Appendix A to FAR 99-20

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

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

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Inquires related to this report should be directed to Clean Energy Systems, Inc. (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisg@energy.state.ca.us.

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We acknowledge and express our thanks to Mr. Joe Asher and California Analytical, Inc. for the use of one of their CO/CO_2 analyzers. Without their contribution, the gas composition data obtained from this program would have been greatly diminished.

EISG Awardee

This project was awarded to Clean Energy Systems, Inc. (CES) of Sacramento, CA. The company is registered with the Secretary of State of California as Clean Energy Systems, Inc. in accordance with California law.

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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. The EISG Program awards grants up to $75,000 for promising public interest energy research that is in the proof-of-concept stage of development.

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

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

For more information on the EISG Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/innovations.

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

Abstract

Clean Energy Systems, Inc. is developing a fossil-fueled, zero-emissions power generation system. The key to this system is the combustion of a 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. The gas generator is the enabling component in the system and is the subject of this program.

The goal of this project is a laboratory-scale proof-of-concept demonstration the of the gas generator. Tests conducted under this project had two primary objectives: (1) to develop and demonstrate a gas generator having a premixing injector design and (2) to demonstrate time-temperature process control in cool-down modules to minimize by-products.

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

- A complete gas generator and test system was built and successfully operated on O_2, CH_4, and deionized water.
- The gas generator operated repeatedly, reliably, and stably during more than 75 starts, for more than 10 hours, and for individual test durations up to 48 minutes.
- The gas generator operated at temperatures up to 2700 °F (1480 °C), pressures up to 300 psia (20 atm), and at various mixture ratios near stoichiometric.
- Product gases are composed almost entirely of steam and CO_2, 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 correlated well with predicted values.

This program experimentally established the "proof-of-principle" for a new method of producing clean high-energy drive gases for the generation of electrical power from fossil fuels.

Key Words:

Zero-emissions power generation, gas generator, oxygen combustion, fossil fuels, stoichiometric combustion, water injection, steam-carbon dioxide mixtures, proof-of-concept demonstration

Executive Summary

Introduction

Clean Energy Systems, Inc. (CES, Sacramento, CA) has defined and is in the process of developing a fossil-fueled, zero-emissions power generation system. The key to this system is the combustion of a 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 the large volume of noncondensible exhaust gas. 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 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 the key component in the system and is the focus and subject of this program. This project's PIER subject area is Environmentally-Preferred Advanced Generation.

Objectives

The goal of this project is to demonstrate the proof-of-concept of the gas generator that provides the enabling technology for zero-emissions power plants. Tests conducted under this project had two primary objectives:

1. To develop and demonstrate a gas generator having a premixing injector element design.
2. To demonstrate time-temperature process control in cool-down modules to promote re-association of by-products, thereby creating a clean, two-species gas.

Data from this project is used in the design of a 10 MWe gas generator and its subsequent product development testing that is being funded separately under a cooperative agreement between CES and the U.S. Department of Energy's National Energy Technology Laboratory (NETL).

Outcomes

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

1. A complete gas generator and test system was built and successfully operated on O_2, CH_4, and deionized (D.I.) water and is available for further research and demonstrations on other feeds.
2. The gas generator operated repeatedly, reliably, and stably:
   - More than 75 starts
   - Total run time of more than 10 hours
   - Individual test durations up to 48 minutes
3. The gas generator operated over a wide range of conditions:
   - Temperatures up to 2700 °F (1480 °C)
   - Pressures up to 300 psia (20 atm)

- Various mixture ratios near stoichiometric

4. Testing demonstrated that O_2, CH_4, and water can be premixed and achieve repeatable ignitions and stable combustion.
5. The product gases from the gas generator are composed almost entirely of 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.
6. The concentration of CO in the product gases was found to correlate well with predicted values.

Conclusions

This program experimentally established the "proof-of-principle" for a new method of producing clean high-energy drive gases for the generation of electrical power from fossil fuels. Integration of such a gas generator into a CES power generation system provides a viable, economical approach to zero-emissions power production from virtually any fossil or biomass fuel. Such a system makes the total recovery of CO_2 possible at the lowest cost and in a form suitable for enhanced recovery of oil or coal bed methane or for sequestration. This project significantly contributes towards demonstrating a viable power plant technology for eliminating both atmospheric pollution and CO_2 which has been implicated in the global warming concern.

Benefits to California

The successful completion of this project has already benefited California by demonstrating its leadership in efforts to bring environmentally friendly advanced power generation systems to its citizens. This program represents the very first public support for development of the zero-emissions, fossil-fueled power plants. Presuming the initial success of this program continues and these zero-emissions, fossil-fueled power plants become widely used, California will reap benefits in many areas, including:

- Advanced power generation technology
- Improvement of cost and availability of California's power
- Improvement of public health and safety
- Invigoration of State and local economies

Recommendations

It is recommended that similar bench-scale demonstrations to be performed on alternative fuels to assure this new technology can be applied to commercial grades of oxygen with virtually any fossil or biomass fuel. In particular, bench-scale "proof-of-principle" demonstrations should be extended to include the evaluation of the following:

1. Commercial grades of oxygen
2. Crude and pipeline-quality natural gas
3. Landfill gas
4. Syngas from oxygen-blown coal gasifiers
5. Syngas from oxygen-blown biomass gasifiers

Cooperative funding of small (demonstration-scale) zero-emissions power plants that are based on a CES gas generator and power generation scheme is also recommended. Similarly, cooperative funding to support contributing technologies on reheaters, advanced turbines, and oxygen separation is recommended.

Development Stage Assessment

The overall efforts required to commercialize CES's zero-emissions power plant were evaluated in terms of the EISG Stages and Gates Process. The work performed under this program, EISG Grant 99-20, specifically addressed the engineering/technical disciplines at Stage 3, Research and Bench Scale Testing, of the critical, enabling component in the system (i.e., the gas generator). However, other total project development activities have and continue to be pursued at various stages under independent funding by CES and through cooperative funding by NETL and CES. The various development activities are at Stages 3 through 6 (research through demonstration) and overall zero-emissions power plant development is approximately half way to commercialization.

Introduction

Background and Overview

Clean Energy Systems, Inc. (CES, Sacramento, CA) has defined and is in the process of developing a fossil-fueled, zero-emissions power generation system. The system is described in detail in papers presented at two recent international conferences[1,2] and is the subject of several patents[3]. A simplified schematic diagram of Clean Energy Systems' (CES's) environmentally clean power generation system is shown in Figure 1. The key to this system is the combustion of a 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 H_2O and CO_2. The gas generator is the key element to the system and is the focus and subject of this program. A schematic diagram of the laboratory-scale gas generator tested under this project is presented in Figure 2.

This project's PIER subject area is Environmentally-Preferred Advanced Generation. The goal of this project is to demonstrate the proof-of-concept of the unique gas generator that provides the enabling technology for fossil-fueled, zero-emissions power plants.

In CES's zero-emissions power systems, 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 reheated (not shown in the simplified diagram) and returned to the gas generator to moderate the combustion temperature and reduce the combustion gases to a temperature acceptable to the turbines. Excess water resulting from the combustion process is removed from the system. This water can be used within the power plant as cooling tower makeup water, processed for other plant uses, sold, or sent to disposal as most appropriate to the site.

Gaseous CO_2 leaving the condenser passes to a recovery system. Residual moisture is removed from the CO_2 in the recovery system where it is also cooled and compressed to conditions necessary for sequestration. The CO_2 may be sequestered in subterranean formations or the ocean. Alternatively, some or all of the CO_2 can be used in enhanced oil recovery (EOR) operations, injected into non-mineable coal seams to recover methane, or processed into saleable products if local markets exist. Atmospheric emissions are totally eliminated.

