CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Environmentally-Preferred Advanced Generation

DEVELOPMENT OF A UNIQUE GAS GENERATOR FOR A NON-POLLUTING POWER PLANT

FEASIBILITY ANALYSIS

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LEGAL NOTICE

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.

Executive Summary

Introduction

Clean Energy Systems, Inc. (CES, Sacramento, CA) has defined and is in the process of developing a fossil-fueled, zero-emission power generation system. The key to this system is the combustion of a relatively clean fuel with oxygen in the presence of recycled water in a unique gas generator that directly produces a high-temperature, high-pressure gas composed almost entirely of steam and CO_2. Fuel for the system can come from a variety of fossil or biomass sources so long as it is composed almost entirely of the elements carbon (C), hydrogen (H), and oxygen (O). Oxygen is used to combust the fuel rather than air as in conventional systems thereby eliminating the formation of NO_x and large a volume of noncondensible exhaust gases. The high-energy gases produced by the gas generator drive multistage turbines that, in turn, drive an electrical generator. Exhaust gases from the turbine go to a condenser where gaseous CO_2 is separated from liquid water. Most of the water is recovered, reheated and returned to the gas generator. Gaseous CO_2 leaving the condenser passes to a recovery system where it is conditioned as necessary for use in enhanced oil or coal-bed methane recovery operations, for commercial sales, or for sequestration.

The gas generator is one of two key components in the system and is the focus of this program. CES successfully demonstrated the gas generator in this project. A high temperature steam turbine is the other key component requiring development. It was not the subject of this study. The CES generation system can operate with conventional steam turbines, albeit at reduced thermal efficiency.

Data from this project is being used in the design of a 10 MWe gas generator that will be used in system development testing under a cooperative agreement between CES and the U.S. Department of Energy's National Energy Technology Laboratory (NETL). Lawrence Livermore National Laboratory in Livermore California is the site being proposed for the demonstration of the CES cycle. If this site is chosen, the research will include CO_2 sequestration in abandoned oil wells.

Objectives

The goal of this project was to determine the feasibility of the CES gas generator element operating at commercial power generation conditions. While based on rocket engine technology, the gas generator for commercial power generation must operate on different fuels for longer periods of times. The following project objectives were established:

1. Develop, build and demonstrate a gas generator having a premixing injector element design. Operate the gas generator on pure oxygen and methane adding water for steam production. The methane and oxygen mixture is not used in rocket technology, nor is it used in conventional power generators.

2. Operate the gas generator stably and reliably for extended periods of time. Gas generators of this type typically do not run on methane fuel, nor do they run for extended periods of time.

3. Operate the gas generator at temperatures and pressures required for a power generator. Temperatures and pressures required for commercial power generation differ from those required for rocket propulsion.

4. Demonstrate reliable premixing of oxygen, water and methane. The test must provide a stable flame over long periods of time to achieve the zero emission goal.

5. Demonstrate time-temperature process control in cool-down modules to promote re-association of by-products, thereby creating a clean, two-species gas. To achieve the zero emission goal the gas generator must burn all of the methane fuel while not creating carbon monoxide.

Outcomes

Significant outcomes of the program and major test results are as follows:

1. A complete gas generator with a premixing injector element was designed, built and successfully operated on oxygen, methane, and de-ionized (D.I.) water. The tests were accomplished at the University of California, Davis campus. This test system is available for further research and demonstrations on other feeds.
2. The gas generator operated repeatedly, reliably, and stably. At the completion of the project it had experienced more than 75 starts with a total run time of more than 10 hours and one individual test duration of 48 minutes.
3. The gas generator operated at temperatures up to 2700 °F (1480 °C), pressures up to 300 psia (20 atm), and at several fuel-air ratios. These conditions allow the gas generator to generate steam for today's commercial steam turbines and for advanced high efficiency steam turbines.
4. The researchers demonstrated repeatable ignition and stable combustion of premixed oxygen, methane, and water.
5. The product gases from the gas generator are composed almost entirely of two gas species (steam and CO_2) with only a minor amount of O_2 and a trace of CO. No hydrocarbons or other volatile organic compounds were detected. The concentration of CO in the product gases was found to correlate well with predicted values

