"A Demonstrated 20 MW_t Gas Generator for a Clean Steam Power Plant."

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ABSTRACT

Clean Energy Systems (CES), of Sacramento CA, has developed and demonstrated a technology which will enable construction and operation of efficient, zero emission power plants. The enabling technology has been tested under a Vision 21 program, cofunded with DOE/NETL. The CES gas generator, combined with a modern gasification technology and current turbine technology, will make possible zero atmospheric emission operation of coal fired power plants at costs comparable to IGCC plants with partial carbon sequestration. To maximize the efficiency of plants using the CES technology it is necessary to bring into service new, higher temperature steam turbines. In addition to explaining the basic CES generating concept, this paper presents the accumulated test results and performance evaluations of the gas generator tested under the Vision 21 program. Also included are examples of applications of the new technology, in conjunction with high performance steam turbines, resulting in substantially higher plant efficiencies. Plant economics and net plant efficiencies for various configurations in the Near Term (5 years) and the Long Term (10 years) are presented in comparison with combined cycle plants of similar output.

THE CES PROCESS

Clean Energy Systems, Inc. (CES) has developed zero-emission fossil-fueled power generation technology, integrating proven aerospace technology into conventional power systems. The core of CES' process involves replacing steam boilers and flue gas cleaning systems with "gas generator" technology adapted from rocket engines. The gas generator burns a combination of oxygen and any gaseous hydrocarbon fuel to produce a mixed gas of steam and carbon dioxide (CO_2) at high temperature and pressure, which can power conventional or advanced steam turbines. A simplified schematic diagram of the process is shown in Figure 1.

Efficiencies higher than any current or planned power systems are obtainable for utility-sized power plants. The gas generator can operate on a range of fuels including natural gas, syngas from coal or biomass, or methane from landfills, and the cycle is a net producer of water, most of which is recycled to the combustor.

From the turbines, the exhaust gas enters a condenser/separator where the drive gas is cooled, separating into its components, water and CO_2, with the CO_2 either sold or sequestered. The gas generator technology has been used successfully in aerospace applications for decades, including in the Space Shuttle main engines, where hydrogen and oxygen are combusted to produce steam at high temperature 1089 K (1500 °F) and pressure 34.48 MPa (5000 psia). Likewise, high-temperature 1700 K (2600 °F), moderate-pressure turbines 2.76 MPa (400 psia) have been used successfully in aerospace applications. Every other component in the CES process is commercially proven and is standard in power generation or other industries.