Fuel for the CES system can come from a variety of sources so long as it is composed almost entirely of the elements, carbon (C), hydrogen (H), and oxygen (O). The primary requirements are that it is a fluid and free of ash. Hydrocarbons, alcohols, carbon monoxide and hydrogen are suitable fuels as are natural gas, syngas, and gasified coal or biomass. Significant fuel processing prior to combustion is required only when the precursor fuel is coal, heavy petroleum, or biomass. In those cases, the crude fuels would normally be processed in oxygen and steam blown gasifiers and cleansed of particulates and sulfur prior to introduction into the gas generator. For the sake of expedient testing, the laboratory-scale “proof-of-concept” gas generator tested in this project used high purity compressed methane as the fuel.

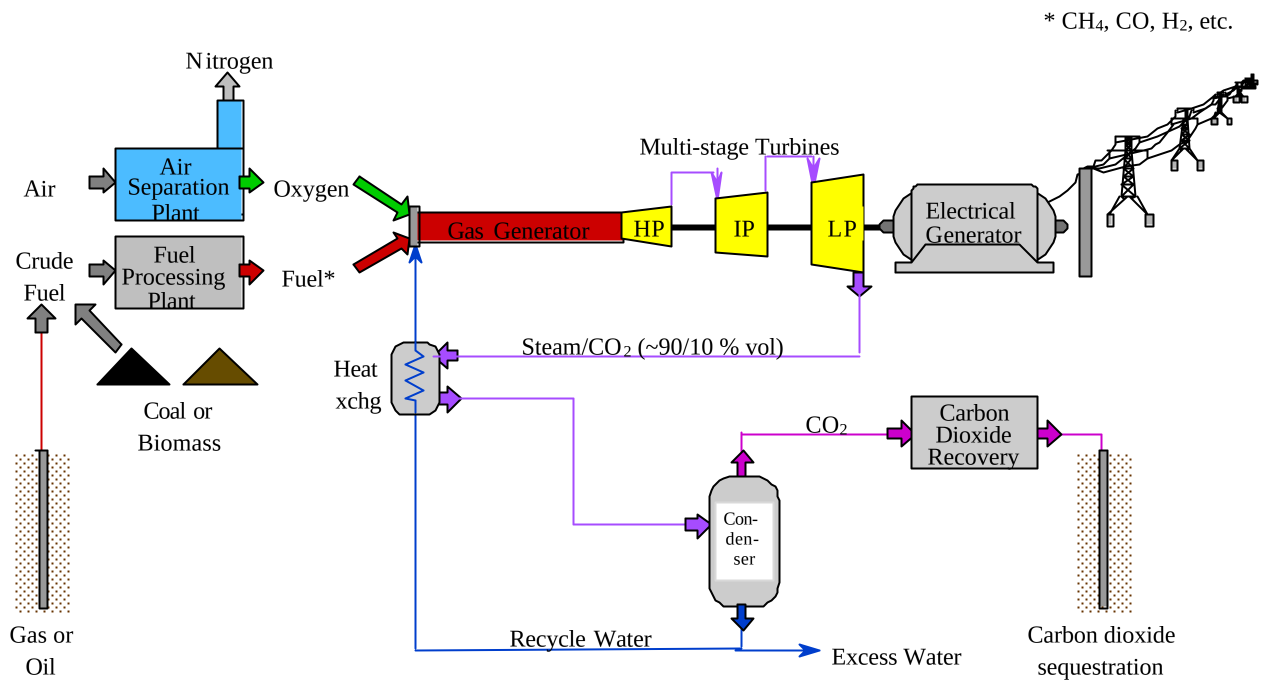

Figure 1. Clean Energy Systems' Zero-Emissions Power Generation System

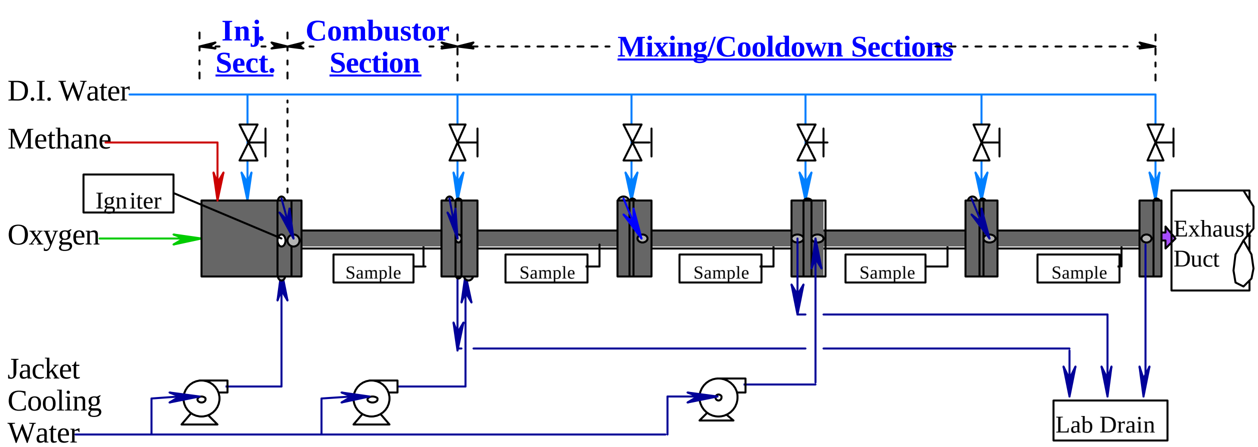

Figure 2. Schematic Diagram of the Single-Element Gas Generator

Oxygen is used to combust the fuel rather than air as in conventional systems thereby eliminating the formation of NO_x and the large volume of noncondensible exhaust gas. The oxygen is obtained from air via a number of processes, including commercially available cryogenic air separation units (ASUs). Advanced air separation technologies such as those based on ion transfer membranes (ITM) hold significant promise for lowering the cost of oxygen and therefore is expected to enhance the economics of future CES power generation systems. The DOE and industry (Praxair and Air Products and Chemicals) are currently developing the ITM air separation technology under ambitious multi-million dollar cost-share DOE/industry cooperative agreements. High purity compressed oxygen was used in the laboratory-scale testing conducted under this program.

Project Objectives

This project involved the laboratory-scale testing of a single-injection-element combustion device to demonstrate the operating principles of the CES gas generator. This gas generator is the enabling device in a new concept for producing **power from fossil fuels or biomass with zero emissions**. The testing had two primary objectives:

1. Develop and demonstrate a premixing injector element design. Computer modeling of the combustion process indicated that uniform mixing of the gases and water-injection-cooling for combustion temperature control is critical to minimizing the formation of by-products.
2. Demonstrate time-temperature process control in subsequent cool-down modules to optimally promote re-association of by-products, thereby creating a clean, two-species gas.

Data from this project is used in the design of a 10 MWe gas generator and its subsequent Stage 2 development testing that is being funded separately under a cooperative agreement between CES and the U.S. Department of Energy's National Energy Technology Laboratory (NETL). The laboratory-scale gas generator tested in this EISG program is nominally a one hundredth scale model of the 10 MWe gas generator.

CES was solely responsible for the design, fabrication, and associated funding of the laboratory-scale gas generator. The California Energy Commission provided joint funding with CES to perform laboratory-scale testing of the gas generator.

