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 2\textsuperscript{nd} and 3\textsuperscript{rd} 2001 in the Washington DC area. We look forward to your future participation in SECA.

Sincerely,

Wayne A. Surdoval
SECA Project Manager
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 CO₂ 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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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.
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 21st 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

The Vision: Fuel Cells in 2010

Low Cost
$400/kW

Multiple Fuels

Reduced CO₂ Emissions
The Vision: *A Core Module for Multiple Applications*

**SECA:***
- An alliance of industry teams, R&D performers, and government funding organizations
- Develops an integrated strategy
- Focuses research
Core Technology Program
The Technology Base

University | National Lab | Industry | Small Business
---|---|---|---
Fuel Processing | Manufacturing | Controls & Diagnostics | Power Electronics
Modeling & Simulation | Materials

Intellectual Property - Cornerstone of the Alliance
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

SECA - Now is the Time

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

Stationary

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

Transportation

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

Military

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

A Paradigm Shift

Overcoming the Pull of The Past

Cleaner, more efficient way to use fossil fuels

Start with the end in mind

Industry cooperating across traditional lines

Adopt principles of contemporary system design
Public Benefits

High Efficiency

Year

Grid Stability

Cost Reduction

$4/W

<4$4/W

Year

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
Responding to the Needs of the Nation
C. U.S. DOE, Office of Transportation Technology, Fuel Cells for Transportation Program

Patrick Davis, Program Manager
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

Medium & Heavy Duty Vehicles
Automotive Program
Portable and Premium Power
Buildings
Distributed Power

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

Projected Mileage, MPG

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<th>Hydrogen Fueled</th>
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<tr>
<td>Highway Fuel Economy</td>
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</tr>
<tr>
<td>Combined</td>
<td>86</td>
<td>111</td>
</tr>
</tbody>
</table>

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

Status indicated by asterisk (*)

SECA Proceedings 24 June 2000
**DOE Transportation Fuel Cell Program**

**Fuel Strategy**

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**

**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

Technology Development Flow
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

<table>
<thead>
<tr>
<th>Systems</th>
<th>Fuel Processing</th>
<th>Stack Subsystem Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug Power/Epyx</td>
<td>NUVERA</td>
<td>Energy Partners, AlliedSignal, IFC, Plug Power</td>
</tr>
<tr>
<td>IFC</td>
<td>Hydrogen Burner</td>
<td>IGT, Electrochem</td>
</tr>
<tr>
<td>Energy Partners, AlliedSignal</td>
<td>McDermott</td>
<td>3M, SwRI/Gore, Foster-Miller</td>
</tr>
<tr>
<td>ANL</td>
<td>Plug Power/UOP</td>
<td>Vairex, A.D. Little, AlliedSignal, Meruit</td>
</tr>
<tr>
<td></td>
<td>AlliedSignal</td>
<td>Spectracorp</td>
</tr>
<tr>
<td></td>
<td>Arcadis</td>
<td>LANL, LBNL</td>
</tr>
<tr>
<td></td>
<td>ANL, LANL, PNNL</td>
<td></td>
</tr>
</tbody>
</table>

FY00: $6.0M           FY00: $17.0M        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.
- Sensors and controls
- AlliedSignal stack demonstrated in JLG boomlift.

---

**Office of Transportation Technologies**
**Interest in Solid Oxide Fuel Cell Technology**

- 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.

**Barriers to transportation applications:**
- Heavy Duty - Cost, Maturity, Durability/Robustness
- Light Duty - Cost, Maturity, Start-up, Thermal Cycling
Summary

• 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

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

SECA Proceedings  June 2000
Transportation Fuel Economy

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

Source: Transportation Energy Data Book: Edition 19

Automotive: Increasing Electrical Power Requirements

Generator Peak Power, kW

Electric Propulsion

w/o Electric Propulsion
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

5 kW Vehicle Auxiliary Power: Impact on Estimated Fuel Usage

![Graph showing fuel usage impact with different power sources]

- Existing Alternator
- Advanced Alternator
- SOFC
- SOFC + Heat Pump

U.S. Department of Energy
Pacific Northwest National Laboratory
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

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
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

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
### “Generic” Automotive APU Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>5 kW net</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>42 Vdc</td>
</tr>
<tr>
<td>Mass Target</td>
<td>&lt; 50 kg (0.1 kW/kg)</td>
</tr>
<tr>
<td>Volume Target</td>
<td>&lt; 50 liter (0.1 kW/liter)</td>
</tr>
<tr>
<td>Operation life</td>
<td>&gt;5000 hrs</td>
</tr>
<tr>
<td>Cold Start Required</td>
<td>&gt;3000 times</td>
</tr>
<tr>
<td>Warm Starts Required</td>
<td>SOFC &lt; 10 minutes</td>
</tr>
<tr>
<td>Maintenance Required</td>
<td>&gt;&gt; 1000 hrs (30 ppm S)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 40%</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>&lt; 45 degrees celsius</td>
</tr>
</tbody>
</table>

## 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*
Potential APU Markets

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

$1000/kW
$600/kW
$200/kW

U.S. Department of Energy
Pacific Northwest National Laboratory
E. SOLID OXIDE FUEL CELLS AND DEPARTMENT OF DEFENSE APPLICATIONS
Herbert Dobbs, National Automotive Center, TACOM
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

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

As of: 1 June 00
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

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 sulfur
- 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
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

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
**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

**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
SOFC’s and Defense Applications

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(810) 574-4228 (voice)
(810) 574-4224 (fax)

dobbsh@tacom.army.mil
F. SOLID OXIDE FUEL CELLS AND STATIONARY APPLICATIONS

W. Peter Teagan, Arthur D. Little, Inc.
Solid Oxide Fuel Cells and Stationary Applications

Presentation to:
Solid State Energy Conversion Alliance (SECA)
June 1-2, 2000
Baltimore, MD

Table of Contents

1 Market Segments Identification and Requirements
2 Market Drivers
3 Special Issues for SOFC Applications
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
- Base-load 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).

### Performance and Cost Requirements for Distributed Generators

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Residential</th>
<th>Commercial</th>
<th>Industrial</th>
<th>Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capacity (kW)</td>
<td>1 - 5</td>
<td>20 - 500</td>
<td>200 - 2000</td>
<td>&gt;100,000</td>
</tr>
<tr>
<td>2. Efficiency %</td>
<td>&gt;35</td>
<td>&gt;35</td>
<td>&gt;40</td>
<td>0.5&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>3. Life (years)</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>&gt;15</td>
<td>0.5&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>4. O&amp;M (hours)</td>
<td>&gt;4000</td>
<td>&gt;1000</td>
<td>ongoing</td>
<td>&gt;200</td>
</tr>
<tr>
<td>6. Cyclability</td>
<td>Important</td>
<td>Not Important</td>
<td>Important</td>
<td>Very Important</td>
</tr>
<tr>
<td>7. Emissions NOx (ppm)</td>
<td>&lt;20</td>
<td>&lt;20</td>
<td>&gt;50</td>
<td>&gt;50</td>
</tr>
<tr>
<td>8. Startup/Time</td>
<td>Important&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Important&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Important&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Very Important</td>
</tr>
</tbody>
</table>

<sup>1</sup> Electric generation only; in cogeneration applications combined-electric/thermal efficiencies approach 85%.

<sup>2</sup> Varies by application and region; emissions reflect trends toward increasingly stringent regulations.

<sup>3</sup> Actual operating time of the power system (not vehicle life).

<sup>4</sup> Importance depends upon operation strategy. Peak-shaving units will require rapid startup, but base-loaded systems will not.
We have used a detailed economic model to estimate the allowable cost of distributed power technologies in a variety of applications.