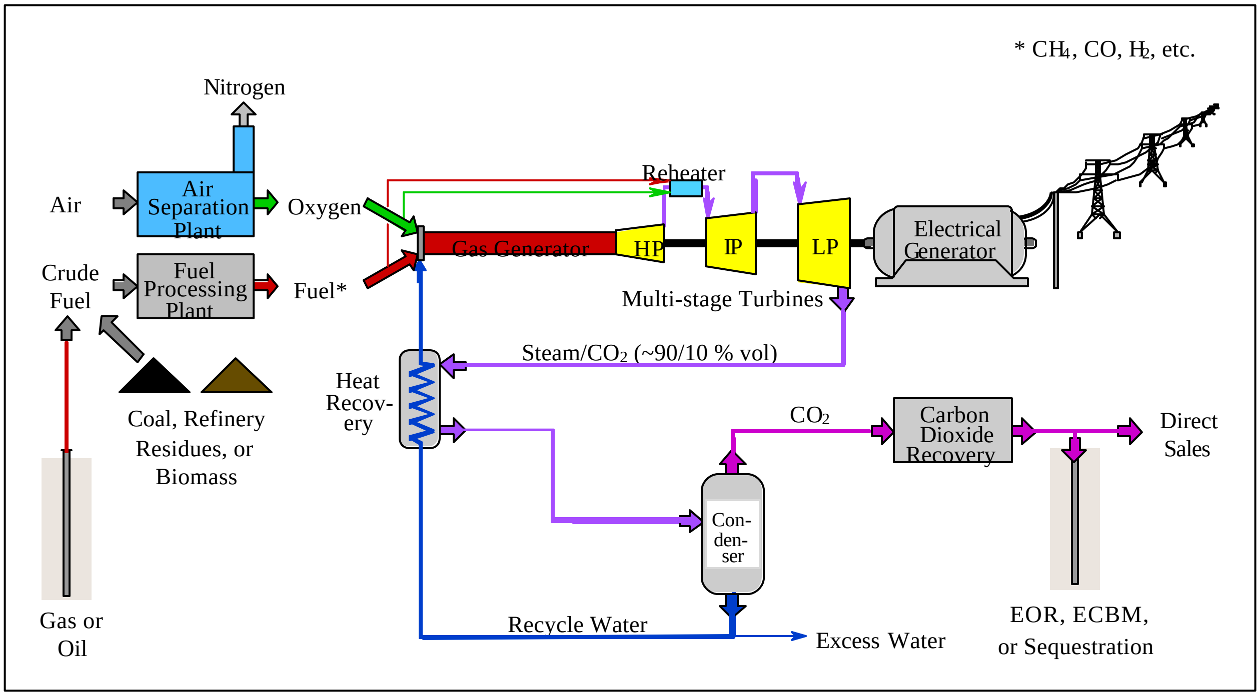

Figure 1. The CES Process

CES' innovation has been to apply gas generators and high-temperature, high-pressure turbines from aerospace applications to power generation, much like the process by which aircraft jet engines were adapted for aero-derivative gas turbines in conventional power plants.

CES technology works with today's turbines to produce power without pollution. The first generation power plants, which could be on-line by 2005, will have energy cost structures below those of other clean energy sources, such as wind and solar power. Since the CES process will be less efficient than conventional combined-cycle plants until the commercial availability of higher-temperature, higher-pressure steam turbines, the company will initially target markets where a premium is placed on clean energy. With the introduction of advanced turbines (which have been held back by historical boiler steam temperature constraints), it is expected that power plants based on CES technology will operate at efficiencies above those achievable with combined cycle plants. At the same time, CES power plants would capture and compress the CO_2 to sequestration conditions.

There are no exhaust gases to be cleaned, and no emissions of sulfur oxides, nitrogen oxides, or other pollutants. On a long-term basis, power plants based on CES technology, including all costs associated with obtaining oxygen, will be cost-competitive with comparable combined-cycle technology. In re-powering situations, the CES gas generator could replace an historical boiler, add to the efficiency of a plant, and eliminate the emission of regulated pollutants.

THE DEVELOPMENT PATH

In 1999 the California Energy Commission awarded to CES an Energy Innovation Small Grant (EISG Grant 99-20) to assist in the construction of a laboratory-scale gas generator capable of demonstrating the intended operations. Under the EISG program, CES built a test bench and operated a lab-scale gas generator at temperatures up to 1756 K (2700 °F) and pressures up to 2.07 MPa (300 psia). The gas generator operated repeatedly, reliably, and stably during more than 75 starts, with individual test durations up to 48 minutes. 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.

In September 2000, the DOE/NETL awarded CES a jointly funded program under the Vision 21 Program to fabricate and test a 20 MW_t ($10MW_e$) gas generator. This program produced a utility scale gas generator which was tested at National Technical Systems in Santa Clarita CA, during 2002 and early 2003. The program goals are to demonstrate a non-polluting gas generator at temperatures up to 1922 K (3000 °F) at 10.34 MPa (1500 psia), and to demonstrate resulting drive gas composition comprising steam and carbon dioxide, that is substantially free of pollutants. The principal objectives called out in the agreement of this program were to design, fabricate and test a prototype gas generator to demonstrate the non-polluting aspects of the concept, evaluate performance, and verify operational characteristics.

The test unit has a nominal size of 10MWe (1361 kg/hr (3,000 lb/hr) of methane). The prototype has been built and tested. It burned methane with oxygen, and deionized water was used to cool the combustor, produce the drive gas, and control the exhaust gas temperature. Parametric data was collected to characterize the operational performance, and gas samples are being taken to determine exhaust gas composition. Post-test inspection and assessment of the device will be conducted to assess any material degradation characteristics. At this writing the test unit was in the final phase of testing.

