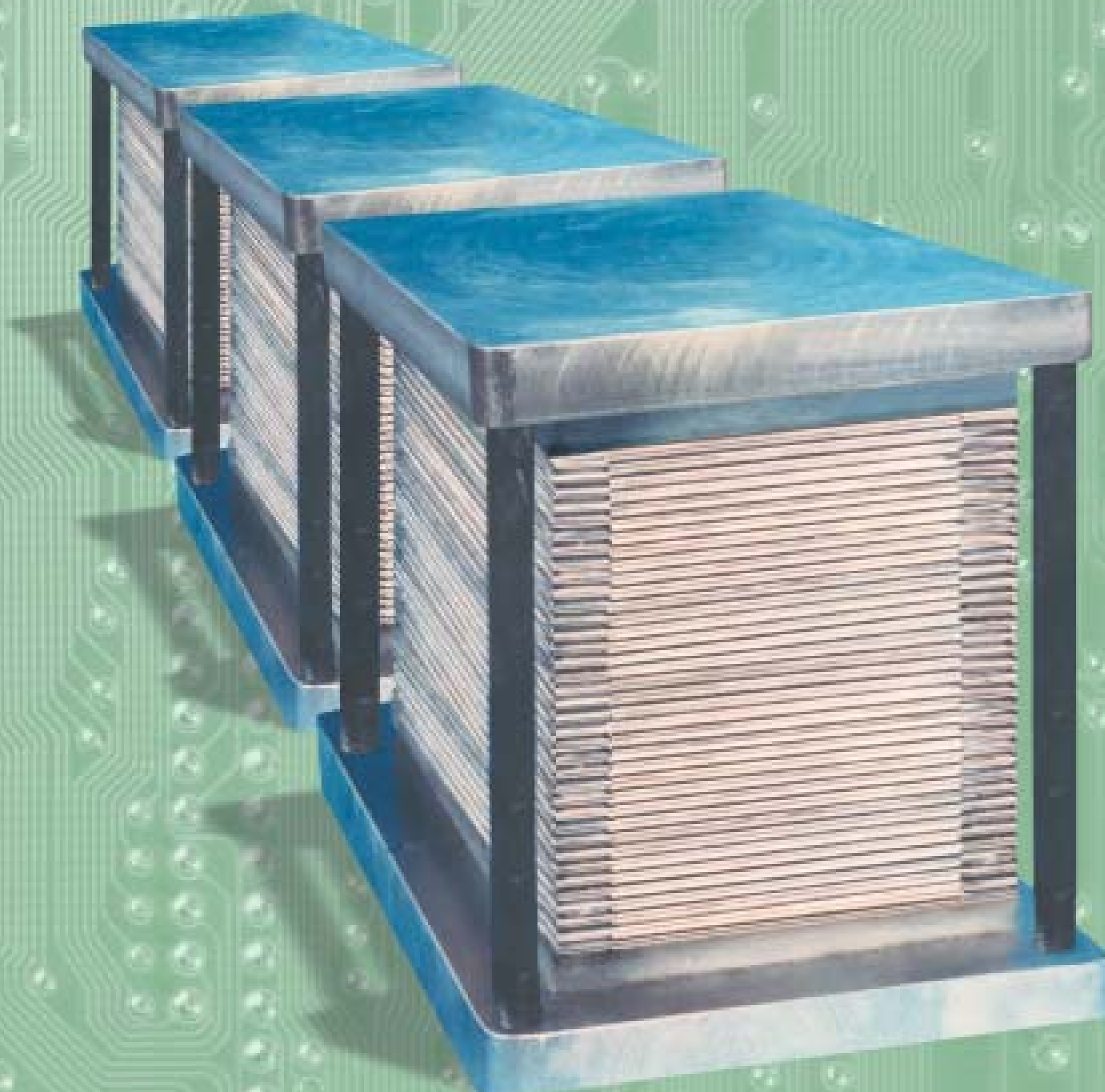
U.S. Department of Energy
National Energy Technology Laboratory — Pacific Northwest National Laboratory

SECA PROGRAM PLAN



Making Fuel Cells Available to America

Availability Note:

The following draft document is undergoing stakeholder review. Until this review is complete, it is available in electronic format only. If you have comments about the contents of this document, please reply to the NETL Fuel Cell Product Manager, Dr. Mark Williams, at mark.williams@netl.doe.gov

Message to Our Stakeholders

The U.S. Department of Energy (DOE) has forged a unique alliance between government, industry, and the scientific community — the Solid State Energy Conversion Alliance (SECA) — to make fuel cells affordable and thereby bring their inherently clean, reliable electric power into virtually all markets. While long offering superior environmental and operational performance, fuel cells have been relegated to niche applications because of their high cost.

This document presents a 10-year program that is designed to produce breakthrough fuel cells capable of shattering current cost barriers and moving the technology into homes, businesses, the transportation sector, and even the military. The product will be a 3-kilowatt to 10-kilowatt solid oxide fuel cell (SOFC) module at a cost of $400 per kilowatt or less, operating at efficiencies nearly twice that of today's conventional technologies, and working off a broad range of fossil fuels including coal, and biomass-derived fuels. This document provides the rationale behind the SECA Program, the strategic and technical approach to achieving the SECA vision, and implications for the future of SOFC technology.

The SECA Program is carried out under the auspices of the DOE Office of Fossil Energy. The DOE National Energy Technology Laboratory (NETL) and its sister Laboratory, the Pacific Northwest National Laboratory, are responsible for program development. NETL is the DOE program office responsible for managing program implementation. Activities are coordinated with NETL's Strategic Center for Natural Gas.

We welcome your comments and suggestions regarding the SECA Program Plan. Please respond directly to us or to the contacts listed on the back cover of this document.

George Rudins
Deputy Assistant Secretary
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Office of Fossil Energy

Rita A. Bajura
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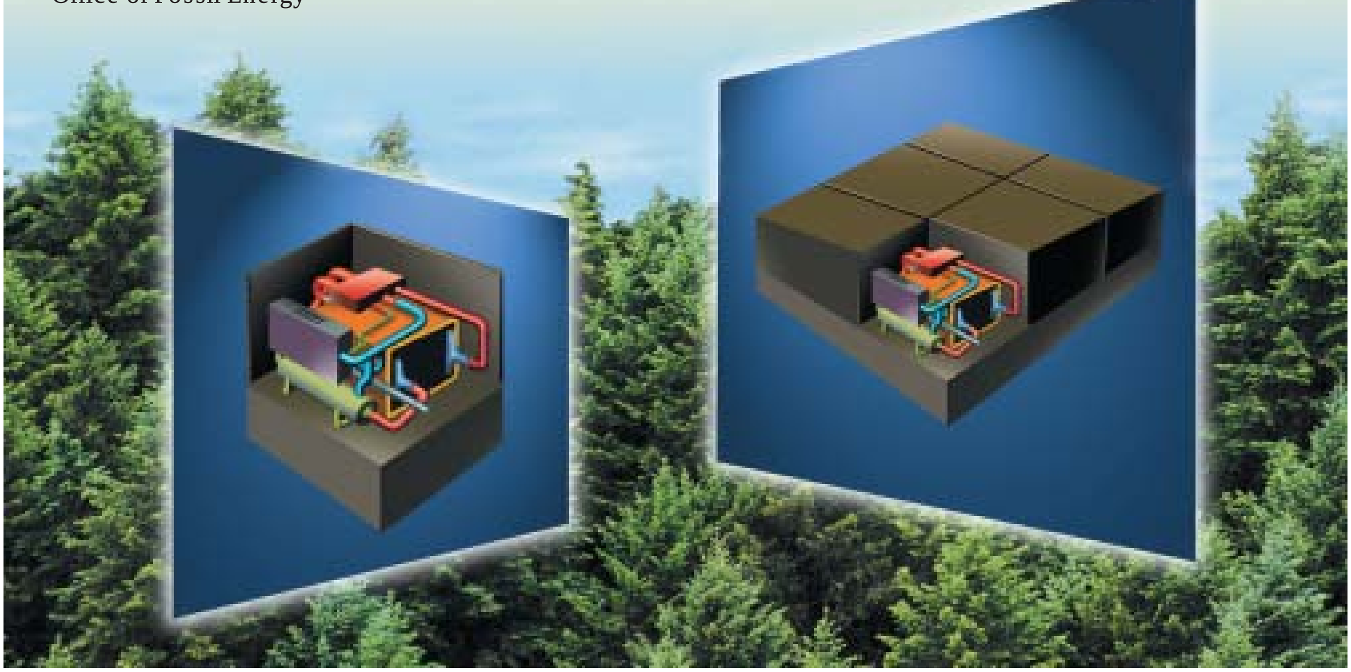

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Introduction

Making Fuel Cells a Market Reality

Fuel cells long have had the potential to radically change electricity generation and use. They are highly efficient, grid independent, virtually pollution free, and fuel-flexible. They also have few moving parts, which allows for reliable, quiet operation. Because of these features, fuel cells can be used just about anywhere for a broad range of applications, enhancing energy security and reliability. Through their application, environmental concerns associated with fossil fuel use essentially can be eliminated. Moreover, fuel cells can operate on hydrogen and a number of renewable-derived fuels, providing a bridge to a hydrogen economy and a means to effectively address global climate change concerns.

Yet, cost remains the final hurdle that must be overcome for fuel cells to realize their potential. Cost is confining fuel cells to today's specialized niche markets, preventing a veritable explosion of fuel cells onto the power market, and impeding the nation from reaping the environmental and energy security benefits associated with their use.