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

<table>
<thead>
<tr>
<th>Market Segment</th>
<th>Typical Capacity</th>
<th>Entry(^1)</th>
<th>Sustained(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial Cogeneration</td>
<td>50 kW - 2 MW</td>
<td>$1,500 - 2,000</td>
<td>$800 - 1,300</td>
</tr>
<tr>
<td>Industrial Cogeneration</td>
<td>5 - 200 MW</td>
<td>$1,000 - 1,200</td>
<td>$800 - 1,000</td>
</tr>
<tr>
<td>Residential Power</td>
<td>0.5 - 10 kW</td>
<td>$1,000 - 2,500</td>
<td>$800 - 1,000</td>
</tr>
<tr>
<td>Distributed Power</td>
<td>5 - 20 MW</td>
<td>$1,300 - 1,500</td>
<td>$800 - 1,300</td>
</tr>
<tr>
<td>Central Station</td>
<td>100 - 500 MW</td>
<td>$900 - 1,100</td>
<td>$700 - 900</td>
</tr>
</tbody>
</table>

\(^1\)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).
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 H₂.

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

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

*Peak loads can be 2-3 times higher.

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

---

**Table of Contents**

1. Market Segments Identification and Requirements
2. Market Drivers
3. 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.

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

**Assumptions**
- Large Commercial Building (Hospitals, etc.)
- 4-5 year payback
- Los Angeles Utility Rates

**Diagram:**
- High Duty Cycle (e.g., Hospitals)
- Low Duty Cycle (e.g., other buildings)
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.
G. Industry Presentations: Fuel Cell Markets

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

- 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

Delco Electronics Systems

Packard Electric Systems

Chassis Systems

Saginaw Steering Systems

Interior & Lighting Systems

Harrison Thermal Systems
Comparison To Major Competitors

1998 Sales $Billions

Source: Automotive News ‘99 Market Data Book

Delphi Bosch Visteon Lear / UT TRW / Lucas Denso Delphi Non-NAO JCI Dana Auto

28.5 18.2 17.8 12.0 11.9 11.8 10.0 8.6 7.1

Major Customers

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

Core Competencies

- 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 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?

SOFC APU = high efficiency electricity + future vision for integration with ICE

PEM FCEV = next generation EV (with smaller battery pack)

Reforming Methods

Thermal Decomposition

Partial Oxidation

Autothermal Reforming

Steam Reforming

\[ C_{n}H_{m} \rightarrow nC + \left( \frac{m}{2} \right) H_{2} \]

\[ C_{n}H_{m} + \left( \frac{m}{2} \right) O_{2} \rightarrow n CO + \left( \frac{m}{2} \right) H_{2} \]

\[ C_{n}H_{m} + n CO + \left( \frac{m}{2} \right) H_{2} \]

\[ C_{n}H_{m} + n CO + \left( \frac{m}{2} \right) O_{2} \]

\[ C_{n}H_{m} + n H_{2}O \]
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 nearly-zero toxic emissions and much reduced CO2 emissions
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 is interested in leveraging multiple applications
(i.e. military, stationary, portable power and automotive)
in the interest of accelerating technology development.
Three year goals

Fuel Cell Design and Manufacturing objectives

- Operating Temperature: 750 to 800 °C
- Current Density (stack): 0.5 to 0.7 A/cm²
- 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

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 Solid Oxide Fuel Cells
Markets and Technology Status

Nguyen Minh
Honeywell Engines & Systems
Torrance, CA

The New Honeywell: A Broader-Based Company

Increased diversification = increased product offerings
Approaches to SOFC Technology

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

Low Cost Manufacturing Process

• Stack fabrication process with tape calendering
• Multilayer electronics fabrication process
SOFC Applications

- **Portable**
  - e.g. emergency, remote, recreational

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

- **Transportation**
  - APUs

- **Stationary**
  - e.g. residential, distributed, central

Solid Oxide Fuel Cell Battery Charger

- Anode Fin
- Alloy Interconnect
- Cathode Fin
- Single Cell
- Oxidant Passage
- Fuel Passage
Honeywell Portable Demonstration Unit

Solid Oxide Fuel Cell System Solutions
Planar SOFC Products - Status of Development

- Fuel Cell Stack
- Fuel Processor
- Thermal Management
- Power Electronics
- Controls
- Balance of Plant

SOFC Specific
Existing capabilities of other systems that apply to SOFC systems

Stationary Power Growth

Demand for Electricity is Growing

Natural Gas-Based Generation is Leading the Growth

Distributed Generation is High Growth
Addressable Stationary Power Market for SOFCs

Data Sources:
- US Department of Energy data
- Arthur D. Little study
- Technomics study
- Escovale study
- Oberman Associates study

Addressable Stationary Power Market for SOFCs

Potential Entry Market

Load: 1 kW 10 kW 100 kW 1 MW 10 MW

Customers:
- Residential
- Strip Malls
- Offices
- Schools
- Hospital
- Transportation
- APU
- Oil & Gas/Remote

Solutions:
- Microturbines
- Gas Turbines
- Reciprocating Engines
- Thermoelectric Generator
- GAP

First Planar SOFC Products

SECA Meeting
June 1, 2000
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
Fuel Cell Markets

SECA Workshop

W. P. Schweizer
June 1, 2000

Clean Energy for the World

SOFCo
Fuel Cell Markets

Military

Stationary

Transportation

Key Drivers

- Enabling Technology
- Performance
- Cost
Fuel Cell Markets

Market Size

- Military
- Stationary
- Transportation

Fuel Cell Markets

Keys to Success

- Make it work!
- Make it cheap!
- Deliver the value!
Fuel Cell Markets

Clean Energy for the World

SOFCo
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.

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.
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
- June 15, 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.
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

<table>
<thead>
<tr>
<th>NAME</th>
<th>AFFILIATION</th>
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<tbody>
<tr>
<td>Gerry Agnew</td>
<td>Rolls-Royce</td>
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<tr>
<td>Bill Barker</td>
<td>ITN Energy Systems, Inc.</td>
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<tr>
<td>Scott Barnett</td>
<td>Northwestern University</td>
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<td>David Bauer</td>
<td>Ford Motor Co.</td>
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<tr>
<td>Donald Beal</td>
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<tr>
<td>Ray Benn</td>
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<tr>
<td>Brian Borglum</td>
<td>Siemens Westinghouse Power</td>
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<td>Mike Cobb</td>
<td>Michael A. Cobb and Co.</td>
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<td>Benson P. Lee</td>
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<tr>
<td>Ron Loehman</td>
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<tr>
<td>Bill Luecke</td>
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<tr>
<td>John A. Olenick</td>
<td>Advanced Refractory Technologies, Inc.</td>
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<td>IGT/GRI</td>
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<td>Bill Schweizer</td>
<td>McDermott/SOFC</td>
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<td>Mohinder Seehra</td>
<td>West Virginia University</td>
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<tr>
<td>Scott Swartz</td>
<td>NexTech Materials</td>
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<tr>
<td>Anil Virkar</td>
<td>University of Utah</td>
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<tr>
<td>Steve Visco, Chairperson*</td>
<td>Lawrence Berkeley National Lab</td>
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<tr>
<td>Conghua Wang</td>
<td>University of Pennsylvania</td>
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<tr>
<td><strong>FACILITATOR:</strong> Howard Lowitt</td>
<td>Energetics, Incorporated</td>
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* = Presenter for report-out
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<tr>
<th>Design interconnects alloy that forms a conducting scale</th>
<th>Chromium-free metallic interconnects</th>
<th>Manufacturing cost models</th>
<th>High temperature corrosion of metal interconnects and interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved BOP/system integration</td>
<td>Cheap protective coatings for metallic interconnects</td>
<td>Design for manufacture</td>
<td>Investigate novel stack designs</td>
</tr>
<tr>
<td>Integrate experiments and modeling to minimize sintering and expansion stresses in co-fired ceramic layers</td>
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<td>Cell stack design</td>
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<td>Develop reliable seals and prove new designs</td>
<td>Develop improved extrusion and molding technology for complex parts</td>
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<td>Integrate experiments and modeling to minimize sintering and expansion stresses in co-fired ceramic layers</td>
<td>New anodes/cells that can use hydrocarbon fuels</td>
<td>New electrode materials</td>
<td>Identify and develop durable, high-temperature metal-based interconnects</td>
</tr>
<tr>
<td>Develop metallic interconnect supported design and fabrication process</td>
<td>New, highly electro-active electrodes and development of electrode-supported cells</td>
<td>Develop cell materials capable of high power density at 700°F and below</td>
<td>Custom formulation of metal interconnects</td>
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<td>Develop metallic interconnect supported design and fabrication process</td>
<td>Development of single-step firing of cells</td>
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<td>New methods for high temperature, multi-material joining and sealing</td>
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<td>Identification of new, high performance, lower cost materials.</td>
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<td>Single step cell fabrication technology</td>
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### Materials and Manufacturing – Session A: Issues