THE 20 MW GAS GENERATOR TEST RESULTS

The NETL/CES Gas Generator program has proceeded through design, fabrication, and testing. Testing of the complete gas generator began in September 2002 at National Technical Services' facilities in Santa Clarita, CA. It is expected that the final extended-duration testing, with gas sampling, will be concluded during February 2003, and a Final Report will be available by mid-2003. At the time of this writing, all the stated objectives of the program had been attained except for the capture and analysis of gas samples during steady-state operation. The igniter for the gas generator had been previously tested successfully at Aerojet–General facilities in Sacramento CA, during the period of September-October 2001. Testing of the 20 MW_t gas generator was performed, with only minor adjustments, in accordance with the DOE program approved Test Plan dated August 2001.

A summary of the planned tests versus those completed as of November 2002 is shown in matrix form in Table I. The upper portion of the table is relevant to component and assemblies and non-firing tests only except for the igniter. The components and assemblies tested include:

(1) the igniter,
(2) igniter/main injector assemblies,
(3) cooldown chamber/diluent injector assemblies, and
(4) main injector/combustion chamber assemblies.

The types of tests conducted on most of these components or assemblies included:

(1) static proof tests to pressures near 20.69 MPa (3000 psia),
(2) leak tests using gaseous nitrogen,
(3) flow calibration of contained flow circuits to define flow rates versus differential pressures using fluids O_2, CH_4 (methane), or H_2O, as appropriate,
(4) valve timing tests to establish the times from actuation signals to the achievement of prescribed pressure or flow responses at downstream points,
(5) pattern checks of the various injectors to assure they produce the desired distributions of the fluids, and
(6) hot-fire testing of the stand-alone igniter at Aerojet

Table I shows that all planned tests of components and subassemblies are completed. The component and assembly test results were satisfactory and the hardware was deemed acceptable for hot-fire testing. The lower portion of Table I is relevant to the various gas generator configurations and the various types of hot-fire tests planned and completed as of November 2002. Gas generator configurations planned for testing include:

(1) the uncooled copper chamber with injector design “A,”
(2) the uncooled copper chamber with injector design “B,”
(3) fully cooled gas generator with injector “A,” and
(4) fully cooled gas generator with injector “B.”

The types of hot-fire tests conducted on these configurations of the gas generator included:

(1) tests of the igniter only installed within the combustion chamber,
(2) low-fire (nominal 20 % of rated full power) gas generator tests,
(3) high-fire, full power (~ 20 MW_t) gas generator tests of various durations:
    (a) short duration (up to ~ 10 sec),
    (b) extended durations (up to ~ 1 min.),
    (c) extended duration with gas sampling (up to ~ 5 min.)

It can be observed from the lower portion of Table I that all but four of the originally planned sets of hot-fire test have been completed (those not done are shown by open blocks). Three of those four “open blocks” relate to tests of the fully cooled chamber with injector “B” and are no longer applicable. In the course of three tests of the uncooled copper chamber with the injector “B”, extensive damage to the injector was observed and as a consequence injector “B” was judged to be an unsuitable design, unfit for further testing. Thus, the only tests remaining to be completed as of November 2002 were extended duration hot-fire testing with gas sampling on the fully cooled gas generator with injector “A”. The program testing as of November 2002 was considered to be at least 90 % complete, as described in the following section.

SUMMARY OF GAS GENERATOR TESTS AND SIGNIFICANT RESULTS/FINDINGS

A summary of all 20 MW_t gas generator testing through November 2002 is presented in Table II. That summary describes the types of tests conducted, the number of valid tests in each category, the accumulative test time and maximum test duration (where applicable), and the corresponding significant results and/or findings derived from those tests. Tests demonstrated that the igniter operates successfully over the prescribed ranges of pressure and mixture ratios, is repeatable, and reliable through more than 80 ignitions. Injector “A” has been operated successfully at both low power (~ 20 % of rated power) and at rated power (~ 20 MW_t) in more than 40 valid tests and

Table I
Summary of 20 MW$_t$ Gas Generator Test Program

Component and Assembly Tests

Component or Assembly	Proof Tests		Leak Tests		Flow Calibration		Valve Timing		Pattern Checks		Hot Fire Tests	
	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd
Igniter	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA	Yes	Yes
Igniter/Main Injector Assemblies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA
Cooldown Cham./Diluent Inj. Assemblies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA
Main Inj./Comb. Chamber Assemblies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA	No	NA

