Tri-Service Power Expo 2003
Norfolk Waterside Marriott
15-17 July 2003

Mobile Propulsion and Fixed Power Production with Near-Zero Atmospheric Emissions

Roger Anderson, Ronald Bischoff
Clean Energy Systems, Inc.

1. ABSTRACT: The US Military needs reliable, secure, and low-environmental impact sources of base and shore power for its installations. US Navy ships need generating systems for main propulsion, on-board power, catapults, heat/air conditioning, and other applications. These needs can be met with a unique, drive-gas generator that produces a high enthalpy mixture of high purity steam and carbon dioxide (CO_2), with little or no nitrogen or sulfur oxides (NO_x, SO_x), volatile organic compounds (VOCs), or particulate material in the effluent. The steam mixture (5-10% CO_2) exits the power cycle as pure water and readily captured CO_2. This system can burn a wide range of fuels with oxygen, and is applicable for fixed and mobile applications. It could be used in fixed-base and shipboard power systems, or be incorporated into improved-efficiency steam power plants.

Base and shore power requirements include reliability, cost-effectiveness, reasonable footprint, and low environmental impact. Naval shipboard needs places value on safety, low life-cycle cost, compact size, ease of maintenance, and efficient use of resources. The proposed gas generator provides efficient steam power that can be used in multiple fixed and mobile applications.

2. BACKGROUND—CES POWER GENERATION PROCESS

The CES system applies well-known aerospace propulsion technology to power generation. The patented CES process for producing near-zero-emissions power from fossil fuels (Figure 1) is based on the near-stoichiometric combustion of a clean gaseous fuel with oxygen in the presence of recycled water to produce a high-temperature, high-pressure turbine drive fluid comprising steam and carbon dioxide. The fuel consists primarily of carbon, hydrogen, and oxygen. It can come from virtually any organic source, including fossil fuels (gaseous, liquid, or solid), biomass, refinery residues, land-fill gases, etc. The main requirement of the fuel is that it be largely cleansed of precursors of priority pollutants (components containing sulfur, nitrogen, mercury, etc.). Raw liquid fuels are generally reformed and cleaned as necessary before being burned. Solid fuels are gasified, normally by reaction with oxygen and steam, and cleaned of particulates and pollutants prior to combustion. The oxygen for combustion is obtained by separating it from air using any of several techniques (cryogenic distillation, vapor pressure swing absorption, ion transfer membranes, etc.). Combustion occurs under carefully controlled conditions which provide a slight excess of oxygen and with water injection to moderate