(scored = Vote for Priority Topic)

<table>
<thead>
<tr>
<th>Scored Topic</th>
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<tr>
<td>Given a good fuel cell? How does one verify – technical test issues</td>
<td>Rapid cooldown technique thermal designs</td>
<td>Activation potential</td>
<td>Sulfur poisoning of anode</td>
<td>Complicated thin film/coating technology</td>
<td>New stack designs</td>
<td>Innovative stack design</td>
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<td>Concurrent operation of metallic plates at operating temperature of ionic conducting ceramics</td>
<td>Interconnect inventory</td>
<td>High working temperature 800°C-700°C</td>
<td>Bi-polar supported (metallic) SOFC for cost reduction</td>
<td>Cathode performance</td>
<td>expensive cathode materials</td>
<td>Synergistic impact of R&amp;D on issues</td>
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<tr>
<td>Better materials for seals low cost, easy to fabricate into stack</td>
<td>Durable sealing (stack design/bonding agent)</td>
<td>Greater, more available body of knowledge and data (knowledge transfer includes from other fields)</td>
<td>Basic knowledge and data relating to interconnects</td>
<td>Multiple materials currently require multiple fabrication steps/processes, single step process needed</td>
<td>Low-cost manufacturing of tri-layer cells</td>
<td>Too many manufacturing steps</td>
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<tr>
<td>Development of thinner cell components to lower amount of material per cell</td>
<td>Hydrogen as fuel, new anode</td>
<td>Stack must survive rapid thermal cycling</td>
<td>Metallic interconnects</td>
<td>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</td>
<td>Lower temperature materials</td>
<td>Materials with higher conductivities at lower temperatures</td>
</tr>
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<td>Stack must survive rapid thermal cycling</td>
<td>Interconnect inventory</td>
<td>High working temperature 800°C-700°C</td>
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<td>Low-cost manufacturing of tri-layer cells</td>
<td>Too many manufacturing steps</td>
<td>Complicated manufacturing procedures requiring multiple firings of ceramics</td>
<td>SOFC materials are not computer components</td>
<td>Optimize fabrication technology</td>
<td>Small scale (size) extrusion technology needed</td>
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<td>Development of multi-material co-firing to lower manufacturing costs</td>
<td>Low cost, efficient materials</td>
<td>Ability of SOFCs to follow load</td>
<td>Single SECA goals (identify intermediate niches)</td>
<td>Lack of anodes capable of high fuel conversion with minimal prereforming (maximized efficiency)</td>
<td>Req. use of high cost, dissimilar material properties materials that cause integration challenges</td>
<td>Long term chemical compatibility data</td>
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# Materials and Manufacturing – Session A: R&D Opportunities

(⊗ = Vote for Priority Topic)

<table>
<thead>
<tr>
<th><strong>Advanced Integrated Fabrication Technology</strong></th>
<th><strong>Component Development</strong></th>
<th><strong>New Stack Design</strong></th>
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<tbody>
<tr>
<td>• Single step SOFC fabrication technique</td>
<td>• Low temperature development &lt;800</td>
<td>• New stack design(s)</td>
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<tr>
<td>• Develop low-cost thin-film fabrication / manufacturing techniques</td>
<td>• Identify new, novel seals and separators for test and evaluation</td>
<td>• New stack, cheap design to minimize inter-connects and seals</td>
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<tr>
<td>• Integrated cell/stack design with fabrication process development</td>
<td>• Development and investigation of metal interconnect technology</td>
<td>• Conduct trade-off studies, i.e., temperature/materials</td>
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<td>• Modeling to enable new design development and cost</td>
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<td>• Design economic simulation model of effect of new designs on manufacturing cost</td>
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<td>• Investigate material vs. design function trade-offs</td>
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<td></td>
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<td>• Miniaturizations</td>
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<td>• Expand knowledge base of SOFC reliability under arbitrary operating conditions</td>
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</table>
Materials and Manufacturing – Session A: What Are the Actions Needed to Take Advantage of the Opportunities?

<table>
<thead>
<tr>
<th>R&amp;D Opportunity</th>
<th>Actions</th>
<th>Type of Action</th>
<th>0-3</th>
<th>3-6</th>
<th>6-10</th>
<th>Industry</th>
<th>Academia</th>
<th>National Labs</th>
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<tbody>
<tr>
<td><strong>LOW TEMPERATURE COMPONENT DEVELOPMENT</strong></td>
<td>• Mechanistic studies of electrode kinetics</td>
<td>R</td>
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<td>A</td>
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<td></td>
<td>• Optimize performance of mixed-conducting cathodes</td>
<td>D</td>
<td>X</td>
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<td>I</td>
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<td></td>
<td>• Develop direct oxidizing anode</td>
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<td>• Oxidation resistant anode</td>
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<td></td>
<td>• Modify anode to control T due to internal reforming</td>
<td>D/E</td>
<td>X</td>
<td>X</td>
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<td></td>
<td>• Investigation of commercially available alloys</td>
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<td>A</td>
<td>N</td>
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<tr>
<td><strong>INVESTIGATE AND DEVELOP METAL INTERCONNECT TECHNOLOGY</strong></td>
<td>• Interconnects designs that minimize material use</td>
<td>E</td>
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<td>X</td>
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<td></td>
<td>• Investigation of interconnect, electrode interface</td>
<td>R</td>
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<td>X</td>
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<td>N</td>
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<td></td>
<td>• Explore thermal spray techniques</td>
<td>D</td>
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<td>X</td>
<td>X</td>
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<td></td>
<td>• Control and optimization of sintering of ceramic multi-layers</td>
<td>R/D</td>
<td>X</td>
<td>X</td>
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<td>I</td>
<td>N</td>
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<tr>
<td><strong>ADVANCED FABRICATION TECHNOLOGIES</strong></td>
<td>• Manufacturing cost estimation studies</td>
<td>D/E</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>I</td>
<td>N</td>
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<td></td>
<td>• Increase mech. strength of electrode support (or SOFC stack)</td>
<td>D/E</td>
<td>X</td>
<td>X</td>
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Key:  
E = Engineering  
D = Development  
R = Research
### Materials and Manufacturing – Session A: Report-Out