The time for the revolution in electric power generation has come. An emerging technology — the solid oxide fuel cell (SOFC) — and remarkable advances in solid state manufacturing hold the promise for finally making fuel cells competitive in virtually any power application. Removing the cost barrier will require merging our nation's scientific, engineering, and manufacturing communities for a common cause. The Solid State Energy Conversion Alliance (SECA) provides the means for this merger.

When SECA began, it set the aggressive objective of reducing solid state fuel cell costs to $400/kW — nearly one-tenth the cost of today's fuel cells. To achieve this objective, four basic strategies were adopted: (1) a "mass customization" approach to resolve the market entry dilemma — initial costs are too high to sell a large number of units, while high volume production is needed to bring the cost down; (2) integration of government, industry, and scientific resources to leverage their respective skills by placing them in appropriate roles; (3) utilization of a common R&D program available to all industrial teams to eliminate redundancy; and (4) intellectual property provisions that enable all industry participants to benefit from breakthroughs by the scientific participants, thereby enhancing technology transfer.

By combining the talents of industry with the research community, and accelerating investment in expertise to design commercially higher-risk SOFC technology, SECA is in the unique position to substantially speed the development of an economical, high power density SOFC for multiple market applications. But more importantly, the SECA program will open new frontiers in power generation — transforming the nation's view of electric power.

"This [SECA Program] is a major drive to make fuel cells the technology of choice for a wide range of tomorrow's energy needs. We know these advanced, clean power systems offer ways to strengthen the reliability of our electricity supply while reducing pollutants. The final hurdle is cost, and with the technology push we are announcing today, we intend to overcome that hurdle."

Spencer Abraham
Secretary of Energy

National Benefits

The SECA Program structure benefits both industry and the research community by providing them an effective forum to achieve breakthrough SOFC development within a short period of time. However, the nation is the ultimate beneficiary. The summary below demonstrates the range of benefits the nation can expect from a mass-produced and affordable SOFC module.

Energy Security & Reliability

- **Provides excellent fuel flexibility**, having the capability to operate on natural gas, gasoline, diesel fuel, alcohol fuels, and synthesis gas derived from coal, biomass, and industrial and municipal wastes.

- **Provides siting flexibility** by virtue of compact-modular construction, superior environmental performance, fuel flexibility, and quiet operation. On-site applications offer further efficiency gains by avoiding line losses and using high heat output for processes, heating, or air conditioning (combined heat and power).

- **Strengthens energy security** by enabling use of low-cost domestic energy resources, by reducing use of premium fuels through significant efficiency gains, and by enabling siting flexibility, which alleviates transmission and distribution (T&D) grid congestion and reduces infrastructure vulnerability.

- **Ensures energy supply reliability** by enabling rapid deployment where needed, without long delays associated with building large central plants. Reliability of energy service is increasingly critical to business and industry in general, and essential to some where interruption of service is unacceptable economically or where health or safety is impacted.

- **Provides power quality** needed in many industrial applications dependent upon sensitive electronic instrumentation and controls. Power quality combined with reliability of service enhances productivity, which can be valued at billions of dollars a year.

Environmental & Health Benefits

- **Mitigates environmental concerns** associated with fossil fuel use by producing negligible pollutant emissions, and by potentially doubling the efficiency of power production in many applications.

- **Doubling efficiency** essentially halves emissions of CO_2, which is a greenhouse gas.

- **Provides a bridge** to a pollution-free hydrogen economy by operating cleanly and efficiently today on abundant hydrogen-rich fossil fuels, and by offering even better performance in the future on pure hydrogen.

Economic Choices

- **Provides a power source** that is grid independent and environmentally friendly for use in undisturbed, natural areas of the nation.

- **Provides more power choices** for residences and businesses. The high efficiency of a combined heat and power (CHP) system along with a choice of fuel, power quality, grid integration or grid independence will provide citizens with choices and will significantly assist de-regulation efforts throughout the nation.

- **Positions U.S. industry to export** a highly cost-competitive distributed generation commodity in a rapidly growing energy market, the largest portion of which has modest or nonexistent transmission and distribution grids.

The Solid Oxide Fuel Cell

Why Use Fuel Cells? Fuel cells react hydrogen (H_2) and oxygen (O_2) electrochemically rather than by direct chemical reaction, or combustion. The electrochemical reaction results in a higher fuel-to-electricity efficiency than a combustion process, which requires the extra step of transforming heat to electricity.

Fuel Cell Principles. Fuel cells operate on the basis of H_2 and O_2 having a strong chemical drive to bond and form water. In a fuel cell, the H_2 and O_2 are physically separated by an electrolyte material, which allows a single electrically charged atom of one of the gases to pass through. The single atom reacts with the gas on the other side causing an electron buildup on the H_2 side — *anode* — and creating an electrical potential between the anode and the O_2 side — *cathode*. Connecting a device such as a light bulb across the anode and cathode causes these electrons to flow like water down a hill. The electron buildup (potential) in the anode overcomes the resistance in the light bulb, producing light.

In order to be used by fuel cells, hydrocarbon fuels must be processed to free the hydrogen from the carbon bonds. Processes used to free the hydrogen include steam reforming (SR), partial oxidation (POX), and a combination of the two, which is autothermal reforming (ATR). SR is efficient and achieves high H_2 yields, particularly in applications using a catalyst to reduce process temperature (typically available in fuel cells). But SR requires a large reactor and is slow to respond to transient conditions because it is indirectly heated. POX provides the heat necessary for reforming directly by combusting a portion of the fuel, which permits quick response and reduces the size of reactor needed by a factor of ten. The penalty for the higher temperature of POX is lower H_2 yields. Catalytic POX (CPOX) lowers the temperature and increases H_2 yields somewhat. ATR closely combines SR and CPOX to leverage the advantages of each process.

SOFC Principles. The SOFC uses ceramics and mixtures of ceramics and metals (cermets) in the anode and cathode (electrodes) and electrolyte to form a solid-state cell. Interconnects of cermet or metallic construction are used to supply fuel and air and connect the cells into stacks. As shown in Figure 1, SOFCs use O_2 ions to build up electrons and the reactions produce water (H_2O), carbon dioxide (CO_2), and heat. The CO_2 is in concentrated form, which facilitates capture and sequestration.

SOFC Advantages. SOFCs offer high power density, which significantly reduces cost. SOFC operating temperatures are optimal for fuel processing — promoting reactions, but avoiding NO_x formation induced at high-temperatures — which enhances both efficiency and environmental performance and eliminates the need for a heat exchanger to provide fuel processing energy. SOFCs use both H_2 and CO as fuel to generate electricity. SOFC materials are relatively abundant and far less costly than the noble metals, such as platinum. Although certain "rare earth" materials are used in the SOFCs, known rare earth ore reserves are about 100 million metric tons compared to only 43,000 metric tons for platinum. Also, the ceramics and cermet materials used are compatible with a number of mass production manufacturing advancements emerging from the semi-conductor industry; and SOFCs are solid state devices similar to many common electrical components. SOFCs provide high quality heat for combined heat and power applications that can potentially increase combined electrical and thermal efficiencies up to 85%. And, the high SOFC operating temperatures is essential for synergistic integration with gas

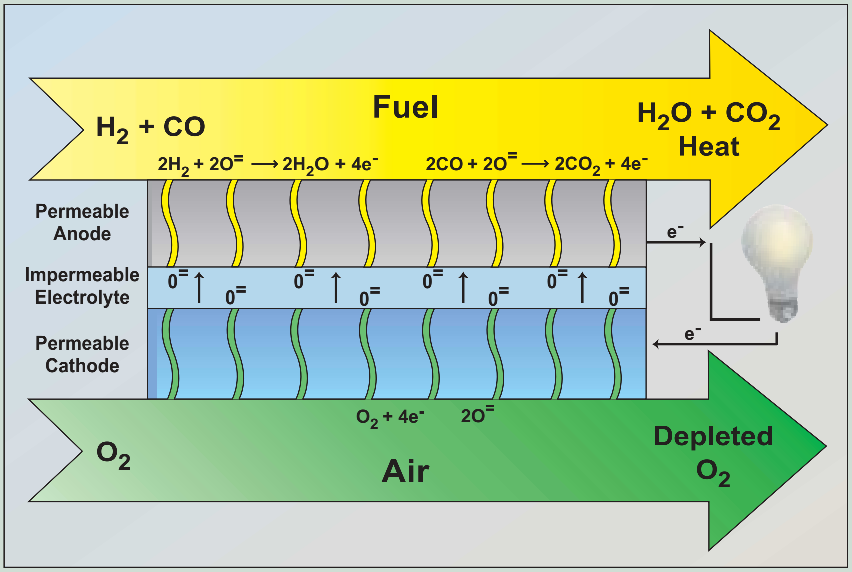


Figure 1. Solid Oxide Fuel Cell

turbines in hybrid systems to increase electric generating efficiencies up to 70%.

SOFC Configurations. There are three basic configurations for SOFCs: tubular, segmented-cell-in-series, and planar. In the tubular technology, shown in Figure 2, air feed tubes take the air to the enclosed end of the tube, which then flows back along the inside surface of the cathode. Fuel passes over the tube exterior anode surface, inducing ion flow through the electrolyte. By enclosing one end of the tube, the design precludes the need for gas seals between cells. Thermal expansion and mismatches in thermal expansion of the different materials is also largely accommodated. However, the sealess tubular designs results in a relatively long current path around the circumference of the cell to the interconnect and the relatively thick support tube represents a large diffusional barrier for the oxygen, both of which limit performance.

The segmented-cell-in-series design consists of segmented cells connected in electrical and gas flow series. The cells are either arranged as a thin banded structure on a porous support (banded configuration), or fitted one into the other to form a tubular self-supporting structure (bell-and-spigot configuration) shown in Figure 3. Some advantages are gained in stack efficiency from these configurations and they are very strong. However, the segmented-cell-in-series design suffers from: (1) long current paths in the electrodes, resulting in significant resistive losses; (2) a large diffusional barrier to the fuel in the banded configuration; (3) high resistive losses due to thick electrolyte in the bell-and-spigot configuration; and (4) the need for high-temperature gas seals.

