct markets exist for stationary SOFC generators, each with distinct characteristics and requirements.

Residential	• Highly variable power requirements • High competing price of power (¢/kWh basis) • Highest requirements for reliability and ease-of-installation • CHP is difficult
Commercial	• Peaky power requirements • Baseload or peak-shaving applications are possible, depending upon rate structures. • CHP potential exists in some applications. • "Premium" power credit can increase the value of on-site generators.
Industrial	• Increased likelihood of dedicated loads • High demand charges in some applications will favor peak-shaving systems. • CHP potential exists in many applications. • "Premium" power credit can increase the value of on-site generators.
Grid-support	• Can be installed to offset T&D and new generation capacity investments • Implies that system is dispatchable by the local utility or ISO • Most attractive for high efficiency systems, where the marginal cost of power is competitive with wholesale rates (1 - 4 ¢/kWh).

Arthur D Little June 2000 CAM STC/SECA.ppt 2

SECA 2000 Market Segment Requirements

Performance and cost requirements for distributed generators vary by market segment.

	Stationary					Transportation	
	Buildings		Industrial	Utility		Automotive	Heavy Duty
	Residential	Commercial		Distributed	Central		
1. Capacity (kW)	1 - 5	20 - 500	200 - 2000	500 - 5000	> 100,000	30 - 90	60 - 2000
2. Efficiency %[1]	> 35	> 35	> 40	> 40	> 55	> 40	> 40
3. Life (years)	> 10	> 10	> 15	20	20	0.5 [3]	2 - 10 [3]
4. O&M (hours)	> 4000	> 1000	ongoing	ongoing	ongoing	> 200	> 200
5. Heat Recovery • Temperature Level	Important 80 - 220° F	Important 80 - 250° F	Important a. 120 - 300° F b. 80 - 220° F	Not Important N.A.	Not Important N.A.	Not Important N.A.	Not Important N.A.
6. Cyclability	Important	Important	Not Important	Important	Not Important	Very Important	Important
7. Emissions[2] NOx (ppm)	< 20	< 20	~ 150	~ 50	~ 150	~ 50	~ 50
8. Startup Time	Important[4]	Important[4]	Important[4]	Not Important	Not Important	Very Important	Very Important

[1] Electric generation only; in cogeneration applications combined electric-thermal efficiencies approach 85%.
[2] Varies by application and region; estimates reflect trends toward increasingly stringent regulations.
[3] Actual operating time of the power system (not vehicle life).
[4] Importance depends upon operation strategy. Peak-shaving units will require rapid startup, but base-loaded systems will not.

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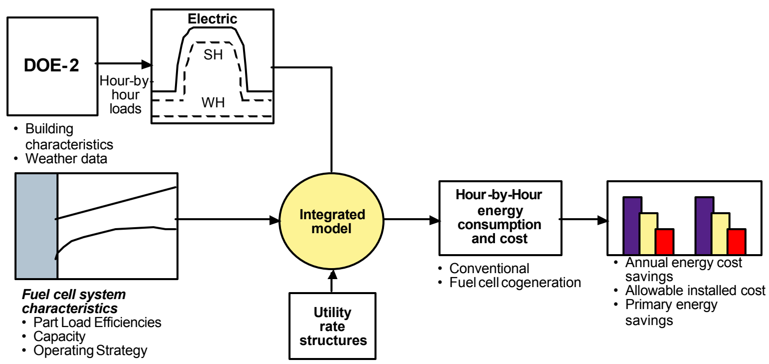
SECA 2000 Market Segment Requirements

We have used a detailed economic model to estimate the allowable cost of distributed power technologies in a variety of applications.



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SECA 2000 Market Segment Requirements

These analyses have shown that distributed generation technologies could generate economic value at installed costs of $2,500 and below.

			Allowable Installed Cost[1] ($/kW)	
	Market Segment	Typical Capacity	Entry[2]	Sustained[2]
On-site	Commercial Cogeneration	50 kW - 2 MW	$1,500 - 2,000	$800 - 1,300
On-site	Industrial Cogeneration	5 - 200 MW	$1,000 - 1,200	$800 - 1,000
On-site	Residential Power	0.5 - 10 kW	$1,000 - 2,500	$800 - 1,000
Utility	Distributed Power	5 - 20 MW	$1,300 - 1,500	$800 - 1,300
Utility	Central Station	100 - 500 MW	$900 - 1,100	$700 - 900

[1] Total installed system costs, including all owners costs. Targets apply widely to industrialized country markets. Costs have been calculated based on a range of electricity and gas rate structures. Allowable costs for hydrogen fueled systems would be considerably lower as merchant hydrogen prices are typically 2-3 times as high as natural gas.
[2] "Entry" costs are based on early high value markets. "Sustained" costs must be realized to achieve significant market penetration.

Note that these costs do not include "premium" power benefits, which might increase the allowable costs by 25% or more above the values shown here (in selected applications).

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SECA 2000 Market Segment Requirements

Residential applications have potential "mass markets", but pose unique technical and cost challenges.

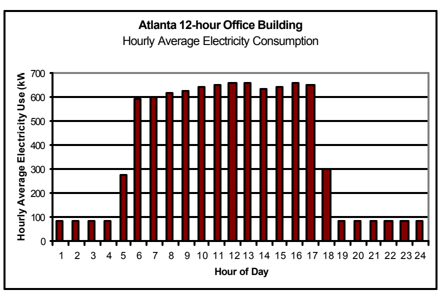
- Electric load profiles are highly variable:
  - Peaks are ~ 10 kW in many homes
  - Baseload is often 0.1 kW or less
  - Average loads can be quite small, ~ 0.5 - 1.5 kW

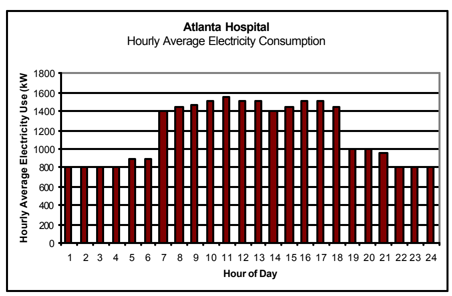
    The most cost-effective on-site generators will be small, baseloaded architectures, provided that they can operate in parallel with the utility grid.
- From the home owners perspective, the generator must "look" like a typical appliance.
  - Minimal installation requirements
  - Minimal service requirements (once per year maximum)
  - Long operating life
- Little coincidence between thermal and electric loads in many US markets, making CHP difficult.
- Unresolved (but certainly challenging) codes and standards issues relating to onsite generators and onsite hydrogen flows, even as dilute H_2.

Arthur D Little June 2000 CAM STC/SECA.ppt 6

SECA 2000 Market Segment Requirements

Commercial building load curves present unique challenges and opportunities for distributed generators.





- Variation in peak and baseload power demand impact multiple generator specifications, including:
  - Capacity factor of load-following systems
  - Opportunities for demand charge reduction
  - Optimal product sizing strategy
  - Turndown requirements

Arthur D Little June 2000 CAM STC/SECA.ppt 7

SECA 2000 Market Segment Requirements

Significant markets exist for generators with rated capacities greater than 10 kW (e.g., non-residential units).

Building Type	Baseload Power Requirements (kW)*	% of US Commercial Electricity Use (kWh)
• Large High-Rise Office • Largest Hospitals • Largest Hotels • Large Shopping Mall	1,000+	20%
• Hospitals (200 - 300 beds) • Large Hotels (750 rooms) • Office (200,000 sq. ft.) • School (125,000 sq. ft.) • Large Retail	200 - 1,000	35%
• Office (50,000 sq. ft.) • Average Hotel (75,000 sq. ft., 125 rm) Multi-family (100 units)	50 - 200	35%
• Fast Food Restaurant (4,000 sq. ft.) • Small Office Building (10,000 sq. ft.) • Multi-family (<25 units)	10 - 50	10%

* Peak loads can be 2-3 times higher.

However, large numbers of potential kWh sales do not necessarily imply large numbers of unit sales!

Arthur D Little June 2000 CAM STC/SECA.ppt 8

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SECA 2000 Market Drivers

As the energy industry deregulates, market drivers for stationary power generation are rapidly changing.

Energy Costs Matter!

- Technologies that can successfully compete with the grid on a ¢/kWh basis can bring value to the end user.
- However, prevailing costs may not be the best indicator of economics:
  - Utilities may adjust their rate strucutres in light of competition from on-site generators
  - Electricity rates are falling in the wake of deregulation.
- Even if the marginal cost of power generation is high, on-site generators may still be able to bring about value through demand charge ($/kW) reduction.
- **Energy cost savings can be a powerful (but complex!) driver for on-site power generation.**

Some power is "premium"

- Growing distribution of electronic devices is increasing users' sensitivity to minor variations in power quality and/or reliability.
- For many users, the cost of a power outage is substantially larger than the cost of power
  - Credit-card processing centers
  - Internet servers
  - Brokerage houses
  - etc.
- Deregulation does not necessarily provide for grid-reliability, thus raising uncertainties in the future.
- **There is an increasing focus on "point-of-use" solutions to power quality issues.**

Who will own the generator?

- Electricity users could own the generator
  - This allows for the full realization of energy cost savings.
  - However, it is beyond the "core business" of many end users.
- Gas/electric utilities could own the generator
  - This allows for the full realization of infrastructure cost savings (avoided T&D costs, etc.)
- Third parties are starting to play a role in DG
  - ESCOs
  - etc.
- **Ownership structures will affect the economic and operating requirements of all distributed generators.**

Arthur D Little June 2000 CAM STC/SECA.ppt 10

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Arthur D Little June 2000 CAM STC/SECA.ppt 11

SECA 2000 Special Issues for SOFC Applications

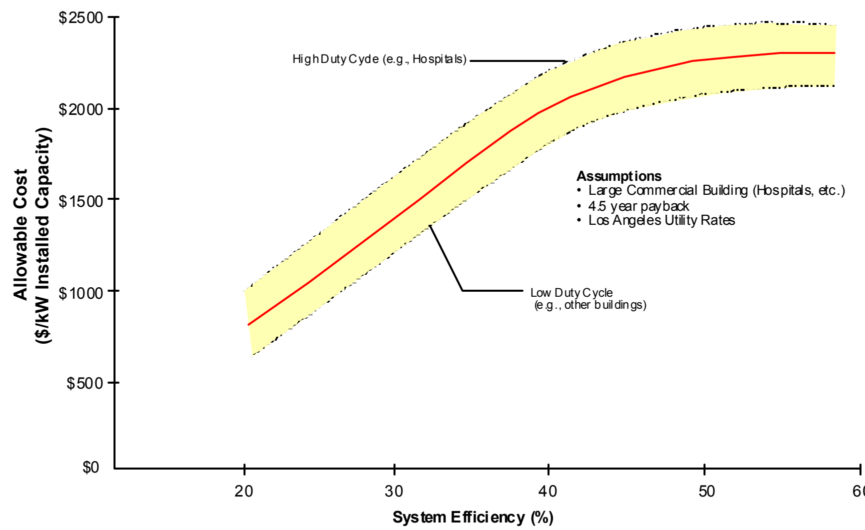
SOFC has attractive characteristics for many (not necessarily all) stationary power applications.

- Heat recovery potential:
  - Can interface with most industrial and commercial thermal needs
  - Allows for operation of multi-effect absorption cooling technology.
- Electric Conversion Efficiency:
  - Allows for higher “allowable costs” than lower efficiency options
  - Higher efficiency can decouple the economics from the need for heat recovery.
- Fuel processing simplicity:
  - Reduces risk and cost of technology.

Arthur D Little June 2000 CAM STC/SECA.ppt 12

SECA 2000 Special Issues for SOFC Applications

SOFC’s high electrical efficiency leads to higher allowable costs than lower efficiency options.



Arthur D Little June 2000 CAM STC/SECA.ppt 13

SECA 2000 Special Issues for SOFC Applications

There are several issues which require quantification to better understand the application range of SOFCs.

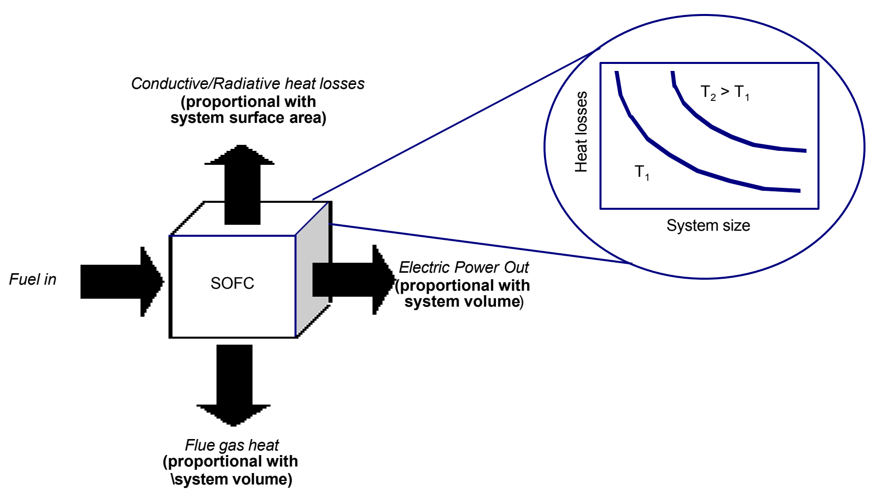
- Thermal losses:
  - At what combination of operating characteristics (capacity factor) and rated capacity do thermal losses become unacceptable? (see next slide)
- Cyclic operation:
  - Can the system be shut off (for example, during periods of low or zero loads)?
  - How many cold start cycles are acceptable? How can the system be designed to minimize fatigue factors relating from thermal expansion/contraction?
  - What are the losses during “idle” periods, and how can they be minimized?
- Start-up time:
  - How fast can the system be started?
  - How should it be maintained (e.g. at what temperature) when idle?

The above issues become increasingly important in lower capacity ranges associated with residential and light commercial service.

June 2000 CAM STC/SECA.ppt 14

SECA 2000 Special Issues for SOFC Applications

Thermal losses for SOFCs become particularly important in lower capacity ranges associated with residential and light commercial service.



June 2000 CAM STC/SECA.ppt 15

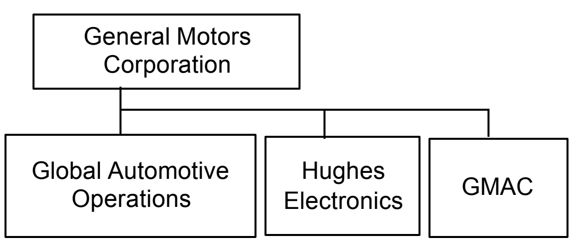
G. INDUSTRY PRESENTATIONS: FUEL CELL MARKETS

1. Carl Miller, Delphi Automotive Systems
2. Nguyen Q. Minh, Honeywell
3. William P. Schweizer, McDermott Technology, Inc.