<table>
<thead>
<tr>
<th>TECHNICAL ISSUES</th>
<th>R&amp;D OPPORTUNITIES</th>
<th>KEY OPPORTUNITIES</th>
<th>ACTIONS</th>
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</thead>
<tbody>
<tr>
<td>• Metallic interconnects</td>
<td>• Component development</td>
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<td>• Optimize fabrication technology</td>
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<td>• New stack designs (current stack designs)</td>
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<td>• Metal Interconnect Technology</td>
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<td>− Trade-offs driving design of stacks</td>
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<td>• Investigation of commercially available alloys</td>
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<td>• Advanced integration fabrication technologies</td>
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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

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<td>Glen Benson</td>
<td>Aker Industries</td>
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<td>Sandy Dapkunas</td>
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<td>Lutgard C. DeJonghe*</td>
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<td>Richard Dye</td>
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<td>Peter Faguy</td>
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<td>Robert Glass</td>
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<td>Jack (John) Hirschenhofer</td>
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<tr>
<td>Udaya Rao</td>
<td>NETL</td>
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<tr>
<td>Carl Reiser</td>
<td>International Fuel Cells</td>
</tr>
<tr>
<td>Richard Rozance</td>
<td>Car Sound Exhaust Systems, Inc.</td>
</tr>
<tr>
<td>Chin Schilling</td>
<td>Iowa State University</td>
</tr>
<tr>
<td>Dinesh K. Shetty</td>
<td>Materials and Systems Research, Inc.</td>
</tr>
<tr>
<td>Subhash C. Singhal</td>
<td>PNNL</td>
</tr>
<tr>
<td>Jeff Stevenson, Chairperson</td>
<td>PNNL</td>
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<tr>
<td>Michael Thompson</td>
<td>PNNL</td>
</tr>
<tr>
<td>Wayne L. Worrell</td>
<td>University of Pennsylvania</td>
</tr>
</tbody>
</table>

**FACTORIATOR:** Rich Scheer  | Energetics, Incorporated

* = Presenter for report-out
### Materials and Manufacturing – Session B: Scientific and Technology Issues

(🔗 = Vote for Priority Topic)

<table>
<thead>
<tr>
<th>MANUFACTURABILITY</th>
<th>INTERCONNECT MATERIALS</th>
<th>COST OF RAW MATERIALS</th>
<th>PERFORMANCE</th>
<th>STACK SYSTEM DESIGN AND INTEGRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• For target power density no high volume, low-cost tri-layer fabrication technology exists</td>
<td>• Lifetime of interconnect materials</td>
<td>• Low demand for LSM, YSE materials</td>
<td>• η of 60 to 70% will require 0.85 V/C; close to theoretical present is 0.7 V/C</td>
<td>• Thermal management</td>
</tr>
<tr>
<td>• Need for system integration of stack components and automated manufacturing</td>
<td>• Interconnect metal or oxide?</td>
<td>• Availability of high V, low-cost raw material</td>
<td>• Slow electrode kinetics at low temperature</td>
<td>• Low cost PEN with controlled morphology electrodes</td>
</tr>
<tr>
<td>• Lack of alternatives to the costly EVD process for depositing the electrolyte</td>
<td>• Lack of inexpensive thermally reliable seals</td>
<td></td>
<td>• Limited temperature range</td>
<td>• Need for inexpensive thermal insulation</td>
</tr>
<tr>
<td>• Basic understanding of how electrode/electrolyte reliability is affected by colloidal deposition parameters</td>
<td>• Metal interconnects needed above 650°C</td>
<td></td>
<td>• Catalysis limiting issues below 700°C</td>
<td>• Fuel delivery to all cells in stack</td>
</tr>
<tr>
<td>• Fabrication of stacks from cells</td>
<td></td>
<td></td>
<td>• Lack of NDE techniques to predict remaining life</td>
<td>• Serviceability of complex fuel stack</td>
</tr>
<tr>
<td>• Thin-film manufacturing cost</td>
<td></td>
<td></td>
<td>• Specific power (W/cm²)</td>
<td>• Materials compatibility</td>
</tr>
<tr>
<td>• Lack of NDE for manufacturing</td>
<td></td>
<td></td>
<td>• Anode composition and structure to permit full in situ reforming</td>
<td>• Settling too soon on tech design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Hydrocarbon tolerances and poisoning</td>
<td>• Gas manifolding on mass customization of core module</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Design of novel interfaces with minimum resistance</td>
<td>• Need to recycle address disposal/ recycling of materials from stack</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Thermal cycling of scaled-up reduced temperature planar stacks</td>
</tr>
</tbody>
</table>
## Materials and Manufacturing - Session B: R&D Opportunities

(投票符号 = Vote for Priority Topic)

### Design
- 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

### Interconnects
- 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

### Fabrication/Manufacturing
- 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

### Materials Properties
- 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

### Interface
- 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

<table>
<thead>
<tr>
<th>R&amp;D Opportunity</th>
<th>Brief Description of Opportunity</th>
<th>Type of Action</th>
<th>Key Action Steps</th>
<th>Lead Roles</th>
<th>Other Points</th>
</tr>
</thead>
</table>
| • 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)

<table>
<thead>
<tr>
<th>R&amp;D Opportunity</th>
<th>Brief Description of Opportunity</th>
<th>Type of Action</th>
<th>Key Action Steps</th>
<th>Lead Roles</th>
<th>Other Points</th>
</tr>
</thead>
</table>
| • 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 over transient 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

<table>
<thead>
<tr>
<th><strong>Design and Manufacturing</strong></th>
<th><strong>Breakout Session Overview</strong></th>
<th><strong>Materials</strong></th>
<th><strong>Closing Remarks</strong></th>
</tr>
</thead>
</table>
| • 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/cm²  
  • 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 H₂S, 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

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dave Berry, Chairperson</td>
<td>DOE/NETL</td>
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<td>Rich Carlin</td>
<td>Office of Naval Research</td>
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<td>Ravi Chandran</td>
<td>MTCI</td>
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<td>Herb Dobbs</td>
<td>U.S. Army TACOM</td>
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<td>Chris Egan</td>
<td>U.S. Navy/NAVSEA</td>
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<td>Lyman J. Frost*</td>
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<td>R. Srinivasan</td>
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<td>Thomas I. Valdez</td>
<td>Jet Propulsion Laboratory</td>
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<td>Jud Virden</td>
<td>PNNL</td>
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<td>Dennis Witmer</td>
<td>University of Alaska Fairbanks</td>
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<td>Joe Woerner</td>
<td>Analysis and Technology</td>
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<td>Richard Woods</td>
<td>Hydrogen Burner Technology</td>
</tr>
<tr>
<td>John Yamanis</td>
<td>Honeywell, Morristown, NJ</td>
</tr>
<tr>
<td><strong>Facilitator:</strong></td>
<td><strong>Joe Badin</strong></td>
</tr>
</tbody>
</table>

* = Presenter for report-out
## Fuel Processing – Session A
What Are the Science and Technical Issues to Achieving Vision?