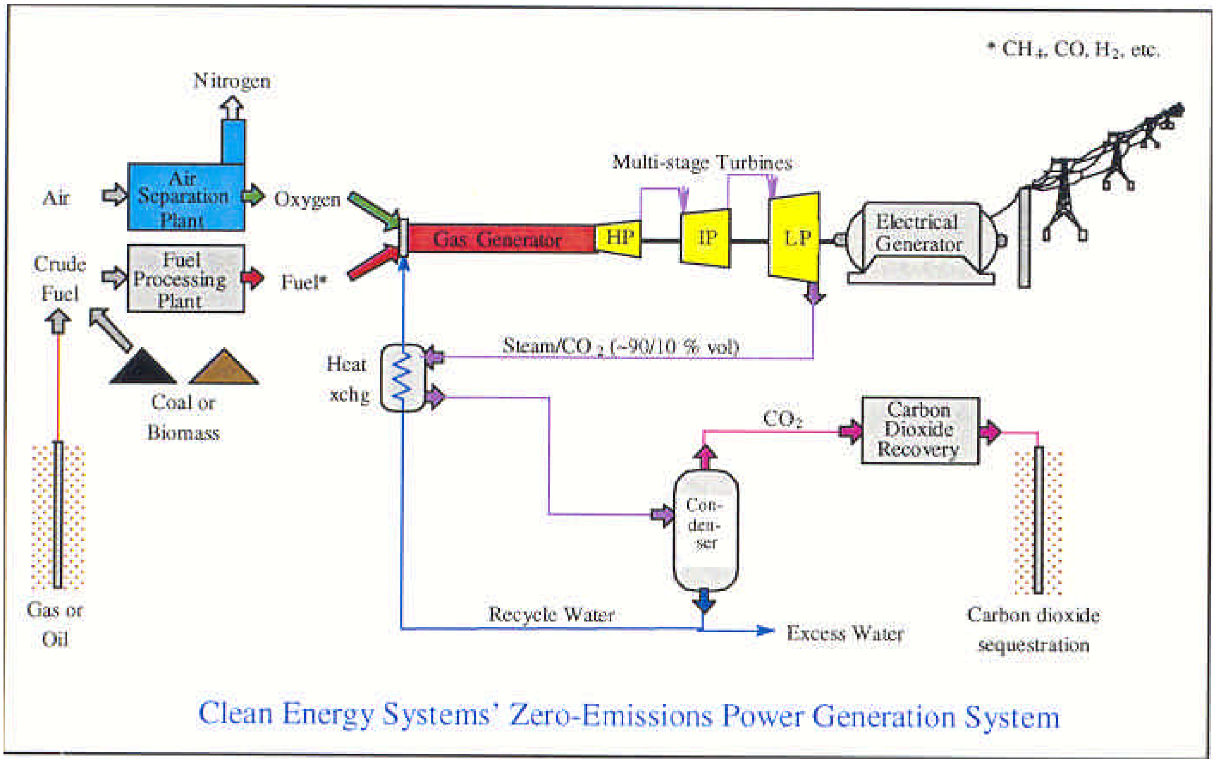
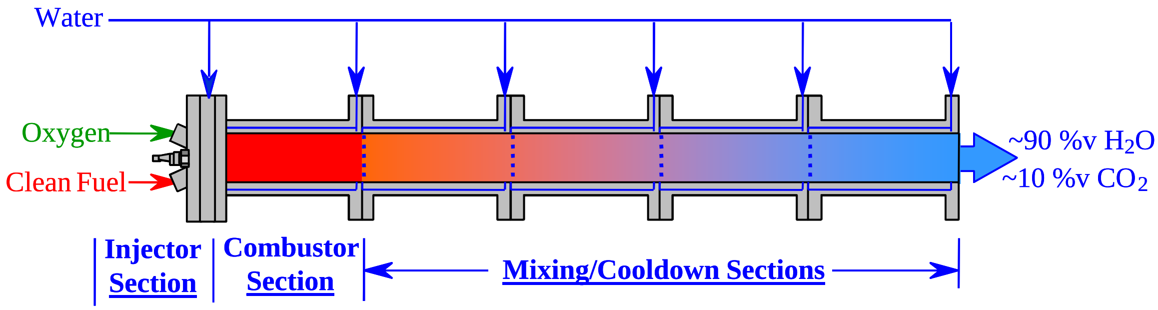


Figure 1

the combustion temperature and minimize the formation of carbon monoxide and VOCs. Additional water is injected in stages to reduce drive gas temperature to a value acceptable to the downstream high-pressure steam turbine. After passing through the high-pressure turbine, the gases can be reheated by direct firing with oxygen and fuel before being directed into intermediate- and low-pressure turbines. After exiting the low-pressure steam turbine, discharge gases are passed through a heat exchanger where residual heat in the turbine exhaust is transferred to de-ionized water prior to its injection into the CES gas generator. The partially-cooled exhaust gases then enter a condenser where water is separated from the carbon dioxide. While most of this high quality water is re-injected into the gas generator, excess water is generated because the process is a net producer of water. The carbon dioxide goes to a recovery system where it is dried and compressed to conditions necessary for shipboard or on-shore use, sequestration, or for direct sales.

Non-Polluting Power Generation Technical System Concept

A key feature of CES technology is that it "prevents pollution" at the front end of the combustion process rather than traditional back-end pollution "clean up". Objectionable pollutants and by-products are avoided by using only clean reactants e.g. clean, light hydrocarbon fuels, syngas from coal or biomass, and oxygen. The enabling element in the CES concept is its unique gas generator (Figure 2) which generates a high enthalpy, two-specie gas composed primarily of steam and carbon dioxide.



CES 10MW Gas Generator (Figure 2)

The gas generator design facilitates near-stoichiometric combustion of gaseous fuel with oxygen in the presence of water. The gas generator consists of an injector section, a combustion section, and a variable number of cool-down sections. The primary function of the injector section, which utilizes advanced platelet injectors based on rocket technology plus an igniter, is to mix oxygen, fuel, and water in precise ratios to yield a combustion temperature that minimizes the formation of VOCs. The injector is internally cooled by the incoming oxygen, fuel, and water.