DELPHI
Automotive Systems

DELPHI
Automotive Systems

The Evolution of Delphi



Spin-Off
May 28, 1999

DPH Listed NYSE
THE NEW YORK STOCK EXCHANGE

- 1900s: 90 years + of history as the in-house supplier to GM
- 1988: ACG Worldwide Group structure created
- 1994: ACG Worldwide established as separate business sector
- 1995: ACG Worldwide became Delphi Automotive Systems
- 1998: Delphi incorporated as a subsidiary
- 1999: Delphi Initial Public Offering; "DPH" on NYSE
- 1999: Delphi becomes a totally independent company

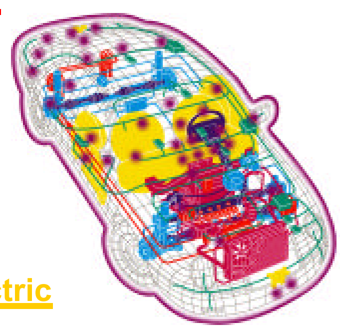
Mission

- Global Automotive Systems Supplier With Component Excellence
- Passionate Pursuit of Customer Satisfaction Through Technology, Quality, Cost, Responsiveness and Attitude
- Grow Revenue Across a Diversified Customer Base
- Increase Stakeholder Value Through Revenue Growth and Superior Returns
- Create an Environment Where Every Employee Can Contribute and Excel

Delphi Automotive Systems

Energy & Engine Management Systems

Chassis Systems



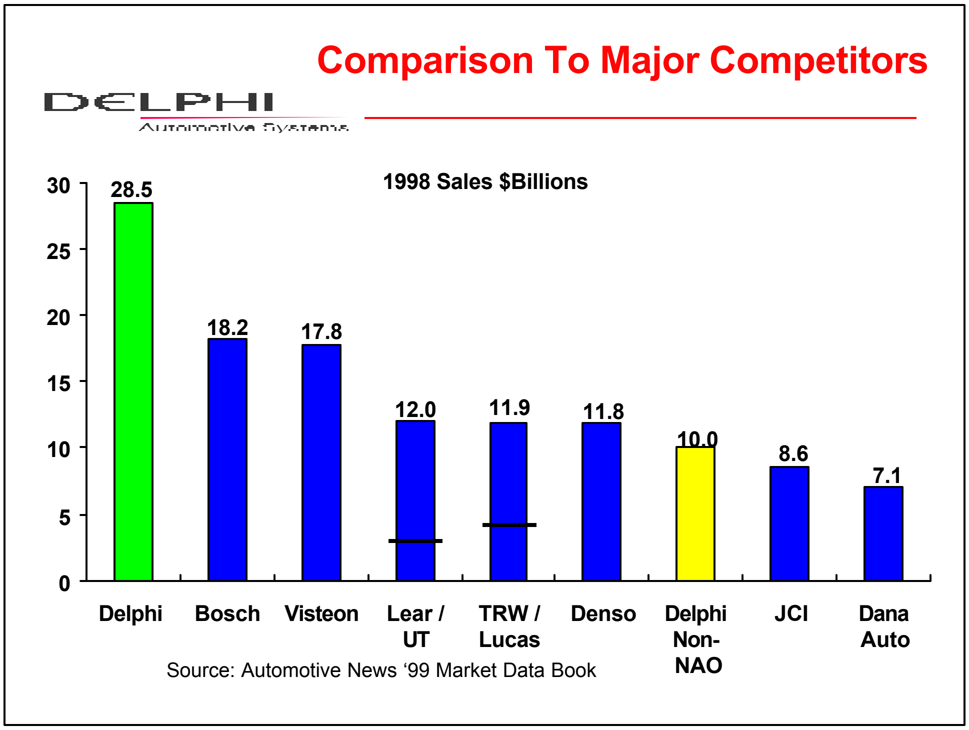
Saginaw Steering Systems

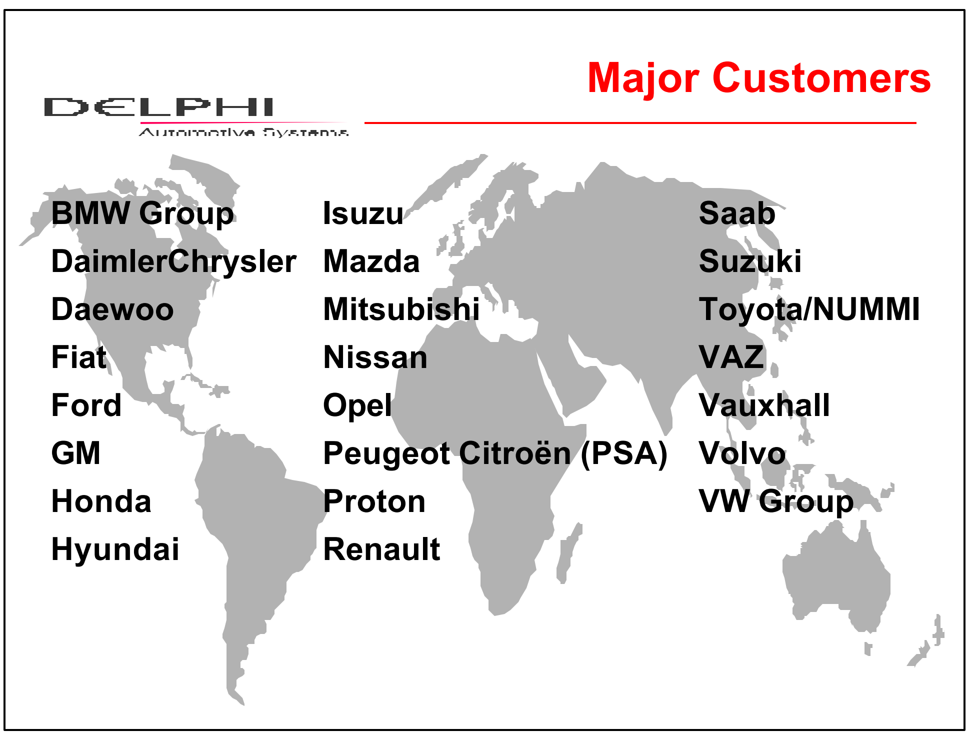
Delco Electronics Systems

Interior & Lighting Systems

Packard Electric Systems

Harrison Thermal Systems


Comparison To Major Competitors
DELPHI
Automotive Systems
1998 Sales $Billions
30
25
20
15
10
5
0
28.5
18.2
17.8
12.0
11.9
11.8
10.0
8.6
7.1
Delphi
Bosch
Visteon
Lear / UT
TRW / Lucas
Denso
Delphi Non-NAO
JCI
Dana Auto
Source: Automotive News '99 Market Data Book


Major Customers
DELPHI
Automotive Systems
BMW Group
DaimlerChrysler
Daewoo
Fiat
Ford
GM
Honda
Hyundai
Isuzu
Mazda
Mitsubishi
Nissan
Opel
Peugeot Citroën (PSA)
Proton
Renault
Saab
Suzuki
Toyota/NUMMI
VAZ
Vauxhall
Volvo
VW Group

Delphi Automotive Systems Core Competencies

DELPHI
Automotive Systems

- Chassis System Design and Integration
- Mechatronics-Electromechanical Integration
- Friction Management
- Fluid Power Management
- Value Enhancing Processing
- Energy Conversion
- Energy Storage
- Sensing & Actuation
- Exhaust & EVAP Emissions
- Fuel Delivery & Combustion Control

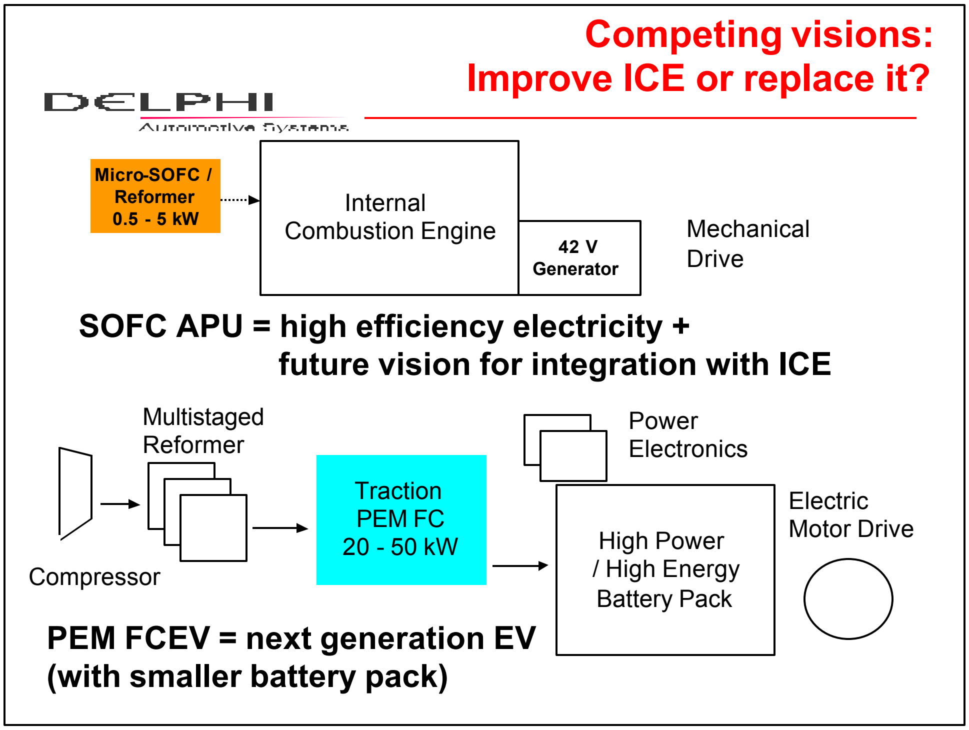
DELPHI
Automotive Systems

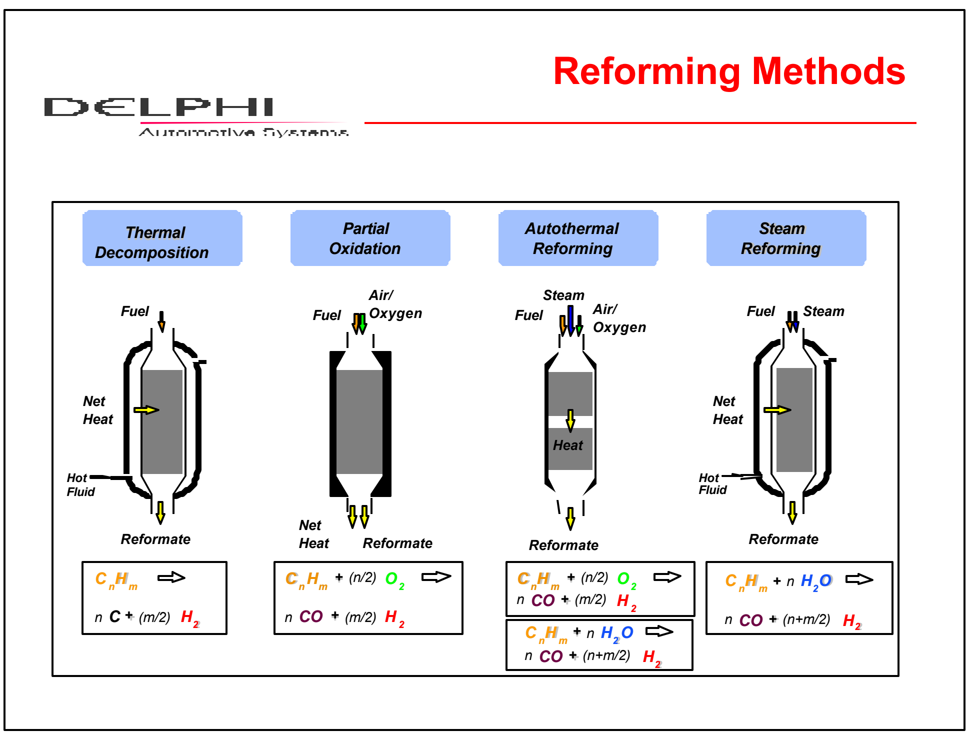
Delphi and BMW Announce Development of Fuel Cell Auxiliary Power Unit.

For Release: April 26, 1999

MUNICH, Germany /PRNewswire/ --

Delphi Automotive Systems (NYSE: DPH) and BMW announced today that they have signed a development agreement to produce vehicles that use a solid-oxide fuel cell as an auxiliary power unit and that have the potential of being clean, high-power-generation vehicles. Under the development agreement, BMW and Delphi are jointly developing a fuel cell system that will be used as an auxiliary power unit for gasoline engines. This will allow BMW to offer more features more efficiently with the potential to reduce the emissions of an internal combustion engine.


Competing visions:
Improve ICE or replace it?
DELPHI
Automotive Systems
Micro-SOFC / Reformer 0.5 - 5 kW
Internal Combustion Engine
42 V Generator
Mechanical Drive
SOFC APU = high efficiency electricity + future vision for integration with ICE
Multistaged Reformer
Compressor
Traction PEM FC 20 - 50 kW
Power Electronics
High Power / High Energy Battery Pack
Electric Motor Drive
PEM FCEV = next generation EV (with smaller battery pack)


Reforming Methods
DELPHI
Automotive Systems
Thermal Decomposition
Partial Oxidation
Autothermal Reforming
Steam Reforming
Fuel
Net Heat
Hot Fluid
Reformate
Fuel
Air/ Oxygen
Net Heat
Reformate
Steam
Fuel
Air/ Oxygen
Heat
Reformate
Fuel
Steam
Net Heat
Hot Fluid
Reformate
$C_nH_m \Rightarrow n\ C + (m/2)\ H_2$
$C_nH_m + (n/2)\ O_2 \Rightarrow n\ CO + (m/2)\ H_2$
$C_nH_m + (n/2)\ O_2 \Rightarrow n\ CO + (m/2)\ H_2$
$C_nH_m + n\ H_2O \Rightarrow n\ CO + (n+m/2)\ H_2$
$C_nH_m + n\ H_2O \Rightarrow n\ CO + (n+m/2)\ H_2$

Technical Challenges

DELPHI Automotive Systems

SOFC has many challenges to be viable as an automotive technology:

(1) Cost
(2) Robustness (especially Thermal Cycling)
(3) Anode oxidation sensitivity
(4) Low Fuel Utilization
(5) Thermal Management (high temperature insulation)
(6) System integration (many new technologies)

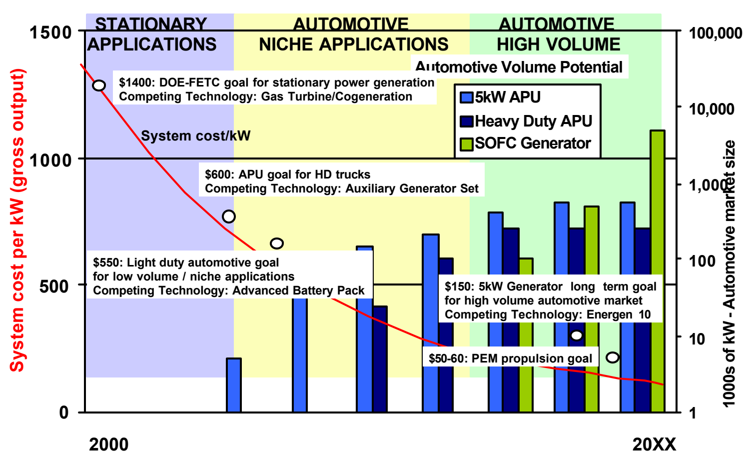
But:

- **SOFC is an attractive automotive fuel cell technology**

- **It has other future mechanizations which support the trend to <u>nearly-zero toxic emissions and much reduced CO2 emissions</u>**

Cost imperatives by market segment

DELPHI Automotive Systems



SOFC
Cost development potential

DELPHI Automotive Systems

Further development to achieve cost targets:

- **Internal Reforming**
  - simplification of thermal management, elimination of various balance of plant issues
- **Thermal Control Subsystem**
  - integration (internal reforming, adiabatic wall) and simplification
- **Waste Energy Recovery Subsystem**
  - simplification, possibly elimination
- **Materials**
  - potential to reduce stack material costs up to 80%
  - potential to use metal interconnects
- **System operating temperature**
  - lower system operating temperature leads to less expensive materials in balance of plant subsystems

Delphi interests

DELPHI Automotive Systems

Delphi is interested in leveraging multiple applications

(i.e. military, stationary, portable power and automotive)

in the interest of <u>accelerating</u> technology development.

Three year goals

DELPHI Automotive Systems

– **Fuel Cell Design and Manufacturing objectives**

• Operating Temperature:	750 to 800 °C
• Current Density (stack):	0.5 to 0.7 A/cm^2
• Power Density (stack)	1.75 kW/L
• Normal Operating Voltage (cell)	0.7 to 0.8 V
• Stack Cross Section (cell)	15 x 15 cm
• Production Cost (stack)	$200 / kW

Priority R&D topics

DELPHI Automotive Systems

SUBSYSTEMS / BALANCE OF PLANT

- validation and optimization of stack / reformer in automotive mechanization
- innovation of low cost, high performance high temperature heat exchangers
- cost effective and standardized electrochemical hardware
- robust low cost, high temperature sensors and actuators
- low cost, high performance insulation

MANUFACTURING - processes for high volume production

- integration: optimize total system for fewer and lower cost components
- reliable low-cost processing
- alternative seal designs
- simple, compact internal reformer

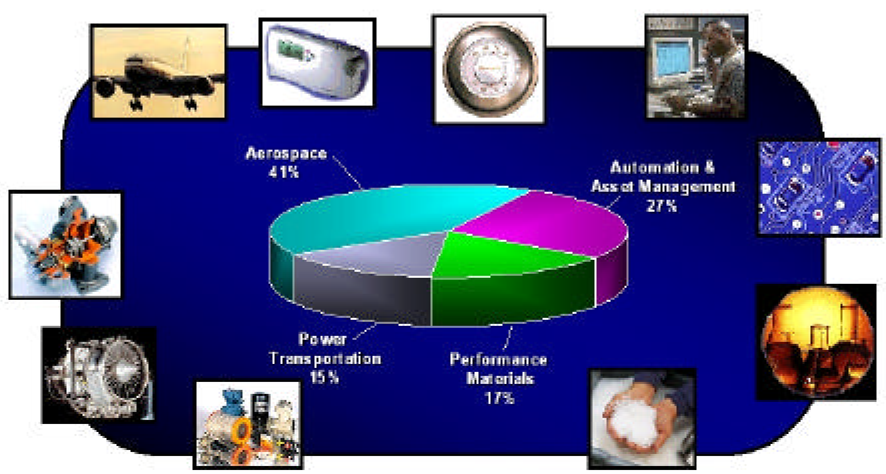
Honeywell

Honeywell Solid Oxide Fuel Cells
Markets and Technology Status

Nguyen Minh
Honeywell Engines & Systems
Torrance, CA

SECA Workshop
Baltimore, MD
June 1-2, 2000

The New Honeywell: A Broader-Based Company



Increased diversification = increased product offerings

Honeywell

SECA Meeting
June 1, 2000

SECA.ppt- 2

Approaches to SOFC Technology

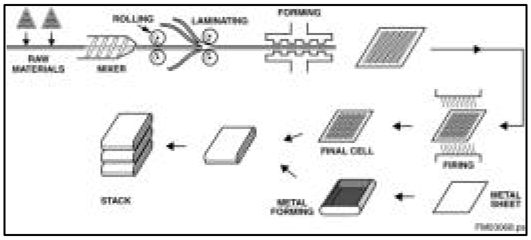
- Light weight and small size
- High performance
- Modularity
- Fuel flexibility
- Low-cost manufacturing and material

