Development and Commercialization of 10KW Solid Oxide Fuel Cell (SOFC) Power Systems

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Objectives

- Develop the Planar Solid Oxide Fuel Cell (pSOFC) design, materials, and manufacturing processes to realize the potential for low-cost manufacturing necessary to make SOFCs competitive in the power generation marketplace.
- Design, develop, and source the Balance of Plant (BOP) including controls and power electronics required to complete a cost-competitive power system.
- Integrate the system into a value package that will substantially displace reciprocating and turbine engine power generation in target markets with attendant national benefits in reduced energy usage and emissions.

Key Milestones

- Developed market-driven comprehensive product profile that identified key end product characteristics, performance, and technical requirements.
- Developed a steady-state system model to derive energy balances, sub-system performance requirements, fuel and air stream flows, and pressure drops.
- Developed a transient model to predict performance during load and temperature transients.
- Modeled start-up.

Approach

Project work is shared between Cummins Power Generation (CPG) and McDermott Technology, Inc.–SOFCo. MTI-SOFCo is developing the hot box assembly, comprising the fuel cell stacks, manifolds, heat exchanger(s), and CPOX reactor. CPG is developing the Balance of Plant (BOP) comprising the air supply, fuel supply, controls, power electronics, packaging and integration.

This work breakdown complements and accelerates MTI-SOFCo's ongoing SOFC development program and draws on CPG's expertise in the integration of generation systems and its strong position in a variety of consumer and commercial power generation markets.

Close project coordination is maintained through regular meetings, teleconferences, and a secure shared database.

Results

A comprehensive product profile has been developed. This activity is consistent with CPG's established new product development process. The process of developing the profile identified a number of applications related challenges and technical issues that provided valuable insight to the development team.

The development of the steady state and transient system model(s) have provided key inputs for the design teams at MTI-SOFCo and CPG, as well as offering encouragement regarding questions raised during the Profile development. For example, during Profile development, we identified start-up time as a key characteristic and a potential issue. Modeling work to date suggests that it may be possible to meet our start-up time objectives through a number of control and configuration strategies.

In conjunction with the system model development, a comprehensive Process & Instrumentation Drawing (PID) has been completed for the C1 proof-of-concept prototype. The PID defines the system configuration, identifies critical values and components, and serves as a key interface document between the design teams.

Through the system modeling work and PID, the team has identified the solid oxide stack configurations for the C1 proof-of-concept and C2 deliverable systems. The stack configuration is critical to meeting the cost objective, and is a good illustration of the synergistic nature of the system design. Stack configuration optimization coordinated considerations extending from the multi-layer ceramic manufacturing process through the design of the boost and output inverter stages of the power electronics section and into the final product physical configuration to meet the space envelope requirements of key applications.

With the identification of the stack configuration, the Power Cell Unit (PCU) design team was able to proceed with the design of manifolding, clamping, and sealing for the stacks and have identified practical approaches for making and sealing the required interfaces.

Key and extremely productive work in the fuel reforming section has identified a CPOX reactor design meeting requirements derived from the Profile development. Through micro-reactor testing and evaluation, catalysts have been identified which are both cost and package space effective and every indication is that we will be able to reform both our target fuel, propane, as well as natural gas with high efficiency and no coking or carbon deposition.

Using input derived from the Profile and the system models, BOP sub-system design alternatives are being investigated and evaluated against performance and cost requirements. Initial work is targeting the air supply and fuel supply components as both cost and performance critical. Consistent with CPG's product development process, potential production vendors are being involved early on in the process to get the benefit of their input on the most cost effective approaches. Preliminary concept layouts of the overall system have been developed that indicate we should be able to meet our packaging objectives consistent with the Profile requirements.

The CPG Controls and Power Electronics work has been closely coordinated in involved with the stack configuration, transient modeling, and PID development described above. A flexible control system platform based on a recently introduced CPG industrial set controller has been selected for the C1 prototype to allow for architecture and algorithm development. Power electronics design work has focused on the selection of cost-critical architecture and components.

Conclusions

An excellent team has been assembled to execute this project. The combined CPG and MTI-SOFCo organizations possess all the essential elements for technical and commercial success. The program has been proceeding according to plan with excellent progress in key areas, including modeling, PCU design, CPOX reactor development, BOP and system integration design. The preliminary indications are that overall system parameters are meeting our Profile objectives for the key markets.

Abstract

Cummins Power Generation (CPG) and McDermott Technology, Inc. have teamed to execute a Cooperative Development Program (DE-FC26-01NT41244) with support from the U.S. DOE under its SECA program. In this program a low-cost, modular, high efficiency 10-kW solid oxide fuel cell system (SOFC) will be developed for several commercial markets. Participating as key subcontractors in this program are Ceramatec, Inc. and M/A-COM, Inc.

CPG is the largest volume manufacturer and distributor of premium generators in the 3-kW_e to 12-kW_e size range for a wide variety of commercial and military mobile and stationary applications. Of CPG's total annual sales of $1.4 billion in the 3 kW_e to 2 MW_e product range, approximately $200 million is in the 3-$kW_e$ to 12-kW_e segment. Meeting the SECA program cost and performance targets will allow SOFC technology to significantly replace current reciprocating engine technology in identified genset products. The driving force for this product replacement is the SOFC system's potential for low noise and vibration and high system reliability.

McDermott Technology, Inc. is the research and development arm of McDermott International, Inc. In

the mid-1980s, MTI recognized the potential of fuel cells as a reliable source of clean, high-quality power. By the early 90s, the company had focused its efforts on the development of pSOFC and on the fuel processors that produce the hydrogen necessary for fuel cells to operate. MTI is also a recognized leader in operating stacks on alternate reformed fuels.