Report Organization

The remainder of the main report is organized into five sections:

- Project Approach
- Project Outcomes
- Conclusions and Recommendations
- Development Stage Assessment
- Benefits to California

Project Approach

The overall project was accomplished within the framework of a multi-task effort funded jointly by CES and the California Energy Commission. CES was solely responsible for funding the task related to the design and fabrication of the laboratory-scale gas generator. Although this work was independent of Grant No. 99-20, that effort is described below for the sake of completeness.

Independent CES Task--Design and Fabrication of the Laboratory-Scale Gas Generator

CES designed and fabricated a prototype laboratory-scale gas generator prior to receiving Grant No. 99-20. Preliminary tests of that device provided valuable insight for the design of the new laboratory-scale gas generator tested in this project. That design incorporated a number of features commonly used in rocket engines that have proven capabilities in controlling very high temperature and high-pressure combustion processes.

The laboratory-scale gas generator tested in this project is an assembly comprising: (1) an injector section, (2) a water-cooled igniter section that contains a spark igniter, (3) a water-cooled combustion chamber; (4) four cool-down modules, (5) four deionized (D.I.) water injectors, and (6) a turbine simulator. The overall gas generator as configured for testing is shown schematically in Figure 2 and as mounted on the test bench in Figure 3.

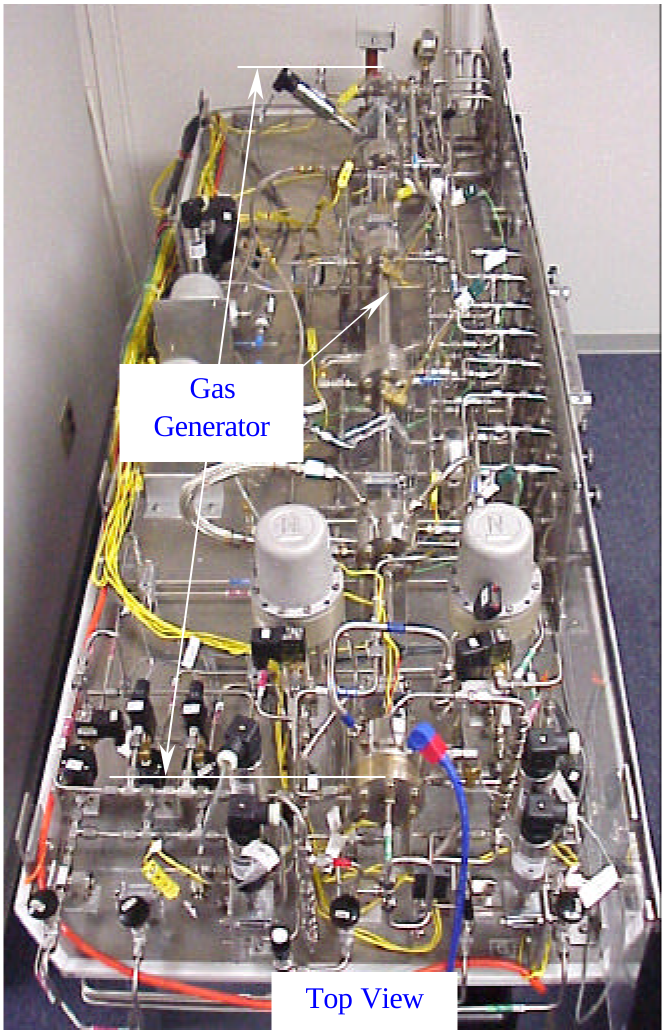

Figure 3. Test Bench with Gas Generator Installed for Testing but without Safety Shields

The functions of the injector section of the gas generator are precise fluid control, metering, and mixing of oxygen, methane and deionized water. Its purpose is to mix the three components completely and uniformly in precise ratios wherein the oxygen and methane ratio is essentially stoichiometric to H_2O and CO_2 and the ratio of deionized water to oxygen and methane is externally adjusted to control the combustion temperature to desired values.

The igniter section is a water-cooled housing that contains the spark igniter and a diagnostic thermocouple to detect ignition.

The combustion chamber section of the gas generator is 12 in. long with an I.D. of 0.42 in. It is constructed of Inconel

625 and has a full-length water-cooling jacket to provide thermal protection to the inner liner. Instrumentation and gas sampling ports penetrate the inner wall approximately 2 in. from the aft end to provide access for a pressure transducer, a thermocouple, and/or a gas-sampling probe.

The four cooldown modules have configurations, instrumentation ports, and gas sampling ports identical to the combustion chamber section. They are separated from the combustion chamber and from one another by deionized (D.I.) water injectors. The function of the cooldown modules is to provide sufficient residence time for dissociated daughter species to recombine as dictated by reaction kinetics.

The gas generator includes four deionized (D.I.) water injectors. The function of each injector is to inject deionized water into the combustion products to both cool the combustion gases and to generate additional superheated steam.

The turbine simulator is located at the aft end of the final (fourth) cooldown module. It is essentially a flanged closure containing a replaceable critical flow orifice insert of a size necessary to produce a desired back pressure simulating that offered by a turbine.

The detailed design of the gas generator is the property to CES but further descriptions are presented in Appendix I. Photographs of the gas generator and its various components are given in Figures I-1 through I-5 of Appendix I.

Fabrication of the gas generator was performed at and/or under the direction of Tecma Co. (Sacramento, CA)

EISG Grant No. 99-20 Tasks

The California Energy Commission under its Energy Innovations Small Grant (EISG) Program, Grant No. 99-20, provided $74,871 towards the joint funding with CES to perform a seven-task testing effort on the laboratory-scale gas generator. Those seven tasks were: 1) test bench design, 2) test bench fabrication and assembly, 3) test system setup and checkout, 4) gas generator testing, 5) data analysis, 6) technical reporting, and 7) administrative reporting.

Task 1--Test Bench Design

The test bench was designed to provide a mounting platform for the laboratory-scale gas generator described above and in Appendix I. The bench, shown in Figure 3, incorporates all the components and laboratory service or subsystem interfaces necessary to test the gas generator. It includes a gas sampling probe and a gas sample cooler, a sample condenser, a condensate separator, and sample dryer. The test bench was designed to interface with the U.C. Davis Combustion Laboratory services (or with similar services at other facilities) and with ancillary subsystems. Components incorporated into the test bench include the plumbing, valves, filters, instrumentation, and mating interfaces with the ancillary subsystems and facility services. Ancillary subsystems provide supplies of pressurized deionized water and pressurized cooling water to the test bench. Data acquisition and control functions for the test bench are supplied by a separate CES designed and provided subsystem. Gas analysis equipment interface with the test bench at the discharge of gas sampling system.

The bench provides flow circuits for the various fluids that are required for testing as follows:

Low-pressure and high-pressure CH_4 (or other fuel)	Low-pressure and high-pressure O_2
N_2 for valve actuation and purging	Deionized water to each injector
Deionized water to the turbine simulator	Cooling water for cooling jackets

Each flow circuit has various items installed on the test bench itself or on the ancillary subsystems that interface with the bench. These items include: (1) manual and/or remotely actuated shutoff valves; (2) check valves; (3) flow control valves, orifices, and/or venturis; (4) filters; (5) pressure regulators; (6) pressure transducers or gages; (7) thermocouples or digital thermometers; and (8) flow meters (for the water circuits). These items permit the measurement and control of flow of the respective fluids to and through the various segments of the gas generator. Each cool-down module and the turbine simulator have their own de-ionized water supply lines with appropriate control valves and instrumentation. Nitrogen gas is used to actuate remote operating pneumatic valves and for purging both the gas generator and the CH_4, O_2, and deionized water feed lines. Thermocouples are attached to the surface of critical elements of the gas generator and inserted into the fluids at key points in the various flow paths for both data collection and test control. Pressure transducers or pressure gages and flow meters are installed at key points in the various flow paths for similar purposes.