SECA Meeting
June 1, 2000

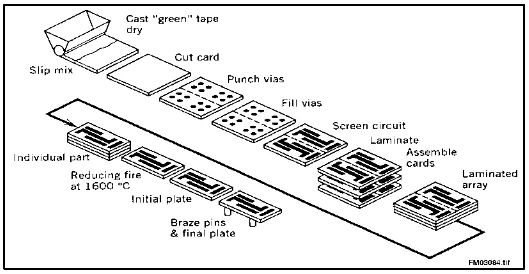
SECA.ppt- 3

Low Cost Manufacturing Process

- Stack fabrication process with tape calendering



- Multilayer electronics fabrication process



SECA Meeting
June 1, 2000

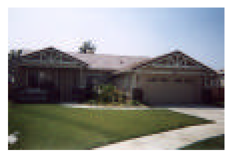
SECA.ppt- 4

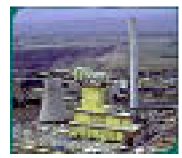
SOFC Applications

Portable
e.g. emergency, remote, recreational

Military
e.g. battery charger, APUs, motive power

Transportation
APUs





Stationary
e.g. residential, distributed, central

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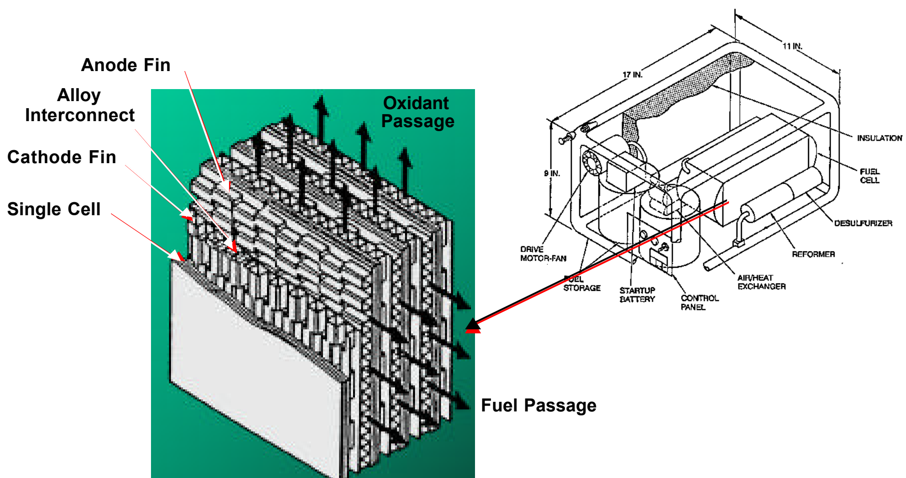
June 1, 2000

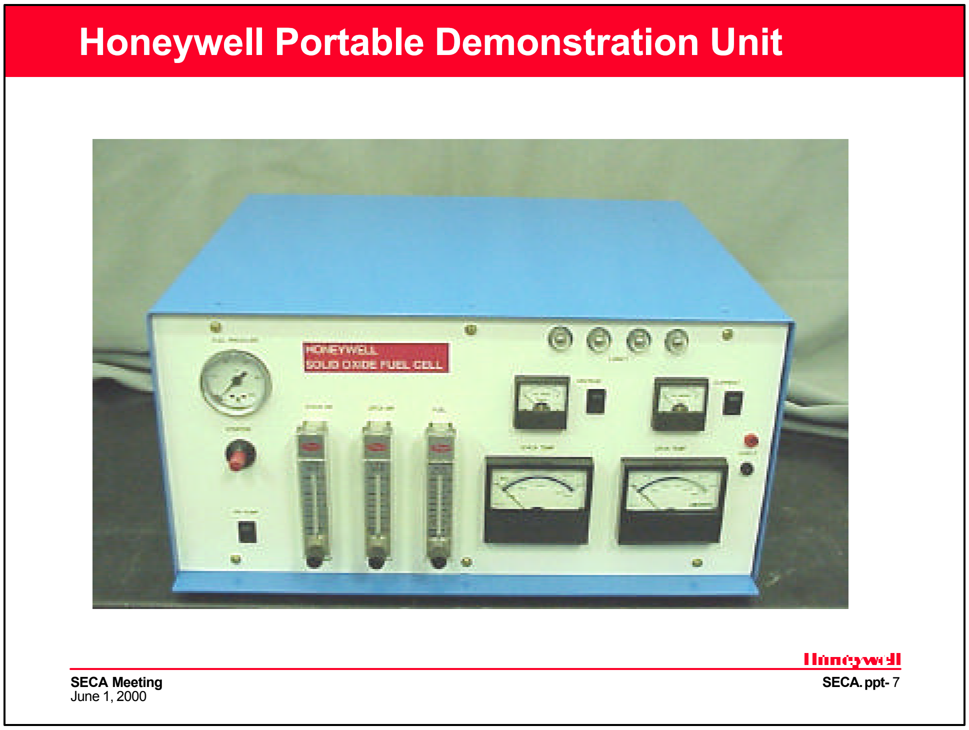
SECA.ppt- 5

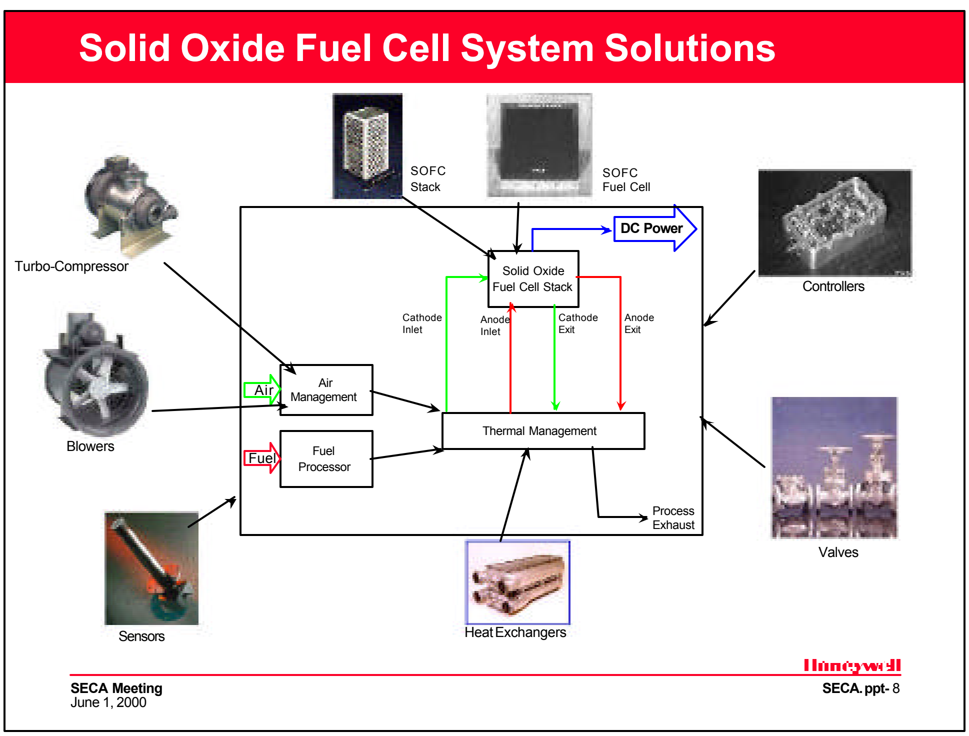
Solid Oxide Fuel Cell Battery Charger



SECA Meeting
June 1, 2000

SECA.ppt- 6


Honeywell Portable Demonstration Unit
HONEYWELL
SOLID OXIDE FUEL CELL
Honeywell
SECA Meeting
June 1, 2000
SECA.ppt- 7


Solid Oxide Fuel Cell System Solutions
SOFC
Stack
SOFC
Fuel Cell
Turbo-Compressor
DC Power
Solid Oxide
Fuel Cell Stack
Controllers
Cathode
Inlet
Anode
Inlet
Cathode
Exit
Anode
Exit
Air
Air
Management
Blowers
Fuel
Fuel
Processor
Thermal Management
Process
Exhaust
Valves
Sensors
Heat Exchangers
Honeywell
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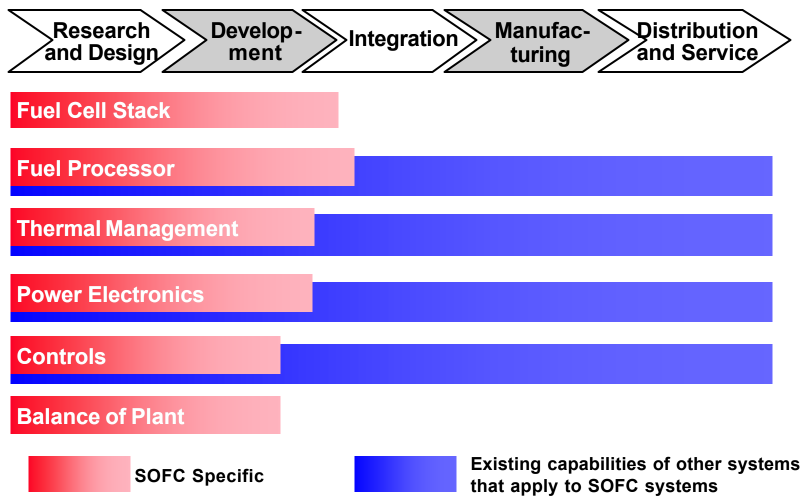
June 1, 2000
SECA.ppt- 8

Planar SOFC Products - Status of Development



Honeywell

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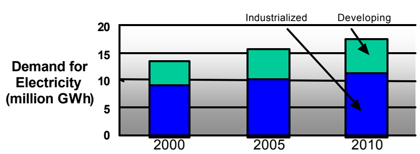
June 1, 2000

SECA.ppt- 9

Stationary Power Growth

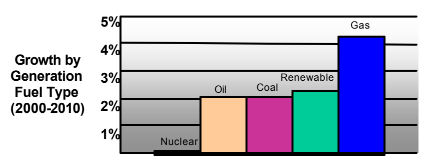


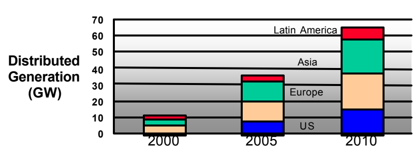
Demand for Electricity is Growing

3% CAGR

Natural Gas-Based Generation is Leading the Growth

4.3% CAGR





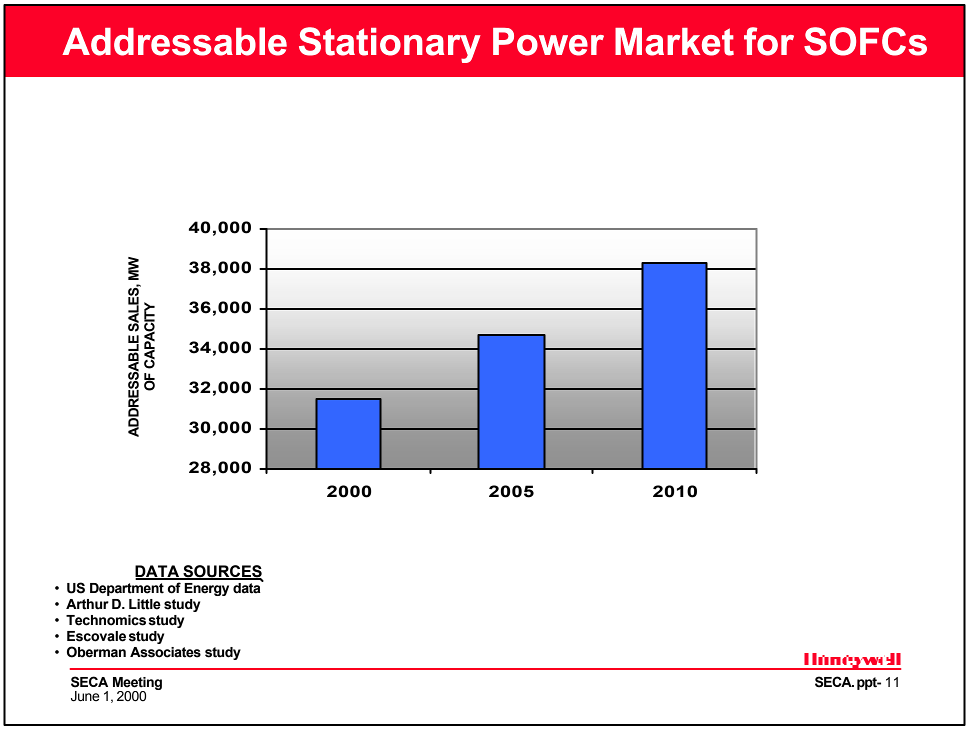
Distributed Generation is High Growth

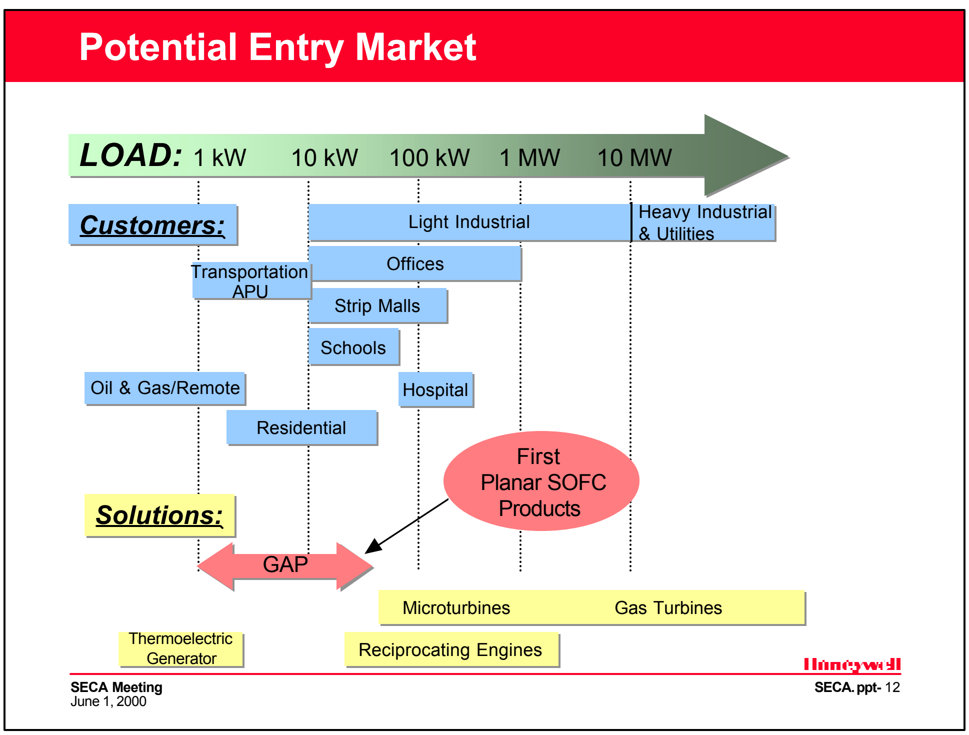
20% CAGR

Honeywell

SECA Meeting
June 1, 2000

SECA.ppt- 10


Addressable Stationary Power Market for SOFCs
ADDRESSABLE SALES, MW OF CAPACITY
40,000
38,000
36,000
34,000
32,000
30,000
28,000
2000
2005
2010
DATA SOURCES
• US Department of Energy data
• Arthur D. Little study
• Technomics study
• Escovale study
• Oberman Associates study
Honeywell
SECA Meeting
June 1, 2000
SECA.ppt- 11


Potential Entry Market
LOAD: 1 kW 10 kW 100 kW 1 MW 10 MW
Customers:
Light Industrial
Heavy Industrial & Utilities
Transportation APU
Offices
Strip Malls
Schools
Oil & Gas/Remote
Hospital
Residential
First Planar SOFC Products
Solutions:
GAP
Microturbines
Gas Turbines
Thermoelectric Generator
Reciprocating Engines
Honeywell
SECA Meeting
June 1, 2000
SECA.ppt- 12

Concluding Remarks

- Honeywell has been developing low-cost, high-performance planar SOFC technology for a broad spectrum of power generation applications
- Honeywell has developed business plans and technology roadmaps to commercialize SOFC products