Gas Generator Hot-Fire Tests

Gas Generator Configuration	Igniter Only		Low-Fire Tests[1]		High-Fire Tests[2]					
					Short Duration		Extended Duration		With Gas Sampling	
	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd	Plan'd	Cmplt'd
Uncooled Copper Chamber with Injector "A"	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA
Uncooled Copper Chamber with Injector "B"	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	NA
Fully Cooled Gas Generator with Injector "A"	No	NA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Fully Cooled Gas Generator with Injector "B"	No	NA	Yes		Yes		Yes		No	NA

[1] Operation at a nominal 20 % of rated, full power (~ 4 MW$_t$) on O_2, CH_4, and water.

[2] Operation at rated, full power (~20 MW$_t$) on O_2, CH_4, and water.

200 sec. of accumulative operation. Injector “B” was tested but exhibited extensive damage after only two low-fire and one high-fire tests and ~ 10 sec. of operation. This indicates that injector “B” is an unacceptable design. The uncooled gas generator configuration (no diluent injectors or cooldown chambers installed) has produced drive gases at temperatures in excess of 1922 K (3000 °F) and greater than 10.69 MPa (1550 psia). The fully cooled gas generator configuration with cooldown chambers and injector “A” operated continuously for more than 60 sec at pressures in the range from 7.59 MPa (1100) to 10.62 MPa (1540 psia) and produced drive gases with temperatures as low as 589 K (600 °F). These tests demonstrated the gas generator to be capable of producing steam-rich turbine drive gases at very high pressures and at temperatures ranging from a high of greater than 1922 K (3000 °F) to as low as 589 K (600 °F).

The testing revealed the need to modify the gas generator to separate the water-cooling and water-injection circuits to the combustion chamber and thereby better assure positive water-cooling of all components exposed to the combustion gases during the critical start transient. Relatively minor hardware modifications to accomplish the separation of water-cooling and water-injection circuits were implemented in December 2002.

Detailed analysis of gas generator test data will not be completed until several weeks following the final phase of testing of the modified gas generator. Preliminary evaluations of the data obtained through November 2002 have, yielded the significant results itemized in Table II.

Data from a typical extended-duration firing of the gas generator (Run # 56, 10/2/02) with an uncooled copper chamber and injector “A” indicated that the gas generator, operated in the low-fire condition (20 % of rated full power) for approximately 1 sec., then ramped rapidly and smoothly to full power and a very stable operating pressure of 10.79 MPa (1564 psia). The calculated gas temperature was 1867 K (2900 °F). The test was conducted essentially at stoichiometric ratio to form H_2O and CO_2 (O_2 to CH_4 equivalence ratio of 1.003). The gas generation rate was 14,966 kg/hr (33,000 lb/hr) at 10.79 MPa (1564 psia) and 1867 K (2900 °F) or 18.6 MW_t LHV.

Data from a typical extended-duration firing of the gas generator (Run # 115, 11/5/02) with a cooled chamber and injector “A,” and four cooldown chambers with diluent injectors, indicated that when this gas generator configuration operated in the low-fire condition (approximately 20 % of rated full power) for approximately 1 sec., then ramped rapidly and smoothly to full power, the steady-state operating pressure was 9.62 MPa (1395 psia) and produced drive gases at 933 K (1220 °F) near the exit of the third cooldown chamber and 853 K (1075 °F) near the exit of the last (fourth) cooldown chamber. The test was conducted slightly above the stoichiometric ratio to form H_2O and CO_2 (O_2 to CH_4 equivalence ratio of 1.03). The gas generation rate was 23,583 kg/hr (52,000 lb/hr) at 9.62 MPa (1395 psia) and 853 K (1075 °F) or 18.5 MW_t LHV. CES expects to complete testing of the 20 MW_t gas generator in February 2003. Results of the final phase of testing will be reported with the presentation of this paper at the Clearwater Conference.