The test bench also provides convenient interface connections with laboratory services and to supporting subsystems. The interfaces with laboratory services include: (1) tubing connections with CH_4, O_2, and N_2 supplies, (2) a plug-in connection to 120 v AC power for the spark plug exciter, (3) an exhaust gas duct that inserts into the laboratory exhaust system, (4) a septum for withdrawing gas samples for analysis by gas chromatography, (5) and a flexible hose connection for discharging cooling-water from the gas generator to the laboratory drain. Interfaces between the test bench and supporting subsystems include: (1) a tubing connection to the deionized water system, (2) flexible hose connections to the cooling-water supply system, (3) a flexible tubing connection to the on-line gas analyzers, and (4) multiple electrical and instrumentation connections with the control and data acquisition system.

The test bench, the services furnished by the test facility (U.C. Davis Combustion Laboratory), and the bench's ancillary subsystems are described and pictured in greater detail in Appendix II.

Task 2--Test Bench Fabrication and Assembly

The test bench, the deionized water supply subsystem, and the high pressure cooling water supply subsystem were fabricated and/or assembled from purchased parts at the Tecma Co. (Sacramento, CA). The assembly/buildup of these systems was performed by a combination of Tecma personnel and private consultants. The data acquisition and control subsystem was designed and built by private consultants at the facilities of the consultants and CES. A consultant (currently a CES employee) wrote computer software for the data acquisition and control subsystem

Task 3--Test System Setup and Checkout

The test system was setup and checked out in two stages. The first stage was performed at Tecma Co. to assure the system was functional and reliable for formal testing purposes prior to transfer to the Combustion Laboratory at the University of California, Davis. The second stage of setup and checkout was conducted after the system was transferred to U.C., Davis.

Task 3A--Test System Setup and Checkout at Tecma Co.

After the assembly of the test bench, the gas generator was installed on the test bench and mated with the supporting deionized water supply and the data acquisition and control subsystems. Electrical continuity tests on the data acquisition and control subsystem and functional tests of remotely controlled components were performed. Cold flow tests were conducted on all the deionized water injectors to define their flow characteristics (i.e., flow rate versus pressure drop) and for comparison with design values. In the course of these tests, the deionized water supply system was found to yield D.I. water containing sufficient particulate contaminants to plug downstream filters on the test bench or to plug the deionized water injectors. This problem was alleviated by designing, fabricating, and installing a high capacity, high-pressure filter at the discharge of the deionized water supply system. This effort made deionized water supply system functional and acceptable for system testing. The injector for introducing O_2, CH_4, and D.I. water into the combustion chamber of the gas generator was similarly flow tested with N_2 and D.I. water as appropriate. These tests established that the flow characteristics and the quality of mixing and atomization achieved by that injector were acceptable for hot testing.

Next, the integrated test bench/gas generator was mated with the high pressure cooling water subsystem. Cold flow tests of the cooling circuits on all the water-cooled components of the gas generator were performed to define their flow characteristics. These tests revealed the need for pulsation dampeners in the discharge lines of the duplex piston pumps that provided the high pressure cooling water to the test bench. The tests accomplished a functional checkout of the high pressure cooling water subsystem and made it acceptable for system testing.

In preparation for ignition tests, time delays and opening times for the valves that control the flow of O_2, CH_4, and D.I. water were measured. These data were used to establish appropriate initial timing sequences to achieve safe, controlled starts and shutdowns of the gas generator. The sequence of computer controlled actions requiring careful timing included the activation and deactivation of the igniter and the opening and closing of O_2, CH_4, D.I. water, and N_2 purge valves.

A detailed test procedure/checklist was prepared and used in a mock test to checkout and assure the procedure was functionally correct. Thirty-one (31) ignition and low-pressure (<5 psig) combustion tests, involving 94 minutes of operating time on the test system, were then performed over a period of six working days. These tests established optimized computer controlled starting and shutdown sequences, appropriate kill parameters, and kill values to safely and reliably operate the gas generator. The entire computer software package for control and data acquisition was thereby proven to be acceptable. Early in the course of these tests, a need for a simple pretest method to determine whether or not the igniter would spark on command was discovered. Without such a methodology, the cause of any failure to ignite could not be quickly ascertained. A simple proprietary pretest method was developed and subsequently that pretest was routinely performed as a step in the test procedure. The functional pretest of the igniter also established the need for a N_2 purge circuit for the spark plug to prevent the collection of short-circuiting moisture on the spark plug. The igniter housing and test bench plumbing were modified to incorporate a spark plug purge circuit.

Following these checkout tests, the test system was disassembled, i.e., broken down into subsystems, to the minimum extent possible and transported to the Combustion Laboratory at U.C., Davis.

Task 3B--Test System Setup and Checkout at U.C., Davis

The subsystems (test bench, deionized water supply, high-pressure cooling water supply, and data acquisition and control,) that constituted the test system as checked out at Tecma Co. were reassembled within the Combustion Laboratory at the University of California, Davis. The test bench was connected to University-supplied high-pressure cylinders of compressed gases (high purity O_2 and CH_4 as gas generator reactants and N_2 for purging and valve actuation), the gas discharge duct from the gas generator was mated to the laboratory's exhaust hood, and the gas sampling system on the bench was connected to the oxygen analyzer. The deionized water supply system was connected to the laboratory's non-potable water supply and to high-pressure cylinders of N_2 for pressurization of D.I. water and for valve actuation. The high-pressure cooling water supply system was connected to the laboratory's non-potable water supply and to an electrical power outlet. The oxygen analyzer was connected to the data acquisition system and to sources of calibration gases.

The overall test system was checked for leaks and functional checks were performed on all remote-operating valves and on the igniter. The test procedure/checklist was updated to reflect the slightly modified configuration of the test setup in the Combustion Laboratory compared with the setup at Tecma Co. The first hot-fire checkout test at U.C., Davis was accomplished approximately two weeks after the move to the Combustion Laboratory.

Over the next four-week period twenty-five additional checkout tests, involving 216 minutes of test system operation, were performed. These checkout tests overcame system problems or deficiencies and brought the test system to a state of readiness for formal testing and data acquisition. The most troublesome and time-consuming problem was getting a fully functional gas analysis capability, which was crucial to achieving testing goals. The gas chromatograph that was originally intended to provide most of the analytical data proved to be difficult to activate and to operate effectively. Modifications to detectors, use of two different columns, and changes in analysis programs ultimately provided the capability to analyze gas samples for C-H compounds and for various "permanent" gases (e.g., O_2, CO_2, CO, etc.) on a non-routine basis. Unfortunately, analyses by gas chromatography were found to be too slow and cumbersome for routine analysis of the many gas samples expected during this program. The oxygen analyzer purchased for this program required the replacement of the sensor before stable operation could be achieved. A NO_x analyzer was provided by the laboratory; however, the very high purity of the O_2 and CH_4 supplied by the University virtually precluded the presence of measurable NO_x in the combustion products of the gas generator. NO_x analyses were, therefore, not attempted during this program. The use of a CO analyzer at the laboratory was offered but a checkout of the instrument showed it to be non-operable. Finally, a dual-beam infrared CO/CO_2 analyzer was loaned to the program through the courtesy of California Analytical Instruments, Inc. That instrument was connected in series with the oxygen analyzer and its output sent to the data acquisition system. At the end of the system checkout, gas samples could be continuously withdrawn and analyzed for O_2, CO, and CO_2 and grab samples could be taken via a septum and analyzed for various other components on the gas chromatograph.