A generic planar configuration is shown in Figure 4. The cathode, anode, and electrode are sandwiched between channeled interconnects that provide the air and fuel and make the electrical connection between anode and cathode of adjacent cells. The planar configuration offers : (1) higher power density and structural ruggedness, which is needed for the expanded market envisioned, (2) an easier configuration to mass produce, (3) lower resistance and voltage loss across stacked cells, and (4) superior heat removal. Challenges include developing high-temperature gas seals and matching thermal expansion coefficients of the cell components to prevent mechanical failure in fabrication and usage.

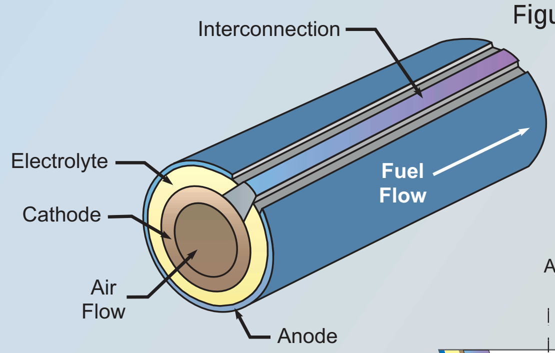


Figure 2. Generic Tubular SOFC Configuration

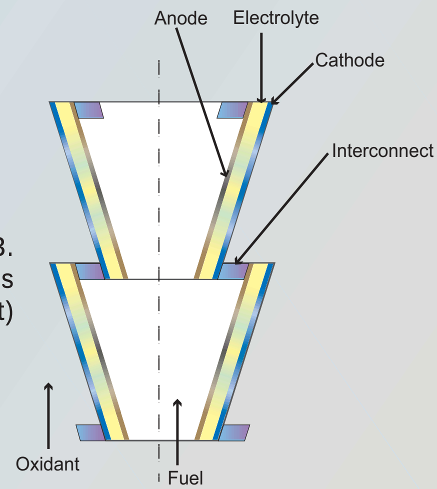


Figure 3. Segmented-Cell-In-Series (Bell-and-Spigot)

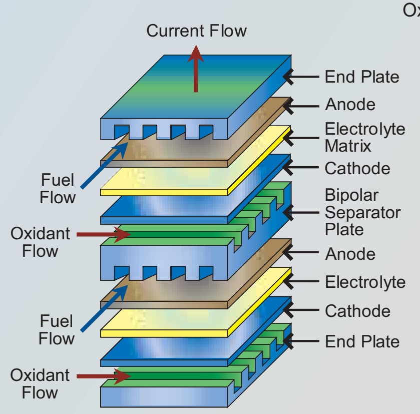


Figure 4. Generic Planar SOFC Configuration

Clearing the Cost Hurdle

SECA was initiated to overcome the historical catch-22 of the fuel cell business — not enough units are sold to bring the price down, yet the price is too high to sell a large number of units. Projected costs at full production currently are $1,500–4,500/kW with existing fuel cell designs. So while fuel cells are being installed commercially today, high costs largely have limited their usefulness to customers that demand premium-quality, highly reliable on-site power.

SECA believes that developing a high power density all-solid-state fuel cell "building block" that can be mass-manufactured is one of the best ways to dramatically lower costs — much like advances in solid state technology have cut the costs of computers and other electronics. A 3–10-kW building block can be combined to meet much larger power needs, but it must be designed with a common set of components to meet a diverse, ready market. New SOFC technology in the areas of ceramic and cermet materials, fuel cell design, and manufacturing technology, indicate that substantially enhanced power densities are possible. High power density of 0.6 W/cm^2 is critical to meeting SECA cost objectives by reducing materials costs and broadening market applications.

Cost-effective fuel cell manufacturing is dependent on the materials used, as well as cell and stack designs. Materials selection supports the system performance and cost competitiveness of SOFC technology. While other fuel cell technologies use expensive noble metals such as platinum in their construction, SOFCs use relatively abundant, rare earth materials. The rare earth compounds, such as lanthanum and yttrium, currently are not inexpensive but they are abundant, providing substantial opportunity for cost reduction as demand increases. Estimates suggest that wholesale bulk use of these compounds will reduce their cost by a factor of five or more.

Table 1. SOFC Stack Material Costs; 0.6 W/cm^2 5kW Module

SOFC Component	Material Cost Current SOFC	Material Cost Lower Temp. SOFC
Electrodes, Electrolyte, End Plates	$22.60/kW	$22.60/kW
Interconnects	$206.25/kW	$10.00/kW
Total	$228.85/kW	$32.60/kW

In planar designs of an SOFC, interconnects can represent over 80% of the fuel cell stack mass. By reducing the material cost of the interconnects, fuel cell costs are expected to drop dramatically.

To reduce costs even further, SECA is moving toward lowering the operating temperature of the SOFC to enable use of less expensive metal alloys, such as stainless steel, in stack components used to deliver fuel and air and to connect individual cells (interconnects). Estimates indicate that use of metallic interconnects over ceramic interconnects can reduce materials costs by as much as 85 percent (see Table 1).

Decreasing SOFC costs also is dependent on establishing low-cost, large-scale, automated processes in lieu of batch techniques. The solid-state construction of SOFCs lends itself to mass production and manufacturing techniques developed in the semi-conductor industry. Simple and cost-effective automated manufacturing techniques such as tape casting, tape calendaring, and screen printing are being applied with new design concepts to accommodate SOFC production.

Leveraging Market Needs

SECA is designed to provide an SOFC module for all possible markets. The SECA Program is uniquely positioned to take advantage of the technological advances in fuel cell technology at a time when markets are receptive to grid-independent sources of electric power. SECA aims to put reliable fuel cells into a more compact, modular, and affordable design. This movement in fuel cell design — akin to the computer industry's move from mainframe to personal computers — will allow widespread penetration into high volume stationary, transportation, and military markets.

Together, these markets provide a basis for large-scale fuel cell production if a common module, or building block, were developed that could meet all market needs with a minimal number of custom features. Using SECA SOFC technology in hybrid power generation systems also is important to achieve the objectives of large power generation plants in 2015 and beyond.

Stationary Markets. While central power generation remains the mainstay for domestic electric power generation, emphasis on power quality and reliability by many is opening up a major new market for distributed power generation — generation at or near the point of use. Many consumers simply are seeking greater control and reliability, something that distributed power generation can provide.

Several distinct markets exist for stationary SOFC generators including home, office, and industrial sites, as well as the traditional power plant. Residential applications have potential for "mass markets," but pose technical and cost challenges. Power needs in the home fluctuate dramatically from hour to hour, and power sources must be able to respond to these needs while still providing the household a competitive power price. From the homeowner's perspective, the power source must look like a typical appliance and have minimal installation and maintenance requirements.

Commercial and industrial consumers, such as office buildings, hospitals, and manufacturing plants, present unique opportunities for SOFC baseload systems. Commercial and industrial consumers typically are characterized as requiring an uninterrupted power supply during the most expensive power production hours of the day. In addition, SOFCs offer superior quality process heat for use in combined heat and power applications, an important strategy addressed in the Administration's National Energy Policy.

In the utility sector, SOFCs can be used as components of central power sources or strategically located to provide utility grid support to offset transmission, distribution, and new generating capacity investments. SOFCs are an essential element in meeting long-term, 2015 Vision 21 Coal and Power Systems efficiency goals of 60% on coal and 75% on natural gas.

> ***"Fuel cells are likely to penetrate everywhere where energy is used, including homes and businesses."***
>
> Robert Savinell
>
> Case Western Reserve University, School of Engineering

Transportation Markets. Fuel cells have a potential early market in Class 8 diesel trucks in the form of auxiliary power units (APUs). APUs allow for full climate control and on-board power while the truck engine is off. A 5-kW fuel cell-powered APU represents an immediate national benefit by reducing fuel consumption

Auxiliary power unit supports vehicle's onboard electric needs.

and emissions, as well as providing a healthier environment for the drivers. Automotive APUs, while not providing as significant a direct national benefit, represent an extremely large market, which would serve to lower the price of fuel cells, and expand usage and consequent environmental benefits.

The SOFC, with its inherently high efficiency, can be used in APUs to power equipment such as air conditioning, onboard electronics, and accessories. Initial market applications are for long-haul Class 8 trucks as well as recreational vehicles. In addition to substantial fuel savings, environmental emission reductions are achieved.

Military Markets. In order to maintain an efficient and effective military, there is a need for different power source technologies for different applications. The power technology must be quiet, rugged, and have a low thermal signature. These requirements make the SOFC a strong candidate for use in field generators, autonomous vehicles, and the U.S. Navy's 21st century all-electric ship.

Since fuel represents 70% of the weight of materials moved in a military operation, any increases in fuel efficiency will provide a cost savings. The U.S. Department of Defense is seeking high-efficiency power sources that can operate on the current slate of defense logistic fuels.

The availability of onboard power, coupled with wireless data transmission, will open numerous possibilities for self-sustaining devices for remote or difficult-to-access military locations. The power and energy needs for these devices may vary considerably depending on their design and function. However, it is generally agreed that battery technology, both present-day and that predicted for the future, is not acceptable in terms of the energy and power densities required. Long-term operation of these devices will require energy densities available only with fuel cells.