Table II
Summary of 20 MW_t Gas Generator Tests Through November 2002

Type of Test	Valid Tests	Accumu. Time, sec.	Max. Dur.,sec.	Significant Results/Findings
Tests Conducted at Aerojet				
Igniter only	17	130	25	Demonstrated satisfactory operation over prescribed ranges of pressures and mixture ratios
Tests Conducted at NTS				
Leak tests	2	NA	NA	Assembled complete gas generator (two configurations) and passed leak tests
Water flow tests	7	NA	NA	Measured flow rates versus ΔP's to define orifice sizes to properly balance flow circuits
CH_4 flow tests	4	NA	NA	Measured flow rates versus ΔP's to define restrictors to properly balance flow circuits
O_2 flow tests	2	NA	NA	Measured flow rates versus ΔP's to define restrictors to properly balance flow circuits
Valve timing	7	NA	NA	Measured valve actuation and line fill times to define appropriate valve sequencing
Igniter in GG	5[1]	35	7	Demonstrated repeatable operation in assembled gas generator at NTS test facility
Uncooled Chamber with Injector "A"				
Low-fire tests	5	8	3.4	Demonstrated successful main chamber ignition and combustion at 20 % of full power
Full power tests	8	22	7.4	Demonstrated full power gas generator operation at rated pressure (≥ 1550 psia)
Uncooled Chamber with Injector "B"				
Low-fire tests	2	8.2	4.1	Demonstrated successful main chamber ignition and combustion at 20 % of full power
Full power tests	1	1.8	1.8	Successful operation at full power and pressure but injector suffered damage
Cooled Chamber with Injector "A"				
Low-fire tests	14[2]	8.3	0.9	Demonstrated successful main chamber ignition and combustion at 20 % of full power
Full power tests	27	158[3]	62	Demonstrated full power gas generator operation at pressures of 1100 to 1540 psia

[1] 21 additional prior tests (10 ignitions and 11 non-ignitions) were required to detect, find, and resolve a facility problem, a failed diaphragm in a fuel pressure regulator.

[2] An additional 27 “low-fire” test operations accompanied the 27 full-power tests.

[3] An additional 27 sec of "low-fire" operation was coincident with the 27 full-power tests.

APPLICATION OF CES TECHNOLOGY IN COAL POWER PLANTS

Currently and for the near future, coal provides a substantial portion of the world's supply of electric energy. Pollution from coal-fired power plants is a pressing environmental problem and the emission of carbon dioxide is of increasing concern in regard to global warming. The CES technology allows economical production of electricity from virtually any gaseous fossil, or biomass fuel with zero atmospheric emissions. The CES approach, which was described in detail in this forum last year,[1] involves oxygen-blown gasification of coal. The resulting gaseous syngas is cleaned of corrosive components and burned with oxygen in the presence of recycled water in a gas generator. The combustion produces the drive gas composed almost entirely of steam and CO_2. This gas drives turbines/electric generators to produce electricity. The turbine discharge gases pass to a condenser where water is captured as liquid and gaseous CO_2 is pumped from the system. The CO_2 can be economically conditioned for enhanced recovery of oil or coal-bed methane, or for sequestration in a subterranean formation.

The performance and cost of the power plants described in this paper are based on the use of syngas obtained from Illinois No.6 coal using a Texaco gasification process. The composition of this syngas is described in Table III.[2]

Table III
Composition of Syngas Derived from Illinois No. 6 Coal, after Sulfur Removal, Using Texaco Gasification Process

Constituent	Mole %, dry basis after sulfur removal	Constituent	Mole %, dry basis after sulfur removal
CO	47.9	CH_4	0.1
H_2	36.9	N_2 + Ar	1.9
CO_2	13.1	NH_3 + HCN	0.1

For a 400 MW_e plant, three gas generators, each with a thermal output of 400 MW_t, would be used. The three gas generators would be installed in parallel. Two of the gas generators would drive the turbines of the plant while the third gas generator would provide a spare during service of the other units. A gas generator with 400 MW_e output operating at a pressure of 10.3 MPa (1500 psia) has an internal diameter of 0.46 m (18 in.) and a length of 1.88 m (6 ft).