(• = Vote for Priority Topic)

<table>
<thead>
<tr>
<th><strong>Catalyst Issues</strong></th>
<th><strong>Fuel Issues</strong></th>
<th><strong>Gas Clean-Up</strong></th>
<th><strong>Operational Issues</strong></th>
<th><strong>Cost Issues</strong></th>
<th><strong>System Integration</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Catalyst availability for variety of fuels</td>
<td>• Operation with little or no water (gasoline, diesel)</td>
<td>• Active sulfur removal gas phase</td>
<td>• Load following fuel source</td>
<td>• Low-cost high temperature heat exchangers</td>
<td>• Fully integrated fuel processor T, heat balance</td>
</tr>
<tr>
<td>• Lack of more predictive catalyst design tools</td>
<td>• Small and efficient P.O. reformer for gasoline and diesel 90% conversion</td>
<td>• Desulfurization technology – needs to be high capacity, without need for hydrogen, compatible with metcaptions and thiophenes</td>
<td>• 20 to 1 turndown sensors</td>
<td>• Materials of construction (high-temperature)</td>
<td>• Size reduction issues – heat management issues</td>
</tr>
<tr>
<td>• Catalysis - Reduction of size of processing hardware for multi-fuel</td>
<td>• Direct diesel (multi-fuel) SOFC, Eliminate reformer</td>
<td>• Requirement for very rapid transient response rapid transient resp.</td>
<td>• Requirement for very rapid transient response</td>
<td>• Hydrogen embrittlement</td>
<td>• Start-up requirements cold-hot</td>
</tr>
<tr>
<td>• Catalyst life</td>
<td>• Partial oxidation of liquid fuels with oxygen</td>
<td>• Pure hydrogen stream</td>
<td>• Reformer stability during transients (startup-shut down – ramp)</td>
<td>• Catalyst cost</td>
<td>• Achieving 60-70% efficiency goal without bottom cycle and in volume/wt envelope is challenging</td>
</tr>
<tr>
<td>• Coking problems</td>
<td>• Feedstock flexible</td>
<td>• Control sensor how do we know when the reformer is deteriorating?</td>
<td>• Feedstock flexible</td>
<td>• Hydrogen embrittlement</td>
<td>• Ability to internally reform (in stack)</td>
</tr>
<tr>
<td>• Electrochemical reformers</td>
<td>• Logistic fuels – compact, fuel-flexible, rapid response</td>
<td>• Freezing protection</td>
<td>• Feedstock flexible</td>
<td>• Natural gas</td>
<td>• Control system</td>
</tr>
<tr>
<td>• Sulfur-tolerance and direct electrochemical oxidation</td>
<td></td>
<td></td>
<td>• Cycling</td>
<td></td>
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</tr>
</tbody>
</table>
### Fuel Processing – Session A

**What Are the R&D Opportunities to Overcome the Issues?**

(投票 for Priority Topic)

<table>
<thead>
<tr>
<th>SYSTEM DEVELOPMENT AND DEMONSTRATION</th>
<th>FUEL CHARACTERIZATION</th>
<th>CLEAN-UP PROCESSES</th>
<th>CATALYST DEVELOPMENT</th>
<th>MODELING</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Develop low cost high temperature heat exchangers</td>
<td>• Define and characterize fuels</td>
<td>• Sulfur removal – gas phase H₂S, organic sulfides</td>
<td>• Catalyst characterization – performance, life, cost</td>
<td>• Develop reaction kinetics modeling</td>
</tr>
<tr>
<td>• DOE work in high “R” insulations</td>
<td>• Decide what fuel is best – reference fuels</td>
<td>• Long life regenerable sulfur sorbents</td>
<td>• Develop multi-fuel single catalyst</td>
<td>• Different fuels</td>
</tr>
<tr>
<td>• Development of low-cost, accurate sensors</td>
<td></td>
<td>• Demonstrate</td>
<td>• Reformer catalyst development</td>
<td>• Different water</td>
</tr>
<tr>
<td>• Modular control system concepts</td>
<td></td>
<td>• Nanoporous ceramic membranes for gas purification</td>
<td></td>
<td>• Coke formation</td>
</tr>
<tr>
<td>• System-level reformer development</td>
<td></td>
<td>• Develop a liquid phase De-S system</td>
<td></td>
<td>• System modeling to identify optimal strategies for integrating stack and reformer designs</td>
</tr>
<tr>
<td>• Microchannel reformers for reduced size and integration</td>
<td></td>
<td>• Mixed oxide conductors for fuel processing</td>
<td></td>
<td>• Modeling heat flows</td>
</tr>
<tr>
<td>• Multi-path approach to demonstrate electro-chemical reformer</td>
<td></td>
<td></td>
<td></td>
<td>• Fundamentals of hydrocarbon refining (in-situ, . . .)</td>
</tr>
<tr>
<td>• Develop low-cost, fully integrated fuel processor module</td>
<td></td>
<td></td>
<td></td>
<td>• Transient control dynamic temperature, temperature and reaction rates in reformer catalysts (chemical modeling)</td>
</tr>
<tr>
<td>• Operational characterization of “state-of-the-art” fuel processors (Team)</td>
<td></td>
<td></td>
<td></td>
<td>• System modeling “optimizations” toward mass customization</td>
</tr>
</tbody>
</table>
**Fuel Processing – Session A**  
**What Are the Actions to Take Advantage of the R&D Opportunities?**

<table>
<thead>
<tr>
<th><strong>SYSTEM-LEVEL REFORMER DEVELOPMENT</strong></th>
<th><strong>SYSTEM MODELING TO INTEGRATE STACK AND REFORMER DESIGNS</strong></th>
<th><strong>FUEL PROCESSOR CATALYST DEVELOPMENT</strong></th>
<th><strong>LEAD ROLE(S)</strong></th>
</tr>
</thead>
</table>
| 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 cost  
- 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

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

<table>
<thead>
<tr>
<th>NAME</th>
<th>AFFILIATION</th>
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<tbody>
<tr>
<td>Buddy Hartberger</td>
<td>U.S. Coast Guard</td>
</tr>
<tr>
<td>Zohair Ismail</td>
<td>U.S. Army CEOM</td>
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<tr>
<td>Craig Linne</td>
<td>Visteon Automotive</td>
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<td>M. Mundschaun</td>
<td>Eltron Research</td>
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<td>M. Mansour</td>
<td>ThermoChem</td>
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<tr>
<td>Kirby Meacham</td>
<td>Michael A. Cobbs &amp; Co.</td>
</tr>
<tr>
<td>Larry Osgood</td>
<td>Consulting Solutions/Propane Council</td>
</tr>
<tr>
<td>Prabhakar Singh</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>Jack Solomon*</td>
<td>Praxair Inc.</td>
</tr>
<tr>
<td>Walter Taschek</td>
<td>U.S. Army CECOM</td>
</tr>
<tr>
<td>W.P. Teagan, Chairman</td>
<td>Arthur D. Little</td>
</tr>
<tr>
<td><strong>FACILITATORS:</strong> Phil DiPietro</td>
<td>Energetics, Incorporated</td>
</tr>
<tr>
<td></td>
<td>Robyn McGuckin</td>
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</tbody>
</table>

* Presenter for report-out
<table>
<thead>
<tr>
<th>PERFORMANCE</th>
<th>STACK SENSITIVITY (SULFUR &amp; SALT) POISON</th>
<th>LOW CAPACITY OF SYSTEM</th>
<th>INTERNAL REFORMING</th>
<th>FUEL EFFECT ON FUEL PROCESSOR</th>
<th>FUEL PROCESSING BOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Long-term testing durability</td>
<td>• Anode Poisoning - Salt - Sulfur</td>
<td>• Difficult for Diesel • Availability of low cost small scale reformer • Thermal losses in small systems • Reliability at small scale</td>
<td>• Poisoning • Cracking • Thermal management • Preconditioning of fuel</td>
<td>• Deactivation of catalyst - Thermal - Coking - Sooting - Poisoning</td>
<td>• Sulfur absorption/disposal (filter cartridge) using alkali metal • Long life desulfurizer • Water sufficiency</td>
</tr>
<tr>
<td>• Long life of reformer materials at low cost</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>• Start-up time</td>
<td></td>
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<td></td>
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<tr>
<td>• Load following</td>
<td></td>
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</tr>
</tbody>
</table>
### Fuel Processing – Session B: Opportunities