The flow meters for measuring the flow rate of deionized water to the gas generator were found to be unresponsive at the very low rates encountered in the early testing. Their sensitivity was increased approximately five-fold by designing, fabricating, and installing reducing inlet orifices. This modification permitted the acquisition of real data at flow rates down to approximately 0.0014 gal/min (5.3 cm^3/min).

The flame front of the combustion appeared to sometimes move from the igniter housing into the main part of the combustion chamber because of their different inside diameters (following experience gained from a prototype gas generator). To overcome this undesired transition, a simple uncooled igniter housing having the same inside diameter as the main chamber was fabricated and tested. Ignition and stable combustion was achieved with the new configuration but, as expected, the housing became hotter than desired. A water-cooled version of the igniter housing was, therefore, fabricated and used successfully thereafter.

Because the gas generator was designed with sufficient jacket cooling to operate at high pressure (~500 psia), heat losses were exaggerated when testing at low pressure. This caused the exhaust gases to be cooler than anticipated and operating pressure to be lower than expected at design values for O_2 and CH_4 feed rates using the fixed-area orifice in the turbine back-pressure simulator. To achieve higher operating pressures at near design O_2 and CH_4 feed rates, the turbine back-pressure simulator was redesigned to accept replaceable orifice inserts with reduced areas. The inserts were subsequently replaced as required during formal testing.

Task 4--Gas Generator Testing

Formal gas generator testing involved operating the gas generator at various, but nominally constant, chamber temperatures and pressures while varying the O_2/CH_4 ratio over the range from essentially stoichiometric to slightly in excess of the stoichiometric ratio. Data from about 35 channels were recorded via the data acquisition system at approximately two-second intervals during the course of each test. The data of primary significance were gas temperatures near the discharges of the combustion chamber and cooldown modules; combustion pressure; O_2, CH_4, and D.I. water flow rates; and the concentrations of O_2 and CO in the dry sample gases. Spot chemical analyses were performed by gas chromatography on grab samples during some tests to look for trace byproducts. The formal testing involved 40 separate tests and nearly 6 hours of test system operation during which more than 10,000 sets of data were recorded.

The original test plan called for testing at 54 test conditions, i.e., two pressures (nominally 50 and 500 psia), at each of three O_2/CH_4 mixture ratios (stoichiometric and 1 and 4 % O_2 in excess of stoichiometric), at each of nine specified combinations of combustion chamber and gas exit temperatures. In practice, the gas generator or gas analysis system had limitations that precluded operating at some of the intended conditions. In particular, the highest planned combustion chamber exit temperatures and pressure were not achieved because of jacket cooling considerations. At low pressures, excessive gas cooling resulted from large heat losses to the jacket that limited combustion chamber and exit gas temperatures. At high pressure and very high combustion chamber exit temperatures, jacket cooling was insufficient to prevent damage to the combustion chamber at a location believed to coincide with the flame front. Also, valid data could not be obtained at O_2/CH_4 ratios very close to stoichiometric because CO concentrations exceeded the upper range of the available CO analyzer. Nonetheless, more extensive data were obtained than anticipated by the original plan and over a wider range of operating conditions.

Sixteen tests yielded complete sets of valid test data. These tests encompassed average operating pressures ranging from 33 to 312 psia, average combustion chamber exit temperatures ranging from 2030 to 2600 °F, and O_2/CH_4 mixture ratios corresponding to 0.4 to 9 % O_2 in excess of stoichiometric. Each valid test produced on the order of 40 to 800 sets of test data. The duration of the valid tests ranged from about 5 to 45 minutes. Overall, the sixteen valid tests covered 4.75 hours of test system operation and approximately 8500 sets of data.

Task 5--Data Analysis and Test Results

The gas generator test data, recorded from approximately 35 data channels at nominal 2-second intervals, were analyzed to define the operating conditions and the corresponding gas compositions for each valid test. Because of the time delay for gas samples to reach the online analyzers and the relatively slow response of the gas analyzers compared with the other instrumentation, gas composition data had to be shifted with respect to time to synchronize gas composition data with the other operating data. This time adjustment was established for each test by plotting O_2/CH_4 mixture ratios defined from rapid response mass flow measurements and those calculated based on O_2 analyses from the online analyzer against time. Time offsets in the differently defined mixture ratios following step changes readily established the appropriate time shifts necessary to "synchronize" gas compositions with the operating conditions. These time offsets typically ranged from 20 to 40 seconds.

Valid tests were defined as those in which all the critical data were recorded for periods sufficient to define multiple "near-steady-state" values during a given test. In general, step changes were made in O_2/CH_4 mixture ratios early in each test to achieve a desired set of operating conditions, then mixture ratios were varied slowly with time at relatively constant operating temperature and pressure. For purposes of data analyses, data were deleted in time intervals corresponding to step changes during which operating conditions and gas compositions were obviously transient. Data sets within a test were combined to define the relationship between the concentration of CO and the concentration of O_2 in dry gas samples (i.e., after condensation and removal of the steam). The concentration of O_2 in the gas samples is a sensitive direct indication of the O_2/CH_4 stoichiometry in the gas generator. Mathematically the percentage of O_2 in excess of the stoichiometric value equals 50(% O_2 in the exhaust)/(100-% O_2 in the exhaust). For small percentages of O_2 in the exhaust, the O_2 in excess of the stoichiometric value is approximately half the percentage of O_2 in the exhaust. Thus, 1 % O_2 in the dry exhaust corresponds to approximately 0.5 % more O_2 in the feed to the gas generator than required for stoichiometric combustion.

A typical set of data is shown in Figure 4. The data clearly show that the concentration of CO in the exhaust decreases rapidly with only slight excesses of O_2 over the stoichiometric requirement. Analytically, CO decreases approximately as a power function of O_2 concentration in the exhaust as indicated by the trendline.