Honeywell

SECA Meeting
June 1, 2000

SECA.ppt- 13

Fuel Cell Markets

SECA Workshop

W. P. Schweizer
June 1, 2000

Fuel Cell Markets

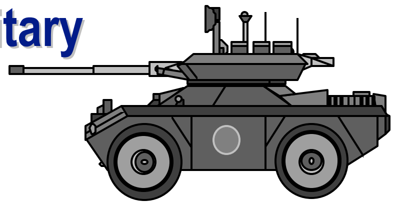
Clean Energy for the World

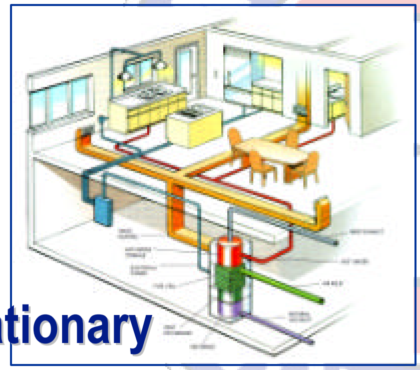
SOFCo

WPS00530 / 2

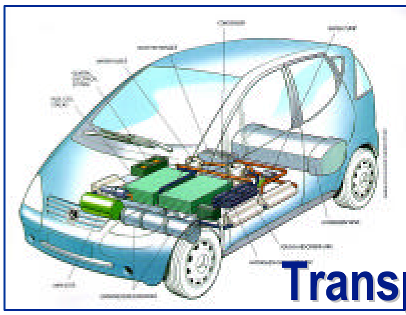
Fuel Cell Markets

Military





Stationary



Transportation

WPS00530 / 3

Fuel Cell Markets

Key Drivers

- Enabling Technology
- Performance
- Cost

WPS00530 / 4

Fuel Cell Markets

Market Size

- Military
- Stationary
- Transportation

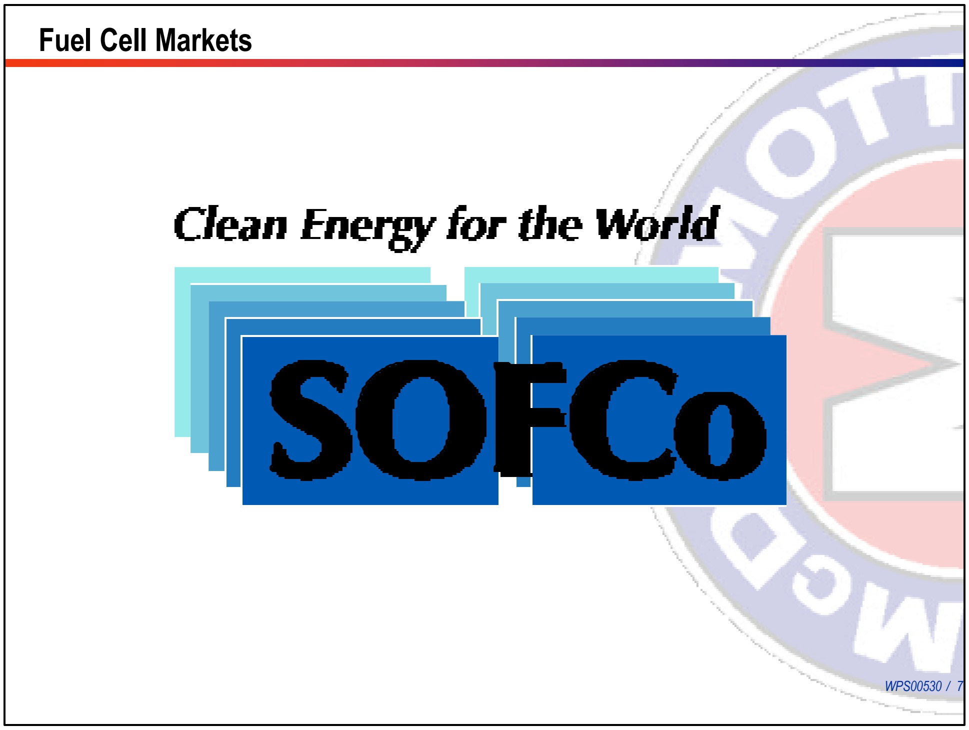
WPS00530 / 5

Fuel Cell Markets

Keys to Success

- Make it work!
- Make it cheap!
- Deliver the value!

WPS00530 / 6


Fuel Cell Markets
Clean Energy for the World
SOFCo
WPS00530 / 7

H. SECA: NEAR-TERM PROGRAM OPPORTUNITIES

Wayne A. Surdoval, SECA Project Manager
U.S. DOE, National Energy Technology Laboratory

SECA SOLICITATIONS

Near-Term Opportunities

Schedule

By Wayne Surdoval
SECA Project Manager
NETL

Near-Term Solicitations

- **Two FY 2001 Solicitations**

  Industry Team Solicitation
  (60% of SECA budget)

  Core Technology Program Solicitation
  (40% of SECA budget)

- **Size of the SECA budget depends on FY 2001 Legislative support for Fuel Cell Technology. Not finalized till later in the summer**

Industry Team Solicitation

- It is anticipated that two to three Industry Teams will be awarded in FY 2001 for a three year performance period.
- The primary deliverable will be a functioning prototype that meets the three year intermediate goals identified in the solicitation.
- Selection will be based on both Business and Technical criteria.
- It is anticipated that Cooperative Agreements will be awarded with 20% cost share for Phase I.

NETL

Core Technology Program Solicitation

- Selection Criteria will be more heavily weighted toward Technical considerations.
- Topics will be based on Industry Team needs. Periodic review meetings will be held.

NETL

Industry Team Solicitation Schedule

- July 14, 2000 - Solicitation issued for Public Comment
- September 15, 2000 - Solicitation posted in the Commerce Business Daily
- October 2, 2000 - Solicitation issued
- December 15, 2000 - Proposals due

Core Technology Program Solicitation Schedule

- April 16, 2001- Solicitation posted in the Commerce Business Daily
- May 1, 2001 - Solicitation issued
- June15, 2001 - Proposals due

II. SECA: Question and Answer Session

Joe Strakey: Thanks, Wayne. I'm sure you all have some questions about the program and about what Wayne just talked about, as well as intellectual property and things of that nature. So I'll ask our panelists to come up, and we're going to take some questions from the floor.

Mark [Williams], Lisa [Jarr], Gary McVay, I'm going to ask all of you to use the microphone so that everybody can hear. If we don't get to your questions, just fill out a slip of paper and drop it off at the registration desk, and we'll get back to you with answers as best we can. [Note: None were submitted.] There are still things that are not 100 percent defined, so you may not get the firm answer that you might like. If we do get stumped, we can always turn to our other participants in the program who may be able to answer some of the questions that we can't.

With the remaining time, we'll try to take some questions for the people who spoke this morning. As I mentioned before, we cut off questions so that we could keep to the schedule. So with that, would someone like to start it off?

By the way, before you start, I should mention the following. You know Wayne [Surdoval]. Mark Williams is the Product Manager for our Fuel Cells Program at NETL. Gary McVay is from PNNL, where he manages Materials Programs, and he's our SECA contact for this program. Lisa Jarr is one of our attorneys. She specializes in the intellectual property area and she has had much to do with the development of the "exceptional circumstance" that will provide for limited non-exclusive licensing within the SECA pilot-program.

Sy Ali (Rolls-Royce): Mr. Rudins mentioned he would like to see $400 per kilowatt by 2010. The speakers indicated values for central power under $700 to $800 per kilowatt without indicating the date. When do they expect to get to $400 per kilowatt?

Wayne Surdoval: The program right now is structured such that the $400 per kilowatt goal is a 2010 goal. It's pretty clear that we will have three phases. Phase 1 and phase 2 will have less aggressive cost goals. However, they will be aggressive enough that we can clearly get into a broad market even at these initial goals.

Joe Strakey: Keep in mind that we're trying to get to large central station plants using solid oxide technology in the 2015-and-beyond time frame for Vision 21 applications.

Lyman Frost (INEEL): Could you speak a little bit more to the sharing of the intellectual property and how that is going to work?

Lisa Jarr: The vision of SECA was that it would be critical to have the technology developed by the Core Technology Program available to all of the Industrial Integration Teams. Because we are a Government agency, we are restricted by law in taking certain rights from small businesses and nonprofits, such as universities, unless there is an exceptional circumstance under which we feel that we need to do that. We feel that this program represents such an exceptional circumstance. So we are going forward to get permission to require the Core Technology Program developers to offer to the Industrial Integration Teams a non-exclusive license, under reasonable terms and conditions, for any patented technology that they develop. This option would be available for a period of time — probably a year after a patent is issued — and the Industrial Integration Teams could express an interest in whether they would like to engage in negotiations for such a non-exclusive license. The negotiations would be between the patent owner and the Industry Integration Teams.

Joe Strakey: Let me add to that. There's an important connection between the Industrial Integration Teams and the crosscutting developers of the Core Technology Program. That is the Industrial Integration Teams have something to gain from the technology that's developed by the Core Technology Program. They can get a non-exclusive license to the technology, which otherwise they may not have access to. With the exception circumstance in place, it will be an incentive for the Industrial Integration Teams to act as a guiding body to give the Alliance ideas, through DOE, of what research is important and relevant to the industry teams. We think that's a very important connection, and we're going to proceed with getting that in place.

Lisa Jarr: Right. And the benefit to the core technology developers is that they have a group of licensees for their technology where they can reap some benefit back to their programs. We think it's a win-win situation for all involved.

Wayne Surdoval: We plan to put a substantial amount of the budget into the Core Technology Program because, in return, it does help the alliance. In terms of this program; focusing this program; keeping it focused; if this relatively minor intellectual property change in fact is available, it will be critical to keeping the program focused. Otherwise, there wouldn't be much motivation for all of the participants in the program to work together.

Momtaz Mansour (ThermoChem): On intellectual property, unless you provide reciprocity, so that patent holders of enabling patents also have the right to license stack technology, then you're going to have a lot of litigation on your hands. If there's reciprocity in the program, there will be cooperation. But if you're going to make it such that technology invented somewhere in a small business has to end up in the hands of a bigger company, it's not going to fly.

Lisa Jarr: We're talking about non-exclusive rights.

Momtaz Mansour (ThermoChem): There's no such thing. Once you non-exclusively license the technology, it's lost its value. The other issue is: 18 to 20 years ago, the question was reduction in cost of the stack and the material cost. I remember the number; it was $285 per kilowatt at that time for a solid oxide fuel cell, and the target was $400 to $500. What is new that we know now that allows this target to be real? What is it? Why is this costing so much? Is it the mass production, the lack of market? What is the issue?

Gary McVay: For the first time, we've got the type of industry interested in and committed to making solid oxide fuel systems that has the low-cost production capability for it to become a reality. I mean, that's what these folks, the suppliers to the auto industries, do for a living. So that's one of the new things. And the other thing is that we have a market pull. We have a customer saying "if you can do, we'll buy it." We've got an order in place for it. And technology has moved along. We haven't stood still since the time you were talking about, and so we have better approaches to things. I think it's a combination of technology advancements and getting high-volume, low-cost producers involved.

Mark Williams: I would like to emphasize that there's been a tremendous amount of progress in the fuel cell industry in the last 18 years, witnessed by numerous scale-ups and improvement in materials and components.

Wayne Surdoval: Some other factors too: One thing we're emphasizing is high power-density design. If you could increase the power density by a factor of two, you can substantially reduce your stack cost by that alone. We have had a number of studies done. If you look at the material cost at the higher volumes of projected production; the more simple manufacturing methods applicable to flat ceramic plates such as tape casting and screen printing; and if metallic interconnects are viable, the cost numbers do come out to $400 per kilowatt as a reasonable goal. We have several studies that show this.

Dave Archer (Carnegie Mellon): I guess I wanted to make a special plea for those of us intended to respond to your multi-level fuel cell fabrication proposal. We had hoped to respond to that, and we're told that a new program that you've announced today would be available. But it seems a rather long time to wait from now, when we had hoped to make a proposal to your multi-level fuel cell proposal, to the time when core support proposals will be entertained, approximately a year from now, I guess. A year's vacancy is a concern.

Wayne Surdoval: Today we are only speaking about the SECA program. There are other programs throughout DOE. There will be many opportunities. There are SBIR opportunities. There are opportunities through AR&TD [Advanced Research and Technology Development]. We actually have a solicitation on the books — it's written, and ready to be issued shortly — that would be directed to the universities. There will be other opportunities. This is strictly SECA. The SECA program will be an industry-driven program, but there will be other work. We also need to keep other work going to achieve the longer-term breakthroughs that can help us down the road.

Joe Strakey: Let me add that in the Government, the budget cycle is at least 2 years, so making a change in program direction is difficult, and we felt that it was important not to get people started in one direction and then change it once the contracts were awarded. So, with this slight delay, we pay a price, but I think in the long run it will provide additional opportunities for developers in this area, and will avoid early terminations or anything like that.

Gerry Agnew (Rolls-Royce): I'd like to return to an earlier topic and raise a question: What happens to the background IPR [intellectual property rights] for the existing stack development technology people who participate in this? And related to that is the question: For somebody who has the option to be in a vertical integration team or who has stack technology developed in-house, if we go in as a vertical integrator, are we just paying for the development programs that other people were involved in when we have a stack program of our own? How are you going to handle the background IPR for the core developers?

Lisa Jarr: The DOE intellectual property provisions will apply to any of these awards. And for large businesses, there is a background patent licensing requirement. It's never been invoked, that I'm aware of, by the Government — at least not by the Fossil Energy program — but it is a statutory requirement. The large businesses will be able to apply for a patent waiver for any inventions that they make under this program. But there is a limited background patent license requirement for purposes of practicing technology developed under the Government-funded program, which in this case would be, I guess, a financial assistance award under SECA. It's something that we really cannot get away from. But as I mentioned, it has not been invoked in any program that I'm aware of.

Gerry Agnew (Rolls-Royce): That would imply then that you don't feel you're building substantially on the existing IPR — the older IPR will be new IPR.

Lisa Jarr: Well, I think the idea is not for us to do fuel cell development, but to help you folks do it. The reason that we would invoke a background patent license would be if you've done work for us under this program and basically put it on the shelf, and we would have somebody that comes to us and say "We want to practice that technology that you paid to have developed," and we need to have a background patent license from Rolls-Royce or someone else. The intention is that you're going to be off practicing this technology in the marketplace and that we're not going to have to get to that point.

Joe Strakey: If there's a market need for a technology that's not being satisfied because somebody is sitting on the invention, that's hard to imagine that's going to happen. I've heard a story that it happened once in DOD, but . . .

Lisa Jarr: Did you have another part to your question?

Joe Strakey: I didn't quite follow the second part.

Gerry Agnew (Rolls-Royce): Yes, the question really is: Will the vertical integrator effectively end up licensing technology that was developed before this program began?

Joe Strakey: Licensing it to core program?

Gerry Agnew (Rolls-Royce): Implicitly.

Lisa Jarr: You're looking at the risk to your existing intellectual property — is that the idea?

Gerry Agnew (Rolls-Royce): Well, essentially, for Rolls-Royce, if we join as a vertical integrator, we're effectively going to be climbing on the back of Honeywell or other people's development programs, and yet we have our own. So, what is the incentive for us to do that? We're just helping those guys in some ways. That's the question in my mind.

Joe Strakey: There's some confusion on this. Your intellectual property rights are the vertical developers' and wouldn't pass on to anyone else. You'd be building on what you've done before.

Joe Strakey: You mean in the horizontal teams?

Wayne Surdoval: Well you can certainly act as a n industrial integration team. I mean a single company can act as a vertical integrator if you can meet all the requirements that will be in the solicitation for a vertical team. I don't really see a conflict myself.

Joe Strakey: More concerned about being of the Core Technology Program?

Wayne Surdoval: Yes, a company can also be part of the Core Technology Program. But in that case, whatever the intellectual property requirements are, you've simply got to accept them. And, if you choose to do that, then you're part of the technology pool. I would fully expect that certain companies would develop intellectual property or technology in-house as part of an industrial team, as well as be interested in what's going on in the core program. The core program is more for breakthrough technology. I would not expect you to be part of the core program if you had a significant prior intellectual property position ready for licensing, and in order to work in the core technology program you had to divulge that. I would think you would keep that in the industry team. There's no reason why you couldn't. That's your choice.

Joe Strakey: Other questions? How are we doing on time here? Are there any quick questions for any of the speakers this morning? You have to come to the microphone.

Steve Visco (LBNL): I have a question. It's kind of an organizational question. It also ties into IP [intellectual property]. If you have these kind of integral, vertical teams, which are, say, self-contained, but they can license technology from these horizontal core technology teams, you've also got the issue of these horizontal teams working, I assume, with the various vertical teams. And there's always this problem of cross contamination. I mean, there's going to be some sensitivities, I would think. You've got a hot project going in a vertical team; you've got members from horizontal teams who are seeing everybody's technical problems and trying to solve them. How are you going to keep the barriers there? How's that done in terms of intellectual property and how these two teams work with one another on two sets of teams?

Wayne Surdoval: I think that's up to the participants. We recognize that cross contamination could exist. I think the national labs in particular deal with that all the time.

Joe Strakey: Let me add to that. I think that maybe there's some misperception. The idea is that the industry team would provide input to the Government. DOE would decide what topics should be pursued on the horizontal teams, and we would issue solicitations. So, it's not like the horizontal team members would be working daily with each one of several vertical developers. I think that probably solves it.

Steve Visco (LBNL): So you will have separation?

Wayne Surdoval: Yes. The core program will consist of very specific contracted pieces of work.

Joe Strakey: See, it goes through our project management. You've got industry input, which feeds through project management, and it keeps it separated that way. Okay, we got a couple more.

Lyman Frost (INEEL): Let me ask one more question, following up on what you've just said. Underneath Federal law, the national labs are not allowed to work exclusively with any particular company. They have to be able to go to any of a number of companies if they want that area of expertise. Are we going to be able to work exclusively with industrial companies to protect their technology base in this area?

Lisa Jarr: Maybe I don't follow completely the restriction on the national labs, but I think . . . you're talking about in the core development program now?

Lyman Frost (INEEL): Yes, in the core development team, if more than one company wants to work with you in a particular area of technology, you have to be willing to work with each one of those equally. So the question I have is: If we were working on one of the core teams, would we be able to work exclusively with an industrial team in a particular area of technology?

Wayne Surdoval: I think in the core program, assuming things go as planned, you would almost by definition be working for everybody.

Joe Strakey: For the public, yes.