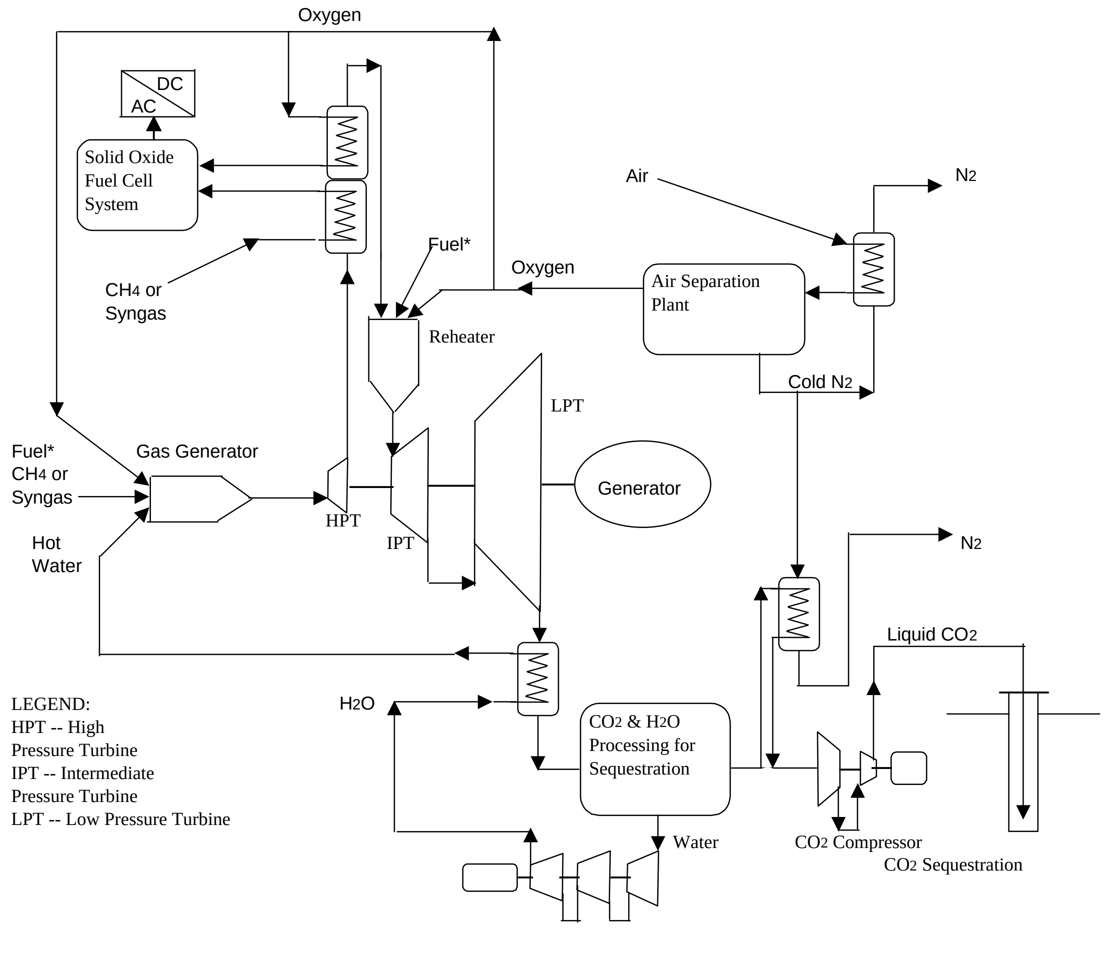
The combustion chamber provides containment of the high-pressure, high-temperature reactive mixture and sufficient residence time for the reactions to approach chemical equilibrium. Generally, combustion pressures range from 1000 to 1500 psia, temperatures near 3000 °F, with the *residence time* of the combustion gases in the combustion section on the order of milliseconds. The walls of the combustion chamber are internally cooled with de-ionized water.

Each cool down section comprises a water injector (referred to as a diluent injector) and a flanged barrel. The diluent injector disperses highly atomized water into the forward end of the section in the quantity necessary to cool gases to a selected temperature. The amount of cooling that occurs in a given section is chosen to optimize the residence time/temperature conditions most favorable for elimination of by-products. The number of cool down sections in a given gas generator is dependent upon the temperature the high pressure turbine can tolerate. The walls of each cool down chamber are internally cooled similar to the combustion chamber.