This program is developing a 10-kW$_e$ SOFC system operating on gaseous fuel that will meet SECA mobile specifications and market requirements. CPG already has significant presence in the existing markets identified and is well qualified to understand customer requirements and product specifications. Markets targeted by the SECA program development work are Recreational Vehicle Auxiliary Power, Commercial Work Vehicle Auxiliary Power, and Telecommunications Emergency Power. Future potential markets outside the scope of the base proposal include Marine Pleasure Boat Auxiliary Power, DoD Mobile Power, Truck Auxiliary Power, and Distributed Generation. The program is a three phase, 10-year development program. The four-year, Phase I portion includes system design and engineering, component design and development, and substantial SOFC stack development and scale-up necessary to meet commercial cost and performance objectives. Phase I will conclude with a demonstration of a pre-commercial, but fully operational 10-kW system.

The next two phases address further development to support full commercialization of the SOFC system. A major emphasis of the program is cost reduction so that SOFC systems will be economically viable. At the end of the entire program, the cost of a 10-kW system is projected to be $400/kW, which is competitive with current reciprocating engine systems in this size range. Meeting this cost target will result in a significant replacement of reciprocating engine technology in existing generator set markets and will result in a production base sufficient to support the required program investments.

Both stationary and mobile power markets will be pursued. The key attributes of SOFC systems that will drive market penetration are low noise, high reliability, low emissions and high efficiency. SOFC fuel cells lend themselves to low cost liquid and gaseous fuel reforming systems and their high operating temperature allows higher fuel efficiency than other technologies. They have no major moving parts and this contributes to their low noise, high reliability, and long life. The modular nature of SOFC systems will permit rapid scale-up in system sizes from 10-kW to 250-kW and beyond.

The SOFC power system will have the following characteristics:

Rating. The system rating will be 10-kW$_e$, supplemented with a battery boost system operating in parallel to provide transient load response. In addition to providing power for peak and transient loads, the battery boost system has the ability to power low loads without the SOFC system operating.

Fuel. Liquid Propane (LP) fuel will be used for system simplicity and cost considerations. Market research indicates that customers will accept LP fuel to gain the SOFC's low noise and vibration performance benefits. Accessing the future potential markets will require development of diesel fuel reforming.

Operating Mode. The SOFC start-up sequence will be initiated from cold when power is needed or anticipated. Mature start-up time for the SOFC from cold is targeted at 15 minutes. This is acceptable considering power is immediately available from the battery boost inverter system for lower kW$_e$ loads. After start-up, power will be available from the SOFC for battery charging and to power loads. When no immediate power is needed, the SOFC will begin an idle mode where it will be kept hot through supplemental firing. The SOFC system will then be shut down when no power requirements are anticipated for a significant time (typically over eight hours).

Installation. The SOFC power system will fit in the same approximate size and weight envelope (15 ft^3/ 660 lbs.) and vehicle installation locations as the present diesel gensets.

The Fuel Cell Power System

The product is defined by three major subsystems: 1) a hot box subsystem, comprising the fuel cell stacks, fuel reformer, and thermal management system; 2) a control and power subsystem, comprising electronic controls, a DC voltage boost module, an AC output inverter module, valves and instrumentation; and 3) a balance of plant subsystem, comprising the fuel and air delivery systems, exhaust system, wiring, and overall product packaging.

The control and power electronics play a major role in making the SOFC an acceptable energy source for commercial applications. The target applications characteristically exhibit large and sudden load changes. Steady state load also changes significantly depending on time of day, ambient temperature, and vehicle operating mode. To accommodate these requirements, the system will build on current CPG designs and technologies to provide high quality, seamless AC power availability under all conditions while optimizing the SOFC operating cycle. The system uses CPG-proven integrated microprocessor control, energy management, and energy sharing power electronics architectures to satisfy this requirement. A key area of development is the control of the SOFC energy conversion process during start-up, load transitions, steady state, and cool down. Cost effective architectures that combine energy sources and boost low DC voltage as required for the AC output inverter are being developed. Instantaneous control of energy sources versus demand and the SOFC process will ensure system performance and efficiency.

The balance of plant (BOP) design approach is based on CPG's extensive experience and commercial success in providing similar equipment to the target markets. This experience and the core design technologies already resident at CPG are directly applicable to the design of the BOP and integration of the SOFC system.

Planar Solid Oxide Fuel Cells

MTI is developing a multi-layer, co-fired pSOFC stack that will provide superior performance and reliability at reduced costs, relative to competing designs. This approach combines state of the art SOFC materials with the manufacturing technology and infrastructure established for multi-layer ceramic (MLC) packages for the microelectronics industry. High quality, low-cost MLC packaging technology has already been demonstrated at high volumes in the semi-conductor industry. With the proper selection of SOFC materials, implementation of MLC fabrication methods offers unique designs for stacks (cells and interconnects) that are not possible through traditional fabrication methods.

The basic design concept for the multi-layer, co-fired pSOFC is illustrated. For the cell, a thin electrolyte layer is supported by a perforated electrolyte lattice layer that serves as the primary load-bearing member for the cell. These two layers are fabricated using tape casting, followed by punching and lamination. Proprietary anode ink is applied to the perforated side of the "green" laminate and a proprietary cathode ink is applied to the other side. The printed laminate can then be fired to form a self-supported cell or combined with the interconnect layers and then co-fired to form single repeat units (as illustrated). Multiple cells and sets of interconnect layers may be combined to form co-fired stacks.