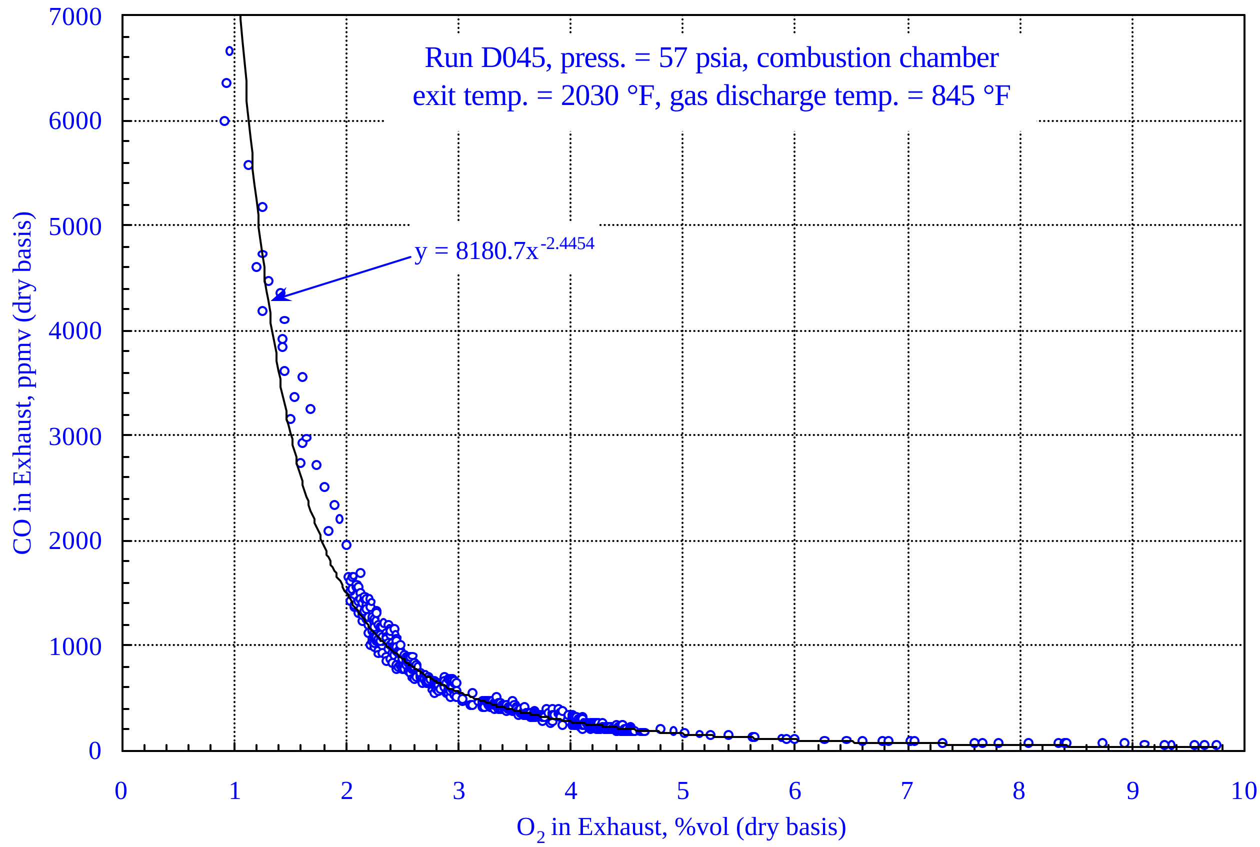

Figure 4. Effect of Excess O_2 on CO Concentration in the Gas Generator Gas Products.

Correlations similar to that shown in Figure 4 were defined for each valid test and each one showed similar behavior (i.e., the concentration of CO in the exhaust decreases rapidly with only slight excesses of O_2 over the stoichiometric requirement).

Kinetics-based computer modeling of the combustion and cooldown processes in the CES gas generator indicates that CO constitutes more than 95 % of all organic by-products of combustion and is, therefore, an excellent diagnostic indicator of combustion behavior. Grab samples of dry exhaust gases were analyzed by gas chromatography using both a flame ionization detector (FID) and a thermal conductivity detector (TCD). The former detector is particularly sensitive to compounds containing C-H bonds while the latter is more sensitive to gases such as O_2 and CO_2. No compound containing a C-H bond or any compound other than O_2 or CO_2 was ever detected by gas chromatography. The limits of detection for the detectors was not experimentally established but are believed to be less than 1 ppm of C-H compounds for the FID and less than 0.1 % vol. of O_2 and CO_2 for the TCD (CO eluted with O_2 and, therefore, could not be defined by the gas chromatograph).

Experimental CO and O_2 concentrations were compared with predictions based on the Chemkin II computer code[4] and the GRI-MECH 2.11 reaction mechanism[5]. Because the temperature in the combustion chamber was measured at only a single location, a time/temperature profile within the combustion chamber had to be assumed to make such a comparison. Assuming the temperature decreases from 5000 °F near the injector to the measured value (near the discharge end of the chamber) as a power function of residence time, measured and predicted concentrations of CO at various O_2 concentrations agree quite well. The comparison between predicted and average measured values for three test runs conducted at 56 psia and combustion chamber discharge temperature of 2100 °F are shown in Figure 5.

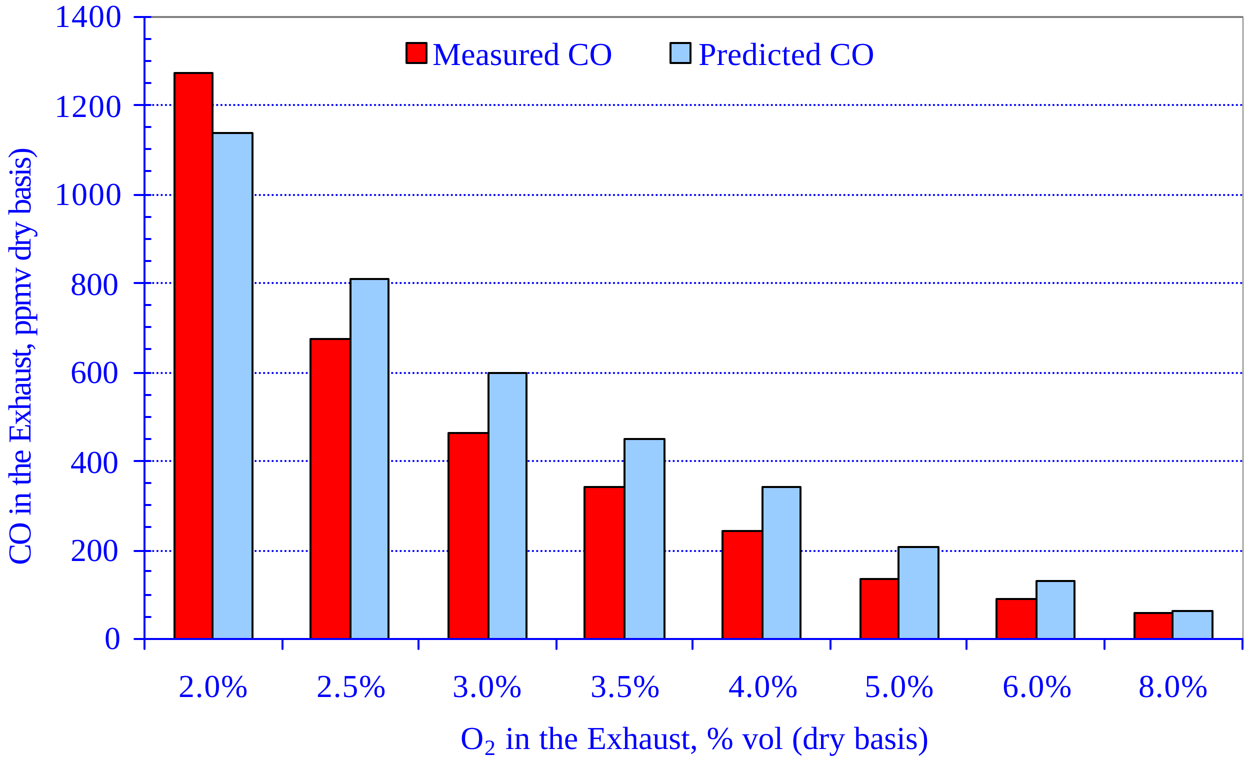

Figure 5. Comparison of Measured and Predicted CO Concentrations in the Exhaust at Nominal Combustion Chamber Operating Conditions of 56 psia and 2100 °F

The comparison in Figure 5 shows general agreement between measured and predicted CO concentrations in the exhaust gases of the gas generator over a range of O_2 concentrations from 2 to 8 % vol. (approximately 1 to 4 % more O_2 than stoichiometrically required for complete combustion). Measured CO concentrations appear to be somewhat higher than predicted values at O_2 concentrations at and below 2 % vol. and somewhat lower at O_2 concentrations above 2 %. The deviation between measurements and predictions are believed to be attributable to deviations between the real gas generator and the analytical model (i.e., well-stirred reactor and assumed time/temperature profile in the combustion chamber) rather than errors in the reaction mechanism or the kinetic data used in the Chemkin II computer model.