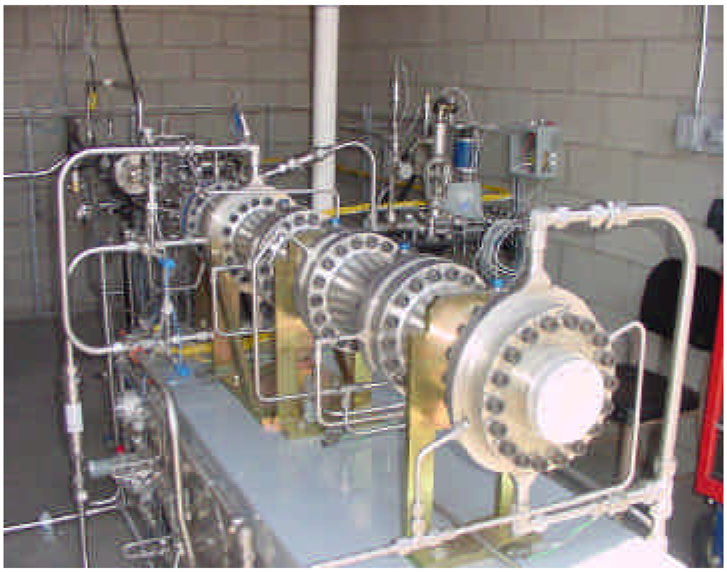
Since the combustion gases directly contact the feed water, steam is produced at temperatures significantly higher than those associated with boilers, which have material limitations at extreme conditions. The production of high enthalpy steam enables the technology to offer cycle efficiencies that exceed those of current Rankine steam cycles or simple cycle gas turbines (30-38%). However, full realization of efficiency benefits (45-55%) will be contingent upon the development of turbines able to utilize the higher temperature drive gas.

Though large aerospace industry investments in gas turbine/jet engine technology have resulted in higher gas turbine operating temperatures via advanced materials and turbine blade cooling techniques, these improvements have not transferred to the steam turbines used in electrical power generation or naval propulsion. The primary impediment has been economic: no previous steam source was able to provide steam above 1200°F in a cost-effective system. In 1995, DOE funded successful development and testing of a steam turbine operating at an inlet temperature of 1500°F[1]. However, this advanced turbine was not transitioned to commercial use because no cost-effective steam source could reach that temperature. The introduction of CES gas generator technology now enables steam/modified gas turbines to be driven at temperatures comparable to those achieved in current gas turbines with corresponding improvements in plant efficiency.

The CES gas generator can be readily adapted to hybrid turbine/fuel cell processes. The synergy between the two systems reaches very high power cycle efficiencies. Figure 3 illustrates a power plant concept that integrates the CES process with solid oxide fuel cells (SOFC). In this process, SOFC effluent is combined with the discharge stream from



Hybrid Turbine/Fuel Cell Power System (Figure 3) the high-pressure steam turbine, heated in a CES reheater, and fed to the intermediate turbine. This process recovers waste heat from the SOFC, and enables the system to attain an overall cycle efficiency near 64%, including CO_2 sequestration and oxygen plant power requirements (Figure 3). CES gas generator experience encompasses three projects. The first project[2] constituted a proof-of-principle hardware demonstration of the CES gas generator. The program demonstrated fuel-oxygen-water mixing with more than 75 starts on command. The gas generator displayed stable operation and effective drive gas specie control and validated computer models of gas composition behavior. The second, a DOE/NETL-sponsored project[3], involved comprehensive testing of a 10MW gas generator (Figure 4) and