Wayne Surdoval: Now, in the other sense, if you wanted to establish a CRADA with a specific company, within the rules of establishing a CRADA, that would also be acceptable.

Lisa Jarr: I think, in that case, you probably would be talking about working with one of the industry integration teams versus the core program. Then, whatever rules and restrictions fall from contracting or doing CRADAs with a certain company would apply. We anticipated . . . and we've had national labs as subcontractors or team members on these teams before . . . and we anticipate that that could happen under these industry integration teams also.

Gary McVay: Almost by definition, when you're working on a core team problem, you're working with all of the industries. They all are interested in the solution of that problem and will receive the output of that research.

Joe Strakey: Just like any national lab project now. I don't see any difference except for this one of intellectual property.

Joe Strakey: Last one before lunch.

Ismail Celik (WVU): I am from the University. I see one component missing from the SECA program. That's the education of the engineering students for supplying the demand for this mass production and maintenance and all these . . .10, 20, maybe 30 to 50 years. How do you envision supplying this demand without a program in curriculum development in solid oxide fuel cell technology or in general fuel cell technology?

Wayne Surdoval: We're working on that now. As I said, the SECA program certainly encompasses universities. And when you encompass universities, typically you are training grad students. At the same time, we have other solicitations available. There is one that is not on the street quite yet, but when you read it, it is specifically written to enhance educational opportunities and support graduate student training for solid oxide fuel cell work. Again, there are other funding avenues besides SECA. This is strictly SECA. This is a very short-term industry driven program.

Joe Strakey: I'm going to have to cut it off because were running late.

III. Intellectual Property Fact Sheet

Exceptional Circumstances for Work Proposed Under the Solid State Energy Conversion Alliance (SECA) Pilot Program

An Exceptional Circumstance determination is required to implement a slightly modified intellectual property agreement (relative to the Department of Energy Acquisition Regulations (DEAR)) in contractual or financial assistance arrangements with members of the Solid State Energy Conversion Alliance (SECA) Core Technology Program (universities, National Laboratories and other research-oriented programs). This modification of the standard DEAR intellectual property agreement is critical to the SECA structure and the implementation of the program. SECA is regarded as a pilot-program demonstrating a new Department of Energy (DOE) business model. Without this modification this pilot-program could not be implemented in a significant way. A brief description of SECA and the modified intellectual property agreement is discussed in the following paragraphs. DOE does not intend to modify any existing practices with regard to background rights. The purpose of SECA is to focus significant resources on a well defined technology target that in DOE's judgment has broad applicability. DOE believes the Exceptional Circumstance will ensure that the individual research organizations that receive substantial resources from the SECA budget will benefit both the Alliance and themselves. If the Exceptional Circumstance were not implemented, the majority of funding available for research would most likely be funneled through the industrial concerns at their discretion as it has been in the past.

The statutory authority for the Exceptional Circumstance follows. The implementation of this Exceptional Circumstance determination will further the goals of 35 U.S.C. § 200, e.g., to promote collaboration between commercial concerns, and nonprofit organizations and small businesses. Exceptional circumstance determinations are authorized by 35 U.S.C. § 202(a) when the agency determines that restricting of the right to retain title to an invention resulting from federal sponsored research and development "will better promote the policy and objectives of this chapter." This Exceptional Circumstance determination will better promote the following policy and objective of the Congress as described in 35 U.S.C. § 200: to use the patent system to promote the utilization of inventions arising from federally supported research or development; to promote collaboration between commercial concerns and nonprofit organizations, including universities; to ensure that inventions made by nonprofit organizations and small business firms are used in a manner to promote free competition and enterprise; and to promote the commercialization and public availability of inventions made in the United States by United States industry and labor.

The DOE is exploring a new business model by implementing the SECA Pilot Program through the National Energy Technology Laboratory (NETL) in partnership with the Pacific Northwest National Laboratory to develop solid-oxide fuel cell technology for a broad range of applications. The major element of the pilot program is the development of highly efficient, cost-effective and mass-producible solid-oxide fuel cell systems. The SECA goal is to enable the implementation of the mass-customization approach developed by U.S. Industry to solid-oxide fuel cell technology. This program offers the prospect of improving the overall efficiency of power generation by a factor of two over traditional technologies and with greatly reduced emissions. These solid-oxide fuel cell systems have also been identified as one of the key enabling technologies for achieving the efficiency goals in DOE's Vision 21 Program.

The SECA will be structured into Industrial Teams and a Core Technology Program (an applied research and development program consisting of universities, National Laboratories, and other research-oriented organizations). A NETL led project management team will maintain responsibility for both of these activities. The Industrial Teams will develop the fuel cell stack, system, and manufacturing capability and the packaging needed for different markets; the number of teams will depend on the level of commitments from sponsors. The Core Technology Program will be focused on finding solutions to the more difficult shared technical barriers in support of the Industrial Teams.

In brief, the proposed intellectual property agreement will require members of the SECA Core Technology Program to offer to each of the Industrial Teams the first option to enter into a non-exclusive license upon terms that are reasonable under the circumstances, including royalties, for subject inventions developed under the SECA program. The field of use of the license could be limited to solid-oxide fuel cell applications, although greater rights could be offered at the discretion of the invention owner. The offer must be held open for at least 2 years after the U.S. patent issues and the invention owner must agree to negotiate in good faith with any and all Industrial Teams that indicate a desire to obtain at least a non-exclusive license. Exclusive licensing may be considered if only one Industrial Team expresses an interest in licensing the invention. Partially exclusive licenses in a defined field of use may be granted to an Industrial Team, as long as doing so would not preclude any other Industrial Team that indicates a desire to license the invention from being granted at least a non-exclusive license for solid-oxide fuel cell applications. The Core Technology Program participant that owns or controls the invention must enter into good faith negotiations with the individual Industrial Team. If no agreement is reached after 6 months of negotiations, the Department of Energy may grant such a license itself if it determines that the invention owner has not negotiated in good faith. Any assignment of the invention must be made subject to this requirement.

The following discussion provides additional justification for the SECA pilot-program exceptional circumstance:

- By making the intellectual property available to the Industrial Teams on a non-exclusive basis, the value of an individual license may be less but the cumulative value may very well be greater. If the intellectual property is important, all Industry Teams will need to have it to remain competitive, the baseline of the technology will be raised.

- Making the intellectual property available to as many Industrial Teams as want it, would ensure that the individual technology pieces are incorporated into the best designs versus that of only the highest bidder (not necessarily the technology with the best chance for commercial deployment). This would benefit U.S. National interests.

- If Core Technology Program participants could exclusively license to anyone they chose, including outside of the SECA Industrial Teams, then it would be unlikely that Industrial Teams would be willing to collaboratively define the Core Technology Program objectives. Based on past fuel cell program experience, Industrial Teams in general would prefer to keep most development work in-house. This is not necessarily the best technical approach or best use of public funds since an individual company would typically not possess a concentration of the best talent; redundant equipment and facilities would have to be purchased; and redundant research and development efforts would have to be performed. This would negate the SECA goal of leveraging the most difficult problems to accelerate commercialization of this nationally important technology.

A market for the intellectual property is being created. The Core Technology Program participants will have a ready set of potential licensees to which they can license their invention(s), and, if the Industrial Teams are successful in commercializing their fuel cell systems, reap income in the form of royalties or cash payment. Also, in many cases where difficult negotiations for exclusive arrangements can keep intellectual property unavailable for significant lengths of time, companies can find ways to bypass intellectual property held by others. There is less incentive for a company to circumvent another entity if a mechanism is in place to make the intellectual property readily and immediately available. Parallel negotiations for non-exclusive licenses and the time limits imposed by the Exceptional Circumstance should significantly shorten the time it takes to implement new intellectual property. In addition, once an agreement is reached with one Industrial Team, agreements with the other Teams should quickly follow if the intellectual property has general applicability.

APPENDIX A
BREAKOUT SESSION RESULTS

I. MATERIALS AND MANUFACTURING – SESSION A GROUP SUMMARY

Issues

In order to achieve the SECA goals, the following technology issues received the largest number of votes:

- Metallic interconnects
- Optimize fabrication technology
- New stack designs
- Better materials for seals that are low cost and easy to fabricate into the stack
- Reducing stack operating temperatures to below 700 C to allow use of bare metallic interconnects

R&D Opportunities

The R&D opportunities were categorized into three header topics. The following are the header topics and the corresponding R&D opportunities that received a multiple number of votes:

Advanced Integrated Fabrication Technology

- Single-step SOFC fabrication technique
- Develop low-cost thin-film fabrication/ manufacturing techniques

Component Development

- Low temperature development   800 C
- Development and investigation of metal interconnect technology

New Stack Design

- New cheap stack design to minimize interconnects and seals
- New stack designs

Actions

The group's blend of industry, academia, government and national laboratory personnel produced several in-depth technical discussions from a theoretical point of view as well as a "real world perspective." These proved to be a very valuable exchange and dialogue for all the participants. Given the timing constraints, it was only possible to develop specific actions for the top three opportunities.

Low Temperature Component Development:

- Mechanistic studies of electrode kinetics
- Optimize performance of mixed conducting cathodes
- Develop a direct oxidizing anode

- Oxidation resistant anode
- Modify anode to control T due to internal reforming
- Investigation of commercially available alloys for metallic interconnects
- Cathode side surface treatments on commercially available metallic interconnect materials
- Investigation of developmental alloys for metallic interconnects

Investigate and Develop Metal Interconnect Technology:

- Interconnect designs that minimize material use
- Investigation of the interconnect and electrode interface
- Explore thermal spray technique
- Control and optimization of sintering of ceramic multi-layers

Advanced Fabrication Technologies:

- Manufacturing cost estimation studies
- Increase mechanical strength of electrode support (or SOFC stack)

In addition to identifying the engineering, development, and research actions, a table was prepared indicating a consensus on the amount of time required to resolve each identified action. In all cases but one, the amount of time required was in the three to six year timeframe. This agrees with the anticipated SECA schedule.

MATERIALS AND MANUFACTURING - SESSION A

PARTICIPANTS

NAME	AFFILIATION
Gerry Agnew	Rolls-Royce
Bill Barker	ITN Energy Systems, Inc.
Scott Barnett	Northwestern University
David Bauer	Ford Motor Co.
Donald Beal	Performance Ceramics Co.
Ray Benn	United Technologies Research Center
Brian Borglum	Siemens Westinghouse Power
Larry Chick	PNNL
Mike Cobb	Michael A. Cobb and Co.
Tom George	DOE/NETL
Diane Hooie	DOE/NETL
Roddie Judkins	Oak Ridge National Laboratory
Benson P. Lee	Technology Management, Inc.
Ron Loehman	Sandia National Labs
Bill Luecke	NIST - Ceramics Division
John A. Olenick	Advanced Refractory Technologies, Inc.
James Ralph	Argonne National Laboratory
Robert J. Remick	IGT/GRI
Bill Schweizer	McDermott/SOFC
Mohinder Seehra	West Virginia University
Scott Swartz	NexTech Materials
Anil Virkar	University of Utah
Steve Visco, Chairperson*	Lawrence Berkeley National Lab
Conghua Wang	University of Pennsylvania
FACILITATOR: Howard Lowitt	Energetics, Incorporated

* = Presenter for report-out

Materials and Manufacturing – Session A: Opportunities Database

• Design interconnects alloy that forms a conducting scale • Improved BOP/system integration • Integrate experiments and modeling to minimize sintering and expansion stresses in co-fired ceramic layers • Aqueous processing and fabrication of SOFC materials (where feasible) • Develop metallic interconnect supported design and fabrication process • Identification of new, high performance, lower cost materials. • Develop new multiplayer fabrication capabilities for cofiring • Search/test new materials for seals	• Chromium-free metallic interconnect • Cheap protective coatings for metallic interconnects • Develop viable electrolyte with 10x higher $0^{=}$ conductivity than YSZ • Develop lower temperature materials • Develop lower cost thin film manufacturing (no UHV) • New anodes/cells that can use hydrocarbon fuels • New, highly electro-active electrodes and development of electrode-supported cells • Development of single-step firing of cells • Single step cell fabrication technology	• Manufacturing cost models • Design for manufacture • Cell stack design • Identify/quantify trade-offs between: pore size dist/amount, gas flow, SOFC performance, and mechanical properties • Develop reliable seals and prove new designs • New electrode materials • Develop cell materials capable of high power density at 700°C and below • Develop new stack designs to simplify manufacturing	• High temperature corrosion of metal interconnects and interfaces • New stack designs • Identify/develop alloys for interconnects • Develop improved extrusion and molding technology for complex parts • Identify and develop durable, high-temperature metal-based interconnects • Custom formulation of metal interconnects • New methods for high temperature, multi-material joining and sealing • Identify and develop seal material/design systems	• Search/test alloys for interconnects • Investigate novel stack designs • Stack modeling • Methods for low cost, high speed deposition of SOFC stack materials • Develop new materials having increased ionic conductivity at reduced temperatures • Develop manufacturing technology which makes stack production cost low

Materials and Manufacturing – Session A: Issues

(✪ = Vote for Priority Topic)

• Given a good fuel cell? How does one verify – technical test issues ✪ • Rapid cooldown technique thermal designs • Activation potential • Sulfur poisoning of anode • Complicated thin film/coating technology • New stack designs ✪✪✪✪ • Innovative stack design	• Concurrent operation of metallic plates at operating temperature of ionic conducting ceramics • Better materials for seals low cost, easy to fabricate into stack ✪✪✪✪ • Durable sealing (stack design/bonding agent) ✪✪✪ • Development of thinner cell components to lower amount of material per cell • Hydrogen as fuel, new anode • Stack must survive rapid thermal cycling	• Interconnect inventory • High working temperature 800°C 700°C • Bi-polar supported (metallic) SOFC for cost reduction • Cathode performance • Expensive cathode materials • Synergistic impact of R&D on issues • Greater, more available body of knowledge and data (knowledge transfer includes from other fields) • Basic knowledge and data relating to interconnects • Multiple materials currently require multiple fabrication steps/ processes, single step process needed • Low-cost manufacturing of tri-layer cells • Too many manufacturing steps ✪	• Metallic interconnects ✪✪✪✪✪✪✪✪ • Metals do not like to live at temperatures where conducting ionic ceramics like to operate so SOFC operating temperature must drop below 700°C to allow use of bare metal ✪✪✪✪✪✪ • Lower temperature materials ✪✪ • Materials with higher conductivities at lower temperatures • Cells/stacks manufacturing process flexibility • Need materials/sealing geometries that can survive extreme thermal stresses of transient operation/fast startup • Quality consistency in the ability to mass manufacture ceramic cells ✪✪✪ • Quality of materials and fabrication processes • Refinement, in process technology for making cells • Electrolyte (thin film) deposition and sintering ✪	• Complicated manufacturing procedures requiring multiple firings of ceramics • SOFC materials are not computer components • Optimize fabrication technology ✪✪✪✪✪✪✪✪✪ • Small scale (size) extrusion technology needed ✪ • Development of multi-material co-firing to lower manufacturing costs • Low cost, efficient materials • Ability of SOFCs to follow load • Single SECA goals (identify intermediate niches)	• Lack of anodes capable of high fuel conversion with minimal prereforming (maximized efficiency) • Req. use of high cost, dissimilar material properties materials that cause integration challenges • Long term chemical compatibility data

Materials and Manufacturing – Session A: R&D Opportunities

(✪ = Vote for Priority Topic)

ADVANCED INTEGRATED FABRICATION TECHNOLOGY	COMPONENT DEVELOPMENT	NEW STACK DESIGN
• Single step SOFC fabrication technique ✪✪✪✪✪✪✪ • Develop low-cost thin-film fabrication / manufacturing techniques ✪✪✪ • Integrated cell/stack design with fabrication process development	• Low temperature development <800 ✪✪✪✪✪✪✪✪ • Identify new, novel seals and separators for test and evaluation ✪ • Development and investigation of metal interconnect technology ✪✪✪✪✪✪✪✪	• New stack design(s) ✪✪✪ • New stack, cheap design to minimize inter-connects and seals ✪✪✪✪✪ • Conduct trade-off studies, i.e., temperature/materials ✪ • Modeling to enable new design development and cost ✪ • Design economic simulation model of effect of new designs on manufacturing cost • Investigate material vs. design function trade-offs ✪ • Miniaturizations ✪ • Expand knowledge base of SOFC reliability under arbitrary operating conditions

Materials and Manufacturing – Session A: What Are the Actions Needed to Take Advantage of the Opportunities?