Task 6--Technical Reporting

Bi-monthly technical progress reports and a final project are deliverable items under this grant. Bi-monthly reports have previously been delivered and summarized prior major accomplishments and/or deviations from planned progress. This report is the final project report.

Task 7--Administrative Reporting

Bi-monthly financial reports along with invoices for reimbursement of expenses incurred during the bi-monthly periods are deliverable items under this grant. These financial reports have previously been delivered and summarized the expenses by category and explained any major deviations from the planned budget.

Project Outcomes

The intent of this program was to develop a modular laboratory-scale version of a unique gas generator for a non-polluting power plant and to demonstrate its ability to produce a clean, two-species gas composed almost entirely of H_2O (steam) and CO_2. That gas generator was designed, fabricated, and integrated into a versatile test system capable of defining its performance characteristics. Significant outcomes of the program are summarized below:

1. A complete gas generator and test system was built and successfully operated on O_2, CH_4, and D.I. water and is now available for further research and demonstration purposes on other feed stocks.
2. The gas generator operated repeatedly, reliably, and stably:
   - More than 75 starts
   - Total run time of more than 10 hours
   - Individual test durations up to 48 minutes
3. The gas generator operated over a wide range of conditions:
   - Temperatures up to 2700 °F (1480 °C)
   - Pressures up to 300 psia (20 atm)
   - Various mixture ratios near stoichiometric
4. Testing demonstrated that O_2, CH_4, and water can be premixed in accordance with CES's patented claims and achieve repeatable ignitions and stable combustion.
5. The product gases from the gas generator were composed almost entirely of 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.
6. The concentration of CO in the product gases was found to correlate well with predicted values.

A typical set of gas compositions (dry basis) presented in Figure 4 clearly shows that the concentration of CO in the exhaust decreases rapidly with only slight excesses of O_2 over the stoichiometric requirement. Figure 5 shows that the concentration of CO in the dry product gases correlate well with theoretical predictions.

Conclusions and Recommendations

Conclusions

A unique laboratory-scale gas generator that represents an enabling technology for a non-polluting (zero emissions) power plant was designed, built, and successfully operated on O_2, CH_4, and D.I. water. Gas analyses of the reaction products showed that uniform mixing of the O_2 and CH_4, proper control of the O_2/CH_4 mixture ratio, and water-injection-cooling for combustion temperature control followed by staged cool-down promotes re-association of by-products, thereby creating a clean steam/CO_2 gas. Analyses of the test data indicate the Chemkin II computer code and the GRI-MECH 2.11 reaction mechanism provide an adequate model for predicting the combustion and cooldown reactions occurring in the gas generator and the composition of the resulting gas products.

This program experimentally established the "proof-of-principle" for a new method of producing clean high-energy drive gases for the generation of electrical power from fossil fuels. Integration of such a gas generator into a CES power generation system provides a viable, economical approach to zero-emissions power production from virtually any fossil or biomass fuel. Such a system makes the total recovery the CO_2 possible at the lowest cost and in a form suitable for enhanced recovery of oil or coal bed methane or for sequestration.

The successful completion of this program demonstrated the "proof-of-principle" for the enabling component of an electrical generating plant capable of significantly reducing the cost of power for Californians, and makes a major contribution to eliminating both atmospheric pollution and global warming.

Recommendations

This program provided the bench-scale "proof-of-principle" demonstration of a new method of producing clean high-energy drive gases for the generation of non-polluting electrical power using pure O_2 and CH_4. Similar bench-scale demonstrations need to be performed on alternative fuels to assure this new technology can be applied to commercial grades of oxygen with virtually any fossil or biomass fuel. In particular, bench-scale "proof-of-principle" demonstrations should be extended to include the evaluation of the following:

- Commercial grades of oxygen
- Crude and pipeline-quality natural gas
- Landfill gas
- Syngas from oxygen-blown coal gasifiers
- Syngas from oxygen-blown biomass gasifiers

Because CES is a small startup company and industry continues to look at the zero-emissions power generation technology described in this report as very interesting but high risk for lack of a commercial heritage, some governmental funding is required to take this technology to a commercially viable stage. Specifically, the cooperative funding of small (demonstration-scale) zero-emissions power plants that are based on a CES gas generator and power generation scheme is recommended.

The full economic advantage and commercialization of this zero-emissions power generation technology will also require advancements in several other technologies. In particular, reheaters and high pressure, high temperature turbines that can accommodate the full capabilities of CES gas generators need to be developed to increase power plant efficiencies. Similarly, advanced oxygen separation technologies, such as ion transfer membranes (ITM), which show promise for reducing the cost of the oxygen should be pursued vigorously. The cost of oxygen has a significant impact on the economics of this power generation technology by virtue of its large-scale use to burn the fuel and also to make syngas fuel from coal or biomass. The advancement of these supporting technologies is recommended.

Development Stage Assessment

The overall development efforts to commercialize CES's zero-emissions power plant concept is described in Table 1 in terms of the EISG Stages and Gates Process. The work performed under this program, EISG Grant 99-20, specifically addressed the engineering/technical disciplines at Stage 3, Research and Bench Scale Testing, of the critical, enabling component in the system, i.e., the gas generator. The matrix presented in Table 1 and the discussions following, however, are directed toward describing the development status of the overall plant.

Table 1. Zero-Emissions Power Plant Project Development Stage Activity Matrix

	Stages							
Activity	Idea Generation	Technical & Market Analysis	Research	Technology Develop-ment	Product Develop-ment	Demon-stration	Market Transfor-mation	Commer-cialization
Marketing/ Connection to the market								
Engineering/ Technical								
Legal/ Contractual								
E&S Risk Assessment/ Quality Plans								
Strategic								
Production Readiness/ Commercial.								
Public Benefits/ Cost								

Marketing/Connection to the Market

A business plan has been developed and continues to evolve in resolution as the markets, suppliers, strategic partners, sources of venture capital, and customers become increasingly defined. Suppliers of components and/or subsystems other than the gas generator, A&E's, hosts for small scale demonstration plants have been identified and letters of intent to support demonstration efforts have been signed by several potential strategic partners/licensees. The technology has been positively received by both the public and private sectors, as evidenced by grants and co-funding received, and by support given to proposed early phase demonstration projects.

During the past four years, CES has consistently sought by all available means to explain and develop its technology. CES has briefed advanced program and program development personnel in 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, the former FETC now NETL, LLNL, the California Air Resources Board, the California General Services Administration, and the California Energy Commission. Relying on past experience, the industry is encouraging, but the companies would like to see the technology in operation.

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 this prototype is expected to begin in the fourth quarter of this year. Candidate sites for demonstration and field tests have been identified, and term sheets or MOUs are being negotiated with the host facilities. CES has made a proposal to the Energy Commission under RFP #500-00-509 for a 500 kW demonstration project, to be located in Antioch, California. Other potential sites are located in the Los Angeles basin. Test durations of at least two-years are anticipated, to obtain suitable RAMD information.

Legal/Contractual

CES holds exclusive rights for the use of gas generators in zero or low-emission power production through 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. There are currently no sales of CES technology or hardware, so it is not possible to quantify benefits with any precision at this time. Sales forecasts have been prepared and can be used for this purpose. These are available to the Commission for purposes of estimating these benefits.

No other company is known to CES to be developing comparable gas generator technology intended for use in fossil fueled zero emission power plants. Other companies are studying the possibility of entering the market using such technology, but as of this writing, market assessment studies have not been completed and no other company is known to have committed to pursue this technology.