Future Power Markets. SECA success provides an SOFC that is ideal for integration with gas turbines to produce a hybrid capable of efficiencies up to 70%; that enables use of our nation's vast coal resources, as well as biomass and wastes, while removing environmental concerns; and that moves our nation towards a hydrogen economy. SECA, in turn, supports Vision 21 goals of providing cost competitive technologies capable of using multiple fuels, producing electricity and/or high-value products, and emitting essentially zero pollutants at efficiencies far higher than those of today's technologies.

SOFC temperatures and ability to operate under pressure make it possible for an SOFC to replace the combustor in a gas turbine. The synergy results in a hybrid with significant efficiency gains. SOFCs are also compatible with synthesis gas derived from gasification of solid fuels such as coal, biomass, and industrial and municipal wastes. Both the hydrogen and carbon monoxide, the major constituents in the synthesis gas, are used by the SOFC. Either the SOFC alone or an SOFC/turbine hybrid can be used in an integrated gasification combined-cycle application that uses both gas and steam to generate electricity.

Moreover, SOFCs provide an effective bridge to a hydrogen economy by offering clean, efficient operation today on hydrogen-rich fuel derived from either fossil or renewable fuels, and by offering even better performance in the future on pure hydrogen. SOFC operation on hydrogen derived from a renewable fuel would provide a carbon neutral, zero-emission energy source. SOFCs also offer superior quality process heat for CHP applications along with inherent high efficiency and low emissions. Both outcomes are stated objectives in the National Energy Policy.

SOFCs also are amenable to carbon sequestration efforts, being pursued in parallel with Vision 21, to eliminate global climate change concerns associated with fossil fuel use. SOFCs are highly efficient and can be configured to produce a concentrated CO_2 stream, allowing for easy capture.

A "Mass Customization" Approach

Mass customization is best defined as a delivery process through which mass-market goods are produced to satisfy a range of specific customers' needs, with minimum individual customization and at an affordable price. SECA applies this concept by mass producing a majority of components and requiring little special packaging for application-specific units. This approach serves as the ultimate combination of "custom-made" and "mass production," and it is rapidly emerging as the organizing business principle of the 21st century. During the last 15 years, choice has become an important ingredient of consumer purchasing decisions. For instance, during that period the number of automobile models has increased from 140 to 260, and computers can now be custom-designed to meet a specific user's needs, with a minimum amount of repackaging of the basic system.

To achieve mass customization of SOFC technology, the SECA strategy is focused on developing a basic building block that consists of a 3–10-kW SOFC module. It is anticipated that this module will be 50–100 liters, depending on a number of customization features, and will be mass-produced and customized for use in residential, mobile, or military applications (see Figure 5).

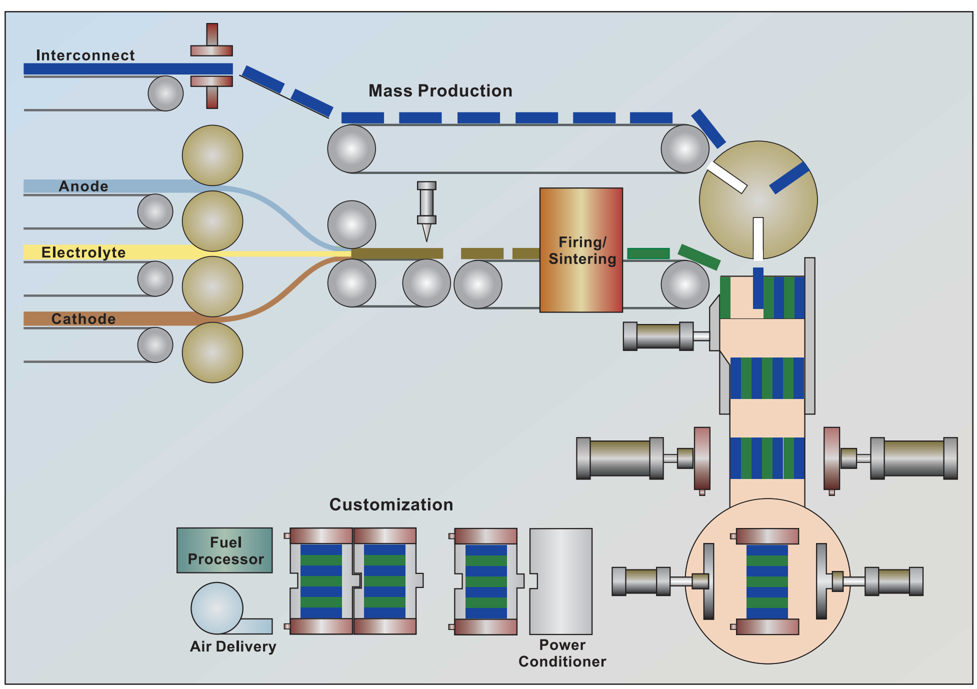


Figure 5. Mass Production in Support of Mass Customization

Transportation applications of fuel cells define the size and weight limits for the SECA fuel cell module. Transportation standards mandate that a 5-kW unit for auxiliary power fit into a volume of 50 liters, weigh less than 50 kilograms, and have a surface temperature less than 45 °C. Size is not as critical for stationary applications, allowing for the addition of more features that will enhance efficiency.

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 specific power ratings.

The modularity of the system will remove a major contributor to current high fuel cell costs — the need to separately design and custom-build fuel cell stacks for each particular application. In addition, the proposed solid state design will leverage numerous recent advances, such as production of thin-film solid electrolyte materials, and precise, automated manufacturing technologies that have been developed largely in the semiconductor industry.

Reduced manufacturing costs, when combined with the traditional high efficiency and outstanding environmental performance of the fuel cell, will make the SECA module the most attractive option for a wide range of electric power needs.

Basic Strategies

Initial SECA planning set an objective of reducing SOFC costs to $400/kW — about one-tenth the cost of current fuel cell technology. A combination of studies showed that a $400/kW target was feasible, based on known technology, and would support a wide range of markets at that cost.

To achieve this objective, four basic strategies have been adopted: (1) a "mass customization" approach to solve the market entry dilemma — fuel cell costs are too high to sell a large number of units, while high-volume production is needed to bring the cost down; (2) integration of government, industry, and scientific resources to leverage their respective skills by placing them in appropriate roles; (3) utilization of a common R&D program available to all industrial teams to eliminate redundancy; and (4) intellectual property provisions that allow all industry participants to benefit from breakthroughs by the scientific participants, enhancing technology transfer.

Federal Government Role

The U.S. Department of Energy and National Energy Policy goals include improving energy efficiency, ensuring reliability of the nation's energy supply, promoting clean energy technologies, expanding energy choices, and cooperating internationally on energy issues. SECA's SOFC technology has the potential to address all of these goals. The SOFC has short-term advantages due its ability to operate well with existing fossil fuels, improve efficiency for applications, and minimize environmental impacts of fossil fuel use. In the longer term, SOFC technology will be able to use hydrogen fuels as they become available. Through cooperation with the European Union and other international organizations, the SECA Program also is positioning the United States for entry into the international fuel cell market.

While SOFC technology shows tremendous promise for the future, incremental improvements with existing systems appear unlikely to reduce costs much below $1,500–1,000 per kilowatt in the near future. To fully realize the environmental and fuel-efficiency benefits of SOFC technology beyond that of large-scale niche applications, it is clear that a significant reduction in costs must soon be realized. With power demands increasing dramatically over the next 20 years, and reliability of power becoming an economic necessity, it is essential that fuel cells move beyond today's limited uses and become an affordable electric power solution for a whole host of applications.

However, it is unrealistic to expect a single company or research institution to provide all of the needed investment and technological know-how to achieve the vision of an affordable SOFC that can be mass-manufactured by 2010. Faced with an uncertain future, private industry remains fo-

cused on short-term R&D investments that provide immediate payback. Likewise, research institutions typically lack associations with industry that are needed to successfully advance their technological breakthroughs from the laboratory to the marketplace. By mobilizing the forces of industry with the research community, and accelerating investment in expertise to develop commercially higher-risk SOFC technology, SECA is in the unique position of being able to substantially speed the development of an economical, high-power-density SOFC for multiple market applications — a technology that could transform the way our nation views electric power.

SECA seeks to leverage federal R&D investments across multiple agencies, encouraging a broad national perspective to SOFC technology development beyond company-specific or parochial interests. The DOE National Energy Technology Laboratory (NETL) and its sister Laboratory, the Pacific Northwest National Laboratory (PNNL) are responsible for SECA Program development. NETL is responsible for managing program implementation, including essential coordination between industry teams developing fuel cell systems, universities, and scientists addressing core problems to achieve the SECA vision. NETL and PNNL will continue to host biannual meetings and workshops for stakeholders to further refine the technology needs of SECA. Policy guidance, planning, and budgeting for SECA are coordinated among individual funding organizations, along with NETL, including the Department of Defense, and DOE's Office of Energy Efficiency and Renewable Energy. Each organization will fund efforts under SECA corresponding to its own end-use interests. Pooling funds from the various organizations will be encouraged to effectively leverage the government's investment in SECA-developed technology. Joint program reviews are held to coordinate the various individual programs.

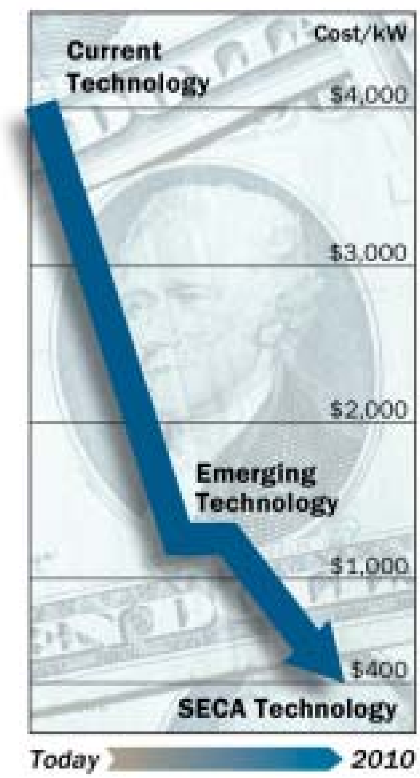


Figure 6. SOFC Costs

Program Drivers

In defining its program strategy, SECA continually analyzes the market for electric power and tracks future projections to assure that the SECA program is focused on market needs consistent with the proper Federal role.