Conclusions

This project experimentally established the "proof-of-principle" for a novel gas generator component of a new system for producing clean electrical power from fossil fuels. The gas generator, based on rocket engine technology, produces high-energy drive gases that feed into steam turbines. Significant system integration tasks remain. Integration of such a gas generator into a power generation system could provide a viable, economical approach to zero-emission power production from a wide variety of fossil or biomass fuel. Such a system could make the total recovery of CO_2 possible at an affordable cost and in a form suitable for enhanced recovery of oil or coal bed methane or for sequestration. This project demonstrates a technically feasible method for eliminating from power plants both atmospheric pollution and CO_2 which has been implicated in the global warming concern.

Benefits to California

The project represents the early development of a zero-emission, fossil-fueled power plant using rocket engine derived combustion technology. When commercially viable these power plants will offer a zero emission alternative to fuel cells for clean power generation. If the produced carbon dioxide is used in enhanced oil recovery, California could gain additional proven oil reserves and the associated economic benefits.

Recommendations

The Program Administrator recommends that California government and environmental agencies support CES in the development of this technology. The next steps are the development of small-scale demonstrators, larger demonstrators, and establishment of a facility for zero emission research. Lawrence Livermore National Laboratory, (LLNL) is currently attempting to secure funding for such a research facility at Livermore, California. That project would demonstrate both the overall zero emission power plant concept and enhanced oil recovery using the CO_2 produced. CO_2 would be sequestered in the process.

High temperature steam turbines represent the other technology advancement needed to commercialize the CES power system for widespread, economically attractive power production. At this time there are no high temperature steam turbines commercially available. The technology to build high temperature steam turbines exists in the rocket engine industry. Significant research and development must be accomplished to take that technology and reduce it to commercial products with long life. Research organizations should also fund bench-scale demonstrations using alternative fuels to verify that this technology can be applied to commercial grades of oxygen with virtually any fossil or biomass fuel.

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 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 needs 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 for the CES gas generator. 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 / Activity	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.

A business plan has been developed and continues to evolve as CES works with the markets, suppliers, strategic partners, sources of venture capital, and customers. CES has identified suppliers of components and/or subsystems, architects and engineers (A&E), and hosts for small-scale demonstration plants. Letters of intent to support demonstration efforts have been signed by several potential strategic partners/licensees.

During the past four years, CES has briefed program development personnel at General Electric Power, Siemens/Westinghouse, ABB/Alstom, Rolls Royce Industrial and Marine Division, Elliot Turbo-machinery, Solar Turbines, Air Liquide, Praxair, Boeing/Rocketdyne Power Division, BP Amoco, Chevron, Kinder Morgan, Kansas Geological Survey, Air Products and Chemicals, Edison International, SMUD, Calpine, Mirant and other IPP's, as well as officials of DOE/NETL, LLNL, the California Air Resources Board, the California Department of General Services, and the California Energy Commission. While the industry response is encouraging, companies would like to see the technology developed into a system and operated for a significant period of time before committing significant resources.

Engineering/Technical

The design for a 10 MW gas generator, co-funded by DOE/NETL, is nearing completion, and major materials have been ordered. Testing of the igniter component is expected to begin in the fourth quarter of this year. Fabrication of the full prototype gas generator is scheduled for completion by the first of next year, (January, 2002). Testing will extend into the second quarter of 2002 based on availability of the test facility.

CES has identified and is negotiating MOUs with hosts of candidate sites for demonstration and field tests. They made a proposal for a 500 kW demonstration project, to be located in Antioch, California. Other potential sites are located in the Los Angeles basin. CES plans two-year test durations to obtain suitable RAMD (reliability, availability, maintainability, durability) information.

Legal/Contractual

CES holds intellectual property rights to the zero-emission power production technology described previously. CES has ten issued patents and more than 50 pending applications in North America, Europe, and Asia. An Intellectual Property Plan is in place and is being actively implemented. Although contracts for small demonstration plants are currently being negotiated, no sales of CES technology or hardware have been completed. Sales forecasts have been prepared and can be made available to government agencies, under proper agreements, for purposes of estimating the benefits of this technology.