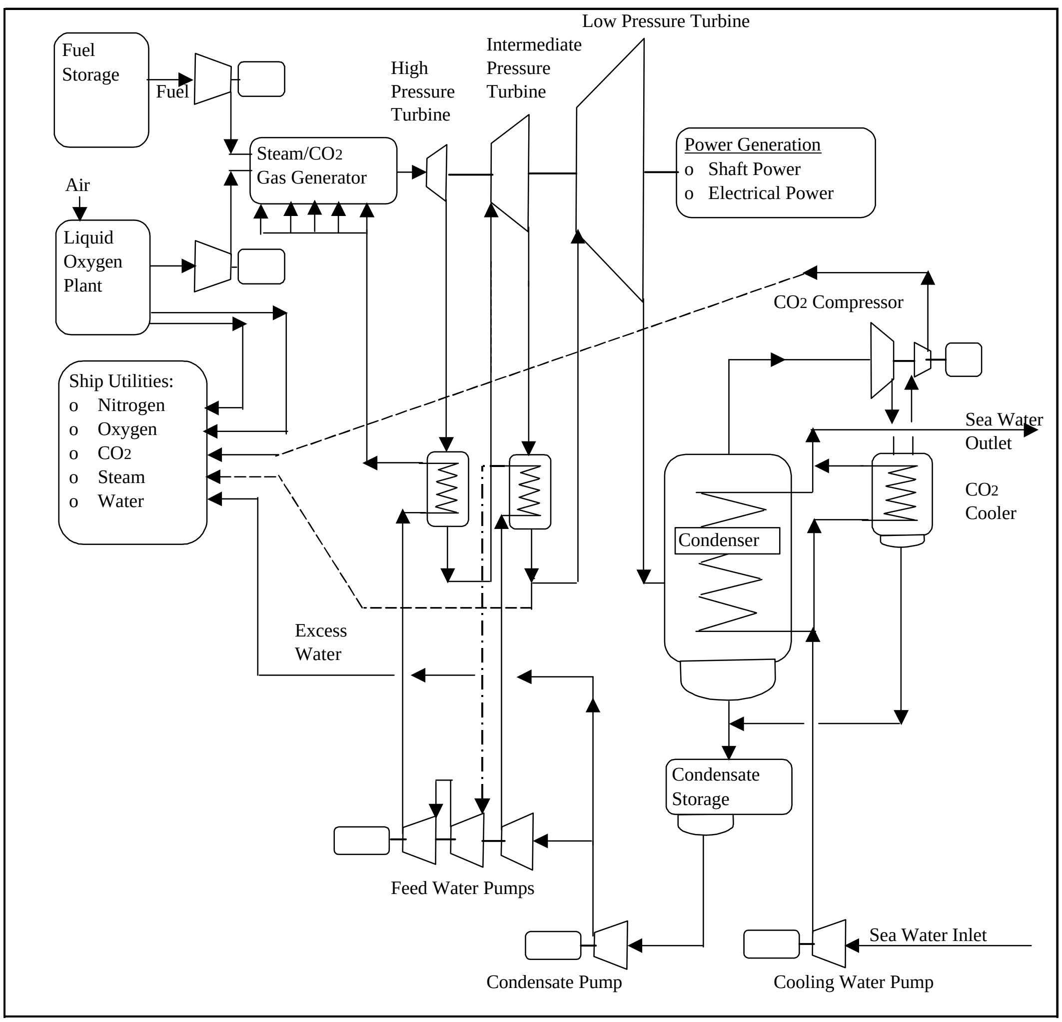
10 MW Gas Generator (Figure 4)

emphasized controlled startup and shutdown as well as sustained operations. The third project utilizes a CES gas generator driving a small (0.5 MW), high-pressure naval turbo-generator as part of a two-year zero-emission power plant demonstration. The extended demonstration will emphasize gas generator reliability and durability. It will also focus specific attention on power plant subsystems including the digital control system, steam turbine, condenser, and CO_2 conditioning equipment.

3. NAVAL APPLICATIONS

The CES gas generator system design enables it to operate synergistically with mobile naval needs. In addition to generating electrical power for ship systems and propulsion, the combustion products from the gas generator—pure water and carbon dioxide—can be utilized as on-board consumables: excess water production can readily used for drinking, cooking, or cleaning while the carbon dioxide is useful for fire suppression, fuel tank inerting, acoustic signature reduction via compressed gas injection along the water line/propellers, and shelf-life extension of refrigerated foods. In addition, the system design eliminates the main contributor to a ship's thermal signature—hot stack gases. All the “exhaust” effluent from the CES gas generator (steam and CO_2) is cooled within the condenser and excess constituents (water/CO_2) is pumped overboard at temperatures near that of ambient sea water.

Oxygen required for gas generator operations is produced onboard by liquefaction equipment (an Air Separation Unit or ASU) upon demand, thus minimizing high-volume oxygen storage needs and attendant safety concerns. The integral ASUs provide useful by-products (e.g. oxygen, nitrogen) that can supply existing shipboard needs and thus reduce/eliminate support system and replenishment requirements. For example, oxygen is needed for medical, fire fighting, and aircrew use and nitrogen is utilized for fire suppression. Pressured CO_2 is produced by the on-board CO_2 extraction system and can supplant shipboard compressed air uses such as injection for acoustic signature suppression. This would eliminate the need for most air compressors. Figure 5 portrays a typical shipboard installation.