Converging market forces have precipitated the need for clean, efficient, and more reliable sources of electric power. These forces include the growing demand for electric power both domestically and abroad, environmental concerns in the power generation sector, energy security, and the pressing need for electric power quality and reliability in an increasingly connected global economy.

Electricity Demand. Estimates indicate that by 2020, demand for electricity in the United States will rise by 43 percent. Already, large amounts of new generating capacity are slated for installation around the country from 2001 to 2004 to meet the nation's growing electricity demands. However, there is a geographic mismatch between where the energy will be generated and where it will be needed. In addition, investment in new transmission capacity has not kept pace with growth in demand and changes in the electric power industry.

SOFCs are one of the technologies that will promote the shift from our current traditional centralized energy supply system to one where there is increased individual choice. Fuel cells offer more flexibility in siting and improved ability to match power sources with end-use requirements.

Globally, the demand for electricity is expected to double in the next 20 years, with the bulk of that demand coming from developing nations whose electric power infrastructure is modest or nonexistent. The market for power generation in remote areas is expected to be quite large and represents a major opportunity for U.S. manufacturers, suppliers, and developers of fuel cell technologies.

Motor vehicles are an integral part of American life, and increasingly they are becoming more dependent upon electrical parts. From power locks and windows to climate control systems and sophisticated onboard computer tracking systems, motor vehicles are expanding their electrical power requirements.

There are some 600 million motor vehicles worldwide, of which about 75% are personal automobiles, and projections call for a 30% increase worldwide within the next decade. Providing auxiliary power units in the expanding market for motor vehicles represents a substantial opportunity for SECA-developed fuel cell technology sales.

The U.S. Department of Defense has a critical need for lighter and more compact power sources for soldier, robotic, and other emerging applications, currently supplied by batteries. However, DoD projects a substantial energy shortfall soon (exceeding a factor of 10 in some cases) if the military continues to rely on batteries to power these systems. Fuel cells represent quiet, clean, and uninterruptible energy that can be delivered at the point of power application.

Environmental Concerns. Regional and global environmental objectives will continue to place a premium on efficiency and environmental performance. The utility industry, increasingly concerned with global impacts of carbon dioxide emissions, is exploring advanced technology including fuel cells to permit continued use of our nation's abundant domestic fossil fuel resources for the foreseeable future.

Security. The United States is very dependent on politically unstable countries for oil supplies. According to estimates, the U.S. imports more than 50% of its oil, expected to increase to 62% by

2020. By using low-cost coal and other domestic energy resources to fuel the SECA fuel cell, the Nation can decrease dependence on foreign fuel supplies. Moreover, when using premium fuels such as natural gas, SECA SOFC efficiencies place little strain on supply. And, because SECA systems offer compact-modular construction, superior environmental performance, and quiet operation, they can be transported and installed rapidly where they are needed in capacities ranging from distributed generation to utility scale.

Reliability. Reliability in electric power supply has become a paramount issue for power providers and consumers, since electricity underpins and integrates the entire U.S. economy. No one can deny the role of electricity in day-to-day life. Since 1990, electricity accounts for more than 80% of total U.S. energy demand growth.

The issue, however, is broader than just the increase in electricity demand. The new importance attached to quality of power, and economic costs associated with power disruptions are testaments to how the new digital economy has affected the demands placed on the electric power industry. Dependence on computer networks has grown so great that even momentary outages can result in widespread disruptions ranging from the mere inconvenience of a frozen cursor to multimillion dollar losses caused by damage of sensitive and very expensive equipment. One study suggests that power failures nationally cost more than $30 billion a year in lost productivity (see Table 2 below). This pervasive dependence on electricity means that a disruption in the system can easily ripple throughout the economy.

Table 2. Electric Power Reliability
The Cost of Power Disruptions

Industry	Average Cost of Downtime per Hour
Cellular Communications	$41,000
Telephone Ticket Sales	$72,000
Airline Reservations	$90,000
Credit Card Operations	$2,580,000
Brokerage Operations	$6,480,000

Source: *Teleconnect Magazine*; Contingency Planning Research 1996

Program Goals and Objectives

Program Goals

The overall goal of the SECA Program is to produce 3–10-kW SOFC modules at a capital cost of no more than $400/kW by 2010, *and* that have the power densities, reliability, and operating characteristics compatible with commercial service in both stationary and transportation power applications. Immediate markets that are identified include distributed generation applications (such as residential or commercial CHP uses), long-haul truck and recreational vehicle auxiliary power units, and corollary military applications. Natural gas, gasoline, diesel fuel, and coal derived fuels will be used for the SECA fuel cell applications.

A longer term related goal is to integrate SOFC modules into Vision 21 plant concepts by 2015 that transcend the immediate distributed generation market for SECA modules and move them into coal-, biomass-, or solid waste-fueled applications. Ultimately, SECA fuel cells will play a role in, and have application to, systems supporting a national hydrogen economy.

Objectives

A phased approach is being taken to achieve the ultimate SECA Program goal, with cost and performance objectives established to measure progress along the way. Table 3 below summarizes cost and performance objectives for the three phases established under the SECA Program. The first two phases reflect where the technology should be before proceeding to the subsequent test phase, and the Phase III objectives are those for the final product.

Table 3. Performance Objectives of 3–10-kW SOFC Module

Phase	I	II	III
Cost	*	*	$400/kW
Efficiency			
Mobile	25–45%	30–50%	30–50%
Stationary	35–55%	40–60%	40–60%
Steady-State			
Test Hours	1,500	1,500	1,500
Availability	80%	85%	95%
Power Degradation per 500 hours	≤2%	≤1%	≤0.1%
Transient Test			
Cycles	10	50	100
Power Degradation after Cycle Test	≤1%	≤0.5%	≤0.1%
Power Density	0.3W/cm^2	0.6W/cm^2	>0.6W/cm^2
Temperature	800 °C	~700 °C	700 °C

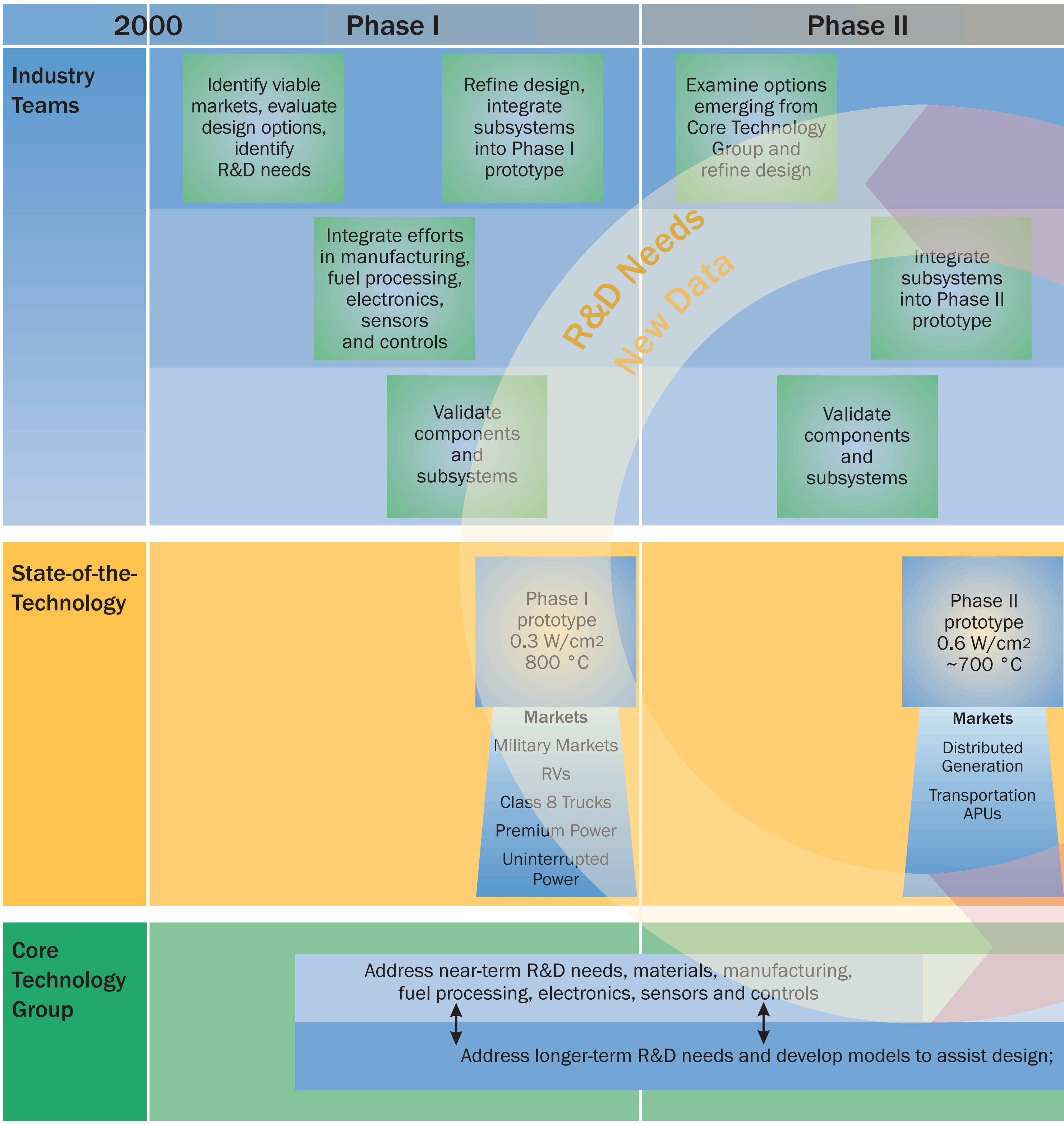
Evaluate for potential to achieve $400/kW