(득 = Vote for Priority Topic)

<table>
<thead>
<tr>
<th>Making Diesel Fuel Processor Work</th>
<th>Propane/Natural Gas Fuel Processor as Cheap as Possible</th>
<th>Internal Reforming</th>
<th>Balance of Plant</th>
<th>Other Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 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</td>
<td>• 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</td>
<td>• 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)</td>
<td>• Sensors • Materials • Manufacturing • Techniques • Reduce parasitic load</td>
<td>• Accelerated durability testing reformer(stack) • Long term materials research and tests • System optimization • Ultra-rich internal combustion engine as POS fuel processor shaft power out quick start • Coking-resistant coating for preconditioner</td>
</tr>
</tbody>
</table>
## Fuel Processing – Session B: Actions

<table>
<thead>
<tr>
<th><strong>Fuel Processor for Diesel and Logistic Fuels</strong></th>
<th><strong>Ultra Low-Cost High Efficiency Fuel Processor for Natural Gas and Propane</strong></th>
<th><strong>Internal Reforming (on-anode)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Novel Processes</td>
<td>• Develop low cost, high efficiency gaseous fuel reforming</td>
<td>• Most effort is on steam reforming, could look at POX as well</td>
</tr>
<tr>
<td>- Ceramic Membrane POX</td>
<td>- Steam</td>
<td>- Lab scale experimentation</td>
</tr>
<tr>
<td>- Integrated heat transfer microchannel /plate reformer</td>
<td>- POX</td>
<td>- Modeling</td>
</tr>
<tr>
<td>- Two stage heavy fuel steam reformer</td>
<td>- Other</td>
<td>- Thermal</td>
</tr>
<tr>
<td>- Materials resistant to impurities</td>
<td>- Thermally integrated reforming</td>
<td>- Chemical</td>
</tr>
<tr>
<td>- Pilot plant</td>
<td>- Build at 5 kW</td>
<td>- Electro-chemical</td>
</tr>
<tr>
<td>- At 20 kW</td>
<td>- Starting point. Simplify fuel processors designed for PEM stacks</td>
<td>• Multi-fuel tolerant core module</td>
</tr>
<tr>
<td><strong>Fuel Pre-processing</strong></td>
<td>- Multi-fuel R&amp;D</td>
<td>• Graded anode</td>
</tr>
<tr>
<td>- Liquid phase desulfurization</td>
<td>- Integrated fabrication development</td>
<td>• Fuel mixing</td>
</tr>
<tr>
<td>- Better ways to remove sulfur during processing</td>
<td>- Design low cost manufacturing</td>
<td></td>
</tr>
</tbody>
</table>
### Fuel Processing – Session B: Report-Out

(⊕ = Vote for Priority Topic)

<table>
<thead>
<tr>
<th>Issues</th>
<th>Opportunities</th>
<th>Actions</th>
<th>Comment</th>
</tr>
</thead>
</table>
| • 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

## Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Said Al-Hallaj*</td>
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<td>RAND</td>
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<td>DOE/NETL</td>
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<td>Jim Miller</td>
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<td>John Plunkett</td>
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<td>William Rogers</td>
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<td><strong>Facilitator:</strong></td>
<td>Ed Skolnik</td>
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<tr>
<td></td>
<td>Energetics, Incorporated</td>
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</tbody>
</table>

* = Presenter for report-out
## Modeling and Simulation: What Are the Science and Technical Issues to Achieving the Vision?

*(☐ = Vote for Priority Topic)*

### Crosscutting Issues
- 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 (☐)

### Cell/Fundamental Models
- 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 micro/fundamental models (☐☐☐)

### Component Models
- Better models for fuel processing (☐☐☐)

### Stack Models
- 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 (☐☐☐)

### System Models
- 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)

<table>
<thead>
<tr>
<th>Validation Opportunities</th>
<th>Cell/fundamental</th>
<th>Component</th>
<th>Stack</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Define precisely what validation data that we need and get it (database)</td>
<td>• Material databases electrochemical and thermal and failure data</td>
<td>• Fuel reformation models</td>
<td>• Develop coupled multi-dimensional multi-physics engineering model for stack with benchmark problem set</td>
<td>• Build reliability model of SOFC system</td>
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<tr>
<td></td>
<td>• Develop tests and test standards for measuring material properties especially interfacial properties</td>
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<td>• Build diagnostic model of SOFC system</td>
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<td></td>
<td>• Fuel cell cost algorithms</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Computation Opportunities (Modeling)</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>• Model SOFC Operations: Start-up, part-load, shut-down (Load following)</td>
<td>• Development of fundamental multi-dimensional models which emphasizes on: electrochemical, kinetic transport aspects on the cell level.</td>
<td>• Fuel reformation models</td>
<td>• Develop coupled multi-dimensional multi-physics engineering model for stack with benchmark problem set</td>
<td>• Build reliability model of SOFC system</td>
</tr>
<tr>
<td>• Handbook of Fuel Cell Model equations and thermal papers</td>
<td>• Develop 3D fundamental multi-scale model for microstructural analysis and design</td>
<td></td>
<td></td>
<td>• Build diagnostic model of SOFC system</td>
</tr>
<tr>
<td>• Thermoeconomic design studies</td>
<td></td>
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<td></td>
<td>• Fuel cell cost algorithms</td>
</tr>
<tr>
<td>• Develop efficient numerics for such complex problems</td>
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<tr>
<td>• Perform uncertainty analysis on fuel cell models at all levels (focus on numerical errors)</td>
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<tr>
<td>Joint Validation/Computation Opportunities</td>
<td>* Benchmarks - more than one group develop and characterize same cell design - more than one group test above and provide detailed data - more than four groups model</td>
<td>* Determine electro-chemical rates and mechanisms: measure and model</td>
<td>• Understand failure mechanisms in stack/cell</td>
<td>• Build reliability model of SOFC system</td>
</tr>
<tr>
<td></td>
<td>* Model Equation Development - Research on kinetics (electrochem and reforming) - Propose and test models - Publish all results</td>
<td></td>
<td></td>
<td>• Build diagnostic model of SOFC system</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>• Fuel cell cost algorithms</td>
</tr>
</tbody>
</table>
### Modeling and Simulation: What Are the Actions to Take Advantage of the R&D Opportunities?