Environmental, Safety, Risk Assessments/ Quality Plans.

Prior to testing of the laboratory-scale gas generator under this project, CES conducted an extensive failure-mode analysis with all project team members. The team identified potential deficiencies and took corrective action. Those efforts were instrumental in the successful outcome of this project.

Energy system air emissions and related environmental issues should be negligible due to the zero-emissions aspect of the technology. The program administrator is not aware of environmental studies relating to CO_2 sequestration.

CES must prepare a comprehensive quality plan during the next stage of development. They should include reliability analysis, failure mode analysis, manufacturability, cost and maintainability analyses, hazard analysis, coordinated test plan, and product safety**.**

Strategic.

This product has no known critical dependencies on other projects under development by PIER or elsewhere. The researchers have identified a possible synergy with PIER fuel cell development activities. They suggest that the gas generator can readily be incorporated into hybrid fuel cells processes. This could result in very high cycle efficiencies. They identified two power plant concepts that integrate the CES process with solid oxide fuel cells (SOFC). In the first process, the SOFC effluent is combined with the discharge stream from the high-pressure steam turbine, heated in a re-heater and fed to an intermediate pressure turbine. This process recovers waste heat from the SOFC, and could attain an overall cycle efficiency of 64%. In the second process, the gas generator is operated under fuel rich conditions, producing a hydrogen-rich reformate for the SOFC anode. The SOFC discharge stream is directed to a reheater and brought up to the operating temperature of the intermediate pressure turbine. In this scheme, cycle efficiencies of 65% might be possible.

Production Readiness/Commercialization.

CES has established industry contacts, and identified potential licensees of its technology. It has discussions underway with two large, multinational corporations active in the energy sector.

CES claims to be capable of manufacturing the enabling technology component – the gas generator. All other components for a system demonstration project are available from existing equipment suppliers. High temperature steam turbines must be developed for future high efficiency units. CES plans to prepare a Production Readiness Plan.

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 primary public benefit offered by the proposed technology is to reduce environmental impacts of the California electricity supply system. This will be accomplished by the elimination of all regulated air emissions and the capture and possible sequestration of CO_2. The CES generation system should be economic to operate for two reasons. First it will eliminate the need for the owner of the system to buy and operate emission reduction equipment, and eliminate the need to buy emission offsets for the remaining emissions. Emission control equipment adds approximately $100/kW to the first cost of a power plant, and adds approximately 2 mils/kW-hr for operation. Emission offset costs vary greatly. Typical costs are $10,000 per ton of NO_x emitted. Second, the CES system will, once high temperature steam turbines are available, deliver fuel efficiencies higher than the best of today's gas turbine combined cycle power plants. This will reduce fuel use and cost. If the CES generation system is built over a "depleted" oil or gas field it could provide additional public benefits by recovering oil or gas that was not otherwise producible.

Demonstrations of this technology should be on the ground in approximately two years. Full benefits will be achieved after long term testing is completed and regular installation of production hardware begins. The Program Administrator estimates this to take about 10 years.

Technology Transfer

An extremely important step toward technology transfer to the market occurred when the California Energy Commission PIER program released a Notice of Proposed Awards on September 10, 2001. CES is listed as a proposed award winner of a major development contract. The award allows CES to build a 500 kW demonstration unit. The Environmentally Preferred Advanced Generation subject area of PIER is funding this effort. In a non-related event, CES was selected to build a 2 MW demonstration unit in the city of Antioch in Northern California.

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 supports the CEC decision to consider this technology for follow-on funding. This assessment is based on the potential for significant public benefits and the technical progress made in this project.

Additional funding is required to pursue the system integration and technology research work. Significant funding is required to develop the high temperature steam turbine equipment necessary for system operation at high thermal efficiencies. Additional funding may be required to test the CES system on alternative fuels. Funding for these activities may have to come from a variety of sources.

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)