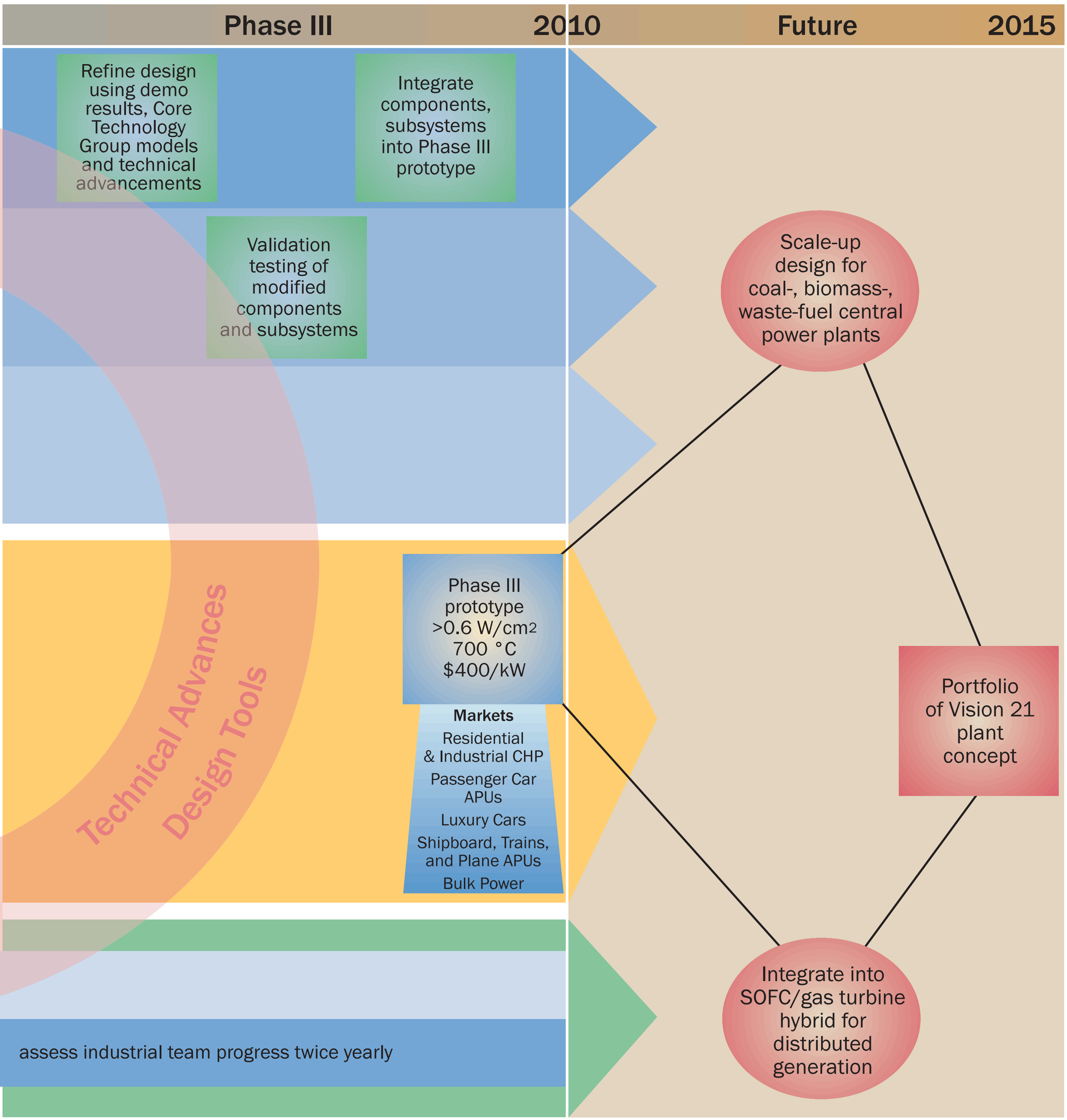
For all three phases, the fuel is to be commercial-grade natural gas, gasoline, or diesel fuel (except for Phase I, where a representative fuel may be used); the maintenance interval is to be greater than 1,000 hours; and the design lifetime is to be five years for stationary applications and 5,000 hours for mobile applications. The test sequence for each phase will be to: (1) operate the fuel cell under normal, steady-state conditions at a constant stack voltage for 1,000 hours; (2) cycle the fuel cell from its normal operating condition to its normal shutdown condition for the prescribed number of times; and (3) return the fuel cell to steady-state operation for 500 hours.

SECA power density requirements are driven by constraints of transportation applications. This relatively high power density requirement will be applied to stationary applications as well because of economic gains inherent in such performance. The power density target is to achieve greater than 0.6 watts per square centimeter (>0.6 W/cm^2).

Temperature also becomes a major consideration. Achieving operating temperatures of 700 °C, or less, enables use of cheap metal alloys in lieu of more expensive materials in stack and balance-of-plant components.

Technology Roadmap





Phase III
2010
Future
2015
Refine design using demo results, Core Technology Group models and technical advancements
Integrate components, subsystems into Phase III prototype
Validation testing of modified components and subsystems
Scale-up design for coal-, biomass-, waste-fuel central power plants
Phase III prototype >0.6 W/cm2 700 °C $400/kW
Markets
Residential & Industrial CHP
Passenger Car APUs
Luxury Cars
Shipboard, Trains, and Plane APUs
Bulk Power
Portfolio of Vision 21 plant concept
Technical Advances
Design Tools
Integrate into SOFC/gas turbine hybrid for distributed generation
assess industrial team progress twice yearly

Program Structure

Organization

SECA is an alliance of the following:

(1) Industry teams who individually plan to commercialize SOFC systems for pre-defined markets;

(2) Research and development institutions involved in solid-state activities that comprise the core technology program; and

(3) Government organizations that provide funding and management.

SECA is a collaborative effort coordinated by two of the U.S. Department of Energy National Laboratories — NETL and PNNL — supported by DOE's Office of Fossil Energy, NETL, and other government agencies. To the extent practical, NETL, in partnership with PNNL, will seek to enlist other relevant SOFC technology R&D programs across multiple federal agencies into the SECA Program, thus creating a coordinated national research initiative focused on today's most promising SOFC technologies (see Figure 7).

This alliance of U.S. industry, universities, and other research organizations represents a new model for joint government and private industry technology development. It also provides for effective use of SECA funding resources, which is critical to the success of the SECA Program. The coordination of "Industry Teams" with a "Core Technology Program" is designed to solve difficult technical issues faster without redundancy of effort, while assuring that the SECA alliance members and end-users benefit. To accomplish this, approximately 60% of the program funding will be used to fund the Industry Teams and 40% will fund the Core Technology Program. A prototype fuel cell will be delivered within four years of industry team project awards.

Industry Teams. Several teams of industry partners will be selected to participate in a co-funded, collaborative process to develop SOFC power generation systems. These teams will: (1) develop their proposed SOFC design to meet a target market; (2) coordinate with end-users and manufacturers to refine design elements that will contribute to a high-power-density SOFC that can be mass-produced; and (3) communicate their R&D gaps to the Core Technology Program. The teams will be independent and will compete with each other; however, all are committed to the concept of mass customization as the route to reducing the cost of fuel cell systems. Industry team performance will be individually audited.

DOE expects its Industry Teams to incorporate feedback from end-users and manufacturers regarding necessary modifications to the designs, as the proposed SOFC designs are being developed. End-users will require particular performance standards, whereas manufacturers may request an adjustment to the design to make the SOFC more amenable to mass production techniques. DOE anticipates that Industry Teams will repeat this feedback process multiple times until an effective SOFC design is created that satisfies producers and consumers, and achieves the SECA cost target.

So while Industry Teams must have not only all the technical components to develop SOFC technology, they must have immediate access to targeted markets to instantaneously springboard their SOFC design from the laboratory to the marketplace. The targeted markets must be sufficiently large at the outset so that SECA cost goals can be met in a short period of time.

The Industry Teams also will provide input to shape the Core Technology Program. As design changes are being incorporated by the Industry Teams, any R&D gaps will be filled using the Core Technology Program — allowing the Industry Teams to continue their development process while much-needed breakthrough technologies are created in parallel. Industry Teams will communicate their R&D needs to SECA program managers who will, in turn, communicate these needs to the Core Technology Program.

The majority of funding will come from DOE's Office of Fossil Energy, with significant leveraged effort coming from other interested government organizations, such as DOE's Office of Energy Efficiency and Renewable Energy, as well as various organizations within the Department of Defense, and California Energy Commission. The number of Industry Teams ultimately selected will depend on the number of government agencies sponsoring the SECA Program and their level of commitment.

Core Technology Program. The Core Technology Program supports the Industry Teams by providing problem-solving research to overcome barriers identified by the Industry Teams. The Core Technology Program provides the focused applied research and development component of SECA — research that is typically longer-term in nature, and thus not the focus of sustained industry investment. The Core Technology Program will focus on the R&D efforts of universities, national laboratories, and other research institutions. Participants in the program will perform work subject to what is termed an "exceptional circumstance" to the Bayh-Dole Act; and the intellectual property will be offered to all Industry Teams as a non-exclusive license. The Core program will be peer-reviewed by independent organizations and industry teams.