In such a plant, a gasifier converts coal to syngas at a rate of 67.7 kg/sec (149.3 lb/sec) while a 60.0 MW_e cryogenic air separation plant produces oxygen for both the gasifier and the gas generator. Two gas streams (syngas and oxygen) enter the gas generator at a pressure of 12.76 MPa (1850 psia) where they are joined by 117.7 kg/sec (259.5 lb/sec) of steam. The syngas from the gasification plant is combusted with oxygen in the gas generator. The combustion products are cooled in steps by adding water until the gas temperature is at the allowable high-temperature turbine inlet temperature of 922 K (1200 °F) to 1256 K (1800 °F). The turbine drive gas leaving the high-pressure turbine is reheated before it enters the intermediate-pressure turbine. A prototype reheater for a CES plant has been designed, fabricated and tested by the U.S. Department of Energy.[3] Further testing of that unit is planned by NETL. Table IV presents the operating conditions for turbines in the anticipated time period of the emerging technologies.

Table IV
Operating Conditions of Turbines for Various Technologies

Turbine technology	**Current technology**	**Near-term (5yr) technology**	**Advanced (10 yr) technology**
Inlet conditions	Press. - Temp., MPa - K	Press. - Temp., MPa - K	Press. - Temp., MPa - K
High-press. turbine	10.34 - 922	10.34 - 1089	10.34 - 1089
Interm.-press. turbine	2.62 - 839	2.62 - 1700	2.62 - 1922
Low-press. turbine	0.31 - 839	0.31 - 1700	0.31 - 1922
Plant efficiency (no syngas plant losses)	40%	56%	60%
Plant efficiency (with syngas plant loss)	32%	48%	53%

The intermediate-pressure turbine exhaust gases are delivered to the low-pressure turbine. The exhaust from the low-pressure turbine is cooled in a feed water heater to the desired condenser inlet temperature. The heated feed water is delivered to the gas generator for use as a coolant to reduce the temperature of the turbine drive gas as described above. The turbine exhaust gases which, by weight, contain approximately 61 % steam, 39 % CO_2, 0.45 % nitrogen and small amounts of oxygen and non-condensables, are cooled in the condenser with 288 K (59 °F) cooling water. In the condenser, the steam condenses at approximately 300 K (80 °F**)** and at 0.0043 MPa (0.62 psia). There is still moisture in the CO_2 stream that does not separate without compression and further cooling.

The mixture of approximately 80% CO_2 and 20% steam, by weight, is then pumped from the condenser using centrifugal compressors and is cooled in stages to remove the remaining water prior to final compression to the injection pressure. The compressed CO_2 is then pumped to a pressure typically ranging from 10.00 MPa to 24.82 MPa (1450 to 3600 psia) for sequestration into subterranean oil strata, coal seams, or aquifers.

The overall plant efficiency is based on several technologies that will be discussed in more detail in the next section of this paper, related primarily to the development of steam turbines that operate at higher temperatures than current steam turbines, and to the reduction of the air separation plant capital costs and power consumption. The turbine operating pressures and temperatures of CES plants at various development stages are shown in Table IV, while the performance characteristics and efficiencies for CES plants and combined cycle plants are listed in Table V.

The advanced air separation technology uses ion transfer membranes (ITM). This technology is projected to have lower capital costs and lower power consumption than those of current cryogenic plants. It is expected that ITM plants will have a capital cost of 73 to 85 % of the cost of cryogenic plants and power requirements that range from 55 to 70% of cryogenic plants.[4] These modest improvements were not included in this study. However, the use of ITMs could reduce the cost of electricity by about 4% for combined cycles and 8% for CES plants.

In Table V, the CES power plants produce no atmospheric emissions, while the combined cycle, plant with efficiency of 46% has no exhaust gas control and the other combined cycle plants has partial exhaust gas sequestration.