<table>
<thead>
<tr>
<th>R&amp;D Opportunity</th>
<th>Actions 0-5 Years</th>
<th>Actions 5-10 Years</th>
<th>Lead Role</th>
<th>Other Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Develop Models for Stack and Cell</strong></td>
<td>• Evaluate (and communicate) existing model base (E)</td>
<td>• Different groups to do different models electrochemical, kinetic, etc. (R)</td>
<td>Government, Industry (NETL) with Industry and Academia</td>
<td>• Consider concurrent engineering</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>• Develop design/applications models that address SECA vision (D)</td>
<td>• Support Vision 21 virtual plant demonstration prototyping</td>
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<td>• Incorporate into overall system model (E)</td>
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<td></td>
<td>• Refine models as necessary (input from benchmarks) (D)</td>
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<td>• Accommodate technical breakthroughs</td>
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<td></td>
<td>• Modeling to accommodate markets (implement models P/E we have developed) (D/E)</td>
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<td></td>
<td>• Reduce the turn-around time to speed the design cycle (D)</td>
<td></td>
</tr>
<tr>
<td><strong>Benchmark Development</strong></td>
<td>• Develop and characterize benchmark cells (D/E)</td>
<td></td>
<td>Government with academia</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>• Test and provide detailed data (D/E)</td>
<td></td>
<td>Government with academia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Model (D/E)</td>
<td></td>
<td>Government with academia and industry</td>
<td></td>
</tr>
<tr>
<td><strong>Model SOFC Operation</strong></td>
<td>• Establish off-design conditions and requirements (E)</td>
<td></td>
<td>Industry with government</td>
<td>none</td>
</tr>
<tr>
<td><strong>(Start up, Part Load, Shut Down)</strong></td>
<td></td>
<td></td>
<td>Government with academia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Development coupled transient models (D/E)</td>
<td></td>
<td>Government with academia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Validate model (D/E)</td>
<td></td>
<td>Government with industry</td>
<td></td>
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<tr>
<td></td>
<td>• Integration with design cycle (E)</td>
<td></td>
<td>Industry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Accommodate technology breakthroughs (D/E)</td>
<td></td>
<td>Government with Academia and industry</td>
<td></td>
</tr>
</tbody>
</table>

Key: E = Engineering  
D = Development  
R = Research
## Modeling and Simulation: Report-Out

<table>
<thead>
<tr>
<th>ISSUES</th>
<th>R&amp;D OPPORTUNITIES</th>
<th>ACTIONS</th>
</tr>
</thead>
</table>
| - 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  
  - 0-5 Validate 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

## Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Don Adams, Chairperson*</td>
<td>Oak Ridge National Lab</td>
</tr>
<tr>
<td>Thom Broe</td>
<td>Sustainable Energy Technology</td>
</tr>
<tr>
<td>T.P. Chen</td>
<td>Nexant, Inc.</td>
</tr>
<tr>
<td>Michel Jullian</td>
<td>OCM Technology</td>
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<td>John Kalmakoff</td>
<td>Sustainable Energy Technologies</td>
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<td>Benson P. Lee</td>
<td>Technology Management, Inc.</td>
</tr>
<tr>
<td>Don McConnell</td>
<td>Pacific Northwest National Lab</td>
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<tr>
<td>Tim McDonald</td>
<td>Pinnacle West Capital Corp (APS)</td>
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<tr>
<td>Tim McIntyre</td>
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<tr>
<td>Steve Satzberg</td>
<td>Office of Naval Research</td>
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<tr>
<td>Tim Theiss</td>
<td>Oak Ridge National Lab</td>
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<tr>
<td>Mark Williams</td>
<td>NETL</td>
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**Facilitator:** Kevin Moore  
Energetics, Incorporated

* = Presenter for report-out
### Power Electronics: What Are the Scientific and Technical Issues to Achieve SECA Vision by 2010?

(☼ = Vote for Priority Topic)

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

<table>
<thead>
<tr>
<th>SIZE, VOLUME, AND WEIGHT</th>
<th>ECONOMIES OF SCALE</th>
<th>COST DISCREPANCY</th>
</tr>
</thead>
</table>
Power Electronics: What Are the R&D Opportunities to Overcome Issues to SECA?

(_votes for Priority Topic)

<table>
<thead>
<tr>
<th>THERMAL MANAGEMENT</th>
<th>INTERFACE</th>
<th>COST</th>
<th>RELIABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Higher temperature components, e.g., capacitors</td>
<td>• Definition of system requirements</td>
<td>• Cost tradeoffs studies</td>
<td>• Improve component materials</td>
</tr>
<tr>
<td>• Direct cooling of silicon or SiC</td>
<td>• Load prediction</td>
<td>• Soft switching topology</td>
<td>• Prognostics</td>
</tr>
<tr>
<td>• Cheap diamond film</td>
<td>• Establish standards</td>
<td>• Integrated devices</td>
<td>• Topology choice, e.g., redundancy, multi-level</td>
</tr>
<tr>
<td>• Integrated electronic within cell</td>
<td>• Challenge 5 kW choice</td>
<td>• Manufacturing process development</td>
<td>• Robust design</td>
</tr>
<tr>
<td></td>
<td>• Plug and Play</td>
<td>• DFMA</td>
<td>• Soft failure</td>
</tr>
<tr>
<td></td>
<td>• Low cost storage high density caps</td>
<td>• Grid interconnect standards</td>
<td></td>
</tr>
</tbody>
</table>
# Power Electronics: What Actions to Take Advantage of R&D Opportunities?

<table>
<thead>
<tr>
<th>R&amp;D Opportunity</th>
<th>Actions 0-5 Years</th>
<th>Type of Action</th>
<th>Actions 5-10 Years</th>
<th>Type of Action</th>
<th>Lead Roles</th>
</tr>
</thead>
</table>
| • 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

<table>
<thead>
<tr>
<th><strong>POWER ELECTRONICS</strong></th>
<th><strong>ISSUES</strong></th>
<th><strong>R&amp;D OPPORTUNITIES</strong></th>
<th><strong>ACTIONS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Is power electronics in the fuel cell “box” or not?</td>
<td>• Complex system interface</td>
<td>• Integrated devices for interface</td>
<td>• Integrated devices</td>
</tr>
<tr>
<td>• Ganged 5 kW modules are not practical for power electronics?</td>
<td>• Modular family architecture</td>
<td>• Reliability – improve component materials</td>
<td>- Align with manufacturers</td>
</tr>
<tr>
<td>• Status</td>
<td>• Lousy load following</td>
<td>• Thermal Management – higher temperature components</td>
<td>- Develop open architecture hardware and software</td>
</tr>
<tr>
<td>- $7/kW mobile in 3 years</td>
<td>• Thermal management</td>
<td></td>
<td>- Identify common denominators from developers</td>
</tr>
<tr>
<td>- 90+% efficiency</td>
<td>• Lifetime</td>
<td></td>
<td>- Develop codes and standards</td>
</tr>
<tr>
<td>- Air-cooled industrial drives</td>
<td></td>
<td></td>
<td>- Communication protocols</td>
</tr>
</tbody>
</table>

- 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

## PARTICIPANTS

<table>
<thead>
<tr>
<th>NAME</th>
<th>AFFILIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sy Ali</td>
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<td>Mike Binder</td>
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<td>Argonne National Laboratory</td>
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<td>Bob Lorand</td>
<td>SAIC</td>
</tr>
<tr>
<td>Irven Miller</td>
<td>I.B. Miller, Inc.</td>
</tr>
<tr>
<td>Eric Simpkins</td>
<td>FuelCell Energy Inc.</td>
</tr>
<tr>
<td>Joe Strakey</td>
<td>DOE/NETL</td>
</tr>
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<td>SAIC</td>
</tr>
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<td>Ed Yarbrough</td>
<td>Honeywell</td>
</tr>
<tr>
<td><strong>FACILITATOR:</strong> Alicia R. Dalton</td>
<td>Energetics, Incorporated</td>
</tr>
</tbody>
</table>

* = Presenter for report-out
# Thermal Systems: What Are the Issues (Science and Technology) to Achieving the Vision?