R&D Opportunity	Actions	Type of Action	0-3	3-6	6-10	Industry	Academia	National Labs
Low Temperature Component Development	• Mechanistic studies of electrode kinetics	R	X				A	
	• Optimize performance of mixed-conducting cathodes	D	X			I		N
	• Develop direct oxidizing anode	R	X	X			A	
	• Oxidation resistant anode	R	X	X			A	N
	• Modify anode to control T due to internal reforming	D/E	X	X		I		N
	• Investigation of commercially available alloys	D	X				A	
	• Cathode side surface treatment on commercially available alloys	D	X	X		I		N
	• Investigation of developmental alloys	D	X	X		I	A	N
Investigate and Develop Metal Interconnect Technology	• Interconnects designs that minimize material use	E	X	X				N
	• Investigation of interconnect, electrode interface	R	X	X			A	N
	• Explore thermal spray techniques	D	X	X				N
	• Control and optimization of sintering of ceramic multi-layers	R/D	X	X		I		N
Advanced Fabrication Technologies	• Manufacturing cost estimation studies	D/E	X	X		I		N
	• Increase mech. strength of electrode support (or SOFC stack)	D/E	X	X	X	I		N

Key: E = Engineering
D = Development
R = Research

Materials and Manufacturing – Session A: Report-Out

Technical Issues	R&D Opportunities	Key Opportunities	Actions
• Metallic interconnects • Optimize fabrication technology • Lower temperature materials • Durable seals • New stack designs (current stack designs)	• Component development – Low temperature electrode development – Develop and investigate metal interconnect technology • New stack design – Minimize interconnects and seals – Trade-offs driving design of stacks • Advanced integration fabrication technologies – Single-step fabrication technique – Low-cost thin-film techniques	• Low Temperature Component Development	• Mechanistic studies of electrode kinetics • Optimize performance of mixed-conducting cathodes • Develop direct oxidizing anode • Oxidation resistant anode • Modify anode to control T due to internal reforming • Investigation of commercially available alloys • Cathode side surface treatment on commercially available alloys • Investigation of developmental alloys
		• Metal Interconnect Technology	• Interconnects designs that minimize material use • Investigation of interconnect, electrode interface • Explore thermal spray techniques • Control and optimization of sintering of ceramic multi-layers
		• Advanced Fabrication Technologies	• Manufacturing cost estimation studies • Increase mech. strength of electrode support (or SOFC stack)

II. MATERIALS AND MANUFACTURING – SESSION B GROUP SUMMARY

Issues

In order to achieve the SECA goals, the following technology issues received the largest number of votes:

- Fabrication of stacks from cells
- Thin-film manufacturing cost
- Interconnects metal or oxide

While the costs of raw materials is not a major concern now, availability of certain materials (e.g., LSM and YSZ) could be problem down the road if the market takes off.

R&D Opportunities

The R&D opportunities were categorized into five header topics. The following are the header topics and the corresponding R&D opportunities that received a multiple number of votes:

Design

- Develop novel, low-cost cell stack design concepts

Interconnects

- Develop new interconnect alloys from fundamental understanding of oxidation kinetics and oxide conductivity

Fabrication/Manufacturing

- Cost-effective fabrication of high-performance cell stacks including tri-layers, thin electrolyte, electrolyte coating, low temperature, and colloidal deposition
- NDE to enhance manufacturability

Materials Properties

- Develop internally reforming stacks (anode or manifold)
- Develop different anode material for different fuels

Interface

- Fundamental investigations into interfaces-microstructures and catalytic properties
- Investigate novel interlayer for adhesion and chemical protection

Actions

Key action steps were developed for the top three opportunities.

Develop cost-effective fabrication techniques for high performance fuel cell stacks:

- Conduct fundamental studies into why defects occur
- Investigate large scale thin film deposition
- Develop in-situ NDE methods for identifying defects
- Adapt existing ceramic technique for specific fuel cell designs
- Develop low cost interconnect and seals

Develop new interconnect alloys from fundamental understanding of oxidation kinetics and oxide conductivity:

- Examine interface and coatings inter-relations and stability
- Examine stability and electric transport at interface
- Conduct surface modification studies

Develop compact, reliable, low cost fuel cell design concepts:

- Immediately study design as function of performance parameters
- Define cost and performance specifications
- Create ability to evaluate thermal and chemical properties with in-situ diagnostic tools
- Determine effects of high power density on long-term performance
- Build in design review to ensure flexibility to respond to change
- Evaluate transport phenomena
- Evaluate feasibility of internal reforming under multi-fuel conditions

MATERIALS AND MANUFACTURING - SESSION B

PARTICIPANTS

NAME	AFFILIATION
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Peter Faguy	MicroCoating Technologies
Robert Glass	LLNL
Jack (John) Hirschenhofer	Parsons
Kevin Huang	University of Texas at Austin
Kevin Krist	GRI
Meilin Liu	Georgia Tech
Scott Mao	University of Pittsburgh
James Marsh	Concurrent Technologies Corporation
Gary G. McVay	PNNL
Nguyen Minh	Honeywell
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Carl Reiser	International Fuel Cells
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Michael Thompson	PNNL
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* = Presenter for report-out

Materials and Manufacturing – Session B: Scientific and Technology Issues

(✪ = Vote for Priority Topic)

Manufacturability	Interconnect Materials	Cost of Raw Materials	Performance	Stack System Design and Integration
• For target power density no high volume, low-cost tri-layer fabrication technology exists ✪✪✪✪✪ • Need for system integration of stack components and automated manufacturing • Lack of alternatives to the costly EVD process for depositing the electrolyte ✪ • Basic understanding of how electrode/electrolyte reliability is affected by colloidal deposition parameters ✪ • Fabrication of stacks from cells ✪✪✪✪✪✪✪✪✪✪ • Thin-film manufacturing cost ✪✪✪✪✪✪✪ • Lack of NDE for manufacturing	• Lifetime of interconnect materials • Interconnect metal or oxide? ✪✪✪✪✪✪✪ • Lack of inexpensive thermally reliable seals • Metal interconnects needed above $650^{o}C$	• Low demand for LSM, YSE materials • Availability of high V, low-cost raw material ✪	• η of 60 to 70% will require 0.85 V/C+; close to theoretical present is 0.7 V/C • Slow electrode kinetics at low temperature • Limited temperature range • Catalysis limiting issues below $700^{o}C$ • Lack of NDE techniques to predict remaining life ✪✪ • Specific power (W/cm^2) ✪ • Anode composition and structure to permit full *in situ* reforming ✪ • Hydrocarbon tolerances and poisoning ✪ • Design of novel interfaces with minimum resistance ✪	• Thermal management • Low cost PEN with controlled morphology electrodes ✪ • Need for inexpensive thermal insulation • Fuel delivery to all cells in stack • Serviceability of complex fuel stack • Materials compatibility • Settling too soon on tech design • Gas manifolding on mass customization of core module • Need to recycle address disposal/ recycling of materials from stack • Thermal cycling of scaled-up reduced temperature planar stacks

Materials and Manufacturing - Session B: R&D Opportunities

(✪ = Vote for Priority Topic)

DESIGN	INTERCONNECTS	FABRICATION/ MANUFACTURING	MATERIALS PROPERTIES	INTERFACE
• Improve thermal cycle • Develop measures to shorten start-up ✪ • Develop novel, low-cost cell stack design concepts ✪✪✪✪✪✪✪ – Compact with improved reliability – Minimize/eliminate sealing issues	• Compliant metallic interconnect ✪ • Investigate novel thin-film coatings for metallic interconnects – low cost • Develop a) low thermal expansion b) high conductivity material that can survive in both reducing and oxidizing environments • Develop new interconnect alloys from fundamental understanding of oxidation kinetics and oxide conductivity ✪✪✪✪✪✪✪	• Cost-effective fabrication of high-performance cell stacks – Trilayers – Low-cost thin electrolyte processing technology – Develop and scale up electrolyte coating process and thin film stack manufacturing – Low temperature – Study colloidal deposition parameters impact on reliability – flaw development during coating/ debinding/firing ✪✪✪✪✪✪✪✪✪✪ • Develop a repetitive manufacturing process • Flaw development in co-firing (suppression) • NDE to enhance manufacturability ✪✪ • Develop process models for fabrication ✪	• Lower operating temperatures • Solve film adhesion problems • Develop different anode material for different fuels ✪✪ – Novel composites for anodes • Develop internally reforming stacks (anode +/or manifold) ✪✪✪✪✪✪ • Study chemical reactions at all interfaces during the fabrication and operation of electrode-supported thin-film stack ✪ • Conduct modeling of material reliability and life-time production • NDE of lifetime prediction of stack components • Examine long-term dimensional stability of flat plate	• Transport across heterogeneous interfaces and electrode architecture performance • Fundamental investigations into interfaces-microstructure and catalytic properties ✪✪✪✪ • Investigate novel interlayer for adhesion, chemical protection ✪✪✪✪

Materials and Manufacturing - Session B: Actions

R&D Opportunity	Brief description of Opportunity	Type of Action	Key Action Steps	Lead Roles	Other Points
• Develop cost-effective fabrication techniques for high performance fuel cell stacks	• Multi-cell stack extrusion • Long term-new ways to make ceramics • Lack of volume is main reason costs of manufacturer is high • Dramatic cost reductions are needed. Capital costs of equipment are high • *In situ* firing? • Core can participate in long term – trilayers and PENs • One-step firing • Defects are a problem for reliability • Start with simple traditional techniques	• R • First 3 years use today's process • Longer term other methods will be needed	• Fundamental studies into why defects occur • Investigate large scale thin film deposition – review existing work • Develop in-situ NDE methods for identifying defects • Adapt existing ceramic technique for specific fuel cell designs • Develop low cost interconnect and seals	• Industry • Longer-term concepts – consortia –NL, U	• Do not use material at temperatures higher than you make it
• Develop new interconnect alloys from fundamental understanding of oxidation kinetics and oxide conductivity	• Very difficult problem! • Chromium-are there other materials? • Compounds Oxides, etc. as coatings? • Need scale that is good conductor • Lowering temperature can help • Coatings are possibility but have own problems	• Mostly R and some D	• Ongoing throughout program • Examine interface and coatings inter-relations and stability • Examine stability and electric transport at interface • Conduct surface modification studies	• National labs and universities • Consortium with industrial input	• Watch over next 3-5 years
• Develop compact, reliable low cost fuel cell stack design concepts	• Design new stacks "core" • Making stacks small involves core design issues • Thermal and mass flow in compact SOFC • Modify existing stacks "Industry Group" • Choice of fuel is key	• Core D and R • Industry E	• Study design as function of performance parameters 1st year • Define cost and performance specifications • Create ability to evaluate thermal and chemical properties in situ diagnostic tools	• Industry lead in design	• Need to have ability to change and avoid "lacking in" to particular designs • Focus as quickly as possible on limited number of designs

Materials and Manufacturing - Session B: Actions *(Continued)*

R&D OPPORTUNITY	BRIEF DESCRIPTION OF OPPORTUNITY	TYPE OF ACTION	KEY ACTION STEPS	LEAD ROLES	OTHER POINTS
• Develop compact, reliable low-cost fuel cell stack design concepts (*con't)*	•	•	• Determine effects of high power density on long term performance • Build in design review to ensure flexibility to respond to change • Evaluate transport phenomena overtransient long term condition • Evaluate feasibility of internal reforming under multi-fuel conditions	•	•

Key: E = Engineering
D = Development
R = Research

Materials and Manufacturing – Session B: Report Out

Design and Manufacturing	Breakout Session Overview	Materials	Closing Remarks

• Design is developed by industry
  – Design affects manufacturability
  – Novel ideas should be explored
  – Address transient operations/thermal cycling
• Near-term – refining tapecasting
• Long-term – “multi-cell extrusion”
	• Achieving cost goals is dominating factor
	• Major materials issues
	  – More specific than manufacturing issues at this time
		• Nature of electrolyte and electrode did not emerge as major issue
		  – Low temperatures, different story (e.g., power densities)
		  – T(E); A/cm^2
		• Interconnects are a major area to address
		  – Membrane contacts
		  – Oxidation
			• Difficult balance – design do not “lock in” too soon but focus as soon as possible
			  – Design reviews
			• Mobile stationary fuels

III. Fuel Processing – Session A
Group Summary

Issues

In order to achieve the SECA goals, the following technology issues received the largest number of votes:

- Catalysis - reduction of the size of processing hardware for multi-fuel
- Operation with little or no water
- Gas contaminant removal or purification
- Very rapid transient response
- Reformer stability during transients
- Fully integrated fuel processor
- Ability to internally reform natural gas

Overall, what is needed is a fully integrated fuel processor with multi-fuel capability that is small and is sulfur tolerant. Also, the reformer must have operational stability during transients, start-up, and shut-down conditions. The critical challenge mentioned repeatedly is either sulfur cleanup or sulfur tolerance. Without resolving this issue, many candidate fuels and markets cannot be considered for solid-state fuel cell system applications.

R&D Opportunities

The R&D opportunities were categorized into five header topics. The following are the header topics and the corresponding R&D opportunities that received a multiple number of votes:

System Development and Demonstration

- System level reformer development
- Development of low-cost, accurate sensors
- Multi-path approach to demonstrate electrochemical reformer

Fuel Characterization

- None

Clean-Up Process

- Develop a liquid phase de-sulfurization system
- Sulfur removal – gas phase H_2S, organic sulfides

Catalyst Development

- Reformer catalyst development
- Catalyst characterization – performance, life, cost
- Combinatorial approaches to catalysts

Modeling

- System modeling to identify optimal strategies for integrating stack and reformer designs
- Transient control, dynamic temperature, and reaction rates in reformer catalysts

Actions

System Level Reformer Development:

- Develop commercial, integrated, reliable reformer
- Develop modular packages for a family of sizes and functions or parameters

Fuel Processor Catalyst Development:

- Determine and characterize catalyst durability vs. fuel and operating conditions
- Improve catalyst yield and efficiency
- Characterize catalysts for sulfur tolerance and fuel consumption
- Develop alternate catalysts via combinatorial approach
- Evaluate sulfur removal techniques in liquid and gas phase
- Define level of sulfur cleanup requirements by fuel
- Evaluate and investigate reaction chemistry
- Evaluate and demonstrate small integrated efficiency reformer
- Maintain data in catalyst database/reformer handbook
- Test method and standard procedures to benchmark designs vs. target requirements
- Evaluate close coupled in-stack reforming
- Evaluate POX and ATR conversion selectivity
- Optimize reformer
- Evaluate integrated system in a remote field location
- Demonstrate catalyst endurance characteristics

System Modeling to Integrate Stack and Reformer Designs:

- Evaluate close-coupled in-stack reforming
- Develop user friendly commercially supported modeling package for reaction kinetics through coupled reformer and stack

The group identified research, development, and engineering actions that would need to be completed within the next 0-5 years and within 5-10 years to achieve the SECA vision. Within the next 5 years much catalyst development and system development activities need to begin. Initially, databases on catalysts and reformers need to be complied and made available based on characterization and trade-off studies and evaluations. From 5-10 years, system optimization and demonstrations should be stressed.

FUEL PROCESSING - SESSION A

PARTICIPANTS

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* = Presenter for report-out

Fuel Processing – Session A
What Are the Science and Technical Issues to Achieving Vision?

(✪ = Vote for Priority Topic)

CATALYST ISSUES	FUEL ISSUES	GAS CLEAN-UP	OPERATIONAL ISSUES	COST ISSUES	SYSTEM INTEGRATION
• Catalyst availability for variety of fuels ✪ • Lack of more predictive catalyst design tools • Catalysis - Reduction of size of processing hardware for multi-fuel ✪✪✪✪ • Catalyst life • Coking problems ✪✪ • Electrochemical reformers ✪ • Sulfur-tolerance and direct electrochemical oxidation ✪✪ – Stable catalyst (sulfur) – Rapid start-up – Partial Ox. Reformer • Sulfur removal, sulfur tolerance to reformer catalyst ✪	• Operation with little or no water (gasoline, diesel) ✪✪✪✪✪ • Small and efficient P.O. reformer for gasoline and diesel 90% conversion ✪ • Direct diesel (multi-fuel) SOFC, Eliminate reformer ✪ • Partial oxidation of liquid fuels with oxygen ✪ • Feedstock flexible ✪ • Logistic fuels – compact, fuel-flexible, rapid response	• Active sulfur removal gas phase ✪ • Desulfurization technology – needs to be high capacity, without need for hydrogen, compatible with metcaptions and thiophenes • Gas contaminant removal (or) purification ✪✪✪ • Pure hydrogen stream • Selective gas separation technologies: oxygen, hydrogen, CO, etc. ✪	• Load following fuel source ✪ • 20 to 1 turndown sensors • Requirement for very rapid transient response rapid transient resp. ✪✪✪ • Reformer stability during transients (startup-shut down – ramp) ✪✪✪✪ • Control sensor how do we know when the reformer is deteriorating? • Freeze protection • Cycling	• Low-cost high temperature heat exchangers ✪ • Materials of construction (high-temperature) • Hydrogen embrittlement • Catalyst cost • O&M	• Fully integrated fuel processor T, heat balance ✪✪✪✪ • Size reduction issues – heat management issues • Start-up requirements cold-hot ✪✪ • Achieving 60-70% efficiency goal without bottom cycle and in volume/wt envelope is challenging • Ability to internally reform (in stack) – Natural gas ✪✪✪ • Control system ✪

Fuel Processing – Session A
What Are the R&D Opportunities to Overcome the Issues?

