



CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Environmentally-Preferred Advanced Generation

**DIRECT OPERATION OF SOLID OXIDE
FUEL CELLS ON NATURAL GAS**

FEASIBILITY ANALYSIS

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which \$2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to \$75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:

<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049 or email

eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at <http://www.energy.ca.gov/research/index.html>.

Direct Operation of Solid Oxide Fuel Cells on Natural Gas

EISG Grant # 99-30

Awardee: Northwestern University
Principal Investigator: Scott Barnett
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Grant Funding: \$74,958
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Introduction

This research project targeted the generation of electricity using natural gas direct from the pipeline to operate fuel cells instead of processed gas. A combination of factors—low noise, high efficiency, ultra-low emissions, and the ability to utilize readily available natural gas—make fuel cells a generally desirable generation method.

Most fuel-cell systems consume hydrogen derived from natural gas using some form of fuel processor. The fuel processor adds considerable complication and expense to fuel-cell systems, exacerbating the problem of bringing costs down to competitive levels, especially for smaller plants. Until recently, it has not been thought possible to operate fuel cells directly on hydrocarbons. Recently, low-temperature, solid-oxide fuel cells (SOFC) have operated directly on methane. This demonstration signals an important new opportunity for making simple, cost-effective fuel cells. Fuel-cell operation on pipeline natural gas is considerably more difficult than operation on pure methane because pipeline gas contains higher hydrocarbons. This project developed a fundamentally new type of fuel-cell anode with a specific anode composition. This anode was successfully tested on propane, a higher hydrocarbon constituent of natural gas.

Objectives

The goal of this project was to determine the feasibility of anodic fuel conversion for a SOFC operating directly on natural gas. The key innovation was to develop the anode composition that satisfied the requirements for fuel-cell operation. Subsequently, the researcher verified that electrochemical oxidation of the higher hydrocarbons present in natural gas could take place without carbon deposition at the fuel-cell anode. The project set the following objectives:

1. Develop multiple SOFC anodes based on ceria with reduced Ni content and Ru-ceria. During the project a third composition using a conductive ceramic was added.
2. Eliminate carbon coking on the anode when the SOFC is operating on propane. Characterize each anode performance by scanning electron microscopy for detection of carbon on the anodes, impedance spectroscopy, and fuel-cell current-voltage measurements.
3. Verify anode performance in a fuel-cell stack. Select the most promising anode compositions for operation with natural gas. Incorporate the selected anodes into fuel cells and test as a function of fuel composition and temperature.

Outcomes

1. Ceria-based anodes with reduced Ni content, Ru-ceria anodes, and anodes using a conductive ceramic with greatly reduced Ni were constructed. Evaluation of these anodes found that they exhibit the required physical characteristics of porosity and conductivity. The conductive ceramic anode reduced the function of the metallic component to that of a pure catalyst. This

allowed the researcher to make a major reduction in the amount of noble metal in the catalyst.

2. The anodes were characterized. Impedance spectra proved acceptable. Coking on the anodes was evaluated. Results showed that Ru and Ni provide similar electrochemical performance. Less coking was found on the anodes with reduced metal fraction. However, at very low metal content, there is insufficient conductivity in the anode. From these data the research developed the innovation of replacing the metal with a conductive ceramic. This is a key outcome of this project. The innovative anode is composed of three materials: an electronically conducting ceramic, an ionically conducting ceramic, and a metallic catalyst. It is highly resistant to coking.
3. Gadolinium-doped-ceria (GDC) anodes with reduced Ni content (Ni-GDC) and the ceramic Ni anodes were chosen for fuel-cell testing. Initial performance using hydrogen fuel and air indicated only small differences between the two anode compositions. All subsequent testing focused on the ceramic Ni anodes. Performance using methane and air was similar to known performance of prior methane fuel cells. When operating on propane fuel and air, the ceramic Ni anode performed better than the Ni-GDC anodes. Further, after several hours of operation at peak power, the ceramic Ni anodes were free of coking, while the Ni-GDC anodes showed heavy carbon deposition (gram quantities).

Conclusions

1. This project has verified the feasibility of operating solid-oxide fuel cells (SOFC) directly on pipeline-quality natural gas. In California the gas is composed of methane and higher hydrocarbons, with controlled amounts of sulfur in the form of mercaptans, odiferous sulfur compounds deliberately added as required by law for safety purposes. Fuel fed to any operational fuel cell presumably would be free of mercaptans to avoid poisoning of the metallic catalyst. Removal techniques include use of activated carbon filters, zinc oxide, or zinc acetate.
2. This project tested SOFC performance on higher-hydrocarbon components of natural gas, and it showed that the fuel cells can be operated with propane.
3. After testing Ni-ceria and Ru-ceria anodes, the researcher determined that anodes with very low Ni content perform well with a ceramic conductor to provide anode conductivity. That is, they provide fast electrochemical oxidation, and hence high power densities, without carbon deposition.
4. This researcher utilized two ceramic constituents with an embedded metallic catalyst in his design approach. Because the relative amounts and the chemical nature of each of the three constituents can be altered to match a specific fuel or operating condition, a designer has great flexibility for improving fuel-cell performance.
5. A major advantage of the new anodes is that they can be cyclically reduced and oxidized without degrading performance. This redox cycling is expected to occur regularly during periodic shutdown of small generators when the fuel flow is stopped. Thus, the new SOFC anodes may enable new applications of SOFCs that rely on the direct use of high-energy-density hydrocarbon fuels or feature frequent on-off cycling (e.g. portable power, auxiliary power units, and distributed generation.) While early stability tests of these anodes are promising, longer-term tests are needed.