(☉ = Vote for Priority Topic)

<table>
<thead>
<tr>
<th><strong>Other</strong></th>
<th><strong>Components</strong></th>
<th><strong>Integration</strong></th>
<th><strong>Operating Strategies</strong></th>
</tr>
</thead>
</table>
| - 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  
- Catalyit and housing material selection driven by temperature  
- Air preheater cost/performance tradeoff  
- 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 difficult 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)*

<table>
<thead>
<tr>
<th>WATER MANAGEMENT STRATEGY</th>
<th>AIR PREHEATER</th>
<th>OVERALL STARTUP SPEED</th>
<th>TRANSIENT STRESSES DURING NORMAL AND ABNORMAL EVENTS</th>
<th>THERMAL ENCLOSURE: MATERIALS, DESIGN, &amp; COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Optimize design</td>
<td>• Configuration – optimize design</td>
<td>• Reduce thermal capacitance</td>
<td>• Ceramics – improve, toughened</td>
<td>• Better insulating materials</td>
</tr>
<tr>
<td>• Designs using recycled steam</td>
<td>• Materials and fabrication</td>
<td>• Optimize idle mode strategies</td>
<td>• Improve hardware design</td>
<td>• Cheaper materials</td>
</tr>
<tr>
<td>• Misc. – Water for fuel processor</td>
<td>• Integrated catalytic combustion</td>
<td>• Develop robust hardware design</td>
<td>• Dynamic modeling (transient)</td>
<td>• Optimize compartment design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Controls design</td>
<td></td>
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</tbody>
</table>
## Thermal Systems: What Are the Actions to Take Advantage of the R&D Opportunities

<table>
<thead>
<tr>
<th>Opportunity – Water Management – Designs Using Recycled Steam</th>
<th>Action</th>
<th>ACTION TYPE</th>
<th>TIMEFRAME</th>
<th>LEADER</th>
<th>Other Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>System study onsite/onboard water vs. recycle steam</td>
<td>E</td>
<td>6 mo.</td>
<td>DOE/DoD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop designs for water recovery</td>
<td>E</td>
<td>18 - 24 mos.</td>
<td>Core Tech</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype (water recovery)</td>
<td>E</td>
<td>1 – 3 yr. (parallel to research)</td>
<td>Industry</td>
<td></td>
<td></td>
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<tr>
<td>Research ways to recover water without phase change</td>
<td>R</td>
<td>1 – 3 yr.</td>
<td>Core Tech</td>
<td></td>
<td></td>
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<tr>
<td>Develop design (without phase change)</td>
<td>E</td>
<td>1 - 3 yr.</td>
<td>Core Tech</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype (without phase change)</td>
<td>E</td>
<td>1 – 3 yr.</td>
<td>Industry</td>
<td></td>
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### Opportunity – Thermal Enclosure – Better Insulating Materials

<table>
<thead>
<tr>
<th>Action</th>
<th>ACTION TYPE</th>
<th>TIMEFRAME</th>
<th>LEADER</th>
<th>Other Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimize Design</td>
<td>E</td>
<td>1 – 2 yr.</td>
<td>Industry</td>
<td>Note: What must be in the box? 1 – Main box design 2 – Feed platelets</td>
</tr>
<tr>
<td>Study family of applicable materials</td>
<td>D</td>
<td>6 mos. – 1 yr.</td>
<td>Core Tech</td>
<td></td>
</tr>
<tr>
<td>Select Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype</td>
<td>E</td>
<td>1 – 2 yr.</td>
<td>Industry</td>
<td></td>
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</tbody>
</table>

**Key:**
- E = Engineering
- D = Development
- R = Research
**Thermal Systems – Report Out**

(◉ = Vote for Priority Topic)

<table>
<thead>
<tr>
<th><strong>Thermal Systems</strong></th>
<th><strong>Categories</strong></th>
<th><strong>Opportunities</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Thermal Systems</td>
<td>- Components</td>
<td>- Categories</td>
</tr>
<tr>
<td>• What are they?</td>
<td>- Operating Strategies</td>
<td>- Air preheater</td>
</tr>
<tr>
<td>• Everything Else</td>
<td>- Integration</td>
<td>- Overall startup speed</td>
</tr>
<tr>
<td>- Air Preheater</td>
<td>- Top Vote Getters</td>
<td>- Transients</td>
</tr>
<tr>
<td>- After burner</td>
<td>- Thermal enclosure</td>
<td>- Thermal enclosure</td>
</tr>
<tr>
<td>- Thermal enclosure</td>
<td>- Air preheater</td>
<td>- H2O Management Strategies</td>
</tr>
<tr>
<td>- H2O management</td>
<td>- Transients during normal &amp; abnormal events</td>
<td></td>
</tr>
<tr>
<td>- Et al.</td>
<td>- Overall startup rate</td>
<td></td>
</tr>
<tr>
<td>• Could be the Achilles Heel</td>
<td>- H2O recovery system</td>
<td>- Design of H2O management system using recycled steam</td>
</tr>
</tbody>
</table>

**Issues**

<table>
<thead>
<tr>
<th>• Categories</th>
<th>• Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Components</td>
<td>- Better insulating materials for thermal enclosure</td>
</tr>
<tr>
<td>- Operating Strategies</td>
<td>- Optimize compartment design</td>
</tr>
<tr>
<td>- Integration</td>
<td>- Air preheater materials and fabrication</td>
</tr>
<tr>
<td>- Top Vote Getters</td>
<td>- Integrated catalytic combustor with air preheater</td>
</tr>
<tr>
<td>- Thermal enclosure</td>
<td>- Reduced thermal capacitance</td>
</tr>
<tr>
<td>- Air preheater</td>
<td>- Dynamic modeling</td>
</tr>
<tr>
<td>- Transients during normal &amp; abnormal events</td>
<td></td>
</tr>
<tr>
<td>- Overall startup rate</td>
<td></td>
</tr>
<tr>
<td>- H2O recovery system</td>
<td></td>
</tr>
</tbody>
</table>

**Opportunity**

<table>
<thead>
<tr>
<th>• Water Management Designs Using Recycled Steam</th>
<th><strong>Actions</strong></th>
<th><strong>Timeframe</strong></th>
<th><strong>Lead</strong></th>
<th><strong>Other</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• System Study: (E) On board Water vs. Recycle Steam</td>
<td></td>
<td>6 months</td>
<td>DOE/DoD</td>
<td></td>
</tr>
<tr>
<td>• Develop Designs for Water Recovery (E)</td>
<td></td>
<td>18 - 24 months</td>
<td>Core Tech</td>
<td></td>
</tr>
<tr>
<td>• Prototype (E) (water recovery)</td>
<td></td>
<td>1 – 3 years</td>
<td>Industry</td>
<td></td>
</tr>
<tr>
<td>• Research Ways to Recovery Water Without Phase Change (R)</td>
<td></td>
<td>1 – 3 years (parallel to above)</td>
<td>Core Tech</td>
<td></td>
</tr>
<tr>
<td>• Develop Design (E) (without phase change)</td>
<td></td>
<td>1 – 3 years</td>
<td>Industry</td>
<td></td>
</tr>
<tr>
<td>• Prototype (E) (without phase change)</td>
<td></td>
<td>1 – 3 years</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>• Thermal Enclosure – Better Insulating Materials</th>
<th><strong>Actions</strong></th>
<th><strong>Timeframe</strong></th>
<th><strong>Lead</strong></th>
<th><strong>Other</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Optimize Design</td>
<td></td>
<td>1 – 2 years</td>
<td>Industry</td>
<td>• What must be in the box?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Main box</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Feed platelets</td>
</tr>
<tr>
<td>• Study Family of Applicable Materials Select Material</td>
<td></td>
<td>6 mos. – 1 year</td>
<td>Core Tech</td>
<td></td>
</tr>
<tr>
<td>• Prototype</td>
<td></td>
<td>1 – 2 years</td>
<td>Industry</td>
<td></td>
</tr>
</tbody>
</table>

Key: E = Engineering  
D = Development  
R = Research
APPENDIX B
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