Contributors to the Core Technology Program will address cross-cutting technology development needs of one, some, or all of the Industry Teams. The Core Technology Program R&D will fall into the following categories:

- Fuel processing/reforming
- Manufacturing
- Controls and diagnostics
- Power electronics

SECA — Targeting $400/kW SOFC Technology by 2010

Industry Teams

- ➔ Competitively selected to develop proposed SOFC technology concept
- ➔ Have ready access to markets
- ➔ Understand end-user specifications
- ➔ Coordinate with manufacturing
- ➔ Supply input to shape Core Technology Program

Core Technology Program

- ➔ Provides problem-solving R&D
- ➔ Consists of universities, R&D companies, and national laboratories
- ➔ Focuses on fuel processing, manufacturing, controls and diagnostics, power electronics, thermal systems, and materials R&D

Federal Government

- ➔ Leverages Federal R&D investments across multiple agencies
- ➔ Encourages broad national perspective to SOFC technology development beyond company-specific interests
- ➔ Integrates and manages Industry Team projects with Core Technology Program

Figure 7. SECA Program Structure

- Thermal systems
- Materials

DOE's Office of Fossil Energy also has pre-existing contracts and awards that provide input to SECA and the Core Technology Program. These projects have been absorbed into the SECA program.

Unique Intellectual Property Approach

SECA's treatment of intellectual property is the cornerstone of the alliance. Since the SECA concept is based on development of a common fuel cell core module — and this common module is essential to reducing the cost — the core module will be expedited only if technologies developed in the Core Technology Program are available for licensing to the Industry Teams. For that reason, intellectual property developed in the Core Technology Program as a result of SECA funding is considered an "exceptional circumstance" under the Bayh-Dole Act, and will be offered to all Industry Teams as a non-exclusive license (including royalties) based on terms that are reasonable. The field of use is limited to SOFC applications, with exclusive licensing permitted for other fields of use. The offer must be held open for at least one year after the U.S. patent has been issued, and the patent owner must agree to negotiate in good faith.

The rationale behind this licensing arrangement stems from DOE's prior fuel cell program experience. If Core Technology Program participants are allowed the opportunity to exclusively license to anyone they choose, including firms outside the SECA Industry Teams, then it is unlikely that Industry Teams will be willing to collaboratively define the Core Technology Program objectives. Industry Teams will be more likely to identify research needs if they are assured that all solutions will be within their reach. Likewise, should Industry Teams keep all development work in-house without tapping into the R&D expertise of the Core Technology Program, there would likely be redundant research and equipment purchases, and a less concentrated pool of talent. SECA avoids such in efficient use of federal funds.

The SECA intellectual property provisions will effectively leverage government funds to address the most difficult fuel cell technology development needs in an effort to accelerate commercialization of this nationally important technology. Other advantages to this approach to intellectual property include the following:

- Technologies developed in the Core Technology Program can be incorporated into any designs that will benefit from them — not just designs of the highest bidder.

- A market for intellectual property is being created. The Core Technology Program members will have an immediate set of potential licensees for their invention(s) and, when Industry Teams are successful in commercializing their fuel cell system, will reap income in the form of royalties or other cash payments.

- By making the intellectual property available to the Industry 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 Bayh-Dole Act

The Bayh-Dole Act, formally known as the Patent and Trademark Law Amendments Act, permits universities and small businesses to elect ownership of inventions made under federal funding, and to become directly involved in the commercialization process. This policy also permits exclusive licensing when combined with diligent development and transfer of an invention to the marketplace for the public good. It was understood that stimulation of the economy would occur through the licensing of new inventions from universities to businesses that would, in turn, manufacture the resulting products in the United States.

SECA requires Core Technology Program inventors to grant a non-exclusive license for their inventions to Industry Teams, upon receiving royalties and/or compensation, thus avoiding any delays in the inventions' use within the SECA Program. This is intended to speed the development of fuel cell technology for all Industry Teams, provide the most practical use of federal funds, provide an incentive to Core Program participants, and accelerate the commercialization of a technology that is in the best interests of the core program participants and the nation.

Addressing Challenges

The present generation of SOFCs use anodes made from nickel particles mixed with zirconium oxide (zirconia) to form what is called a cermet. The zirconia provides compatible thermal expansion properties with the electrolyte, which is composed of zirconia with a small amount of yttrium oxide for structural stabilization. This yttrium stabilized zirconia (YSZ) electrolyte is conducive to the flow of oxygen ions but prevents physical contact of the fuel and air. The present SOFC cathode uses a ceramic composed of lanthanum-strontium-manganite (LSM). High temperatures, currently 800–1,000 °C, are required for rapid diffusion and high reactivity of reactant gases in the electrodes, and for ion conductivity across the electrolyte, necessary for commercially viable cell voltages. Because of the high temperatures, cell interconnections typically use a lanthanum chromite (chromium oxide) composition or high-alloy metals.

The power of the fuel cell is the result of the amount of current developed multiplied by the voltage maintained across the stack. When no current is drawn, the open-cell voltage (OCV) reflects the chemical "potential" between fuel and oxidant gases, similar to the potential energy derived from a dam building up a head of water. OCV is determined by fuel and oxidant concentration and pressures. As current is drawn, the voltage drops in proportion to the resistance related to diffusion of reactant gases in the electrodes; reaction of these gases at the electrodes; ion transport through the electrolyte; and electron transport through the electrodes, interconnects, and end plates. Collectively, these resistance mechanisms often are referred to as polarization, with low polarization being desirable. The cell electrochemical energy conversion efficiency is directly proportional to the cell voltage.

Lowering Operating Temperatures. A major thrust of the SECA Program is to moderate the temperature regime to enable use of low-cost metal alloys in the interconnects such as stainless steel. In planar designs, interconnects can represent over 80% of the stack mass. While newer SOFC designs have enabled temperatures to drop from 1,000 °C to 800 °C, survivability of stainless steel at 800 °C remains an issue, primarily due to chromium oxidation. An important objective in Phase II is to lower the temperature to 700 °C. In Phase III, SECA envisions that new materials will be used to optimize the cell and system. Similar uses of stainless steel at 700 °C suggest that reasonable durability can be achieved.

While cost is the primary driver for lower operating temperatures, other benefits accrue. Lowering the temperature in general: (1) reduces thermal stress on the stack, (2) offers a greater number of sealing options, (3) lessens degradation of stack materials and performance over time from sintering and creep (common in ceramics), (4) shortens start-up time, and (5) reduces the amount of insulation needed to achieve acceptable surface temperatures.

Enhancing Cathode Reactivity. The cathode is the temperature-limiting component in the present SOFC fuel cell stack, and therefore is considered to be the most critical aspect of cell improvement. At temperatures below 800 °C, polarization increases in the lanthanum-strontium-manganite (LSM) to the point where stack performance becomes unacceptable. An improved cathode would allow the cell to get to 700 °C. Substantial work is ongoing with LSM to enhance the surface area for oxygen ion formation, and to incorporate mixed ionic and electronic conductivity which together support both conversion of oxygen to oxygen ions *and* movement through the media. Also, work is being expanded in the area of understanding surface exchange mechanisms in the cathode to pave the way for new, more active cathode materials.

Improving Anode Durability. The nickel/zirconia cermet anode suffers little polarization relative to the cathode at temperatures of 700 °C and below. However, the nickel in the cermet, already susceptible to sulfur poisoning, becomes even more sensitive as operating temperatures decrease. Also, nickel remains subject to chemical bonding with carbon that is released in the reforming process.

New strategies for direct oxidation of fuels on the anode, as opposed to using a separate fuel processing unit, are being explored as well. This approach significantly reduces balance-of-plant costs. But there are tradeoffs that require evaluation, such as the effect on power density, which also affects cost.

Achieving Needed Electrolyte Conductivity. The YSZ electrolyte will not become limiting, in terms of ionic resistivity, until about 700 °C — assuming that: (1) an electrolyte layer can be applied at a thickness of approximately 10 microns (a fraction of the thickness of a human hair); and (2) it can sustain stresses induced and maintain separation between the reactant gases. More conductive electrolytes are under investigation, such as cerium-based materials and lanthanum-strontium-gallium oxide-magnesium oxide compositions. By exploring new materials for electrolytes, innovative options for more reactive cathode materials will become possible. The requirement for chemical and mechanical property compatibility of adjacent cell components, particularly thermal expansion compatibility to minimize stress on the thin components, limits the materials that can be considered. Broadening the range of options available for one component broadens the range of options for the adjacent components. And, changes have a ripple effect — changing the composition of one component can lead to a new ensemble of cell materials.

Moving to Low-Cost Interconnects. As discussed, the ultimate objective for new interconnect materials is to achieve effective operating temperatures of 700 °C or less so that cheap metallic material like stainless steel might be used in the interconnects. In Phase I of the SECA Program, operating temperatures are likely to remain at 800 °C. High-alloy metals emerging from intensive ongoing research are likely to be used. The lanthanum chromite currently used in tubular configurations is expensive (see Cost Table 1, page 4), and does not work well in planar designs due to high sintering temperatures, which introduces fabrication problems. Also, lanthanum chromite tends to warp in reducing environments. The challenge in using metallic materials is to control the protective corrosion films that form so that they remain conductive and do not propagate and lead to significant structural deformation.

Evolving Fabrication Techniques. Fabrication of an SOFC cell requires integration of components varying in thickness from millimeters down to less than 10 microns. While techniques evolving from the semiconductor industry make such fabrication possible, the challenge is to design the process so that the cell components operate effectively together when joined to make a cell. This requires integration of materials science with advanced fabrication technology.