Environmental, Safety, Other Risks Assessments/Quality Plans

Prior to testing of the laboratory-scale gas generator under this project, an extensive failure-mode analysis was conducted, with all project team members participating. Potential deficiencies were identified and corrective action was taken, and the successful outcome of this project is a result in part due to these efforts. Environmental issues are negligible due to the zero-emissions aspect of the technology.

A comprehensive quality plan will need to be prepared during the next stage of development.

Strategic

CES technology fulfills most of the major PIER policy objectives. The gas generator can readily be incorporated in fuel cell hybrid processes. The synergies between the two systems could result in very high power cycle efficiencies. Two power plant concepts that integrate the CES process with solid oxide fuel cells have been identified. In the first process, the SOFC effluent is combined with the discharge stream from the high-pressure steam turbine, heated in a CES reheater and fed to an intermediate pressure turbine. This process recovers waste heat from the SOFC, and can attain an overall cycle efficiency of 64%, including CO_2 sequestration. 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% are possible.

This project complements and builds upon the usefulness of two other related projects – one existing and one proposed. The DOE/NETL-sponsored project that is underway will involve comprehensive testing of a 10MW gas generator. The prototype gas generator subsystem will be well characterized before it is included in the overall power generation process. As mentioned earlier, CES has made a proposal under Energy Commission RFP #500-00-509 for a 500 kW demonstration project. This proposed project will allow more attention to be focused on the operation of the power plant as a whole, and on subsystems such as the steam turbine, condenser, and CO_2 conditioning equipment. This project, the federal program, and the proposal under RFP #500-00-509 effectively represent PIER Stages 3, 4, 5, and 6, representing important coordination and implementation of state, federal, and private sector objectives.

Production Readiness/Commercialization

Extensive industry contacts have been established, and potential licensees of CES technology have been identified. Discussions are currently underway with two large, multinational corporations active in the energy sector. Commitments to license agreements are expected within the next twelve months.

CES is fully capable of manufacturing the enabling technology component – the gas generator. All other components are readily available from the existing equipment suppliers. As part of the proposal under Commission RFP # 500-00-509, CES will prepare a Production Readiness Plan.

Public Benefits/Costs

Economic benefits from CES technology can be categorized as follows:

- Lower Electricity Prices
- Zero Emissions
- Benefits from Integrated Fuel Cell Hybrid Projects
- Distributed Generation Opportunities

Public benefits from lower electricity prices and reduced pollution have been estimated, indicating a public/private allocation of benefits of approximately 89%/11%. A quantitative analysis of the benefits resulting from integrated fuel cell hybrid projects and distributed generation opportunities needs to be prepared.

There are no material changes in the public benefit-cost analysis as a result of this project.

Benefits to California

California has already benefited from this program by showing it is in the forefront of efforts to bring environmentally friendly advanced power generation systems to its citizens. This program represents the very first public support for development of the zero-emissions, fossil-fueled power plants described in the Introduction section of this report.

Presuming the initial success of this program continues and these zero-emissions, fossil-fueled power plants become widely used, California and the world will reap benefit in many areas:

- Advanced power generation technology
- Improvement of cost and availability of California's power
- Improvement of public health and safety
- Invigoration of State and local economies

Advanced Power Generation Technology

The electric power industry in California is faced with at least three critical problems: (1) the cost and availability of electrical power, (2) emission of atmospheric pollutants, and (3) emission of greenhouse gases. CES believes that viable solutions to these problems require new technologies related to power plant design and operation. The CES technology offers ways to improve the cost and availability of electricity in California while eliminating pollution and improving public health. CES technology facilitates the siting of new power plants and re-powering of old power plants. These new or re-powered plants can operate on alternative fossil fuels, the most plentiful and economic source of non-nuclear energy available. CES technology also provides a practical and economic way to separate carbon dioxide for commercial sale or sequestration, and appears to offer the best available control technology for pollution prevention in power generation[6,7].

Improvement of Cost and Availability of California's Power

The cost and availability of electric power is critically important to all Californians. Although the power generation concept described in this report was developed to address critical environmental issues, it also improves cost and availability issues, because they are intimately linked. The CES gas generator is the enabling component in economical, zero-emissions power generation systems.

The CES power systems have several cost-reducing features. The zero-emission feature enables power plants to be sited in clean air non-attainment areas, the plant can be sized to local power needs, it can be made a stand-alone plant or a co-generation plant, and it can use various fossil fuels. When located within or near the using community, as in "distributed generation," transmission and distribution costs are greatly reduced. In most cases, transmission and distribution costs are larger than the generation costs (some times adding 100% of generation costs, or more to the price of electricity being delivered) to California rate payers.

Improvement of Public Health and Safety

The CES technology permits large-scale power generation with zero emissions to the atmosphere at competitive cost. The benefit of no emissions has been well documented and has been reiterated at the 1997 Kyoto Conference in Japan. If the electric power generating plants in the US that reach their planned operational life in five years were replaced by plants based on this new technology, future yearly NO_x emissions would be reduced by 300,000 tons, and CO_2 emissions would be reduced by 85 million tons, thereby reducing health hazards and global warming[8].

All the components of the CES technology package involve well-known commercial technologies and processes. The CES gas generator is designed for reliability and safety, and will equal or exceed the strictest standards for safety. All parts of the CES technology package are known to the industry, except the gas generator which occupies a small fraction of the volume of a boiler producing a comparable volume of steam. An air separation plant is a major part of a zero-emissions power plant. Such plants are, however, already commonly found in cities across the US and have excellent safety records.

Invigoration of State and Local Economies

The commercialization of CES's zero-emissions power plant technology will engender a significant expansion of California's electric power industry. The long-range commercialization of this technology will expand opportunities in the design, engineering, development and manufacturing of equipment for both new plants and for updating and re-powering existing plants. Hardware manufacturing will provide economic activity at local plants, including new enterprises throughout the state. These activities will invigorate the steam turbine industry, and some of the world's largest turbine producers have operating centers in California. For these reasons, CES technology is inherently a technology that will encourage, support, and sustain economic growth in California. These activities will provide jobs, economic stimulation, and tax revenues for both the state and local communities.

Glossary

A&E	Architect and engineer
AC	Alternating current
ASU	Air separation unit
CES	Clean Energy Systems, Inc. (Sacramento, CA)
C	Refers to the chemical element, carbon
C-H	Refers to a chemical bond between carbon and hydrogen
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
D.I.	Deionized [water]
DOE	Department of Energy
EISG	Energy Innovation Small Grant [program]
EOR	Enhanced oil recovery
FETC	Federal Energy Technology Center
FID	Flame ionization detector
H	Refers to the chemical element, hydrogen
H_2O	Liquid water or gaseous water (steam)
I.D.	Inside diameter
IPP	Independent power producer
ITM	Ion transfer membrane
LLNL	Lawrence Livermore National Laboratory
MOU	Memorandum of understanding
MWe	Megawatt, electrical
N_2	Molecular form of nitrogen
NETL	National Energy Technology Laboratory
NO_x	Nitrogen oxides
O	Refers to the chemical element, oxygen
O_2	Molecular form of oxygen
PIER	Public Interest Energy Research [program]
ppm	parts per million
RAMD	Reliability, availability, maintainability, and durability
SMUD	Sacramento Municipal Utility District
SOFC	Solid oxide fuel cell
TCD	Thermal conductivity detector
U.C.	University of California
ZEST	Zero-Emission Steam Technology

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8. Assumes future conventional plants would have an efficiency of 45 % and produce NO_x at 10 ppm.