(✪ = Vote for Priority Topic)

System Development and Demonstration	Fuel Characterization	Clean-Up Processes	Catalyst Development	Modeling

• Develop low cost high temperature heat exchangers ✪
• DOE work in high "R" insulations ✪
• Development of low-cost, accurate sensors ✪✪
• Modular control system concepts
• System-level reformer development ✪✪✪✪✪✪✪✪
• Microchannel reformers for reduced size and integration
• Multi-path approach to demonstrate electro-chemical reformer ✪✪
• Develop low-cost, fully integrated fuel processor module ✪
• Operational characterization of "state-of-the-art" fuel processors (Team)
	• Define and characterize fuels
	• Decide what fuel is best – reference fuels
		• Sulfur removal – gas phase H_2S, organic sulfides ✪✪
		• Long life regenerable sulfur sorbents – demonstrate
		• Nanoporous ceramic membranes for gas purification
		• Develop a liquid phase De-S system ✪✪✪
		• Mixed oxide conductors for fuel processing
			• Catalyst characterization – performance, life, cost ✪✪
			• Develop multi-fuel single catalyst
			• Reformer catalyst development ✪✪✪✪✪✪✪
			  – Steam reforming
			  – POX reforming ✪
			  – ATR ✪
			• Regenerable catalyst, also with in-situ gas cleanup
			• Low temperature (400-600°C) catalysts for direct oxidation ✪
			• Combinational approaches to catalysts ✪✪
			• Nanostructural catalysts
			• Catalyst R&D
			  – "Dry" reforming
			  – Sulfur tolerant
			  – Long life
			  – Low cost
			  – Size reduction
				• Develop reaction kinetics modeling
				  – Different fuels
				  – Different water
				  – Coke formation
				• System modeling to identify optimal strategies for integrating stack and reformer designs ✪✪✪✪
				• Modeling heat flows
				• Chemical reaction modeling for POX ✪
				• Fundamentals of hydrocarbon reforming (in-situ, . . .) ✪
				• Transient control dynamic temperature, temperature and reaction rates in reformer catalysts (chemical modeling) ✪✪✪
				• System modeling "optimizations" toward mass customization

Fuel Processing – Session A
What Are the Actions to Take Advantage of the R&D Opportunities?

System-Level Reformer Development	System Modeling to Integrate Stack and Reformer Designs	Fuel Processor Catalyst development	Lead Role(s)

• Develop a commercial, integrated, reliable reformer
• Modularity – packages/family of sizes and functions (parameters)
	• Evaluate close coupled in-stack reforming
	• Develop user friendly modeling package for reaction kinetics through coupled reformer and stack
	  – Commercially supported platform
	  – Demonstrate and validate
		• Determine, characterize catalyst durability vs. fuel and operating conditions Database (0-5 years)
		• Improve catalyst yield/efficiency life (Research)
		• Characterize catalysts for:
		  – S tolerance
		  – Steam/C ratio (min)
		  – Fuel composition
		• Develop alternate catalysts (combinatorial approach)
		  – Lower cot
		  – Non-noble metal
		  – 0-5 years: membranes? Benefits/tradeoffs
		  – Sulfur tolerance removal
		• Evaluate S removal techniques in liquid and gas phase
		  – Disposable
		  – Regenerable
		  – Active
		• Define level of S clean-up requirements (by fuel
		• Evaluate; investigate reaction chemistry (Research, Development)
		  – Liquid fuels
		  – Steam
		  – Pox
		  – ATR
		  – Electro-chem
		• Evaluate and demonstrate small integrated efficiency reformer (Engineering, Development) (Gaseous)
		  – Gaseous fuels
		  – Steam
		  – Pox
		  – ATR
		• 0-5 Years – Maintain data of catalyst database/ reformer handbook
		• Test method and standard procedures to benchmark designs vs. target requirements
		• Evaluate close coupled in-stack reforming
		• 0-5 years - Evaluate determine P.O.-sooting, ATR conversion selectivity (temp range) diesel and gasoline JPx
		• Trade-offs of reformer types by application (Engineering)
		• 5-10 Years – Optimize reformer (Engineering)
		• 5-10 Years – Evaluate integrated system in remote field location
		• Evaluate and demonstrate a small, integrated, eff. reformer (Engineering)
		• 5-10 years - Demonstrate catalysts endurance characteristics
			• Ultimately – industry
			• Core tech – university and national labs

Fuel Processing - Session A: Report-Out

SCIENCE AND TECHNICAL ISSUES	R&D OPPORTUNITIES	ACTIONS

• Cost Issues
• Integration
  – Fully integrated fuel processor
• Operational
  – Reformer stability during transients (startup, shutdown, etc.)
• Gas Cleanup
  – Gas contaminant cleanup (include S)
• Fuel Issues
  – Min S/C ratios
• Catalyst Issues
  – Develop for multi-fuel and size
  – S-tolerance
	• Modeling
	  – Reaction kinetics
	  – Systems modeling
	• Catalyst Development
	  – New catalysts and characterization of current
	  – S-tolerance
	• Clean-Up Processes
	  – S-removal!!
	  – Other contaminants
	• System Development
	  – Reformer integration with other components
	• Fuel characterization
		• System Level Reformer Development
		  – Split – gaseous
		        – liquid
		  – Further – steam, Pox, ATR, Electrochemical (liq)
		• Fuel Processor Catalyst Development
		• Systems Modeling
		• System (0-5 years)
		  – Evaluate, investigate reaction chemistry
		  – Characterize small reformers
		  – Database on catalysts and reformers
		  – Standard procedures for test/targets
		  – Trade-offs by reformer type and application – list all parameters (soot conversion, others)
		• System (5-10 years)
		  – Optimize
		  – Demonstrate
		• Catalyst Development (0–5 years)
		  – Improve catalyst conv. efficiency and life
		  – Characterize existing catalysts (S, S/C, etc.)
		  – Develop alternate catalysts (cost , S)
		  – S cleanup, liq phase
		  – Membranes
		• Catalyst Development (5-10 years)
		  – Demonstrate!
		• Systems Modeling
		  – Evaluate coupled reformer/stack
		  – Develop user friendly commercially supported modeling for reaction kinetics coupled reformer/stack

IV. FUEL PROCESSING – SESSION B
GROUP SUMMARY

Issues

In order to achieve the SECA goals, the following technology issues received the largest number of votes:

- Availability of low-cost, small-scale reformers to deal with diesel and logistic fuels
- Deactivation of catalyst
- Internal reforming thermal management and poisoning
- Performance with respect to durability, life, and load following.

R&D Opportunities & Actions

The R&D opportunities were categorized into five header topics. However, the group did not vote on specific opportunities, but instead they voted on the header topics. Therefore, the following are the three header topics that received the most votes with only the first three bullet details presented.

Making Diesel Fuel Processor Work

- Make poison resistant partial oxidation reactor
- Demonstrate a two-stage diesel steam reformer
- Develop liquid fuel processors to remove sulfur

Propane/Natural Gas Fuel Processor as Cheap as Possible

- Develop low-cost, high-efficiency gaseous fuel reformer
- Develop a very inexpensive oxidative reforming unit
- Design for low cost manufacturing

Internal Reforming

- Design and build models for internal reforming stack
- Develop graded anode
- Develop oxidative internal reforming process for natural gas and propane

Actions

The group developed actions from the top three categories of R&D opportunities.

Develop a Compact Fuel Processor for Diesel and Logistics Fuels:

- Novel fuel conversion processes, e.g., advanced oxygen sources for partial oxidation and micro-channels to enhance heat transfer

- Fuel pre-processing systems to remove troublesome impurities before they are charged to the fuel processor
- Anode catalysts that are resistant to sulfur and carbon
- Advanced balance of plant systems

These activities were categorized as spanning research and development.

Make Light Fuels Processors (Natural Gas, Propane, and Gasoline) as Low Cost and Compact as Possible:

- Thermal integration
- Miniaturization of equipment for 5 kW
- Start by simplifying fuel processors designed for PEM
- Multi-fuel R&D
- Integrated fabrication development
- Lowering components costs through DFMA and other means

These activities were categorized as primarily engineering.

Develop Internal (On-Anode) Reforming Technology:

- Steam reforming and POX
- Lab tests of internal reforming systems and use the data acquired to develop electrochemical and thermodynamic models of processes and obtain fundamental knowledge of them
- Multi-fuel tolerant core module
- Graded anode technology
- Advanced fuel-mixing concepts to facilitate heat transfer and management

Internal reforming was described as the "holy grail" of fuel processing, and activities supporting it are staunchly in the research end of the action spectrum.

FUEL PROCESSING - SESSION B

PARTICIPANTS

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Fuel Processing- Session B: Issues

(✪ = Vote for Priority Topic)

PERFORMANCE	STACK SENSITIVITY (SULFUR & SALT) POISON	LOW CAPACITY OF SYSTEM	INTERNAL REFORMING	FUEL EFFECT ON FUEL PROCESSOR	FUEL PROCESSING BOP
• Long-term testing durability ✪ • Long life of reformer materials at low cost ✪ • Start-up time • Load following ✪	• Anode Poisoning - Salt - Sulfur	• Difficult for Diesel ✪ • Availability of low cost small scale reformer ✪✪✪✪✪ • Thermal losses in small systems • Reliability at small scale	• Poisoning ✪ • Cracking • Thermal management ✪✪ • Preconditioning of fuel	• Deactivation of catalyst ✪✪✪ - Thermal - Coking - Sooting - Poisoning	• Sulfur aborption/disposal (filter cartridge) using alkali metal • Long life desulfurizer ✪ • Water sufficiency

Fuel Processing – Session B: Opportunities

(✪ = Vote for Priority Topic)

MAKING DIESEL FUEL PROCESSOR WORK k k k k k k k k k k	PROPANE/NATURAL GAS FUEL PROCESSOR AS CHEAP AS POSSIBLE k k k k k k k k k k	INTERNAL REFORMING k k k k k k k	BALANCE OF PLANT k k k	OTHER ITEMS
• Make poison resistant partial oxidation reactor - ceramic membrane • Demonstrate a two stage (diesel) steam reformer (fluid-bed/Plug Flow) for 100 kWe system and work backwards down • Liquid fuel processors to remove sulfur—disposable filter-1 gallon can processes 20 gallons of fuel • Come up with a dual catalyst that tolerate sulfur anode and coking • Integrated reformer/heat transfer approach - Microchannel - Plate reformers • Fuel preprocessor - Remove sulfur - Increase fuel quality • Develop inert, stable materials	• Develop low-cost, high efficiency gaseous fuel reformer • Very inexpensive oxidative reforming unit for natural gas and propane • Design for low cost manufacturing • Integrated fabricate development	• Models for internal reforming stack – design – build • Graded anode development • Oxidative internal reforming process for natural gas and propane • Mixing fuel in cell rather than plug flow to improve internal reforming • Develop a multi-fuel tolerant internal reforming core module (cell)	• Sensors • Materials • Manufacturing • Techniques • Reduce parasitic load	• Accelerated durability testing reformer/stack • Long term materials research and tests • System optimization • Ultra-rich internal combustion engine as POX fuel processor shaft power out quick start • Coking-resistant coating for preconditioner

Fuel Processing – Session B: Actions

Fuel Processor for Diesel and Logistic Fuels	Ultra low-cost high efficiency Fuel Processor for Natural Gas and Propane	Internal Reforming (on-anode)
• Novel Processes - Ceramic Membrane POX - Integrated heat transfer microchannel /plate reformer - Two stage heavy fuel steam reformer - Materials resistant to impurities - Pilot plant - At 20 kW • Fuel Pre-processing - Liquid phase desulfurization - Better ways to remove sulfur during processing • Materials research to develop anode catalyst to resist sulfur and carbon • BOP - 5 KW - Systems integration - Perform R&D on components with integration in mind - Thermally integrated reforming	• Develop low cost, high efficiency gaseous fuel reforming - Steam - POX - Other - Thermally integrated reforming - Build at 5 kW - Starting point. Simplify fuel processors designed for PEM stacks - Multi-fuel R&D - Integrated fabrication development - Design low cost manufacturing	• Most effort is on steam reforming, could look at POX as well • Lab scale experimentation - Modeling - Thermal - Chemical - Electro-chemical • Multi-fuel tolerant core module • Graded anode • Fuel mixing

Fuel Processing – Session B: Report-Out

(✪ = Vote for Priority Topic)

Issues	Opportunities	Actions	Comment
• Dealing with diesel and logistic fuels • Lack of demonstrated internal reforming capability • Low capacity • Sensitivity of stack to sulfur, soot and salt • Lack of demonstrated performance durability • Reliability, long life, start up, multiple fuels, • Diesel and logistic fuels makes problem much more difficult • Internal reforming not clear you can be successful • Low capacity • Sulfur, soot, salt • Performance 3	• Developing a compact (5-20 kW) diesel fuel processor ✪✪✪✪✪✪✪✪✪✪ • Light fuels (natural gas, propane, gas) as low cost and compact as possible ✪✪✪✪✪✪✪✪✪✪ • Internal reforming (on-anode) ✪✪✪✪✪✪✪ • Developing a compact diesel fuel processor full preprocessor, sulfur removal, coking pox, steam • Light fuels processor mass manufacturing to get low cost reliability, POX, steam, novel • Internal	• Diesel and logistic fuel - Novel processing - Fuel pre-processing - Anode to resist sulfur and carbon - BOP • Natural gas, propane and gasoline - Thermal integration - Small size - DFMA • Internal reforming - Lab tests/modeling - Graded anode - Fuel mixing	• Requirement of heavy fuels complicates vision - Other goals at risk • Alternate strategy – focus on natural gas for market introduction • Early stage R&D on heavy fuels

V. MODELING AND SIMULATION GROUP SUMMARY

Modeling and simulation issues for fuel cells are best discussed by considering issues that impact the fundamental cell, component, stack, or system, or crosscut through all of these scales.

Issues

The following issues received the most votes:

- Validation/benchmark data for models/modeling
- Barrier – posing of critical questions answerable by appropriate models
- Electro-chemical reaction rates and mechanisms
- Lack of suitable multi-physics engineering models
- Diversity of scales hinders Computational Fluid Dynamic (CFD) applications in multi dimensions at stack level.
- Total life cycle cost/performance analysis and optimization

R&D Opportunities

The R&D opportunities were categorized into five header topics. The following are the header topics and the corresponding R&D opportunities that received a multiple number of votes:

Crosscutting

- Joint validation benchmarks where more than one group develops, characterizes, tests, and models
- Model SOFC operations: start-up, part-load, shut-down (load following)
- Define precisely what validation data are needed and get it
- Perform uncertainty analysis on fuel cell models at all levels (focus on numerical errors)

Cell/Fundamental

- Development of fundamental multi-dimensional models with emphasis on electrochemical and kinetic transport aspects
- Determine electro-chemical rates and mechanisms: measure and model
- Develop 3D fundamental multi-scale model for micro-structural analysis and design

Component

- None

Stack

- Develop coupled multi-dimensional multi-physics engineering model for stack with benchmark problem set

System

- Build reliability model of SOFC system

Actions

To take advantage of the top three R&D opportunities, the following actions should be carried out:

Develop Models for the Cell and for the Stack:

- Multi-dimensional, multi-physics
- Develop benchmark problem set (for stack)
- Electrochemical, kinetic, transport emphasis for cell

Benchmark Development:

- Developed and characterize benchmark cells
- Test to provide data on benchmark cells
- Models will be developed for benchmark cells

Model SOFC Operation (Start Up, Part Load, Shut Down):

- Industries establish the off-design conditions and requirements
- Develop coupled transient models
- Validate the models

MODELING AND SIMULATION

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Modeling and Simulation: What Are the Science and Technical Issues to Achieving the Vision?

(✪ = Vote for Priority Topic)

CROSSCUTTING ISSUES	CELL/FUNDAMENTAL MODELS	COMPONENT MODELS	STACK MODELS	SYSTEM MODELS
• Validation/benchmark data for models/modeling ✪✪✪✪✪✪✪✪ • Barrier—posing of critical questions answerable by appropriate models ✪✪✪✪ • Cost functions (accurate) {lack thereof} ✪✪ • Dynamic communication with materials and manufacturing groups (lack thereof) ✪✪ • Lack of education and training on fuel cell technologies ✪ • Connection and communication between modeling (scales of modeling) groups ✪ • Lack of public domain software ✪ • Need real-life values for model parameters ✪ • Lack of operating codes and standards for design modeling • Lack of benchmark for verification	• Electro-chemical reaction rates and mechanisms ✪✪✪✪ • Lack modular cell-level physical-mathematical models for transport processes ✪ • Simulating direct Internal reformation transport phenomena ✪ • There is a need for greater detailed information from models • Need constitutive equations for mirco/fundamental models	• Better models for fuel processing ✪✪	• Lack of suitable multi-physics engineering models - Thermal, electro-chemical, transport coupling ✪✪✪✪✪✪ • Diversity of scales hinders computational fluid dynamic (CFD) applications in multi-dimensions at stack level ✪✪✪ • Lack of a public domain research code for multi-dimensional modeling at the stack level ✪ • Methods for determining fabrication stress ✪ • Simulating indirect internal reforming transport phenomena • Interface properties for PEN material and seals • Reliability model • Need for handbook approach for stack	• Total life cycle cost/performance analysis and optimization - Model cost/ maintenance trade-offs - Fuel cell fabric. Auxiliary equipment installation ✪✪✪ • Reliability/ Availability/ Maintainability (RAM) models

Modeling and Simulation: What Are the R&D Opportunities to Overcome the Issues?