Benefits to California

The PA's assessment is that the benefits to be derived by the California electric ratepayer from the continuation and successful conclusion of this line of research accrue in the area of

distributed generation. Distributed generation benefits directly from the availability of a quiet, low-emission, cost-effective power source using a readily available fuel. By operating on both natural gas and propane, these fuel cells can be configured as uninterrupted power sources for the communities they serve. At an estimated thermal efficiency of from 40% to 60%, these fuel cells reduce the amount of carbon dioxide produced per unit of electricity, thereby reducing the detrimental effect from this assumed greenhouse gas. Production of high-grade heat ($\sim 700^{\circ}\text{C}$) as a byproduct can substantially improve the overall fuel efficiency of the distributed-generation network by situating the generator facilities as combined heat and power installations. Such a configuration is feasible given the quiet, non-polluting nature of fuel cells.

Recommendations

In order to advance this technology towards commercialization, R&D efforts must be carried out to improve and optimize the structure and composition of the new ceramic anodes for use with natural gas. This research should investigate and determine the following:

- The effects of sulfur-containing compounds should be assessed in order to determine whether the SOFC generators using these new anodes will require the removal of sulfur from the fuel. If filtering of the gas is required, toxicity of used filters and their proper disposal require evaluation.
- The long-term behavior of SOFC fuel cells incorporating these anodes must be assessed.
- Development criteria should require that the anodes achieve stable long-term performance.
- The long-term test should include frequent cycling of operating conditions, including exposure to air, as expected in the real operation of small SOFC generators.
- Finally, the anodes should be used as the support element of thin-electrolyte SOFCs. This matches the SOFC configuration being commercially developed and will provide the best overall performance.

This research effort should be undertaken in tandem with a commercializing partner. If these anodes can be incorporated into the existing SOFC configuration of commercial interest, it will maximize the prospects for this new technology.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description of the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: <http://www.energy.ca.gov/research/innovations> and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage need to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop- ment	5 Product Develop- ment	6 Demon- stration	7 Market Transfor- mation	8 Commer- cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/ Public Benefits/ Cost								

The Program Administrator’s assessment was based on the following supporting details:

Marketing/Connection to the Market

This research discovered a new method of composing SOFC anodes. As such, it has been premature to consider the market until now. Very little has been done beyond recognizing the proper mechanical design to enable the retrofitting of the new anode into the existing designs of fuel cells under development. A commercializer has yet to be chosen.

Engineering/Technical

This project was limited to a feasibility study, but it discovered a heretofore unrealized method of SOFC anode composition. It will take additional testing to understand and optimize the operating parameters for the method and for other fuels.

Legal/Contractual

Northwestern University, the Principal Investigator, and the research team have registered a patent disclosure for this innovation. The California Energy Commission may hold certain rights.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality planning must be done prior to completion of stage 4 development. Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental Plans.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

Significant research and development remains before production can occur, but but recognition that the new anode may be a retrofit item in existing designs means that fuel cells incorporating this new technology could enter the marketplace very quickly.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The technology developed in this project advances fuel-cell development in general, which is considered a key technology for distributed generation. The use of fuel cells in distributed generation offers the following potential benefits to California electric ratepayers: (a) reduces harmful environmental emissions that result from central power plants using combustion technologies, (b) reduces the need for power-distribution infrastructure, (c) increases grid reliability, (d) increases the quality of the power grid and eliminates power-line losses.

In addition to the general benefits derived from distributed generation, the specific technology developed in this project has the potential to reduce the capital and operating costs of Solid Oxide Fuel Cells. The inventor has made significant progress in designing a fuel cell to run directly on natural gas. That eliminates the need for an expensive and complex reformer, and it allows the fuel cell to be connected directly to existing natural gas lines to serve as the fuel source. SOFCs also can be configured to generate hot water or heat, further increasing their energy efficiency.

Fuel cells generally have high thermal efficiency. When compared to conventional electric generators, this means that a higher percentage of the fuel is converted to electricity. Less fuel is consumed and less carbon dioxide gas is produced. The reduced greenhouse emissions and the lower consumption of expensive imported fuel are benefits which extend beyond the electric ratepayer to the population in general.

Program Administrator Assessment

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.

Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)