Table V
Comparative Electricity Cost for 400 MW$_e$ Plants Using Syngas,
and Operating on CES and Combined Cycle Technologies

Plant Operating Factors	**CES**[5]			**Combined Cycle**[6,7]	
Turbine Technology	***Current***	***Near-Term***	***Advanced***	***Current Technology***	
Plant Thermal efficiency, (With Syngas Plant)	32	48	53	46	37
ASU plant type	Cryo	Cryo	Cryo	Cryo	Cryo
ASU Plant Size - Metric Ton/Day	8774	5849	5297	2118	2633
Capital Cost - US$/kWe	1872	1412	1318	1457	1865
Coal cost - US$/GJ (LHV)	1.19			1.19	
Emissions of NO_x - kg/MWhe	0.00			0.03	0.04
Emissions of CO_2 - kg/MWh	***0.00***			***745***	***139***
	Unit Costs, $				
Capital Unit Cost - $/kWh	0.040	0.030	0.028	0.031	0.040
Fuel Cost - $/kWh	0.013	0.009	0.008	0.009	0.012
Maintenance Cost - $/KWh	0.008	0.006	0.005	0.006	0.008
Cost of Electricity - $/kWh	***0.061***	***0.045***	***0.041***	***0.046***	***0.060***
CO_2 Sequest. Cost - $/Metric Ton	***6.3***	***4.6***	***4.2***	***None***	***29.1***
Carbon Seq. Cost - $/Metric Ton	***23.2***	***17.0***	***15.5***	***None***	***107***

The CES near-term plant technology is expected to become commercially available in less than one decade. When this technology is available, the cost of electricity of a CES plant with ***full*** exhaust gas sequestration is comparable to the cost of electricity of a combined cycle plant with ***no*** exhaust gas sequestration. Table V shows that the cost of sequestration per metric ton of CO_2 in CES plants, ranges from $4.2 to $6.3/metric ton versus $29.5/metric ton CO_2 for a combined cycle plant. These values are based on energy required to separate and compress CO_2 from 0.10 MPa (14.7 psia) to 14.48 MPa (2100 psia). For this task, CES plants require 102 kWh/metric ton and a combined cycle plant, using an exhaust absorption/endothermic stripping process, requires approximately 485 kWh/metric ton CO_2.[8] The ideal minimum energy required to isothermally (300 K (80 °F)) compress CO_2, over this specified pressure range, is 74 kWh/metric ton CO_2. Also, an additional cost of $3.0/metric ton, for transporting (pumping) the CO_2 from the generating station to the oil field, was used by Ruether *et al.*[9] and Wallace.[10] Using these values, the total cost for conditioning and transporting CO_2 to the injection site is approximately $8/metric ton for CES plants and the $32/metric ton for combined cycle plant.

BASES FOR COST AND PERFORMANCE DETERMINATIONS

A method for assessing the economics of a power plant is to calculate the unit cost of electricity (COE) produced by the plant.[11] To determine this cost, the following information is used:

A - Unit capital cost, (\$/kWh)
B - Plant net thermal efficiency
C - Fuel cost, (\$/kWh)
D - Operating and maintenance cost, (\$/kWh).

If income from plant by-products is excluded to simplify the calculations, the cost of electricity is given by: COE = A + C + D, where C is a function of B, and where D is conservatively estimated to be D = 0.15 x (A + C). Plant capital cost was based on 85% utilization, 20-year life span, and 15% capital recovery cost.

The comparative electricity costs for various CES plants versus various types of combined cycle plants are listed in Table V. Table V shows that the cost of electricity for CES plants ranges from \$0.041/kWh to \$0.061/kWh. This variation of 33 % illustrates that the unit capital cost (67%) dominates the cost of electricity, while plant efficiency and fuel cost (20%) have a secondary effect. Others report similar result.[12]

Assessment of the other integrated gasification combined cycle (IGCC) plants listed in Table V shows that the cost of electricity varies from a low of \$0.046/kWh with <u>no</u> exhaust gas sequestration to approximately \$0.060/kWh <u>with</u> sequestration. This latter cost is approximately one third higher than the corresponding electricity cost of CES plants using near-term steam turbine technology. CES plants using current steam turbine technology have electricity costs comparable to combined cycle plants that sequester CO_2.

An advantage of the CES technology over combined cycle technology is the lower cost to condition CO_2 for sequestration of US\$4.6/metric ton versus \$29.1/metric ton. This lower CO_2 conditioning cost could provide additional revenue for CES plants where the CO_2 could be used for enhanced oil or coal bed methane recovery, or could be sold as an industrial by-product.