Naval Process Schematic (Figure 6)

The compact size of the CES gas generator and the elimination of stack-gases simplify ship design and construction. Its reduced power plant footprint helps offset Air Separation Unit space requirements and enables space reallocation for stores, equipment or personnel. Elimination of stack gases improves shipboard helicopter operations (improved flight visibility, less turbulence) and neutralizes the primary source of the ship's infrared signature.

A comparison of this high enthalpy generator versus a typical gas turbine power plant is shown in Table 1, below. The thermal efficiency of the CES system includes the power necessary to drive the ASU. A typical Navy configuration would be self-sufficient, provide a high power density, deliver efficient fuel consumption, avoid air pollution, and eliminate the ship's main thermal signature.

Table 1: Ship's Power Plant Performance Comparison

Plant Efficiency Level	**LM-2500 Gas Turbine**	**CES Power Plant**
Net Thermal Efficiency	**37.5** %	**45.9** %
Assumptions:	*(Simple Cycle)*	*(3-Turbine Stages)*
Turbine Inlet Pressure (psia)	275	1,200, 275, 15
Turbine Outlet Pressure (psia)	14.7	0.68
Turbine Inlet Temperature (°F)	2,300	1,200, 2,300, 1247
Turbine Efficiency (%)	91 %	90, 91, 92 %
Generator Efficiency (%)	98 %	98 %
Pump/Compresser Efficiency (%)	n/a	85 %

Need to assess size vs. efficiency trade-offs

3. FIXED-BASE APPLICATIONS

Commercial power supplies for US military installations in the continental United States and abroad are now being studied for means to improve supply security and reliability in light of rapidly evolving external security threats. Several long-term solutions involve the addition of power generation facilities at on-site locations. While on-site power generation simplifies security and reliability concerns, these alternatives must address plant efficiency and environmental concerns. Additional factors will include plant footprint, air and water quality impacts, and (potentially) CO_2 disposal.

The CES power generation system offers intrinsic advantages for improving the security of base and shore power. Environmentally, the closed CES system requires no make-up feed water since the GG is a net producer of high quality water. Perhaps most importantly, the CES system produces no atmospheric emissions, a factor in *non-attainment* air districts.

The small size of the GG may reduce plant footprint. The GG can burn virtually any gaseous or liquid fuel, improving supply flexibility. Its CO_2 removal system efficiently and economically separates CO_2 during condenser operations. The condenser can also be air cooled if cooling water is limited at land-based power plant sites.

Oxygen required for GG operations is produced on-site by air separation unit (ASU) liquefaction equipment on a demand basis. The latter reduces local oxygen storage needs. The ASU can also provide a ready source of nitrogen, argon, and oxygen, if needed locally. Projected cost per kilowatt/hr are listed in Table 2.

Table 2: Projected kWHr Costs

Plant Operating Factors	**Current CES 50 MW**	**Near-Term CES 50 MW**
Overall Plant Efficiency	33%	48%
ASU Plant Size (metric tons/day)	1,080	720
Capital Cost ($/kW)	2,000	1,575
Natural Gas Cost ($/ MM Btu)	$3.00	$3.00
NO_x Emissions	None	None
CO_2 Emissions	None	None
Gross Electricity Cost ($/MWhr)	0.067	0.050
Note: CES plants include cost of ASU and CO_2 capture		

Conclusion

The zero emission characteristics of CES power generation system create a very attractive method for clean power generation, especially in environmentally sensitive areas. Electricity costs are already competitive with today's renewable energy systems, and costs are expected to be competitive with large combined cycle gas turbine plants as plant sizes increase and advanced steam turbines become available. Carbon dioxide can be economically captured for sequestration or industrial uses.

[1] Duffy, T., Schneider, P., “1500ºF Steam Plant for Industrial Cogeneration Prototype Development Tests”, Final Report Phase III, SR94-R-5527-101, under DOE contract DE-AC02-87CD40812, January 1996.

[2] Anderson, R., Baxter, E., “Development of a Unique Gas Generator for a Non-Polluting Power Plant,” EISG Final Report, EISG 99-20, under California Energy Commission Public Interest Energy Research (PIER) grant 99-20, 1 May 2001.

[3] Anderson, R., Baxter, E., Doyle, S. “Fabricate and Test an Advanced Non-Polluting Turbine Drive Gas Generator,” Final Report, under DE Cooperative Agreement No. DE-FC26-00NT 40804, 1 September 2000 to 1 June 2003.