Tape casting, tape calendaring, and screen printing are inexpensive manufacturing techniques that have been developed largely for the semiconductor industry. In tape casting, a ceramic slurry, dispersed in solvent, is spread to a thin layer of controlled thickness using precisely calibrated "doctor" blades. Tape calendaring involves squeezing a softened thermoplastic polymer/ceramic mix between two rolls to produce a continuous ceramic tape of constant thickness and high uniformity. Screen printing is precise spraying of thin layers of materials in predetermined patterns. The techniques developed have the potential to fabricate thin-film cell components as thin as 10 microns, apply them to other cell components, form and cut them to precise dimensions, and prepare them for firing to sinter and join the ceramic materials. Fabrication also includes sintering, a step often required to achieve the density needed for efficient performance.

At high fabrication temperatures, reactions can occur at the component interfaces that are detrimental to cell performance, such as formation of an interstitial layer offering high ionic/electronic resistance or permeability. Therefore manipulation of the materials *and* the process, by incorporating additives and modifying techniques, will be essential to efficient cell performance. Alternate, lower temperature techniques are being explored to reduce detrimental interfacial reactions and to reduce the high costs associated with energy-intensive processes. Ultimately, techniques developed to mass produce the individual fuel cell must be extended to automated, high-speed manufacturing of the stack.

Fuel Processing/Reforming. Processing the fuel for effective conversion to electricity by the fuel cell is an integral part of, and important to, system efficiency and cost. Effective use of process heat to convert fuels to a form usable by the fuel cell is essential to system efficiency. Fuel processing (reforming) may be an integral part of thermal management in the fuel cell because reforming controls the heat produced in the electrochemical reactions (see Figure 8, below).

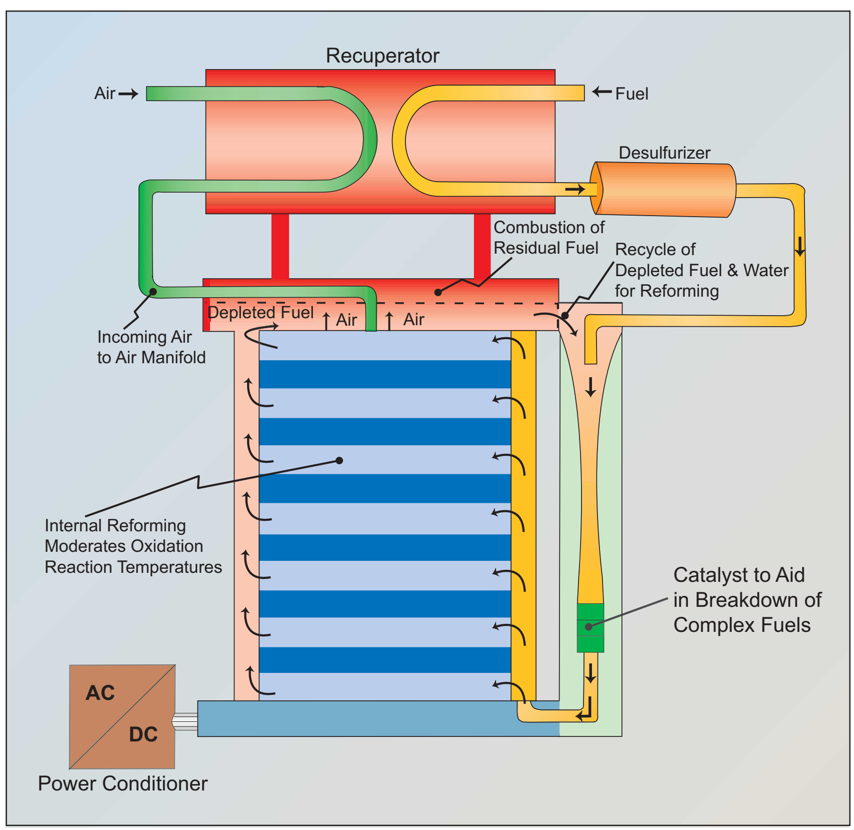


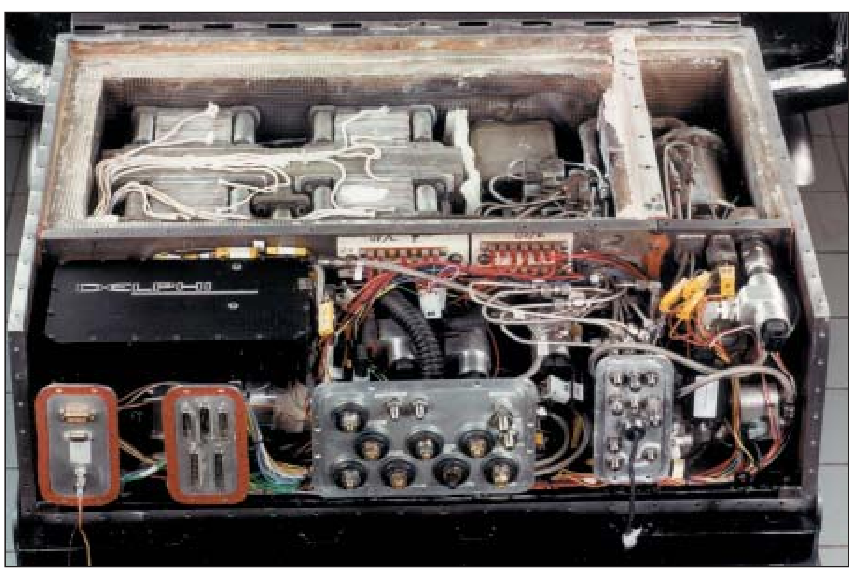
Figure 8. Thermal Management in SOFCs

What is needed is a fully integrated fuel processor with multi-fuel capability that is small, and either removes sulfur before reforming or uses sulfur-tolerant materials in reforming. The reformer must have operational stability during load variations, start-up, and shutdown. These needs are driven largely by the expanded fuel cell market envisioned, which includes transportation applications that use either gasoline or diesel fuel. These liquid fuels can contain sulfur, and place difficult requirements on the reformer.

A number of avenues warrant pursuit including development of sulfur-tolerant catalysts, sulfur removal technologies, efficient high-temperature heat exchangers, and use of partial oxidation (partial fuel combustion) to minimize size and to increase energy input to the reforming process. The overriding requirement is to achieve simplification in reforming and associated thermal management.

Power Conditioning/Sensors and Controls. The electrical output must be conditioned to match demand, and sensors and controls must be incorporated into the fuel cell system to measure key operating parameters and maintain them in a range conducive to efficient fuel cell operation. All components need to be better, faster, cheaper, and possibly tolerant of the high-temperature environment. Again, the potential range of fuel cell applications includes conditions where the loads are highly variable and the system may be started up and shut down repeatedly over a short period of time. These transient conditions impose a significant burden on the power conditioning and control system that must deliver needed power while protecting fuel cell integrity.

Modeling. A tool that will be used extensively throughout the SECA development effort is modeling. Modeling can save an enormous amount of time and money in investigating issues and developing solutions. Models will be used, for example, to address: (1) stack issues, such as structural reliability and transient/steady state design; and (2) system issues, such as thermal cycling, load following, start-up, and shut down. By developing these tools, such complex issues as identifying optimal strategies for integrating stack and reformer design, and determining sensor and control requirements, can be addressed effectively.



Prototype APU developed by Delphi, showing four SOFC stacks (upper left corner)

Pathways to Advanced SOFC Designs

There are four separate design paths that are presently being pursued to achieve SECA goals and objectives. The designs are not fixed, but the design concepts are established.

Tube Design. As mentioned, one of the approaches derives from tubular cell development. The cathode forms the structural base for the cell. One possible fabrication method will be to extrude the cathode in a flattened tube shape, and add the electrolyte and interconnects by spray techniques and the anode by sequential slurry deposition. Advantages carried over from the original tubular design include: (1) elimination of the need for seals, and (2) some accommodation of thermal expansion because the tubes are not tightly constrained.

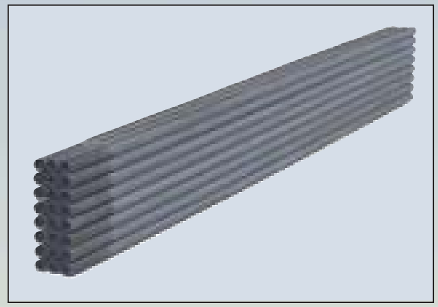


Photo courtesy of Siemens Westinghouse

Electrode Supported Planar Design. This approach typically uses a square, flat-plate configuration with cross- or co-flow of the reactant gases. The electrode provides the structural support for the cell. The likely fabrication method will be to tape cast or calendar the support electrode and to use screen printing or vapor depositon techniques for the electrolyte and non-support electrode to complete the cell. The flat-plate/cross- or co-flow configuration offers high power density due to short, large area conduction paths, and lends itself to low-cost mass production. The seals must be gas tight,

Photo courtesy of Honeywell

Radial Design. The radial design is manufactured similar to the electrode-supported design, but introduces reactant gases at the center of a cylindrical stack, making gas flow in a radial pattern. The symmetry of this design permits relatively easy control of flow and thermal distributions compared to less symmetrical designs. The approach retains many advantages of the electrode supported design while significantly minimizing the sealing area. One significant advantage of the radial design is improved ruggedness, due to the stack being un-constrained at the perimeter. This design also is an electrode-supported design that lends itself to low-cost mass production.

Monolithic (Co-Sintered) Design. This approach uses a flat-plate configuration, but focuses on assembling tape cast and screen printed cell components and interconnects into stacks, and firing the stacks as a whole. In this manner, manufacturing steps are significantly reduced, such as high-cost sintering.

Generic Planar

Photo courtesy of Honeywell

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