REQUIRED STEAM TURBINE IMPROVEMENT

The economic studies, summarized in Table V, show the cost benefits of improved steam turbine technology over today's designs that operate at 839 K (1050 °F). The goal for the near-term high-pressure turbine is 1089 K (1500 °F). The near-term technology has been set at approximately 1089 K (1500 °F) to eliminate blade cooling when using high-temperature nickel alloys such as: IN 718, IN 617, IN625, Waspaloy or Haynes 230. With modest cooling requirements, existing low cost stainless steel steam turbine materials could be used.

The near-term technology has been demonstrated in the DOE/Solar program[13] by design analysis per ASME Boiler Code and by tests of 105 hrs. The space shuttle fuel turbo pump has operated repeatedly over a twenty-year period at temperatures of 1030 K (1400 °F) and at a pressure of 47.9 MPa (6950 psia), which is substantially higher than the 10.34 MPa (1500 psia) pressure that could be used in the high-pressure turbine.

The near-term intermediate pressure turbine that operates at approximately 1700 K (2600 °F) will require the transfer of existing aero-derivative cooling technology while using warm 500 K (440 °F) steam rather than air as the blade coolant. For the more advanced goal of 1922 K (3000 °F) the latest land-based gas turbine technology developed under DOE’s Advanced Turbine Systems program by Siemens-Westinghouse and General Electric would need modest extension. These turbines required closed-loop steam cooling rather than compressor discharge air to achieve the high turbine efficiency goal of 60%. Recent cascade testing on turbine blades in Japan[14] using steam at 1973 K (3092 ^oF) demonstrated operation on model size stator and rotor blades. The blade heights were 71mm (2.8 in.) and the test pressure was 2.81 MPa (408 psia) for the stator and 3.53 MPa (512 psia) for the rotor. Test times at rated temperatures were 24 minutes and 22 minutes respectively for stator and rotor tests. The stator and rotor blades were made of FSX-414 and CMSX-4 respectively. Both were coated with thermal barrier coating (TBC) of ZrO_2 – 8% Y_2O_3. Since steam cooling has more than twice the cooling capacity than air, it may be possible to use existing low cost steam turbine materials for the intermediate and low pressure turbines without incurring excessive cooling losses – at least for near-term designs.

NEXT STEPS TOWARD COMMERCIALIZATION

In December 2001, the California Energy Commission awarded CES a $2 million grant for co-funding a small power plant. This proposal was jointly developed with Air Liquide and Mirant. Engineering and procurement activities are currently underway, and plant startup is scheduled for early 2004. Since the original proposal and award of this program, several features of the program objectives and the schedule have been modified.

Information obtained from the 20 MW_t gas generator testing, described above, demonstrated certain limitations in the original test program plan and execution. More testing appears to be required in off-optimal design conditions, and additional test time will add to durability data. In an operational environment, the gas generator will require throttling. Such capability will require variable flow control valves and a variety of control feedback loops. These capabilities would enable testing under part-load conditions and under dynamically changing operating conditions. Further, reduced loads will allow longer test durations.

In consultation with the California Energy Commission (CEC), CES has proposed, and the Commission has approved, addition of selected subtasks to the CEC program. An integrated digital control system will be developed for the gas generator. The revised program adds testing of the integrated unit in a stand-alone mode. The added testing time and schedule adjustment will allow full testing of the integrated unit with the control system prior to initiating plant construction and purchase of the remaining plant equipment.

The gas generator test unit is planned to be operated over a range from 0.5 to 5 MW_e (1.5 to 15 MW_t) and independently controlled by a digital control system designed for that purpose. Testing will include full load, part load, and transient conditions. Temperature, pressure, and mass flow rates will be individually varied while other parameters are held constant to evaluate the system's robustness and response to simulated steam turbine throttling. The plant, once on line, is planned to operate continuously for two years to build durability data on the gas generator.

In addition, CES is working on projects in the 20 MW_e to 70 MW_e range, primarily in California. Discussions are also being held with multinational oil companies for possible projects in the Netherlands and Norway. Other potential applications of the technology are being explored, but are not at sufficient levels of development to warrant public discussion.

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