(✪ = Vote for Priority Topic)

	CROSSCUTTING	CELL /FUNDAMENTAL	COMPONENT	STACK	SYSTEM
Validation Oportunities	• Define precisely what validation data that we need and get it (database) ✪✪✪✪	• Material databases electrochemical and thermal and failure data • Develop tests and test standards for measuring material properties especially interfacial properties			
Computation Opportunities (Modeling)	• Model SOFC Operations: Start-up, part-load, shut-down (Load following) ✪✪✪✪✪ • Handbook of Fuel Cell Model equations and thermal papers ✪ • Thermoeconomic design studies✪ • Develop efficient numerics for such complex problems ✪ • Perform uncertainty analysis on fuel cell models at all levels (focus on numerical errors) ✪✪	• Development of fundamental multi-dimensional models which emphasizes on: electrochemical, kinetic transport aspects on the cell level. ✪✪✪✪✪ • Develop 3D fundamental multi-scale model for microstructural analysis and design ✪✪	• Fuel reformation models ✪	• Develop coupled multi-dimensional multi-physics engineering model for stack with benchmark problem set ✪✪✪✪✪✪ • Coordinated joint effort to develop a multi-dimensional robust, public domain computer code for stack ✪ • Develop modeling tools for predicting residual stress due to fabrication	• Build reliability model of SOFC system ✪✪ • Build diagnostic model of SOFC system • Fuel cell cost algorithms ✪
Joint Validation/ Computation Opportunities	• Benchmarks - more than one group develop and characterize <u>same</u> cell design - more than one group test above and provide detailed data - more than four groups model ✪✪✪✪✪✪✪ • Define metrics or figure of merit and how they relate to one another ✪	• Determine electro-chemical rates and mechanisms: measure and model ✪✪✪ • Model Equation Development - Research on kinetics (electrochem and reforming) - Propose and test models - Publish all results		• Understand failure mechanisms in stack/cell ✪	

Modeling and Simulation: What Are the Actions to Take Advantage of the R&D Opportunities?

R&D Opportunity	Actions 0-5 Years	Actions 5-10 Years	Lead Role	Other Issues
Develop Models for Stack and Cell • Multi-dimensional, multi-physics • With benchmark problem set (for stack) • Electrochemical, kinetic, transport emphasis for cell	• Evaluate (and communicate) existing model base **(E)**		Government, Industry (NETL) with Industry and Academia	• Consider concurrent engineering • Support Vision 21 virtual plant demonstration prototyping
	• Different groups to do different models electrochemical, kinetic, etc. **(R)** • Develop design/applications models that address SECA vision **(D)** • Incorporate into overall system model **(E)**	• Refine models as necessary (input from benchmarks) **(D)** - Accommodate technical breakthroughs • Modeling to accommodate markets (implement models P/E we have developed) **(D/E)** • Reduce the turn-around time to speed the design cycle **(D)**	Government initiates, develops consortium of government, industry, academia; academia or national lab appointed to coordinate	
Benchmark Development • >1 Group development and characterize same cell design • >1 Group test cell and provide detailed data • >4 Groups model	• Develop and characterize benchmark cells **(D/E)**		Government with academia	none
	• Test and provide detailed data **(D/E)**		Government with academia	
	• Model **(D/E)**		Government with academia and industry	
Model SOFC Operation (Start up, Part Load, Shut Down)	• Establish off-design conditions and requirements **(E)**		Industry with government	none
	• Development coupled transient models **(D/E)**		Government with academia	
	• Validate model **(D/E)**		Government with industry	
		• Integration with design cycle **(E)**	Industry	
		• Accommodate technology breakthroughs **(D/E)**	Government with Academia and industry	

Key: E = Engineering
D = Development
R = Research

Modeling and Simulation: Report-Out

ISSUES	R&D OPPORTUNITIES	ACTIONS
• System modeling - Total life cycle cost performance analysis optimization • Stack Models - lack of suitable multi-physics engineering models (thermal, electrochemical, transport coupling) • Cross-cutting Issues - Validation/benchmark data for models	• Stack computational Coupled multi-dimensional Multi-physics engineering model (with benchmark problem set) • Cell Computational Fundamental models (multi-dimensional) with emphasis on: – Electrochemical – Kinetic – Transport aspects • Benchmarks - Characterize cell design - Obtain detail test data - Develop model	• Models for Cell /stack – 0-5 Years, Evaluate existing models, G/I – 0-5 Develop electrochemical, kinetic, models G/I – 0-5, Application models for SECA vision G/I – 0-5, Incorporate into system Model G/I – 5-10 Refine models (for tech. Breakthroughs) G/I – 5-10 Market-specific models G/I – 5-10 Reduce turnaround time to speed design cycle G/I • Benchmark – 0-5 Develop/characterize benchmark cells G – 0-5 Test and provide detailed data G/A – 0-5 Model development G/A/I • SOFC Operation Model – 0-5 Establish off-design conditions/requirements I – 0-5 Develop transient model G – 0-5Validate model G/I – 5-10 Integrate with design cycle I – 5-10 Accommodate technical breakthrough G

Key: I = Industry
G = Government
A = Academia

VI. POWER ELECTRONICS GROUP SUMMARY

Issues

The following issues received the most votes:

- Complex system interface
- Modular family architecture
- Poor load following
- Use of SiC – silicon carbide
- Cooling thermal management
- Lifetime
- Cost discrepancy

Opportunities

The R&D opportunities were categorized into four header topics. The following are the header topics and the corresponding R&D opportunities that received a multiple number of votes:

Thermal Management

- Higher temperature components, e.g., capacitors

Interface

- Integrated devices
- Systems dynamic modeling

Cost

- DFMA –design for manufacture and assembly

Reliability

- Improve component materials

Actions

By combining the component opportunities, actions were developed for the top two opportunities.

Integrated Devices Interface:

- Align with manufacturer
- Develop open architecture for common module hardware and software toolkits

- Identify common denominators from developers across applications
- Assess packaging interconnections
- Develop codes and standards across industries
- Develop communication protocols
- Develop predictive controls

Components Reliability and Thermal Management:

- All components need to be better, faster, smaller, and cheaper
- Re-engineer capacitor
- Improve higher temperature capabilities for connections, solder, circuit boards, and substrate
- Improve switching characteristics with lower losses and higher temperature
- Improve heat sink integrated thermal management

POWER ELECTRONICS

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Power Electronics: What Are the Scientific and Technical Issues to Achieve SECA Vision by 2010?

(✪ = Vote for Priority Topic)

INTERFACE	TOPOLOGY	RELIABILITY	COST
• Domain vs. stationary • Synchronize to grid ✪✪ • Complex system interface ✪✪✪✪✪✪✪ • Dynamic range • System inverter ganging • Output power quality • BOP – Balance of Plant • Modular family architecture ✪✪✪✪✪✪ • Integrated controls • DC chopper • Programability on fly • Remote dispatch • Black start • Lousy load following ✪✪✪✪✪	• Switches topology ✪ • Passive components ✪ • SiC – Silicon Carbide ✪✪✪	• Cooling thermal management ✪✪✪✪✪ • Graceful degradation • Noise control • Lifetime ✪✪✪✪✪ • Telemetry remote diagnostics	• Size, volume, and weight ✪✪ • Economies of scale • Cost discrepancy ✪✪✪

Power Electronics: What Are the R&D Opportunities to Overcome Issues to SECA?

(✪ = Vote for Priority Topic)

THERMAL MANAGEMENT	INTERFACE	COST	RELIABILITY
• Higher temperature components, e.g., capacitors ✪✪✪✪✪ • Direct cooling of silicon or SiC ✪ • Cheap diamond film • Integrated electronic within cell ✪	• Definition of system requirements ✪✪ • Load prediction • Establish standards • Challenge 5 kW choice • Plug and Play ✪✪ • Low cost storage high density caps • Systems dynamics modeling ✪✪✪ • Functional tradeoff studies • Integrated devices ✪✪✪✪✪✪✪ • Ganging inverters	• Cost tradeoffs studies ✪ • Soft switching topology • Integrated devices ✪✪ • Manufacturing process development • DFMA ✪✪✪✪ • Grid interconnect standards • Packaging of PE module	• Improve component materials ✪✪✪✪✪✪ • Prognostics • Topology choice, e.g., redundancy, multi-level ✪ • Robust design ✪ • Soft failure

Power Electronics: What Actions to Take Advantage of R&D Opportunities?

R&D Opportunity	Actions 0-5 Years	Type of Action	Actions 5-10 years	Type of Action	Lead Roles
• Integrated Devices "Interface" – Board or chip module – Fuel cell electronics with power electronics – Transformerless design – PE-DC Bus in box; PE-AC-Grid outside	• Align with manufacturer	E			• Industry
	• Develop open architecture for common module hardware and software toolkits	E,D			• Industry, University, Government
	• Identify common denominators from developers across applications	E			• University, Government
	• Packaging interconnections	E,D,R			• Industry, University, Government
	• Develop codes and standards across industries	E			• Government, University, Industry
	• Communication protocols	E,D			• Government, University, Industry
	• Predictive controls	E,D,R			• Government, University, Industry
• Improve Component Materials "Reliability" and Higher Temperature Components, "Thermal Manage" – Capacitors-inductors – Connections – Switch – Solder – Circuit boards – Substrates – Heat sinks	• Better, faster, smaller, cheaper	D,R	• Better, faster, smaller, cheaper	E,D	• Government, University, Industry
	• Re-engineer capacitor	R	• Re-engineer capacitor		• Government, University, Industry
	• Higher temperature capabilities – Connections – Solder – Circuit Boards – Substrate	D,R	• Higher temperature capabilities	E,D	• Government, University, Industry
	• Switch – Improved switching characteristics – Lower losses – Higher temperature	D,R	• Switch	E,D	• Government, University, Industry
	• Heat sink-integrated thermal management	D,R	• Heat sink	E,D	• Government, University, Industry

Key: E = Engineering
D = Development
R = Research

Power Electronics: Report-Out

Power Electronics	Issues	R&D Opportunities	Actions
• Is power electronics in the fuel cell "box" or not? • Ganged 5 kW modules are not practical for power electronics? • Status – $7/kW mobile in 3 years – 90+% efficiency – Air-cooled industrial drives	• Complex system interface • Modular family architecture • Lousy load following • Thermal management • Lifetime	• Integrated devices for interface • Reliability – improve component materials • Thermal Management – higher temperature components	• Integrated devices – Align with manufacturers – Develop open architecture hardware and software – Identify common denominators from developers – Develop codes and standards – Communication protocols • Component materials: capacitors, inductors, connections, switches, solder, circuit boards, substrates, heat sinks – Better – Faster – Smaller – Cheaper

VII. THERMAL SYSTEMS GROUP SUMMARY

Issues

The following issues received the largest number of votes:

- Thermal enclosure
- Water recovery system
- Air pre-heater cost/performance trade-off
- Excessive heat losses in small high temperature systems
- Afterburner pre-heater
- Waste heat utilization (power generation/co-generation)
- Transient stresses during normal and abnormal events (loss of cooling air)
- Start-up overall speed

Opportunities

The R&D opportunities were categorized into five header topics. The following are the header topics and the corresponding R&D opportunities that received a multiple number of votes:

Water Management Strategy

- Designs using recycled steam

Air Preheater

- Materials and fabrication
- Integrated catalytic combustion
- Configuration – optimize design

Overall Startup Speed

- Reduce thermal capacitance
- Optimize idle mode strategies

Transient Stresses During Normal and Abnormal Events

- Dynamic modeling (transient)

Thermal Enclosure: Material, Design, & Cost

- Better insulating materials
- Optimize compartment design

Actions

Due to time constraints, only two of the highest priority opportunities could be analyzed.

Water Management - Designs Using Recycled Steam:

- System study of onsite/onboard water vs. recycle steam
- Develop designs for water recovery
- Prototype water recovery
- Research ways to recover water without phase change
- Develop design without phase change
- Prototype without phase change

Thermal Enclosure – Better Insulating Materials:

- Optimize design of the compartment
- Study family of applicable materials and select material
- Prototype

THERMAL SYSTEMS

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Thermal Systems: What Are the Issues (Science and Technology) to Achieving the Vision?

(✪ = Vote for Priority Topic)

Other	Components	Integration	Operating Strategies
• Sulfur in fuel creates many of the thermal system issues	• Materials • No high temperature recycle blower available to recycle anode exhaust back to inlet to provide water • Thermal enclosure – Materials – Design – Cost ✪✪✪✪✪✪✪ • Catalyst and housing material selection driven by temperature • Air preheater cost/ performance trade off ✪✪✪ • Air preheater: need high active heat exchange surface area per unit active volume/weight ✪✪ • Water Recovery System ✪✪✪✪✪ • (Seals) Maintaining system integrity due to temperature gradients in space and time ✪✪ • Nox (Emissions) governed by temperature	• Excessive heat losses in small high temperature systems ✪✪✪✪ • Using afterburner as startup ✪ • Waste heat utilization (power generation/co-generation) ✪✪✪ • Reformer/Stack ✪ • Afterburner/Preheater ✪✪✪✪ • Air cooled fuel cell stack is too difficult to manage • Temperature gradients with air flow uniformity, maintenance • (Seals) Maintaining system integrity due to temperature gradients in space and time ✪✪ • NOx (Emissions) governed by temperature	• Designing for extremes ✪ • Transient stresses during normal and abnormal events (loss of cooling air) ✪✪✪✪✪ • Thermal/overall operator training, diagnostics • Temperature/flow control system ✪✪ • Startup – Overall speed ✪✪✪✪✪ – Thermal • Human Safety – Noise – Emissions – Heat • Air cooled fuel cell stack is too diffi cult to manage • Temperature gradients with air flow uniformity, maintenance

Thermal Systems: What Are the R&D Opportunities to Overcome the Issues?

(✪ = Vote for Priority Topic)

Water Management Strategy	Air Preheater	Overall Startup Speed	Transient Stresses During Normal and Abnormal Events	Thermal Enclosure: Materials, Design, & Cost
• Optimize design • Designs using recycled steam ✪✪✪✪✪✪ • Misc. – Water for fuel processor	• Configuration – optimize design ✪✪✪ • Materials and fabrication ✪✪✪✪ • Integrated catalytic combustion ✪✪✪✪	• Reduce thermal capacitance ✪✪✪✪ • Optimize idle mode strategies ✪✪✪ • Develop robust hardware design ✪✪	• Ceramics – improve, toughened ✪✪ • Improve hardware design ✪ • Dynamic modeling (transient) ✪✪✪✪ • Controls design ✪	• Better insulating materials ✪✪✪✪✪ • Cheaper materials ✪✪ • Optimize compartment design ✪✪✪✪

Thermal Systems: What Are the Actions to Take Advantage of the R&D Opportunities

Opportunity – Water Management – Designs Using Recycled Steam	Action	Action Type	Timeframe	Leader	Other Factors
	System study onsite/onboard water vs. recycle steam	E	6 mo.	DOE/DoD	
	Develop designs for water recovery	E	18 - 24 mos.	Core Tech	
	Prototype (water recovery)	E	1 – 3 yr.. (parallel to research)	Industry	
	Research ways to recover water without phase change	R	1 – 3 yr..	Core Tech	
	Develop design (without phase change)	E	1 - 3 yr..	Core Tech	
	Prototype (without phase change)	E	1 – 3 yr..	Industry	
Opportunity – Thermal Enclosure – Better Insulating Materials	**Action**	**Action Type**	**Timeframe**	**Leader**	**Other Factors**
	Optimize Design	E	1 – 2 yr.	Industry	Note: What must be in the box? 1 – Main box design 2 – Feed platelets
	Study family of applicable materials Select Material	D	6 mos. – 1 yr.	Core Tech	
	Prototype	E	1 – 2 yr.	Industry	

Key: E = Engineering
D = Development
R = Research

Thermal Systems – Report Out

(✪ = Vote for Priority Topic)

Thermal Systems	Issues	Opportunities
• Thermal Systems • What are they? • Everything Else – Air Preheater – After burner – Thermal enclosure – H2O management – Et al. • Could be the Achilles Heel	• Categories – Components – Operating Strategies – Integration • Top Vote Getters – Thermal enclosure ✪✪✪✪✪✪✪ – Air preheater ✪✪✪✪✪ – Transients during normal & abnormal events ✪✪✪✪✪ – Overall startup rate ✪✪✪✪✪ – H_2O recovery system ✪✪✪✪✪	• Categories – Air preheater – Overall startup speed – Transients – Stresses – Thermal enclosure – H_2O Management Strategies • Top Vote Getters – Design of H2O management system using recycled steam ✪✪✪✪✪✪ – Better insulating materials for thermal enclosure ✪✪✪✪✪ – Optimize compartment design ✪✪✪✪ – Air preheater materials and fabrication ✪✪✪✪ – Integrated catalytic combustor with air preheater ✪✪✪✪ – Reduced thermal capacitance ✪✪✪✪ – Dynamic modeling ✪✪✪✪

Opportunity	Actions	Timeframe	Lead	Other
• Water Management Designs Using Recycled Steam	• System Study: (E) On board Water vs. Recycle Steam	6 months	DOE/DoD	
	• Develop Designs for Water Recovery (E)	18 - 24 months	Core Tech	
	• Prototype (E) (water recovery)	1 – 3 years	Industry	
	• Research Ways to Recovery Water Without Phase Change (R)	1 – 3 years (parallel to above)	Core Tech	
	• Develop Design (E) (without phase change)	1 – 3 years	Industry	
	• Prototype (E) (without phase change)	1 – 3 years		
• Thermal Enclosure – Better Insulating Materials	• Optimize Design	1 – 2 years	Industry	• What must be in the box? – Main box – Feed platelets
	• Study Family of Applicable Materials Select Material	6 mos. – 1 year	Core Tech	
	• Prototype	1 – 2 years	Industry	

Key: E = Engineering
D = Development
R = Research

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